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LETTER

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A direct AC-DC converter integrated with SSHI circuit for piezoelectric energy harvesting

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Abstract: In this letter, a direct AC-DC converter for piezoelectric (PE) energy harvesting is proposed, which integrates a Synchronous Switch Harvesting on Inductor (SSHI) circuit, to achieve a resistive impedance matching. An SSHI circuit intends to deal with high impedance of the PE transducer. Then, the converter working in discontinuous conduction mode (DCM), with relative high switching frequency, delivers the harvested energy into the load. The circuit is self-powered and can start even if the storage elements are completely drained. The experimental results show that the proposed circuit has better power extraction capability with a higher output voltage, compared with conventional SSHI rectifier under the same excitation.

Keywords: AC-DC power conversion, piezoelectric energy harvesting, SSHI

Classification: Energy harvesting devices, circuits and modules

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1 Introduction

The SSHI circuit is able to effectively increases the output power of the piezoelectric (PE) transducer by using a nonlinear technique [1, 2]. Fig. 1 shows a conventional SSHI rectifier, consisting of the SSHI circuit followed by a full-bridge rectifier, which rectifies AC output voltages from the PE transducer. In addition to rectifying AC to DC, the SSHI rectifier flips the internal capacitor voltage when the PE transducer current crosses the zero point. In this way, energy harvesting capability of the SSHI rectifier is claimed to be up to 9 times higher than that of full-bridge rectifier at a certain vibration frequency [1]. Compared to a prohibitively large inductor for complex conjugate matching, the SSHI circuit only needs a small inductor in a short period of time. Due to above advantages, the SSHI method becomes increasingly popular way for small-scale piezoelectric energy harvesting. Ramadass and Chandrakasan implemented a integrated SSHI rectifier [2]. Nevertheless, the controller for switch timing of the SSHI circuit is rather complex. In order to simply the controller for the switch timing, it inserts the diode into the resonant circuit [3, 4, 5]. Liao et al. further simplify the controller by integrating a SSHI circuit with a full-bridge rectifier [6, 7, 8].

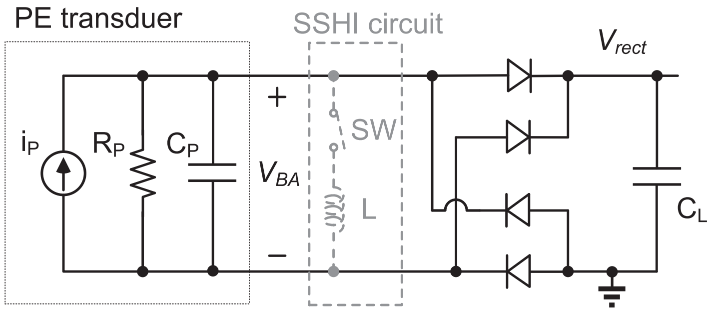

Fig. 1. A conventional SSHI rectifier

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However, the SSHI circuits reported in [1, 2, 3, 4, 5, 6, 7, 8] are relied upon a low-frequency full-bridge rectifier. In fact, the full-bridge rectifier limits power extraction from the PE transducer. If the PE transducer directly connects to a resistive load, its maximum available power by the load is $\pi/2$ times higher than that if through the full-bridge rectifier. This is because disconnection between the load and the PE transducer occurs in every half vibration cycle if using a full-bridge rectifier, due to existence of the internal capacitor C_P.

In this brief, we propose a direct AC-DC converter integrated with the SSHI circuit. The proposed circuit has a single stage to achieve AC-DC conversion. Furthermore, the circuit can flip the internal capacitor voltage when the PE transducer current crosses the zero point.

2 Operating principle

The PE transducer can be modeled as a current source i_P in parallel with a capacitor C_P and a resistor R_P at or close to resonance as shown in Fig. 1 and also Fig. 2 [2]. The transducer current is represented as $i_P = I_P \sin(2\pi f_P t)$, where f_P is the vibration frequency. Fig. 2 shows the proposed circuit, which can achieve direct AC-DC conversion as well as the SSHI operation, and two of them run time does not overlap. The inductor L is in series with the transducer. The rectifier is formed by two switches (S1 and S2) and four diodes (D1, D2, D3 and D4). The active diode (D3 or D4) is composed of a common-gate op-amp and a pMOS device [6]. The diodes D1 and D2 can be implemented by passive or active ones. A simple controller consists of a filter, a valley detector, several digital circuits and a oscillator, as shown in Fig. 2. According to the node voltages V_A and V_B, the controller generates appropriate signals $G1$ and $G2$ to drive the switches S1 and S2, respectively.

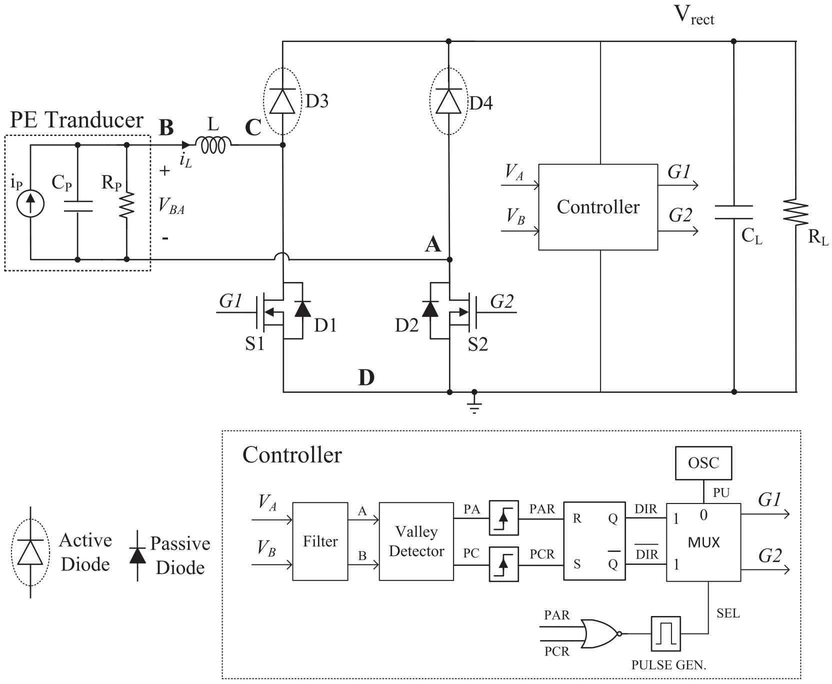

Fig. 2. Proposed direct AC-DC converter integrated with SSHI circuit

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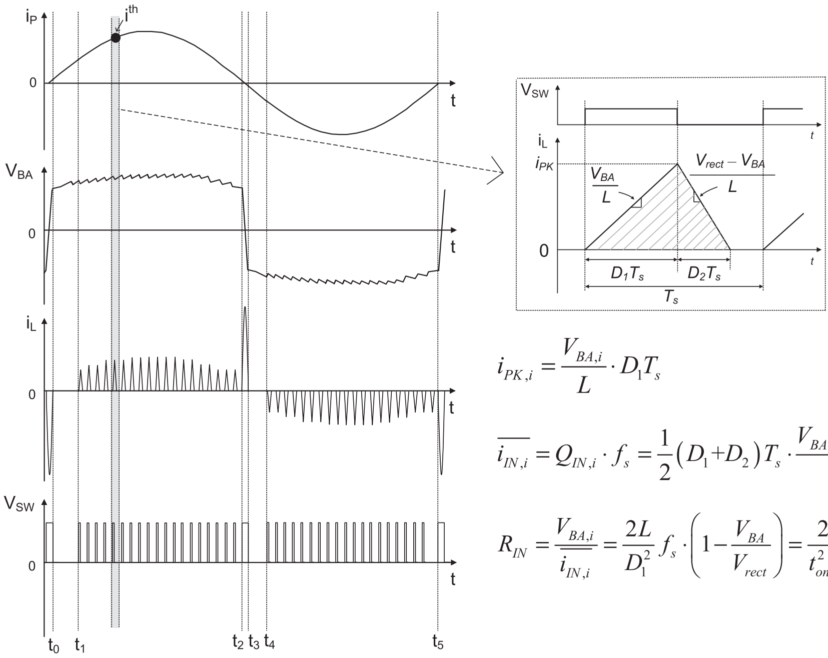

$$i_{PK,i} = \frac{V_{BA,i}}{L} \cdot D_1 T_s$$

$$\overline{i_{IN,i}} = Q_{IN,i} \cdot f_s = \frac{1}{2}(D_1 + D_2) T_s \cdot \frac{V_{BA,i} D_1 T_s}{L} \cdot f_s$$

$$R_{IN} = \frac{V_{BA,i}}{\overline{i_{IN,i}}} = \frac{2L}{D_1^2} f_s \cdot \left(1 - \frac{V_{BA}}{V_{rect}}\right) = \frac{2L}{t_{on}^2 f_s} \cdot \left(1 - \frac{V_{BA}}{V_{rect}}\right)$$

Fig. 3. The associated current and voltage waveforms

Referring to the waveforms as shown in Fig. 3, operating principle of the proposed circuit is described in the following. The circuit has two main operation modes, i.e., the AC-DC conversion mode as well as the SSHI mode. Let's consider the positive half-cycle of i_P. During $t_1 < t < t_2$, the proposed circuit works in the AC-DC conversion mode and delivers the harvested energy into the load under high switching frequency. In this mode, signals $G1$ and $G2$ select the signal PU (i.e. signal V_{SW}) from the oscillator. If the signal PU goes high(low), the controller turns both two nMOS transistors (S1 and S2) ON(OFF). As the transistors S1 and S2 are both ON, the transducer current i_P flows through the loop B-C-D-A-B, and hence i_L intends to ramp up. As the transistors are both OFF, the inductor current i_P free-wheels through D3, the load, D2 and the PE transducer, and hence i_P ramps down. The circuit behaves like a boost converter with varying input voltage. Fig. 3 shows the close-up view of the inductor current i_L in the dash box. Note that the converter operates in DCM. The AC-DC converter keeps running until t_2. After t_2, current i_p becomes negative, and capacitor voltage V_{BA} starts to decrease, which is detected and then set signal DIR high. The circuit enters into the SSHI mode now. The signals G1(G2) selects the signal $DIR(\overline{DIR})$ to drive the switch S1(S2), resulting in S1 being ON, and S2 being OFF. Consequently, a resonant loop is formed through S1, D2, C_P and L during $t_2 < t < t_3$. The energy stored in capacitor C_P transfers to the inductor L, and then the inductor energy is transferred back to capacitor C_P with a flipped voltage across the capacitor. Due to the diode D2 in the loop, the current only flows in the direction of B → C → D → A. After the entire energy from inductor L is transferred back to C_P, the voltage flipping procedure finishes by itself. Note that the nMOS transistor S1 is complementary with S2 during the SSHI mode. Due to the symmetrical circuit topology, the operating principle in the negative half-cycle of i_P is the same as that in the positive half-cycle described above. Obviously, the diode D1 instead of D2 is inserted in the resonant loop in the negative half-cycle.

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In order to maximize power from the PE transducer, it is of importance to set appropriate control parameters, such as duty cycle, switching frequency and etc. As analyzed in [9, 10], the output of the PE transducer exists an optimal resistive load. As shown in Fig. 3, the effective input impedance R_{in} of the AC-DC converter during one switching cycle is obtained as

$$R_{in} = \frac{V_{BA,i}}{\overline{i_{L,i}}} = \frac{2L}{D_1^2 T_S}\left(1 - \frac{V_{BA,i}}{V_{rect,i}}\right) \tag{1}$$

Where i is integer that indicates the number of the switching pulses, T_S is the switching period, and D_1 is the duty cycle. The parameters (such as L, T_S and D_1) should be selected properly to achieve a effective input impedance as expected during the AC-DC conversion mode. The switching time of the SSHI circuit is determined automatically due to insertion of the diode (D1 or D2) during the SSHI mode [3, 4, 5, 6, 7, 8].

3 Experiment results

We designed the proposed circuit using a 0.35 µm CMOS process and verified it by simulation. The simple model of the PE transducer is used for simulation [2]. The model parameters $I_P = 160\,\mu A$, $C_P = 19\,nF$ and $f_P = 140\,Hz$. The load $R_L = 150\,k\Omega$, and $C_L = 500\,nF$. Note that several building blocks (such as active diodes, reference current generator, etc) of the proposed circuit have been verified by tape-out in [6].

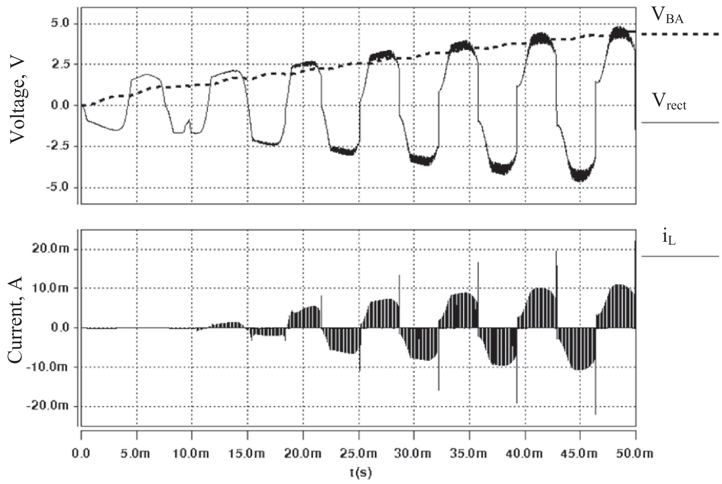

Fig. 4. Current and voltage waveforms

Fig. 4 shows the voltage and current waveforms of the proposed circuit, including the waveforms of V_{rect}, V_{BA} and i_L. As can be seen from Fig. 4, during $0\,ms < t < 10\,ms$, the waveforms illustrate the cold-start of the proposed circuit. In fact, the full bridge rectifier consisting of four body diodes is utilized to charge the load. Voltage drops of the passive diodes incurs large voltage difference between $|V_{rect}|$ and $|V_{BA}|$. Since active devices are activated as V_{rect} increases, the voltage difference becomes smaller and smaller. Eventually, the circuit is fully activated, and the waveforms is similar to the waveforms shown in Fig. 3. The different

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operation modes can be distinguished by the waveform of the inductor current i_L. During the cold-start, the current is very small, only a few hundred μAs. Once the switches (S1 and S2) are driven by high switching frequency during the AC-DC conversion mode, the corresponding current pulse appears as expected. When i_P crosses the zero, a high current pulse occurs, which indicates the SSHI operation. Finally, the total power consumption including the controller, op-amps of the active diodes and reference current generator is only 8 μW.

Fig. 5 shows comparison of output power for three different types of circuits under the same excitation. These circuits are a full-bridge rectifier, a conventional SSHI rectifier and the proposed circuit. As can be seen from Fig. 5, the proposed circuit harvests the highest power when V_{rect} is above 3 V. The proposed circuit harvests the maximum power of 210 μW when $V_{rect} = 7$ V.

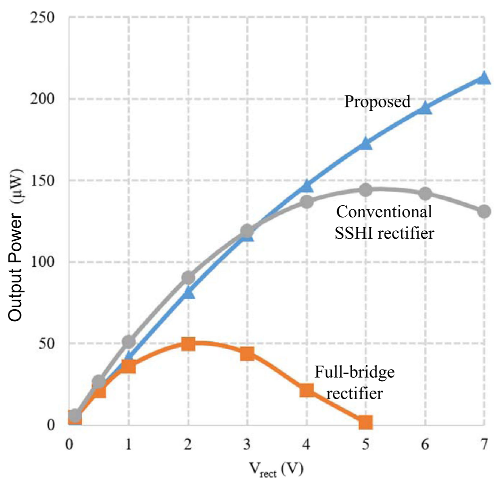

Fig. 5. Comparison of output power for three different types of circuits under the same excitation

4 Conclusion

A direct AC-DC converter integrated with the SSHI circuit for piezoelectric energy harvesting is presented. The proposed circuit is designed using a 0.35 μm CMOS process, which can achieve AC-DC conversion with high switching frequency as well as the SSHI operation. The experimental results show the circuit is self-powered, and the output power of the proposed circuit is higher than that of a full-bridge rectifier or a conventional SSHI rectifier with a higher DC output voltage.

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