An Comparator Based Active Rectifier for Vibration Energy Harvesting Systems

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***Abstract*—Harvesting ambient vibration energy through PE means is a popular energy harvesting technique. The main limitation of this harvesting system is in their interface circuitry. In this paper, a highly efficient active switch-only rectifier is proposed. By replacing the conventional full bridge rectifier with the cross-coupled active one in the passive switch-only rectifier, together with simple and effective control circuits, the proposed rectifier shows both good power extraction and power conversion capability. Based on 0.18 um CMOS technology, the simulated power efficiency of the proposed rectifier is 91%, and the output power is 144 uW with a 1 uF capacitor and a 95 kΩ load. The proposed active switch-only rectifier improves upon the extractable power and efficiency by 1.9 times and 1.5 times, respectively, compared to the conventional one; and improves upon the efficiency by 1.5 times compared with passive switch-only rectifier.**

***Keywords*—Energy Harvesting, Vibration Energy Harvesting, PE, Transducer, Active Rectifier, Comparator**

I. INTRODUCTION

Energy harvesting is the process by which energy is derived from environment (e.g., solar power, thermal energy, wind energy, and kinetic energy…), captured, and stored [1]. It is a promising alternative to batteries and receiving significant attention nowadays owing to the emerging development of wireless sensor networks, implantable medical electronics, and tire-pressure sensor networks [2–4], as well as issues of climate change and global warming.

As a typical type of energy harvesting technique, piezoelectric (PE) vibration energy harvesting is appealing because of their moderate power densities, which is not the case for energy derived from heat, internal lighting, and vibration via electromagnetic and electrostatic means [5].

Figure 1 shows the typical architecture of PE vibration energy harvesting system. As shown in Figure 1, the PE transducer is located in the first stage of the energy harvesting system. It is used to convert kinetic energy from motions and vibrations to electrical power. The output of the PE transducer is an ac quantity. Therefore, it has to be processed by a power converter to produce a suitable DC output voltage to meet the requirements of the end application. As shown in Figure 1, the power converters consist of a front end rectifier followed by a standard buck or boost DC-DC converter. Rectifier is used to convert AC to DC, and the DC-DC converter is used to regulate the DC voltage. The efficiency of a PE energy harvesting system depends on the power extraction and conversion efficiency of rectifier, and efficiency of DC-DC converter. Therefore, high performance rectifier with high power extraction and conversion efficiency is essential for high efficiency vibration energy harvesting system.

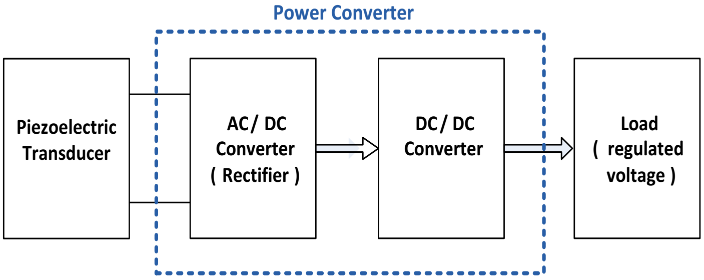

Figure 1. Typical Architecture of PE vibration energy harvesting system.

In this paper, an active switch-only rectifier with high power extraction and conversion efficiency is proposed. Section II introduces the state of the art rectifier designs. Section III describes the design details of the proposed high performance active rectifier together with the quantitative analysis of the power extraction ability. Section IV discusses the simulation results. Section V concludes.

II. STATE OF THE ART RECTIFIER DESIGNS

Figure 2 show most commonly used rectifier structures. With most of the previously reported rectifier circuits, diode and diode configured transistor rectifiers (Figure 2(a) and Figure 2(b)) are simplest and most robust [6]. Figure 2(e) is a conventional full wave rectifier which consists of four diodes or diode-tied MOS transistors. This full wave rectifier starts to work when the input voltage exceeds two threshold voltages (forward voltage drops (V_D)) of the diode. With a typical NMOS transistor threshold voltage of 0.5 V, there is a significant reduction in the output voltage of the rectifier and the overall power efficiency. Moreover, the output voltage generated by the PE transducer in the vibration energy

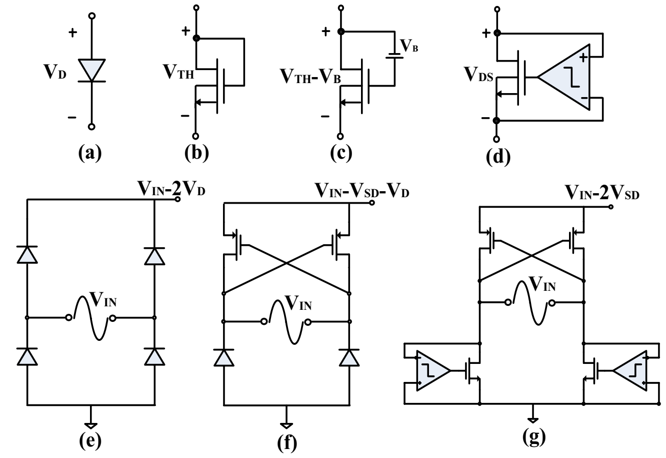

Figure 2. (a) diode, (b) diode-connected, (c) VTH-cancelled, (d) comparator-controlled, (e) diode-based, (f) cross-coupled, (f) active cross-coupled rectifiers.

harvesting system normally is small. Therefore, the diode and diode configured transistor rectifiers is not suitable for vibration energy harvesting system.

One way of reducing V_D is to superimpose a bias voltage V_B onto the gate of the MOSFET that effectively cancels the drop associated with threshold voltage V_{TH} (Figure 2(c)) [6]. However, the additional voltage (V_B) generator circuit is needed which adds complexity to the rectifier design.

Another way to overcome the limitation of the voltage drop is to use a comparator controlled rectifier [7]. As shown in Figure 2(d), a NMOS transistor is used as a switch to control the conduction in the forward path. When the input to the rectifier is higher than its output voltage, the comparator output goes to the positive and turns on the switch to allow the charge flowing to output load. Conversely, when the input voltage of the rectifier is lower than the output voltage, the comparator output goes low, the switch is turned off and the forward conduction path is disconnected. The comparator controlled rectifier significantly reduces the diode voltage drop. However, design the ultra low power comparator is challenge. If this power is excessive, it can outweigh the benefits of the reduction in the diode voltage drop.

On the other hand, the input voltage comes out of the transducer is AC. Therefore, cross coupling complementary inputs can drive and enhance the gates of the rectifying transistors (Figure 2.2(f)) [6, 8]. However, the efficiency is still limited by the drop voltage of the diode.

In Figure 2(g) [9], the author combines the cross coupled rectifier together with the unbalanced comparator controlled rectifier, which provide better performance.

In section III of this paper, a high performance active rectifier is proposed. It has good power extraction and conversion ability, small forward voltage drop, and simple and low power control circuits.

III. PROPOSED HIGH PERFORMANCE RECTIFIER

In this section, the design details of the proposed high performance active rectifier are introduced. The power extraction and power conversion performances are analysed.

A. Transducer Modelling

As shown in Figure 1, PE transducer is the first stage in the vibration energy harvesting system. In order to design rectifier, a circuit model of the PE transducer is needed to simulate the rectifier. Figure 3 shows the circuit model of the PE transducer which is usually represented electrically as a current source in parallel with it's an electrode capacitance C_P and an internal resistor R_P. The current source provides current proportional to the input vibration amplitude. The input vibrations are assumed to be sinusoidal in nature and the current is represented as, $i_P = I_P \sin \omega_P t$, where $\omega_P = 2\pi f_P$, and f_P is the frequency with which the PE transducer is excited [3].

B. Power Extraction and Conversion Analysis of Conventional Full Bridge Rectifier

In order to give the insight of the proposed rectifier, the power extraction and conversion ability of the conventional full bridge rectifier is analysed first. Figure 4 shows a conventional full bridge rectifier circuit together with its associated voltage and current waveforms. From Figure 4, the amount of charge available from the transducer could not be delivered to the output of rectifier all the time. Assuming idea diode is used, every cycle, the current from transducer has to charge parallel capacitor C_P from $-V_{REC}$ to $+V_{REC}$ and vice-versa before the diode transistors turn-on. This amount of lost charge limits the amount of power that can be extracted using the conventional full bridge rectifier. The charge that actually flows into the output capacitor C_{REC} is just the difference between the total available charge and the lost charge [3]. The quantitative analysis is shown as follows: the total amount of charge available from the transducer is given by

$$Q_{av/cy} = \int_0^{1/f_P} i_P dt = \frac{4I_P}{\omega_P} = 4C_P V_P \tag{1}$$

where V_P is the output voltage across transducer. The amount of charge lost every cycle can be given by

$$Q_{loss/cy} = 2C_P(V_{REC} - (-V_{REC})) = 4C_P V_{REC} \tag{2}$$

There for the actual charge flows into the output transistor is given by

$$Q_{REC/cy} = 4C_P(V_P - V_{REC}) \tag{3}$$

The total energy delivered to C_{REC} every cycle is given by

$$E_{REC/cy} = Q_{REC/cy} \times V_{REC} = 4C_P V_{REC}(V_P - V_{REC}) \tag{4}$$

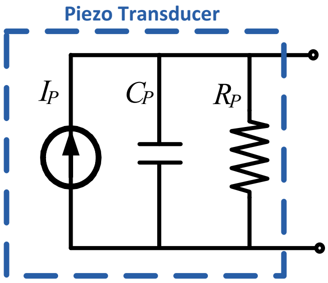

Figure 3. The circuit model of the PE transducer.

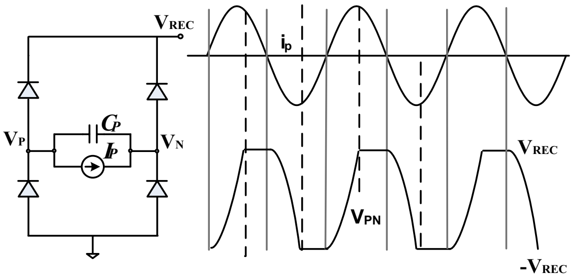

Figure 4. A full bridge rectifier and its associated voltage and current waveforms [3].

The cycle repeats at a frequency of f_P. Therefore, the power delivered to the output by the conventional full-bridge rectifier is

$$P_{RECT,FB} = E_{REC/cy} \times f_P = 4C_PV_{REC}f_P(V_P - V_{REC}) \quad (5)$$

From equation (5), it shows that the output power of the rectifier is vary with V_{REC} and reach a maximum at $V_{REC}=V_P/2$. Therefore, the maximum power that can be obtained using the conventional full-bridge rectifier is given by

$$P_{REC,FB}(\max) = C_Pf_PV_P^2 \quad (6)$$

Other than the poor power extraction ability of the conventional full bridge rectifier, the forward voltage drops across each diode in the full bridge rectifier incur considerable power losses during the delivery process. Overall, the conventional rectifier shows both poor power extraction and power conversion ability.

In order to improve the power extraction ability of the conventional rectifier, a passive switch-only rectifier is proposed which shows two times power extraction improvement [3]. However, the forward voltage drops across each diode in that proposed passive switch-only rectifier incur considerable conduction power losses leading to the poor efficiency. Moreover, the complex control circuit further decreases the efficiency.

C. Structure and Operational Principle of The Proposed Active Rectifier

To enhance the power extraction and conversion ability of conventional full bridge rectifier, as well as the efficiency of the passive switch-only rectifier introduced in [3], an cross-coupled active switch-only rectifier together with simple and effective control circuit is presented in this paper. Figure 5 shows the conceptual diagram of the proposed active switch-only rectifier. As shown in Figure 5, the proposed active switch only rectifier adds on switch S_1 in parallel with the transducer and following by the active full bridge rectifier.

1) Switch operation and control circuits: The switch operation is same as [3]. The switch is turned on for a brief time when I_P crosses zero in either direction. When the switch is ON, it discharges the C_P immediately to ground. Once has been discharged, switch is turned OFF. Without switch, I_P has to charge C_P from $-V_{REC}$ to $+V_{REC}$ or discharge C_P from $+V_{REC}$ to $-V_{REC}$. Now the I_P only has to charge parallel capacitor C_P from 0 to $\pm V_{REC}$ and vice-versa before the diode transistors turn-on. In order to compare with the conventional full bridge rectifier, the same quantitative analysis and same total amount of charge available from the transducer are applied to the proposed rectifier: the amount of charge lost every cycle can be given by

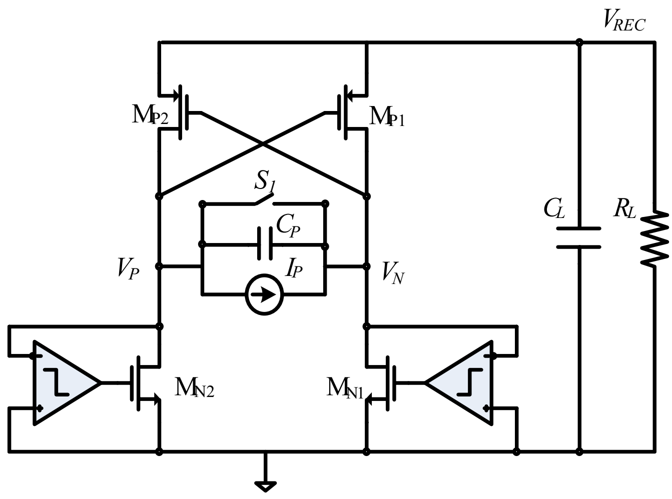

Figure 5. Conceptual diagram of the proposed rectifier

$$Q_{loss/cy} = 2C_P(V_{REC} - 0) = 2C_PV_{REC} \quad (7)$$

There for the actual charge flows into the output transistor is given by

$$Q_{REC/cy} = 2C_P(2V_P - V_{REC}) \quad (8)$$

The total energy delivered to C_{REC} every cycle is given by

$$E_{REC/cy} = Q_{REC/cy} \times V_{REC} = 2C_PV_{REC}(2V_P - V_{REC}) \quad (9)$$

The cycle repeats at a frequency of f_P. Therefore, the power delivered to the output by the proposed active switch only rectifier is

$$P_{RECT,FB} = E_{REC/cy} \times f_P = 2C_PV_{REC}f_P(2V_P - V_{REC}) \quad (10)$$

From equation (10), the maximum power that can be obtained using the proposed rectifier is given by

$$P_{REC,FB}(\max) = 2C_Pf_PV_P^2 \quad (11)$$

when $V_{REC}=V_P$. Compare equation (6) and (11), its shown that the proposed active switch only rectifier can extract two times power compared with conventional full bridge rectifier. In the proposed rectifier, the switch S_1 is realized by two PMOS transistor in series. S_1 need to be turned ON when transducer current I_P cross zero. Therefore, a zero-crossing detect circuit is needed. It is a continuous time comparator which is modelled based on the circuit described in [8]. Followed by zero-crossing detector is the pulse generator. The pulse generator is a simple NAND gate where the signal is

NANDed with a delayed inverted version of itself. The seven stage delay cells are used to make sure C_P is completely discharged. The final output is the control signal for turn on the switch S_1 when transducer current I_P cross zero.

2) Cross-coupled active full bridge rectifier operation: Comparator based cross-coupled full bridge rectifier is the popular way to overcome the limitation of the voltage drop [9]. As shown in Figure 5, the gates of bottom two NMOS transistor are controlled by comparator. When the negative input to the comparator is lower than ground, the comparator output goes to the positive and turns on the switch to allow the charge flowing to output load. The comparator controlled rectifier significantly reduces the diode voltage drop. In summary, the ability to convert nearly the entire voltage applied at the input to the output is the advantage of the proposed rectifier compared with original passive switch only rectifier. The forward voltage drop with proposed rectifier is only about 10 mV. Moreover, the proposed rectifier shows two times more power extraction ability by adopting a simple switch,

IV. SIMULATION RESULTS

The proposed active switch-only rectifier, together with conventional full bridge rectifier, passive switch-only rectifiers, is designed in TSMC 0.18um CMOS technology. Under the same PE transducer condition, where I_P=125uA; f_P=200Hz; C_P=25nF; R_P=1MΩ, the load resistor is changed from 10kΩ to 100kΩ. Under this transducer condition, for conventional full bridge rectifier, the theoretical maximum output power according to equation (6) is 79uW. For passive switch-only and proposed rectifier, the theoretical maximum output power according to equation (11) is 158uW. Figure 6 shows the transient behaviour of the discussed rectifiers. From Figure 6, the passive switch-only rectifier has nearly the same output voltage characteristic as the conventional full bridge rectifier. While the proposed rectifier reaches nearly the input voltage. Figure 7 shows the rectified output voltage V_{REC} of discussed rectifiers. From Figure 8, the V_{REC} are 1.51, 2.64, 3.7 V respectively. The actual calculated maximum output power of conventional full bridge, passive switch-only, proposed rectifiers are 45uW, 93uW, 144uW, respectively. The peak conversion efficiencies are 57%, 58%, and 91%, respectively. From simulation results, the proposed rectifier shows a strong increase of the efficiency, as well as the output power. Table I summarize and compare the performance of different rectifiers. The proposed active switch-only rectifier improves upon the extractable power by 1.9 times compare to the conventional full bridge rectifier, the efficiency by 1.5 times compare to the conventional full bridge rectifier and passive switch-only rectifier .

V. CONCLUSIONS

The conventional full bridge rectifier, passive switch only rectifier and the proposed active switch only rectifier are introduced, simulated. The power efficiency of the proposed rectifier is enhanced compared with original passive switch-only rectifier by using active rectifier to minimize the voltage drop along the conduction path. Together with simple and accurate control circuit, the efficiency of proposed rectifier are further increased. Designed in TSMC 0.18um technology, simulation results show that the proposed active switch-only rectifier improves upon the extractable power by 1.9 times compared to the conventional full bridge rectifier, the efficiency by 1.5 times compare to the both conventional full bridge rectifier and passive switch-only rectifier.

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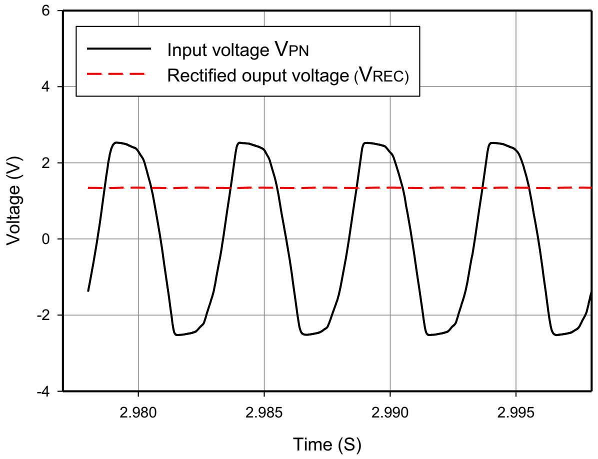
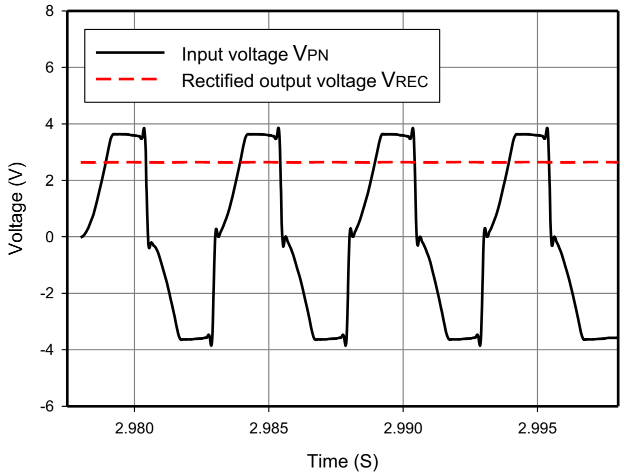
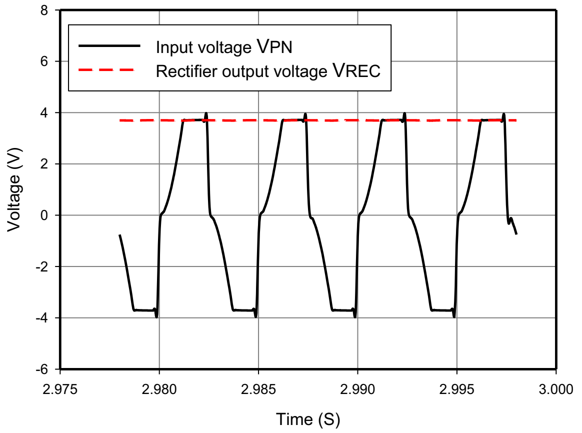


(a)



(b)



(c)

Figure 6. Transient behavior of discussed rectifiers. (a): conventional full bridage rectifier; (b): passive switch only rectifier; (c): proposed active switch only rectifier.

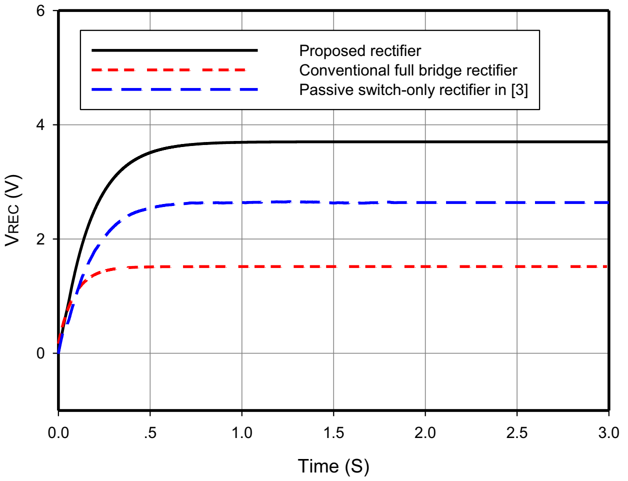


Figure 7. Rectified output voltage V_{REC} of discussed rectifiers.

TABLE 1. PERFORMANCE SUMMARY AND COMPARISION

Parameters	CFB	PSO	Proposed
Theoretical maximum output power [uW]	79	158	158
V_{REC} [V]	1.51	2.64	3.7
Actual maximum output power [uW]	45	93	144
Conversion efficiency	57%	58%	91%

CFB: Conventional full bridge rectifier; **PSO**: Passive switch-only rectifier
Proposed: Proposed active switch-only rectifier

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