Letters

Multi-Input SECE Based on Buck Structure for Piezoelectric Energy Harvesting

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and Zhidong Chen

***Abstract*—At present, most piezoelectric energy harvesters (PEHs) are developed based on a single piezoelectric transducer (PZT). But in practical applications, a vibration source can be equipped with PZT array in order to harvest more power. The time-shared multiplexing scheme is mainly employed for multi-input PEHs. There is less study on the synchronized multi-input PEH. In this article, a multi-input synchronous electric charge extraction (MI-SECE) interface based on buck structure for piezoelectric energy harvesting is proposed. Both theoretical analysis and experimental test results demonstrate the effectiveness of the proposed interface. The results show that the MI-SECE interface can extract energy from multi-PZTs simultaneously with any phase difference (0–2π).**

***Index Terms*—Energy harvesting interface, multi-input piezoelectric transducer (PZT).**

I. INTRODUCTION

PIEZOELECTRIC energy harvester (PEH) can be used as an alternative for conventional batteries and it shows a promising application prospect. According to the electromechanical coupling characteristic of the piezoelectric transducer (PZT), the PZT can generate electricity when strain is produced. Since the deformation of the vibrating device is alternating, the generated current is also alternating [1]. Therefore, an interface circuit with rectification is required between the PZT and the load [2]. The simplest interface is the standard energy harvesting circuit consisting of a rectifier bridge and a storage capacitor with a low harvesting efficiency.

For higher efficiency, Lefeuvre *et al.* [3] proposed a parallel synchronized switch harvesting on inductor (P-SSHI) circuit, and the experimental results show that the extracted electrical energy may be increased beyond 400%. Later, they proposed a synchronous electronic charge extraction (SECE) circuit, and experiments proved that the maximum output power of the SECE can reach four times that of the rectifier bridge [4]. On the basis of the SECE and P-SSHI, they proposed the series-synchronized switch harvesting on inductor (S-SSHI) circuit. The experiment proved that the circuit improves the harvested power, and the power harvested by the circuit is higher than that of the SECE and P-SSHI when the load voltage is low [5]. Currently, most of these technologies are applied to a single PEH. However, in the real application scenario, a single vibration source can be equipped with multiple PZTs for harvesting more power. Hence, research effort is made on multi-input piezoelectric energy harvesting technique. Romani *et al.* [6] proposed a multi-input PEH with a shared inductor. Boisseau *et al.* [7] presented a power management circuit implementing a synchronous electric charge extraction on the PEH, which can handle multiple PZTs operating at different frequencies and different output voltages with a single inductor. Shareef *et al.* [8] proposed a rectifier-less ac–dc converter, which is capable of harvesting energy from multiple PZTs. Meng *et al.* [9] proposed a PEH chip to harvest piezoelectric energy from multi-PZTs. The above multi-input interfaces are extended from the typical SECE, and inductor is shared through time-division multiplexing.

However, in some specific industrial application scenarios, multiple piezoelectric patches may deform simultaneously. If so, two or more piezoelectric patches have to use the inductor at the same time. Obviously, the typical time-sharing multiplexing method does not work properly. In this article, a multi-input synchronous electric charge extraction (MI-SECE) circuit based on buck structure is proposed. It can not only harvest energy from multiple PZTs in serial time division multiplexing but also harvest energy from multiple PZTs in parallel simultaneously.

II. PROPOSED MI-SECE

A. Analysis of the Proposed Interface

The proposed interface is shown in Fig. 1. It mainly consists of two diodes, two switches, an inductor, and an energy storage capacitor. Normally, the PZT can be modeled as a current

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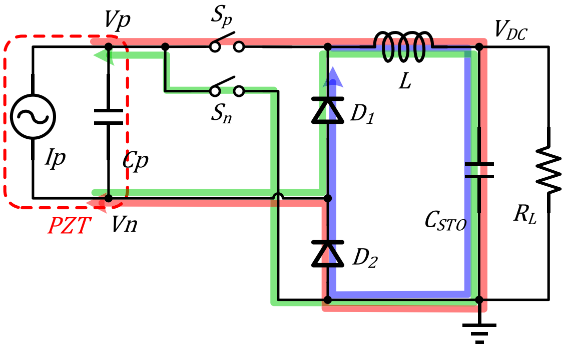


Fig. 1. Proposed SECE based on buck structure.

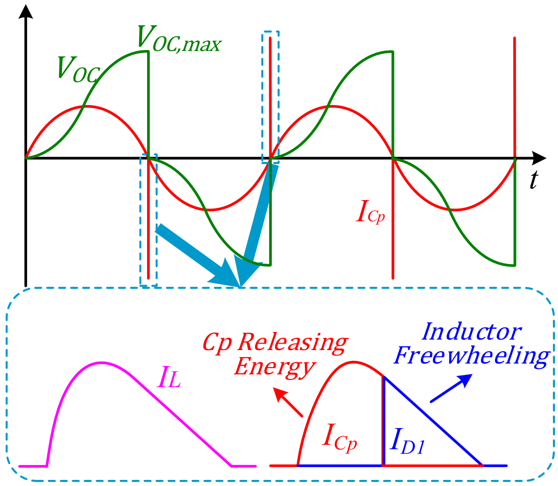


Fig. 2. Waveforms of the ideal working state of the proposed interface.

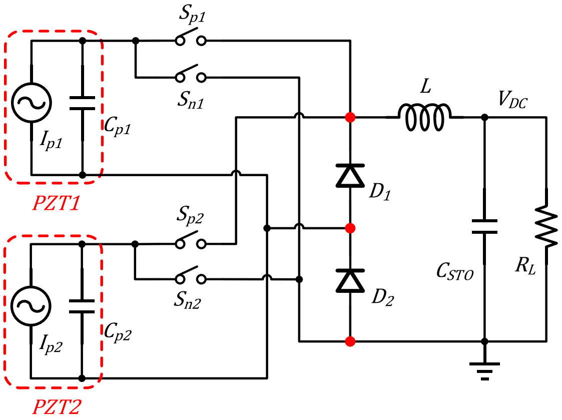


Fig. 3. Proposed MI-SECE.

source paralleled with a parasitic capacitor C_p. During most of a vibration cycle, both switches are OFF, parasitic capacitor C_p is charged by equivalent current source I_p so that the open-circuit voltage of the PZT keeps rising as shown in Fig. 2.

When the open-circuit voltage of the PZT reaches the peak, the energy accumulated in the C_p reaches the maximum. Then the switches are turned ON, and the energy accumulated in C_p is transferred to the load through the LC resonance circuit. Take the positive half cycle as an example. The voltage V_p is higher than V_n. When the switch S_p is turned ON, the circuit enters the phase of the capacitor releasing energy. The parasitic capacitor C_p, inductor L, and the energy storage capacitor C_{STO} form a *CLC* loop (as shown in the red loop in Fig. 1). The charge accumulated in C_p is gradually released until the charge is completely transferred. During this phase, the energy transferred to the load can be expressed as

$$E_{re} = C_p V_{\text{OC,max}} V_{\text{DC}}. \tag{1}$$

When the open-circuit voltage of the PZT drops to zero, the switch is turned OFF, and the circuit enters the phase of inductor freewheeling (as shown in the blue loop in Fig. 1). During this phase, the freewheeling current of the inductor transfers the remaining energy in the inductor to the load. Assuming that the power loss of the circuit is not considered, and according to energy conservation, in this phase, the energy transferred to the load is

$$\begin{aligned} E_{if} &= \frac{1}{2} C_p V_{\text{OC,max}}^2 - E_{re} \\ &= C_p V_{\text{OC,max}} \left(\frac{1}{2} V_{\text{OC,max}} - V_{\text{DC}} \right). \end{aligned} \tag{2}$$

It can be known from the equation that when the output voltage $V_{\text{DC}} \leq 1/2V_{\text{OC,max}}$, all the energy on C_p can be transferred to the load. If $V_{\text{DC}} > 1/2V_{\text{OC,max}}$, the harvesting efficiency of the buck-based SECE decreases significantly. In reality, since the equivalent resistance in the circuit has to be considered, the V_{DC} should be lower than $1/2V_{\text{OC,max}}$.

Through these two phases, the energy accumulated in the positive half cycle is transferred to the load while in the negative half cycle the similar working principle is shown in the green and blue loop in Fig. 1.

B. MI-SECE Based on Buck Structure

The interface described above can be expanded into a multi-input interface, as shown in Fig. 3. Although only two PZTs are shown in the circuit, more PZTs can be connected to three red nodes. From Fig. 2, it can be found that each PZT occupies a very small time slice of the inductor. Hence, multiple PZTs can share the inductor in different time slices. However, in some specific application scenarios, a small phase difference among the output voltages of different PZTs may exist or even the output voltages are completely synchronized. In this case, multiple PZTs need to use the inductor at the same time, and the conventional time-division multiplexing method does not work.

When the phase difference between two PZTs is small, there are three cases, as shown in Fig. 4. Two PZTs need to use the inductor at the same time. In order to avoid the conflict, a queuing mechanism is needed to determine the working order. The conventional queuing mechanism is on the first-come-first-served basis, but such a scheme requires additional control circuit, which makes a simple analog circuit be incompetent.

An ideal queuing mechanism is that the inductor adaptively selects and successively extracts energy from multiple PZTs. From Fig. 3, two PZTs are located in parallel branches and then

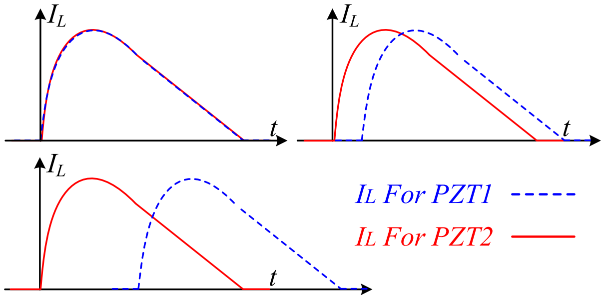


Fig. 4. Small phase difference for two PZTs.

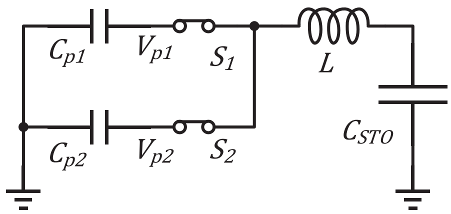


Fig. 5. Simplified model for MI-SECE.

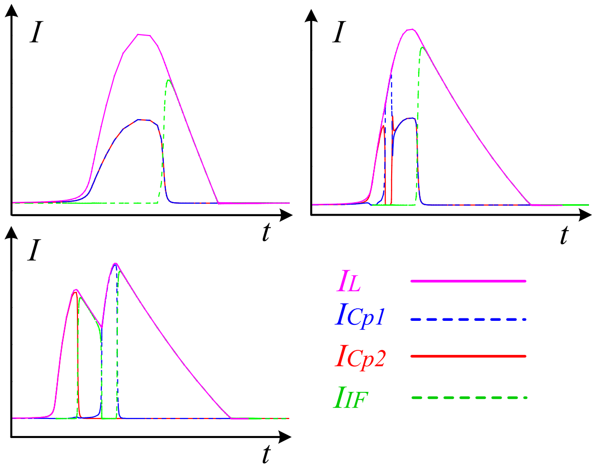
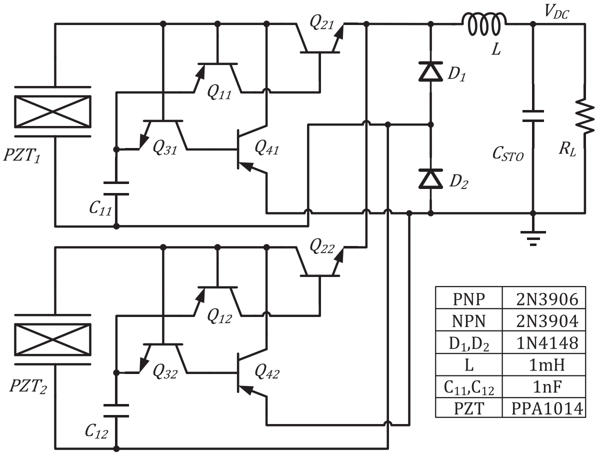


Fig. 6. Current waveforms with small phase difference.

connected in series with the inductor. Assuming that the two PZTs reach the peak voltage at the same time, the circuit in Fig. 3 can be simplified to the model in Fig. 5. At this time, it can be found that only one capacitor can transfer energy to the inductor, though both switches are turned ON. As the capacitor with higher voltage releases charge, its voltage will gradually decrease. When its voltage equals to that of the capacitor with low voltage, two capacitors begin to transfer charges to the inductor simultaneously.

Based on the above analysis of the simplified model, it can be considered that there is an invisible comparison mechanism to solve the queuing problem for using the inductor. According to the model, the actual working states under the above three phase differences are built, as shown in Fig. 6, which is the simulation result of the LTspice. When the phases of two PZTs are completely synchronized, and the maximum displacement



PNP	2N3906
NPN	2N3904
D_1,D_2	1N4148
L	1mH
C_{11},C_{12}	1nF
PZT	PPA1014

Fig. 7. Self-powered MI-SECE for two PZTs.

is equal, C_{p1} and C_{p2} simultaneously transfer energy to the inductor; when their voltage drops to zero, the remaining energy in the inductor is transferred to the load through the freewheeling diode, as shown in the upper left of Fig. 6. If the releasing charge process of C_{p2} is not ended while the C_{p1} reaches the peak, C_{p2} immediately stops releasing charge while C_{p1} starts releasing charge until the voltages of the two capacitors are equal, and then both capacitors discharge charges simultaneously until the voltages drop to zero; then, the remaining energy in the inductor is transferred to the load through the freewheeling diode, as shown in the upper right of Fig. 6. If C_{p2} is in the inductor freewheeling process and C_{p1} reaches the peak, the inductor immediately stops freewheeling and enters the releasing charge process of C_{p1}; when the charge of the C_{p1} is completely released, the inductor enters the freewheeling process again, the remaining energy is transferred to the load, as shown in the bottom left of Fig. 6. In the above three cases, the currents of the capacitors are all higher than or equal to zero, which show that there is no reverse current in the process of releasing energy for the capacitors. Hence, there is no backflow energy.

III. EXPERIMENTAL WORK

In order to verify the above theoretical analysis, a self-powered MI-SECE is implemented, as shown in Fig. 7, and the experimental tests are carried out. Four transistors and a capacitor form a simple self-powered switch, which can turn ON the switches when the voltage of the C_p reaches the peak, and turn OFF the switches when the voltage of the C_p is zero.

The experimental system with a function signal generator, an oscilloscope, two PZTs (the PPA-1014 from MIDE Technology with an internal capacitance of 41 nF), a power amplifier, and the MI- SECE circuit are built, as shown in Fig. 8. The sinusoidal signal generated by the signal generator is used to control the shaker after being enhanced by the power amplifier. Before the circuit is connected, the frequency needs to be adjusted by the signal generator. Only when the vibration frequency is adjusted to the resonance state, does the open-circuit voltage of the PZT reach the maximum.

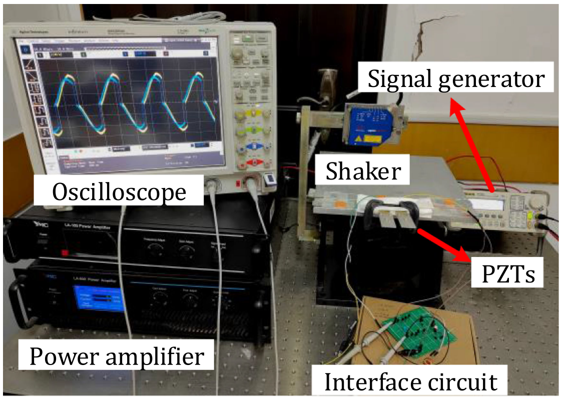


Fig. 8. Experimental setup.

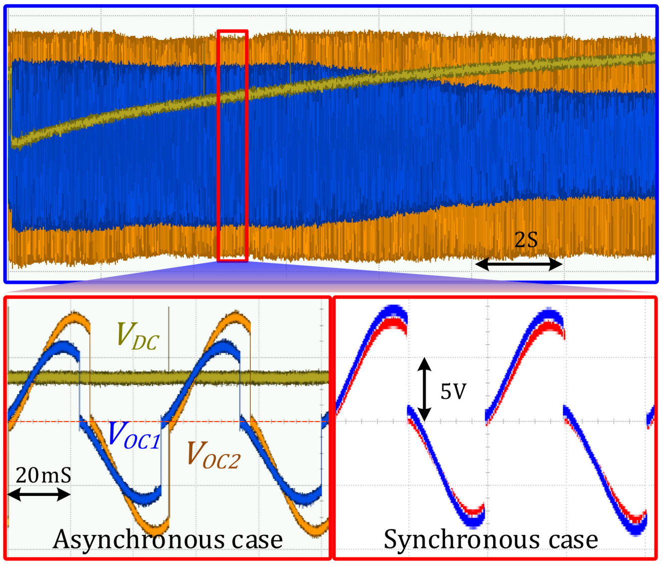


Fig. 9. Experimental waveforms.

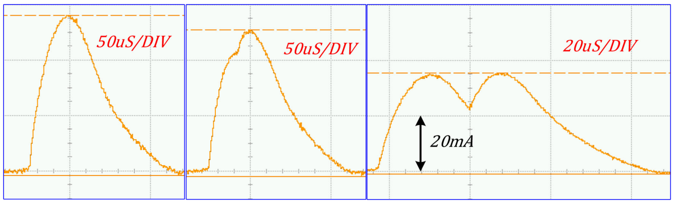


Fig. 10. Inductor current waveforms.

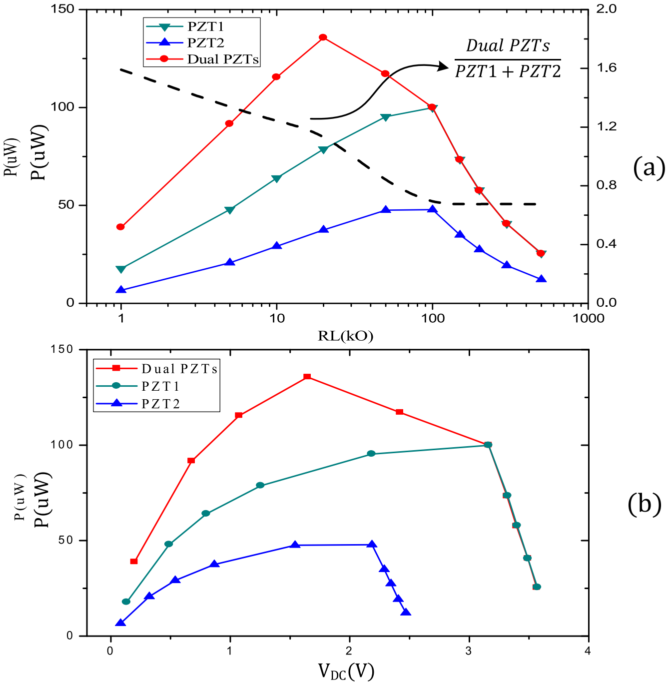


Fig. 11. Output power varies with (a) load and (b) output voltage.

Fig. 9 shows the open-circuit voltage of the PZTs and the output voltage waveforms. The output voltage V_{DC} gradually increases with time. When the V_{DC} is close to the maximum open-circuit voltage V_{OC1} of the PZT1, the V_{OC1} begins to gradually decrease. When V_{DC} is higher than the maximum V_{OC1}, the PZT1 will return to the original state and not transfer energy to the load. In the enlarged diagram, the open-circuit voltages of the PZTs will quickly drop to zero after the peak is reached because the charge on the PZTs is transferred to the load, which is consistent with the previous analysis.

In order to test the situation where the phase difference between the two PZTs is small, two piezoelectric patches with the same model (PPA-1014) are used, and two masses with the same weight (the total mass of the metal mass and fixing screws is 12.84 mg) at the same position are fixed, respectively. The measured current waveforms of the inductor are shown in Fig. 10, which is consistent with the previous theoretical analysis for Fig. 6. It shows that the interface proposed in this article can be expanded to a multi-input PEH without worrying about the phase coincidence between different PZTs.

Fig. 11 shows the power harvested from two PZTs separately and the power harvested from two PZTs simultaneously under different loads and output voltage. The original maximum open-circuit voltages of two PZTs are 8 and 6 V, respectively [V_{OC} on a 10 MΩ probe (sine waveform without connected circuit)], and the vibration frequency is maintained at 20 Hz. It can be found that as the load resistance (or output voltage) increases, the output power curve first increases and then decreases. This is that when the output voltage is low, the efficiency of the inductor freewheeling phase is low, and most of the energy is consumed by the freewheeling diode. Therefore, from Fig. 11(a), it can be seen that when the load resistance is small, the power output from the dual PZTs is higher than the sum of the power output from the PZT1 and PZT2. Because the output power of dual PZTs is higher than that of a single PZT when the load resistance is the same, the inductor freewheeling phase of dual PZTs is more efficient, which also means that the circuit can harvest more power. In addition, it can be found that when the output voltage is higher than a certain value, the output power curve drops rapidly, which is consistent with the description of (2).

IV. CONCLUSION

In this article, the SECE based on the buck structure is presented. Compared with the typical SECE, it is not only suitable for weak coupling PEHs but also suitable for strong coupling PEHs. In addition, the method to simultaneously harvest the energy from multiple PZTs is presented. An extensible multi-input interface circuit for piezoelectric energy harvesting is proposed. Both theoretical analysis and experimental test results demonstrate the effectiveness of the proposed interface. The results show that the MI-SECE based on buck circuit can extract energy from multi-PZTs simultaneously with any phase difference (0–2π).

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