HIGH EFFICIENCY PIEZOELECTRIC ENERGY HARVESTER WITH SELF TRIGGERED DIRECT SSHI INTERFACE

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Abstract: This paper presents a new piezoelectric energy harvesting device for optimizing the power transfer from the energy harvester to a storage element. The so called DIRECT SSHI device consists of 2 piezoelectric generator structures realized on one substrate, in combination with a SSHI interface circuitry and a control unit. The first piezoelectric structure acts as main generator. The second piezoelectric structure acts as trigger generator that provides the exact trigger points for the SSHI circuitry. Both structures are realized on the same one sided swinging bimorph and are therefore exposed to the same mechanical excitation. The results of parameter studies for an optimal generator design as well as simulation and first measuring results obtained with a generator testing device are presented and discussed in this paper.

Keywords: energy harvesting, piezoelectric, SSHI, vibration, power transfer optimization

INTRODUCTION

As energy autonomous systems become more ubiquitous, the need of a continuous energy supply to realise periodic operation sequences becomes more important. Unfortunately the power delivered by energy harvesting devices is commonly non-continuous, fluctuant and unstable in their voltage amplitude. Therefore, an energy buffer is needed which compensates the energy requirement between the actual generator output and the energy consumption of the application [1]. Caused by a mismatch between the energy buffer and the energy harvester, a more or less part of the energy delivered by the generator remains unused. In order to harvest continuously the maximum possible energy, a permanent load adaptation of the generator as well as an efficient rectification, voltage conversion and energy storage is required [2]. To maximise the available energy, it is important to optimize the mechanical properties of the harvester as well as the energy transfer from the harvester to the storage element. A big amount of the produced energy gets lost on its way from the harvester to the storage cell. One method to overcome this situation is described by Guyomar et al. [3]. The SSHI technology can be used to maximize the energy yield.

For the SSHI technology an additional interface circuit with a control unit is connected to the standard energy harvesting device. A diagram of the complete energy harvesting device, consisting of a mechanical generator, a SSHI interface, a control unit, a voltage rectifier and energy storage is shown in Fig. 1. The basic concept of the SSHI technology [4] is to switch-on momentary a coil in parallel to the piezoelectric generator as shown in the simplified model of a SSHI circuit in Fig. 2.

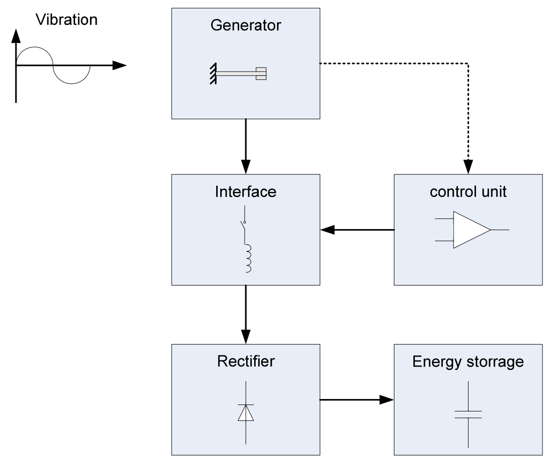

Fig. 1: Energy harvesting device with additional SSHI-Interface and control unit

This results in an amplification of the voltage as well as a maximization of the power transfer from the energy harvester to the energy storage.

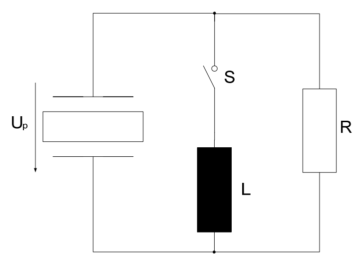

Fig. 2: Simplified model of a SSHI circuit, consisting of piezoelectric harvester, switch, inductor and load resistor

In practice it is rather difficult to realize the SSHI algorithm with the needed accuracy. Especially under varying excitation conditions an unknown phase deviation takes place in the system which cannot be eliminated in a reproducible manner. Unfortunately, the phase drift is a highly sensitive influencing parameter [5]. This problem can be solved by using a sensor which monitors the mechanical movement of the piezoelectric bimorph. Fig. 3 shows the correlation between the output voltages of a sided clamped swinging piezoelectric bimorph and its mechanical displacement.

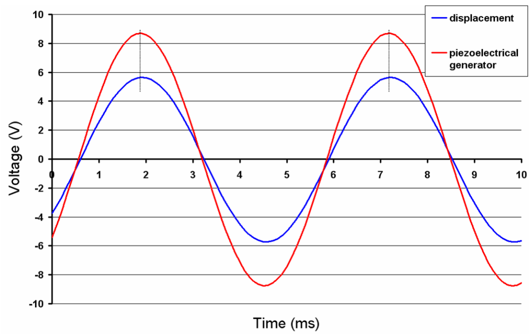

Fig. 3: Measurement of the correlation between output voltage and mechanical displacement of a piezoelectric generator

The knowledge of the movement can be used to determine the exact trigger points for the SSHI circuitry. But the use of a sensor may cause a bad energy balance of the entire system.

GENERATOR DESIGN

To solve this problem the direct SSHI technology had been developed. Two electrode structures had been realized on one piezoelectric bimorph. The bigger electrode structure acts as the main generator that provides the energy. The second electrode structure can be designed much smaller than the first structure, because it remains totally unloaded and doesn't consume any energy. The so called trigger generator provides the SSHI/SSHC-algorithm with all necessary information.

A first prototype of a piezoelectric bimorph with two electrode structures is shown in Fig. 4. The both electrodes for the main and the trigger generator had been separated by a chemical etch process.

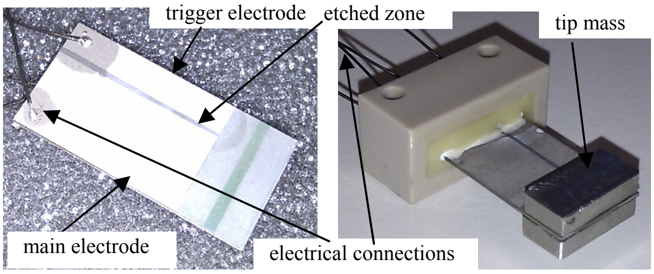

Fig. 4: piezoelectric bimorph with 2 different electrode structures

For calculation of resonance frequency and output voltages of the piezoelectric generator a finite element model has been developed. The resulting displacements and voltages were calculated by harmonic analyses in ANSYS WB 12. The model is shown in fig. 5.

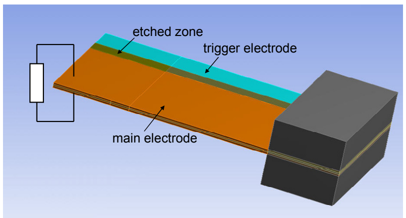

Fig. 5: FEM-Model of the piezoelectric generator

The both electrode structures remain unloaded. The structure is being deflected by a sinusoidal displacement of 0,25µm. The mechanical damping is 0,012. Fig. 6a shows the frequency responses of the output voltages of the main and the trigger generator. The corresponding measurement results are shown in fig. 6.b.

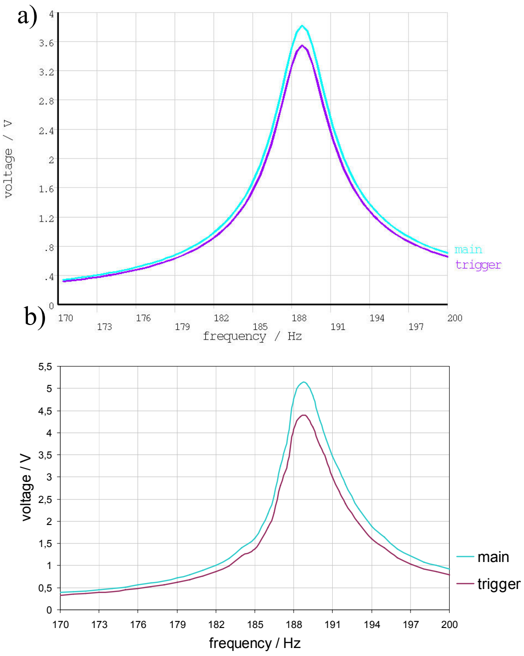

Fig. 6: FEM simulation results (a) and measurement results (b) of the piezoelectric output voltages.

The resonance frequency of the bimorph is 187 Hz. The measurements fit very well with the simulation results.

ELECTRICAL CHARACTERIZATION AND SIMULATION

An equivalent circuit was developed to simulate the electrical behavior of the mechanical generator. With this equivalent circuit it is possible to simulate the SSHI circuitry (fig. 7) under realistic conditions.

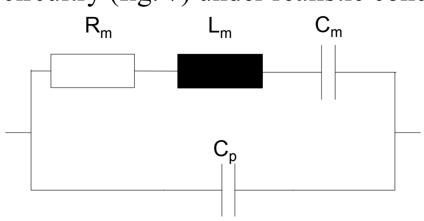

Fig. 7: electrical equivalent circuit of the energy harvester

The admittance of the equivalent circuit can be calculated as:

$$Y = \frac{1-\omega \cdot C_p \cdot \left(\omega \cdot L - \frac{1}{\omega \cdot C_m}\right) + j \cdot \omega \cdot C_p \cdot R}{R + j \cdot \left(\omega \cdot L - \frac{1}{\omega \cdot C_m}\right)} \qquad (1)$$

A gain phase analysis of the generator had been made to determine the parameters for the components of the equivalent circuit. Fig. 8 shows the results of a frequency sweep.

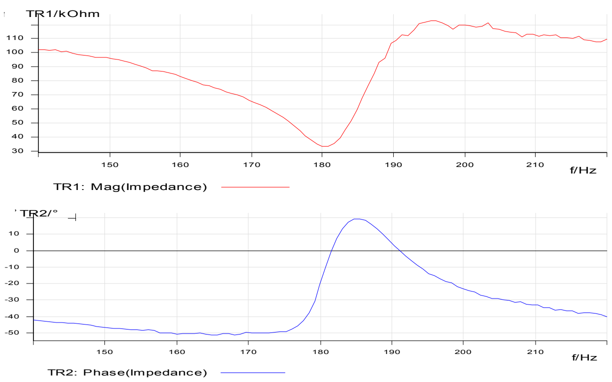

Fig. 8: gain phase measurement of the piezoelectric generator (main electrode)

By measuring the impedance characteristics of the piezoelectric bimorph, it is possible to calculate the values of the passive components. The frequency and the acceleration of the vibration source define the parameters of the AC voltage source. The measurement results set the parameters of the equivalent circuit components to:

component:	value:
C_p	5,8nF
C_m	813pF
L_m	994,4H
R_m	21kΩ

Table 1: Parameters of the equivalent circuit

The values of the components had been used to simulate the SSHI circuitry in interaction with the mechanical energy harvester. The parameters for the simulation were:

parameter:	value:
vibration frequency	160Hz
vibration amplitude	0,06g
switching inductor	100µH
switching pulse width	2,39µs

Table 2: Simulation parameters

The results of the simulation are outlined in fig. 9.

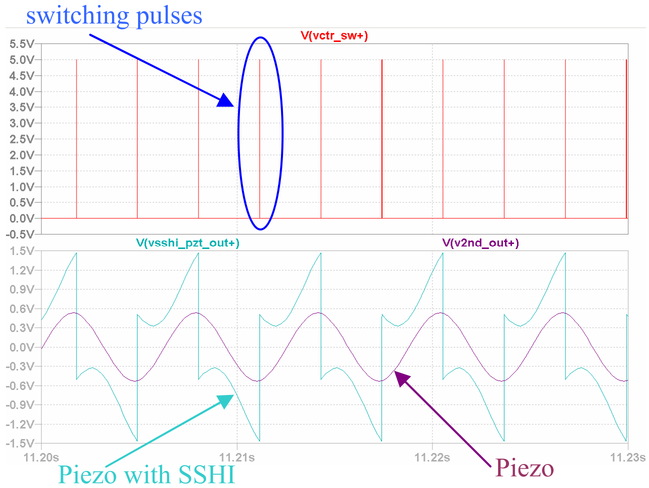

Fig. 9: Simulation results of the output voltages of the piezoelectric energy harvester with and without additional SSHI interface

The simulation results show the output voltages of the SSHI circuitry in combination with the equivalent circuit model of the energy harvester and the output voltages of the energy harvester without any adaptive circuitry. The SSHI circuitry increases the output voltage by factor 3.

EXPERIMENTAL

For experimental characterization the generator was attached to a lab shaker. The applied vibration frequency was tuned to 160Hz, the vibration amplitude to 0.06g. Fig. 10 shows the results of the voltage measurement of the two electrode structures. The output voltages of the both generators are in phase. Therefore the trigger generator can be used to determine the exact trigger points for the switching sequence of the SSHI circuitry.

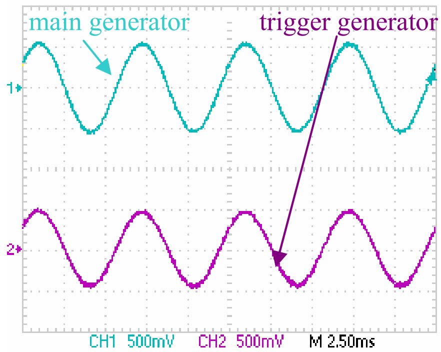

Fig. 10: Voltage output of the trigger and the main generator (mechanical excitation with a vibration amplitude of 0,06g)

The trigger generator was connected to a high impedance peek detector. Therefore it remains almost unloaded. The output of the peek detector was used to set the trigger points for the SSHI circuitry. The direct SSHI circuitry was connected to the main generator. The results of measurement are outlined in fig. 11.

The output voltages of the main generator are increased by factor 3.

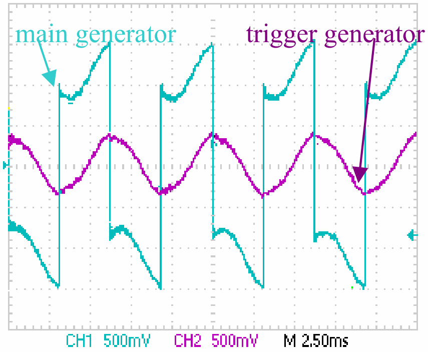

Fig. 11: Voltage output of the trigger and the main generator with additional SSHI interface. (mechanical excitation with a vibration amplitude of 0,06g)

A detailed view of the switching process is outlined in fig. 12. Some losses appear during the switching process caused by the not optimal shape of the trigger pulse and the natural frequency of the coil.

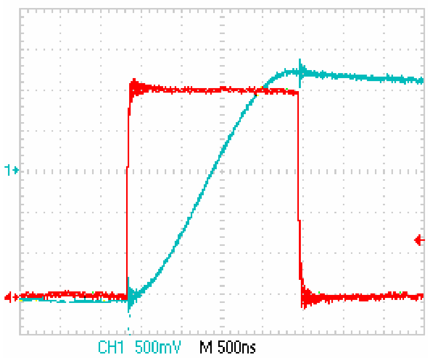

Fig. 12: Detailed view of the SSHI switching process

These losses may be reduced by the use of a smaller inductor with higher quality factor and therefore a faster switching process.

The ensemble was used to charge a 10µF capacitor. Therefore the applied vibration frequency was tuned to 160Hz. The vibration amplitude was 0.1g. The charging process is outlined in fig. 13.

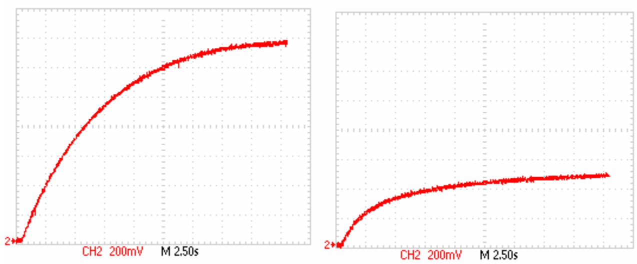

Fig. 13: charging a 10µF capacitor with (a) the piezoelectric generator with SSHI circuitry (b) the piezoelectric generator without SSHI circuitry

The piezoelectric generator was connected to a rectifier and the 10µF capacitor. After 22,5s the energy stored in the capacitor was 1,25µJ. With additional SSHI circuitry the energy stored in the capacitor after 22,5s was 9,8µJ. However the energy consumption of the triggering circuitry was not considered in these measurements.

CONCLUSION AND FUTURE WORK

A new energy harvesting device, called direct SSHI, consisting of a one sided clamped swinging piezoelectric bimorph, a SSHI interface and a control unit was presented. To optimize the power transfer from vibration driven energy harvesters to a storage element a first prototype for experimental characterization was shown. The necessary information to determine the optimal trigger signals, needed for the SSHI interface, were provided by the piezoelectric bimorph itself. Therefore two different electrode structures were realized on the generator substrate. The bigger structure was used as main generator that provides the energy. The smaller structure was used as trigger generator. Simulation results for an optimal generator design as well as first measuring results were presented in this paper. Ongoing tasks consider the optimization of the switching process, to reduce the energy losses. The next step will be to integrate the hybrid generator into the SSHI-System and to determine the profit in efficiency obtained with the complete energy harvesting module.

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