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Capacitive energy harvesting using soft dielectric elastomers: Design, testing and impedance matching optimization

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Energy harvesting based on dielectric elastomeric materials, in nature, embodies a capacitive kinetic energy conversion mechanism where the soft DE generator (DEG) interactively cooperates with conditioning circuits. Based on the principle of passive charge pump, this paper proposes a design concept for a self-cycling energy harvesting circuit driven by DEG cyclic deformation, with its essential behavioral mode laid on the electrical reciprocity between the DEG intrinsic capacitor and another capacitor connected in series. By detailed simulation experiments, the working process and dynamic characteristics of the proposed system, as well as the influence of circuitual, operating, and load parameters on system performance are quantitatively investigated, with intensive discussions for the time delay behaviors caused by changes of load resistance, along with the different impacts of its value regions. Then, the theoretical analyses are effectively validated by experimental tests for a specially-designed annular DEG prototype. Under the global optimization framework based on impedance matching, this paper presents some guidelines for circuit design, e.g., the selection criteria of the capacitance and load resistance. In addition, the potential of this emerging technology is also demonstrated by experiments. © 2018 Author(s).

I. INTRODUCTION

With a soft variable capacitor, mechanical energy can be used to pump charges from a low electrical potential to a higher one, so that the electrical energy difference can be harvested. Although the fundamental seems to be simple and has been proven, it is still not clear to what extent the approach is practically useful.1

Such soft capacitors can be achieved by using a type of membranous polymers so-called dielectric elastomers (DE, mostly derived from acrylics and silicones). Belonging to the family of electro-active polymers (EAPs) which can exhibit large strains under electrical stimuli, DE have suggested their favorable use as actuators in adaptive structures, such as optic switches, tactile displays, grippers, artificial muscles, etc.2–7 As an inverse process of actuation, the aforementioned electrical energy increasing controlled by the capacitive kinetic mechanism is referred to as DE-based energy harvesting, or generation. Compared to other functional materials, DEs can offer an attractive potential of applications in energy harvesting principally because of their high specific elastic energy density up to 3.4 J/g, 100 times greater than those available with piezoelectric ceramics.8 They also enable soft, lightweight, and green energy harvesters with excellent mechanical impedance.

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matching to human muscle, which makes them exhibit good performance especially in low frequencies with large deformation. As a consequent, various DEG prototypes capable of harvesting mechanical energy from different-scale energy sources, e.g., from human gait to wind and ocean waves, have been reported.\textsuperscript{5–17}

More complicated than the actuation behavior, DE-based energy harvesting is a continuous and multi-stage process characterized by cyclic deformations of the DE generator (DEG) that is essentially a variable capacitor in electrical sense. In one operation cycle, the orderly extension/recovery of the soft device possesses certain interactions with the external inputs, the output loads, as well as the on-off control of different functional circuits, showing a systematic behavior mechanism in which multiple factors are affected and restricted each other. A number of fundamental investigations have been focused on this issue, including its energy conversion mechanism and basic electromechanical behaviors, the optimization for cyclic path and control strategy, as well as the primary factors affecting the energy harvesting performance.\textsuperscript{18–24} However, most of these studies, such as maximization of the energy harvested,\textsuperscript{25–30} are usually conducted under idealized assumptions, and only characterize the behaviors of the solo DEG. While the interactive synergy between the deformable device and the conditioning circuit which is precisely crucial to the practical use of this emerging technology, seems to be ignored yet to some extent.

Actually, a number of studies have been reported on circuit design of piezoelectric-based energy harvesting.\textsuperscript{31–36} But for dielectric polymers, there is an intractable feature that they cannot be self-polarized through deformation, and need an external power supply to accomplish this task. Once the electrical energy captured by DEG is harvested, the de-energized device must be polarized again so that energy harvesting can continuously proceed. Therefore, the basic role of the circuit for DE-based energy harvesting is to comply with and allow two alternating functions, i.e., supply charge to the generator and extract it after each voltage boost. Mckay T et al.\textsuperscript{37,38} proposed and designed a self-priming circuit by which the initially applied low bias voltage can be automatically boosted to a higher level through DEG deformation cycles. C. Jean-Mistral et al.\textsuperscript{39} presented a new mode which uses the edge effects of the electric field introduced by electret to polarize the DE membrane, making the system out of dependence on a separate external supply. Eitzen et al.\textsuperscript{40} proposed a circuit topological that matches the bilateral DC-DC switching of high-voltage power supply. As for harvesting of the electrical energy, Lo et al.\textsuperscript{41} put forward two conditioning circuits, i.e., based buck converter and passive charge pump, respectively. Even so, the work in this area is yet insufficient and requires further in-depth exploration.

In this paper, we will present an energy harvesting circuit prototype, in an attempt to achieve the above functions with a simple and convenient form. The essential design concept is based on the electrical reciprocal behaviors between the DEG deformable capacitor and another capacitor in series with it. By this, the alternation of DEG charging (polarization) and discharging (electrical energy harvesting) can be carried out continuously and automatically through the cyclic deformation of the soft device, thereby getting rid of the periodic dependence on the external power source. In our design, the output current can be controlled by adjusting the component parameters and operate parameters, which overcomes the shortcoming of the scheme presented in Ref. 41 where the output can only be restricted to the forward turn-on voltage of the Zener diode. In addition, a bilateral rectifier bridges is adopted to increase the time efficiency of energy harvesting. In response to this design concept, we attempt to reveal the synergistic effects of some major parameters on system performance through meticulous simulation analysis and experimental tests, laying emphasis on impacts of the fixed capacitor and load resistance. The time constant variation and voltage delay response caused by changes of the above two parameters are discussed for the first time in this paper. Finally, we will present some specific guidelines for circuit design in a global parameter optimization framework based on impedance matching.

**II. CONDITIONING CIRCUIT DESIGN**

**A. Principle of DE-based energy harvesting**

In a DE-based energy harvesting system, DEG, which serves as a core functional device, is a common carrier of elastic strain energy and electrostatic energy. The essence of this process is that,
DEG changes its strain state and intrinsic capacitance through a periodic and orderly elastic deformation, to realize an incremental conversion of electrical energy. Cooperated with the conditioning circuit, the electrical energy is eventually captured and converted into an appropriate form that can either power external loads in real time, or stored as an independent power source. Fig. 1 illustrates the fundamental principle of DE-based generation. In brief, a typical cyclic process consists of sequential switching between four energy states, or four basic steps: mechanical stretching (mechanical energy input), charging (electrical energy input), elastic recovery (energy conversion), and electrical energy output (be harvested). The increase of the potential energy during the recovery process is essentially attributed to the negative work done by the electrostatic stress (so-called Maxwell stress) inside the membrane.

In practice, energy harvesting can take a number of specific ways, only generally follows the four stages of division. Each stage involves the behavioral synergy or cooperation with the control or conditioning circuit. Therefore, it is crucial to design such a circuit that meets the requirements of energy harvesting functions, for instance, easy to be achieved, and has a small loss. More importantly, the harvested electrical energy should be recycled and supplied to the DEG to polarize it again. In this way, the whole process can be continuously carried out without the periodic dependence of the external power supply (only the first pre-polarization is required).

### B. Circuit prototype and analysis

In this study, based on passive charge pump effect, we propose a self-cycling conditioning circuit model for harvesting electrical energy automatically, as shown in Fig. 2. The overall circuit consists of a DEG capacitor (with intrinsic capacitance denoted as $C_{int}$), a fixed capacitor $C_f$, a bilateral diode rectifier bridge, an electrical load $R_L$, and a high DC bias supply $V_0$. A more realistic circuit model should take into account the resistance of the electrodes $R_s$, and that of the dielectric elastomer itself, $R_p$. The DEG is thus equivalent to the model where a variable capacitor $C_{int}$ and $R_p$ are connected in parallel and then in series with $R_s$, to describe the parasitic represented by leakage current (as illustrated in Fig. 2(a)).

The pre-charge process (when the trigger switch $K$ closed), as depicted in Fig. 2(b), determines the initial operating point of the system. To obtain better performance, DEG is generally at its maximum stretch while being pre-charged, i.e., $C_{int}(0)=C_{max}$. The total charge stored in the circuit, $Q_T$, then consists of two parts after the pre-charging is completed.

$$Q_T = V_0 C_{max} + V_0 C_f$$

where the two items of right side of the equation denote the charge stored in $C_{int}$ and $C_f$, respectively.

According to Section II A, after being pre-charged, the energy harvesting process specifically includes two alternating steps: 1) DEG gets relaxed from the maximum stretch, the intrinsic capacitance decreasing and the charge outflowing to supply the load (power is harvested and utilized). This
FIG. 2. The equivalent electrical representation of the energy harvesting system: (a) The initial state; (b) Pre-charge phase; (c) Discharge phase; (d) recharge phase.

step, in terms of DEG electrical behavior, is called as discharge phase. 2) DEG is stretched again, the capacitance increasing and the charge flowing back into DEG. It is therefore recharged but no longer dependent on any external power. Correspondingly, this step is defined as recharge phase of DEG.

The equivalent circuit of DEG discharge phase is shown in Fig. 2(c). Since the charge in DEG cannot mutate instantly, the decrease of $C_{int}$ will initially lead to an increase of the voltage across the device (denoted as $V_{int}$). It consequently brings a potential difference between DEG and $C_f$, pushing the charge flow through $C_f$ and the load $R_L$ (a tiny part may be leaked through the membrane due to its non-ideal dielectric properties). The injection of the charge makes the voltage across $C_f$ (denoted as $V_f$) increase accordingly, which would reduce the voltage difference between it and the DEG (the latter is meanwhile becoming smaller due to the outflow of charge). However, under certain parameter conditions, there always exists the relation $V_{int} > V_f$. Until at the time of $t=0.5T$, i.e., the end of the relax phase ($T$ is the behavioral period of DEG), the two voltages tend to be the identical (labeled as $V^\ast$). $V^\ast$ is also the maximum value of $V_f$.

The above process can be briefly described by the following kinetic equations. The current flowing through the main loop is expressed as

$$I_R = \frac{d(V_{int}C_{int})}{dt} - I_{leak} = C_{int} \frac{dV_{int}}{dt} + V_{int} \frac{dC_{int}}{dt} - I_{leak}$$  \hspace{1cm} (2)$$

where $I_{leak} = V_{int}/R_P$ denotes the leakage current through the dielectric membrane.

According to Kirchhoff’s voltage law (KVL), we can obtain

$$V_{int} = V_f + I_R(R_S + R_L)$$  \hspace{1cm} (3)$$

The last two items on the right side of Eq. (3) denote the voltage dissipated by the electrodes and that across the load, respectively. As for the voltages across the two capacitors, they each represent the superposition of the initial static value (bias voltage) and the fluctuation part caused by the charge change (for the DEG capacitor, the effect of change in the capacitance itself will also be coupled). They can be specifically expressed as follows

$$V_{int} = \frac{1}{C_{int}(t)} \left( V_0 C_{int}^{max} - \int (I_R + I_{leak}) dt \right)$$  \hspace{1cm} (4)$$

$$V_f = V_0 + \frac{1}{C_f} \int I_R dt$$  \hspace{1cm} (5)$$

In fact, for this passive circuit, the two capacitors in turn act as a power supply to achieve the functions of electric energy harvesting and DEG re-polarization. Obviously, the difference of the above two voltages is critical to system performance.
Fig. 2(d) shows the equivalent representation for the recharge phase. After discharge, the circuit system reaches a temporary balance. When DEG is stretched once more, $C_{\text{int}}$ increases again while $V_{\text{int}}$ decreases due to the tardive change of charge. The resulting potential difference drives the charge to flow from $C_f$ to DEG (repaying the charge that flows into $C_f$ before). Similarly, in this phase, the relation of $V_f > V_{\text{int}}$ always exist, although $V_f$ is gradually decreased as the charge flows away. The circuit equations for this phase can be derived by reference to the situation of discharge, and will not be presented in detail.

Fig. 3 gives some time curves of the principal circuit parameters along with the change of DEG capacitance. It may provide an intuitive description and interpretation of the above process. When $C_{\text{int}}$ varies according to different laws, the resulting variables also change in different ways. For simplicity, two typical regular $C_{\text{int}}$ variations here are presented for comparison, i.e., the sinusoidal form (left) and the ramp form (right).

**FIG. 3.** Time-varying curves of electrical variables 2 cycles. (Left: sinusoidal; Right: ramp): (a) DEG equivalent capacitance; (b) Voltage across DEG vs. Voltage across $C_f$; (c) Load current $I_R$. 
When $C_{\text{int}}$ varies in sinusoidal, the simulation results are well consistent with earlier theoretical expectations: In phase 1 or discharge phase ($0 \rightarrow 0.5T$), along with the decrease of $C_{\text{int}}$, $V_{\text{int}}$ will first increase, driving the charge outflow, and then decreases for the reason that the effect of capacitance decrease changes to be less than that of charge losing. The voltage across $C_{f}$, however, shows a monotonous and slow rising trend in this interval. This makes the difference between them, i.e., the voltage drop on the load, presents an approximate peak wave shape in each half cycle. The load current, of course, certainly has the same shape, as shown in the left sub-graph of Fig. 3(c). As for phase 2 or recharge phase, it can be clearly seen that the DEG voltage $V_{\text{int}}$ shows anti-symmetry centered on the balance voltage, while the other two variables, $V_{f}$ and $I_{R}$, are both basically symmetrical with their respective changes in the first phase.

Yet when $C_{\text{int}}$ changes in the ramp form, the situation will be different. Still choose the first half cycle ($0 \rightarrow 0.5T$) as a case example. During the process of DEG capacitance decreasing, the voltage across it will abruptly jump to a value at the very start, and then steadily increase in sync with the voltage across $C_{f}$. Since the potential difference is nearly constant, the current in this interval is substantially kept constant. At the time of $t = 0.5T$, the voltage will produce a symmetrical saltation along with the switch of DEG’s behavioral state. This phenomenon may be interpreted as follows. At the moment immediately prior to the turning point, $C_{\text{int}}$ is still decreasing and there is a positive voltage difference between it and $C_{f}$. However, just at the next moment, a reverse increase of $C_{\text{int}}$ occurs. $V_{\text{int}}$, hence needs to abruptly decline to form a reverse potential difference with an equal magnitude to maintain the circuit balance. The second half cycle or the recharge phase follows the same principle. In short, at each half-cycle time node, the DEG voltage and the current curves will appear singularities because of the voltage salutations.

The above process can also be analyzed by the Q-V diagram. It is visually a closed loop in electrical plane whose area is numerically equal to the energy harvested during a cycle of capacitance variation. An ideal Q-V diagram is a rectangle that is internal to the triangle OAB, but it is hard to apply in reality. Fig. 4 presents the Q-V diagram of our circuit. For the foregoing two capacitance change cases, the two Q-V path loops are approximately ellipse (for sinusoidal change) and parallelogram (for ramp change), respectively. They are tangent to two points, A and B, corresponding to the maximum and minimum capacitance of DEG, i.e., $C_{\text{int}}^{\text{max}}$ and $C_{\text{int}}^{\text{min}}$ respectively. It can be seen that for the capacitance variation with the same amplitude, the energy harvested by different change form is not identical, and the sinusoidal form performs better than another one.

### III. SYSTEM ANALYSIS FOR GLOBAL OPTIMIZATION

#### A. Influence analysis of key circuit parameters

In general, the bulk resistivity of DE material is at a high level of $10^{15} \, \Omega\cdot\text{cm}$, and thus can be approximately regarded as an insulator in theoretical analysis. While that of the electrode, usually no
more than a few hundred ohm, e.g., for the commonly used conductive carbon paste (MG Chemicals 846), the value is about 114 $\Omega \cdot \text{cm}$. Compared to the load resistance under normal operating conditions, the two resistors are often negligible in theoretical analysis. Therefore, they will not be taken into account in the discussion below.

1. The fixed capacitor

As we have seen, the circuit prototype proposed is very simple in its form. Different from the SHE circuit widely used in piezoelectric energy harvesting, there is a fixed capacitor connected in series with DEG in our circuit. Collaborating with DEG capacitor and alternately changing in charge/discharge states, it provides a necessary condition for power transfer and circulation. The phase of DEG’s recovery and discharging, apparently, is not only the process where electrical energy is effectively harvested, but also the process during which the dynamic charge is stored and transited by $C_f$. While for the reverse phase of DEG’s re-stretch and charging, the device is re-polarized, accompanied by the charge release of $C_f$ (repaying the accumulated charge in the previous phase). $C_f$ here plays the role of a bias power source. It is this reciprocal flow of the charge driven by the DEG deformation that allows the system to possess a "self-cycle" functionality that no longer relies on an external power supply.

As a basic parameter of the circuit, the value of $C_f$ has a very important impact on the system function and performance regulation. Ignoring the charge leakage, the net out-flowing charge $Q_R$ from DEG (i.e., the charge flow through the load) in half a behavioral cycle can be obtained according to the variations of DEG capacitance and voltage

As mentioned above, at the time $t = 0.5T$, there will be $V_f = V_{eq} = V^*$. The voltage $V^*$ is a result of the charge redistribution between DEG and $C_f$ after the system has stabilized temporarily. It thus can be expressed as

$$Q_R = \int_0^{T/2} I_R dt = V_0 C_{int}^{\text{max}} - V^* C_{int}^{\text{min}}$$

where $Q_T$ has been defined by Eq. (1).

By substituting Eq. (7) into Eq. (6), we arrive at

$$Q_R = \int_0^{T/2} I_R dt = V_0 \left( C_{int}^{\text{max}} - C_{int}^{\text{min}} \right) \left( \frac{C_f + C_{int}^{\text{max}}}{C_f + C_{int}^{\text{min}}} \right)$$

Remain the other parameters unchanged, more charge would flow through the load at a higher value of $C_f$. The relation of $C_f \gg C_{int}$ thus should be satisfied in the design. It can be explained fundamentally that such a considerable capacitance difference leads to a larger voltage difference between the two capacitors, consequently driving more charge to participate in the flow. However, as to be discussed, too large $C_f$ may have adverse effect on the time characteristics of charge change and voltage response. Therefore, choosing an appropriate $C_f$ needs to combine other factors into consideration.

2. Time delay and the impedance

In the present design, the transient charge flows back and forth between DEG and $C_f$. As we know, the time constant of the charge/discharge process is determined by the size of capacitance and load resistance ($\tau = RC$). When the time constant reaches a certain order of magnitude, the voltage response will significantly lag behind the change in capacitance, and consequently influence the change laws of other electrical variables.

Keeping the other parameters unchanged, Fig. 5 shows the simulation results when the load resistance is further increased (take the case that DEG capacitance changes in sinusoidal rule as an example). As can be seen, the voltage waveforms of both the DEG and $C_f$ undergo shape changes compared with Fig. 3. And this time delay is more obvious in DEG’s charging phase during which $C_f$ is employed as a discharge power supply. The reason is not difficult to infer. Since $C_f$ is much larger than $C_{int}$, there must be a difference in the time constant when they alternately serve as
FIG. 5. Electrical variables under larger load as a function of time: (a) Voltage across DEG vs. Voltage across $C_f$; (b) Load current.

power supplies, resulting in asymmetry of the voltage and current between the two half cycles. As shown in Fig. 5(b), for the current, this asymmetry appears more explicit: one has a larger peak and a shorter period, while another is just the opposite. In addition, the time lag will also make the charge flowing into $C_f$ does not participate in the flow collectively, but leaving a small portion from the first cycle. An intuitive presentation in the figure is that the minimum value of $V_f$ is slightly larger than the bias voltage $V_0$. All of these problems are unfavorable for energy harvesting.

B. Multi-parameter collaborative analysis

It can be seen from the above analysis that the influences of the circuit parameters on the system performance are interdependent. Thus, in the design, the sizes of the capacitor $C_f$, intrinsic capacitance $C_{int}$ and load resistance $R_L$, need to be considered in coordination and matched reasonably to achieve the best performance.

By means of the general software platform, i.e., MATLAB/Simulink, the influence of circuit component parameters on energy harvesting performance can be simulated. Denote the harvested energy of one circle in steady state as $E_h$, acting as an evaluation index of system performance, it thus can be written as follow

$$E_h = W_R = \int_0^T I_R^2(t)R_L dt$$

(9)

Fig. 6 illustrates the simulation results of the harvested energy $E_h$ as a function of with $C_f$ and $R$, when the DEG intrinsic capacitance varies across different scales. The simulation conditions are set as: bias voltage $V_0=1200$ V, operation frequency $f = 1$ Hz, and intrinsic capacitance changes according to the law of harmonics. In the three-dimensional graph, the two variables in the horizontal plane adopt logarithmic coordinates. Comparing the three sub-graphs depicted in Fig. 6, it can be seen that with the tenfold increase of the range of $C_{int}$, the harvested energy also increases synchronously. This indicates that this variable is indeed the most important factor that determines the amount of the energy harvested.

The impact of the load resistance varies with the value range. When the resistance is relatively small, in the certain conditions, DEG can be approximated as an alternating current source, and the load resistance hardly has any influence on the average current, i.e., there is a linear relationship between the harvested energy and load resistance (exponential shapes here are presented thanks to the use of logarithmic coordinates). As the load resistance continues to increase, the current trends to decline, and the circuit system enters a zone where the output energy rises very gently with increase of the load resistance. After that, with further increase of the resistance, the current begins to drop sharply, and the output energy, in consequence, declines more dramatically too. In summary, as the load resistance gradually increases, the system behavior will transform from the linear zone (energy multiplication zone) into the nonlinear zone. The latter can be further divided into two sub-zones: a flat zone and an attenuation zone. The linear zone and the flat zone are both considered suitable operating regions for energy harvesting. Obviously, the specific distribution of this load interval, that
FIG. 6. Three-dimensional diagram of the energy harvested under different parameter conditions ($C_{\text{int}}$ vary according in sinusoid form, @ $f=1$ Hz, $V_0=1200$ V): (a) $C_{\text{int}}$ varies in [2∼10] nF; (b) $C_{\text{int}}$ varies in [20∼100] nF; (c) $C_{\text{int}}$ varies in [200∼1000] nF.

is, the resistance range corresponding to each interval, will be affected by both $C_{\text{int}}$ and $C_f$, but the former is dominated. In fact, when $C_f$ gets large enough (the threshold is about $C_f > C_{\text{int}}^{\text{max}}$), its impact on system behavior and performance is nearly negligible.

As for the above law, it performs most typically while $C_f$ is relative larger. On the contrary, when $C_f$ is small, there will appear a steep energy peak in the large resistance zone, which is about 2 times of the steady peak in the case of larger capacitance. In spite of this, we do not advocate the use of a smaller $C_f$ in practice, because: 1) the peak is too steep, and the maximum harvested energy corresponds to a small range of resistance. That is, the energy is more sensitive to resistance changes; 2) the larger current is mainly due to the higher charge transfer velocity under small capacitance conditions, but in fact, according to the previous analysis, the charge involved in the flow is relatively less in this case. This will affect the efficiency of energy harvesting, especially in practical applications where the charge loss is always inevitably existing.
Through the analysis of the above simulation data, as well as the experimental testing and verification, we will draw a conclusion that in practical applications, as long as the following conditions are met, \( C_f > C_{\text{int}}^{\text{max}} \) and \( RC_{\text{int}}^{\text{max}} \leq 0.01T \) (\( T \) denotes the behavioral cycle). DEG can be approximately equivalent to a constant current source, and the ideal electrical energy output would be achieved under a specific load.

**C. Impedance matching optimization**

As is evident from the above discussion, the load resistance has significant effects on system performance. Under certain working conditions, there must be a best matched resistance to make the system performance get a full play. According to the maximum power transfer theorem, such an optimal value is met when the load impedance equals to that of the source as viewed from its output terminals. As mentioned previously, in the proposed circuit, the DEG and the capacitor in series with it can be collectively regarded as a power supply. The equivalent source impedance then can be derived as

\[
Z_{\text{source}} = \frac{1}{j\omega C_{\text{eq}}} = \frac{1}{2\pi f C_{\text{eq}}}
\]

therein \( C_{\text{eq}} = \frac{C_{\text{int}} C_f}{C_{\text{int}} + C_f} \approx C_{\text{int}} \) for the case of \( C_f \gg C_{\text{int}} \).

Obviously, the DEG intrinsic capacitance and the operating frequency play important roles in determining the optimal load resistance. Under this theoretical framework, in order to further explore the influence of other control parameters such as the bias voltage on system performance, more detailed simulation experiments are carried out.

Assume that DEG capacitance varies in a range of 2 ∼ 10 nF according to cosine law (i.e., \( C_{\text{int}} = 4 \cos(2\pi ft) + 6 \) nF). The frequency \( f \) is fixed as 1 Hz at first, while the bias voltages are set to 400V, 800V, 1200V and 1600V, respectively. Fig. 7 illustrates a group of simulation curves for the electrical energy harvested (in one cycle) under different bias voltages, as a function of load resistance. It can be seen that as the bias voltage increases, the harvested energy rises nonlinearly (for example, the maximum energy at 400 V is only 0.79 mJ, but the value at 1600 V reaches 12.63 mJ, with an increase nearly 16 times). Meanwhile, it can also be found that for different bias voltages, the laws of the harvested energy changing with the load resistance are basically the same: when the resistance is small (∼ 10 MΩ), its increase will result in a linear increase in energy (different slopes, of course, for different bias voltages). It is then followed by a zone where the energy slowly and nonlinearly increases with the resistance (corresponding to the flat zone under the logarithmic coordinates in Fig. 6). The optimal resistance corresponding to the maximum energy, that is, the turning point from the zone where the harvested energy slowly increases to the zone where the energy becomes lowered, is around 30 MΩ. This result is consistent with the maximum power transfer theorem. That is to say,
the bias voltage does not affect the optimal resistance, but influence the size of the harvested energy strongly.

Then keep other conditions unchanged, and make the bias voltage remain as 1200 V. The operating frequencies are set as 0.5 Hz, 1 Hz, 1.5 Hz and 2 Hz, respectively. The simulation results for the harvested energy as a function of load resistance are shown in Fig. 8.

Also accordant with theoretical expectations, for different frequencies, the optimal load resistances, as well as the suitable working ranges of resistance, are different. A smaller frequency corresponds to a larger optimal load resistance instead: at the equally spaced 4 frequencies from 0.5 to 2 Hz, the optimal resistance values are approximately 70 MΩ, 30 MΩ, 20 MΩ, and 15 MΩ in sequence. However, the maximum energy values at different frequencies are basically the same.

IV. EXPERIMENTS

A. Device fabrication and experiment platform

In order to construct the DE-based energy harvesting prototype, an annular DEG is fabricated according to the procedures described in Fig. 9(a). Thanks to the material properties, DEG can theoretically be tailored into structures of arbitrary shape. However, in this study, we propose an annular-shaped DEG structure with equal radial deformations, for it can achieve a membrane
deformation type very close to the ideal equi-axially stretch mode, which has been proven by previous investigations to be the most beneficial for generation. Fig. 9(b) illustrates the deformation states before and after the device is driven.

In our design, each DEG device consists of two basic units. When the two units are bonded together back to back, the faying surface then serves as a public electrode (e.g., the anode) and the two outboard surfaces are set as interconnected electrodes whose polarity is opposite to that of the public one (in this step the air between two membranes should be exhausted so as to reduce its effects on the capacitance). This design, compared with the conventional way of connecting two capacitor units in parallel, is more compact in structure by reducing the size of the device in the thickness direction, as well as the complexity of electrical leads. Moreover, this basic device can be more conveniently expanded to a stacked structure. Here the DE membrane of VHB 4910 (3MTM) is employed as the base material, while the compliant electrodes are made by 846-type carbon paste (MG Chemicals). As described previously, each DEG unit contains of two circular rings as rigid frames. In this fabrication, the outer and inner diameters of the larger ring are 100 mm and 80 mm, respectively. While for the smaller one, its outer and inner diameters are 30 mm and 8 mm, respectively.

The DEG energy harvesting performance experimental setup is shown in Fig. 10. It consists of two parts, a motion control platform and an energy harvesting PCB circuit. The former is composed of a computer, an electric cylinder and a series of control components. The computer is programmed to control the servo system and drive the motor rotate in the specified manner. The rotation of the motor, through the screw transmission system integrated in the electric cylinder, makes the push rod of cylinder output a linear motion. It then drives the inner ring of DEG to reciprocate linearly along the direction perpendicular to the plane of the device, so that the DE membrane is periodically stretched and relaxed. In this way, we can programmatically control the tensile ratio, tensile rate and deformation direction of DEG, to simulate various loads and operating conditions during the energy harvesting cycle conveniently.

B. Results and discussions

In this section, we will validate the proposed circuit through performance tests for our annular DEG. We set the uniform reciprocating stroke (the displacement of the device’s inner ring) as 45 mm, and the operating frequency as 1 Hz. Under certain bias voltages and load resistances, we can measure the current and use it to calculate the harvested electrical energy. Two groups of comparative experiments are performed, in which a 3×3 pre-stretched basic annular DEG is employed. For the first group, the other parameters kept unchanged, the harvested energy values are tested and calculated at the bias voltage of 400V, 800V and 1200V, respectively, and compared with the simulation results, as shown in Fig. 11(a). And for the second group, to explore the impact of operating frequency, the harvested energy at 0.5 Hz is also tested and calculated (the bias voltage is set as 1200V), and compared with their respective simulation results, as shown in Fig. 11(b). Each experimental data in the figure is the average of five testing runs.
FIG. 11. Comparisons of the energy harvested between experimental and simulation results: (a) At different bias voltages; (b) At different operating frequencies.

As can be seen, for each experimental condition, the experimental values are not completely consistent with the simulation. In spite of this, due to the viscoelasticity of DE materials especially VHB acrylics (this viscoelastic behavior appears to be more complicated under dynamic conditions, see Refs. 44 and 45), as well as those systematic or random factors in experiments, errors may be inevitable. Overall, there is a good agreement between the simulation and experimental results. It not only verifies the rationality of the proposed equivalent circuit model, but also confirms the parameter influence laws on the system performance derived from the previous simulations. In addition, through further calculations, it can be obtained at 1200 V, the optimal load is about $27.25 \Omega$, the corresponding energy density is 4.24 mJ/g and power output 4.24 mW.

V. CONCLUSION

DE-based energy harvesting is a kinetic circulation system composed of soft DEG devices, conditioning circuits, as well as external loads. For its research, more attention should be paid to the system-level behaviors and characteristics. The simple circuit prototype proposed in this paper, not only succeeds in getting rid of the periodic dependency on the external power supply, but provides continuous current to electrical loads automatically by means of the cyclic deformations of DEG, without needing for any additional buck converters.

The key to the ‘self-cycling’ operation of this system is that the DEG and the capacitor in series alternately serve as the power supply, and drive the charge bilaterally flowing through the load by means of the potential difference between them. The two circuit functions required, i.e., electrical energy harvesting and DEG re-polarization, are therefore unified into one process. This results in a combined effect of multiple parameters on system performance. By a series of simulation experiments based on parameter influence analysis, the global parameter regions according to optimal behaviors are consequently found, and a few guidelines for circuit design are recommended. The experimental tests for a kind of annular DEG verify the conclusions drawn from simulations well. The tests also show that using a very small amount of material (less than 1 g), effective electrical power in milliwatts can be obtained even at low frequencies (~1 Hz). This demonstrates not only the viability, but the potential of such an emerging technology. Nevertheless, how to combine other factors such as material properties and structural geometry, into a more broadly global analytical framework, to improve the energy conversion efficiency and optimize system performance further, still remains a complicated issue that needs to be studied in depth.

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