

MULTILAYER PIEZOELECTRIC ENERGY HARVESTING USING SINGLE SUPPLY PRE-BIASING FOR MAXIMUM POWER GENERATION

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Abstract: This paper studies the method of increasing output power of multilayer piezoelectric energy harvesters using Single Supply Pre-biasing (SSPB). In SSPB, it is important that the pre-biasing voltage be applied at the right moment. Multilayer piezoelectric energy harvesters are well suited SSPB as there is no phase lag between piezoelectric charge displacement on each layer and one layer can therefore be used for switch timing control. Compared to previously reported SSPB circuits, the power consumption of the circuit has been significantly reduced. Experimentally, the output power of a bimorph single-layer energy harvester using SSPB has been increased by a factor of three compared to that using a bridge rectifier. Furthermore, the possibility of implementing SSPB in bimorph double-layer energy harvesters has also been investigated.

Keywords: single supply pre-biasing, multi-layer piezoelectric

INTRODUCTION

Wireless devices such as biomedical sensors are limited in their application by the finite energy stored by the battery powering them. Thus energy harvesters are being designed to eliminate this constraint by extracting power from the local environment. However it is not simply a case of finding a transduction method and powering a device. A complete system must be designed taking into account the transduction method and the power electronics attached to the output.

Piezoelectric vibrational energy harvesters generate a sinusoidal voltage when a mechanically oscillating sinusoidal stress is applied to the device. The simplest form is a cantilever beam with a single-layer of piezo attached to one side of a substrate. However the output power can be increased by attaching a second layer on the bottom of the beam [1] to form a bimorph structure. The benefit of this structure is that the two piezo layers are moved further away from the neutral line to experience more stress and thus potentially generate more energy.

Output power can be further increased by manufacturing bimorph double-layer energy harvesters. They have approximately 40% higher output power than single-layer energy harvesters when the total thicknesses of piezoelectric layers in the two cases are the same [2] when connected to an optimized resistive load.

Rectification of the piezo's output must be performed in order to store the energy on a capacitor or battery. The obvious solution is a bridge rectifier, however more power can be extracted by optimizing the electrical damping applied to the piezo [3]. The

most successful method is Single Supply Pre-biasing (SSPB), which can theoretically generate twice as much power as Synchronous Switched Harvester on Inductor (SSHI), [3] and has been shown experimentally to generate 14% more power [4] than theoretically possible by SSHI [5]. This paper presents the combining of these two power maximization strategies.

THEORY OF OPERATION

Figure 1 shows cross sections of the bimorph single-layer and bimorph double-layer energy harvesters. In bimorph energy harvesters there is no phase lag between piezoelectric layers. This is advantageous as a layer can be used to provide a sense signal for switch control timing.

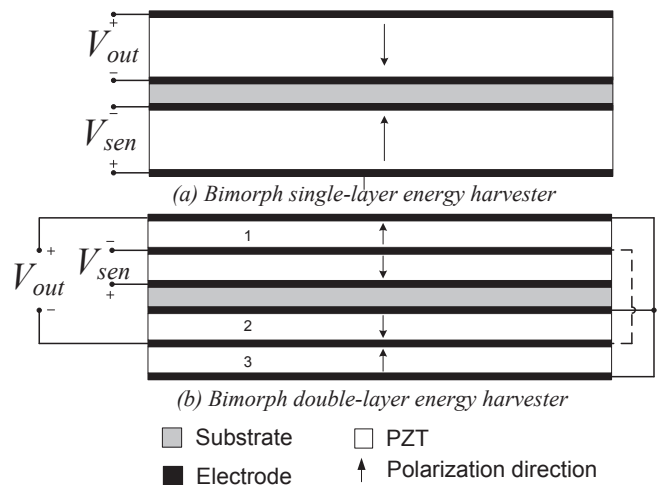


Figure 1: Multilayer piezo construction.

For the single-layer energy harvester, one piezo layer is used for energy harvesting and the other is used for sensing. Therefore, only half of the total available capacitance can be used to harvest. By contrast, only one of the four piezoelectric layers is used to provide the sensing signal in the double-layer energy harvester and thus three quarters of the total available piezo can be used for harvesting.

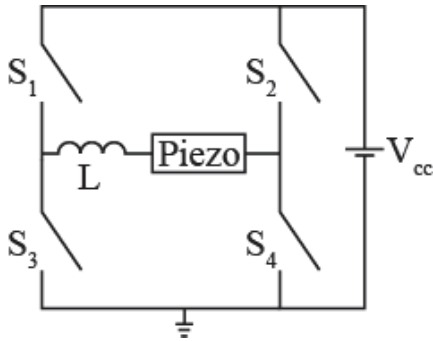


Figure 2: SSPB H-bridge circuit for discharging and pre-biasing the piezo [4].

SSPB operates by placing charge on the piezoelectric beam at its maxima points of travel by closing switch pairs (Figure 2). The charge generates a piezoelectric force which opposes the motion of the beam as it travels in the opposite direction whilst all switches are open. This increases the work done by the beam and hence more power can be extracted.

When the beam reaches the opposite point of extreme travel, the pre-bias charge and the generated charge are both discharged into the energy storage component through the same set of switches, before the beam is pre-biased with opposite polarity by the second pair of switches and the operational cycle repeats. Figure 3 shows a typical waveform of the output voltage using SSPB.

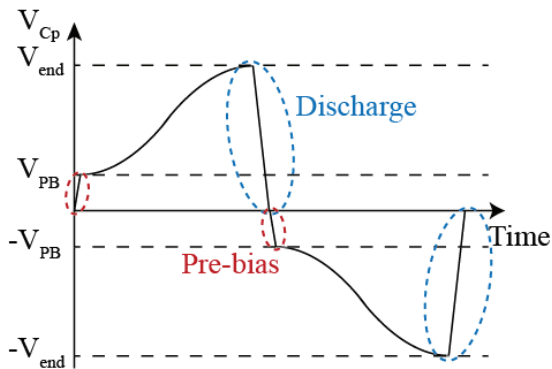


Figure 3: Voltage waveform across piezo when pre-biasing is applied to increase power extraction [6].

IMPLEMENTATION

Implementation of the system can be considered in four main blocks: transduction, peak detection, piezo pre-biasing, and switch timing control (Figure 4).

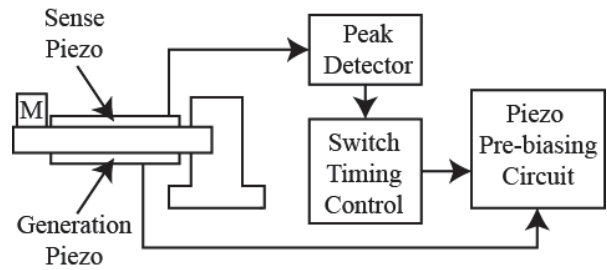


Figure 4: Multilayer piezo connected to SSPB circuit implementation.

The chosen transduction method was a multilayer piezoelectric energy harvester (as shown in Figure 5) fabricated using screen printing techniques. Each layer was printed via its respective pre-meshed screen and was then dried and cured at specific temperatures. After the fabrication processes, the piezo layers were polarized under constant electric field at 200°C. Details in fabrication can be found in [1].

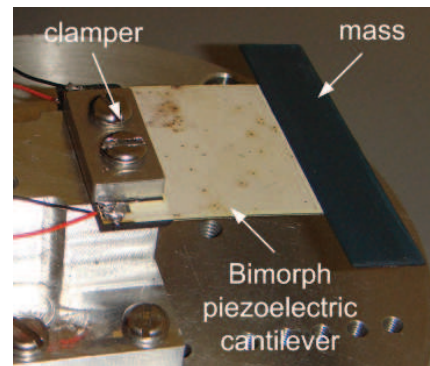


Figure 5: Photo of the multilayer piezo energy harvester.

The peak detection circuit (Figure 6) operates by measuring the differential voltage across the sense piezo using a low power AD8500 operational amplifier [4]. The instantaneous voltage is compared to a lossy peak-hold version held by a capacitor to generate the triggers for the switch timing control.

Power consumption of the peak detector was reduced over previous implementations [4] by 91% to 8.64 μ W. This improvement was achieved by analyzing the current paths in the circuit and subsequently increasing the resistor values of the lossy peak-hold circuits.

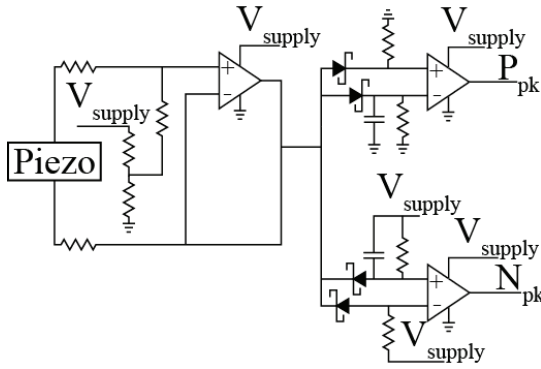


Figure 6: Low power peak detection circuit [7].

The switches need to be operated in pairs (P_1 - N_4 , P_2 - N_3) and held on for a half electrical resonance cycle formed by the piezo and inductor. A low power IGLOO nano FPGA was selected to implement the control algorithm (Figure 7). When a peak is detected, the FPGA pulls the input to the discharge timing resistor and fires the required switch pair. The signal is held high until the voltage on the capacitor reaches the FPGA's input high threshold. A $1 \mu\text{s}$ timer then begins to prevent shoot-through, before the pre-bias switch pair are fired and timed in the same way.

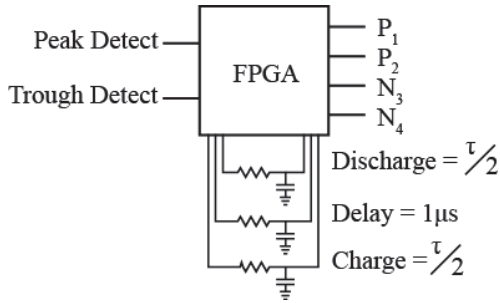


Figure 7: Switch timing control circuit [4].

The voltage across the piezo increases above the V_{cc} voltage rail as well as below the ground rail, hence the switches must block in both directions. Current must also flow in both directions in order to pre-bias and discharge the piezo. Previous implementations used optically isolated TRIACs to provide the necessary switching characteristics [6], however they are power intensive to control and have a slow turn-on and turn off times.

A better solution is shown in Figure 8 along with their gate drives [4]. The series connected p-type (BSH201) and n-type (BSS138) MOSFETs ensure the piezo is electrically isolated. The n-type is driven directly from the FPGA (IGLOO AGLN250), however the p-type MOSFET required the voltage to be level shifted so a capacitor and voltage clamping diode were used. The high side p-type MOSFET is

driven using a DC decoupled potential divider.

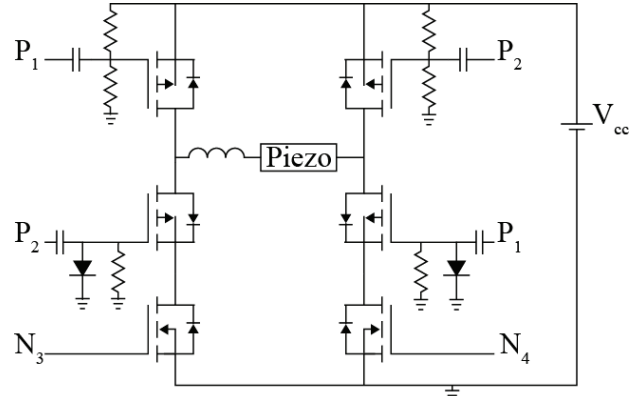


Figure 8: H-bridge circuit implementation [4].

The inductor chosen was designed to maximize power generation with minimal volume [7], thus a 5.354 mH with volume 0.152 cm^3 from Coilcraft was selected.

EXPERIMENTAL RESULTS

The single-layer bimorph was tested first using one layer to generate and one layer to sense. The generation layer had a piezo capacitance of 28.5 nF and when combined with the inductor, the Q -factor was measured to be 4.9. A mechanical excitation force of $200 \text{ mG}_{\text{rms}}$ at 70 Hz was applied inducing a 2.2 V open circuit voltage across the piezo.

The power generated was measured using a Yokogawa WT210 Digital Power Meter for both a bridge rectifier and the SSPB circuit. The theoretical maximum power extraction possible using SSHI was also calculated from [3].

Table 1 presents the results from the testing. Under a relative small excitation the output the SSPB circuit generates over three times as much power as the simple bridge rectifier. However it performs only equally well compared to the theoretical limit of SSHI due to the peak detection circuit being slightly late in detecting when the cantilever is at its extreme point of travel as can be seen in Figure 9.

Table 1: Average charging power at optimal voltage for single-layer bi-morph energy harvester using different electrical interfaces.

Electrical interface to beam	Average charging power (total charged energy divided by charging time)
Bridge rectifier	$18 \mu\text{W}$
SSHI (theoretical)	$60 \mu\text{W}$
SSPB (experimental)	$60 \mu\text{W}$

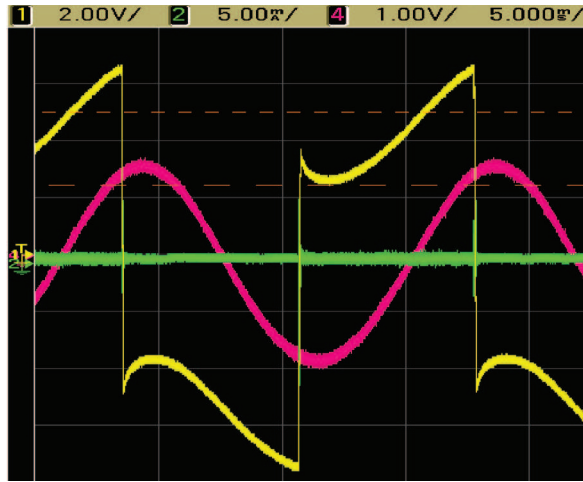


Figure 9: Generation piezo voltage (yellow), sense piezo voltage (pink) and inductor current (green) waveforms with respect to time for single-layer bimorph energy harvester with SSPB output.

The energy lost is due to the early firing of the switches. The expression for the theoretical maximum power extracted by SSPB [3] can be modified to allow for this by multiplying by a correction factor, $(1-\sin(\omega t))$ where t is the timing inaccuracy and ω the angular excitation frequency. The timing inaccuracy can be found by measuring the time between the switch firing and the actual peak. In this case the correction factor is $(1-\sin(0.16\pi))$, thus the power loss is approximately $58 \mu\text{W}$.

$$\text{Power loss} = V_{po}^2 f_0 C_p (8Q/\pi) (1-\sin(\omega t)) \quad (1)$$

The testing on the bimorph double-layer energy harvester was less successful than the single-layer energy harvester. This is suspected to be due to the sensing layer and the three harvesting layers sharing a common connection (see the dotted line in Figure 1b). Therefore, the sensing signal is not completely decoupled from the generated power signal. When the power signal is pre-biased, the sensing signal is also affected, which caused the system to fire at the wrong time.

CONCLUSION

A complete design for piezoelectric energy harvesters has been presented. Improvements in control circuitry power consumption have been made, however a better peak detection implementation is still required to reach the theoretical limits of single supply pre-biasing.

Preliminary results using a single-layer bi-morph with SSPB are encouraging however future work is required in redesigning the double-layer energy harvesters so that the sensing layer and generating layers can be isolated.

Furthermore, a simulation will be run to study the deformation of the three parallel connected generating layers under the same voltage and possible solutions will be proposed based on the simulation results.

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