HARVESTING ENERGY FROM MULTI-FREQUENCY VIBRATIONS WITH A TUNABLE ELECTRICAL LOAD

S.C. Chang[1], M. Ocalan[2], J. Pabon[2], and J.H. Lang[1]
[1]EECS Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Schlumberger-Doll Research, Cambridge, MA 02139, USA

Abstract: This paper reports the design, fabrication, and successful demonstration of a power-electronic switching circuit that improves the performance of a vibration energy harvesting system through external electrical loading. As a demonstration, the circuit is applied here to solve two harvesting problems: piezoelectric capacitance cancellation and dual-frequency energy harvesting. The power-electronic circuit provides a tunable electrical impedance, large inductance implementation and automatic voltage rectification. It is suitable for magnetic, electrostatic and piezoelectric energy harvesting systems; a piezoelectric version is demonstrated.

Keywords: vibration energy harvesting; multi-frequency energy harvesting; tunable electrical impedance

INTRODUCTION

Vibration energy harvesting [1] has drawn significant interest for its potential to power wireless sensor nodes and other lower-power applications. During harvester development, most researchers have focused on designs that resonantly harvest energy from a single fixed frequency. However, most ambient vibration sources display characteristics including shifting vibration frequencies and multiple harmonics as shown in Figure 1. Harvesters designed to work from a fixed single-frequency vibration source exhibit limited performance in such cases.

Recently, electrical loading has been used to modify and improve harvester performance in the presence of the non-ideal vibration characteristics mentioned above. Typical modifications include resonant frequency tuning and impedance matching by adding passive reactive loads such as capacitors and inductors [2], which can be very large in size. A more compact implementation [3] utilizes power electronics to synthesize the desired load impedance while performing AC-to-DC rectification. Such power electronics can implement much more than a resistive, inductive or capacitive load. More generally, they can be used to harvest energy from varying multi-frequency vibrations. While there has been previous work on tracking vibration frequencies [4], there has yet to be a report of harvesting energy from multi-frequency vibration sources.

The power electronics implemented here presents a tuned electrical load impedance to the harvester. This impedance can in principle maximize output power at a given vibration frequency. In addition, it enables large inductance implementation, and can create additional electrical resonances for multi-frequency energy harvesting. Finally, the circuit provides in-situ AC-DC voltage rectification.

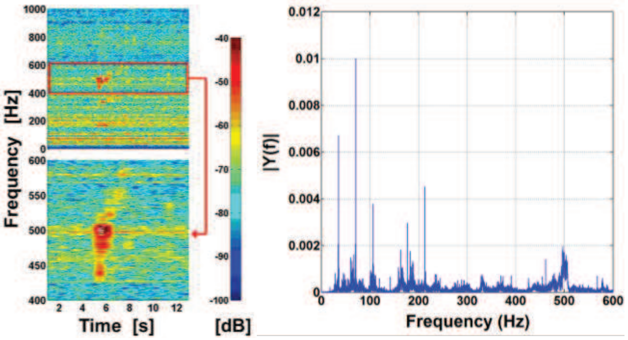


Figure 1: Spectrogram and Fourier analysis of the vibration recorded from an office window. The frequency shifting and multi-frequency phenomena can both be observed in the figures.

POWER ELECTRONICS

System Architecture

The power-electronic switching circuit used here is inspired by power factor correction (PFC) circuits [5], commonly applied in high-power utility/dc interfaces to make the load current and voltage in-phase. The goal here, however, is to make the load current and voltage achieve a more complex relation such that the power electronics present a complex impedance load to the harvester. Analyses in previous research has shown that proper electrical loading can improve system performance [2][3][4][6]. In [3] it is shown that such loading can be implemented with switching power electronics. This paper demonstrates switching power electronics that implement the loading equivalent to a parallel inductor and resistor; a richer load impedance is certainly possible. The equivalent

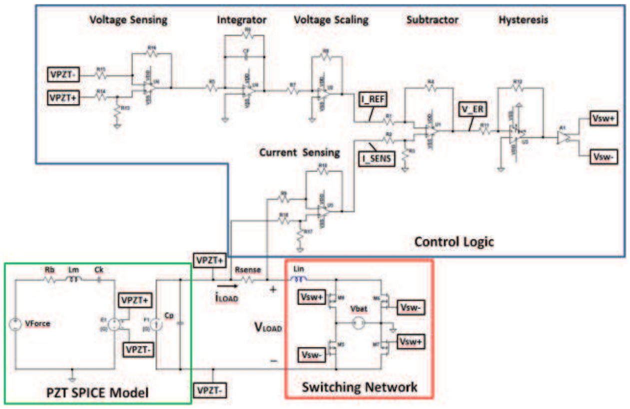


Figure 2: System overview of the tunable loading electronics and energy harvester.

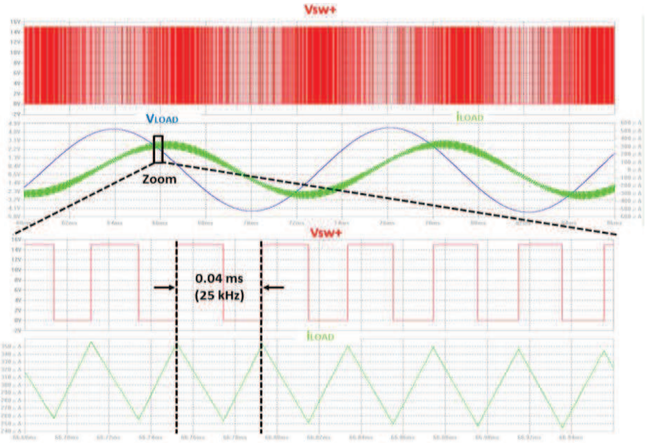


Figure 3: Waveforms of the synthesized parallel RL circuit

resistor absorbs and stores real harvested energy while the equivalent inductor provides reactive energy that improves system performance. A high-level schematic of the harvesting system is shown in Figure 2. The system consists of three major blocks: the piezoelectric harvester (green), control logic (blue), and the switching power electronics (red).

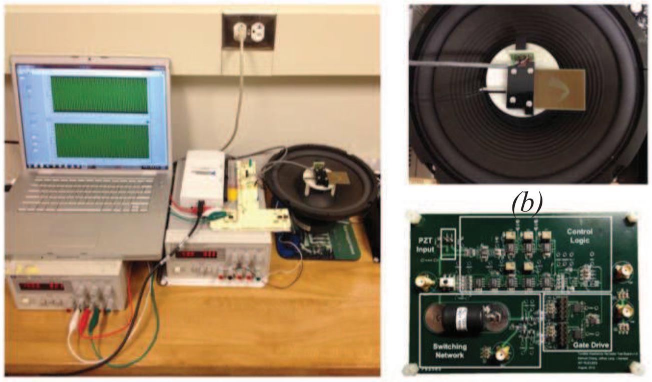
The green box shown in Figure 2 is the equivalent circuit model of a piezoelectric harvester, which can be replaced with a magnetic or electric harvester model depending on the application. In the blue box in Figure 2, the control senses the harvester voltage (VPZT) and determines the reference current (I_REF) that corresponds to the desired loading. In this particular schematic, the desired loading is a parallel connected inductor and resistor. The reference and actual currents (I_SENS) are compared, and the difference is passed through a hysteresis block to generate the switching signals (Vsw+ and Vsw-) for the four-FET bridge in the switching network. The bridge, together with an inductor that smooths the current ripple, is shown in the red box.

SPICE-simulation waveforms of the power electronics are shown in Figure 3. In this case, the desired current is that which implements a parallel inductor and resistor. It is important to note that the energy delivered to the equivalent resistor is physically delivered to the reservoir/supply (Vbat) connected to the FET bridge, and that the same reservoir supplies the reactive energy of the equivalent inductor.

The major improvement of the electronics in Figure 2 compared to previous work [3] is its large inductance implementation capability. This circuit can generate the load voltage-current characteristics of a 30 H inductor. This greatly decreases the power losses and provides dynamic tunability of the complex load. The electronics are demonstrated using the test bench shown in Figure 4(a). The piezoelectric harvester mounted on a shaker table as shown in Figure 4(b). The table receives vibration commands from a USB-6211 control box by National Instruments. The power electronics are implemented on a four-layer printed circuit board (PCB) as shown in Figure 4(c). The switching network includes a 1 H inductor and 4 low-voltage, low-resistance transistors made by Fairchild Semiconductors. Critical resistances in the control logic are all tunable.

APPLICATIONS

For demonstration purposes, the power-electronic loading is used here to solve two harvesting problems: (1) optimal loading of the piezoelectric harvester by compensating for its internal 130nF capacitance while providing a real matched load for maximum power output; and (2) introducing an additional resonance which allows simultaneous harvesting from multiple vibration frequencies.



(b)

(a) (c)

Figure 4: (a) Experiment setup of the harvesting system; (b) piezoelectric harvester mounted on a shaker table; (c) PCB implementation of a tunable RL impedance for a piezoelectric harvester.

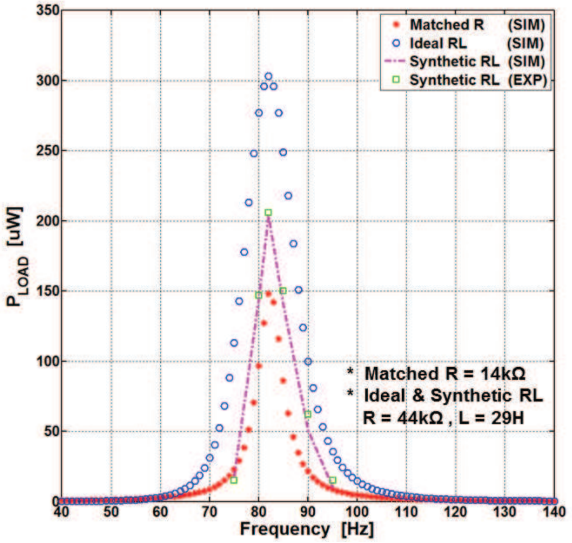


Figure 5: Simulated and experimental result of a RL-loaded piezoelectric harvester for parasitic capacitance cancellation application driven at 0.7g.

Piezoelectric Capacitance Cancellation

Figure 5 shows the SPICE-simulated power delivered to a 14 kΩ resistor load (red), and to a load comprising a 44 kΩ resistor (blue) in parallel with a 29 H inductor, both as functions of vibration frequency. The 14 kΩ resistor is optimal by itself. The 44 kΩ resistor is optimal with the 29 H inductor that compensates the harvester capacitance at mechanical resonance thereby permitting greater power output. Also shown are the SPICE-simulated (purple) and the experimental (green) power into the reservoir when the power electronics implement the parallel resistor and inductor. These two match well demonstrating the accuracy of the simulation. The ideal (blue) and power-electronic (purple) power differ due to parasitic gate capacitance in the bridge FETs.

Dual-Frequency Energy Harvesting

The second application is creating resonances in addition to the original mechanical resonant frequency of the piezoelectric. Figure 6 shows the simulated and experimental results of an arrangement in which the harvester capacitance and power-electronic inductor create a second resonance at 98 Hz to improve harvesting at that frequency. As shown in the table in Figure 6, this arrangement permits the simultaneous resonant harvesting of vibrations at the mechanical resonance of 82 Hz and the electrical resonance of 98 Hz. The output power in the presence of both vibrations is the sum of the output powers in the presence of the individual vibrations.

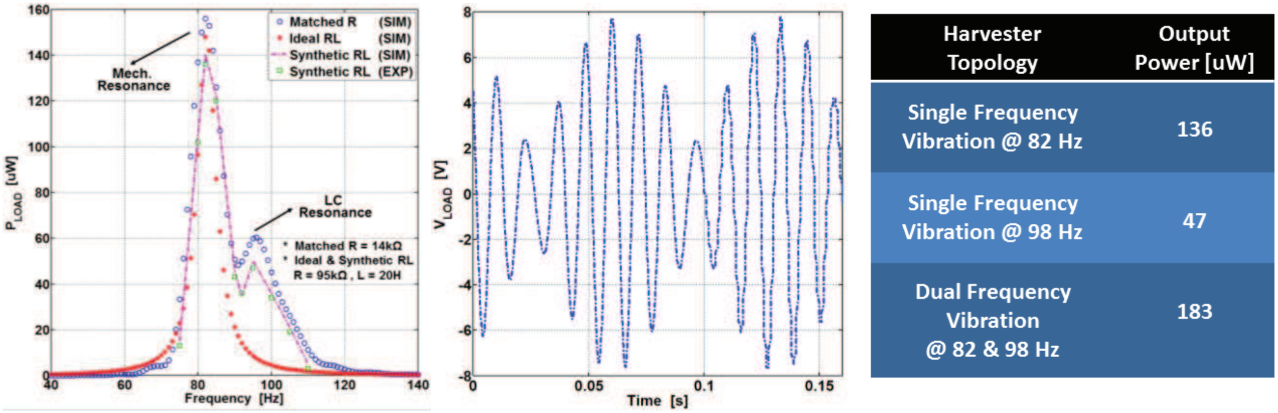
In using the load inductor to create a second resonance, its function of compensating the piezoelectric capacitance is lost, so overall energy harvesting suffers. A more complex loading with additional synthesized passives can serve both functions. For simplicity only the second resonance feature is shown in Figure 6.

Triple-Frequency Energy Harvesting

Yet more complex loading could be used to improve harvesting at multiple frequencies. A three-resonance example is shown in Figure 7. That figure shows a schematic implementation and simulated results of a circuit capable of harvesting energy from three frequencies.

DISCUSSION

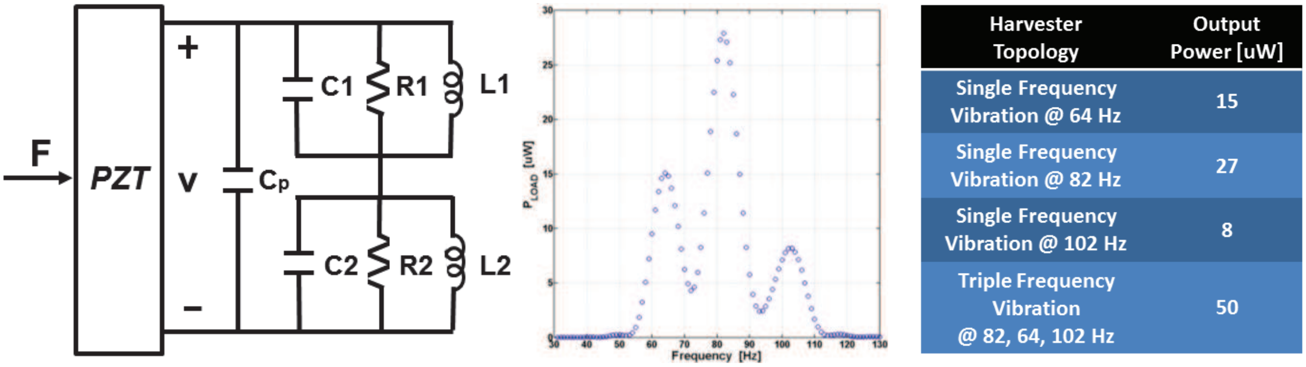
From Figures 4, 5 and 7, it is apparent that the power electronics shown here offer great advantages in terms of increasing the output power of the harvester at resonance and with multi-frequency vibrations.



Harvester Topology	Output Power [uW]
Single Frequency Vibration @ 82 Hz	136
Single Frequency Vibration @ 98 Hz	47
Dual Frequency Vibration @ 82 & 98 Hz	183

(a) *(b)* *(c)*

Figure 6: Simulated and experimental results of power electronics introducing a second resonance which allows simultaneous harvesting from two vibration frequencies both driven at 0.7g; (a) frequency response of the dual resonant frequency harvester; (b) load voltage during dual frequency harvesting from vibrations at 82Hz and 98 Hz; (c) output power summary of experiments



Harvester Topology	Output Power [uW]
Single Frequency Vibration @ 64 Hz	15
Single Frequency Vibration @ 82 Hz	27
Single Frequency Vibration @ 102 Hz	8
Triple Frequency Vibration @ 82, 64, 102 Hz	50

(b) *(b)* *(c)*

Figure 7: Simulated results of power electronics introducing two additional resonances which allows simultaneous harvesting from three vibration frequencies driven at 0.7g; (a) high level schematic of proposed triple frequency circuit; (b) frequency response of the triple-frequency harvester (blue); (c) output power summary of experiments with one frequency, the other frequency and both frequencies present.

However, the power cost of the more complex controls must be accounted. Table 1 shows the power losses of the PCB implemented circuit along with the estimated power losses by using ultra-low power devices in a 0.18um CMOS process [7]. It can be seen that by integrating the circuit into a chip, the total power loss greatly decreases. While the total power loss is still considerably large compared to the harvested power, a digital control implementation might offer yet further decreases. Therefore, the power electronics are a good candidate for integrated circuit implementation. It also serves as a good platform for even more complex impedance tuning such as multi-frequency energy harvesting. The application of this circuit to magnetic and electric harvesting systems is also much easier than piezoelectric systems since they do not display the large parasitic capacitances that must be cancelled. The parasitic inductance of an electromagnetic harvester is normally on the scale of nano-to-micro Henries and is therefore much easier to compensate.

	PCB	0.18um CMOS
Control Logic	60 mW	50 uW
Power Path	20 uW	10 uW
Gate Driver	3.5 mW	140 uW
Total	63.5 mW	200 uW

Table 1: Power loss comparison of PCB and integrated circuit implementations of proposed circuit.

CONCLUSION

The design, fabrication, and demonstration of a power-electronic switching circuit that improves a vibration energy harvesting system through external electrical loading is reported. One advantage is that it introduces resonances beyond a single mechanical resonant so as to harvest energy well from multi-frequency vibrations. Additional advantages of the proposed circuit include optimal electrical impedance matching, large inductance implementation, and automatic voltage rectification. Future work will include the implementation of harvesting energy from three or more frequencies and dynamic frequency sensing and control.

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