An Efficient Parallel SSHI Rectifier for Piezoelectric Energy Scavenging Systems

Xuan-Dien Do, Young-Hun Ko, Huy-Hieu Nguyen, Huy-Binh Le and Sang-Gug Lee
Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, South Korea
dien207@kaist.ac.kr, gnsstar@kaist.ac.kr, huyhieu@kaist.ac.kr, binh@kaist.ac.kr, sglee@ee.kaist.ac.kr

***Abstract* —Today green energy plays an important role in human life; thus, many methods have been used to harvest green energy from the surrounding environment for the service of humankind. One of the most popular methods involves the use of a piezoelectric (PE) material to harvest energy from vibration sources. A PE energy scavenging system has two functional sections: a transducer, which converts potential energy into electrical energy; and an electrical interface, which is used to manage this electrical energy. One of the most important parts of the electrical interface is a rectifier, such as an AC-DC converter. This paper proposes a new control scheme for an efficient parallel rectifier based on a synchronized switch harvesting on inductor (SSHI) process; the inductor is parallel with an active full-bridge rectifier. The proposed control scheme circuit helps parallel SSHI rectifier can significantly increase the amount of power extracted from PE material. The parallel inductor enables the voltage across the internal capacitor of the PE material to be flipped instead of uselessly discharged every half cycle. Furthermore, an active full-bridge rectifier is used instead of a passive rectifier to reduce the threshold voltage of the passive diode. The simulation results show that the proposed rectifier has a power conversion efficiency of more than 92% and can extract four times more energy than a active full-bridge rectifier.**

***Keywords*—Green energy, energy harvesting, piezoelectric, full-bridge rectifier, SSHI rectifier.**

I. INTRODUCTION

Energy harvesting is a process of capturing green energy sources (such as solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), which are readily available in the environment, and converting them into usable electrical energy to provide electrical power for small electronic and electrical devices. These sources have less of a negative impact on the environment than common energy sources such as fossil fuels, which are often produced with harmful side effects. Mechanical energy harvesting is the most promising of several energy harvesting techniques: it uses piezoelectric (PE) components that are deformed by different means, and the deformations are directly converted to an electrical charge via a direct PE effect. The electrical energy can be subsequently regulated or stored to power electronic devices, particularly in systems where the replacement of batteries is impractical, such as wireless micro sensor networks, implantable medical electronics, and tire pressure sensor systems. A PE transducer based on the PE effect is typically used to convert mechanical vibration energy into electrical energy. The electrical energy at the output of the transducer is a strong and irregular function of time; hence, an AC-DC rectifier is needed to produce a DC supply source. The AC-DC rectifiers commonly used in PE harvesting systems are full-bridge rectifiers and voltage doubler rectifiers. The main limitation of these rectifiers is the low power extraction. Ramadass [1-2] introduced a switch-only rectifier that can provide double the power extraction efficiency through the addition of a single switch. Further improvement was achieved with a synchronized switch harvesting on inductor (SSHI) technique. There are two SSHI categories: parallel SSHI [1-5] and serial SHHI [4]. Both categories are based on a flipping phenomenon: that is, a resonant loop is created by an internal capacitor and inductor to flip the voltage across the internal capacitor, thereby producing a significantly reduced power loss. The loop is opened immediately after half of the resonant cycle when all the energy from the inductor is transferred back to the internal capacitor. Therefore, the timing of the flipping occurrence is very important because it determines the efficiency of the rectifier. To precisely control the ON-time and OFF-time of the indicator, the researchers in [1] and [2] use a complex circuit with external tuning. With external tuning, the bias-flip rectifier [1-2] can extract more than four times the power of an existing full-bridge rectifier. To overcome this problem of precisely control signal, [7] reports that the addition of a switch to prevent reverse flipping after a half resonant cycle enables. By this way, the rectifier doesn’t need narrow pulse in each half cycle. However, the control circuit is complexity and this rectifier proposed in [7] uses a external supplies voltage to increase output power. Although this rectifier uses external supply voltage, the rectifier extracts only 2.5 times more energy than passive full-bridge rectifier. The proposed rectifier improves the rectifier as reported in [7] by using a simple control circuit to obtain more power extraction performance than the rectifier has introduced in [7]. Furthermore, all of the passive diodes in the full-bridge rectifier are replaced by active diodes to reduce the voltage drop and to enhance the power extraction efficiency. More details of the proposed circuit, the rectifier operational principle, the design of an auxiliary circuit are presented in section II. Section III discusses about the simulation results. Finally, the conclusion is given in section IV.

II. ARCHITECTURE AND CIRCUIT IMPLEMENTATION

A. Structure and Operational Principle

As shown in the left part of Fig. 1, a PE transducer is usually modeled as a sinusoidal current source, $i_P(t) = I_P \sin 2\pi f_P t$, in parallel with a capacitor, C_P, and a resistor, R_P. The magnitude of the PE current, I_P, varies with the mechanical excitation level of the PE element, though it is assumed to be relatively constant regardless of the external loading [6]; and f_P is the excited frequency of the PE harvester [1]. The output of the transducer is the AC voltage, which needs to be converted to DC by an AC-DC rectifier before it can be transferred to the load or battery. In Fig. 1 the parallel SSHI rectifier connecting the transducer and the load, which consists of a full-bridge rectifier and a parallel SSHI circuit that has one inductor, L_F, two diodes, D_1 and D_2, and two switches, SW_1 and SW_2. The operational principle of the parallel SSHI rectifier is illustrated by the current and voltage waveforms shown in Fig. 2 with the assumption that the diodes are ideal. At t_1, when $V_B<V_A<V_{rect}$, SW_1 is on and D_1 is off in the first branch of the parallel SSHI circuit and SW_2 is off and D_2 is off in the second branch. Thus, no current flows from A to B through the parallel SSHI circuit, and no current flows to the output. The capacitor, C_P, is charged by the current source, $i_P(t)$, until t_2 when $V_A=V_{rect}$. At this moment, D_3 and D_6 are turned on and the current flows to the output. At t_3, when $i_P(t)$ crosses zero and changes direction, C_P is discharged and V_A starts decreasing; D_3 and D_6 are then turned off. After that, SW_1 is turned off, SW_2 is turned on, therefore C_P, SW_2, D_2, and L_F subsequently for a resonant loop. The resonant loop, including L_F and C_P, helps to flip the voltage across C_P. All the energy in the capacitor is initially transferred to the inductor, and this energy is then transferred back to the capacitor where the voltage is reversed. Due to the presence of D_2 in the loop, the current flows only from A to SW2, D2, and B. Thus, the flipping procedure automatically finishes after all the energy from L_F is transferred back to C_P without any conditional control circuit, as was the case in [1] and [2]. A similar effect occurs in the negative half cycle of the transducer current; and after the flipping process the voltage across the internal capacitor is charged from $-V_{rect}$ to V_{rect}.

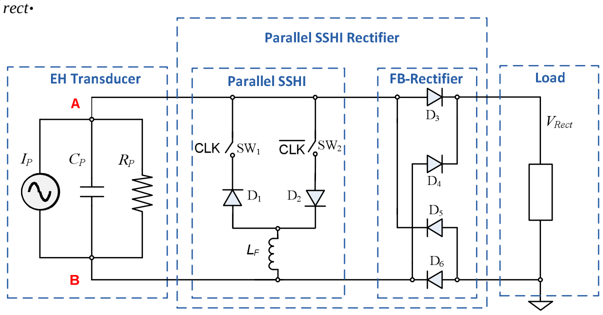

Figure 1. Conceptual diagram of the proposed rectifier

In an ideal case, the resonant loop flips the voltage across C_P with the same absolute value. However, due to the on-resistance of SW_1 and SW_2, the drop voltages on the diodes, and parasitic resistance of the inductor, the voltage is flipped to $\pm V_f$ instead. The flipping efficiency of the circuit is defined as

$$\eta_F = \frac{V_f + V_{rect}}{2 \cdot V_{rect}} \tag{1}$$

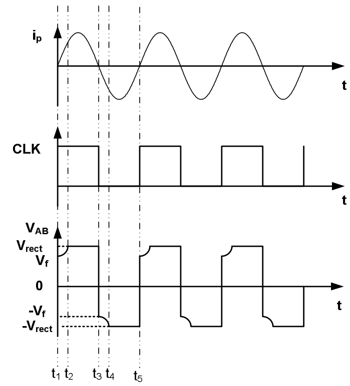

Figure 2. Current and voltage waveform

In each cycle, the current source must charge C_P from V_f to V_{rect} and then discharge C_P from $-V_f$ to $-V_{rect}$. In full-bridge rectifier, on the other hand, the current source must charge C_P from $-V_{rect}$ to V_{rect} and then discharge $-V_{rect}$ to $-V_{rect}$. The amount of charge loss in each cycle of the proposed rectifier is given by

$$Q_{loss} = 2C_P(V_{rect} - V_f)\,. \tag{2}$$

The total amount of charge available from the PE harvester in each cycle is given as follows [2]:

$$Q_{total} = \int_0^{\frac{2\pi}{w_P}} i_P dt = \frac{4I_P}{w_P} = 4C_P V_{OC}\,, \tag{3}$$

where $V_{oc} = \dfrac{I_P}{2\pi C_P f_P}$ is the open voltage circuit of the transducer [1- 2],[6].

The charge then flows into the output capacitor, and the output power is expressed as

$$Q_{rect} = Q_{total} - Q_{loss} = 2C_P(2V_{OC} - V_{rect} + V_f) \tag{4}$$

$$P = 2C_P f_P (2V_{OC} - V_{rect} + V_f)V_{rect}\,. \tag{5}$$

The flipping efficiency value is between 0 and 1. From Eq. (1), V_f can be expressed as

$$V_f = (2 \cdot \eta_F - 1) \cdot V_{rect}\,.$$

If V_f is incorporated into Eq. (5), the output power is expressed as

$$P = 4C_P f_P [V_{OC} - (1-\eta_F)V_{rect}] \cdot V_{rect} \tag{6}$$

The maximum output extracted power can be given by

$$P(\max) = C_P f_P \frac{V_{OC}{}^2}{1-\eta_F} = \frac{I_p^2}{4\pi^2 C_P f_P (1-\eta_F)} \quad (7)$$

When

$$V_{rect} = \frac{V_{OC}}{2(1-\eta_F)} = \frac{I_P}{4\pi C_P f_P (1-\eta_F)}, \quad (8)$$

Eq. (8) can be used to calculate the maximum amount of power extracted from the full-bridge rectifier and other variants of the full-bridge rectifier. In a conventional rectifier, η_F=0, which means there is no flipping effect; the maximum extracted power is $\frac{I_P^2}{4\pi^2 C_P f_P}$ at $V_{rect} = \frac{I_P}{4\pi C_P f_P}$. In the switch-only rectifier reported in [1] and [2], η_F=0.5; which means the maximum extracted power is $\frac{I_P^2}{2\pi^2 C_P f_P}$ at $V_{rect} = \frac{I_P}{2\pi C_P f_P}$. There results match the results of the calculations in [1], [2], and [5]. As was the case in [1] and [2], an off-chip inductor was added to the proposed rectifier to increase the flipping ratio (>0.5). The simulation shows that the parallel SSHI rectifier can provide a flipping ratio of 0.7, which is as high as the flipping ratio estimated for the parallel SSHI rectifier proposed in [1] and [2]. The results of using η_F=0.7 in Eq. (8) confirm that the proposed rectifier extracts 3.3 times more power than a active full-bridge rectifier.

B. *Circuit Design*

As shown in Fig. 1, the parallel SSHI rectifier includes a full-bridge rectifier and a parallel SSHI circuit. For this study, active diodes are used instead of passive diodes in the full-bridge rectifier to reduce the dropped voltage in the passive diodes. The proposed circuit also includes rail-to-rail switches, a digital control unit that generates CLK/$\overline{\text{CLK}}$ control of two rail-to-rail switches.

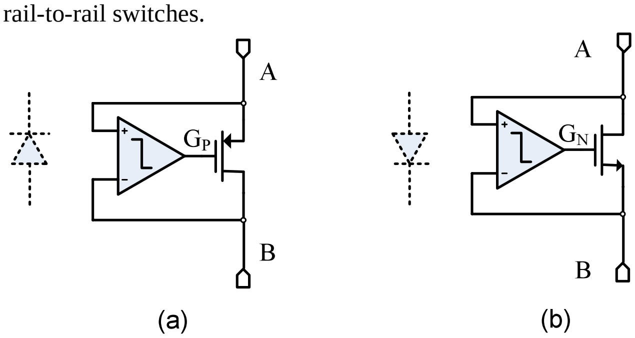

Figure 3. Model of active diodes: (a) D_5 and D_6; (b) D_3 and D_4

a. Active diodes

Four diodes in the full-bridge rectifier are replaced with active diodes to reduce the voltage drop in the passive diodes. As shown in Fig. 3, an active diode consists of a comparator and a transistor: PMOS transistors are used for D_3 and D_4 (Fig. 3(a)), and NMOS transistors are used for D_5 and D_6 (Fig. 3(b)). In Fig. 3(a), when V_A<V_B, the voltage, G_P, decreases and turns on the PMOS transistors. However, when V_A>V_B, G_N increases and turns off the PMOS. Diodes D_5 and D_6 act in a similar manner. Furthermore, the signal of G_N in D_5 and D_6 is the input of the digital unit. This aspect of digital control is discussed in part (c).

b. Rail-to-Rail Switch

Fig. 4 shows the rail-to-rail switch, which consists of one NMOS and one PMOS transistor. When the input, Ctr, generated from the digital unit is low, both transistors are off; and when the input is high, the switch is on in the full range.

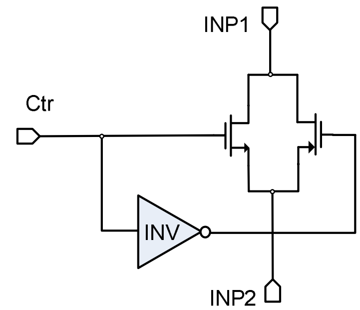

Figure 4. Rail–to-rail switch

c. Digital Control Circuit

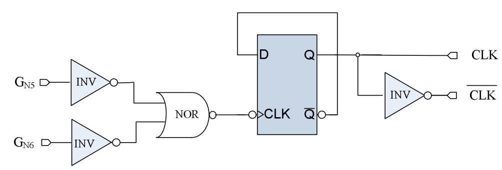

Figure 5. Digital control circuit

Fig. 5 shows the digital control unit as it generates CLK and $\overline{\text{CLK}}$ signals to control the two switches. The CLK and $\overline{\text{CLK}}$ pulses are created from the G_N (G_{N5} and G_{N6}) signal of the comparators of D_5 and D_6. During a cycle of $i_P(t)$, D_5(D_6) is turned on when V_A(V_B) is higher than V_{rect}. The pulses of G_{N5} and G_{N6} are shown in Fig. 6. The digital control circuit first detects the cross zero point of $i_P(t)$ and then creates the CLK and $\overline{\text{CLK}}$ signals. This relatively simple method is very effect in controlling the parallel SSHI circuit. It overcomes the drawback of the control signal in [1] and [2]. Furthermore, the proposed control scheme circuit is simpler than the control circuit has implemented in [7], and the system doesn't need any externals supply voltage as [7] does.

III. SIMULATION RESULTS

The proposed rectifier was simulated with the following transducer parameters: I_P=80 μA, f_P=200 Hz, C_P=26 nF, and R_P=1 MΩ. The inductor used in this simulation has an L value of 400 µH with assumption that the inductor parasitic resistor is 5 Ω. The output is connected to a 160 KΩ resistor in parallel with a 1 μF capacitor. Fig. 7 compares the efficiency of the proposed rectifier with that of a conventional rectifier.

The active full-bridge rectifier has an efficiency value of zero, whereas the proposed rectifier has an efficiency value of 0.7. The maximum power extracted from the proposed rectifier is determined theoretically from Eq. (8) to be 76.5 μW at V_{rect}=3.57 V. The simulation results in Fig. 7 show that 70.9 μW of power can be extracted when the output voltage of the proposed rectifier is 3.42 V. For the same load, the conventional output voltage is only 1.7 V and the extracted power is 17.5 μW. These results indicate a power conversion efficiency of 92.6%. For the same load, the proposed rectifier achieves a power extraction efficiency that is 4.5 times that of a standard rectifier.

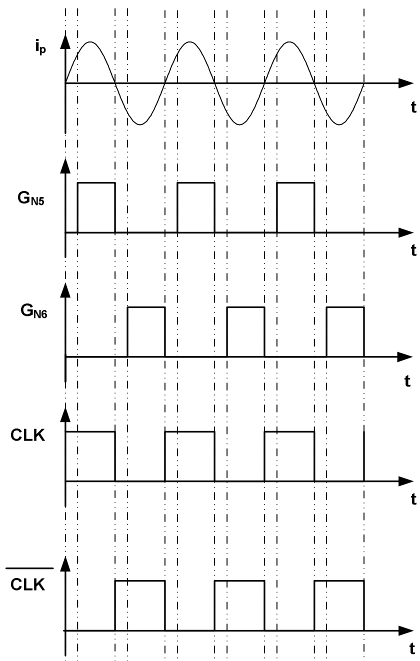

Figure 6. The input and output waveforms of the digital unit

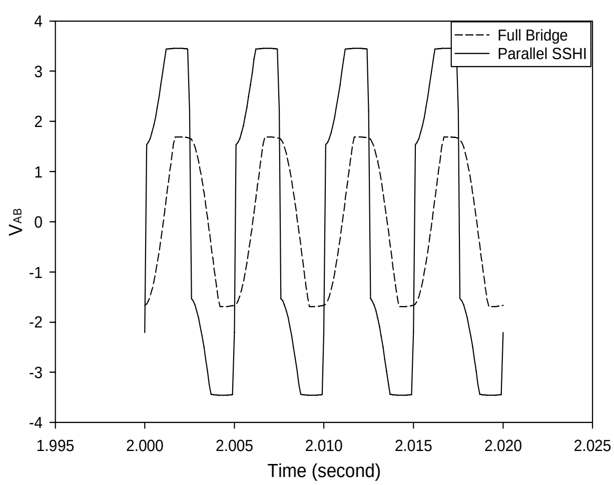

Figure 7. Flipping efficiency of the rectifier

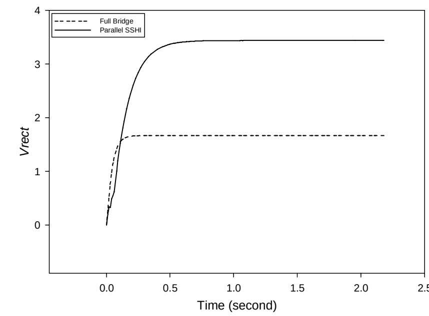

Figure 8. The output voltage (Vrect) of the rectifier

IV. CONCLUSION

This paper has identified problems that exist with a rectifier that uses a PE energy harvesting system. The proposed rectifier overcomes the drawback of previous rectifiers. When a parallel inductor is used, the voltage across the internal capacitor of the PE is flipped to extract more power. An active full-bridge rectifier is used instead of a passive rectifier to reduce the threshold voltage of the passive diode. Furthermore, a new control scheme simplifies the control of the switches in the SSHI circuit. The proposed rectifier achieves a power extraction efficiency that is 4.5 times that of a active full-bridge rectifier under the same load conditions; it also achieves a power conversion efficiency of more than 92%.

ACKNOWLEDGEMENT

This work was sponsored by the ETRI SoC Industry Promotion Center's Human Resource Development Project for IT SoC Architect; the CAD tools were supplied by IDEC of KAIST.

REFERENCES

[1] Y. Ramadass, and A. Chandrakasan, *An efficient piezoelectric energy harvesting interface circuit using a bias-flip rectifier and share inductor*, in IEEE J. Solid-State Circuit, vol. 45, no. 1, pp. 189-204, Jan. 2010.

[2] Y. Ramass , and A.Chandrakasan, *An efficient piezoelectric energy harvesting interface circuit using a bias-flip rectifier and share inductor*, in Int. Solid-State Circuit Conf.- Dig. Tech. Papers, Feb. 2009, p. 296-297.

[3] D. Guyomar, A. Badel, E. Lefeuvre and C. Richard, *Toward energy harvesting using active materials and conversion improvement by nonlinear processing*, IEEE Trans. Ultrason. Ferroelectr. Freq. Control Vol. 54, No. 4, Apr. 2005.

[4] E. Lefeuvre, A. Badel, C. Richard, L. Petit, and D. Guyomar, *A comparison between several vibration – powered piezoelectric generators for standalone systems*, in Elsevier Sensors and Actuator A: Physical, vol. 126, Issue 2, pp. 405-416, Feb. 2006.

[5] L. Garbuio, M. Lallart, D. Guyomar, C. Richard, and D. Audigier, *Mechanical energy harvester with untralow threshold rectification based on SSHI nonlinear technique*, in IEEE Trans. on Industrial Electronics, vol. 56, no. 4, pp. 1048-1056, Apr. 2009

[6] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre , *Adaptive piezoelectric energy harvesting circuit for wireless remote power supply*, in IEEE Transaction on Power Electronics, vol. 15, no.5, Sept. 2002.

[7] N. Krihely, and S. B. Yaakov, Self contained resonant rectifier for piezoelectric sources under variable mechanical excitation, in accepted in IEEE Trans. on Power Electronic, 2010.