ANALYSIS OF ENERGY HARVESTING ENHANCEMENT SCHEMES FOR FREQUENCY-UP CONVERSION

D. A. Sanchez[1*], T. Hehn[1], A. Frey[2], and Y. Manoli[1, 3]
[1]Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineering – IMTEK, University of Freiburg, Germany
[2]Faculty of Electrical Engineering, Augsburg University of Applied Sciences, Germany
[3]HSG-IMIT – Institute of Micromachining and Information Technology, Villingen-Schwenningen, Germany

Abstract: This paper presents an analysis, comparison and proof of concept of three different piezoelectric energy harvesting enhancement schemes in combination with Frequency-Up Conversion for the case of single impulse excitation. The analyzed schemes are the Parallel and Series Synchronized Switch Harvesting on Inductor (SSHI) and the Synchronous Electric Charge Extraction (SECE). Comparisons are made in terms of the characteristics of the schemes, the harvested energy during one excitation cycle and its dependency on the output voltage. The SSHI schemes are implemented on discrete level while chip level simulation results are used for the SECE.

Keywords: Energy Harvesting, Piezoelectric Generator, Power Extraction

INTRODUCTION

Due to the quickly developing trend of wireless devices, efforts to find new technologies for powering these systems have increased. Piezoelectric Generators (PGs) based on cantilever beams have been widely presented as structures for energy extraction from vibrations. The output of PGs is an AC voltage but the majority of wireless devices require a DC voltage source. Full bridge diode rectifiers and voltage doublers are commonly used as standard interface circuits for AC to DC conversion, but they drastically limit the power extractable from the generator [1].

Different interface schemes have been investigated in order to determine which one enables maximum energy extraction and under which conditions. Usually, a continuous excitation force at a frequency near the PG resonance is considered. This is often not the case for ambient vibrations which occur at different amplitudes and frequencies. Frequency-Up conversion using a cantilever beam overcomes this by allowing the extraction of energy from low mechanical frequencies by conversion to a higher resonant frequency mode [2].

To evaluate the performance of the interface schemes, a single excitation with a step form is used, generating a piezoelectric voltage (V_P) of a magnitude that decays as the oscillation is damped (Fig. 1).

The interfaces analyzed in this work are the Parallel-SSHI, Series-SSHI and SECE and have been proven to harvest more than 4 times the amount of energy compared to the standard interface circuits for continuous excitation mode [1, 3, 4].

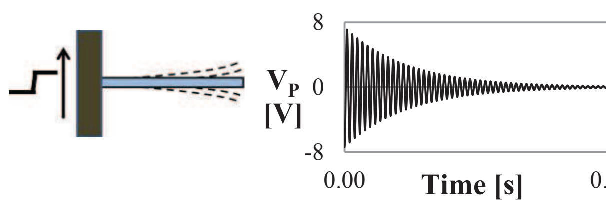

Fig. 1: Sketch of the piezoelectric generator and the voltage at its terminals.

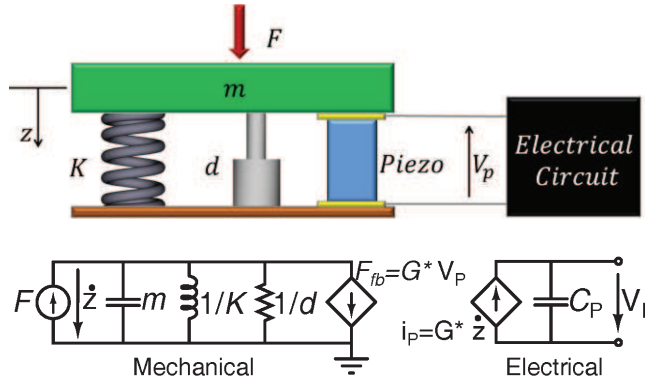

Fig. 2: Model of a piezoelectric generator.

PIEZOELECTRIC GENERATOR MODEL

PGs based on cantilever beams are typically modeled as an electromechanically coupled mass-spring system (Fig. 2). In order to work in an electrical simulation the mechanical parameters are modeled in the electrical domain.

The force F applied to the tip of the cantilever is represented by a current source, the effective mass of the cantilever m by a capacitor. The inverse of the stiffness K and the mechanical damping d are represented by an inductor and a resistor respectively. The coupling is done with current sources dependent on the velocity $\dot{z}$ for the electrical and the generator voltage V_P for the mechanical side, and a coupling factor G. The PG has a piezoelectric inherent capacitance C_P in parallel to the output terminals (Fig. 2).

PARALLEL - SSHI

In the parallel-SSHI scheme a switch and an inductor L are connected in parallel to the PG and the rectification stage (Fig. 3). The AC-DC conversion is done with a full-bridge diode rectifier. The switch is closed when i_P crosses zero, creating a C-L circuit between C_P and L. The resonance causes the polarity of C_P to be reversed and after half a period the switch is open again. Therefore the power of the PG is not wasted charging and discharging C_P, allowing i_P to flow directly to C_{out}.

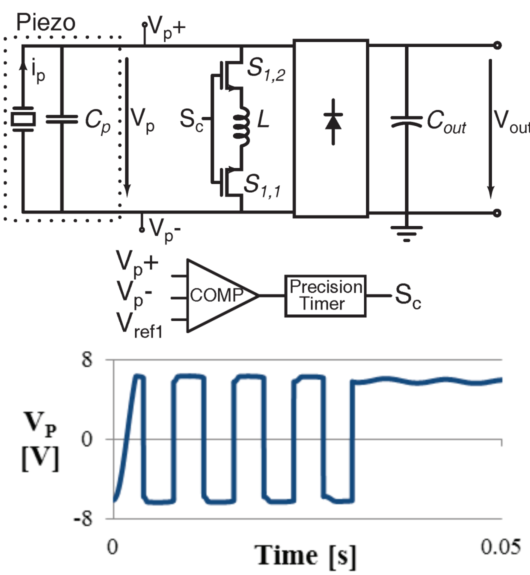

Fig. 3: Parallel-SSHI schematic and waveform.

To transfer energy to C_{out}, V_P has to reach a level higher than the output voltage plus the forward voltage of two diodes (V_{out}+2V_d). C_{out} is considered to be large so that V_{out} is nearly constant. The total energy harvested can be calculated using Eq. 1. Since the output current i_{out} is independent of V_{out}, a higher output voltage allows the scheme to harvest more energy, as long as it does not exceed V_P.

$$E_{hrv} = \int_0^t v_{out}(t) i_{out}(t) dt \approx V_{out} \int_0^t i_P(t) dt \quad (1)$$

The magnitude of the open circuit piezoelectric voltage decreases as the system is damped. Since V_{out} is nearly constant, there is a specific efficient output voltage $V_{out,eff}$, at which the scheme extracts the most energy during an excitation cycle. Determining $V_{out,eff}$ is challenging. However a good approximation is presented it Eq. 2, where $V_{P,oc}$ is the peak value of the first half wave cycle of V_P in open circuit.

$$V_{out,eff} \approx \frac{3}{4}\left(V_{P,oc} - 2V_d\right) \quad (2)$$

The parasitic losses of the inductor and the switch cause the flipping of V_P to be non-ideal, not reaching the required voltage for energy transfer. Therefore i_P has to charge C_P until V_P reaches the required level, lowering the amount of energy extracted.

The switch is implemented with two n-MOSFETS. Each bulk contact is connected to a terminal of the inductor, cancelling the effect of the bulk diode.

SERIES – SSHI

The series-SSHI functions similar to the parallel-SSHI but the inductor and the switch are placed in series with the PG. In this case the PG works in open circuit most of the time (Fig. 4).

When C_P is charged and i_P is equal to zero the switches are closed forming a C-L-C loop, thus transferring the charge stored in C_P to C_{out}. Due to the properties of a C-L-C circuit, some charge is fed back to C_P but in the opposite polarity, creating an offset voltage from which the next cycle starts to charge. This allows the system to reach high voltage levels (even higher than $V_{P,oc}$) leading to a higher energy transfer per cycle.

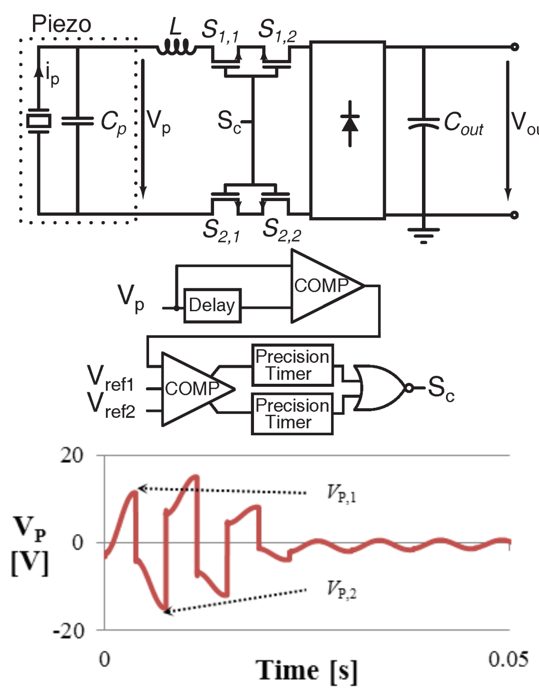

Fig. 4: Series-SSHI schematic and waveform.

The energy harvested can be calculated using Eq. 3, where $V_{P,n}$ is the piezoelectric voltage at the instant n when the switch is closed (Fig. 4). Similar to the case of the parallel-SSHI, it is challenging to determine $V_{out,eff}$, but an approximation is provided in Eq. 4.

$$E_{hrv} \approx \sum_{n=1}^{i} 2V_{out}\left(\left|V_{P,n}\right| - V_{out} - 2V_d\right)\sqrt{\frac{C_p}{L}} \quad (3)$$

$$V_{out,eff} \approx \frac{3}{8}\left(V_{p,oc} - 2V_d\right) \quad (4)$$

In order to properly isolate the system, a switch is utilized in each terminal of the PG. The switches are implemented in the same form as the parallel-SSHI. The non-ideal resistances of the switches and the inductor lie inside the energy path, limiting the capabilities of extraction.

SECE

In the SECE scheme an inductor and three switches are placed after the rectifying block (Fig. 5). The generator works in open circuit most of the time. After C_P is fully charged and i_P crosses zero, S_1 is closed and all the electrostatic energy stored in C_P is transferred to magnetostatic in L. When all the charge is transferred, S_1 is opened and S_2 and S_3 are closed simultaneously, to transfer the energy from L to C_{out}.

An important characteristic of this scheme is the decoupling of the energy transfer path by storing the energy temporarily in L, allowing the energy to be transferred independently of the output voltage.

$$E_{hrv} = \sum_{n=1}^{i}\left(\frac{1}{2}V_{p,n}^2 - 2V_d^2\right)C_p \quad (5)$$

S_1 and S_2 are implemented with n-MOSFETs while S_3 is implemented like the switches in the previous schemes to avoid the bulk diode effect. The parasitic resistance in the energy transfer path, due to the inductor and the switches non-idealities, decreases the efficiency of the scheme.

IMPLEMENTATION

In order to make a comparison between the different schemes, these have been implemented using discrete devices. The PG used is the 21B manufactured by MIDE. The extracted parameters are $m=2.58$g, $K=1672.73$N/m, $d=0.55$Kg/s, $G=0.00136$ and $C_P=37.2n$F, excited by a force of 0.248N.The discrete components used in the control circuits and main schematics are listed in Table 1. All the voltage references (V_{ref}) and supply voltages for the control circuits are provided externally. Since in discrete level the power consumption of the control circuits exceeds the harvested power by far, it is not relevant for the comparison of the schemes.

All the schemes are simulated using Orcad PSpice 16.3. The SSHI schemes are also implemented in a PCB, while for the SECE, a simulation an integrated circuit [4] is used for comparisons.

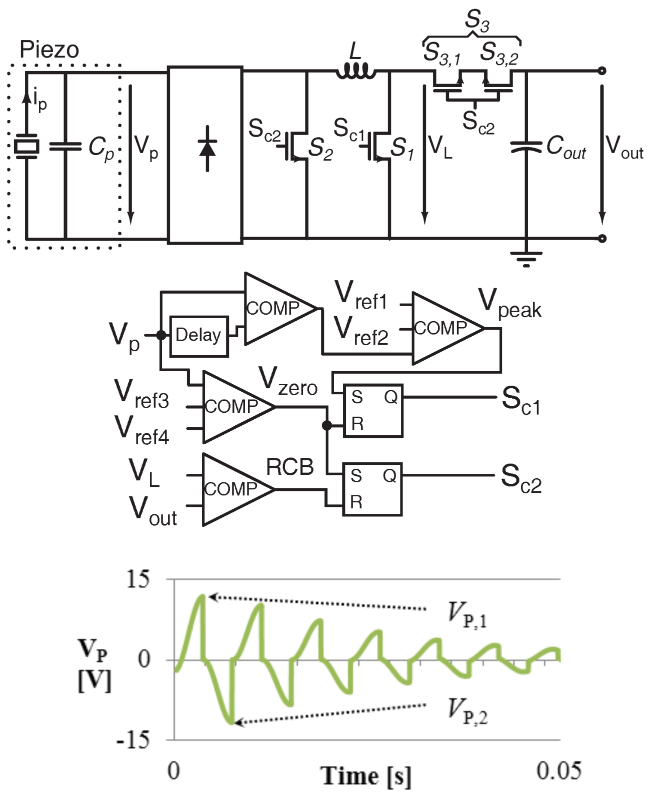

Fig. 5: SECE schematic and waveform.

Table 1: Components used in the implementation.

Part	Description
BS170	n-MOSFET
BS250	p-MOSFET
BAT85	Schottky Diode
KEMET ESC	470µF Cap.
Bourns 2124-RC	1mH Inductor
OPA4131	OPAMP

SCHEMES COMPARISON

Schematic and Control Circuit

The simplest comparison that can be made between the different schemes is the schematic of the main block circuit. The advantage of the parallel-SSHI is that only the rectifier diodes are in the current path to C_{out}. In the other two schemes the current has to flow through the inductor and switches, making the efficiency directly dependent on the non-idealities of these elements.

An important factor in this regard is the proper sizing of the inductor. The smaller the inductance, the faster the energy transfer process, however the higher the peaks of current generated. This comes into consideration by realizing that the higher the current, the higher the resistance that the MOSFET presents when the switch is in on state.

The block diagrams of the proposed control circuits are presented in Fig. 3-5. The control circuit of the parallel-SSHI scheme is the one with the lowest complexity, while the one for the SECE is the most complex one.

Energy Harvest

A simulation was made to compare the schemes developed on discrete level, in addition to the measurement of the SSHI prototypes and the integrated circuit simulation of the SECE. To enable maximum energy extraction V_{out} was set to *6*V and *2.5*V, according to calculations using Eq. 2 and Eq. 4, for the parallel-SSHI and series-SSHI schemes respectively, and *2.5*V for the SECE.

According to the results depicted in Fig. 6 the SSHI techniques have a better performance in simulations. The parallel-SSHI is the most efficient in the case of the measurements.

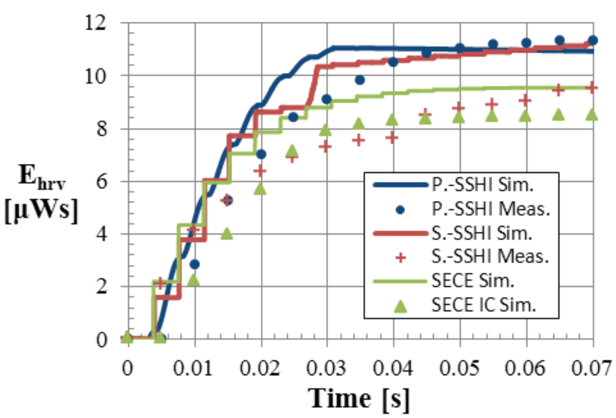

Fig. 6: Simulated and measured energy harvested by the different schemes during a single excitation cycle.

Efficient Output Voltage

Another important characteristic of the different schemes is their ability to harvest energy at different output levels. Fig. 7 shows the simulation and measurement results for the schemes, with the SECE being able to harvest the same amount of energy over a wide voltage range. Nevertheless the SSHI schemes extract more energy than the SECE over a relatively broad range of voltages.

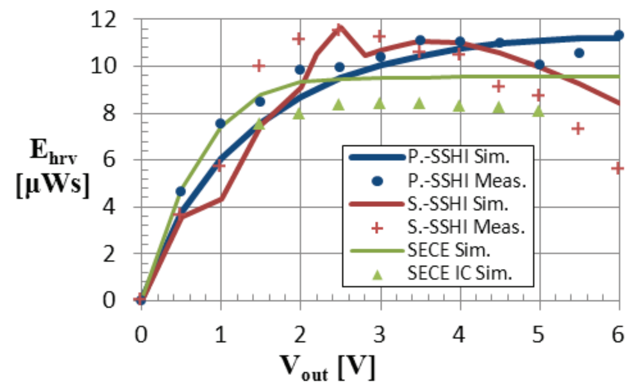

Fig. 7: Energy harvested by the different schemes at different output levels.

CONCLUSION

We implemented, compared and identified the characteristics of three different energy harvesting enhancement techniques for PGs under single excitation.

The parallel-SSHI requires the least complexity for the control circuit compared to the other two schemes. The component non-idealities have the lowest effect on the efficiency of extraction.

The series-SSHI has the capability to scale up the voltage generated by the PG. It is highly efficient but only at a specific output voltage value.

Finally the SECE is out-performed by the other two schemes in terms of extraction efficiency, but it has the capability of extracting the same amount of energy over a wide range of output voltages.

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