Design of Efficient CMOS Rectifiers for Integrated Piezo-MEMS Energy-Harvesting Power Management Systems

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Abstract—MEMS-based piezoelectric energy harvesters are promising energy sources for future self-powered medical implant devices, low-power wireless sensors, and a wide range of other emerging ultra-low-power applications. However, the small form factors and the low vibration frequencies can lead to very low (in μW range) harvester output power. This makes the design of integrated CMOS rectifiers a challenge, ultimately limiting the overall power efficiency of the entire power management system. This work investigates two different fully integrated rectifier topologies, i.e. voltage doublers and full bridges. Implemented in $0.35\text{-}\mu\text{m}$, $0.18\text{-}\mu\text{m}$, and 65-nm CMOS technologies, the two rectifier architectures are designed using active diodes and cross-coupled pairs. These are then evaluated and compared in terms of their power efficiency and voltage efficiency for typical piezoelectric transducers in such ultra-low-power applications which generate voltages between $0.27\text{--}1.2\text{ V}$. Furthermore, analytical expressions for the rectifiers are verified against circuit simulation results, allowing a better understanding of their limitations.

I. INTRODUCTION

Harvesting energy from the environment is an attractive choice for powering wireless sensors and medical implants. Utilizing piezoelectric (PE) transducers to extract energy from vibrations is particularly appealing due to its high energy density [1] and the wide availability of ambient vibration sources. A typical power management unit (PMU) in a PE harvester system is depicted in Fig. 1 which converts the alternating electrical output from the PE transducer into a steady voltage to supply a load circuit. The PMU has to maximize the power extracted from the PE transducer while supplying the specific voltage/current to the load circuit. Power consumption in the PMU must be minimized to limit energy loss. The focus of this work is on the rectifier sub-block of the PMU.

Consider the electrical equivalent circuit of a PE transducer shown in Fig. 2 [2]. Assuming a high Q value, the open-circuit voltage $V_P = I_P / 2\pi f_P C_P$ where f_P is the frequency of vibration. In form-factor constrained applications with low ambient vibration levels (upto a few hundred Hz), the output power and voltage (V_P) generated by the PE transducer are typically low [3]. The design of CMOS rectifier circuits which provide high power and voltage efficiency at low operating voltages presents significant challenges. Several works which improve upon conventional rectifier topologies have been reported [2]–[5]. Unlike a majority of these works which utilize

Fig. 1. Power management unit in a PE harvester system.

Fig. 2. Electrical equivalent circuit of a PE transducer.

$V_P \geq 1.2\text{ V}$, we have considered V_P between $0.27\text{--}1.2\text{ V}$ that better represent μW PE transducers. Four variations of active rectifiers reported in literature have been simulated in $0.35\text{-}\mu\text{m}$, $0.18\text{-}\mu\text{m}$ and 65-nm CMOS process technologies. Advantages and limitations of the selected rectifier topologies and CMOS technology nodes are illustrated based on the simulated power and voltage efficiency at specific values of V_P . The rest of the paper is organized as follows. Section II describes the rectifier topologies while Section III constitutes the analysis of the different topologies. Section IV compiles the simulation results and compares the performance of different rectifier topologies. Conclusions are drawn in Section V.

II. RECTIFIER TOPOLOGIES

Full-bridge rectifiers and voltage doublers are the two important types of rectifier circuits widely found in piezoelectric energy harvesting systems [2]. Different variants of these rectifiers have been simulated in this work. Since PN-junction diodes and diode-connected MOSFETs entail substantial voltage drops and consequently lower the power efficiency of the rectifier, they have been excluded.

Fig. 5. P_{In} and P_{Out} for the Active NMOS XC PMOS rectifier in 0.18- μm .

where $V_{Eff} = V_{DD} - V_{Th,n}$ for the active NMOS diode. The power efficiency which is defined as the ratio of output power, P_{Out} , to input power, P_{In} , can be calculated as

$$\eta_P = \frac{P_{Out}}{P_{In}} = \frac{I_{Load} V_{Out}}{V_{PE} \left(\frac{2I_P}{\pi} - 4C_P V_{PE} f_P \right)}. \quad (5)$$

Figure 5 shows the plot of P_{Out} and P_{In} from (5) along with the corresponding values from simulation for the 0.18- μm AN rectifier with $I_P = 88 \mu\text{A}$. A comparator with an offset of 17 mV was used. The discrepancy for higher load currents is caused by the low V_{PE} which increases the voltage drop across the cross-coupled PMOS diodes.

IV. SIMULATION RESULTS

In this paper we consider the three scenarios shown in Table I which correspond to different levels of input acceleration on the PE transducer. At higher acceleration, higher values of I_P and V_P are obtained. The rectifier topologies in Fig. 3 were simulated for the I_P values listed in Table I with a constant current load and a 1 μF smoothing capacitor connected to the output node V_{Out} . For each value of I_P , the load current of the rectifier was swept in order to determine the maximum load current provided by the rectifier. The variation in power and voltage efficiency of the rectifier with the load current was determined. The selected CMOS process nodes differ significantly in their nominal supply voltage V_{DD} , threshold voltage V_{Th} , and the intrinsic gain of the MOS transistors. V_{Th} plays a major role in determining the minimum input voltage (V_P) supported by a rectifier while the intrinsic gain and transconductance are crucial in determining the performance at large load currents. Since the control circuitry for the active diodes use the nominal supply voltage, their performance is significantly impacted by the choice of the CMOS process.

All figures in this section use the acronyms for the rectifiers provided in Fig. 3 to distinguish each rectifier topology. Figures 6-8 plot the variation in power efficiency of the rectifiers

Fig. 6. Power efficiency for $I_P = 34 \mu\text{A}$.

Fig. 7. Power efficiency for $I_P = 88 \mu\text{A}$.

with load current for the specified values of I_P . The corresponding plots for voltage efficiency are shown in Figs. 9–11. For the voltage doublers, the voltage efficiency has been computed as $V_{Out}/0.5V_{PE}$. For $I_P = 34 \mu\text{A}$, the rectifiers simulated in more advanced CMOS process nodes achieve higher power and voltage efficiency while those simulated in 0.35- μm never get activated since $V_P = 271 \text{ mV}$ is insufficient to turn ON the transistors which have a $V_{Th} \approx 0.6 \text{ V}$. When the load current increases, resulting in a lower V_{Out} , the higher intrinsic gain of the 0.18- μm transistors provides increased efficiency over a wider load interval as illustrated in the power and voltage efficiency plots. Even though the 0.35- μm simulations are functional at $I_P = 88 \mu\text{A}$, the poor transconductance of the devices stemming from low gate-overdrive voltage leads to diminished efficiency at medium and high load currents as shown in Figs. 7 and 10. For $I_P = 150 \mu\text{A}$, the 65-nm and 0.18- μm rectifiers maintain substantial power and voltage efficiency even at fairly large load currents. From the plots in Figs. 6–11, it is seen that the AN rectifier sustains higher efficiency over a wider range of load currents compared to other topologies since the comparator for the active NMOS diode utilizes the full nominal supply voltage of the CMOS process. In contrast, the comparator for the active PMOS diode shown in Fig. 4 uses the rectifier input and output voltage as its supply voltage. In the power and voltage

TABLE I

PE TRANSDUCER MODEL PARAMETERS FOR DIFFERENT ACCELERATIONS.

I_P [μA]	C_P [nF]	R_P [M Ω]	f_P [Hz]	V_P [V]
34	100	100	200	0.271
88	100	100	200	0.7
150	100	100	200	1.19

efficiency plots, some of the curves experience a steep decline which can be attributed to the control circuitry becoming non-functional due to low V_{Out} at higher load currents. To provide

Fig. 8. Power efficiency for $I_P = 150 \mu\text{A}$.

a fair comparison between the different CMOS processes and I_P values employed, the quiescent power consumption of the control circuits was not included in the calculation of the power efficiency.

V. CONCLUSION

Rectifier topologies which are suitable for extracting energy from μW -range PE transducers that generate open-circuit voltages in the range of 0.27-1.2 V have been investigated. Analytical expressions for the rectifier input power and output power have been verified against simulated values and found to match closely. The selected rectifier topologies have been simulated in three CMOS process nodes which have substantially different process parameters. Based on the variation in power and voltage efficiency across load currents, the merits and drawbacks of the selected rectifier topologies and CMOS processes are elucidated.

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Fig. 9. Voltage efficiency for $I_P = 34 \mu\text{A}$.

Fig. 10. Voltage efficiency for $I_P = 88 \mu\text{A}$.

Fig. 11. Voltage efficiency for $I_P = 150 \mu\text{A}$.

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