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A parallel-SSHI rectifier for ultra-low-voltage piezoelectric vibration energy harvesting

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Abstract: An idling scheme of Synchronous Switch Harvesting on Inductor (SSHI) is proposed for piling up output voltage of the piezoelectric energy (PE) harvester cycle by cycle, to deal with the PE harvester's low output voltage. The proposed rectifier integrates active diodes and a parallel-SSHI technique with a simple control scheme, and therefore has a high efficiency. The simulation results demonstrate the feasibility of proposed rectifier, which is able to extract energy from a ultra-low-voltage PE harvester.

Keywords: energy harvesting, SSHI, active rectifier, pile-up voltage, ultra-low-voltage

Classification: Energy harvesting devices, circuits and modules

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1 Introduction

The Synchronous Switch Harvesting on Inductor (SSHI) technique is highly effective for piezoelectric energy (PE) harvesting [1, 2], which increases the power extraction from a PE harvester by significantly eliminating the ill effect of the internal capacitive impedance and also can be potentially extended to deal with vibrations of varying frequency and/or amplitude. Along with the advancement of small-scale PE harvesters like a piezoelectric MEMS energy harvester, the design of a sophisticated rectifier is mandatory in order to extract energy from the harvester, whose output voltage is rather low. Since SSHI technique can potentially boost the PE harvester's output voltage swing, it provides an effective means of rectifying ultra-low-voltage out of the PE harvester.

Fig. 1 shows a parallel SSHI circuit followed by a diode bridge rectifier. The PE generator can be modeled as a sinusoidal current source ($= I_P \sin(2\pi f_S t)$) in parallel with a resistor R_P and a capacitor C_P. Where I_P is the current's peak amplitude and f_S is the resonance frequency of a PE generator. Suppose that the rectifier output has a stable DC voltage V_{RECT} in view of a large filter capacitor C_L.

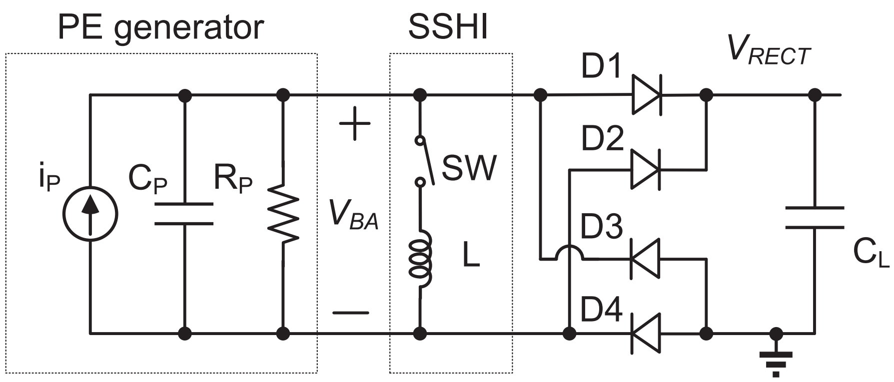

Fig. 1. Parallel SSHI circuit followed by a diode bridge rectifier

To self-start the SSHI circuit, many approaches have been proposed to find a right time to close the switch SW. In Fig. 1, the techniques in [3, 4] used two continuous-time comparators to detect ON/OFF state of the diodes D3 and D4. Once one of the diodes transitions from ON to OFF, which indicates an asymptotical zero-crossing point (ZCP) of the current i_P, the circuit closes the switch SW and then starts the SSHI process. Since an active diode incorporates a comparator, the ZCP of current can be detected by itself. The variations of rectifier with a parallel SSHI circuit utilized an active diode rather than a continuous-time comparator, and thereby further saving the power [5, 6, 7, 8, 9]. However, the circuits in [3, 4, 5, 6, 7, 8, 9] would be problematic when a PE generator's output voltage is much lower than the rectifier's output voltage V_{RECT}. This often occurs in the ambient environment where the PE generator is excited at weak or rapidly changing excitations. In these situations, no energy can be extracted and the operation of the SSHI circuit would cease due to the lost a trigger signal from detecting ZCP of current.

In this brief, we propose an efficient parallel-SSHI active rectifier for piezoelectric vibration energy harvesting, which adopts the SSHI technique and active

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diodes, with a simple controller. Furthermore, an idling SSHI scheme is presented to boost the voltage swing of the PE generator and thereby being capable of extracting energy from low input voltage PE sources. Therefore, the proposed rectifier is particularly suitable for ultra-low-voltage PE harvesting applications.

2 Self-start conditions of the SSHI circuit

In Fig. 1, to extract energy from the PE generator, the minimum input voltage of the diode bridge rectifier is required above 1.4 V, which is forward the voltage drops of the two diodes. Suppose active diodes instead of passive diodes are used for rectifying PE generator's voltage. So the voltage drop of a diode could be negligible in the analysis. Hence, the self-start condition of the SSHI circuit should satisfy the following expression.

$$V_{BA(open)} > V_{RECT} \tag{1}$$

Where $V_{BA(open)}$ is the peak voltage when the PE generator is in open-circuit. Note that the self-start condition of the SSHI circuit in [3, 4, 5, 6, 7, 8, 9] is subject to Eq. (1). Now suppose the SSHI circuit keeps running even if Eq. (1) is not met. The output voltage of the generator can be piled up cycle by cycle up to V_{RECT}. In this way, Eq. (1) can eventually be met to harvest the energy. Therefore, in theory, the rectifier circuit can extract energy from infinitesimal voltage PE sources as long as the SSHI circuit keeps running. However, the required minimum input voltage of $V_{BA(open)}$ is imposed by the characteristics of the LC tank used for flipping capacitor voltage. Due to cumulative parasitic resistances, per say R, in the tank, the capacitor voltage cannot be flipped completely in reality. A flipped voltage ratio η_F is defined as Eq. (2) in [2, 9], generally ranged from 0.7 to 0.9, which indicates the quality of the flipping voltage and related to the quality factor Q of the LC tank.

$$\eta_F = \frac{V_F + V_{RECT}}{2V_{RECT}} = \frac{1 + e^{-\frac{\pi}{2\sqrt{Q^2 - \frac{1}{4}}}}}{2} \tag{2}$$

Where V_F, referred to Fig. 3, is a flipped voltage after crossing the zero voltage point, and $Q = \frac{1}{R}\sqrt{\frac{L}{C_P}}$ (see Fig. 1). Consequently, the required voltage of $V_{BA(open)}$ for keeping the SSHI circuit operation can be expressed as Eq. (3).

$$V_{BA(open)} > V_{RECT}(1 - \eta_F) \tag{3}$$

As can be seen from Eq. (1) and Eq. (3), the required voltage $V_{BA(open)}$ of Eq. (3) is much lower than Eq. (2). Besides, minimum voltage to self-start the SSHI circuit increases as V_{RECT} rises. Yuk et al. used the Synchronous Electrical Charge Extraction (SECE) technique to boost the PE harvester's output voltage swing [10]. While in this brief, we use the SSHI technique to boost the voltage swing by using a simple controller, thereby being capable of extracting energy from ultra-low-voltage PE sources.

3 Ultra-low-voltage active parallel-SSHI rectifier

Fig. 2 shows the proposed active rectifier, which consists of an inductor, two switches M3 and M4, two associated passive diodes D3 and D4, two active diodes D1 and D2, and a controller. The two valley detectors are employed to alternately

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detect the valley voltage at nodes B and D depended upon the direction of the current i_P and then generate indicator signals PB and PD. A digital module generates a CLK signal based on signals PB and PD. Two switches M3 and M4 receive the CLK signal doing ON/OFF operation. An inductor L and the internal capacitor C_P form an LC tank shortly in every half vibration cycle, to complete a capacitor voltage's inversion automatically. Hence, the circuit realizes the function of the SSHI circuit.

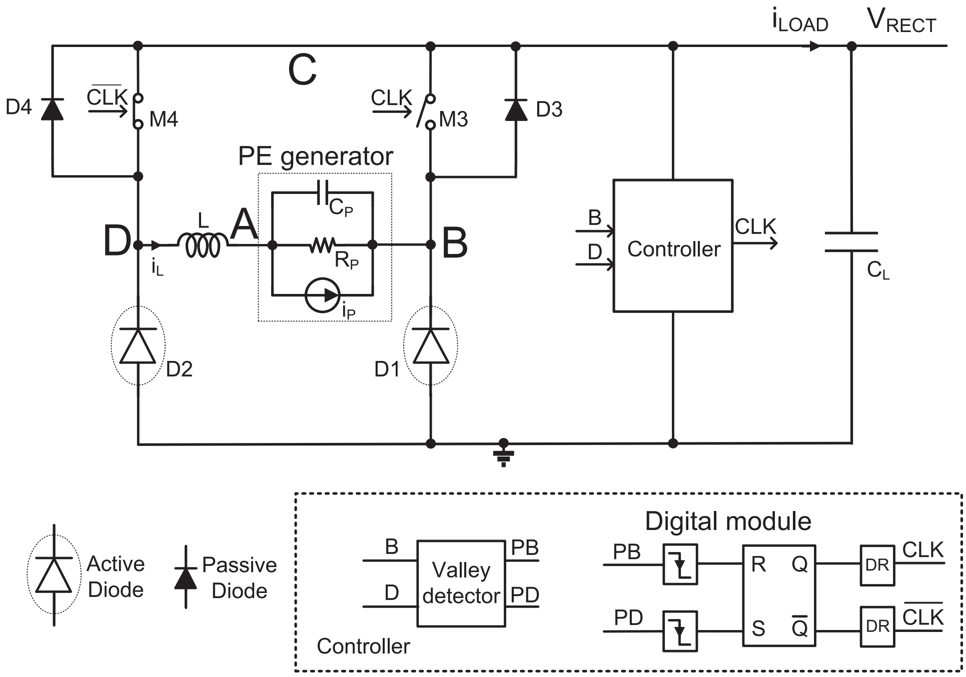

Fig. 2. The proposed active parallel-SSHI rectifier

a. Normal operation of the SSHI circuit

Fig. 3 shows the associated current and voltage waveforms when the rectifier works in normal operation, under the assumption that there is a sufficient vibration input. The operating principle of the proposed rectifier can refer to Fig. 2. Before t_3, M3 is closed, M4 is open, D1 is OFF and D2 is ON. A positive current loop (w.r.t. i_P) is formed through the loop A-B-C-D-A. Charges are transferred to the load through this loop. Now, current i_P becomes negative at t_3 and hence the voltage V_D increases to turn off the diode D2. This instant is detected by the valley detector. Then, it outputs a 1-bit detection signal PB. This signal is received by a digital module to generate the clock signal CLK accordingly, which results in M3 OFF and M4 ON. During the time between t_3 and t_4, an LC tank through the path A-B-C-D is formed. The energy stored in C_P is transferred to the inductor L, and then is transferred back to the C_P with a flipped voltage across the capacitor. Due to the diode D3 in the LC loop, the current can only flow through A→B→C→D. When the energy stored in the inductor is entirely transferred back to the C_P, the voltage flip procedure is finished by itself. Therefore, the circuit has an optimal flipping time. During the time between t_4 and t_5, a negative current i_P discharges the

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capacitor C_P, the voltage at node B decreases gradually. Once the voltage is lower than ground potential, the active diode D1 is conducting, and negative current loop (w.r.t. i_P) is formed through the loop B-A-D-C-B. According to the same principle and the symmetrical circuit structure, there is basically the same LC tank used for flipping capacitor voltage as i_P crosses zero from negative to positive. At this time, D4 instead of D3 is, however, put into the LC tank.

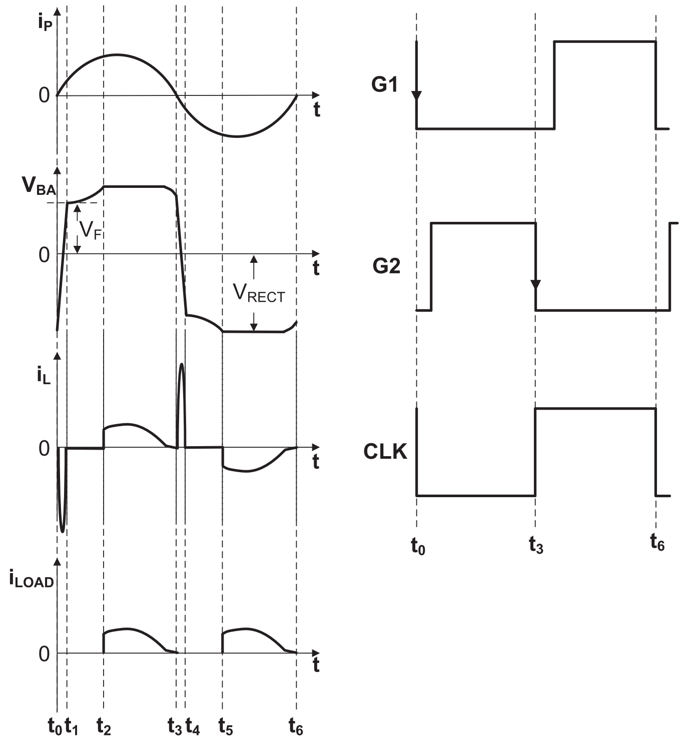

Fig. 3. The associated current and voltage waveforms of the normal operation of the SSHI circuit

b. Idling operation of the SSHI circuit

Fig. 4 shows the associated current and voltage waveforms when there is a weak vibration input. It is assumed that the voltage V_{RECT} keeps constant and the output voltage of the PE harvester satisfies Eq. (3) but is lower than V_{RECT}. Suppose the CLK signal is initially low. So M3 is ON and M4 is OFF at t_0. The positive current i_P discharges capacitor C_P and hence the voltage V_D at node D decreases. Since i_P is so small that V_D could not be discharged below zero in the half vibration cycle. As a result, the active diode D2 keeps OFF. Once i_P changes its direction, V_D increases due to C_P being charged now. The valley detector detects this instant and generates a 1-bit detection signal PD. Then, M3 is turned off and M4 is turned on following the same operating principle as presented in the normal operation of the SSHI circuit. Hence, there is a flipped voltage across the capacitor at t_1 without any energy being extracted by the load. We call this procedure as the idling operation of the SSHI circuit. This operation ends till voltage V_B or V_D drops to the ground potential. So, the rectifier is back to the normal operation at t_7. In this way, the rectifier is able to harvest the energy from ultra-low-voltage PE sources.

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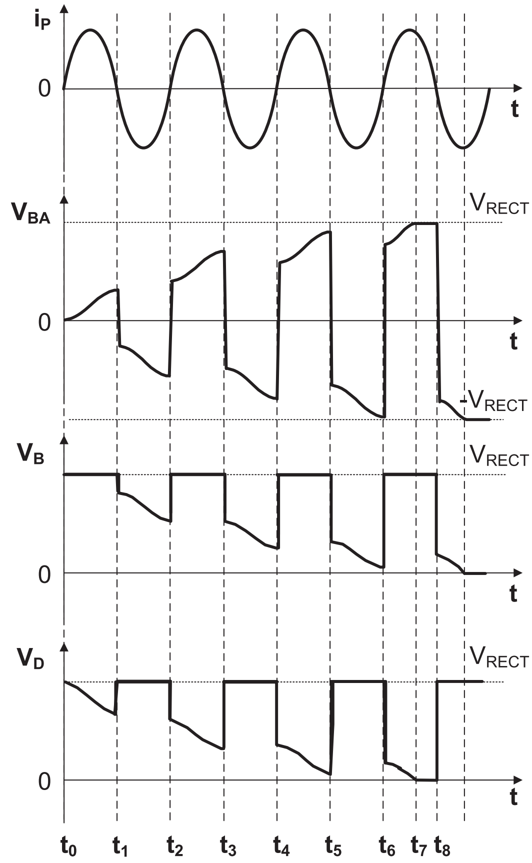

Fig. 4. The associated current and voltage waveforms of the idling operation of the SSHI circuit

4 Simulation results

Based on a 0.35 µm CMOS process, the rectifier circuit is simulated and verified. A commercial piezoelectric generator (Volture V22B) was used for characterization. The parameters are $R_P = 66\,\text{K}\Omega$, $C_P = 19\,\text{nF}$, and the resonant frequency f_S is 135 Hz [3]. The inductor L is set to 220 µH for our simulations.

The simulated self-start-up of the SSHI circuit waveforms are shown in Fig. 5 with a rectifier output voltage of 4 V. Assumed at the beginning vibration cycles, the rectifier works in normal operating condition. Therefore, the PE harvesters output voltage V_{BA} is clamped at 4 V. With the current i_P decreasing from 20 µA to 3 µA, the circuit stops working after going through the transitory idling operation of the SSHI circuit. It is because that, in steady state, the required input voltage of the rectifier does not satisfy Eq. (3). Once i_P increases up to 10 µA, i.e., original open-circuit peak output voltage of 0.62 V from the piezoelectric harvester, the rectifier works in idling operation condition. Then, the PE harvesters output voltage is piled-up cycle by cycle. Once it exceeds V_{RECT} and is clamped to V_{RECT}, the circuit goes back to the normal operation and then harvests energy out of the PE harvester of ultra-low-voltage as low as 0.62 V.

Fig. 6 shows the extracted power versus V_{RECT} under different constant excitations i.e., different i_P. The maximum voltage of V_{RECT} is set to 7 V that is the highest breakdown voltage tolerated by the process. It should note that the output power already takes out the power consumed by a controller. As can be seen,

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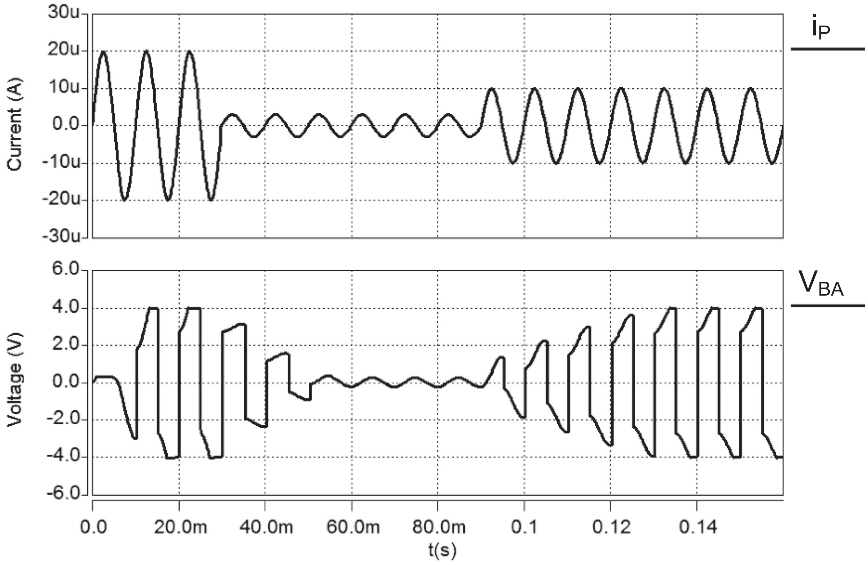

Fig. 5. The simulation waveforms of current i_P and voltage V_{BA}

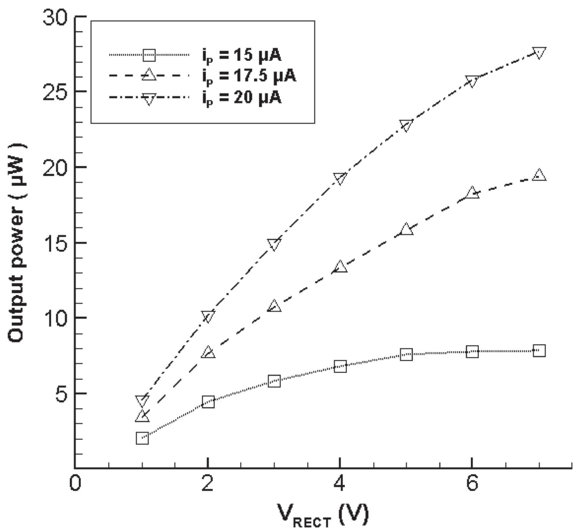

Fig. 6. Extracted power versus V_{RECT} under different constant excitations

the output power increases as V_{RECT} increases, but the slopes of the curves decrease. This is because idling operation of the SSHI circuit boosts the output voltage swing of the PE harvester and hence the output power. However, the improvement of the output voltage swing is limited by η_F.

5 Conclusions

In this brief, a parallel-SSHI rectifier for ultra-low-voltage piezoelectric vibration energy harvesting is proposed. Using an idling operation scheme of the SSHI circuit to pipe up output voltage swing of the PE generator, the rectifier can self-start the SSHI circuit with an ultra-low peak open-circuit voltage.

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