A novel piezoelectric energy harvester designed for single-supply pre-biasing circuit

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Abstract. In this paper, the design and test of a novel screen printed piezoelectric energy harvester for the single-supply pre-biasing (SSPB) circuit is presented. It was demonstrated previously that by using the SSPB circuit, power delivered to the load was over three times greater than that in the case of using a bridge rectifier circuit. For maximum power extraction from energy harvesters using the SSPB circuit, the SSPB switches must be triggered when the piezoelectric beam reaches its maximum point of displacement. These points coincide with the peaks and troughs of the voltage across the piezoelectric material, thus accurate peak detection is required. A new design of piezoelectric energy harvester was presented to integrate a sensing piezoelectric component with the main piezoelectric layer for energy harvesting. Maximum power generation by SSPB requires the sensing voltage to be in phase with the generating voltage in order to correctly detect the peaks. However, the difference in areas between the sensing piezoelectric component and the energy harvesting piezoelectric component leads to a difference in capacitance that causes phase shift between the two signals. To overcome this issue, impedance matching was performed. Simulations and experimental rests were presented.

1. Introduction

Energy harvesting is the process of capturing and accumulating energy from ambient energy sources. Vibration energy harvesting is receiving increasing interest as an alternative power source to batteries for autonomously operating devices dues to their longer lifetime, lower cost and lower environmental impact.

The three main transduction methods used to convert mechanical vibration energy into electrical energy are electromagnetic, electrostatic or piezoelectric transducers [1][2]. Over the past decade, the last has received special attention due to their simplicity in structure, which makes them easily to be integrated into self-powered systems.

Power extraction circuits for piezoelectric energy harvesters were compared in [3], which showed that the single-supply pre-biasing (SSPB) circuit is the most suitable for low amplitude energy harvesting applications. In [4], a multilayer piezoelectric harvester with a SSPB circuit was demonstrated to deliver more than three times the power to the load than a bridge rectifier circuit.

The SSPB circuit discharges and pre-biases the piezoelectric beam using switches in an H-bridge configuration [5]. To achieve maximum power extraction from the energy harvester, the switches must be triggered when the piezoelectric beam reaches its maximum point of displacement, which coincides with the peaks and troughs of the voltage generated across piezoelectric material. Triggering early or late causes a drop of energy output [4], thus accurate peak detection is vital to achieving maximum power extraction. One can use an external sensor to detect peaks. However, it increases complexity in fabrication of energy harvesters. A piezoelectric sensing layer can be added to the harvester, however it must be electrically isolated from the generation layer, otherwise the sensing signal will be adversely effected by the pre-biasing circuit operation [4].

This paper presents a new way to generate the piezoelectric sense signal by integrating an electrically isolated piezoelectric segment into the design of the piezoelectric harvester. The complete design is presented and its performance is evaluated through simulations and experiments.

2. Design of the piezoelectric generator with integrated sensing area

Figure 1 and Figure 2 show the single layer harvester with two separate PZT (lead zirconate titanate) areas, respectively. The larger area is for power generation while the smaller area is dedicated to generating the sensing voltage required by the SSPB circuit. The performance of the piezoelectric generator simulated using ANSYS simulation with direct coupled field analysis and a coupled physics circuit ANSYS simulation. A 3D structure was designed on SolidWorks and imported in ANSYS Workbench to improve the accuracy of the results. The RMS amplitude of the sensing signal was chosen as 1.8V based on the experimental set-up in [4]. Figure 2 shows the sensing area designed in a corner near the clamping area. This simplifies the wire connections to the bottom and top electrodes around the sensing PZT and to impose greater stress to the sensing area and generate a higher voltage.

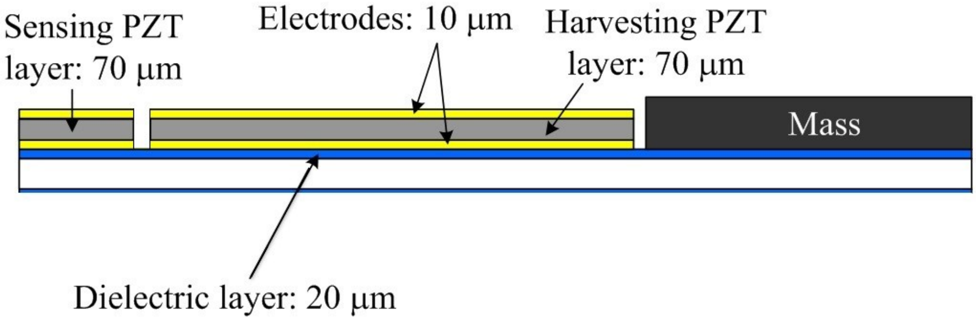

Figure 1. Cross section illustration of the piezoelectric harvester

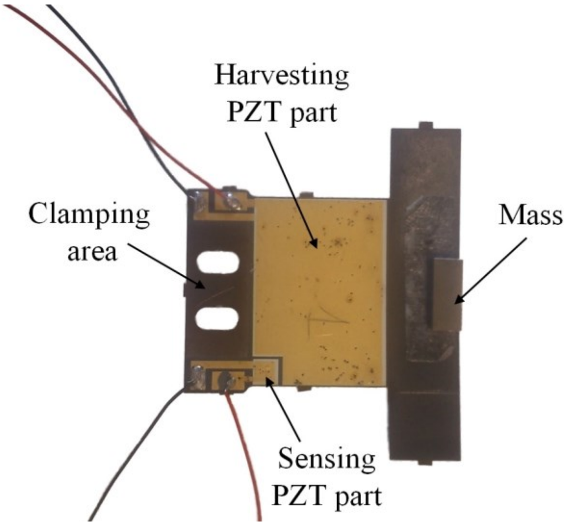

Figure 2. Top view of the T-shape piezoelectric harvester.

Three different structures were designed using a fixed PZT area is 27 × 20 mm^2 and mass area is 47 × 10 mm^2. Each structure has a different area for the sensing PZT component (3 × 3 mm^2, 4 × 4 mm^2, and 5 × 5 mm^2). The simulation results showed that the 3 × 3 mm^2 area would be great enough to generate the open circuit voltage requested for accurate peak detection, which is 1.8V$_{pk}$.

For all layers, materials are defined and connections between them are set with the Normal Lagrange formulation. The structure is fixed at one end and an acceleration of 1.96 m·s^{-2} is applied to the structure to simulate the vibration. To model the piezoelectric circuit, the CIRCU94 element was added to the ANSYS model in Workbench, where the simulation of the open circuit voltage is performed by connecting a high value load between the bottom and top electrodes. The electrodes of the sensing PZT are electrically isolated from the electrodes of generating PZT. The modal analysis is performed to find the natural frequency of the structure and then harmonic analysis is used to estimate the output voltage of the harvester at the resonant frequency found during the modal analysis.

Results of the simulation show that the natural frequency is at 48 Hz while the open circuit voltage generated by the sensing PZT and harvesting PZT components are 3.2 V and 4.4 V, respectively.

Screen printing technology was used to fabricate the harvester. The main advantages of this technology are the low cost of fabrication and its simplicity. Detailed fabrication process can be found in [6].

3. Experimental results

The SSPB circuit requires the sensing voltage to be in phase with the generating voltage to accurately detect the peaks. The difference in areas of the two parts however, results in a difference in capacitance. As the harvesting and sensing section do not share a common ground, the difference in capacitance leads to a phase shift between the two voltages. Simulation and experimental results show that the phase difference can be cancelled if the impedance of the sensing part is matched to the impedance of the harvesting part.

Furthermore, the harvester was tested on a shaker (Labworks ET-126) with a programmable resistance box and a computer with LabVIEW software collecting the data under the sinusoid vibration with the amplitude of 1.96 m·s^{-2}. As expected, both results show phase shift between the sensing voltage and the harvesting voltage because of the difference in capacitance of the two areas. The small PZT sensing section has a capacitance of 0.47 nF while the larger harvesting section has a capacitance of 24.88 nF, resulting in a phase shift of 66.24°. Figure 3 illustrates the phase shift between the two signals measured experimentally.

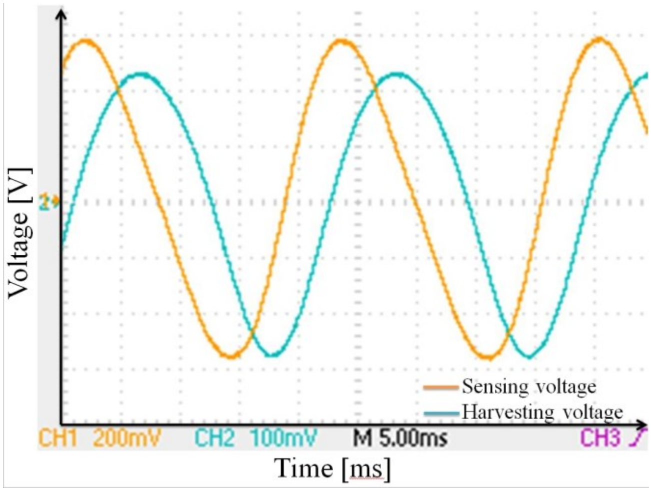

Figure 3. Experimentally measured waveforms showing piezoelectric open circuit voltage.

It was simulated and experimentally verified that sharing a common ground between generation and sense elements was able to cancel the phase shift. However, this arrangement adversely effects the operation of the SSPB circuit as shown in previous study [4]. Therefore, impedance matching was used to avoid the phase shift by connecting a 25 nF capacitor in parallel with the sensing voltage. Figure 4 shows the two signals when this capacitor was connected.

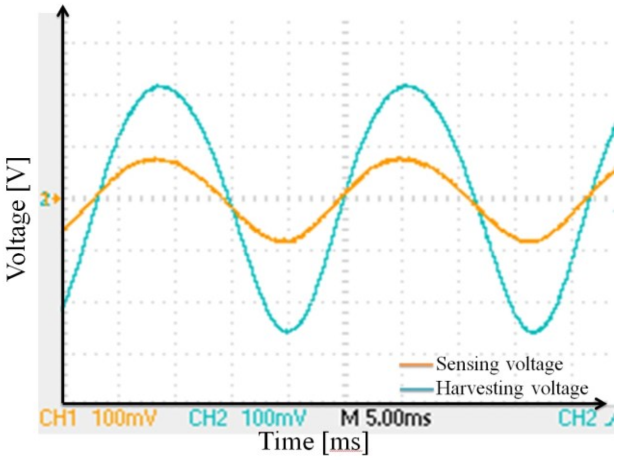

Figure 4. Experimentally measured waveforms showing piezoelectric open circuit voltage with a capacitance of 25 nF connected in parallel to the sensing PZT.

The open circuit voltages measured experimentally of both the harvesting part and the sensing part are shown in Figure 5. The output power measured experimentally with respect to the frequency at its optimum load resistance (96 kΩ) is shown in Figure 6.

Difference between experimental results and simulation results presented in Section 2 is caused by the different target and actual printed thicknesses of PZT layer. Actual thickness of PZT was measured to be between 60 to 64 µm compared to the target thickness of 70 µm, which causes a lower actual resonant frequency and lower open circuit voltages.

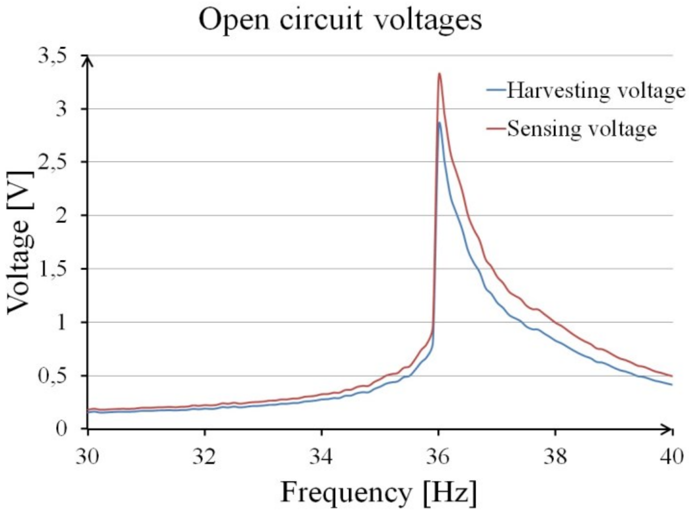

Figure 5. Open circuit voltages of the piezoelectric energy harvester.

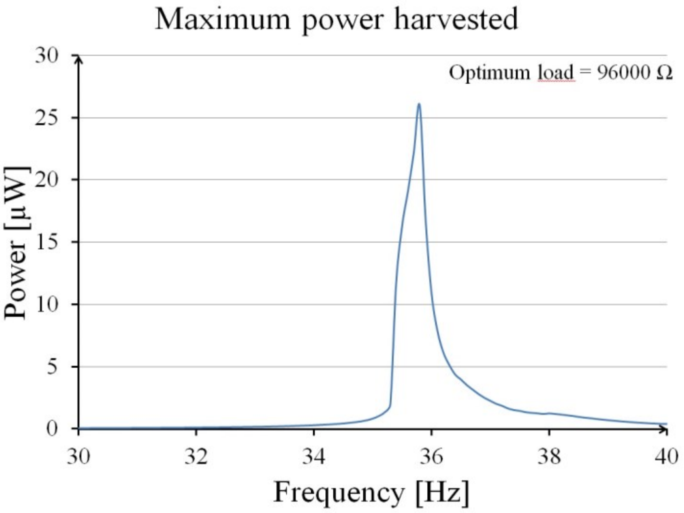

Figure 6. Maximum output power of the piezoelectric energy harvester.

4. Conclusions

In this paper, design and test of a novel screen printed piezoelectric energy harvester for the single-supply pre-biasing circuit is presented. The SSPB circuit needs a sensing signal to detect the timing of the maximum deflection of the piezoelectric beam which is unaffected by the SSPB circuit operation. The new energy harvester design integrated peak sensors with the energy harvester in the same fabrication processes, i.e. a larger area used for energy harvesting while a smaller area generating an electrically isolated sensing voltage.

The difference in areas of these two parts resulted in a difference in capacitance. Since the harvesting and sensing areas do not share a common ground, the difference in capacitance leads to a phase shift between the two voltages. The phase difference can successfully be cancelled by matching the impedance of the sensing part to the impedance of the harvesting part. Although the amplitude of the sensing signal can also be reduced by the impedance matching, it can be amplified in the peak detection circuit.

Future work will consist of power generation improvement achieved by this new harvester design when connected to a SSPB circuit. The expected improvement in peak detection should result in a large improvement in the power generation.

Acknowledgements

This work was supported by the contribution of European Union, in the framework of POR-FESR 2007/2013 within a technology transfer project of Autonomous Region of Aosta Valley and the Ministry of Labour and Social Policy.

References

[1] Beeby S P, Tudor M J and White N M 2006 *Measurement Science and Technology* **17** 175-195
[2] Priya S and Inman D 2008 Energy Harvesting Technologies (Springer)
[3] Dicken J, Mitcheson P, Stoianov I and Yeatman E 2012 IEEE Transactions on Power Electronics 27 4514-4529
[4] Elliott A, Zhu D, Beeby S and Mitcheson P 2012 *PowerMEMS 2012, Atlanta, USA*
[5] Dicken J, Mitcheson P D, Elliott A D T and Yeatman E M 2011 *PowerMEMS 2011, Seoul, South Korea*
[6] Zhu D, Beeby S P, Tudor M J and Harris N 2011 *Sensors and Actuators A* **169** 317-325