Simulation of a Self-Excited Power Generation System for Dielectric Elastomer Generation

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Abstract. In recent years, global warming is a serious international problem. We focused on dielectric elastomer power generation to solve the problem. The dielectric elastomer generation has characteristics such as compactness and flexibility. The dielectric elastomer generation can harvest electric energy from renewable energy sources such as sea wave, wind, and human motion. However, the dielectric elastomer generation has a weakness dependent on an external power supply. In this paper, we proposed a self-excited dielectric elastomer generation circuit using piezoelectric elements. As a circuit verification method, circuit simulations are performed using MATLAB / Simulink, and the circuit behavior is confirmed from the results. From results, it is considered that dielectric elastomer generation can be performed without using the external power supply.

Introduction

In recent years, global warming caused by carbon dioxide emissions has become a serious problem internationally. As a major cause of carbon dioxide emissions, there is an energy conversion delivered from fossil fuel. Therefore, renewable energy generations that do not emit carbon dioxide are focused as a solution to global warming. The renewable energy power generation is a generation method, which does not emit CO₂ and wreak depletion of resources. The renewable energy power generation includes solar power generation, wind power generation, geothermal power generation, biomass power generation, and the like.

Among various types of renewable energy generation, the Dielectric Elastomer Generation (DEG) is focused and developed [1]. The DEG is a power generation method that converts various mechanical energy into electric energy by using a Dielectric Elastomer (DE). In the previous research of [2], the DEG is used to generate electricity from wave power, hydraulic (Karman vortex), and wind power. The DEG has superior characteristics such as compactness, flexibility, and lightweight. The power generation cost is lower than that of conventional power generations using rotating machines. Therefore, the development as a new type of generator is expected.

The practical application of DEG has various problems. However, an electrical problem of DEG is focused in this paper. The DEG needs an external power supply to charge DE. Additionally, the DEG circuit requires a high DC voltage for charging the DE. In addition to storing the electric energy generated by the DEG, a step-down converter is required to use the generated electric energy as a power supply for other equipment. The Step-Down Converter (SDC) converts a high DC voltage to a low DC voltage. The SDC requires a power supply for controller. As described above, the conventional DEG circuit requires two external power supplies. The additional external power supplies not only complicate the power generation system but also use the electric energy generated by the DEG. As the result, the power generation efficiency of the DEG decreases. In this paper, a self-excited DEG power generation circuit using piezoelectric elements is proposed. Also the proposed circuit is simulated with MATLAB/Simulink, and the circuit operation is verified.
Principle of DEG

This chapter describes the principle of DEG. The DE can be treated as a variable capacitor applied to an electric circuit, and the capacitance is changed due to DE’s expansion and contraction caused by mechanical force. The DEG generates electric power by applying the change of capacitance between extended state and contracted state. Figure 1 (a) shows the model of DE in the extended state, and figure 1 (b) shows the model of DE in the contracted state. Assuming that the thickness of DE in the extended state is \( T_{st} \) and the area is \( S_{st} \), the electrostatic capacitance \( C_{st} \) is described as follows.

\[
C_{st} = \varepsilon_0 \varepsilon_{DE} \frac{S_{st}}{T_{st}}
\]  

(1)

Assuming that the thickness of the expanded DE in the contracted state is \( T_{re} \), and the area is \( S_{re} \). The electrostatic capacitance \( C_{re} \) is as follows.

\[
C_{re} = \varepsilon_0 \varepsilon_{DE} \frac{S_{re}}{T_{re}}
\]  

(2)

From the equations (1) and (2), it can be seen that \( C_{st} > C_{re} \). Here, assuming that the charge is constant during the power generation cycle, \( V_{re} \) can be represented by \( C_{st} \), \( C_{re} \), \( V_{st} \) as follows.

\[
V_{re} = \frac{C_{st}}{C_{re}} V_{st}
\]  

(3)

From this equation, it can be seen that \( V_{re} \) is larger than \( V_{st} \). The power generation energy \( E \) can be expressed as follows.

\[
E = \frac{1}{2} C_{st} V_{st}^2 \left( \frac{C_{st}}{C_{re}} - 1 \right)
\]  

(4)

From the above equation, it is clear that the DEG can generate electricity by changing the electrostatic capacity.

In the circuit simulation conducted in this paper, the DE is modeled as a variable capacitor that changes from \( C_{st} = 1.28 \times 10^{-8} \) [F] to \( C_{re} = 1.28 \times 10^{-9} \) [F]. In addition, the cycle in which the electrostatic capacity changes is set to 1/30 [sec].

Simulation Circuit

In this chapter, the circuit configuration and behavior procedure of the proposed self-excited DEG circuit are explained. Figure 2 shows the proposed circuit, and Table 1 shows the parameters of proposed circuit. The proposed circuit was simulated with MATLAB / Simulink.
**Circuit configuration**

A piezoelectric element and a Cockcroft-Walton circuit (CW circuit) were introduced on the input side of the proposed circuit [3]. A piezoelectric element is an element that converts mechanical vibration into an AC voltage. The CW circuit is a boosting circuit, and it is possible to design a magnification that boosts by the number of diodes and capacitors. In this simulation, the piezoelectric element is made equivalent to an ideal AC power supply (amplitude 200 [V], frequency 30 [Hz]). The CW circuit is designed to boost the voltage of the piezoelectric element by 10 times. Therefore, for the entire input side, the parameter design is performed so that the charging voltage $V_{CW}$ of DE becomes 2000 [V].

A ringing choke converter (RCC) is introduced on the output side of the proposed circuit [4]. The RCC is a DC-DC step-down converter that does not require a power supply used for switching control. During the ON period, the energy is stored in the transformer, and during the OFF period, the voltage is output at the amount of energy stored to the secondary side. In this circuit, since the DE outputs a high voltage, an IGBT with high breakdown voltage is used as a switching element. The switching is started when the generated voltage $V_{DE}$ of DE exceeds a certain value according to the parameters of $R_3$, $R_4$, $R_5$ and $C_{12}$. In this simulation, the parameters are designed so that switching starts when $V_{DE}$ exceeds 3000 [V]. When the switching is started, the output side voltage $V_{o1}$ is gradually output. $V_{o1}$ is designed to be 100 [V].

![Fig.2 The proposed DEG circuit](image)

**Table.1 Parameter of the proposed circuit**

| Symbol | Set value | Symbol | Set value |
|--------|-----------|--------|-----------|
| $C_1$~$C_{10}$ | $1.3 \times 10^{-4}$[F] | $R_4$ | $1.0 \times 10^{3}$[Ω] |
| $C_{11}$ | $4.7 \times 10^{-6}$[F] | $R_5$ | $2.0 \times 10^{3}$[Ω] |
| $C_{12}$ | $1.0 \times 10^{-4}$[F] | $R_6$~$R_8$ | $1.0 \times 10^{3}$[Ω] |
| $C_{13}$~$C_{15}$ | $3.5 \times 10^{-6}$[F] | $N_p$ | 221 |
| $R_1$ | $1.5 \times 10^{3}$[Ω] | $N_d$ | 2 |
| $R_2$ | $1.0 \times 10^{3}$[Ω] | $N_{s1}$~$N_{s3}$ | 18 |
| $R_3$ | $2.5 \times 10^{6}$[Ω] |

$C_x$: Capacitance, $R_x$: Resistance, $N_x$: Number of turns in a coil ($x = 1,2,3,...$)
《Circuit behavior》

First, 200 [V] is outputted from the piezoelectric element (modeled as an ideal AC power supply). Thus, the $V_{CW}$ is gradually boosted. As the $V_{CW}$ is boosted, the $V_{DE}$ also rises. When the $V_{DE}$ exceeds 3000 [V], the IGBT is turned on. During switching ON time, the generated electric energy is stored in the transformer. When all the generated energy is stored in the transformer, the IGBT turns off. When the IGBT turns OFF, the $V_{o1}$ is output. The $V_{DE}$ rises again while the IGBT is OFF.

By repeating this operation, the proposed circuit performs DEG without any external power supply. Also, the generated voltage can be taken out. In order to verify that operation of this circuit, the voltage waveforms of $V_{CW}, V_{DE}$ and $V_{o1}$ are estimated by the simulation.

Simulation Results

Figure 3 shows the estimated waveforms of $V_{CW}$. Figure 4 shows the estimated waveform of $V_{DE}$. Figure 5 shows the estimated waveform of $V_{DE}$.

First, boosting operation is carried out from 0 seconds to 2.4 seconds from the result of $V_{CW}$. When it reaches 1730 [V], it decreases to 1400 [V], and thereafter it repeats rising and descending. And the maximum voltage value decreases to 1650 [V] with time, and becomes substantially constant.

Next, from the result of $V_{DE}$, the $V_{DE}$ turned out that the first switching started at the moment when the $V_{DE}$ reached 3230 [V] at 2.4 [sec]. It is shown that the maximum voltage drops to 1500 [V] when the IGBT is OFF, and the voltage rises to 3100 [V] during the ON period. The switching operation is performed periodically.

Finally, from the result of $V_{o1}$, it is shown that the output is started about 2.6 seconds and draw a stair-like waveform. The rise of the voltage also becomes moderate over time.

![Figure 3. Simulations result of $V_{CW}$.](image)

![Figure 4. Simulations result of $V_{DE}$.](image)
Based on the above simulation results, it is confirmed that switching of RCC starts at approximately 2.4 [sec] when the $V_{DE}$ reached 3230 [V], and the $V_{o1}$ is output. It is confirmed that the switching operation is repeated at the switching frequency of 1.01 [Hz]. However, the output voltage does not reach a constant value of 100 [V] which is a desired value. In the future, the circuit parameters will be optimized to solve this problem.

**Summary**

In this paper, the circuit simulation is performed on the self-excited DEG circuit using the piezoelectric element using MATLAB / Simulink, and circuit operation is verified. From the simulation results, it was found that when $V_{DE}$ reached 3200 [V], switching was performed and $V_{o1}$ was output. This result was close to desired value for the design of the parameter.

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