AUTONOMOUS PIEZOELECTRIC ENERGY HARVESTING SYSTEM FOR IMPROVED ENERGY EXTRACTION USING A CMOS INTEGRATED INTERFACE CIRCUIT

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Abstract: This paper presents a piezoelectric energy harvesting system demonstrating the output power enhancement when using a CMOS integrated pulsed-resonance converter (PRC) instead of a simple Schottky diode bridge rectifier. The combination of a storage capacitor, a blinking light emitting diode (LED) and a voltage detector forms a fixed voltage regulator and visualizes the output power extracted out of the piezoelectric generator. At a fixed capacitor voltage of 2.1 V, the output power is increased by a factor of 1.7 using the PRC. The active load components of the energy harvesting system are exclusively powered by the generator and thus need no external power supply.

Keywords: Energy harvesting, piezoelectric generator, power extraction, interface circuit

INTRODUCTION

Energy harvesting based on piezoelectric generators is very attractive in applications where vibration is present, e.g. in industrial environments with vibrating machinery, especially when replacement of batteries is not economical either because of difficult access or due to a large number of distributed sensor nodes [1]. An interface circuit between the generator and the load is extremely important since it converts the AC waveform into a DC voltage and increases the power drawn out of the generator in case of an active nonlinear interface [2].

Most harvesters in practically usable forms can provide an output power of 10-100 µW [3], setting a constraint on the average power that can be consumed by the interface circuit for self-powered operation. Using a CMOS process to design low-power electronics can fulfill this constraint. The ASIC shown in [4] consumes little power but needs an externally set reference voltage which makes the circuit impractical for wireless applications. Furthermore, the output power suffers from being dependent on the storage capacitor voltage which makes it difficult to ensure an optimal operating point.

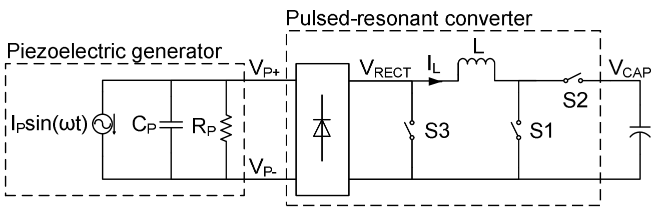
The energy harvesting setup shown in this paper works completely autonomous and offers a power extraction enhancement which is independent of the voltage on the storage capacitor.

THEORY OF OPERATION

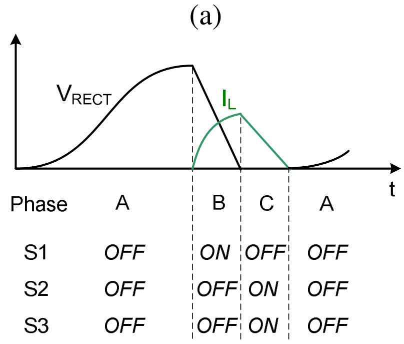
Pulsed-resonant converter

Consisting of an inductor and three switches, the pulsed-resonant converter (PRC) forms a nonlinear load for the piezoelectric generator (see Fig. 1 (a)). The operation principle of the PRC has been described in detail in [5]. The switching technique is mainly based on the principle presented by Xu et al. [6] which works as follows (see Fig. 1 (b)). During phase A, the piezoelectric generator is driven in open-circuit condition until the rectified generator voltage V_{RECT} reaches a maximum. Then, during the transfer process, the energy is first transferred into the inductor (phase B) and finally into the storage capacitor (phase C).

Since the energy of the generator is extracted in a very short time compared to the excitation period, the PRC ensures almost perfect decoupling of the load and the generator, which means that the transferred power is almost independent of the load. This holds true of course only for the ideal assumption of a lossless converter circuit.



(a)



(b)

Fig. 1: (a) Schematic of the energy harvesting system. (b) Timing diagram of the pulsed-resonant converter including switch positions.

Power extraction

Fig. 1 (a) shows one possible equivalent circuit of the piezoelectric generator that will be used throughout the paper for calculation and simulation. The AC current source represents the vibrating beam whereas the current amplitude I_P is proportional to the vibration amplitude. The internal impedance composed of the parallel connection of C_P and R_P is related to the generator losses. The generator parameters have been extracted from a custom-made bending generator with frequency tuning mechanism [7] such that the measured and simulated output power characteristics using a resistive load match. The extracted parameters are $I_P = 70\ \mu A$, $R_P = 360\ k\Omega$ and $C_P = 30nF$; these values are only valid for an excitation frequency $\omega = 2\pi * 114.4\ Hz$ which is the natural resonance frequency of the generator.

The power extraction efficiency (PEE) is an appropriate means to evaluate and to compare different interface circuits regarding their performance with a given piezoelectric generator. The PEE values of the PRC and of the diode bridge rectifier circuit are calculated as [8]

$$P_{MAX} = \frac{R_P I_P^2}{8} \qquad (1)$$

$$PEE_{RECT} = \frac{P_{RECT}}{P_{MAX}} = \frac{4}{\pi \omega \tau_P} \qquad (2)$$

$$PEE_{PRC} = \frac{P_{PRC}}{P_{MAX}} = \frac{4}{\pi} \frac{\omega \tau_P}{1 + (\omega \tau_P)^2} \left(1 + \exp\left(\frac{-\pi}{\omega \tau_P} \right) \right)^2 \qquad (3),$$

where $\tau_P = R_P C_P$ is the time constant of the piezoelectric impedance, P_{MAX} is the output power of a piezoelectric generator with complex conjugate load (i.e. the absolute maximum output power), and P_{RECT} and P_{PRC} are the maximum output power values using the diode rectifier and the PRC, respectively. Note that PEE_{RECT} and PEE_{PRC} are theoretical values neglecting the forward voltage drop of the rectifier diodes, any conduction losses within the PRC and the power consumption of the PRC.

IMPLEMENTATION OF THE PULSED-RESONANT CONVERTER

The block diagram of the PRC ASIC which has been fabricated in a 0.35 µm CMOS process is shown in Fig. 2. The rectifier, the gate signal generator and the switches are on-chip, whereas the coil, the storage capacitor and the generator have to be connected externally. The switches S1, S2 and S3 have been implemented as special purpose MOSFETs tolerating a maximum 7 V generator voltage. The peak detector initiates the transfer process when the rectified generator voltage V_{RECT} reaches a maximum. After the zero crossing detector has identified the end of the energy transfer from the generator into the coil, the energy is being transported into the storage capacitor. The comparator COMP_AD switches S2 off shortly before current backflow starts in order to avoid capacitor discharge. A more detailed description of the PRC can be found in [5].

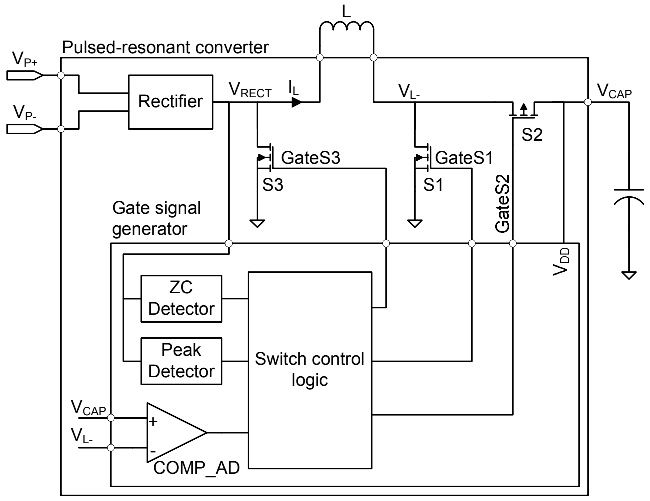


Fig. 2: Block diagram of the pulsed-resonant converter ASIC. The piezoelectric generator is not shown.

The gate signal generator is powered exclusively by the storage capacitor. Since the capacitor voltage V_{CAP} is varying dependent on the external load and the generator amplitude, a supply independent biasing has been implemented in order to ensure equal timing conditions over V_{CAP} ranging from 1.2 V to 3.6 V.

DEMONSTRATOR SETUP

The demonstrator consists of printed circuit board (PCB) which can be plugged onto the piezoelectric generator. The schematic diagram of the PCB is depicted in Fig. 3. Either the full bridge rectifier composed of BAS40 Schottky diodes with 250 mV forward voltage or the PRC can be connected manually to the load by a mechanical single pole double throw (SPDT) switch. A voltage detector with hysteresis (Microchip TC54VC210) monitors the voltage V_{CAP} on the 100 µF storage capacitor and feeds it through to the LED when a fixed threshold voltage of 2.16 V is exceeded. As a result, the LED illuminates until V_{CAP} falls below the lower voltage threshold

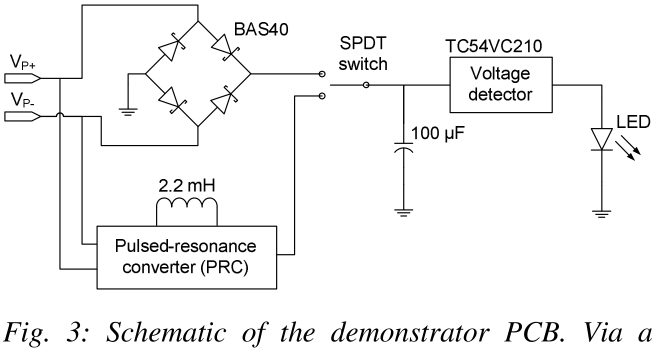
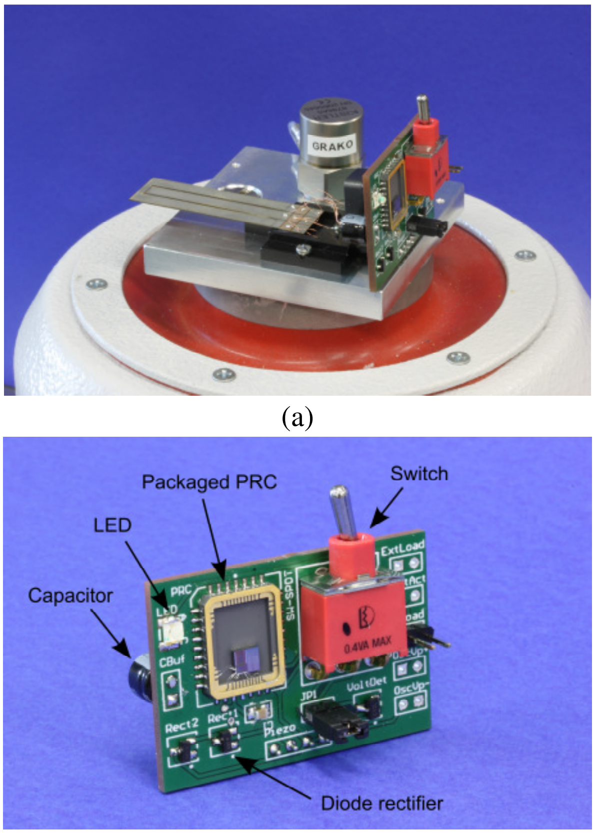


Fig. 3: Schematic of the demonstrator PCB. Via a switch, either the diode rectifier or the PRC can be used as an interface for the piezoelectric generator.



(a)

(b)

Fig. 4: (a) Demonstrator setup with shaker, piezoelectric bending generator and PCB. (b) Demonstrator PCB. The 100 µF-capacitor and the 2.2 mH-coil are placed on the back side.

which is about 2.08 V, decoupling the LED and recharging the storage capacitor. The blinking frequency is directly proportional to the extracted energy and thus an indicator for the power extraction efficiency of the interface circuit. Photographs of the demonstrator setup and of the demonstrator PCB are shown in Fig. 4 (a) and (b). The generator is attached to a shaker vibrating at a constant amplitude.

Since no internal startup functionality is implemented in the PRC, manual startup has to be performed by charging the storage capacitor passively via the diode rectifier and switching to the PRC when a voltage of about 1.2 V is reached.

MEASUREMENT RESULTS

The piezoelectric generator has been excited using a shaker with 5 m/s² and 114.4 Hz which is the natural resonance frequency of the generator. Under these conditions, the open-circuit voltage amplitude is 3.2 V. In pre-evaluations, the load characteristics of the diode rectifier and of the PRC using different coils have been determined (see Fig. 5).

The load curve of the diode rectifier shows a peak power of 29 µW at $V_{CAP} = 1.4$ V which is a little bit less than one half of the open-circuit generator voltage. As shown in Table 1, the measured and calculated power extraction efficiencies determined by equation (2) are 13.2 % and 16.4 %, respectively. The discrepancy is due to the fact that the diode losses are not considered in equation (2).

Table 1: Calculated and measured power extraction efficiencies and power gain between the rectifier and the pulsed-resonant converter (PRC).

	Calculation	Measurement
PEE_{RECT}	16.4 %	13.2 %
PEE_{PRC}	44.9 %	17.2 %
Power gain ($V_{CAP} = 1.4$ V)	2.7x	1.3x
Power gain ($V_{CAP} = 2.1$ V)	-	1.7x
Power gain ($V_{CAP} = 2.7$ V)	-	5x

The highest output power of the PRC is achieved using a Tyco 2.2 mH SMD coil with 5.4 Ω wire resistance. The output power is quite constant within $V_{CAP} = 1.5$ V … 2.5 V. For $V_{CAP} > 2.5$ V, the losses due to charging and discharging of the MOSFET gate capacitances become more dominant, hence the output power drops. Since a smaller coil inductivity means a higher current flowing during the transfer process and thus higher losses in the CMOS chip, the output power is lower with the 1 mH and 470 µH coils. Using these coils, the PRC chip stops operation for $V_{CAP} > 2.1$ V due to design problems. The rectified generator voltage V_{RECT} and the coil current I_L during the transfer process are shown in Fig. 6. Whereas the peak and the zero crossing of V_{RECT} is detected properly, switch S2 turns off before I_L vanishes. This means that V_{L-} (see Fig. 2) rises for one threshold voltage in order to keep the current flowing through PMOS transistor S2, wasting energy generator energy. This is one reason for the discrepancy of the measured and calculated power extraction efficiencies 17.2 % and 44.9 %, respectively, as determined by equation (3) (see also Table 1). Other factors justifying the discrepancy are conduction losses and the power consumption of the PRC which are not considered in equation (3).

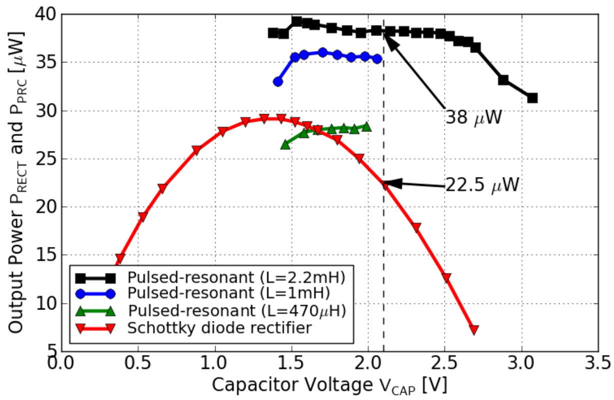


Fig. 5: Measured output power using a Schottky diode bridge rectifier and the pulsed-resonance converter with different coils. The dashed line denotes the operating point using the demonstrator board.

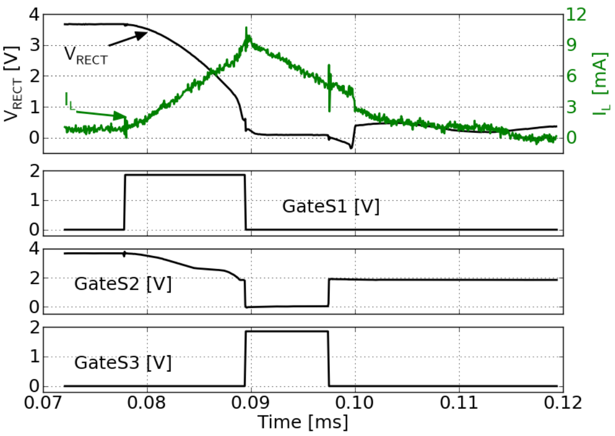


Fig. 6: Measured rectified generator voltage V_{RECT} and coil current I_L (top) and gate signals (bottom) of the switches during a transfer process.

The power gain of the PRC compared to the diode rectifier at different capacitor voltages is now being discussed (see Table 1 and Fig. 5). At $V_{CAP} = 1.4$ V which denotes the maximum power extraction using the diode rectifier, the power gain is 1.3x. At $V_{CAP} = 2.1$ V which is the regulated voltage using the demonstrator board, the power gain is 1.7x. The permanent charging and discharging of the storage capacitor generates a saw tooth waveform with a frequency directly linked to the power being extracted from the generator. The frequency using the pulsed-resonant converter is about 1.7x higher than the frequency using the Schottky diode rectifier which corresponds to the power gain denoted by the dashed line in Fig. 5. Since the output power using the diode rectifier diminishes for higher capacitor voltages whereas the output power using the PRC remains quasi-constant, the power gain increases dramatically; e.g. at at $V_{CAP} = 2.7$ V, the power gain is 5x.

CONCLUSIONS

A completely autonomous energy harvesting setup composed of piezoelectric generator, interface circuit and load has been presented. With a blinking LED load regulating the voltage of the storage capacitor to 2.1 V, the power extracted out of the generator could

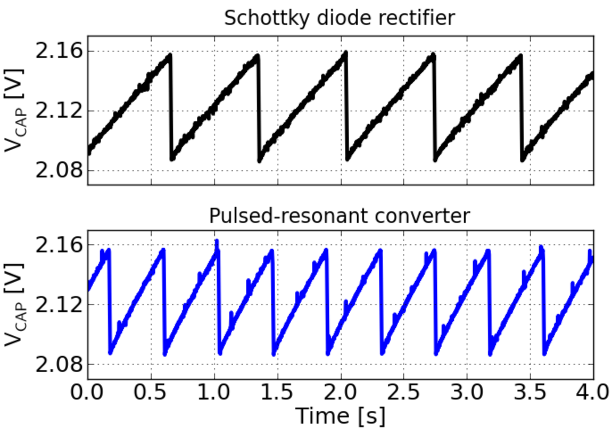


Fig. 7: Capacitor charging and discharging cycles using diode rectifier (top) and pulsed-resonance converter (bottom). The higher the frequency, the more efficient the conversion.

be increased by 1.7x using the pulsed-resonant converter instead of a Schottky diode rectifier. This power gain is directly visualized by the blinking frequency of the LED. For higher storage capacitor voltages, the power gain is even higher and reaches 5x and more due to the fact that the output power using the pulsed-resonant converter is quasi-independent of the load. Timing problems in the current design affecting one switch to turn off too early cause unnecessary energy loss. Future work will comprise eliminating this problem in order to enhance overall efficiency and thus to extract more output power. Due to the fact that no external power supply is needed, the presented system could be used in real wireless applications.

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