Interface circuit analysis of wind-induced vibration power generation with piezoelectric bimorph

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Abstract. Wind-induced vibration energy recovery has been widely used in wireless sensor nodes as well as portable electronic devices. Because of the high energy density, simple structure and easy system integration, it is particularly suitable for micro systems with independent power supply. A circuit equivalent model of piezoelectric bimorph was developed with the basic structure of piezoelectric energy recovery device. Standard, SECE, and SCEI interface circuit and their control process was simulated via LT-spice software. Both SECE and SCEI performed stable output power over a large load range, while the remaining three interface circuits are somewhat deficient in output power or stability. The control of SECE interface circuit is simpler than SCEI, and the SECE interface circuit is more suitable for wind-induced vibration power generation with piezoelectric bimorph.

1. Introduction

Over the past decade, research on wind-induced vibration power generation with piezoelectric materials has received more and more attention. These studies have focused on three aspects [1]: structure and materials, interface circuits and storage elements, and applications. These can be briefly described as follow.

In order to improve the efficiency and performance of the wind-induced vibration power generation with piezoelectric materials, the commonly used methods are [2-5]: changing the properties of the piezoelectric material, changing the working mode of the piezoelectric unit, and increasing the effective volume of the piezoelectric body by utilizing the multi-layered structure, changing the structure of the piezoelectric oscillator and adjust the resonant frequency of the system [6]. Among them, the properties of piezoelectric materials have the most significant influence on the system performance. Piezoelectric bimorph is a cantilever used for actuation or sensing which consists of two active layers. In the wind-induced vibration power generation, the bimorph bended by wind produces voltage which can used for energy recovery.

In view of the current research status of wind-induced vibration power generation, the energy recovery interface technology was analyzed and three kinds of efficient interface circuit technologies were compared in this paper. The interface circuit responsible for energy collection is the core part of the device. A well-designed interface circuit can greatly improve the energy conversion efficiency of the device. Kim [7] et al. used an interface consisting of a standard interface (full bridge rectifier and charging capacitor) to form a standard energy interface circuit. Han et al. [8] developed an efficient energy recovery interface circuit consisting of interface circuits 1 and 2, namely a rectifier and a DC-DC converter, with an energy recovery efficiency five times that of the standard interface circuit. Lefeuvre et al. [9-11] proposed an adaptive circuit called synchronous electric charge extraction (SECE) technology.
With the basic structure of the wind-induced vibration power generation, an electromechanical coupling model of the energy recovery system was established, and its key factors were analyzed. According to the properties of the piezoelectric material, a circuit equivalent model of the bluff body with piezoelectric bimorph was developed for the simulation of Standard, SECE, and SCEI interface circuits [12]. A compare of these three different interface circuits were performed in LT-spice software.

2. Operational principle of interface circuit for wind-induced vibration power generation

The interface circuit is an important part of the wind-induced vibration power generation [13, 14]. As mentioned in the previous section, the function of the interface circuit is mainly to optimize the waveform of the voltage of the piezoelectric bimorph, so that it can increase the electromechanical conversion energy of power generation system. A well-performed interface circuit can greatly improve the generated energy and stability of the entire system. The Structure diagram of the bluff body with piezoelectric bimorph for wind-induced vibration power generation is shown in figure 1, and the power generation device was shown in figure 2.

![Figure 1. Structure diagram of the bluff body with piezoelectric bimorph for wind-induced vibration power generation.](image1)

![Figure 2. Experimental setup.](image2)

2.1. Standard interface circuit

The standard interface circuit diagram can be seen in figure 3, which connects a bridge rectifier $D$ consisting of four diodes behind the piezo-electric chip. Its role is to convert the alternating current generated by the piezoelectric bimorph into direct current. After the filter capacitor $C_r$, the device is often set at the outlet section of the rectifying circuit, and the function is to reduce the AC ripple level, and the regulated DC voltage $V_{DC}$ can be used for the load.

![Figure 3. Standard interface circuit schematic.](image3)
2.2. SECE interface circuit
The schematic diagram of the SECE interface circuit can be seen in figure 4 [15, 16]. Compared with the Standard interface circuit, a buck-boost converter is added before the filter capacitor and the load. Like the previous text, \( C \) represents the storage capacitor, and the \( R_L \) load represents the equivalent load.

![Figure 4. SECE interface circuit schematic.](image)

2.3. SCEI interface circuit
The SCEI interface circuit, the full name of Synchronous Charge Extraction and Inversion Interface Circuit, its schematic diagram is shown in figure 5 [15, 16]. Compared with the SECE interface circuit, a step-up and step-down converter is added before the load.

![Figure 5. SCEI interface circuit schematic.](image)

3. LTspice-based interface circuit simulation
A circuit model of the bluff body with piezoelectric bimorph was developed, and the simulation with the model were performed to analyze the working process and generated energy of the three interface circuits of Standard, SECE, and SCEI in LTspice software.

In the circuit simulation, it is difficult to model the vibration caused by wind. To simplify the model of wind-induced vibration is a necessary method for the circuit analysis. In order to compare and analyze different interface circuits for wind-induced vibration power system, the piezoelectric bimorph can be simplified as a current source in LTspice. The results of circuit simulation are very important for circuit design, which will be applied in the experiment under real wind condition.

3.1. Equivalent circuit of the bluff body supported by piezoelectric bimorph
In order to simulate the above interface circuit in LTspice, it is necessary to establish an equivalent model of the bluff body supported by piezoelectric bimorph. If the movement law of the mechanical vibration displacement of the power generation device is a sine function, the piezoelectric bimorph can be represented by a clamp capacitor \( C_0 \) connected in parallel with the sinusoidal current source.

3.2. Interface circuit simulation
To compare the generated power with different interface circuits, excitation force should be setup to get the same displacement vibrational amplitude. To meet this condition, the maximum of the current source \( I_m \) was chosen to be same for all the simulation. This ensures that the generated power with all interface circuits is not affected by the system parameters.
3.2.1. Standard interface circuit. The simulation circuit diagram of the Standard interface is shown in figure 6. The filter capacitor \( C_r \) is 1\( \mu \)F, which make the generated power stable and quickly.

![Figure 6. Circuit model of standard interface in LTspice.](image)

After simulated for 0.5 s, the generated power with standard circuit has basically reached a stable value. Figure 7 shows the waveforms of voltage on piezoelectric bimorph and load, the current through the piezoelectric bimorph, and the output power. The average of the generated power with standard interface is 50.343\( \mu \)W.

![Figure 7. Simulation result with Standard interface: (1) Generated voltage on the piezoelectric bimorph; (2) Load voltage; (3) Current flow through the piezoelectric bimorph; (4) Generated power for the load.](image)

3.2.2. SECE Interface Circuit. The simulation circuit diagram of SECE interface can be seen in figure 8. The filter capacitor \( C_2 \) is also 1\( \mu \)F, the inductor \( L_1 \) is 100mH, and the switch was designed with a voltage controlled switch model in LTspice. Its parameters are shown in the upper right corner of figure 8, where \( V_t=0.1V \) and \( V_h=0.1V \). Since the negative pole of the switch is grounded, the switch will be turned on when the positive input voltage of
the switch higher than $V_t + V_h = 0.2V$; when the positive input voltage is less than or equal to $V_t - V_h = 0V$, the switch will be turned off.

**Figure 8.** Circuit model of SECE interface in LTspice.

According to the theoretical analysis, the on-time of the switch should be 112μs. The voltage signal that controls the switch is provided by the voltage source model in LTspice. Simulation result shown in figure 9 indicates that the average of generated power is 279.23 μW.

**Figure 9.** Simulation result with SECE interface: (1) Generated voltage on the piezoelectric bimorph; (2) Load voltage; (3) Current flow through the piezoelectric bimorph; (4) Generated power for the load.
3.2.3. SCEI Interface Circuit. The SCEI interface circuit requires two switches, corresponding to two control signals. In addition, the interference between switches S₁ and S₂ must also be considered as shown in figure 10.

![Circuit model of SCEI interface in LTspice.](image)

The closing time of the switch S₁ is \(\pi \sqrt{L₁C₀} \), and the closing time of the switch S₂ is \(\cos^{-1} \gamma \cdot \sqrt{L₂C₀} \). Substituting \(\gamma=0.5\), \(C₀=51nF\), \(L₁=20mH\), \(L₂=100mH\) into the on-times of the switches S₁ and S₂ can be 100μs and 74μs, respectively. However, in the simulation, when the conduction time of S₁ and S₂ is found to be 100 μs and 80 μs, respectively, by changing the conduction time, the maximum generated energy is obtained. Then the parameters of voltage sources for the two switch are as follows:

![Simulation result with SCEI interface: (1) Generated voltage on the piezoelectric bimorph; (2) Load voltage; (3) Current flow through the piezoelectric bimorph; (4) Generated power for the load.](image)

Figure 11 shows simulation result with SCEI interface circuit. The average of the generated power is 240.47 μW.
3.3. Comparison and analysis of results
The above simulation results are obtained under the condition of load $R=100\,\Omega$. In actual applications, the wind-induced power generation may work with variable load. More simulations were performed with different load, and their results were listed in table 1.

| Interface Circuit | $10^2$ | $10^2.5$ | $10^3$ | $10^3.5$ | $10^4$ | $10^4.5$ | $10^5$ | $10^5.5$ | $10^6$ |
|-------------------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| Standard          | 0.32   | 0.98     | 2.71   | 6.48     | 16.71  | 36.48    | 50.34  | 36.59    | 16.42  |
| SECE              | 235.72 | 240.15   | 258.32 | 262.64   | 268.69 | 275.13   | 279.23 | 277.84   | 280.86 |
| SCEI              | 388.35 | 370.34   | 388.01 | 387.54   | 381.94 | 381.82   | 381.21 | 380.47   | 377.66 |

Figure 12. Comparison of acquisition power of interface circuits under different loads.

Figure 12 shows the power changes with Standard, SECE, and SCEI interface circuits under different loads. It can be seen that the generated power with the SECE interface circuit and the SCEI interface circuit keeps a constant over a large range. This indicates that the SECE and SCEI can adapt to changing load environments, and its performance is more stable.

Comparing the maximum power collected by each interface circuit in figure 12, it can be concluded that the wind-induced vibration power system with SCEI interface circuit generates the largest generated energy, and the power system with Standard interface generates least energy.

4. Conclusions
Wind-induced vibration power generation has attracted more and more attention in recent years. Interface circuit is the important part of this type of power system. In this paper, three wideband interface circuits were analyzed for wind-induced vibration power system. The simulations of interface circuit were performed with LTspice software. The conclusions are as follows:

1. Standard interface circuit is characterized by no external control signal, and the circuit structure is simple, mature technology, so its most widely used. However, it cannot collect vibration energy to the maximum extent, and the power that can be recovered under load mismatch is more limited, which is also its limitation.

2. Both SECE and SCEI have large generated energy and good stability over a large load range. Although the SCEI is superior to the SECE interface circuit both in terms of maximum power recovery and load sensitivity, there is only one switch and control signal in the SECE, and there are two in the SCEI. Compared to the SECE, the control is simpler. Therefore, the SECE interface circuit is more attractive in wind-induced vibration power system.
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