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Actively controlled synchronized-switch harvesting on inductor for piezoelectric transducers

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Abstract. Vibrational energy harvesting by means of piezoelectric transducers has been of particular interest in recent years for powering autonomous, wireless devices. In this context, a non-linear treatment of piezoelectric voltage greatly enhances electromechanical conversion. This paper presents an ultra-low power circuit implementation of the technique called Synchronized Switch Harvesting on Inductor (SSHI). The circuit detects the zero-current condition through the rectifier with a series shunt resistor and a nano-power comparator. Simulations show that the maximum power extracted is approximately 6.7 times greater than with a passive rectifier. The estimated overall consumption of the circuit components is 4 μA. The measured voltage flip efficiency is between 91% and 94%.

Keywords: Piezoelectric Transducers, Energy Harvesting, SSHI, Micropower, Power conversion.

1 Introduction

Energy harvesting is the process by which energy present in the environment is extracted, stored and converted into directly usable electricity. It is necessary to resort to energy harvesting whenever it is not possible to use a battery, e.g. in harsh environmental conditions or due to difficulties in recharging. Another large-scale objective of energy harvesting is to reduce the number of produced batteries, avoiding their environmental impact. In the world of energy harvesting, the problem is that energy sources are intermittent and characterized by low power densities. This creates difficulties in the power conversion optimization process. This is truer for energy harvesting from vibrations. Many transducers used to derive energy from vibrations exploit piezoelectricity, which is a property of some materials that develop a charge partition on their surface when subject to a mechanical stimulus. Conversely, they exhibit a mechanical deformation when a voltage is applied to their terminals. Piezoelectric transducers (PTs) consist of beams, membranes or cantilevers made of piezoelectric materials with metal electrodes. The PT develops an electrical charge proportional to the mechanical deformation applied to it. A mechanically generated electric current charges the capacitance between the electrodes of the PT. Therefore, in a first approximation, the PT can be modeled as a current source with a mainly capacitive impedance in parallel.

The simplest solution to extract energy from PTs is called Standard Interface or Standard Energy Harvester (SEH) and consists in a rectifier connected to the PT, with a storage capacitor and a load connected in parallel to its output. The current flows towards the load only when the voltage of the PT (in module) becomes greater than the rectified voltage. Then, the rectifier is not conducting for a part of the time, although there are still charge displacements following the vibrations of the PT. After the rectifier stops conducting, a voltage inversion driven by vibrations starts, which involves the dissipation of energy that is not transferred to the load. Another disadvantage of a passive rectifier is that the maximum power is extracted from the PT only for a specific load value, which cannot be clearly identified with irregular vibrations and highly variable loads, as is the case in many energy harvesting applications.

An alternative and more efficient solution involves the use of switching power converters triggered in a synchronous way with input vibrations. These non-linear solutions also require dedicated control circuitry that consumes additional power. However, the additional harvested power is typically higher, even in presence of weak and irregular vibrations. This paper elaborates on the specific and well-known technique called Synchronized-Switch Harvesting on Inductor (SSHI), introduced by *Taylor et al.* in [1] and described by *Lefeuvre et al.* in [2]. SSHI solves the drawbacks of the SEH by adding, in parallel to the PT, a switch and an inductor in order to create an RLC resonant circuit operated synchronously with vibrations (Fig. 1a). The switch is closed each time the rectifier stops conducting and must be reopened exactly after a half-period of the RLC circuit in order to fully flip the PT voltage. This brings the PT voltage at the opposite conduction threshold of the rectifier. Since the PT current is crossing zero and changing sign, the rectifier immediately restarts conducting. In this way, the rectifier always conducts. At the same time, it is worth to note that control circuits draw power and losses in the RLC circuit may lead to a partial voltage inversion. Therefore, a tradeoff between voltage flip efficiency, delays and consumption must be pursued.

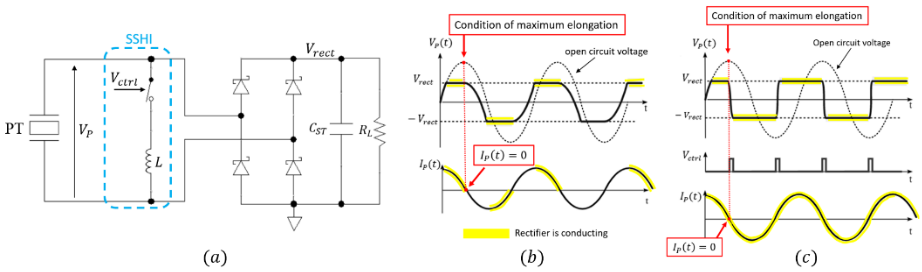

Fig. 1. Energy harvesting interfaces. $I_P(t)$ is the piezoelectric current induced by vibrations. (a) SSHI interface; (b) waveforms when SSHI is disabled, i.e. SEH; (c) waveforms when SSHI is enabled, ideal case with 100% voltage flip efficiency.

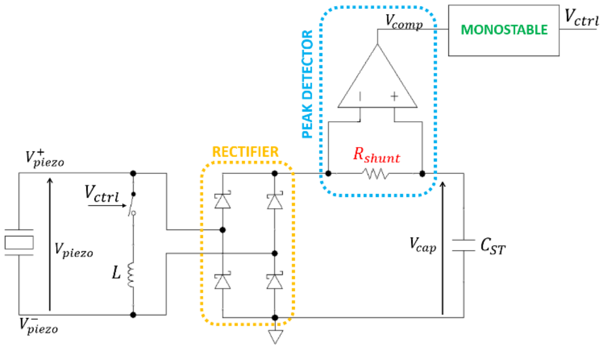

Fig. 2. Implementation of the proposed solution.

2 The proposed solution

The goal of the work was to implement an alternative and complete circuit implementation of a power converter based on SSHI that maximizes the voltage flip efficiency and still achieves an ultra-low power consumption. Fig. 2 shows the proposed solution. The switching condition is detected by means of a shunt resistor in series between rectifier and storage element. In this way, the difference between the rectified voltage and the voltage across the storage capacitor becomes zero when the current on the shunt resistor is zero. Detecting the zero-crossing of the current on the shunt resistor corresponds to detecting the switching off the rectifier. In this implementation, a nano-power comparator senses the voltage across the resistor. The signal at the output of the comparator is then processed by a subsequent tunable monostable that provides the correct timing for controlling the switch.

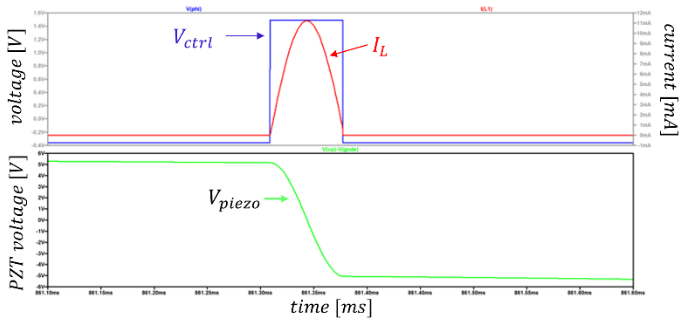

Fig. 3. Detail of one inversion of the voltage across the PT when the SSHI is enabled.

2.1 Simulation results

Simulation analysis was performed to ensure that the circuit operates correctly. Circuit simulations with available models of components highlight that the voltage inversion occurs correctly and exactly when the PT current is crossing zero. In correspondence with each inversion, the inductor is able to fully charge and discharge itself (Fig. 3). In this way, it allows a complete voltage flipping.

The graphs in Fig. 4 show the extracted average power as a function of the load voltage and as a function of the load resistance. The graphs compare the trend in the case of the rectifier alone (SEH) with the trend obtained with the proposed solution based on SSHI. The maximum power extracted with the proposed solution is approximately 6.7 times greater than with the SEH.

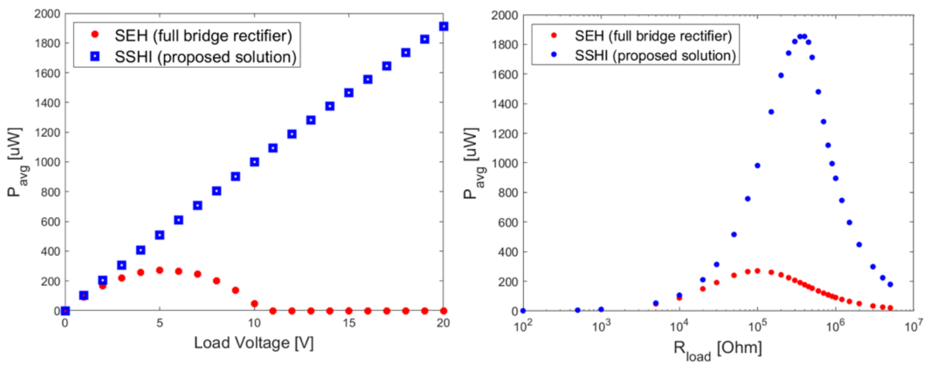

Fig. 4. Simulation results. Operating conditions: V_{P0} = 10V, f_0 = 53Hz, C_P = 48.6nF, L = 4.7mH, C_{ST} = 10µF, R_{shunt} = 3kΩ, real model for diodes and comparator, ideal model for the monostable.

2.2 Experimental results

The circuit was implemented with off-the shelf components that were chosen to guarantee adequate performance and low power consumption. While solutions reported in literature [3][4] typically achieve a maximum voltage inversion efficiency between 80% and 90%, the proposed circuit achieves about 91-94% (Fig. 5). Lower voltage flip efficiencies imply longer times with no conduction through the rectifier until the PT voltage reaches the conduction threshold again. The increase in the extracted power compared to the use of the SEH is evident (Fig. 6). As the voltages approaches the maximum operating voltages of components, some performance degradation is observed. However, power is still higher than with the SEH.

Fig. 5. Oscilloscope waveforms obtained with the proposed solution and detail of the voltage across the PT. The transducers used are the PPA (Piezo Protection Advantage) type, made by Midé Technology. Vibrations are applied with an electrodynamic shaker.

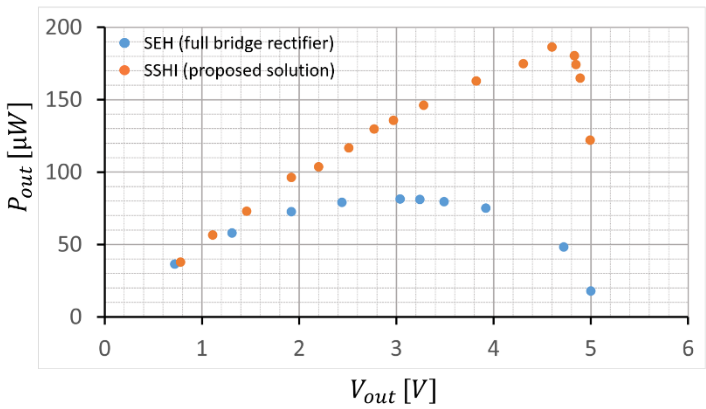

Fig. 6. Experimental characterization of the extracted power.

Conclusions

Even if exhaustive energy assessments require further progress, the estimated consumption of the circuit is approximately equal to 4μA of which 210nA is the typical static consumption of the peak detector, about 50nA of the switch and 3μA is the maximum consumption of the monostable. The low intrinsic consumption of the implementation and the significantly higher extracted power make it a viable and suitable solution for supplying, with vibrations characterized by low amplitudes, low-power electronic systems, such as personal healthcare devices or sensing nodes.

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