Proposal for a circuit for extracting power piezoelectric transducers using switch-only rectified with DC-DC converter

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Abstract. *In recent years power harvesting or energy harvesting has become a popular issue. It consists of developing new technologies in order to get energy from many different sources and convert it into usable electrical energy. In this context, those technologies with wireless transmission and low power consumption electronic devices deserve an especial mention because of their capability to allow implementation of the "power harvesting" concept. One method for obtaining this energy is to use the vibration of mechanical structures by piezoelectric transducers. One of the limitations of these systems is the low quantity of power generated by the transducer. Therefore, it is mandatory to reduce the losses at the electronic components and extract the maximum power possible from the piezoelectric to improve the performance. The system proposed in this paper is composed by mechanical structure, piezoelectric transducers, rectifier and DC-DC converter. The mechanical structure consisted of a cantilever bean where piezoelectric transducers were placed. This transducer is used to convert mechanical energy into electrical energy. The voltage will be switch-only rectified and then stored in a battery or super capacitor, for to be used by electronic circuits. The DC-DC converters were used to achieve maximum transfer power from piezoelectric transducer to the supercapacitor. This work describes the design of circuits necessary for power harvesting systems using piezoelectric transducers. The work objective was extracted the maximum power and achieve the maximum performance of these system.*

Keywords*: Power Harvesting, piezoelectric transducer, extracting power, switch-only rectified, DC-DC converter.*

1. INTRODUCTION

Nowadays air pollution caused mainly by the consumption of fossil fuels (oil, natural gas, coal) has become an important issue. Researchers have been searching for alternatives to generate energy without damage to the environment. These alternative ways do not emit harmful gases or residues to the environment in their consumption, so they are called clean energy.

In this context, a technique knowing as power harvesting has attracted much interest. It consists on converting other types of energy into electrical energy. In other words, power harvesting is the action of capturing and converting renewable sources in electrical energy. It can be acquired by mechanical vibration; solar energy; gravitational field; flow of fluids; sound pressure; among others.

The main application of the power harvesting is the remote sensing, where power is rare due to lack of infrastructure. Through this technique, systems that require batteries for their operation can be self-replenish.

One method of power harvesting is to get energy trough the vibration of a mechanical structure using piezoelectric material. Piezoelectric material is a transducer which should transform mechanical vibration energy into electrical energy, this energy could be stored in a battery to be used later in electronics circuits.

One of the limitations of these systems are the low energy generated by these transducer, usually about microwatts. This occurs mainly by mechanical properties of piezoelectric. This low power output requires a design of electronic circuit with very low power consumption and an efficient performance to extract the maximum power available.

Gonsalez *et al* (2010) analyzed the influence of the piezoelectric transducer coupled to the electronic circuit. This study commends that the optimization of the load for the system is extremity important to ensure efficiency of the harvesting system. Leufeuvre *et al* (2007) used a DC-DC converter to maximize the power flow. Several studies (Ottman, 2003; Han, 2004; Kim, 2007; Tabesh e Fréchette, 2010) employ DC-DC converters to improve efficiency of the systems.

Guyomar *et al* (2005) investigated another method which is to periodically remove the electric charge stored on the internal capacitor of the transducer. With the concept of this method Ramadass and Chandrakasan (2010) presented a switch-only rectifier and a bias-flip rectifier, these circuits improve the efficiency in 200% and 400% respectively.

This paper analyzes the use of different rectifiers in order to extract the maximum power from piezoelectric transducer and proposes a discrete low power strategy to control the switch-only rectifier. Furthermore uses the DC-DC converter to achieve electromechanical coupling.

2. POWER HARVESTING MODEL AND CIRCUITRY

The systems of power harvesting are divided in three parts: the piezoelectric transducer, the circuits of power extracting, and the storage devices. The piezoelectric transducer is where the mechanical energy is converted into electrical energy. The circuits of power extracting are electronic circuits used to extract the maximum power possible from piezoelectric. These are made in three parts: rectifier, power stage, and control circuit. The storage devices are rechargeable batteries or supercapacitor.

2.1. Piezoelectric transducer

The piezoelectric material, when submitted to pressure, produces electrical energy (direct effect), and when submitted to electrical voltage it suffers a deformation and / or mechanical stress (inverse effect), as shown in Fig. 1. That is piezoelectric transducer converts mechanical energy into electrical, or the opposite.

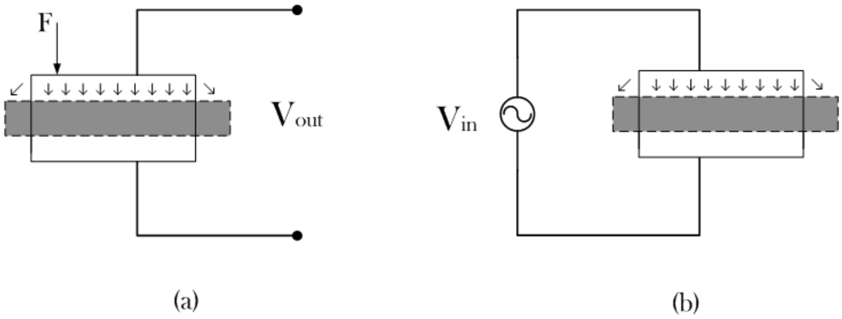


Figure 1. Schematic representation of the piezoelectric energy conversion: (a) direct effect, (b) inverse effect.

At resonance frequency the piezoelectric circuit is able to be modeled into to electrical domain. According to Pearson (2006), piezoelectric transducer can be modeled in a simple way with a current source in parallel with a capacitor (Fig. 2(a)), where capacitor is an internal parameter of piezoelectric transducer. By the Thevenin equivalent circuit can be represented by a voltage source in series with a capacitance (Fig. 2 (b)).

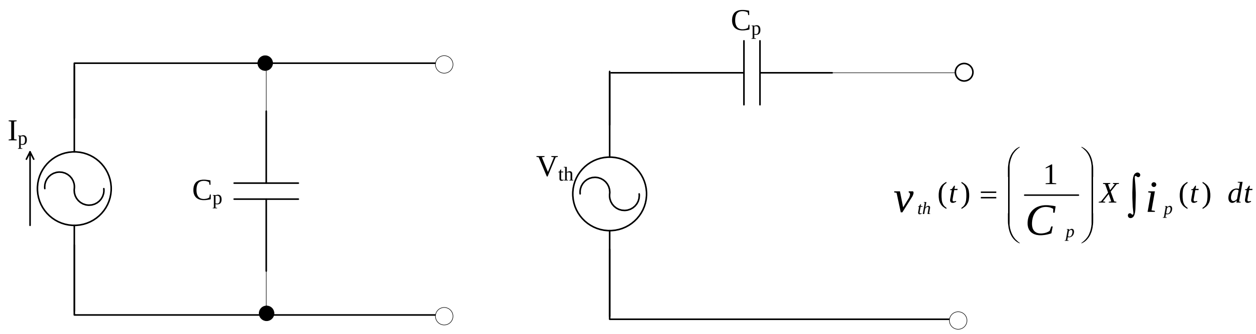


Figure 2. Electrical modeled of piezoelectric: (a) current source, (b) voltage source

Pearson (2006) defines the capacitance of the piezoelectric dependent of the electric permittivity (ε_0), the dielectric constant of the material (K), Young modulus (Y_0) and the dimensions of the material. The Eq. 1 is show this dependence.

$$C_p = \frac{\varepsilon_0 \times K \times Y_0 \times c \times l}{a} \quad (1)$$

Where: c – length of the piezoelectric
l - width of the piezoelectric
a - height of the piezoelectric.

For the circuit of Fig. 2 can be seen that the load current is a difference between the current generated by current source and the current through the capacitor. Thus the load current can be calculated by:

$$i(t) = i_p(t) - i_c(t) \quad (2)$$

Tabesh and Fréchette (2010) defined the current as a sinusoidal source:

$$i_p = I_p \sin(wt) \tag{3}$$

Where: $I_p = k\,\omega\,U_m$, being that ω is vibration frequency of the beam, and U_m is maximum deflection from piezoelectric.

From Eq. (3) and knowing that the capacitor current is the value of the capacitance multiplied by the voltage change over time, the equation can be rewritten by:

$$i(t) = k\,\omega\,U_m \sin(\omega t) - C_p \frac{dv_p}{dt} \tag{4}$$

2.2. Rectifier circuit

Rectifier circuit is used to convert alternating current to direct current. For every half-cycle, piezoelectric current flows through internal capacitor to either charge or discharge it. It happens because of the internal characteristics of piezoelectric. During this interval no current is delivered to the charge. Next will be analyzed how these facts are related to full-bridge rectifier, voltage doublers, and switch-only rectifier.

2.2.1 - Full-bridge rectifier

Full-bridge rectifiers are the most used circuits for this propose. The circuit is composed by diodes according to Fig. 3. The maximum rectified voltage is equal to peak of the voltage generated by the piezoelectric reduced in two voltage drops from diodes. In order to reduce energy loss due the voltage drop a Schottky diode is used (voltage drop is equal to 0.4V).

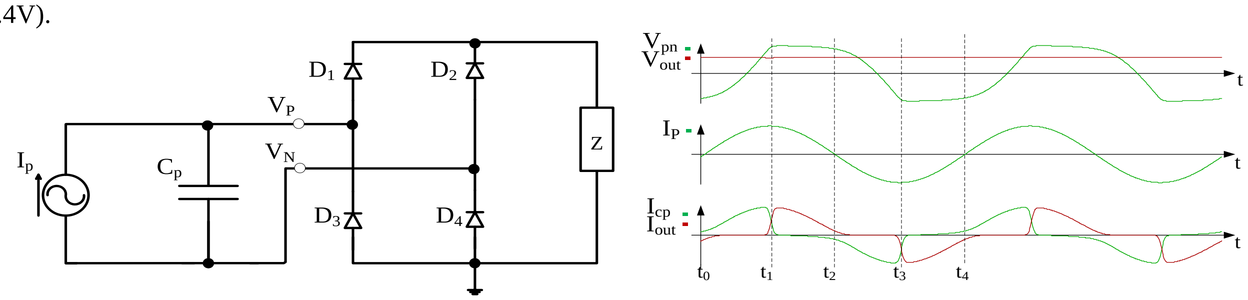


Figure 3. Full-bridge rectifier

At the beginning of positive half cycle the internal capacitor is negatively charged, so piezoelectric current flows to discharge it (current I_{cp}). This condition continues until the voltage across the capacitor becomes positive (t_1), all diodes are reversed biased and no current flows to load. Once capacitor is already charged, current flows through diodes D_1 e D_4 and the load, interval between t_1 and t_2 (current I_{out}).

At the negative half cycle the piezoelectric current inverts direction (t_2), now it flows through the internal capacitor discharging it and then charging it negatively. During this down slope all diodes are reversed biased. Once capacitor is already charged negatively, current flows through diodes D_2 e D_3 and the load, interval between t_3 and t_4 (current I_{out}). The current I_{out} flows through the load. This process repeats periodically.

2.2.2 - Voltage doublers

Voltage doubler is another circuit, largely used to rectification. This circuit is composed by two diodes as shown Fig. 4.

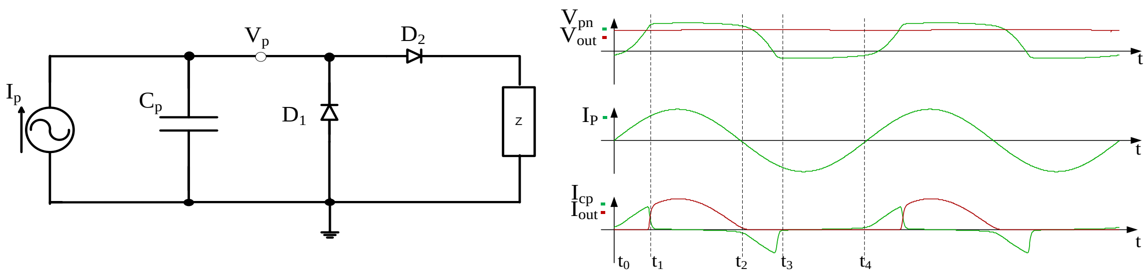


Figure 4. Voltage doubler

During the negative half cycle, piezoelectric current flows through D_1, interval between t_3 and t_4. The internal capacitor is grounded and remains discharged (ideal diodes). At this time there is no current flow through to load. At the positive half cycle, the current flows to charge the internal capacitor positively (t_1). This is, the current can charge the capacitor start from zero voltage. During this interval diodes D_1 e D_2 are reverses biased and no current flows load. Once capacitor is already charged positively the current flows through diodes D_2 and the load, interval between t_1 and t_2 (current I_{out}).

2.2.3 - Switch-only rectifier

The main limitation of the full-bridge rectifier and voltage doublers is that a significant part of the current does not flow through the load. This loss of the current occurs due to charge and discharge of the internal capacitor. This fact limits the maximum power that can be extracted from the piezoelectric transducer. In order to reduce this loss we used the switch-only rectifier, which aims to improve the ability to extract power from piezoelectric.

Switch-only rectifier is compost by MOSFET transistor, used for switching electronic, connected between piezoelectric and full-bridge rectifiers, as shown Fig. 5. The switch will be turn on for a brief time at every the piezoelectric current cross by zero (V_{cont}).

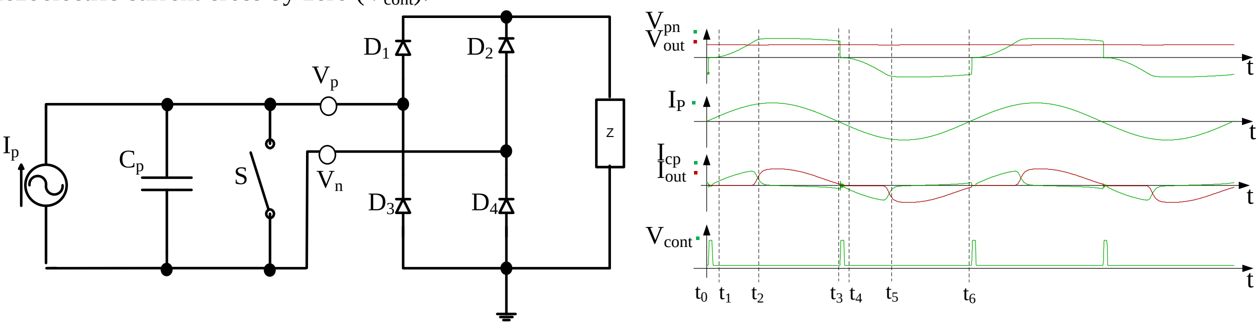


Figure 5. Switch-only rectifier

This circuit is similar to voltage doublers, but both half-cycle are rectified. When the switch turns on, the internal capacitor is then grounded and discharged (time t_1 and t_4). Once the capacitor has been discharged the switch turns off and the piezoelectric current flows to charge the capacitor (interval between t_1 and t_2 and t_4 and t_5). Then, current flows through diodes, according of the half-cycle, and the load (interval between t_2 and t_3 and t_5 and t_6). This process is repeated in all half-cycle.

In this circuit the piezoelectric current must to charge the internal capacitor only, then the current flows through the load. Thus, the current is more useful at load and has smaller loss. This is observed by the waveform I_{out} that lasts longer in this circuit

However this circuit has a disadvantage, it requires a circuit of control to switch MOSFET transistor. An important point is that the project does not connect with an external source. This means that the system must consumed less power than the generated by the transducer. The control technique should be as simple as possible, so the control circuit consumes lowest power. Considering this, the circuit control was designed with low power components.

The transistor MOSFET need to be turned on when the piezoelectric current cross by zero. At this point the voltage from the piezoelectric is peak (positive or negative) and this voltage is starting go down. So the zero-crossing of the piezoelectric current is detected by derived from the voltage from the piezoelectric (positive voltage - V_p and negative voltage - V_n). The derivatives are performed using capacitors and resistors. A discrete circuit of control was designed, as shown Fig. 6.

The circuit of control is composed by derivatives circuits, comparators and operational amplifier. First, the circuit of control compares the derivative from the positive voltage (V_{dp}) and negative voltage (V_{dn}) from the piezoelectric. For the signal control of the positive half cycle compares the derivative V_{dn} with the derivative V_{dp}. For the negative half cycle is opposite (comparison V_{dp} with V_{dn}). The output from the comparator of the control of the positive half cycle is 180 degrees out of phase with respect to the output from the negative half cycle. In the remainder of circuit occurs a similar process between the control of the positive and negative half cycle. So the circuit will be analyzed without distinction of which half cycle is about.

The output of the comparator C_{omp1} and C_{omp3} are square wave, and the polarity of the waveform is changed 25 degrees before the current zero crossing. In order to the output adjust the signal with the zero-crossing of the piezoelectric current, a comparator is used to comparison the V_{ref1} voltage and the derived of the output C_{omp1} and C_{omp3}. The output of the comparator C_{omp2} and C_{omp4} are derived and compared with the V_{ref2} voltage to determine the width of the signal according to the intended. After that, the non-inverting summing amplifier (OA) is used to sum and increases value of the voltage control signal. The output of this circuit (V_{cont}) is the signal of control of the MOSFET transistor.

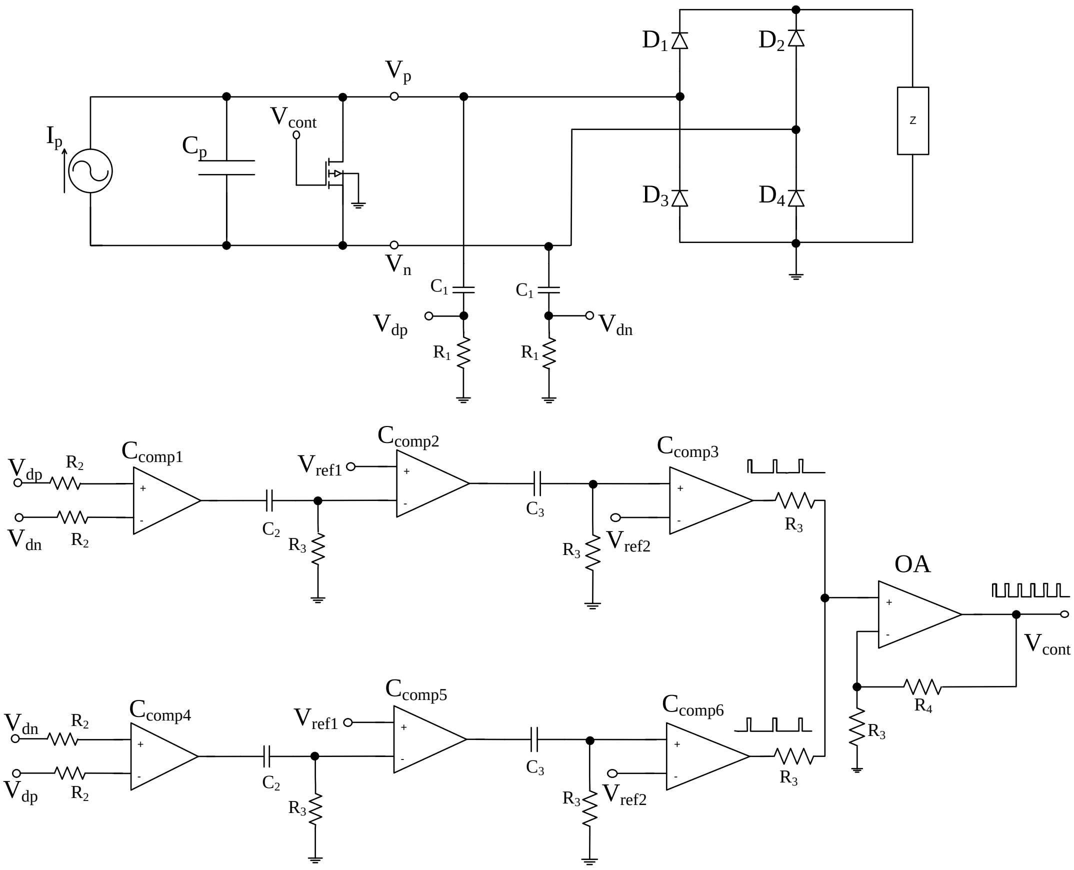


Figure 6. Discrete circuit of control for switch-only rectifier

2.3. Buck-boost Converter

The power generated by piezoelectric transducer depends of the load connected. Gonsalez (2010) shows that for the maximum power obtained, there is the optimal electrical impedance, whose value is determined by characteristics and vibration frequency from transducer piezoelectric. DC-DC converter is used to obtain matching optimal impedance. In this paper it was used buck-boost converter.

The buck-boost converter, Fig. 7, is used to control power flow between the load and source. The converter is controlled by MOSFET transistor, used as a switch electronic. If transistor operation is cut off there is no conduction of current. If it operates in saturation, the transistor allows conduction current through the load.

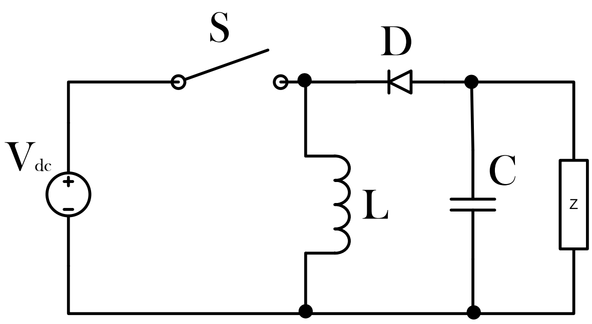


Figure 7. Buck-boost Converter

The output of buck-boost converter can be lower or higher than the input voltage, depending on duty cycle. Duty cycle is the fraction of time that transistor is conduction, it can be defined by:

$$D = \frac{t_{on}}{T} \tag{5}$$

Where: t_{on} – is the duration that transistor is conduction, T – is the period of the switching.

In the first stage the transistor is saturation and the inductor accumulates energy from input voltage source, the diode is reverse biased, and energy of the output load is supplied by capacitor. Next stage of the transistor is cutoff, the inductor transfers energy not only to load but also to capacitor.

The converter can operate in continuous current mode (CCM) or discontinuous current mode (DCM). The converter operates in continuous current mode if the inductor current never falls to zero. Still, discontinuous current mode occurs if the inductor current falls to zero before that the transistor turn on again.

In power harvesting the focus is on the operation in discontinuous current mode, considering that in this mode the buck-boost converter has performance similar as resistor, according to the equation below.

$$R_{in} = \frac{V_{re\,t}}{i_{ret}} = \frac{2\,L f_{sw}}{D^2} \tag{6}$$

So the converter can be represented by equivalent resistance. This resistance depends on the inductor, the switching frequency, and duty cycle; all parameters are known and controlled. Thus the optimal electrical impedance is obtained through buck-boost converter.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The transducer piezoelectric was excited by shaker, which simulates ambient vibrations. The frequency and amplitude of voltage of the piezoelectric was driven using the function generation and amplifier connected to shaker, as shown Fig. 8. The Piezoelectric was excited in transverse mode of operation by sine function generated by function generation Minipa MFP-4220 20 MHz and high-power current amplifier Veb Metra Mess LV 103. The frequency used is resonance frequency, whose is 166 Hz. The peak of voltage in open circuit was 3 V. The output signal from the transducer was monitored using oscilloscope and multimeter. The transducer piezoelectric used is PSI-5H4E, whose parameters are shown on Tab. 1. The dimensions of the piezoelectric and beam are shown on Tab. 2.

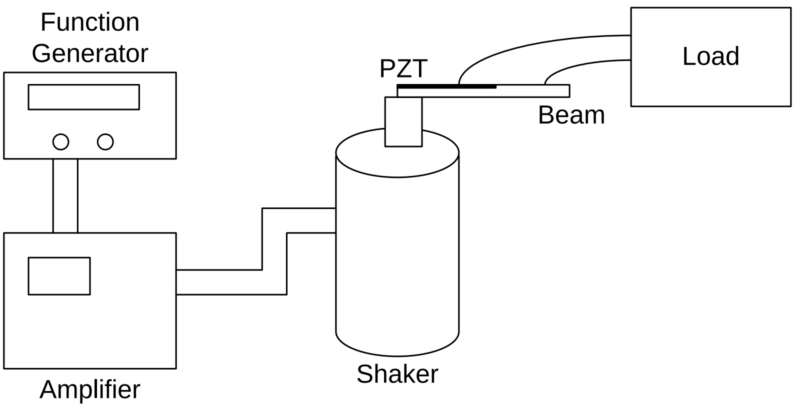


Figure 8. Experimental diagram

Table 1. Properties of the piezoelectric material PSI – 5H4E

Properties			
Relative Dielectric Constant	K^T_3	3800	
Piezoelectric Strain Constant	d_{31}	-320×10^{-12}	meter/Volt
Piezoelectric Voltage Coefficient	g_{31}	-9.5×10^{-3}	Volt meter/ Newton
Coupling Coefficient	k_{31}	0,44	
Polarization Field	Ep	1.5×10^6	Volt/ meter
Initial Depolarization Field	Ec	3.0×10^5	Volt/ meter
Elastic Modulus	Y^E_3	5.0×10^{10}	Newton/meter ^{2}
	Y^E_1	6.2×10^{10}	Newton/meter ^{2}
Density	ρ	7800	Kg/meter ^{2}
Thermal Expansion Coefficient		$\sim 3 \times 10^{-6}$	meter/meter ˚C
Curie Temperature		230	˚C

Table 2. Dimensions of the piezoelectric and beam

	Piezoelectric	Beam
Width (mm)	20.90	20.90
Length (mm)	61.00	75.70
Height (mm)	0.27	1.30

First the piezoelectric transducer was connected to the circuit full-bridge rectifier represented on Fig. 4, composed by BAS4002A-RPP low VF Schottky diode array, a 10uF tantalum capacitor and a variable resistor. Figure 9 presented the shaker, the piezoelectric transducer and the circuits mounts. Initially the circuit was connected to several values of resistance to analyze the influence of the piezoelectric transducer coupled to the load. The waveforms of the voltage from piezoelectric and the voltage output for load resistance 10 kΩ are shown in Fig. 10.

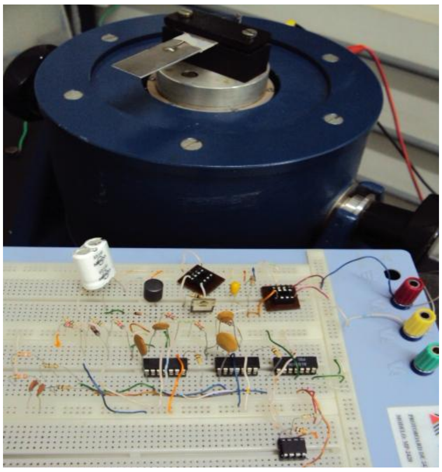
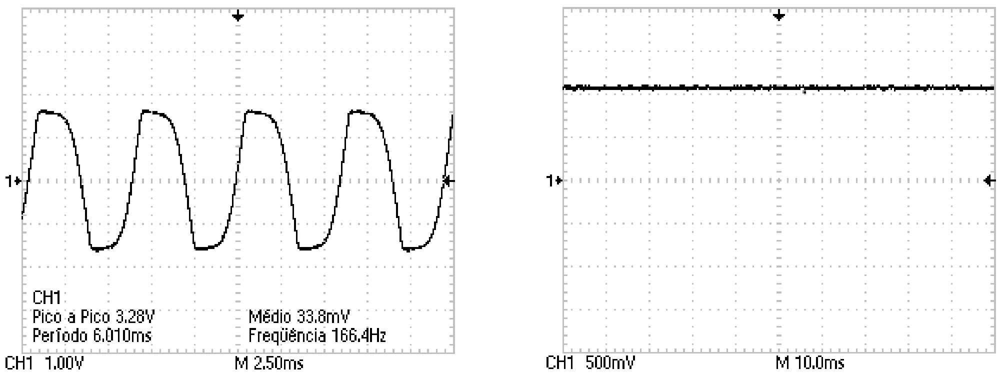


Figure 9. Picture of the experimental

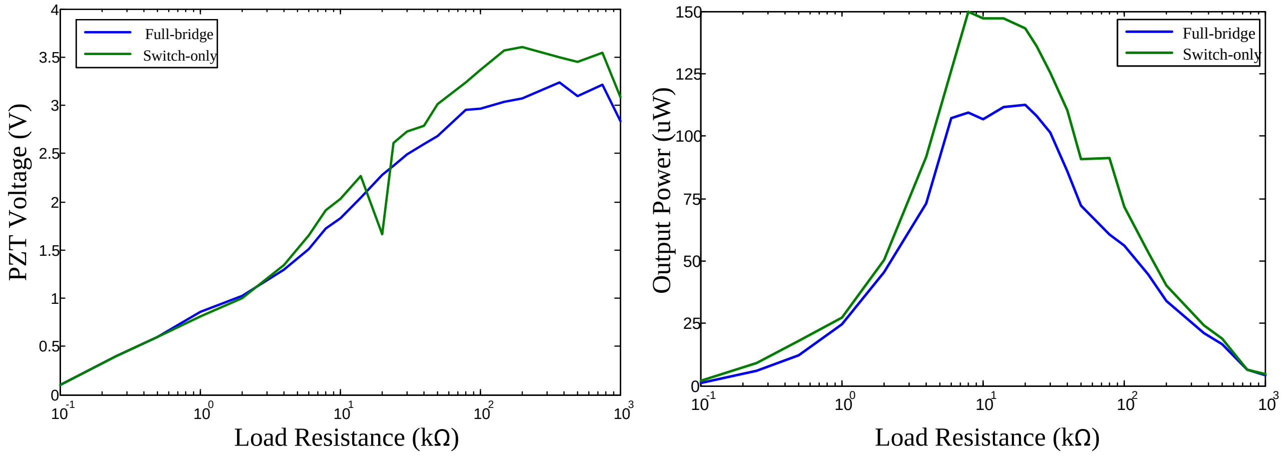
Figure 11 (a) are shown amount of voltage of the piezoelectric as a function of load resistance. In this figure is observed that when the load tends to zero (close to short circuit) the voltage of the piezoelectric is smallest, and when the value load is great the voltage of the piezoelectric is like an open circuit (no circuit connected).

In Fig. 11 (b) presents the power extracted as a function of load resistance. According to the results presented in this figure the power becomes very small when the load tends to zero and the value load is great. However, the region of the maximal power is obtained to load in the 6 kΩ to 30 kΩ range. In the circuit full-bridge rectifier the highest power extracted was 112.50 uW with load of 20 kΩ, the peak voltage in the piezoelectric is 2.28 V and the rectified voltage on the load of about 1.5 V (this drop of 0.8V tension is due to the Schottky diode).



(a) (b)

Figure 10. The waveforms from oscilloscope of the circuit full-bridge rectifier: (a) Piezoelectric voltage; (b) Output voltage

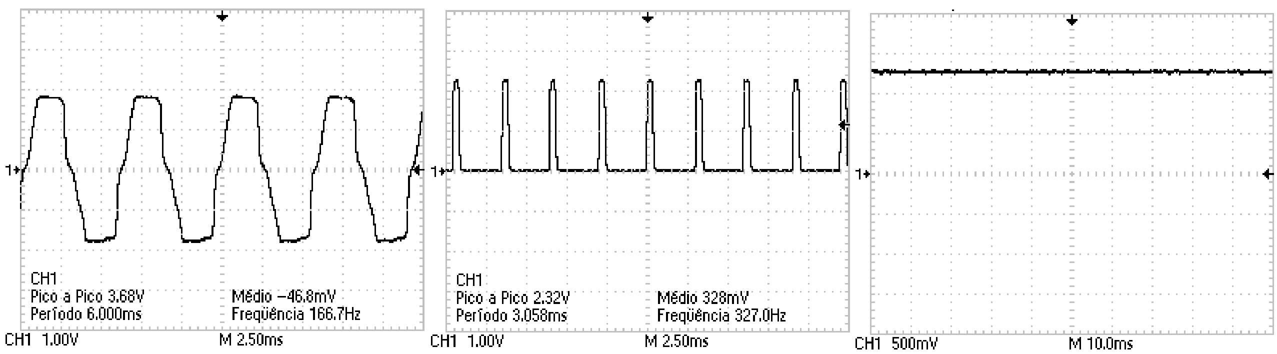


(a) (b)

Figure 11. (a) The voltage from piezoelectric as a function of load resistance; (b) The power extracted as a function of load resistance

Then, the piezoelectric transducer was connected to the circuit switch-only rectifier represented on Fig. 6. Besides the components used to full-bridge rectifier, the circuit is composed by 10 nF, 40 nF and 20 nF ceramic capacitor (respectively C_1, C_2 and C_3) and 40 kΩ, 100 kΩ, 8 kΩ and 50 kΩ (respectively R_1, R_2, R_3 and R_4). Two CI quad comparators 6544 and dual operational amplifier 6142 are used. The V_{ref1} is 1.42 V and V_{ref2} is 0.69 V. These voltages are obtained to voltage divider (50 kΩ and 20 kΩ for V_{ref1}; 50 kΩ and 8 kΩ for V_{ref2}). The transistor MOSFET used is the ALD1106 N-channel. The power supply source of the circuit of control is the supercapacitor charged. The circuits are shown in Fig. 9. The waveforms of the voltage from piezoelectric, the control and the voltage output for load resistance 10 kΩ are shown in Fig. 12.

The voltage from piezoelectric and power extracted for different resistances values can be seen in Fig. 11. The analysis of the result is the same, but on the switch-only rectifier the higher power extracted was 149.90 uW with load of 8 kΩ, the peak voltage available from the piezoelectric is 1.92 V and the output voltage is 1.09 V. This circuit of control consumes less than 18 uW, and the supercapacitor can supply power the circuit without prejudice to the power load.

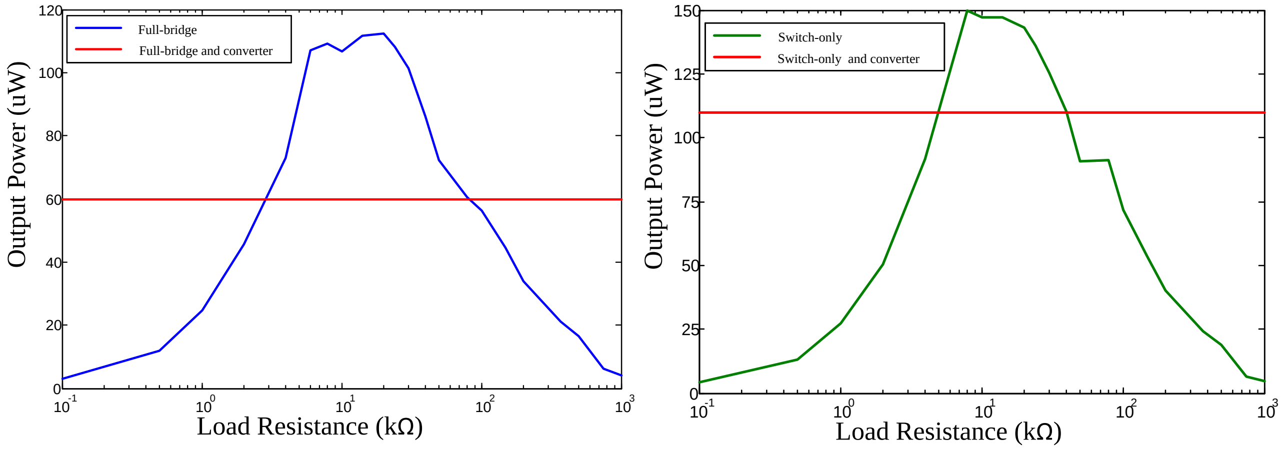


(a) (b) (c)

Figure 12. The waveforms from oscilloscope of the circuit switch-only rectifier: (a) Piezoelectric voltage; (b) Control voltage; (c) Output voltage

A comparison with the topologies of the rectifier circuit shows that the switch-only rectifier circuit has a best performance. The switch-only rectifier circuit extracts more voltage from the piezoelectric and more power from the system with a smaller load than the full-bridge rectifier.

The power extracted is dependent on the load impedance. So the buck-boost converter was used and designed to behave with the resistance value that is obtained higher power extraction. The converter is composed by 10uF tantalum capacitor and diode. The control is done with low power crystal oscillator 32 kHz (SMD EM-7604-C7). The oscillator current consumptions 300 nA, and has a duty cycle fixed in 50%. The value of inductor is defined through Eq. 6, and is 30 mH. Figure 13 show that the DC-DC converter can be adapted to adjust to a magnitude of the output impedance.



(a) (b)

Figure 13. Comparison the power extracted as a function of load resistance with converter: (a) circuit full-bridge rectifier; (b) circuit switch-only rectifier

The Tab. 4 are shown the maximal power extracted and the tension of the piezoelectric for each circuit. In all cases which used the buck-boost converter the tension of the piezoelectric transducer remained in according with the equivalent resistance. The buck-boost converter has a power consumption of about 50 uW.

Table 4. Comparison between the simulated circuits with converter buck-boost

Circuit	**Power extracts (uW)**	**Tension at PZT (V)**
Full-bridge rectifier	112.50	2.28
Full-bridge rectifier with converter	60.00	2.38
Switch-only rectifier	149.90	1.92
Switch-only rect. with converter	110.68	2.01

4. CONCLUSION

In this paper was designed and tested electronics circuits for power harvesting system. The purpose was not only to extract the maximum power from piezoelectric transducer but also to store this power in a supercapacitor to be used later in electronic circuits. After analysis, simulations and tests was established that the most appropriate electronic circuits for power harvesting are: the switch-only rectifier, which is able to extract more power than any other rectifier quoted, and buck-boost converter, which improves the systems performance. The circuits of control used to switch-only rectifier and buck-boost converter consume lower power than the produced by transducer piezoelectric. So these circuits are able to maximize the power extracted from transducer piezoelectric.

5. ACKNOWLEDGEMENTS

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