# PIEZOELECTRIC ENERGY HARVESTER WITH CONSTANT STRESS DISTRIBUTION AND DIRECT INITIAL ENERGY INJECTION INTERFACE CIRCUITRY

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**Abstract:** The presented device consists of a vibration driven piezoelectric energy harvester in combination with a synchronized switching interface circuitry to maximize the amount of harvested energy. The piezoelectric energy harvester has been designed to guarantee a constant stress distribution on the whole generator structure. The interface circuitry is based on the initial energy injection technique described by Lallart et. all. [1]. The injected energy, needed for this interface technology is delivered by an additional piezoelectric structure, realized on the generator substrate. Thus, the energy buffer of the system can be left unaffected, due to the second generator structure.

**Keywords:** energy harvesting, synchronized switching, interface, piezoelectric

## INTRODUCTION

Wireless sensor systems with improved features are increasing the demand for vibration driven energy harvesting micro-generators. The possibility of a long term, battery free and wireless operation is certainly the most important advantage of those systems. However, the power delivered by the micro-generators is commonly non-continuous, fluctuant and low in their voltage amplitude. In contrast most of the applications need periodic operation sequences with corresponding power supply requirements. Because of the asynchronous nature of the generator an energy buffer is needed, which compensates the energy requirement between the actual generator output and the energy consumption of the application [2]. 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 [3]. To improve the performance of wireless condition monitoring systems (Figure 1) it is important to improve the conversion of the mechanical to the electrical energy as well as to optimize the energy transfer from the generator to the energy storage [4].

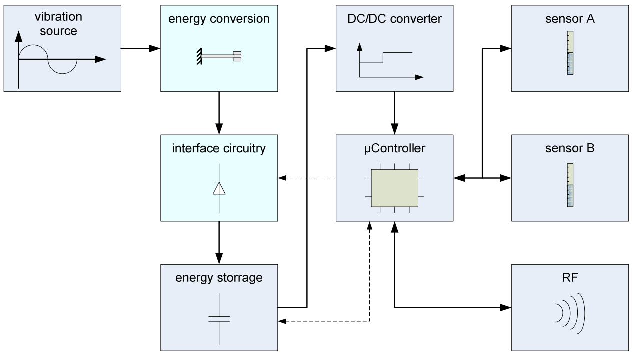


*Figure 1: Wireless condition monitoring system with piezoelectric energy harvester and interface circuitry.*

The presented device addresses both issues of optimization. It consists of a new kind of piezoelectric energy generator with an additional synchronized switching interface circuitry.

## ENERGY CONVERSION

An electromechanical model of the energy harvesting system can be considered as a coupled spring-mass-damper system [5] as shown in figure 2.

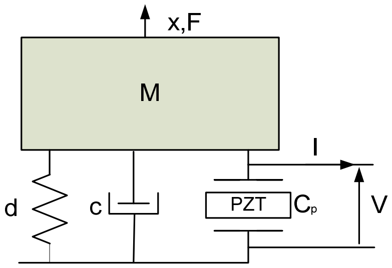


*Figure 2: Coupled spring-mass-damper system of the piezoelectric energy harvester.*

The system can be described by Newton's law with M being the effective value of the mass, d of the spring constant and c of the damping. $C_p$ is the capacity of the clamped capacitor. The coefficient α describes the electromechanical coupling of the system. Equations 1 and 2 result with the deflection of the piezo x(t), its time derivatives and the output voltage of the system $V_p(t)$:

$$M\ddot{x} + c\dot{x} + dx = F - \alpha V_p \tag{1}$$

$$I = \alpha\dot{x} - C_p\dot{V}_p \tag{2}$$

Equation 2 multiplied by $V_p$ and integrated in the time domain over [to;to+τ] results in the energy analysis of the system:

$$\underbrace{\int_{t_0}^{t_0+\tau} V_p I dt}_{\text{transferred energy}} + \underbrace{\frac{1}{2}C_p\left[V_p^{\,2}\right]_{t_0}^{t_0+\tau}}_{\text{electrostatic energy}} = \underbrace{\alpha\int_{t_0}^{t_0+\tau} V_p \dot{x} dt}_{\text{converted energy}} \qquad (3)$$

Increasing the output voltage and the coupling coefficient, or reducing the phase shift between the velocity and the voltage will lead to a maximized energy conversion [6], according to equation 3.

The first task of the energy conversion process is to convert the mechanical energy, delivered by the vibration source, into electrical energy. In the presented device the conversion is done by a piezoelectric element. The piezoelectric energy harvester has been designed to achieve a constant stress distribution over the whole generator structure. The result is a constant electrical potential on the electrodes of the generator structure and therefore no occurrence of equalizing currents.

The second task is to transfer the electric energy from the piezoelectric element to a storage element. A synchronized switching interface circuitry is applied to the system. The initial energy injection technique described by Lallart et. all. [1] provides initial energy to the piezoelectric energy harvester in form of short energy pulses. As a result the energy harvesting process is improved.

Usually the energy pulses needed to realize the injection algorithm are delivered by the energy storage of the system. Caused by the special shape of the generator it is possible to provide the energy pulses directly from the unused structures of the piezoelectric generator. Hereby it is no longer necessary to use complex electronic circuitries for the energy injection.

## GENERATOR DESIGN

Most piezoelectric harvesters are designed as a one sided clamped cantilever beam with a mass at the other end of the beam [7]. The design presented in this paper uses a four-point-bending principle. Four masses are attached to the beam. Both ends of the piezoelectric beam are pivot-mounted on the housing. Therefore the stress on the electrodes between masses is nearly identical at each point of this region. Figure 3 shows a schematic view and a picture of a first prototype of the generator.

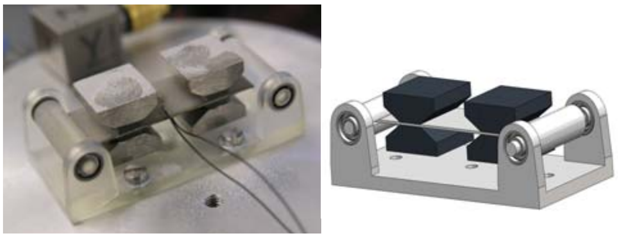


*Figure 3: Picture and schematic view of the piezoelectric energy harvesting device with constant stress distribution.*

A brass reinforced 2-Layer rectangular bending actuator has been used. The dimensions of the bimorph are 31.8 x 10 x 0.38 mm³. It was structured by laser beam cutting. The nickel electrode layer has been removed at areas where the masses are placed. By doing this, 3 electrode regions were separated. The electrode structure in the middle is used as generator structure, because of its constant stress distribution (Figure 5). This electrode structure is called main generator. The other electrode structures are used to provide the energy pulses needed for the injection algorithm. Figure 4 shows the piezoelectric beam. The dark areas mark the regions with the removed electrodes.

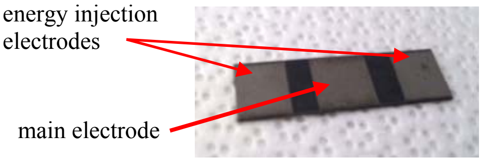


*Figure 4: Piezoelectric beam with three different electrode structures.*

A harmonic FEM model has been developed, to calculate the eigenfrequencies, the deflection and the power output of the energy harvester. Figure 5 shows the stress distribution along a path on the lower side of the beam. The red marked area highlights a nearly constant stress distribution at the main electrode.

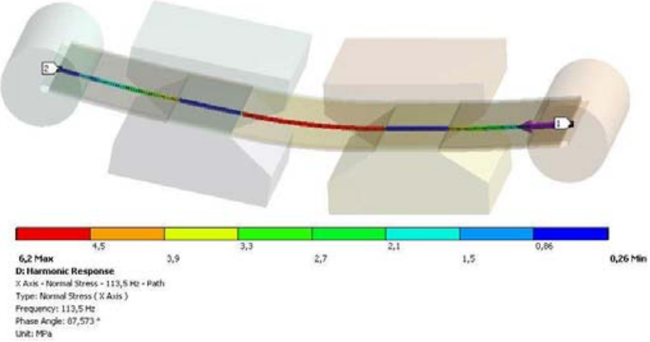


*Figure 5: Stress distribution of the piezoelectric energy harvester.*

## INTERFACE CIRCUITRY

The initial energy injection technology is able to enhance the energy conversion of piezoelectric energy harvesters up to 40 times compared to standard energy harvesting circuits [1]. The basic concept of the initial energy injection technology is to extract the energy of the piezoelectric element each time a maximum of the output voltage is reached. The energy is transferred to a storage element by using a transformer as shown in figure 6.

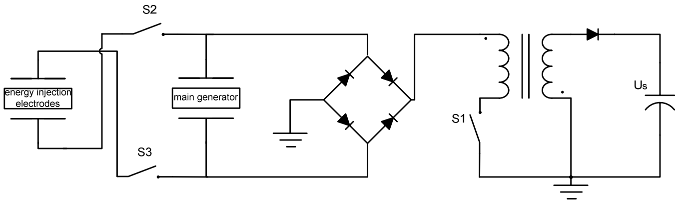
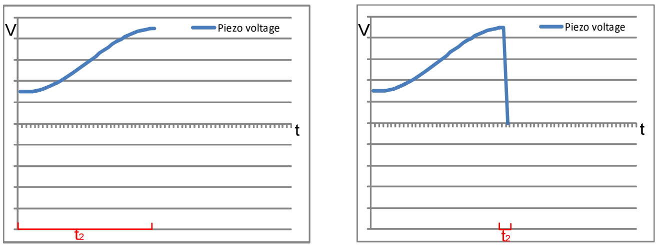
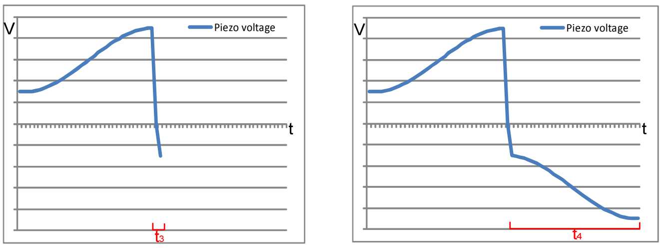


*Figure 6: Simplified model of the direct energy injection circuitry.*

Once the energy is transferred to the storage the main generator will be connected to an external energy source to generate a voltage offset. This results in an enhancement of the converted energy, according to equation 3. The direct energy injection technique, presented in this paper, uses the energy injection electrodes to provide the needed voltage offset. Therefore there is no need to place additional load on an external energy source or the energy storage element. The energy extraction process is shown in figure 7.



t1: S1 open, S2 open, S3 open    t2: S1 closed, S2 open, S3 open



t3: S1 open, S2 closed, S3 closed    t3: S1 open, S2 open, S3 open

*Figure 7: Direct energy injection algorithm with the voltage signal of the main generator.*

## SIMULATION RESULTS

To simulate the electrical behavior of the mechanical generator an equivalent circuit can be used. With electro-mechanical analogies used to convert the mechanical properties of the piezo into electrical circuit components [8] it is possible to simulate the SSHI control circuitry under realistic conditions. Numerical SPICE-based simulation tools can be used for these simulations.

The mechanical model of the piezoelectric energy harvester is shown in figure 2. Figure 8 shows the electrical simulation model of the energy harvester as a result of the electro-mechanical analogies.

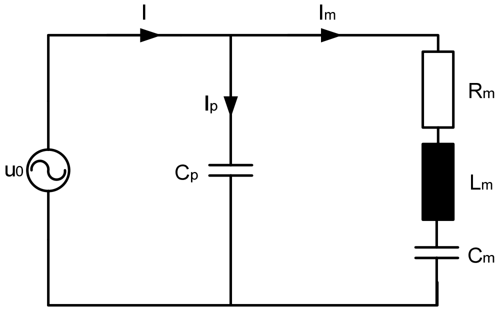


*Figure 8: Electrical equivalent circuit of the piezoelectric element.*

The electrical analogues for the mechanical system are outlined in table 1.

Table 1: electrical and mechanical analogues:

| mechanical: | electrical: |
|---|---|
| mass | inductor |
| spring | capacitor |
| damping | resistor |

The resulting admittance of the equivalent circuit is calculated by equation 4:

$$Y = \frac{1 - \omega \cdot C_p \cdot \left( \omega \cdot L_m - \frac{1}{\omega \cdot C_m} \right) + j \cdot \omega \cdot C_p \cdot R_m}{R_m + j \cdot \left( \omega \cdot L_m - \frac{1}{\omega \cdot C_m} \right)} \tag{4}$$

The calculation of the values of the electric components of the equivalent circuit was made by measuring the impedance characteristics of the piezoelectric energy harvester during a frequency sweep.

The maximum and the minimum of the Bode magnitude plot are labeled $fm_1$ and $fm_2$. These characteristic frequencies mark the parallel and the series resonance of the piezo. The characteristic frequencies can be calculated by assuming $R_m = 0$ in equation (4). That leads to equation (5):

$$Y = \frac{1 - \omega \cdot C_p \cdot \left( \omega \cdot L_m - \frac{1}{\omega \cdot C_m} \right)}{j \cdot \left( \omega \cdot L_m - \frac{1}{\omega \cdot C_m} \right)} \tag{5}$$

The maximum of the conductance can be found, if the denominator is set to zero:

$$\omega_1 = \frac{1}{\sqrt{C_m \cdot L_m}} \tag{6}$$

The minimum of the conductance can be found, if the numerator is set to zero:

$$\omega_2 = \sqrt{\frac{\frac{1}{C_p} + \frac{1}{C_m}}{L_m}} \tag{7}$$

The quotient $(\omega_2/\omega_1)^2$ leads to equation (8):

$$\left( \frac{\omega_2}{\omega_1} \right)^2 = 1 + \frac{C_m}{C_p} \tag{8}$$

Because of $\omega_2 > \omega_1$ the relation of Cp and Cm must be $C_p >> C_m$. According to the measured frequencies $f_1$ and $f_2$,, the Quotient $C_m/C_p$ is 0.13. For low frequencies the conductance depends mainly on $C_p$ and the conductance is calculated by:

$$Y = j\omega \cdot \left(C_p + C_m\right) \qquad (9)$$

For high frequencies the conductance depends mainly on $C_m$ and the conductance is calculated by:

$$Y = j \cdot \left( \frac{\omega \cdot C_p - 1}{\omega \cdot L_m} \right) \qquad (10)$$

$C_p$, $C_m$ and $L_m$ can be determined with equations (7), (8). The values of the components have been used to simulate the synchronized switching circuitry in interaction with the mechanical energy harvester. Figure 9 shows the simulation result with the typical output voltages of the direct initial energy injection circuitry.

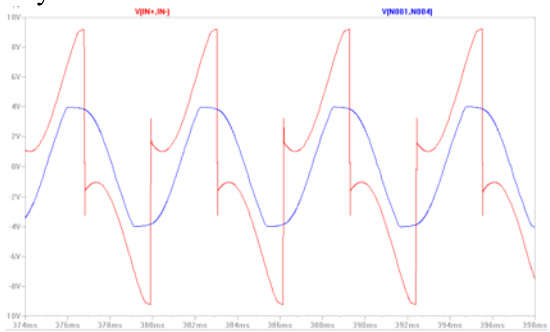


*Figure 9: Voltage signal of the piezoelectric element with (red signal) and without (blue signal) the direct initial energy injection technique.*

## EXPERIMENTAL

For experimental characterization the generator was attached to a lab shaker. The applied vibration frequency was tuned to 114Hz, the vibration amplitude to 0,3m/s². Figure 10a shows the measurement results of the generator open circuit voltage. Figure 10b shows the measurement results of output voltage of the generator connected to the direct initial energy injection interface.

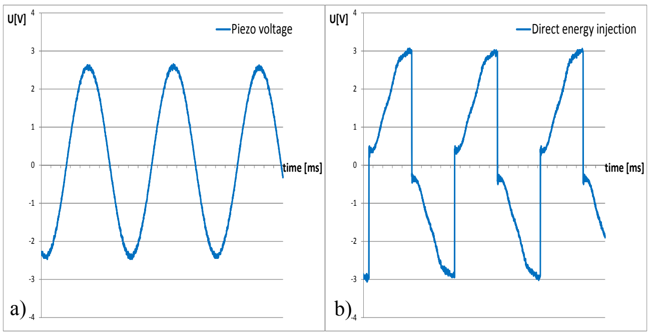


*Figure 10: Voltage signal of the piezoelectric element without (a) and with (b) the direct initial energy injection technique.*

## DISCUSSION

An optimization strategy concerning the mechanical harvester itself as well as an interface circuit was presented in this paper. A first prototype for experimental characterization was shown. The presented piezoelectric energy harvester was characterized by a constant stress distribution over the whole harvesting structure. Therefore the harvester was designed using a four-point-bending principle. The surface of the piezoelectric element was separated into a so called main electrode and the initial energy region. The main region was used as generator that provides the energy and was directly connected to the interface circuitry. The other region delivers the needed energy for the direct initial energy process, whereas no additional energy source is needed. 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 initial energy injection process, to reduce the energy losses.

## ACKNOWLEDGEMENTS

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