An integrated, self-priming dielectric elastomer generator

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Dielectric elastomer generators are a form of variable capacitor electricity generator with a high energy density and high flexibility. Currently, dielectric elastomer generators require external circuitry which makes the system bulkier and less flexible. In this paper we present a system that minimizes the external circuitry to six diodes so that high energy density and flexibility is maintained at the system level. An energy density of 12.6 mJ/g was experimentally demonstrated, comparing favorably with similarly sized electromagnetic and electrostatic power generators. © *2010 American Institute of Physics*. [doi:10.1063/1.3478468]

Waves and wind are renewable energy sources that can provide large amounts of power. Dielectric elastomer generators (DEGs) show considerable promise for harvesting this energy because they can be directly coupled to large rectilinear motion without gearing, and work efficiently over a broad frequency range.[1] DEG are flexible and have few moving parts, increasing their robustness. DEG can also achieve superior energy densities compared to traditional variable capacitor, piezoelectric, and electromagnetic generators.[1,2]

DEG consist of a compliant elastomer sandwiched between flexible electrodes. Electrical energy can be produced from a stretched, charged DEG by relaxing its mechanical deformation while maintaining the charge on its electrodes. This increases the distance between opposite charges and packs like-charges more densely, increasing the voltage and electrical energy in the system.

The DEG cycle requires a source of electrical charges for priming. Previously, this has been provided by an external high voltage source.[1,3,4] In earlier studies, the self-priming circuit was presented that enabled the system to be initially primed from a low voltage source such as a photovoltaic cell, without the need for a high voltage transformer, reducing system mass, cost, and complexity.[4,5] However, the self-priming circuit required an external capacitor bank to be connected to the generator. The integrated self-priming system presented here does not require this; the only components external to the generator membrane are a small number of diodes. The active DEG membranes are used to store priming charges instead of external capacitors. This reduction in external circuitry means that the energy density of the total system is closer to that of a DEG alone. Also, this system presents the opportunity to produce fully flexible DEG systems.

The integrated self-priming DEG consisted of two pairs of DEG elements (Fig. 1). The DEG were deformed 180° out of phase so that when one pair was stretched, the other was relaxed.

As illustrated in Fig. 2, the integrated self-priming DEG was charged to 10 V before the first cycle from the initial priming reservoir (IPR) and a 5 GΩ resistor ladder (sensor) was used to monitor the DEG voltage during each cycle. The system used some of the generated energy to boost charge in the following manner: when DEG pair 1 moved from a stretched to relaxed state, its capacitance decreased while DEG pair 2 underwent the opposite change in state. In this state current flowed from DEG pair 1 to DEG pair 2. The diodes controlled the current so that DEG pair 1 was electrically connected in parallel and DEG pair 2 was in series. When the deformation was reversed, the DEG pairs toggled state and current flowed in the opposite direction. These toggles between series and parallel configurations resulted in a charge boost to the energy generated by one pair of DEG before it was used to prime the other pair; thus a portion of the generated energy was used to boost the charge in the system. In conventional electronics terms, the system could be described as two charge pumps consisting of variable capacitors operating 180° out of phase. The mechanically induced capacitance oscillations provided additional energy and voltage fluctuations that were required for the charge pumps to operate. A detailed discussion of self-priming DEG can be found in a previous study by our group.[4]

The DEG were produced by prestretching VHB4905 membranes equibiaxially to nine times their original area and adhering them to a frame. An inner hub was fixed to the center of the membrane (see Fig. 1). Two compliant elec-
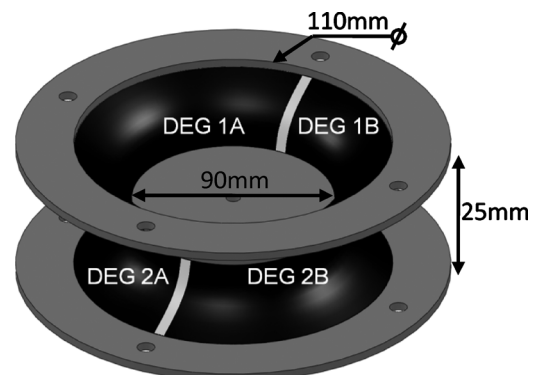

FIG. 1. The generator consisted of two pairs of DEG oscillated 180° out of phase.

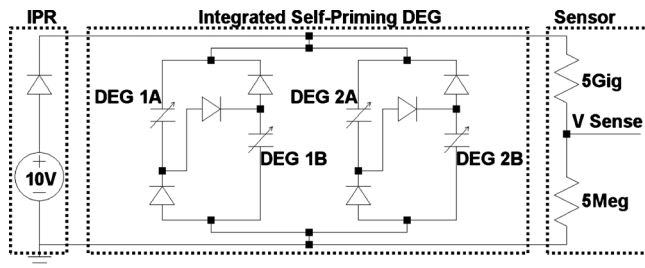[a]Electronic mail: thomas.mckay@auckland.ac.nz.

FIG. 2. A schematic of the electrical system which consisted of an initial priming reservoir, integrated self-priming DEG and high voltage sensor connected in parallel.

FIG. 3. Voltage output vs time for an integrated self-priming DEG deformed at 3 Hz.

trodes were added by brushing Nyogel 756G carbon grease onto each membrane surface, thus forming a pair of DEG. The two DEG pairs were fixed together at their inner hubs and their outer frames were separated by spacers. The DEG system consisted of ~0.35 g of active material. The inner hub was cycled sinusoidally out of plane at an amplitude of 20 mm and frequency of 3 Hz.

Since the system consisted of two DEG pairs being cycled 180° out of phase, the system acted as a frequency doubler and two voltage peaks were produced per cycle. This is demonstrated in Fig. 3 where six peaks are visible between the times of 3–4 s when cycled at 3 Hz. Figure 3 also demonstrates that this system is able to voltage boost. The output voltage increased from 10 V to 2 kV in 4.7 s. Boosting the voltage is desirable as it increases DEG efficiency.[1,4,6]

The generated energy in one cycle was calculated as the sum of the energy delivered to the sensor and the change in energy stored in the system.[4] A maximum energy output of 4.4 mJ was produced during one stroke, corresponding to an energy density of 12.6 mJ/g, and a power density of 37.8 mW/g. This energy density is comparable to the practical maximums for piezoelectric (17.7 mJ/g), electrostatic (4 mJ/g), and electromagnetic (4 mJ/g) generators of similar size.[2] The energy density is superior to the 2.8 mJ/g figure achieved for the self-priming DEG system presented previously.[4] A key difference from the previous results is the lower rated reverse current of the diodes used in this study, which reduces losses. Also, the larger inner diameter DEG used here has a smaller active mass. It should be noted that our energy density is far below a theoretical limit of 2700 mJ/g presented by Koh *et al.*[7] Strategies for bridging this gap include driving the DEG to higher electric fields, frequencies, and strokes, improved DEG design, and better electrical load matching.[4]

The mass of the external power supply was not considered in the energy densities quoted above. This additional mass is reduced in the integrated self-priming system. For instance, the mass of the components in the external capacitor bank of the previously presented self-priming circuit was 13.4 g; this mass has been reduced to 1.26 g in the similarly sized integrated self-priming system. By including this external mass the energy density of the system presented here becomes 2.7 mJ/g whereas the energy density of the previously presented self-priming DEG becomes 0.06 mJ/g. The
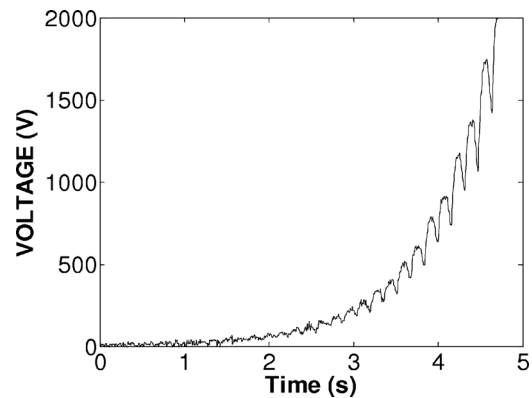
diodes used are rated to withstand a forward current 1000 times higher than that in our experiments. Therefore, no additional external mass would be required for an integrated self-priming circuit producing over three orders of magnitude more power, whereas a significantly larger mass of capacitors would be required for a self-priming circuit with an external capacitor bank.

Using our previously presented method,[4] the maximum measured integrated self-priming DEG efficiency was 7.8%, which is similar to that achieved by the similar system with an external capacitor bank.[4] The major source of energy loss is mechanical, due to the viscoelastic nature of 3M VHB4905. DEG produced from less viscous materials such as silicone or polyurethane present opportunities to achieve higher efficiencies.

Pelrine *et al.*[1] produced DEG shoe inserts that generated electricity from the heel's impact energy when walking, demonstrating the potential of human motion as a source of electrical power for wearable devices. The only rigid components in the integrated self-priming DEG system presented here are the diodes. Since it does not require a rigid, bulky external priming source, it presents an opportunity to produce generators that can be comfortably interfaced with the human body or robots made from flexible materials, that can ride ocean waves without buoyancy aids, or actively flex with the breeze like a tree.

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