ULTRA LOW POWER STAND-ALONE CIRCUITRY FOR HARVESTING ENERGY FROM A MICRO-POWER PIEZOELECTRIC GENERATOR

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Abstract: A stand-alone circuit with ultra low power consumption is described and demonstrated in this paper which adaptively maximizes the harvested power from a vibrating piezoelectric element. The proposed circuitry consists of an ac-dc voltage rectifier connected to a battery via a switch-mode dc-dc converter. The converter is simply controlled by three comparators in a single analog chip to: (i) generate a gating signal for the dc-dc converter switch; (ii) regulate the rectified voltage via the gating signal; and (iii) sense the piezoelectric terminal voltage as a feedback for the control loop. The control unit power consumption is only 50 μW at 2.5 V which facilitates development of a viable stand-alone control unit for the converter. Experimental results show that: (i) the proposed energy harvesting circuitry can notably increase the extracted power from the piezoelectric element compared to directly connecting a battery to the piezoelectric rectifier; and (ii) the overall efficiency is dominantly determined by its switching circuit since the controller power loss is negligible in comparison with switching loss.

Key words: Power Harvesting, Energy Scavenging, Piezoelectric Bending Generator, Power Management Circuit

1. INTRODUCTION

Vibrating piezoelectric elements, which convert mechanical vibration energy to electricity, have recently been considered as long life micro-power generators for low power wireless apparatuses [1]. A piezoelectric generator electrically behaves as a capacitive ac source with variable amplitude whereas electronic apparatuses require fixed dc voltages [1,2]. Thus, an energy harvesting circuitry consists of an ac-dc rectifier and power management circuitry, is needed to deliver the extracted power of the piezoelectric element at a desired dc voltage level. To have an efficient energy harvester, reducing the non-scaleable dissipations in the electronic circuitry is of critical importance due to the low power of piezoelectric generators for wireless sensor applications (0.5-5 mW).

Various energy harvesting circuits have been suggested and demonstrated experimentally [2-5]. However, they need complex electronics (often microcontrollers [2]) and/or complex sensing (e.g. position or current sensors [2-4]). This paper proposes and demonstrates an ultra low power energy harvesting circuitry that works stand-alone and simply uses voltage as a sensed quantity. We identified four qualities for a viable energy harvesting circuit: efficiency, adaptivity, autonomy, and compatibility with microelectronics implementations. Using these criteria, the proposed circuitry will be compared with other energy harvesting circuits to reveal its advantages over the other energy harvesting solutions.

2. ENERGY HARVESTING CIRCUITRY

2.1 Rectifying Circuit

Figure 1 shows the *full bridge* and *voltage doubler* diode rectifiers as two alternatives for a piezoelectric voltage rectifier. In the full bridge configuration, the rectified voltage (Vrec) under no-load condition is ideally equal to the peak open-circuit voltage at the piezoelectric terminals (Voc) whereas in the voltage doubler, the no-load voltage is twice this voltage (2Voc). Ottman et al. [2] analytically show that for the full bridge configuration, the maximum power extracted from a piezoelectric device occurs when the rectified voltage is maintained at one-half of the no-load voltage (i.e. Vrec=Voc/2). By using similar analysis, one can show that for the voltage doubler configuration, the maximum power extraction occurs when the rectified voltage is also one-half of no-load voltage i.e. Vrec=2Voc/2=Voc. We will validate these statements experimentally, in the following section.

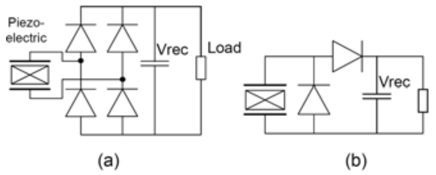

Fig. 1: Simple passive rectifiers: (a)Full bridge, and (b) Ac-dc voltage doubler configurations.

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The dc voltage of a load is often fixed by a battery whereas the piezoelectric voltage can vary in a wide range due to the variation of mechanical vibration excitations. Therefore, direct connection of a battery to a rectifier, which results in a constant Vrec, will be an inefficient energy harvester. To enhance extracted power, one method is to add a dc-dc power converter to adaptively adjust the rectified voltage with respect to the piezoelectric open-circuit voltage (Voc).

2.2 Switching Circuit

Fig. 2 shows a voltage doubler rectifier and the details of a step-down switched mode power converter that we propose as an ultra-low power, stand-alone energy harvesting. We selected the voltage doubler configuration as a rectifier for two reasons; (i) it will be shown in Section 3 that the power dissipation in voltage doubler is less than that one in full bridge configuration, and (ii) it provides a valuable voltage feedback which is critical for development of a low power control circuit (other harvesting circuits use current or position as sensing feedbacks that need additional circuits to convert the signal to a voltage for processing). The switching circuit converts the rectified voltage (Vrec) to the load's dc voltage (Vbat) and the control unit adaptively regulates the rectified voltage to follow variations of the piezoelectric voltage (i.e. Vrec=Voc) to extract the maximum power. The control unit simply consists of three analog comparators denoted by C1 to C3 in Fig. 2. C1 compares the piezoelectric terminal voltage with a reference signal (Vref1=0) and generates a pulse with a duty cycle proportional to Voc, Fig 3. Then, the pulse applied to an analog low pass filter (RC circuit) which results in a dc control signal proportional to Voc, (Vct on Figs. 2 and 3). The dc control signal is compared with Vref2 to create a synchronous pulse which determines the frequency of a saw-tooth oscillator. The last comparator uses the saw-tooth waveform to generate on/off control signals for the switch driver which turns on/off the converter switch. It is of most importance that the power consumption of the circuitry is maintained as low as possible to have an efficient energy harvester.

3. EXPERIMENTAL SETUP AND RESULTS

The proposed circuitry is tested using an experimental setup consisting of a piezoelectric actuator as a mechanical vibration source that drives a piezoelectric generator. A two-layer piezoelectric bending beam (cantilever configuration) was used as the piezoelectric generator (Quick-mount Q220-A4-303YB of Piezo Systems, Inc.). A similar beam was also used as the piezoelectric shaker in actuator mode.

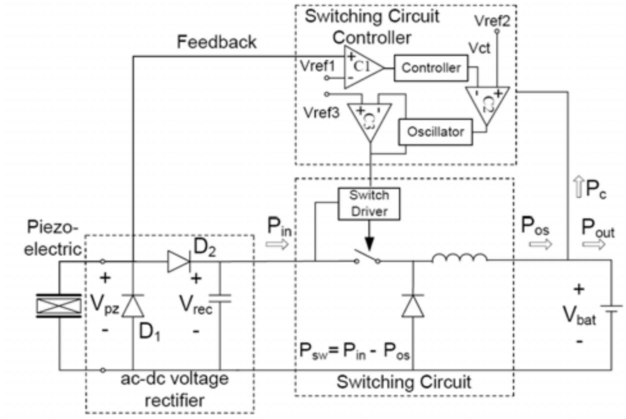

Fig. 2: The proposed adaptive energy harvesting circuitry using piezoelectric voltage as a feedback.

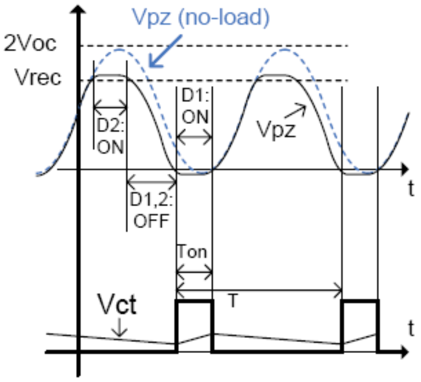

Fig.3: Controller unit signals; Vpz is the sensed voltage and Vct is the generated control signal.

The beam is made of PZT-5A4E material, polled for series operating mode. The beam dimensions are: 31.8 mm length, 12.7 mm width, and 0.51 mm thickness (the center brass shim thickness is 0.13 mm). The actuator and generator beams were fixed at one end, and simply contacted face-to-face at the free end, without using any adhesive material. The frequency and amplitude of the actuator was controlled with a function generator connected to the beam via a power amplifier. The frequency of the actuator was fixed at 250 Hz (resonant frequency of the beam) and its voltage amplitude was adjusted to obtain desired peak open-circuit voltages during the tests.

The electronic circuit for the energy harvester is composed of Schottky diodes (for the ac-dc rectifier and switching circuits), BJT transistors as the switch and driver, and a 1 mH inductor for the step-down converter (Fig. 2). We used the analog comparator chip MAX924 by *MAXIM* to build the control unit. This chip includes four ultra low power comparators and a built-in reference voltage. The switched circuit was connected to the two AA-size rechargeable batteries (SONY 2700mAh NI-MH), connected in series with an overall fixed voltage of Vbat=2.57 V. This voltage level is sufficient for powering many

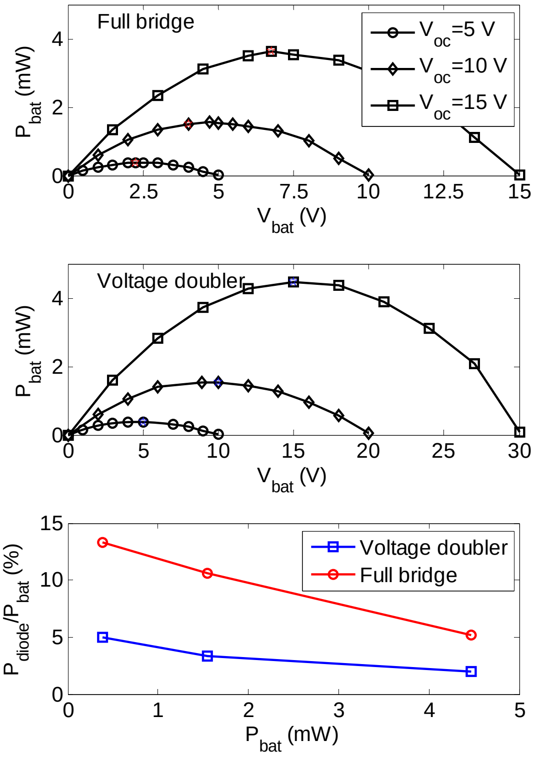

Fig.4: Extracted power versus rectified voltage for the full bridge and voltage doubler rectifiers.

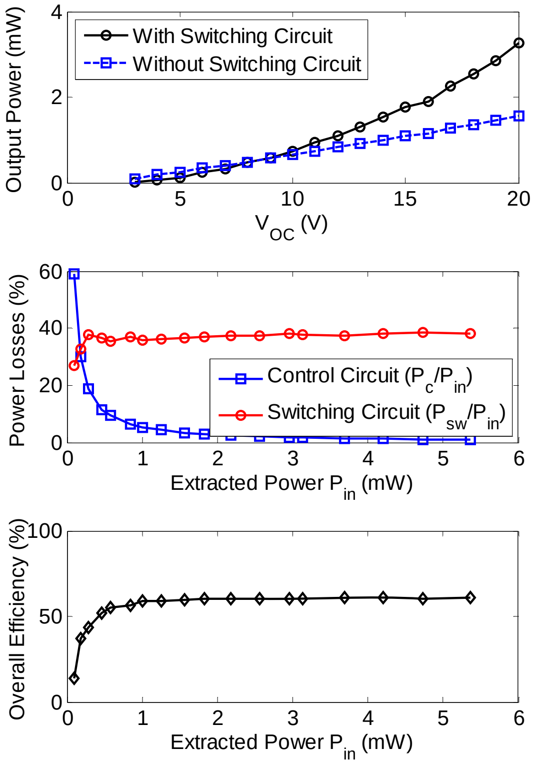

Fig.5: Extracted useful power, power losses and efficiency of the proposed power harvesting circuitry at different open-circuit voltages.

types of low power wireless sensor nodes.

The experiment included two parts. First, we investigated the effect of rectified voltage on the extracted power for the full bridge and voltage doubler rectifiers of Figs. 1 (a) and (b). For this test, we used a variable dc source instead of a battery and each test was repeated for three peak open-circuit voltages; Voc=5, 10, and 15 V. Figure 4 shows the graphs of the extracted power versus rectified voltage for the full bridge and voltage doubler rectifiers. The graphs confirm that for the full bridge rectifier, maximum power is extracted at a dc voltage close to half of the peak open-circuit voltage whereas in the voltage doubler rectifier, the maximum extracted power occurs at the peak open-circuit voltage. Comparing the peak power of the voltage doubler and full bridge rectifiers (the first and second graphs of Fig. 4) shows that the extracted power by using voltage doubler rectifier is slightly higher than that obtained using the full bridge rectifier. The reason is that in the voltage doubler, the power is extracted at a higher voltage which means a lower current for a fixed power. The lower current means less voltage drop across the diodes which in turn means lower power losses. Furthermore, the voltage doubler circuit has one diode in the filter capacitor path whereas the full bridge configuration has two diodes. Therefore, we can expect higher power dissipation for the full bridge circuit. The third graph of Fig. 4 compares the normalized power losses at maximum power showing that the losses for the full bridge are higher than the voltage doubler.

The next experiment examined the role of switching circuit to improve the extracted power from the piezoelectric element. For this test, first we directly connected the fixed 2.57 V rechargeable batteries to the rectifier and measured the extracted power at different piezoelectric open-circuit voltages ranging from 3 to 20 V. Then, we used the switching circuit as shown on Fig. 2, and repeated the test. The first graph of Fig. 5 compares the power of a directly connected battery with the output power of the switching circuit. As Fig. 5 shows, for open-circuit voltage less than 6 V, the extracted power using a direct connection is almost the same as the extracted power using the power circuit. However, for an open-circuit voltage above 6V the useful output power of the switching circuit rapidly increases compared to the directly connected batteries since the switching circuit adaptively matches the rectified voltage with the open-circuit voltage. As the first graph in Fig. 5 shows, the switching circuit increases the useful extracted power (Pout on Fig. 2) up to 200% at Voc=20 V compared to a directly connected batteries. The second graph of Fig. 5 compares the normalized power losses of the switching circuit and the control circuit versus the extracted power (Pin on Fig. 2). The graph shows that for an extracted power above 0.5 mW, power losses are dominantly determined by the switching circuit and the contribution of the control circuit in power dissipation becomes negligible. The last graph of Fig. 5 depicts the overall efficiency of the power circuit that asymptotes to 60%.

4. PERFORMANCE EVALUATION

Criteria of an ideal energy harvesting circuitry can be listed as: (i) efficiency, (ii) stand-alone operation, (iii) adaptivity, and (iv) micro-scale compatibility. The circuitry must be efficient such that power losses are small compared to the input power. The stand-alone characteristic means that an energy harvesting circuitry can operate independent of the other components of a wireless sensor node, for example. Adaptivity here means that the circuitry is able to adjust the rectified voltage to ensure maximum power extraction. Finally, the micro-scale compatibility criterion illustrates the potential for implementation as an integrated circuit, which reduces cost and improves overall efficiency and energy density. Using the above criteria, the proposed circuitry along with four other energy harvesting circuits are compared in Table I. The first circuit is the simple full bridge passive rectifier depicted on Fig. 1 (a). The second one is an adaptive energy harvester based on control of rectified voltage to maximize the extracted power. This method uses output current signal as a feedback in a control loop and its control algorithm is developed on a DSP module [2]. The third circuit adaptively extracts maximum power using passive components. However, this circuit needs a position sensor to obtain a synchronous signal for its operation [3,4]. The fourth energy harvester uses a capacitive charge pump circuit connected to a synchronous rectifier that is highly compatible with micro-scale IC technologies [5]. However, the circuit does not control the rectified voltage which degrades its performance and efficiency. The micro-scale compatibility of the second and last circuits are ranked “Fair” since they requires an inductor which is a bulky component. Comparing features in Table I shows that the proposed circuitry is a promising energy harvester since it presents a stand-alone, efficient, and adaptive circuitry with a simple topology.

Table I: Comparing the features of different piezoelectric energy harvesters

Method	Efficiency	Adaptivity	Stand-alone	Sensor	u-Scale Compatibility
Simple Passive Rectifier Fig. 1	Low	No	Yes	-	High
Adaptive Energy Harvester (Full Bridge Rectifier) [2]	Low	Yes	No	Current	Fair
Synchronized Switch Harvesting [3,4]	Fair	Yes	Yes	Position	Low
Synchronous Rectifier and Charge Pump [5]	Low	No	Yes	-	High
Energy Harvester proposed in this paper	Fair	Yes	Yes	Voltage	Fair

5. CONCLUSION

We proposed and demonstrated a circuit for harvesting energy from a vibrating piezoelectric element. The circuitry increases the useful extracted power up to twice compared to directly connecting a battery and has an efficiency of about 60%.

The significant features of the proposed circuitry are: (i) it controls the rectified voltage to maximize the extracted power from the piezoelectric element, (ii) it uses terminal voltage of the piezoelectric generator as a feedback which simplifies the implementation of the circuitry and decreases its power consumption, and (iii) its control unit consists of a simple analog circuit that operates as a stand-alone subsystem.

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