A review of nonlinear piezoelectric energy harvesting interface circuits in discrete components

Bin ZHANG\(^1\), Hongsheng LIU\(^1\), Shengxi ZHOU\(^2,\dagger\), Jun GAO\(^1\)

1. School of Mechanical, Electrical and Information Engineering, Shandong University, Weihai 264209, Shandong Province, China;
2. School of Aeronautics, Northwestern Polytechnical University, Xi’an 710072, China

(Received Oct. 4, 2021 / Revised Nov. 25, 2021)

Abstract Piezoelectric energy harvesting is considered as an ideal power resource for low-power consumption gadgets in vibrational environments. The energy extraction efficiency depends highly on the interface circuit, and should be highly improved to meet the power requirements. The nonlinear interface circuits in discrete components have been extensively explored and developed with the advantages of easy implementation, stable operation, high efficiency, and low cost. This paper reviews the state-of-the-art progress of nonlinear piezoelectric energy harvesting interface circuits in discrete components. First, the working principles and the advantages/disadvantages of four classical interface circuits are described. Then, the improved circuits based on the four typical circuits and other types of circuits are introduced in detail, and the advantages/disadvantages, output power, efficiency, energy consumption, and practicability of these circuits are analyzed. Finally, the future development trends of nonlinear piezoelectric energy harvesting circuits, e.g., self-powered extraction, low-power consumption, and broadband characteristic, are predicted.

Key words piezoelectric, nonlinear, energy harvesting, discrete component, interface circuit

Chinese Library Classification O322, O441.3
2010 Mathematics Subject Classification 70K99, 74H45

1 Introduction

With the development of integrated circuits and low-power sensing technologies, wireless sensor networks have been widely implemented in bridge load-bearing monitoring\(^[1]\), marine...
environment monitoring, structure health monitoring, and other fields. When the sensor nodes have worked in remote, harsh, or embedded environments for a long period, the chemical battery will no longer meet the requirements due to the limited capacity, environmental pollution, high replacement cost, and low-temperature sustainability. Therefore, harvesting energy from the environments such as solar, wind, wave, and vibrations has been studied to make the sensor nodes self-powered, among which the harvesting piezoelectric energy is relatively high power density, small volume, and non-electromagnetic interference.

A piezoelectric energy harvesting system usually consists of a mechanical base structure, piezoelectric elements, and an interface circuit. The mechanical base structure is used to collect the vibration energy and transfer it to the piezoelectric elements. Different types of nonlinear structures, e.g., impact structures, frequency up-conversion, monostable structures, and multi-stable structures, have been developed to broaden the working bandwidth of piezoelectric energy harvesters (PEHs) so as to improve the total harvested energy and environment serviceability. Researchers have also concentrated on improving piezoelectric materials to enhance the dielectric property, storage capacity, stability, and piezoelectricity. As the piezoelectric output is alternating, in high voltage, high impedance, and small current, it is impossible to be applied directly by most devices. The interface circuit can rectify and accumulate the output power of the piezoelectric converter and enhance the impedance matching capability to meet the requirements of the load.

In most cases, a resistor is directly connected to the piezoelectric element to evaluate the performance of the piezoelectric energy harvesting system. Though high output power is able to be obtained with a purely resistive load, it will drop sharply when the resistance value deviates from the optimal value. Thus, a nonlinear energy harvesting interface circuit composed of nonlinear electrical elements (e.g., diodes, transistors, and nonlinear inductors) is used as a rectifier and voltage regulator. The output current/voltage will not linearly change along with the input excitation, where the superposition theorem is not applicable. The standard energy harvesting (SEH) circuit is the most fundamental nonlinear energy harvesting circuit. Furthermore, other types of nonlinear circuits are derived to enhance the harvested energy. The electric charge can be flipped and accumulated along with the displacement changes of piezoelectric converters to enhance energy extraction.

To understand the working mechanism of nonlinear piezoelectric energy harvesting interface circuits, the modeling of electromechanical coupling and the basic interface circuits (SEH circuit, synchronous electric charge extraction (SECE) circuit, parallel synchronized switch harvesting on inductor (P-SSHI) circuit, and series synchronized switch harvesting on inductor (S-SSHI) circuit) are introduced in the following two sections. Then, different derived nonlinear circuits based on the above-mentioned circuit are reviewed and analyzed.

# Electromechanical coupling model for PEHs

A bimorph cantilever beam type PEH is shown in Fig. 1. It is simplified to a single-degree-of-freedom (SDOF) system, and works near the first-order natural frequency to provide the optimum output. As shown in Fig. 2, it includes a mass $M$, a damping $C$, a spring $K$, and piezoelectric elements (lead zirconate titanate, PZT).

The mechanical components of the PEH can be further equivalent to the corresponding electronic elements for a better electrical analysis, as shown in Fig. 3. Notably, when the PEH works near the resonant frequency, the electromechanical coupling model can be simplified to an electrical model, as shown in Fig. 4. It includes an alternating current (AC) source $i_p$, an internal capacitance $C_p$ of the PZT, and a resistance $R_p$, which is usually very large and can be neglected in some cases. It should be noted that since the output current of the PEH is very small, typically at the $\mu$A level, and the open-circuit output voltage is relatively high, the
outputs also vary with the external excitation conditions, e.g., amplitude and frequency. Therefore, it is necessary to design a suitable circuit to improve the output performance for a specified excitation condition.

3 Four basic piezoelectric energy harvesting interface circuits

Four classical interface circuits, i.e., SEH\(^{[51]}\), SECE\(^{[52]}\), P-SSHI\(^{[53]}\), and S-SSHI\(^{[54]}\), for piezoelectric energy harvesting are shown in Fig. 5.

The SEH interface circuit consists of a full-bridge rectifier and a filter capacitor. The rectifier bridge converts AC electricity into direct current (DC) electricity, the filter capacitor provides a stable DC voltage to the load when the charging and discharging progresses are balanced. However, the energy extraction process only occurs when the PZT voltage is higher than the rectified voltage. Because of the phase difference between the current and the voltage, the undelivered charge will be neutralized. The energy conversion efficiency is low, and is greatly influenced by the load impedance\(^{[62]}\). To avoid these shortcomings, Lefeuvre et al.\(^{[52]}\) designed...
the SECE interface circuit connecting a full-bridge rectifier bridge and a buck-boost converter after the PZT. When the energy loss of the buck-boost converter is ignored, the output power of the SECE circuit is about four times higher than the maximum output power of the SEH circuit. However, this circuit requires a separate external switch controller. When the PZT voltage reaches the extreme, the switch is controlled by the external signal to close the 1/4 LC oscillation period to transfer all charges generated by the PZT to the inductor. Then, the magnetic energy stored in the inductor is transferred to the load and filter capacitor through the freewheel diode. This progress increases the complexity of the circuit to some extent, but greatly improves the energy conversion efficiency and load adaptability.

Lallart et al.\cite{53} designed the P-SSHI interface circuit, in which a switch and a synchronous inductor were connected in parallel with the PZT based on the SEH circuit. When the PZT voltage reached its peak, closed the switch. Then, the PZT and inductor formed an LC resonant circuit. After a 1/2 oscillation period, the PZT voltage was flipped. It increased the PZT voltage and reduced the effect of the phase difference between the current and the voltage on energy conversion, thus improving the energy conversion efficiency. In the P-SSHI interface circuit, the voltage flipping coefficient had a significant effect on the output power. When the coefficient was between 0.5 and 0.8, the maximum output power was 4 to 10 times that of the SEH circuit\cite{63}. However, the output power of this circuit was influenced by the load. Similar to the SECE circuit, the P-SSHI interface circuit requires an external switch controller, making it more challenging to be realized.

Taylor et al.\cite{54} and Lefeuvre et al.\cite{64}, respectively, connected synchronous switching inductors in series with the PZT and rectifier bridge to propose the S-SSHI interface circuit, whose principle is similar to the P-SSHI circuit. However, this circuit is open most of the time and only conducts when the PZT voltage reaches its extreme value. Similarly, its load adaptability is similar to the P-SSHI circuit. The maximum output power is 3 to 9 times higher than the SEH circuit when the voltage flipping coefficient is between 0.5 and 0.8. Compared with the P-SSHI circuit, the maximum output power of the S-SSHI circuit is slightly smaller than that of the P-SSHI circuit, while the optimal load is 1/4 of that of the P-SSHI. Therefore, the S-SSHI circuit is superior in cases of smaller loads.

4 Improved circuits

4.1 Improved circuits based on the SECE circuit

The above analysis shows that the output power of the SECE interface circuit is load-independent and is substantially higher than the SEH circuit. However, the control of switches in a circuit usually depends on the external devices and microcontrollers, and the on-time of the circuit is very short compared to the vibration period. Therefore, researchers have also made improvements to the SECE circuit.

To overcome the problems of load matching and switching control in the interface circuit, Zhu et al.\cite{65} used a flyback transformer with the PKD switching technology to improve the SECE circuit, named as the self-powered synchronous charge extraction (SCE) circuit. It can extract all charges of the PZT when the voltage reaches the peak. Thus, the output power is independent of the load impedance. The operating principle is shown in Fig. 6. The PKD switching circuit detects the peak voltage of the PZT, and the switch turns on after the voltage reaches the peak and then drops slightly. Due to the self-inductance of transformers, the energy stored in the inductor can flow to the filter capacitor $C_r$ and the load $R_L$ through the freewheel diode so that the output power will not be influenced by the load. Zhu et al.\cite{65} conducted energy harvesting experiments on the self-powered SCE circuit and the SEH circuit. They demonstrated that the self-powered SCE circuit could harvest up to 4 times more power than the SEH circuit, and the energy consumed by the electronic switching circuit was less than 2% of the harvested energy. This circuit is able to collect energy from the detection capacitor $C_1$. 
To investigate the output performance of the self-powered SCE circuit under different operating conditions, Nechibvute and Chawanda tested this circuit against the SEH circuit using different acceleration excitations and under resonant and non-resonant conditions. First, the excitation frequency was fixed, and the piezoelectric oscillator was in resonance. Second, a series of resistors were tested when the excitation levels were 0.1 g, 0.2 g, 0.3 g, 0.4 g, and 0.5 g, and the maximum output powers of the two circuits were compared. Third, the excitation level was fixed at 0.5 g, and a series of resistors were used as loads under resonant and non-resonant conditions, respectively. The experimental results demonstrated that, with the increase in the excitation acceleration level, the self-powered SCE circuit had a more obvious enhancement compared to the SEH circuit, with a maximum of 0.7 times enhancement. Moreover, the enhancement under the non-resonant condition was about 1.34 times, which was much higher than that under the resonant condition.

Lallart et al. proposed that the narrow frequency bandwidth and limited energy conversion capability constrained the piezoelectric energy harvesting system. The frequency bandwidth can be widened with nonlinear dynamics methods, and can be improved by using nonlinear energy harvesting interface circuits. Therefore, Lallart et al. verified the coupling characteristics between the nonlinear tristable energy harvester and the nonlinear SCE circuit experimentally. The circuit was connected after the tristable piezoelectric beam, which could extract the converted energy. However, the resulting reverse coupling effect could affect the multistable boosting bandwidth and even severely reduce the displacement amplitude of the vibration. To find a balance, they optimized the switching interval between the actual on-time and the theoretical on-time by controlling the input signal $V_{\text{cont}}$, as shown in Fig. 7, to enhance the energy conversion efficiency and frequency bandwidth at the same time.

In order to adapt to the broadband vibration in the environment, Wu et al. proposed an optimized synchronous electric charge extraction (OSECE) circuit, as shown in Fig. 8. The circuit can form an LC resonant circuit between the inductive transformer coil and the PZT for...
charge extraction, where the transformer consists of two coils with opposite directions for both positive and negative directions. This circuit adopts the contact switching method, i.e., the surface of the mass block of the cantilever beam and the surface of the block are coated with the electrode material. When the cantilever beam is in contact with the block, the switch is on, and the charge of the PZT is extracted to $L_3$ through the transformer. When the mass block is detached from the block, the switch is off, and the magnetic energy stored in $L_3$ is transferred to the filter capacitor through the freewheel diode. This circuit can work in a broader frequency band of vibration, and has a higher output power than the SEH circuit.

4.2 Improved circuit based on the SSHI circuit

The synchronized switch harvesting on an inductor interface is a nonlinear energy harvesting technology with higher energy conversion efficiency and higher output power compared with the SEH circuit\cite{81–82}. It can reduce the influence of diode and transistor conduction voltage drops when the open-circuit voltage of the PZT is low. Similarly, this method also relies on the $LC$ oscillation circuit to achieve voltage inversion and energy transfer. Therefore, it is necessary to control the switching time precisely.

In order to make the switch self-powered, Lallart and Guyomar\cite{53} proposed a PKD switch circuit, including an envelope detector, a comparator, and a digital switch, as shown in Fig. 9. Lallart and Guyomar\cite{53} proposed the self-powered P-SSHI (SP-SSHI) circuit by replacing the P-SSHI switch circuit with this PKD switch circuit. The results showed that the voltage could be flipped when the PZT voltage reached its extreme. It helps to reduce the sizes of the energy harvesting system, the external auxiliary equipment, etc. Moreover, the circuit can recover the energy in the peak detection capacitor $C$.

To reduce the number of components in the self-powered SSHI circuit and the energy loss caused by electronic components, Eltamaly and Addoweesh\cite{83} proposed a novel self-powered SSHI circuit, as shown in Fig. 10. $C_1$ and $C_2$ are used for voltage peak detection, and $C_1$ is much smaller than $C_2$. The states of the transistors $T_1$ and $T_2$ depend on the voltage of $C_1$, and $T_3$ and $T_4$ act as electronic switches in the positive and negative directions, respectively. The
experimental results showed that, under the same conditions, the circuit reduced the energy dissipation by 26%, increased the output power by 15%, improved the energy conversion efficiency by 10%, and widened the operating frequency bandwidth substantially.

Compared with the P-SSHI circuit, the optimal load impedance of the S-SSHI circuit is much smaller. Liang and Liao [84] improved the S-SSHI circuit based on the PKD switch circuit, and proposed an SP-SSHI interface circuit which could control the switch status autonomously without external signals, as shown in Fig. 11. The circuit has a “second inversion” phenomenon. When the positive voltage flipping progress is completed, the current in the inductor has a reverse tendency. The $T_3$ path is not conducted due to the reverse cut-off of the diode $D_5$, and $T_4$ is also in an off state. Since the transistor has an internal parasitic capacitance, the current in the inductor $L$ can be flipped through the $T_4$ path. As the parasitic capacitance is very small, the flipping time is short, as shown in Fig. 12.

![Fig. 10 Schematic diagram of the novel self-powered SSSI circuit][83]

![Fig. 11 Schematic diagram of the SP-SSHI circuit][84]

![Fig. 12 Theoretical waveform of the SP-SSHI circuit][84] (color online)
From the above analysis, it can be found that the SP-SSHI interface circuit can automatically turn on when the PZT voltage reaches the extreme moment. However, the second inversion of this circuit has a negative effect on energy harvesting, which not only reduces the output voltage but also causes misjudgment of the voltage peak detection. Therefore, the resistors $R_1$ and $R_2$ introduced to eliminate this interference are necessary.

Because of the voltage drop of the diode and the emitter-base conduction voltage of the transistor, there is switching delay (SD) in the PKD switch circuit, i.e., the PZT displacement extreme time and the actual switch-on time are not completely synchronized. In fact, there is a phase difference $\varphi$ between them, which will reduce the harvested energy and affect the working performance of the system. Lallart and Guyomar\cite{53} studied the SD caused by the diodes and transistors in the self-powered S-SSHI circuits, and theoretically analyzed the effects of both positive and negative SD on the self-powered SSSI circuit. Liang and Liao\cite{84} discussed the influence of capacitance and resistance on the SD, and stated that the SD varied with the open-circuit voltage. Zhu et al.\cite{81} considered the effect of the SD caused by the envelope detector, and claimed that the negative effect could be well tuned by selecting relevant passive components with the optimal parameters.

For the PKD switch circuit, as shown in Fig. 9, Chen et al.\cite{85} proposed that there were three reasons for the formation of the SD $\varphi_1$, as shown in Fig. 13. During the charging phase, the phase shift $\alpha$ between the PZT displacement and the voltage is caused by the PZT internal capacitance $C_p$ and the peak detection capacitor $C$. The phase shift $\theta$ between the PZT voltage and the envelope detector voltage is caused by the peak detection capacitor $C$. The delay $\beta$ between the PZT voltage peak time and the switching-on time is mainly induced by the emitter-based threshold voltage of the comparator transistor.

![Fig. 13](image_url)  
**Fig. 13** Schematic diagram of the three sources of the SD\cite{85} (color online)

By means of theoretical derivation, Chen et al.\cite{85} derived the switching delay as follows:

$$\varphi_1 = \beta - \alpha.$$  \hspace{1cm} (1)

They concluded that the comparator delay $\beta$ was dominant in the sources of the SD compared with $\alpha$ and $\theta$, and the SD could be reduced mainly by decreasing $\beta$. Besides, the base voltage of the transistor $T_1$ could be reduced during the forward motion of the PZT so that the PZT voltage started to decrease after the peak while the peak detection capacitor $C_1$ voltage was still rising. It could significantly reduce the switching delay $\beta$ caused by the comparator. They proposed an improved SP-PSSI (ISP-PSSI) circuit based on the SP-PSSI circuit, as shown in Fig. 14. The improved circuit can reduce the transistor base voltage and thus reduce the value of $\beta$ by the voltage divider. However, the resistor $R_3$ will affect the flipping coefficient of the LC oscillation circuit. Moreover, the reduction in $\beta$ is not apparent when the resistance value of $R_3$ is too high. When $R_3$ is reduced, the flipping coefficient $\gamma$ of the LC oscillation circuit will be reduced. Therefore, it is essential to determine the value range of $R_3$ in the design of the voltage divider.
The SSHI circuit can flip the PZT voltage to boost the output voltage and extract more energy to transfer to the storage capacitor and load. It can significantly increase the output power. However, considering the energy dissipation caused by the voltage drop of diodes under low open-circuit voltage conditions, Lallart and Guyomar[53] proposed a new model, as shown in Fig. 15. To reduce the number of diodes, switches are used to replace the diodes in the rectifier bridge. It reduces the energy loss caused by diodes, and realizes self-powered by using the PKD switch circuit. Experiments have shown that the energy consumed by the PKD switch circuit is about 5% of electrostatic energy on the PZT. The output power of the system can be significantly increased. Compared with the SEH circuit, the improved circuit can obtain 160% more power.

### 4.3 Inductorless energy harvesting interface circuit

In SSHI circuits, the inductor is generally larger than other components, and often requires more space when it is integrated with other modules. Du and Seshia[86] proposed the synchronous switch harvesting on capacitors (SSHC) circuit to use one or more capacitors instead of inductors to achieve voltage inversion of the PZT. As shown in Fig. 16, the single-capacitor SSHC circuit can utilize the principle of charge transfer between capacitors instead of energy conversion in the LC oscillation of the P-SSHI circuit, where the capacitor $C_1$ is named as the synchronous capacitor. The circuit has three sets of switches, i.e., the forward switch $\Phi_p$, the reverse switch $\Phi_n$, and the switch $\Phi_0$.

First, at the moment that the PZT voltage ($V_p$) is at the extreme value and begins to decrease, close the switch $\Phi_p$. Then, the PZT is connected to the capacitor $C_1$, and the charge stored in the PZT starts to transfer to $C_1$ until the voltages are equal. Second, disconnect the
switch \( \Phi_p \), and close the switch \( \Phi_0 \). Then, the internal capacitor of the PZT is shorted, which will cause the charge generated by the PZT to be neutralized and the capacitor \( C_1 \) remains unchanged. Third, disconnect the switch \( \Phi_0 \), and close \( \Phi_n \). Then, the capacitor \( C_1 \) is connected to the PZT in the opposite direction, and \( C_1 \) starts to charge the PZT in the reverse direction until their voltages are equal. Finally, disconnect the switch \( \Phi_n \). Then, the voltage of the PZT can be flipped from positive to negative. The theoretical waveform is shown in Fig. 17. The voltage \( V_p \) after the flipping is

\[
V_p = -(V_r + 2V_D) \frac{x}{(1 + x)^2}, \tag{2}
\]

where \((V_r + 2V_D)\) is the voltage before flipping, and \(x\) is the ratio of \( C_1 \) to \( C_p \) from which it can be found that the flipping efficiency of this process is only 1/4 when the two capacitance values are the same. When the PZT voltage is flipped from negative to positive, as the voltage value of \( C_1 \) is not zero at this time, the voltage of the PZT after a similar flipping process can be expressed as

\[
V_p = \frac{5}{16} (V_r + 2V_D). \tag{3}
\]

It can be found that the multiple voltage flipping progress can achieve higher voltage inversion efficiency. For a single-capacitor circuit, when the capacitance values of capacitors \( C_1 \) and \( C_p \) are equal, the maximum voltage inversion efficiency is 1/3, and the main factor limiting this inversion efficiency is the energy loss caused by the charge neutralization process of the capacitor \( C_p \) when the switch \( \Phi_0 \) is closed. To improve the voltage inversion efficiency, the energy loss in the charge neutralization process must be reduced. Du and Seshia\cite{86} proposed to use multiple synchronous capacitors to extract the charge in the PZT so that the charge in the neutralization process of \( C_p \) could be as small as possible. With eight synchronous capacitors, the voltage inversion efficiency of the P-SSHC interface circuit could reach 0.8, and its energy harvesting efficiency was 9.7 times that of the SEH circuit.

![Waveform of the single-capacitor SSHC\cite{86} (color online)](image-url)
However, in the P-SSHC circuit, an additional circuit or control unit is required for precisely driving the switches, which increases the complexity of the circuit and energy dissipation. Wu et al.\cite{87} proposed an integrated SSHC rectifier circuit, as shown in Fig. 18. Compared with the classical P-SSHC circuit, the integrated SSHC rectifier circuit uses active diodes to reduce the forward voltage drop of the ordinary diodes, and integrates a capacitor into the rectifier to eliminate the special switch driver. According to the simulation results, the voltage inversion efficiency of this circuit is up to 92\%, which is much higher than the classical P-SSHC circuit.

![Integrated SSHC rectifier circuit\cite{87}](image)

The above analysis shows that when the number of synchronous capacitors increases, the voltage inversion efficiency also rises. The theoretical maximum voltage inversion efficiency in the SSHC circuit when $C_k = C_p$ is shown in Table 1.

| Number of capacitors | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|----------------------|------|------|------|------|------|------|------|------|
| Voltage inversion efficiency | 1/3  | 1/2  | 3/5  | 2/3  | 5/7  | 3/4  | 7/9  | 4/5  |

Yue and Du\cite{88} found that in the energy transfer process, when the voltage balance was reached, the remaining charge of the PZT when $C_k \gg C_p$ would be much smaller than that when $C_k = C_p$. When $C_k = 100C_p$, the relationship between the voltage inversion efficiency and the number of $C_k$ is shown in Table 2. It can be found that when the same inversion efficiency is achieved, the number of capacitors listed in Table 2 is half of that in Table 1. However, when the capacitance value of the synchronous capacitor $C_k$ increases, its charging time will also increase, thus requiring more switching cycles to achieve a maximum inversion efficiency.

| Number of capacitors | 1    | 2    | 3    | 4    |
|----------------------|------|------|------|------|
| Voltage inversion efficiency | 1/2  | 2/3  | 3/4  | 4/5  |

### 4.4 Other improvement methods and circuits

#### 4.4.1 Hybrid-mode interface circuits

Based on the above circuit analysis, it can be found that the P-SSHI circuit can significantly improve the energy conversion efficiency, but its harvested power is greatly affected by the load. The harvested power of the SECE interface circuit is not affected by the load, but its maximum harvested power is smaller than that of the P-SSHI. Wang et al.\cite{89} proposed a synchronous charge extraction and voltage inversion (SCEVI) circuit by combining the advantages of the SECE and P-SSHI circuits, as shown in Fig. 19.
The circuit can harvest energy twice in each vibration period, as shown in Fig. 20. Taking the period from \( t_0 \) to \( t_0 + T/2 \) as an example, when the PZT voltage reaches the extreme value (\( V_p \)), \( S_2 \) closes, and the SECE circuit works. After extracting part of the energy, \( S_2 \) breaks quickly and the voltage PZT drops to \( V_M \). Then, the energy stored in the inductor \( L_2 \) transfers into the filter capacitor \( C_r \) and the load through the freewheel diode \( D_5 \). The moment \( S_2 \) breaks and \( S_1 \) closes, the P-SSHI circuit works. After a 1/2 \( LC \) oscillation period, the PZT voltage flips rapidly from \( V_M \) to \( V_m \). When \( S_1 \) is disconnected, the circuit is in an open state. As the piezoelectric element moves in the reverse direction, the voltage gradually increases toward the negative peak value. When the peak value is reached, the second energy extraction is performed, whose process is similar to the above. Through theoretical calculations, the maximum energy that this circuit can harvest is approximately at the same level as the P-SSHI circuit, and the output power is 1.5 times higher than that of the SECE interface circuit, and it is not influenced by the load.

Lallart et al.\cite{90} combined the characteristics of the two basic circuits to propose the synchronous inversion and charge extraction (SICE) circuit with similar schematic diagram to the SCEVI circuit but different switching control strategy, as shown in Fig. 21. First, the circuit acts as the P-SSHI circuit for several voltage inversions and natural charging, during which \( S_2 \) is always off. When the PZT voltage is high enough, \( S_1 \) breaks and \( S_2 \) closes. Then, the circuit is equivalent to the SECE circuit, which transfers all charges stored in the PZT to the inductor \( L_2 \) in the form of magnetic energy. After this process, \( S_2 \) turns off and the inductor freewheel phase starts. The SICE technology can be used for low coupling, high damping, and
non-resonant occasions, which can harvest up to 5 times the energy compared to the SEH circuit, and the output power is not influenced by the load. Multiple voltage inversion progresses can increase the voltage of the PZT, eliminate the effects of the diode voltage drop and transistor conduction threshold on the circuit conduction, and meet the voltage requirements of the load. Due to the internal impedance of electronic components, there is energy dissipation in the process of voltage inversion. Both switching strategies can improve energy conversion efficiency and load adaptability. The SCEVI circuit can extract energy twice in one vibration period, while the SICE interface only extracts energy in a specific period.

Xia et al.\cite{82} built a self-powered SECE and P-SSHII hybrid operation mode circuit based on the PKD switch circuit, as shown in Fig. 22. The circuit performs a process similar to the charge extraction in the positive half-cycle and the voltage inversion progress in the negative half-cycle. To reduce the SD caused by this conduction voltage of transistors, the metal-oxide-semiconductor field-effect transistors (MOSFETs) are gate-source short-circuited to act as diodes with a fixed forward voltage drop, which are in the series connection of the transistors and the PZT, so that the fast conduction of the transistors can be achieved. The number of MOSFETs can be selected based on certain conditions.

From Fig. 23, the circuit can extract energy twice in one vibration period, and the conductive time is increased compared to the above circuits. It is demonstrated that the output power of the circuit can reach 85.7 µW when the open-circuit voltage is 3 V, which is at least twice of the SEH circuit. Therefore, the optimal operating voltage range is widened accordingly.
Based on the S-SSHI circuit and the SECE circuit, Lallart et al.\cite{91} designed a double synchronized switch harvesting (DSSH) circuit. As shown in Fig. 24, the DSSH circuit can be divided into two parts. One is before the rectifier bridge and similar to the S-SSHI circuit, and the other is behind the rectifier bridge and is a typical buck-boost DC-DC converter. The capacitor $C_{\text{int}}$ acts as the intermediate capacitor, which can store part of the energy transferred by the PZT, and the stored charge on the capacitor $C_{\text{int}}$ is transferred to the inductor $L_2$ through the switch $S_2$. When the above process is finished, the switch $S_2$ also breaks, and thus the energy stored on the inductor $L_2$ can be finally transferred to the capacitor $C_S$ and the load $R_L$ through the diode $D_0$. Theoretical derivation and experiments prove that the DSSH circuit can harvest more energy, which is about 5 times that of the SEH circuit. However, the circuit requires precise switching signals to control the switching time, and the multiple energy transfers consume lots of energy.

![Fig. 24 Schematic diagram of the DSSH circuit\cite{91} (color online)](image)

To achieve a good balance between the rectified peak output power (RPOP) and the optimal rectified voltage range (ORVR), Xia et al.\cite{92} proposed an S-SSHI and SECE hybrid-mode rectifier, as shown in Fig. 25, where $L_1$ and $L_2$ are two winding inductors of the flyback transformer, and $M_1$ is an N-metal-oxide-semiconductor (NMOS).

As shown in Fig. 25(b), when the PZT voltage reaches its positive extreme, the circuit flips the PZT voltage and transfers some energy to the inductor $L_2$ like the S-SSHI circuit, thus increasing the output power; when the PZT voltage reaches its negative extreme, the charge transfers from the PZT to the inductor $L_1$, acting as an SECE circuit. Finally, the energy stored in $L_1$ is transferred to the filter capacitor $C_f$ through $L_2$, widening the optimal rectified voltage range. The experimental results prove that the maximum output power can reach 0.28 mW when the open circuit of the PZT voltage is 6 V. Under the same conditions, the output power is 1.55 times that of the SECE circuit, and the optimal rectified voltage range is 4.55 times that of the S-SSHI circuit, which can achieve a good balance between the RPOP and the ORVR.

![Fig. 25 (a) Schematic diagram of the S-SSHI and SECE hybrid-mode rectifier; (b) predicted operating waveform\cite{92} (color online)](image)
4.4.2 Energy harvesting interface circuit improvement with the DC-DC technology

As the ambient vibration is random either in the amplitude or in the frequency, the output voltage of PEH varies. In some cases, the rectified voltage cannot meet the devices’ requirements, and thus the DC-DC technology is used to convert the rectified voltage into the target amplitude. Ottman et al. [93] analyzed the buck converter in discontinuous current conduction mode, and obtained the expression for the duty cycle-power relationship, where there was an optimal duty cycle maximizing the harvested energy. The interface circuit is shown in Fig. 26. Theoretical derivation and experiments verified that the optimal duty cycle tended to become constant as the vibration excitation level increased by adding a switching control module. Under the same conditions, the energy harvested by this circuit was increased by about 325%. However, in the experiment, the efficiency of the buck converter fluctuated in the range from 0% to 70%. Thus, there exists lots of energy loss.

To overcome the problem of low output voltage under low excitation levels or low coupling conditions, Wahab et al. [94] used a boost converter to boost the output voltage to a usable value, as shown in Fig. 27. The duty cycle can be adjusted to control the input and output voltage relationship and significantly increase the output voltage. However, the output power of this circuit is affected by the load, and is sensitive to energy loss, which can be optimized by using energy dissipation reduction methods.

4.4.3 Voltage multiplier circuit

A rectifier bridge is usually applied in most piezoelectric energy harvesting circuits to convert AC input to DC output. Tabesh and Fréchette [95] compared the half-wave voltage doubler (VD) circuit (as shown in Fig. 28) with the SEH circuit, and claimed that the number of diodes in the VD rectifier was half that of the SEH circuit. The energy dissipation caused by the diodes is lower than that caused by the SEH circuit. However, the maximum output power is the same in theory, and can be obtained for the VD circuit when the filter voltage $V_F$ is higher (when $V_F = V_{oc}$, where $V_{oc}$ is the open-circuit voltage). It is twice the SEH circuit ($V_F = V_{oc}/2$), and the VD circuit is more suitable for the low current situations.

Kushino and Koizumi [96] pointed out that the “energy return phenomenon” [97] of the SEH circuit could be avoided in the SSHI circuit because the current and voltage could be synchronized by implementing an $LC$ resonant circuit. However, the switch and inductor cannot be
connected to the half-wave VD circuit and a full-wave rectifier circuit with the same characteristics is considered, as shown in Fig. 29. Based on this, a full-wave VD with the synchronized switch and inductor circuit was proposed, as shown in Fig. 30.

![Fig. 29 Schematic diagram of the full-wave voltage doubler circuit](color online)

![Fig. 30 Schematic diagram of the full-wave VD circuit with a switched inductor](color online)

The SEH full-wave VD rectifier and the full-wave VD rectifier with switched-inductor circuits were tested when the open-circuit voltage of the piezoelectric element was 5 V. The experimental results showed that the optimal filter voltage corresponding to the maximum output power of the SEH full-wave VD circuit was close to 2.5 V or 5 V, which is consistent with the theoretical prediction. Besides, the maximum output power of the full-wave VD circuit is larger than the maximum output power of the SEH circuit because of the lower energy dissipation caused by the diodes. The maximum output power obtained by the full-wave VD rectifier with a switched-inductor circuit is approximately 70 µW larger than the maximum output power obtained by the full-wave VD circuit, and is about 1.56 times that of the SEH circuit.

4.4.4 Piezoelectric energy injection circuit

Researchers have paid much attention to the energy transfer from the PZT to the energy storage. Considering the pulsed bidirectional energy flow between the PZT and the energy storage element, Lallart and Guyomar proposed a piezoelectric energy injection circuit, as shown in Fig. 31, to improve the harvested power through artificial energy injection and thus the overall coupling coefficient.

![Fig. 31 Piezoelectric voltage energy injection circuit](color online)

As shown in Fig. 31, the circuit is the SECE circuit accompanied by an energy injection module. The process can be divided into two parts. One is the energy extraction progress, and the other is the energy injection progress. $S_{01}$ is used for the positive half-cycle energy extraction ($S_{02}$ is for the negative one), and the working principle is the same as that of the SECE circuit. Accordingly, $S_{12}$ and $S_{22}$ are used for the positive direction energy injection on the PZT ($S_{11}$ and $S_{21}$ are for the negative direction one). When the positive energy injection switch is on, the negative one is off. If an initial voltage $V$ is given to the PZT, the initial energy of the PZT is

$$E = CV^2/2.$$ (4)
When the piezoelectric element moves to the extreme value, energy extraction is carried out. After extraction, the PZT voltage is null. The voltage of the piezoelectric element increases to $V_0$ through energy injection. When the piezoelectric element moves to the next extreme value, the voltage is $(V + V_0)$. At this moment, the energy stored in the piezoelectric element is

$$E = \frac{1}{2}C(V^2 + V_0^2 + 2VV_0).$$

(5)

Under ideal conditions, the circuit can harvest up to 20 times more power than the SEH circuit. However, the whole working process of the circuit is influenced by the energy injection efficiency and the energy conversion efficiency. This technology can also be applied to other conversion mechanisms, e.g., thermoelectric energy harvesting fields. In this mode, the number of switches that need to be controlled is too large, and the implementation is complicated, which will bring difficulties to practical applications.

Becker et al.\cite{99} presented a novel piezoelectric generator consisting of two separate structures, as shown in Fig. 32. The first one acts as the “main harvester” and is connected to the energy harvesting interface circuit. The second one is used as “injection electrodes” to deliver the required energy to the main generator. A voltage offset for the main generator can be achieved when it finishes the discharge progress, and thus can have an initial voltage after the end of the charge extraction phase, which is different from the traditional SECE circuit. They used the peak detector and microcontroller to build this generator for testing. When the energy consumed by the above-mentioned module was ignored, the energy conversion efficiency could reach 3 times that of a standard device.

Based on the synchronized multiple bias-flip (SMBF) model\cite{100}, Liang et al.\cite{101} proposed a parallel synchronized triple bias-flip (P-S3BF) interface circuit, as shown in Fig. 33. It is mainly composed of three parts, i.e., a PZT equivalent, a harvesting branch, and a bias-flip branch in which an auxiliary capacitor $C_b$ is set up to realize energy injection to the PZT, whose value is much larger than the piezoelectric inherent capacitor $C_p$. Different from the P-SSHI circuit, the auxiliary capacitor $C_b$ can provide a bias voltage when the voltage progress ends, and thus a large initial voltage can be obtained. The P-S3BF circuit can improve the output power by 24.5% than the P-SSHI circuit and by 287.6% than the SEH circuit.

With the improvement of the interface circuit for various working environments and excitation conditions, researchers have greatly improved the energy harvesting, and improved the energy conversion efficiency, reduced the circuit loss, and promoted the use of the piezoelectric energy harvesting system. Table 3 summarizes the characteristics of the above-mentioned circuits. It should be noted that the data were all obtained under the respective experimental conditions. When the experimental conditions or experimental parameters are different, the obtained data are different.
Fig. 33  Schematic diagram of the P-S3BF circuit\textsuperscript{[101]}

Table 3  Summary of interface circuits

| Circuit                      | Maximum output power | Load adaptability | Self-powered | Features                                                                 |
|------------------------------|----------------------|-------------------|--------------|--------------------------------------------------------------------------|
| SEH\textsuperscript{[51]}   | 1                    | Bad               | √            | Simple, easy to build, and low energy conversion efficiency              |
| SECE\textsuperscript{[52]}  | 4                    | Good              | ×            | Good load adaptability and high energy conversion efficiency            |
| P-SSHI\textsuperscript{[53]} | 4–10                 | Bad               | ×            | High output voltage, high energy conversion efficiency, and large optimal load resistance |
| S-SSHI\textsuperscript{[54]} | 3–9                  | Bad               | ×            | High output voltage, high energy conversion efficiency, and low optimal load resistance |
| Self-powered SCE\textsuperscript{[65]} | 4             | Good              | √            | The energy of the voltage peak detection capacitor can be harvested, the size is big, and there exists SD |
| Synchronous discharge circuit\textsuperscript{[67]} | –                  | Not clear         | ×            | For tristable PEHs, the energy conversion efficiency and frequency bandwidth can be enhanced through controlling the SD, and the external signal is required |
| OSECE\textsuperscript{[80]}  | –                    | Not clear         | √            | Physical contact switching is used, nonlinear collisions can broaden the frequency band, and self-powered charge extraction can be realized |
| NCP SP-SSHI\textsuperscript{[83]} | 1.15/SP- PSSH | Bad               | √            | Small number of electronic components and large optimal operating voltage range |
| SP-SSHI\textsuperscript{[84]} | 3                    | Bad               | √            | Self-powered; there is a phenomenon of “second inversion”              |
| ISP-SSHI\textsuperscript{[85]} | 1.11/SP- PSSH | Bad               | √            | The SD is small, the resistance of the voltage divider needs to be calculated precisely, and the calculation should consider several factors |
| Improved circuit based on the S-SSHI circuit\textsuperscript{[53]} | 2.6                 | Bad               | ×            | The voltage drop of the diode on circuit conduction can be reduced under low output voltage conditions |
| Inductorless interface circuit\textsuperscript{[86–88]} | –                   | Bad               | ×            | Small size, large number of capacitors, and troublesome switching control strategy |
| Circuit                                               | Maximum output power | Load adaptability | Self-powered | Features                                                                 |
|------------------------------------------------------|----------------------|-------------------|--------------|--------------------------------------------------------------------------|
| SCEVI$[^{89}]$                                       | 1.5/SECE             | Good              | ×            | Improve the energy conversion efficiency and load adaptability at the same time, and extract energy twice a vibration period |
| SICE$[^{90}]$                                        | 5                    | Good              | ×            | The voltage flipping progress can be carried out several times, the load adaptability is good, and the energy is extracted when the PZT voltage is enough high |
| Hybrid-mode circuit based SECE and P-SSHI$[^{92}]$   | 2                    | Good              | ✓            | Energy transfer occurs twice a vibration period, and MOSFETs are used to reduce the SD |
| DSSH$[^{91}]$                                        | 5                    | Good              | ×            | The energy conversion efficiency and load adaptability are improved simultaneously, the switching control is complex, and there is energy loss in multiple energy conversions |
| Hybrid-mode circuit based SECE and S-SSHI$[^{92}]$   | 1.55/SECE            | Good              | ✓            | Energy transfer occurs twice a vibration period, a good balance is achieved between the rectified peak output power and the optimal rectified voltage range |
| Step-down DC-DC converter$[^{93}]$                  | 3.25                 | –                 | ×            | As the vibration excitation increases, the optimal duty cycle tends to be constant; the output voltage can be adjusted |
| Boost converter interface circuit$[^{94}]$          | –                    | –                 | ×            | Can be used for low voltage piezoelectric energy harvesting under low excitation level or low coupling conditions; the output voltage is adjustable; and the circuit is sensitive to the component power dissipation |
| Half-wave VD circuit$[^{95}]$                       | 1                    | Bad               | ✓            | The number of diodes is half of the SEH circuit, and the optimal theoretical filter voltage is approximate twice the SEH circuit |
| Full-wave VD circuit$[^{96}]$                       | 1.19                 | Bad               | ✓            | Fewer diodes and more suitable for high voltage situations |
| Full-wave VD circuit with switched-inductor$[^{96}]$ | 1.56                 | Bad               | ✓            | Self-powered; a combination of the P-SSHI and full-wave VD circuits |
| Piezoelectric voltage energy injection circuit$[^{98}]$ | 20                   | Bad               | ×            | The overall coupling coefficient is improved with energy feedback techniques; the charge power output increases; the practicality is low, and it is very difficult to implement |
| Direct energy injection circuit$[^{99}]$            | 3                    | Good              | ×            | The main harvester part and the injection electrode part are separate; the circuit is improved based on the SECE circuit; the initial voltage is large |
| P-S3BF circuit$[^{99}]$                             | 3.88                 | –                 | ×            | An auxiliary capacitor is needed; the circuit is improved based on a synchronized multiple bias-flip model |

Note: If not otherwise specified, the column of the maximum output power represents the ratio of the maximum output power of the circuit to the SEH circuit. “–” represents that the corresponding result was not mentioned in the literature.

5 Prospect for energy harvesting circuits

In view of the high pollution of fossil fuels, more and more researchers have begun to look for alternative energy sources$[^{64,102}]$. The piezoelectric energy harvesting system has the advantages
of simple structure, enormous output power, easy miniaturization, and integration, and has a good application prospect\cite{103}. At present, most research on piezoelectric energy harvesting circuits is still in the stage of simulation, theoretical calculation, and experiment. There is still a long way to go before it is put into practical applications. Through the above summary of piezoelectric energy harvesting system circuits, we can predict the future development directions of interface circuits as follows.

(i) Study self-powered interface circuits. In some cases, the energy consumed by the external devices is more than the energy harvested by the PEHs, making it meaningless in practical applications. Therefore, using self-powered modules instead of conventional switches to achieve correct switch sequence is an inevitable trend in the development of interface circuits.

(ii) Study the high efficiency and low-power consumption of interface circuits. Usually, although the energy density of the PEH is high, the electronic components in the interface circuit will also consume part of the energy, which causes energy dissipation and reduces the conversion efficiency. Therefore, the power consumption of the interface circuit cannot be ignored. With the rapid development of the electronic technology, using low-power electronic components, such as diodes with low forward voltage drops and transistors with low conduction thresholds, to build interface circuits has also become a research hotspot.

(iii) Study the wide frequency band applications of interface circuits. In most cases, piezoelectric energy harvesting systems work best only in the resonance state. Therefore, it is necessary to widen the working frequency band of interface circuits to accommodate the environmental vibrations to harvest more energy.

(iv) Study integrated interface circuits. The integrated circuit technology has become increasingly mature. Reducing the size of the PEH without affecting the interface circuit is crucial for practical applications. The rapid development of the micro-electro-mechanical system (MEMS) technology has facilitated the integration of piezoelectric energy harvesting systems.

6 Conclusions

Nowadays, the piezoelectric energy harvesting technology has become a research hotspot. Using this technology can extend the lifespan of distributed sensors and meet the power requirements in particular fields. It is of great significance to design an interface circuit with the requirements of small size, reliable operation, high conversion efficiency, and suitable output power to improve the working performance of piezoelectric energy harvesting systems. First, the electromechanical coupling model of the cantilever beam energy harvester is analyzed, which can be simplified to an electrical model in or near a resonant state. Next, existing studies on energy harvesting interface circuits are introduced. The four basic interface circuits for piezoelectric energy harvesting are described, and the operating principle, operating mode, and load matching of each circuit are analyzed. Finally, the improved circuits are reviewed, including their working principles, advantages, shortcomings, and possible improvements.

In summary, studies on interface circuits have made significant progress, but the design of interface circuits has the potential to be greatly improved. The design of future interface circuits can be started from self-powered, low-power consumption, broadband, and integration. With the continuous development of electronic technology, micromachining technology, and interface circuits, it is believed that the PEH will be put into practical applications in the near future and is expected to replace the traditional energy supply in certain fields.

Open Access  This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.
References

[1] WHELAN, M. J., GANGONE, M. V., and JANOOYAN, K. D. Highway bridge assessment using an adaptive real-time wireless sensor network. *IEEE Sensors Journal*, 9, 1405–1413 (2009)

[2] JOUHARI, M., IBRAHIMI, K., TEMBINE, H., and BEN-OTHMAN, J. Underwater wireless sensor networks: a survey on enabling technologies, localization protocols, and internet of underwater things. *IEEE Access*, 7, 96879–96899 (2019)

[3] SUN, J. Z. and HUANG, Q. Wireless sensor network based bridge health monitoring system for long-span bridges. *Advanced Materials Research*, 905, 575–579 (2014)

[4] ZHENG, G. S., PFERSICH, S., ELDRIDGE, A., ZHOU, J. S., TIAN, D. X., and LEUNG, V. C. M. Wireless acoustic sensor networks and edge computing for rapid acoustic monitoring. *IEEE/CAA Journal of AutomaticaSinica*, 6, 64–74 (2019)

[5] MA, D. X., MA, J., XU, P. M., and PANG, Y. The application research progress of wireless sensor networks. *Applied Mechanics and Materials*, 475-476, 520–523 (2014)

[6] RAMYA, R., SARAVANAKUMAR, G., and RAVI, S. *Energy Harvesting in Wireless Sensor Networks*, Springer India, Delhi (2016)

[7] DU, S., JIA, Y., and SESHIA, A. A. An efficient inductorless dynamically configured interface circuit for piezoelectric vibration energy harvesting. *IEEE Transactions on Power Electronics*, 32, 3595–3609 (2016)

[8] WANG, X., XUE, C., and LI, H. Nonlinear primary resonance analysis for a coupled thermo-piezoelectric-rectangular plate model of piezoelectric thin plates. *Applied Mathematics and Mechanics (English Edition)*, 40(8), 1155–1168 (2019) https://doi.org/10.1007/s10483-019-2510-6

[9] JUNG, H. J., SONG, Y., HONG, S. K., YANG, C. H., HWANG, S. J., JEONG, S. Y., and SUNG, T. H. Design and optimization of piezoelectric impact-based micro wind energy harvester for wireless sensor network. *Sensors and Actuators A: Physical*, 222, 314–321 (2015)

[10] LI, Z. J., LIU, Y., YIN, P. L., PENG, Y., LUO, J., XIE, S. R., and PU, H. Y. Constituting abrupt magnetic flux density change for power density improvement in electromagnetic energy harvesting. *International Journal of Mechanical Sciences*, 198, 106363 (2021)

[11] WANG, L., ZHAO, L. B., LUO, G. X., ZHAO, Y. H., YANG, P., JIANG, Z. D., and MAEDA, R. System level design of wireless sensor node powered by piezoelectric vibration energy harvesting. *Sensors and Actuators A: Physical*, 310, 112039 (2020)

[12] HUANG, D. M., CHEN, J. Y., ZHOU, S. X., FANG, X. L., and LI, W. Response regimes of nonlinear energy harvesters with a resistor-inductor resonant circuit by complexification-averaging method. *Science China Technological Sciences*, 64, 1212–1227 (2021)

[13] YANG, T., ZHOU, S. X., FANG, S. T., QIN, W. Y., and INMAN, D. J. Nonlinear vibration energy harvesting and vibration suppression technologies: designs, analysis, and applications. *Applied Physics Reviews*, 8, 031317 (2021)

[14] MIAO, G., FANG, S. T., WANG, S., and ZHOU, S. X. A low-frequency rotational electromagnetic energy harvester using a magnetic plucking mechanism. *Applied Energy*, 305, 117838 (2022)

[15] WANG, H. R., HU, H. P., YANG, J. S., and HU, Y. T. Spiral piezoelectric transducer in torsional motion as low-frequency power harvester. *Applied Mathematics and Mechanics (English Edition)*, 34(5), 589–596 (2013) https://doi.org/10.1007/s10483-013-1693-x

[16] CHEW, Z. J., RUAN, T., and ZHU, M. Power management circuit for wireless sensor nodes powered by energy harvesting: on the synergy of harvester and load. *IEEE Transactions on Power Electronics*, 34, 8671–8681 (2018)

[17] DUAN, X. J., CAO, D. X., LI, X. G., and SHEN, Y. J. Design and dynamic analysis of integrated architecture for vibration energy harvesting including piezoelectric frame and mechanical amplifier. *Applied Mathematics and Mechanics (English Edition)*, 42(6), 755–770 (2021) https://doi.org/10.1007/s10483-021-2741-8

[18] LAN, J. F., ZHENG, L., AN, Z. Q., HOU, D. S., SUN, D. P., and ZHU, J. L. High power density and flexible self-powered piezoelectric nanogenerator based on solution crystallization. *Journal of Applied Polymer Science*, 138, 50896 (2021)
[19] ZHANG, B., LI, D. Z., LI, Y. R., DUCHARNE, B., and GAO, J. Double peak derived from piezoelectric coefficient nonlinearity and proposal for self-powered systems. Transactions of Nanjing University of Aeronautics and Astronautics, 35, 109–115 (2018)

[20] MAHALE, B., KUMAR, N., PANDEY, R., and RANJAN, R. High power density low-lead-piezoceramic-polymer composite energy harvester. IEEE Transactions on Ultrasونics, Ferroelectrics, and Frequency Control, 66, 789–796 (2019)

[21] PARK, S., KIM, H., KIM, J., LEE, T. H., and CHO, S. G. Taguchi design of PZT-based piezoelectric cantilever beam with maximum and robust voltage for wide frequency range. Journal of Electronic Materials, 48, 6881–6889 (2019)

[22] PENG, Y., XU, Z. B., WANG, M., LI, Z. J., PENG, J. L., LUO, J., XIE, S. R., PU, H. Y., and YANG, Z. B. Investigation of frequency-up conversion effect on the performance improvement of stack-based piezoelectric generators. Renewable Energy, 172, 551–563 (2021)

[23] RUI, X. B., ZHANG, Y., ZENG, Z. M., YUE, G. X., HUANG, X. J., and LI, J. B. Design and analysis of a broadband three-beam impact piezoelectric energy harvester for low-frequency rotational motion. Mechanical Systems and Signal Processing, 149, 107307 (2021)

[24] CAO, D. X., XIA, W., and HU, W. H. Low-frequency and broadband vibration energy harvester driven by mechanical impact based on layer-separated piezoelectric beam. Applied Mathematics and Mechanics (English Edition), 40(12), 1777–1790 (2019) https://doi.org/10.1007/s10483-019-2542-5

[25] WU, Y. P., LI, S., FAN, K. Q., JI, H., and QIU, J. H. Investigation of an ultra-low frequency piezoelectric energy harvester with high frequency up-conversion factor caused by internal resonance mechanism. Mechanical Systems and Signal Processing, 162, 108038 (2022)

[26] ZHOU, S. X., CAO, J. Y., and LIN, J. Theoretical analysis and experimental verification for improving energy harvesting performance of nonlinear monostable energy harvesters. Nonlinear Dynamics, 86, 1599–1611 (2016)

[27] LU, Z. Q., SHAO, D., FANG, Z. W., DING, H., and CHEN, L. Q. Integrated vibration isolation and energy harvesting via a bistable piezo-composite plate. Journal of Vibration and Control, 26, 779–789 (2020)

[28] WANG, C., LAI, S. K., WANG, Z. C., WANG, J. M., YANG, W., and NI, Y. Q. A low-frequency, broadband and tri-hybrid energy harvester with septuple-stable nonlinearity-enhanced mechanical frequency up-conversion mechanism for powering portable electronics. Nano Energy, 64, 103943 (2019)

[29] WANG, C., ZHANG, Q. C., and WANG, W. Low-frequency wideband vibration energy harvesting by using frequency up-conversion and quin-stable nonlinearity. Journal of Sound and Vibration, 399, 169–181 (2017)

[30] YANG, Y. X., SUN, L., ZHANG, Y., and SU, Y. K. Efficient and broadband four-wave mixing in a compact silicon subwavelength nanohole waveguide. Advanced Optical Materials, 7, 1900810 (2019)

[31] KUANG, Y., HIDE, R., and ZHU, M. L. Broadband energy harvesting by nonlinear magnetic rolling pendulum with subharmonic resonance. Applied Energy, 255, 113822 (2019)

[32] ZHOU, S. X., CAO, J. Y., ERTURK, A., and LIN, J. Enhanced broadband piezoelectric energy harvesting using rotatable magnets. Applied Physics Letters, 102, 173901 (2013)

[33] SONG, R. J., SHAN, X. B., LV, F. C., LI, J. Z., and XIE, T. A novel piezoelectric energy harvester using the macro fiber composite cantilever with a bicylinder in water. Applied Sciences, 5, 1942–1954 (2015)

[34] JEYASEELAN, A. A. and DUTTA, S. Improvement in piezoelectric properties of PLZT thin film with large cation doping at A-site. Journal of Alloys and Compounds, 826, 153956 (2020)

[35] YAN, X. H., LI, G., WANG, Z. Y., YU, Z. C., WANG, K. Y., and WU, Y. C. Recent progress on piezoelectric materials for renewable energy conversion. Nano Energy, 77, 105180 (2020)

[36] SUKUMARAN, S., CHATBOURI, S., ROUXEL, D., TISSERAND, E., THIEBAUD, F., and BEN-ZINEB, T. Recent advances in flexible PVDF based piezoelectric polymer devices for energy harvesting applications. Journal of Intelligent Material Systems and Structures, 32, 746–780 (2021)
[37] KLIMIEC, E., KACZMAREK, H., KRÓLIKOWSKI, B., and KOŁASZCZYŃSKI, G. Cellular polyolefin composites as piezoelectric materials: properties and applications. *Polymers*, **12**, 2698 (2020)

[38] KAMENSHCHIKOV, M. V., SOLNYSHKIN, A. V., and PRONIN, I. P. Dielectric response of capacitor structures based on PZT annealed at different temperatures. *Physics Letters A*, **380**, 4003–4007 (2016)

[39] SAMANTA, S., SANKARANARAYANAN, V., and SETHUPATHI, K. Band gap, piezoelectricity and temperature dependence of differential permittivity and energy storage density of PZT with different Zr/Ti ratios. *Vacuum*, **156**, 456–462 (2018)

[40] ZHANG, S., LIN, X. J., LIU, H., YUAN, Z., HUAN, Y., YUAN, X., HUANG, S. F., and CHENG, X. High-performance flexible piezoelectric nanogenerator based on necklace-like PZT particle chains. *International Journal of Energy Research*, **45**, 6213–6226 (2021)

[41] HUAN, Y., ZHANG, X. S., SONG, J. N., ZHAO, Y., WEI, T., ZHANG, G. G., and WANG, X. H. High-performance piezoelectric composite nanogenerator based on Ag/(K, Na) NbO$_3$ heterostructure. *Nano Energy*, **50**, 62–69 (2018)

[42] SONG, H. C., KIM, H. C., KANG, C. Y., KIM, H. J., YOON, S. J., and JEONG, D. Y. Multilayer piezoelectric energy scavenger for large current generation. *Journal of Electroceramics*, **23**, 301 (2009)

[43] NADAUD, K., POULIN-VITTRANT, G., and ALQUIER, D. Influence of topology and diode characteristics of AC-DC converters for low power piezoelectric energy harvesting. *Sensors and Actuators A: Physical*, **330**, 112901 (2021)

[44] LIANG, J. and LIAO, W. H. Impedance modeling and analysis for piezoelectric energy harvesting systems. *IEEE/ASME Transactions on Mechatronics*, **17**, 1145–1157 (2011)

[45] LI, Z. Y., TANG, L. H., YANG, W. Q., ZHAO, R. D., LIU, K. F., and MACE, B. Transient response of a nonlinear energy sink based piezoelectric vibration energy harvester coupled to a synchronized charge extraction interface. *Nano Energy*, **87**, 106179 (2021)

[46] GIULIANO, A. and ZHU, M. L. A passive impedance matching interface using a PC permalloy coil for practically enhanced piezoelectric energy harvester performance at low frequency. *IEEE Sensors Journal*, **14**, 2773–2781 (2014)

[47] PRIYA, S. Modeling of electric energy harvesting using piezoelectric windmill. *Applied Physics Letters*, **87**, 184101 (2005)

[48] YAN, B., ZHOU, S. X., and LITAK, G. Nonlinear analysis of the tristable energy harvester with a resonant circuit for performance enhancement. *International Journal of Bifurcation and Chaos*, **28**, 1850092 (2018)

[49] PEIGNEY, M. and SIEGERT, D. Piezoelectric energy harvesting from traffic-induced bridge vibrations. *Smart Materials and Structures*, **22**, 095019 (2013)

[50] WANG, J. H., ZHAO, B., LIAO, W. H., and LIANG, J. R. New insight into piezoelectric energy harvesting with mechanical and electrical nonlinearities. *Smart Materials and Structures*, **29**, 04LT01 (2020)

[51] OTTMAN, G. K., HOFMANN, H. F., BHATT, A. C., and LESIEUTRE, G. A. Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. *IEEE Transactions on Power Electronics*, **17**, 669–676 (2002)

[52] LEFEUVRE, E., BADEL, A., RICHARD, C., and GUYOMAR, D. Piezoelectric energy harvesting device optimization by synchronization of electric charge extraction. *Journal of Intelligent Material Systems and Structures*, **16**, 865–876 (2005)

[53] LALLART, M. and GUYOMAR, D. An optimized self-powered switching circuit for non-linear energy harvesting with low voltage output. *Smart Materials and Structures*, **17**, 035030 (2008)

[54] TAYLOR, G. W., BURNS, J. R., KAMMANN, S. A., POWERS, W. B., and WELSH, T. R. The energy harvesting eel: a small subsurface ocean/river power generator. *IEEE Journal of Oceanic Engineering*, **26**, 539–547 (2001)

[55] SHEN, H., QIU, J. H., JI, H. L., ZHU, K. J., BALSI, M., GIORGIO, I., and DELL’ISOLA, F. A low-power circuit for piezoelectric vibration control by synchronized switching on voltage sources. *Sensors and Actuators A: Physical*, **161**, 245–255 (2010)
[56] GUYOMAR, D., BADEL, A., LEFEUVRE, E., and RICHARD, C. Toward energy harvesting using active materials and conversion improvement by nonlinear processing. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 52, 584–595 (2005)

[57] RICHARDS, C. D., ANDERSON, M. J., BAH, D. F., and RICHARDS, R. F. Efficiency of energy conversion for devices containing a piezoelectric component. *Journal of Micromechanics and Microengineering*, 14, 717–721 (2004)

[58] ROY, A., and WRIGHT, P. K. A piezoelectric vibration based generator for wireless electronics. *Smart Materials and Structures*, 13, 1131–1142 (2004)

[59] AJITSARIA, J., CHOE, S. Y., SHEN, D., and KIM, D. J. Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation. *Smart Materials and Structures*, 16, 447–454 (2007)

[60] ZHANG, B., LIU, H. S., LI, D. Z., LIANG, J. H., and GAO, J. Analytical modeling and validation of a preloaded piezoceramic current output. *Micromachines*, 12, 353 (2021)

[61] RAMADASS, Y. and CHANDRAKASAN, A. P. An efficient piezoelectric energy-harvesting interface circuit using a bias-flip rectifier and shared inductor. *International Solid-State Circuits Conference*, 45, 189–204 (2009)

[62] SHU, Y. C. and LIEN, I. C. Efficiency of energy conversion for a piezoelectric power harvesting system. *Journal of Micromechanics and Microengineering*, 16, 2429–2438 (2006)

[63] SHU, Y. C., LIEN, I. C., and WU, W. J. An improved analysis of the SSHI interface in piezoelectric energy harvesting. *Smart Materials and Structures*, 16, 2253–2264 (2007)

[64] LEFEUVRE, E., BADEL, A., BENAYAD, A., LEBRUN, L., RICHARD, C., and GUYOMAR, D. A comparison between several approaches of piezoelectric energy harvesting. *Journal De Physique IV*, 128, 177–186 (2005)

[65] ZHU, L. Y., CHEN, R. W., and LIU, X. J. Theoretical analyses of the electronic breaker switching method for nonlinear energy harvesting interfaces. *Journal of Intelligent Material Systems and Structures*, 23, 441–451 (2012)

[66] NECHIBVUTE, A. and CHAWANDA, P. L. A. Applicability of self-powered synchronized electric charge extraction (SECE) circuit for piezoelectric energy harvesting. *International Journal of Engineering and Technology*, 4, 212608868 (2014)

[67] PANYAM, M., MASANA, R., and DAQAQ, M. F. On approximating the effective bandwidth of bi-stable energy harvesters. *International Journal of Non-Linear Mechanics*, 67, 153–163 (2014)

[68] PAN, D. K., LI, Y. Q., and DAI, F. H. The influence of lay-up design on the performance of bi-stable piezoelectric energy harvester. *Composite Structures*, 161, 227–236 (2017)

[69] PAN, D. K. and DAI, F. H. Design and analysis of a broadband vibratory energy harvester using bi-stable piezoelectric composite laminate. *Energy Conversion and Management*, 169, 149–160 (2018)

[70] TANG, Q. C., YANG, Y. L., and LI, X. Bi-stable frequency up-conversion piezoelectric energy harvester driven by non-contact magnetic repulsion. *Smart Materials and Structures*, 20, 125011 (2011)

[71] QIAN, F., HAJJ, M. R., and ZUO, L. Bio-inspired bi-stable piezoelectric harvester for broadband vibration energy harvesting. *Energy Conversion and Management*, 222, 113174 (2020)
A review of nonlinear piezoelectric energy harvesting interface circuits in discrete components

[76] ZHOU, S. X., CAO, J. Y., INMAN, D. J., LIN, J., LIU, S. S., and WANG, Z. Z. Broadband tristable energy harvester: modeling and experiment verification. *Applied Energy*, **133**, 33–39 (2014)

[77] ZHOU, S. X., CAO, J. Y., INMAN, D. J., LIN, J., and LI, D. Harmonic balance analysis of nonlinear tristable energy harvesters for performance enhancement. *Journal of Sound and Vibration*, **373**, 223–235 (2016)

[78] ZHOU, S. X. and ZUO, L. Nonlinear dynamic analysis of asymmetric tristable energy harvesters for enhanced energy harvesting. *Communications in Nonlinear Science and Numerical Simulation*, **61**, 271–284 (2018)

[79] MA, X. Q., LI, H. T., ZHOU, S. X., YANG, Z. C., and LITAK, G. Characterizing nonlinear characteristics of asymmetric tristable energy harvesters. *Mechanical Systems and Signal Processing*, **168**, 108612 (2022)

[80] WU, Y. P., BADEL, A., FORMOSA, F., LIU, W. Q., and ABOSSOU, A. Nonlinear vibration energy harvesting device integrating mechanical stoppers used as synchronous mechanical switches. *Journal of Intelligent Material Systems and Structures*, **25**, 1658–1663 (2014)

[81] ZHU, L. Y., CHEN, R. W., and LIU, X. J. Synchronous charge extraction and voltage inversion (SCEVI): a new efficient vibration-based energy harvesting scheme. *Journal of Vibroengineering*, **17**, 1037–1050 (2015)

[82] LALLART, M., GARBUIO, L., PETIT, L., RICHARD, C., and GUYOMAR, D. Double synchronized switch harvesting (DSSH): a new energy harvesting scheme for efficient energy extraction. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **55**, 2119–2130 (2008)

[83] OTTMAN, G. K., HOFMANN, H. F., and LESIEUTRE, G. A. Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode. *IEEE Transactions on Power Electronics*, **18**, 696–703 (2003)
[94] WAHAB, S. A., BHUYAN, M. S., SAMPE, J., and ALI, S. H. M. Parametric analysis of boost converter for energy harvesting using piezoelectric for micro devices. 2014 IEEE International Conference on Semiconductor Electronics, Pittsburgh (2014)

[95] TABESH, A. and FRÉCHETTE, L. G. A low-power stand-alone adaptive circuit for harvesting energy from a piezoelectric micropower generator. IEEE Transactions on Industrial Electronics, 57, 840–849 (2009)

[96] KUSHINO, Y. and KOIZUMI, H. Piezoelectric energy harvesting circuit using full-wave voltage doubler rectifier and switched inductor. 2014 IEEE Energy Conversion Congress and Exposition, Pittsburgh (2014)

[97] LIANG, J. R. and LIAO, W. H. Piezoelectric energy harvesting and dissipation on structural damping. Journal of Intelligent Material Systems and Structures, 20, 515–527 (2009)

[98] LALLART, M. and GUYOMAR, D. Piezoelectric conversion and energy harvesting enhancement by initial energy injection. Applied Physics Letters, 97, 014104 (2010)

[99] BECKER, P., HYMON, E., FOLKMER, B., and MANOLI, Y. High efficiency piezoelectric energy harvester with synchronized switching interface circuit. Sensors and Actuators A: Physical, 202, 155–161 (2013)

[100] LIANG, J. R. Synchronized bias-flip interface circuits for piezoelectric energy harvesting enhancement: a general model and prospects. Journal of Intelligent Material Systems and Structures, 28, 339–356 (2017)

[101] LIANG, J. R., ZHAO, Y. H., and ZHAO, K. Synchronized triple bias-flip interface circuit for piezoelectric energy harvesting enhancement. IEEE Transactions on Power Electronics, 34, 275–286 (2018)

[102] DONG, Y., LI, D. Z., DUCHARNE, B., WANG, X. H., GAO, J., and ZHANG, B. Impedance analysis and optimization of self-powered interface circuit for wireless sensor nodes application. Shock and Vibration, 2018, 8475896 (2018)

[103] LIU, H. C., ZHONG, J. W., LEE, C. K., LEE, S. W., and LIN, L. W. A comprehensive review on piezoelectric energy harvesting technology: materials, mechanisms, and applications. Applied Physics Reviews, 5, 041306 (2018)