A self-powered zero-quiescent-current active rectifier for piezoelectric energy harvesting

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Abstract: A self-powered zero-quiescent-current active rectifier for piezoelectric energy harvesting is proposed. It consists of two cross-biased PMOS transistors and two active diodes. To achieve zero quiescent-current, a bias-free clamping circuit is designed to clamp the drain-source voltage of the NMOS transistor of the active diode. Post-simulation and measurement results show that the proposed active rectifier achieves an efficiency improvement of more than 40\% vs. the ordinary full-bridge rectifier; the power transferred by the rectifier from the piezoelectric energy harvester (PEH) to the storage capacitor is increased significantly, especially even when the output power of PEH is low.

Keywords: zero-quiescent-current, active rectifier, piezoelectric energy harvesting

Classification: Energy harvesting devices, circuits and modules

References

1 Introduction

Wireless sensor networks (WSNs) are widely used in areas such as intelligent industry, traffic control, medical electronics, environmental monitoring, etc. However, the high cost and difficulty of replacing the batteries of WSN nodes poses challenges for the design of the power management units. Thus, there is a growing demand for a self-consistent sensor node that harvests minute amounts of energy from the environment [1]. Piezoelectric energy harvesting has been widely studied, due to the availability of vibration energy, the high output voltage of piezoelectric energy harvesters (PEHs) and easy integration of the harvesting system [2].

A tiny PEH generates an AC output voltage in the microwatt range, so a high performance rectifier is needed. A full-bridge rectifier is commonly used, but passive diodes have high forward voltage drop and small conduction angle that resulted in high power consumption and decreased efficiency in extracting energy. Hence, a rectifier with active diodes is adopted to achieve higher efficiency [3, 4, 5, 6, 7, 8, 9, 10]. The power transistor that is driven by a comparator or an op amp of the active diode has very low forward voltage drop. However, the auxiliary circuit needs a biasing circuit with a power supply. Moreover, the power consumption of the comparator or op amp will decrease the energy transferred to the storage capacitor and the load.

In this research, a self-powered active rectifier with zero quiescent current is proposed so as to increase the energy extracted from the PEH and to transfer more energy to the storage capacitor and the load.

2 Design of the proposed rectifier

In order to increase the electrical energy extraction from PEH and transfer more energy to the storage capacitor and the load, the proposed rectifier is designed to have low threshold voltage and low power consumption. Fig. 1 shows the schematic of the proposed active rectifier. The equivalent circuit of the PEH is shown in the upper left dashed frame; it consists of an AC current source Ip, a capacitor Cp and a large resistor Rp. The rectifier is made up of PMOS transistors MP1 and
MP2, and active diodes D1 and D2. MP1 and MP2 are cross-biased to have large turn-on voltages such that the drain-source voltages \(V_{DSP}\) are much lower than the forward voltages of passive diodes \(V_d\). The active diodes D1 and D2 are implemented by large NMOS transistors with corresponding clamping circuits. To achieve zero-quiescent-current, the clamping circuits are bias-free and powered by the AC input of the rectifier.

The proposed active rectifier is symmetrical, and the working principle of the active diode can be expounded with that of D1. The source (drain) of the large NMOS MN1 is the anode (cathode) of the active diode D1. When \(V_{IN1} < -V_{TH}\) \(V_{TH}\) is the threshold voltage of NMOS), MN3 turns on. As \((W/L)_{MN3} = (W/L)_{MN4} = k\), \(I_{MN4} = I_{MP4} = I_{MP3} = I_{MN3}\). In order to reduce the operating current of the clamping circuit, \(k\) is designed to be smaller than 1. The gate-source voltage of MN1 can then be expressed as

\[
V_{GS1} = V_{GS4} = V_{TH} + \sqrt{\frac{2I_{MN4}}{\mu_n C_{ox} (W/L)_{MN4}}}.
\]

Thus, MN1 is turned on, which means that the active diode is on, and the forward voltage is

\[
V_F = -V_{DS1} = V_{GS3} - V_{GS4} = \sqrt{\frac{2I_{MN4}}{\mu_n C_{ox} (W/L)_{MN3}}} - \sqrt{\frac{1}{(W/L)_{MN4}}}
\]

\(V_F\) is clamped to a small value that is around tens of millivolt if \((W/L)_{MN3}\) and \((W/L)_{MN4}\) are set to appropriate values. In this design, \((W/L)_{MN3}/(W/L)_{MN4}\) is set to be 1/3 and \(V_F\) is clamped to around 30 mV.

When the PEH converts vibration energy to electrical energy, the generated AC power would activate the active rectifier. In the positive half-cycle, \(V_{IN} = V_{IN1} - V_{IN2}\) increases. When \(V_{IN} > V_{OUT}\) and \(V_{IN2} < V_{OUT} - |V_{TP}|\) \(V_{TP}\) is the threshold voltage of PMOS), MP1 is turned on, \(V_{IN1}\) is clamped to \(V_{OUT} + V_{DSP}\). However, before D2 is turned on, no current runs through MP1, so \(V_{DSP}\) is 0. When \(V_{IN2} < -V_{TH}\), Clamping Circuit 2 starts to work and clamps \(V_{IN2}\) to \(-V_F\) and D2.
turns on. Thus, $V_{IN} = V_{OUT} + V_{DSP} + V_F$ when the rectifier is on, and the threshold voltage $V_T$ is approximately $V_{OUT} + V_{TH}$. When $I_p$ crosses 0, $V_{GS6}$ decreases and MN6 turns off such that $I_{MN5} = I_{MN6} = 0$ and $V_{GS2} = V_{GS} = 0$, and MN2 is also turned off. Next, the negative half-cycle begins. In the entire positive half-cycle, MP2 and D1 are off and consume no power. In the negative half-cycle, the dual mechanism repeats. Hence, no additional power and bias current is needed in all working states. When there is no vibration, the AC input voltage is 0 and there is no power for the clamping circuits. Note that there is no bias circuit for the active rectifier, and the quiescent current of the proposed active rectifier is 0.

Qualitative description is followed by the following detailed theoretical calculations. Assume that the AC current of $I_p$ is sinusoidal: $i_p = I \sin 2\pi ft$. Where $I$ and $f$ are the current amplitude and frequency, respectively, and $T = 1/f$ is the period. As $R_p$ is large enough such that current consumption can be neglected. The threshold voltage $V_T$ can be expressed as

$$V_T = V_O + V_{TH} = \left[ \frac{1}{C_0} \int_{NT/2}^{NT/2+ft_{b1}} i_p dt \right] - (V_O + V_{DSP} + V_F). \quad (3)$$

Where $V_O$ is the voltage of the storage capacitor $C_L$, and is considered to be constant in one vibration cycle. $N$ is nonnegative integer and $0 < t_{b1} \leq T/2$.

The average input power in one cycle is $P_{AI}$, which is also the average output power of the PEH, and is expressed as

$$P_{AI} = 2f \int_{NT/2+ft_{b1}}^{(N+1)T/2} (V_O + V_{DSP} + V_F) i_p dt. \quad (4)$$

The average output power in one cycle is

$$P_A = P_{AI} - P_{MP} - P_{MN} - P_C. \quad (5)$$

Where $P_{MP}$, $P_{MN}$ and $P_C$ are the average power consumptions of PMOS (MP1 and MP2), NMOS (NM2 and MN1) and the clamping circuits, respectively. Now, $i_p = i_{MP} + i_{MN} + i_C$ and $i_C$ is designed to be small. Thus, the following approximation can be made:

$$P_A \approx 2f \int_{NT/2+ft_{b1}}^{(N+1)T/2} V_O i_p dt. \quad (6)$$

The efficiency of the proposed active rectifier $\eta_A$ is given by

$$\eta_A = \frac{P_A}{P_{AI}} \approx \frac{V_O}{V_O + V_{DSP} + V_F}. \quad (7)$$

Similarly, theoretical formulae for an ordinary full-bridge rectifier consisting of passive diodes can be deduced. The comparison between the two rectifiers is shown in Table I. “A” is the proposed active rectifier and “D” is the ordinary full-bridge rectifier. $V_I$ is the input voltage when the rectifier is on, $t_w$ is the working time, $P$ is the average output power and $\eta$ is the efficiency of the rectifier.

3 Post-simulation and experimental results

Post simulation is performed to verify the design. Fig. 2(a) shows the average output power of the proposed active rectifier and the ordinary full-bridge rectifier at
different amplitudes and frequencies of $i_p$ (caused by different vibration amplitudes and frequencies of the PEH). The curves show that the proposed active rectifier is better than the ordinary full-bridge rectifier on the average output power under the same conditions. In the case of low input energy (50 µA, 100 Hz in Fig. 2), the ordinary full-bridge rectifier is unable to output any energy, but the proposed active rectifier can still harvest more than 10 µW. Fig. 2(b) is the efficiency of the proposed active rectifier and the ordinary full-bridge rectifier. It shows that the efficiency improvement is more than 40%.

The proposed active rectifier is designed in 0.18 µm CMOS process. Fig. 3(a) shows the layout, in which the shadow region is the circuits not for our design. The layout of our design includes clamping circuits, PMOS, NMOS and five pads. The chip size is about 850 × 1150 µm², and Fig. 3(b) is the chip photo. Fig. 3(c) shows the experimental setup. A 60 mm × 30 mm piezoelectric element is used and the amplitude of the open-circuit voltage set to be about 7 V @ 20 Hz. The measured voltage drop of the active diode $V_F$ is only about 30 mV, exactly the same as the designing target, and the measured $V_{DSP}$ is close to 25 mV. Fig. 4 shows the measured average output power and the efficiency of the proposed active rectifier. When the output voltage is 3.32 V with the load resistor is 54 kΩ, the output power of the proposed active rectifier is more than 200 µW and the efficiency is about 96%.

Table II compares the performance of the proposed active rectifier with recently reported active rectifiers for piezoelectric energy harvesting. The proposed rectifier has the best efficiency and zero quiescent-current.

![Fig. 2. Post simulation results: (a) Average output power; (b) Efficiency](image)
4 Conclusion

A self-powered and zero-quiescent-current active rectifier is proposed to increase electrical energy extraction from PEH and energy transfer to the storage capacitor and the load and to get a higher efficiency of rectification. Clamping circuits without bias are used to reduce the power consumption of active diodes. The results show that the design can significantly improve the rectifier efficiency and the energy extraction and transfer.

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