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In order to solve the problem that a dielectric elastomer generator (DEG) requires an external high voltage bias supply to improve the autonomy and security of the power generation system so that it could adapt to a changeable environment, and to improve the efficiency of power generation, a new self-biasing circuit integrated with a self-supplementary circuit has been proposed in this paper. Under the same input conditions, the maximum output potential of the new self-biasing circuit is 2.23 times that of the traditional circuit. The pumping capability of the self-biasing circuit is greatly improved. At the same time, based on this circuit, in order to explore the factors affecting the energy conversion of the DEG, the overall electromechanical parameters of the circuit are compared and optimized by simulation experiments in this paper. The simulation and experimental results show that the capacitance-to-strain ratio of DEG and the mechanical frequency should be as large as possible within the safe range to obtain larger output potential, and the capacitance of charge pump should be 0.75 times of the capacitance of DEG in the initial state to improve efficiency.

ABSTRACT

INTRODUCTION

Dielectric elastomer generator (DEG) is a miniature energy harvesting device based on the variable capacitance principle to collect vibration energy in the environment, consisting of a dielectric elastomer (DE) material and coating. The surface consists of flexible electrodes that have a "sandwich" structure. As a new type of multifunctional intelligent material, the DE is mostly used in power generation, drives, and sensors because of its electrical characteristics of variable capacitors. In recent years, domestic and foreign scholars have carried out profound research in the field of power generation. According to the characteristics of the DE's own energy density, flexibility, light weight, and large deformation, it can be used in renewable energy fields such as ocean energy and wind energy and has broad application prospects. However, each power generation cycle must be charged to the DE by adding high-voltage bias supply, which limits the application of the DEG.
electromechanical parameters that best match the new charge pump circuit.

**CIRCUIT DESIGN AND SIMULATION**

**Working principle of the self-biasing circuit**

At present, there are three main types of self-biasing circuits applied to the DEG: (1) power electronic converter circuit, (2) charge pump circuit, and (3) integrated self-biasing circuit. Figure 1 is a typical buck-boost converter circuit, and its working process is as follows: when the DE is under tension by an external force, the switch $S_{\text{boost}}$ is closed, and electric energy is transferred from the capacitor $C$ to the DEG to realize the boosting. When the DE shrinks under the action of external force, the switch $S_{\text{buck}}$ closes, and electric energy is transferred from the DEG to the capacitor $C$ to achieve voltage reduction. In theory, the maximum energy conversion efficiency of this circuit can reach 90%. A multistage charge pump circuit and an integrated charge pump circuit are proposed in Refs. 25 and 26. The multistage charge pump circuit is shown in Fig. 2. The dotted line in the circuit represents the omitted series. McKay et al. simulated and optimized the multistage charge pump circuit and determined that the capacitance value in Fig. 2 is the optimum charge pump capacitance value. The secondary charge pump circuit is shown in Fig. 3. The integrated charge pump circuit is shown in Fig. 4. The DEG is used to replace capacitance in the multistage charge pump circuit, and its working principle is similar to that of the charge pump circuit.

The boost process of the self-biasing circuit is illustrated with the example of the secondary charge pump circuit in Fig. 3. When the charge pump circuit is charged by the DEG, assuming that the charge voltage is $V_1$, at this time, the capacitance value between the AB terminals is $\frac{3}{2}C$, the charge pump circuit operates in the low voltage and high charge state, and then, the charge stored in the charge pump circuit is as follows:

$$Q = \frac{3}{2}C \times V_1.$$  \hspace{1cm} (1)

When the charge pump circuit discharges to the DEG, it is assumed that the charge in the circuit is constant at the time of conversion; at this time, the capacitance value of the AB terminals of the charge pump circuit is $\frac{1}{3}C$, and the port voltage charging the DEG of the charge pump circuit is

$$V_2 = \frac{9}{4}V_1.$$ \hspace{1cm} (2)

Charge flows from the charge pump circuit to the DEG, and the circuit works in the high voltage and low charge state. The DEG further pumps the charge potential and the DEG input voltage is $V_1'$ and $V_1' > V_1$, when the next generation cycle DEG charges to the charge pump circuit. After several generation cycles, the potential of the electric charge in the circuit is continuously pumped up, and the charge pump circuit realizes the self-biasing function while supplying electric energy out simultaneously.

**Analysis of comparison of simulation results of self-biasing circuits**

In addition, Japanese scholar Tashiro et al. proposed the self-supplementary circuit, as shown in Fig. 5. The working process of the circuit is as follows: DEG starts to work, when the DEG is in the stretching stage, and the power supply $V_{\text{in}}$ charges to the DEG through the diode D1 (through loop 1). When the DEG is in the contraction stage, the DEG voltage is higher than the capacitor voltage, the diode D1 is cut off, and the DEG is discharged to the outside. Meantime, the capacitor $C_s$ and the power supply are charged (through loop 2), and supplement power charges the load $C_s$ simultaneously.
The above-mentioned buck-boost converter circuit, secondary charge pump circuit, self-supplementary circuit, and DEG electromechanical coupling model are now combined to establish a self-biasing DEG model. The model is shown in Fig. 6. With the external mechanical stress on the DE simulated by the voltage source $F$, box 1 contains an electrical analogy model of the mechanical model; $i(t)$ is the output of the mechanical model (deformation velocity of DE), box 2 contains an integral circuit, which converts the velocity ($a$) into the deformed distance of the nonlinear variable capacitance model; box 3 is the equivalent nonlinear variable capacitor model of DE; and the right end is connected with the self-bias circuit. The simulation is compared and analyzed by using the Orcad/Pspice simulation tool. The parameters are shown in Table I.

In order to compare the above three self-biasing circuits with the DEG matching effect, it is known from Table I that the three self-biasing models have a bias voltage of 50 V and the input external force is 6 N, which further ensures the same input energy. The special input mechanical frequency is 2 Hz. In order to make the simulation results easy to observe and compare, the capacitance values in the above circuits are all set to 10 nF; the simulation time is set to 30 s, and the measured values are selected as the voltage values across the storage capacitor. The simulation results are shown in Fig. 7.

It can be seen from the simulation results that the charge pump circuit in the above three self-biasing circuits has the best boosting effect, and the voltage can be continuously pumped up. Followed by a self-supplementary circuit, the circuit can raise the voltage from 50 V to 80 V in a short time. The buck-boost circuit is the worst boosting effect, and the voltage fluctuates around 50 V. The simulation results show that the matching effect between the charge pump circuit and the DEG is the best, and the matching effect between the self-supplementary circuit and the DEG is second, and the buck-boost circuit has the worst matching effect.

**Analysis of comparison of simulation results of new and old charge pump circuits**

Based on the comparison and analysis of the simulation results of the above three self-biasing circuits, this paper combines the best advantages of the charge pump circuit and DEG matching effect and the advantages of the self-supplementary circuit itself to design a new type of charge pump circuit, as shown in Fig. 8. The specific work process is as follows:
(1) When the DEG starts working, the DEG is in the stretched state, and the power source supplies power to the DEG through the diode D1 during the stretching process.

(2) When the DEG starts to shrink, the DEG discharges to the outside, $V_1 > V_{in}$; D1, D2, and D4 are cut off; the charge pump circuit is in series; and the DEG charges to the capacitors C1 and C2 and the power source.

(3) During the second power generation cycle, when the DEG is in the stretched state, the voltages of the capacitors C1 and C2 are higher than the power supply voltage, D1 and D3 are cut off, and the charge pump is in parallel, that is, the power supply and the capacitors C1 and C2 are connected in series and charges to DEG, and the voltage across the DEG is $V_1, V'_1 > V_{1}$. When the DEG begins to shrink, the DEG discharges to the outside, and the DEG charges to the capacitors C1 and C2 and the power supply. Since then, D2 has been cut off, the DEG and charge pump circuit continue to repeat the process of step (3), and the capacitance C1 and C2 continuously improve the potential, thus realizing the function of voltage pumping.

The new charge pump circuit can not only realize the self-replenishing function but also increase the potential of the charge pump. It can provide high-voltage bias for the DEG without an additional high-voltage power supply, and the circuit structure is simple and easy to carry. No additional control unit is needed, and there is no need to consider the problem of powering the control unit. Compared with the traditional charge pump circuit, the new charge pump circuit works better under the same conditions. The DEG electromechanical coupling model is used to compare and simulate the secondary traditional charge pump circuit with the new charge pump circuit. The simulation results of new and old charge pump circuits are shown in Fig. 9. The new charge pump circuit refers to the circuit established in this paper as shown in Fig. 8. The old charge pump circuit refers to the traditional two-stage charge pump circuit, as shown in Fig. 2.

The simulation results show that under the same conditions, the boost effect of the new charge pump circuit is better, and the boost value of the voltage pump in the same time is 2.23 times that of the traditional charge pump circuit.

### RESEARCH AND ANALYSIS OF EXPERIMENTAL INFLUENCING FACTORS

#### Experimental platform

The VHB™ produced by 3M Company was used as the matrix; after prestretching, the carbon grease electrode was evenly coated on both sides of the film; and the DEG experimental material was fabricated, as shown in Fig. 10. According to the generating principle of the DEG and in order to make the DE film deform more, a biaxial stretching device was used in the experiments. The experimental platform was set up as shown in Fig. 11. The experimental device mainly consists of a motor, motor controller, push rod, sliding slider, and measuring instrument. The motor controller is used to control the frequency and period of the motor, the DEG experimental sample is fixed on the fixture, the fixture is fixed on the fixed slider, the pusher is connected with a circular cake at one end and a movable slider at the other end, and the movable slider is driven by the motor to move the crank slider; under the pusher, the DEG produces periodic deformation.

#### Experimental verification of a new charge pump circuit

In order to verify the actual working effect of the circuit proposed in this paper, the simulation environment is compared and some experimental parameters are set as shown in Table III. The experiment is a new secondary charge pump circuit. The minimum capacitance of the circuit is 10 nF. The relationship

| Parameter name         | Parameter value |
|------------------------|-----------------|
| Capacity-to-strain ratio | 2.5             |
| Initial bias voltage    | 30 V            |
| Mechanical frequency    | 2 Hz            |
| DEG work cycle          | 200 times       |
between voltage and time at both ends of the charge pump is shown in Fig. 12. It can be seen from Fig. 12 that the voltage variation curves in the experiment and the simulation tend to be the same, the amplitudes are similar, and the voltage is raised from 0 V to about 1233 V. This fully shows that the new charge pump circuit proposed in this paper has a very accurate coincidence with the DEG. In order to further study the relevant factors affecting the self-biasing circuit and optimize the performance of the DEG, the following key factors will be studied experimentally, such as the capacity-to-strain ratio $\alpha$ (the ratio of capacitance in the maximum stretching state to that in the initial state of the DEG), mechanical frequency, and charge pump capacitance, to determine the optimal electromechanical parameters and improve the overall power generation efficiency of the DEG.

**Analysis of factors affecting the DEG output**

According to the analysis of generator theory, the main factors affecting DEG working efficiency are the capacity to strain ratio, charge pump capacitance, and mechanical frequency. Among them, mechanical frequency is a mechanical factor, and charge pump capacitance is an electrical factor. The capacity to strain ratio of the DEG is both a mechanical factor and electrical factor, which not only reflects the process of capacitance change but also reflects the change in the DEG stretching distance. Since the capacity to strain ratio of the DEG is related to the safe use range of the DEG, this paper will first study the mechanical factors, determine the appropriate capacity-to-strain ratio of the DEG, and then study the mechanical frequency and charge pump capacitance separately. The optimal electromechanical parameters of the charge pump circuit design are further determined.

**Relation between capacity-to-strain ratio and DEG output voltage**

Considering the safe working range of the DEG, from small to large, since the capacitance value and the stretching distance are not linear in the experiment, changing the same stretching distance is not linear. Thomas mentioned in the document that DEG needs to produce minimum voltage amplitude in order to change the charge pump structure, and the change in the charge pump structure can continuously increase the potential of low charge. The minimum voltage amplitude is 50%, that is to say, $\alpha \geq 1.5$. This paper starts with more than 1. During the experiment, the input mechanical frequency is 2 Hz, the initial bias voltage is 30 V, and the working...
TABLE III. Experiments and simulation conditions.

| Parameter name          | Parameter value |
|-------------------------|-----------------|
| Capacity-to-strain ratio| 2.5             |
| Initial bias voltage    | 30 V            |
| Mechanical frequency    | 2 Hz            |
| DEG work cycle          | 200 times       |

Fig. 12. Experimental simulation comparison.

It can be seen from the curve that as the capacity-to-strain ratio increases, the charge pump potential becomes higher and higher, and its potential rises faster and faster. The abrupt change in the figure is about 0 in 30 seconds. The reason for the analysis is that under the capacity-to-strain ratio condition, the DEG deformation is too large, and the DE film is fatigued and finally ruptured after multiple stretching. In order to ensure the safety of the DEG, α ≤ 2.57, it can be seen from the local magnification diagram that the charge pump potential does not rise when it is too small, that is, the minimum voltage amplitude cannot be produced to change the structure of the charge pump, in order to make the charge pump circuit have the ability to boost, α > 1.5. Based on the above experimental results, the capacity-to-strain ratio should be selected as follows: 1.5 ≤ α ≤ 2.57.

Relationship between mechanical factors and DEG output potential

According to the above experimental analysis, the DEG is affected by the mechanical frequency during the working process. In order to ensure that the DEG works in a safe range, this experiment adopts a two-factor experimental research method. At the same time, the mechanical frequency and capacity-to-strain ratio are studied. The relationship between them on the output voltage of the DEG is analyzed experimentally. The experimental parameters are set as shown in Table V. The relationship between the mechanical frequency and the capacity-to-strain ratio and the DEG output voltage is shown in Fig. 14.

From Fig. 14, it can be seen that with the increase in the capacity-to-strain ratio and the mechanical frequency, the maximum potential of the output is getting higher and higher. In addition, through comparison, it is found that the effect of the capacity-to-strain ratio on the output is greater than that of mechanical frequency on the output. When the capacity-to-strain ratio or frequency is small, the maximum output potential is very low and the energy conversion efficiency of the DEG is low. Therefore, in order to obtain a larger output potential, the capacity-to-strain ratio and mechanical frequency should be increased as much as possible under the safe working conditions of the DEG.

Relation between charge pump capacity and output potential of DEG

In order to explore the charge pump capacitance matching with DEG experimental samples, a new type of secondary charge pump circuit was optimized by the DEG electromechanical coupling model. The charge pump capacitance described here refers to the capacitance of each capacitor in a new charge pump circuit. The initial capacitance of the DEG is 2.3 nF. In order to study the relationship between the capacitance of the charge pump and the capacitance of the DEG, the capacitance of the charge pump of 0.1 nF, 10 nF, and 100 nF is selected. The simulation analysis is carried out by using the Orcad/Pspice simulation software. The simulation parameters are shown in Table VI.

The curve of the relationship between the charge pump capacitance and the output potential is shown in Fig. 15. It can be seen from the figure that the output potential is the largest when the charge pump capacitance is close to the DEG capacitance value C₀, and the output potential is greater than that of the charge pump capacitance value 100 nF when the charge pump capacitance value is 0.1 nF. The value of the charge pump capacitance affects the stability of the output potential. The larger the charge pump capacitance value is, the more stable the output potential is, and the smaller the capacitance value is, the greater the fluctuation of the output potential is.

The charge pump capacitance should be further optimized so that it could be more compatible with the experimental sample of DEG, and the detailed study of the charge pump capacitance is as follows. Figure 15 shows that the DEG has the best...
output potential when the charge pump capacitance is 10 nF. When the charge pump capacitance is 0.1 nF, the maximum output potential of the DEG is lower than 10 nF and larger than that of the charge pump capacitance that is 100 nF. Therefore, the integer multiple of the $C_r$ capacitance is selected to refine the research, i.e., 0.5, 1, 2, and 3 times of the $C_r$ capacitance (the capacities are 1.15 nF, 2.3 nF, 4.6 nF, and 6.9 nF, respectively). As shown in Table VI, the simulation results are shown in Fig. 16. It can be seen from the figure that when the charge pump capacitance is 0.5 times of the $C_r$ capacitance, the output potential is the largest, followed by one

**TABLE V.** Experimental parameters of mechanical frequency and capacitance ratio for the output potential of the DEG.

| Parameter name                  | Parameter value |
|---------------------------------|-----------------|
| Capacity-to-strain ratio        | 1.58, 2, 2.53   |
| Mechanical frequency            | 1–5 Hz          |
| Initial voltage                 | 30 V            |
| Number of working cycles of the DEG | 100 times      |

**TABLE VI.** Simulation parameters of charge pump capacitance for the output potential of the DEG.

| Parameter name                  | Parameter value |
|---------------------------------|-----------------|
| Capacity-to-strain ratio        | 2.5             |
| Mechanical frequency            | 2 Hz            |
| Initial voltage                 | 30 V            |
| Number of working cycles of the DEG | 100 times      |
time, and the output potential is the smallest by three times. Next, the charge pump capacitance is further optimized, taking 0.5, 1, 2, and 3 times of the capacitance of $C_r$ (i.e., 0.575 nF, 1.15 nF, 1.725 nF, and 2.3 nF, respectively) to simulate and finally to determine the best matching charge pump capacitance with DEG experimental samples. The simulation results are shown in Fig. 17. It can be seen from the figure that the maximum output potential is 0.75 times of the charge pump capacitance, i.e., the turning point is 0.75 times of the charge pump capacitance. When the charge pump capacitance is greater than 0.75 times of the $C_r$ capacitance, the output potential decreases with the increase in the capacitance. That is to say, the optimal charge pump capacitance is 0.75 times of the $C_r$ capacitance.

To verify the above simulation results, three orders of magnitude of charge pump capacities were selected for optimization and comparison experiments under different capacity-to-strain ratio conditions. Since the capacitance value actually purchased is a fixed specification, the capacitance is not as flexible as that in the simulation software. Therefore, the capacitor with a similar capacitance is used for the experiment. The experimental conditions are shown in Table VII.

The experiment obtained the maximum potential of 0.1, 10, 100 nF, three orders of magnitude compared with the optimized charge pump capacitance value, as shown in Fig. 18. It can be seen from Fig. 18 that the boost effect of the charge pump circuit is not obvious when the difference between the charge pump capacitance and $C_r$ is too large. When the capacity-to-strain ratio of the DEG is too small, the influence of the capacitance of the charge pump on the output potential is small, and the charge pump circuit cannot realize the boost function, so the weight of the influence of the capacity-to-strain ratio of the DEG on the output is larger than that of the charge pump capacitance. In addition, through comparative analysis, when the capacity-to-strain ratio is within an appropriate range, regardless of the specific value, the maximum potential can almost always be output at the capacitance value of the charge pump of 0.75$C_r$. There are differences between experiment and simulation results, the maximum output potential in experiment is about one fifth of

| Parameter name                        | Parameter value |
|---------------------------------------|-----------------|
| Capacity-to-strain ratio              | 1.53, 1.92, 2.5 |
| Mechanical frequency                  | 2 Hz            |
| Initial voltage                       | 30 V            |
| Number of working cycles of the DEG   | 100 times       |
| Charge pump capacity (nF)             | 0.1, 10, 100    |

![FIG. 16. Relation between the different multiple charge pump capacitance and the output potential.](image1)

![FIG. 17. Relation between refined charge pump capacitance and output potential.](image2)

![FIG. 18. Optimized contrast experiment.](image3)
that in simulation, but the maximum output potential in simulation and experiment is the highest when the charge pump capacitance is $0.75C_r$. The biggest factor causing the difference is the leakage of capacitors. In simulation, capacitors are all ideal capacitors, the leakage resistance is infinite, and there is no self-discharge phenomenon in the experiment. There is a self-discharge phenomenon in capacitors. As a result, the experimental output potential is much lower than the simulation results.

CONCLUSIONS

Based on the analysis of three kinds of self-biasing circuits, a new type of charge pump circuit is designed by combining the self-supplement circuit and traditional charge pump circuit. It is simulated and analyzed by the Orcad/Pspice circuit simulation software. The simulation results show that the matching degree between the DEG and the new type of charge pump circuit is better than that of the traditional charge pump circuit. Under the same input conditions, the output potential of the new charge pump is 2.23 times that of the conventional one. In this paper, the actual performance of the new charge pump circuit is verified by making DEG experimental samples and setting up an experimental platform. The experimental results show that the output potential curve of the new charge pump circuit is basically consistent with the simulation output. At the same time, the electromechanical parameters of the new charge pump circuit are compared and optimized by simulation experiments. The simulation and experiment results show that the output potential increases with the increase in the capacity to strain ratio and mechanical frequency within the safe working range of the DEG, but when the capacity to strain ratio is too small, the increase in mechanical frequency has little effect on the output, so the influence of the capacity to strain ratio on the output is much greater than that of mechanical frequency. The optimum capacitance of the charge pump is about $0.75C_r$, as too large or too small will lead to a decrease in the output potential of the charge pump. However, when the capacity to strain ratio is too small, the change in the capacitance of the charge pump has little effect on the output, so the influence of the capacity to strain ratio on the output is much greater than that of the charge pump. These results provide a good theoretical basis for the development of subsequent generators and the improvement of DEG generation efficiency. Both the experimental and simulation results show that the DEG output potential is large, and the ratio of the tolerance should be considered as the primary consideration. That is, within the safe range, the DE film should be deformed as much as possible. Second, the mechanical frequency of the DEG is as large as possible without affecting the stability of the DEG. Finally, the charge pump capacitance should be chosen close to $0.75C_r$, avoiding the selection of excessive or too small charge pump capacity, so that the voltage across the DEG could reach a safe high voltage quickly, reduce the time during which the DEG operates in the low voltage field, and improve the efficiency of DEG power generation.

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