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Human body activity energy harvesting system with a piezoelectric transducer

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Abstract

The objective of this project is the energy quantification that can be collected from the movement of the human body with a simple scheme of conversion with a piezoelectric transducer. It will be examined how to accumulate the energy, given the current that is obtained from the piezoelectric transducer responsible of transform the mechanical energy into electrical energy is reduced and discontinuous. Work consists of three stages that, through the power electronics, are based on 1) design and 2) construct the necessary circuit for the signal treatment and later 3) extract results. The circuit to be designed aims to prepare the signal produced by the piezoelectric to be sufficiently stable to be used to supply a system. After designing the circuit and perform the necessary simulations to know the theoretical behaviour, with an idea of the voltage level that the system will provide, an appropriate component is chosen to be used as a load and the real operation is checked through a PCB design which allow different component combinations to realize the tests. Once the tests have been performed it is done a comparison of the actual results and the ones according to the simulations and it is chosen the components combination that allow a better system efficiency. Finally it is proposed the development of a system of greater consumption completely autonomous that could work through the study that has been realized in this project by arranging more piezoelectrics to produce more energy.

Resum

Aquest projecte té com a objectiu la quantificació de l'energia que es pot recollir a partir del moviment del cos humà amb un esquema simple de conversió amb un transductor piezoelèctric. S'examinarà la manera d'acumular l'energia, donat que el corrent que s'obté del transductor piezoelèctric encarregat de transformar l'energia mecànica en elèctrica es reduït i discontinu. El treball consta de tres etapes que, mitjançant l'electrònica de potencia, es basen en 1) dissenyar i 2) construir el circuit necessari per al tractament de senyal i posteriorment 3) extreure resultats. El circuit a dissenyar pretén preparar la senyal produïda pel piezoelèctric per a que sigui prou estable per a ser utilitzada per alimentar un sistema. Després de dissenyar el circuit i realitzar les simulacions necessàries per conèixer el seu funcionament teòric, amb una idea del nivell de tensió que proporcionarà el sistema, es tria un component adequat per utilitzar com a càrrega i es procedeix a la comprovació del funcionament real mitjançant el disseny d'una PCB que permet diferents combinacions de components per realitzar les proves. Una vegada realitzades les proves reals es fa una comparació entre els resultats reals i el esperats segons les simulacions i es tria la combinació de components que permeten un millor rendiment del sistema. Finalment es proposa el desenvolupament d'un sistema de major consum completament autònom que podria funcionar mitjançant l'estudi que s'ha realitzat en aquest projecte disposant de més piezoelèctrics per a produir més energia.

Resumen

Este proyecto tiene como objetivo la cuantificación de energía que se puede recoger a partir del movimiento del cuerpo humano con un esquema simple de conversión con un transductor piezoeléctrico. Se examinará la manera de acumular la energía, dado que la corriente que se obtiene del transductor piezoeléctrico encargado de transformar la energía mecánica en eléctrica es reducida y discontinua. El trabajo consta de tres partes que, mediante la electrónica de potencia, se basan en 1) diseñar y 2) construir el circuito necesario para el tratado de señal y posteriormente 3) extraer resultados. El circuito a diseñar pretende preparar la señal producida por el piezoeléctrico para que sea suficientemente estable para ser utilizada para alimentar un sistema. Después de diseñar el circuito y realizar las simulaciones necesarias para conocer su funcionamiento teórico, con una idea del nivel de tensión que proporcionará el sistema, se escoge un componente adecuado para utilizar como carga y se procede a comprobación del funcionamiento real mediante el diseño de una PCB que permite diferentes combinaciones de componentes para realizar las pruebas. Una vez realizadas las pruebas reales se escoge la combinación de componentes que permiten un mejor rendimiento del sistema. Finalmente se propone el desarrollo de un sistema de mayor consumo completamente autónomo que podría funcionar mediante el estudio que se ha realizado en este proyecto disponiendo de más piezoeléctricos para producir más energía.

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The PCB was fabricated by Vicente Ruiz of the Electronics Laboratory of the ETSETB.

1. Introduction

This study arises from the current environmental situation in relation to the generation of electric energy. Energy harvesting allows to obtain electric energy capturing and transforming energy from external sources, therefore taking advantage, in each situation, of the most suitable type of energy such as thermal energy, kinetic energy, solar energy, etc. Collecting energy through this process provides little amount of electrical energy, but given the advance in low-power electronics and the current need for renewable energy sources, the energy harvesting is currently an important focus of study. What's more, this way to generate electrical energy favours the advancement of autonomous systems, since it does not require the maintenance of batteries and allows supply systems in different conditions taking advantage of the energy available around it, therefore increases the options of providing energy.

In this study we will consider the kinetic energy generated by a person as a source of energy, since generally we make much movement throughout the day and this can be used to supply energy to the devices that we usually carry.

1.1. Goals

The main objective of the project is to quantify the energy that can be obtained by transforming the kinetic energy generated by a person in motion using a piezoelectric and a simple conversion scheme. There is no energy value to be achieved but we will try to get the most of the energy produced by the piezoelectric. With the result obtained it is expected to supply a system whose requirements match the obtained energy and that way prove the operation of the designed circuit. To achieve these goals, the project is divided into the following sections with their corresponding purposes:

- Circuit design: With the aim of conditioning energy that is obtained from the piezoelectric, we design a circuit with which operating simulations are performed and which will then be built to obtain results.
- Results: Results will be taken by varying circuit parameters which have previously been analysed, then real results and those of the simulations will be compared.

1.2. Work plan

The work plan set out at the beginning of the project has been followed, no time changes have been made although certain tasks have been done differently. Tasks are divided into: previous tests with the piezoelectric, circuit design and simulations, circuit construction and realizations of documents. The only change was instead of performing the simulations at the end of the corresponding task, these were performed while the circuit was designed.

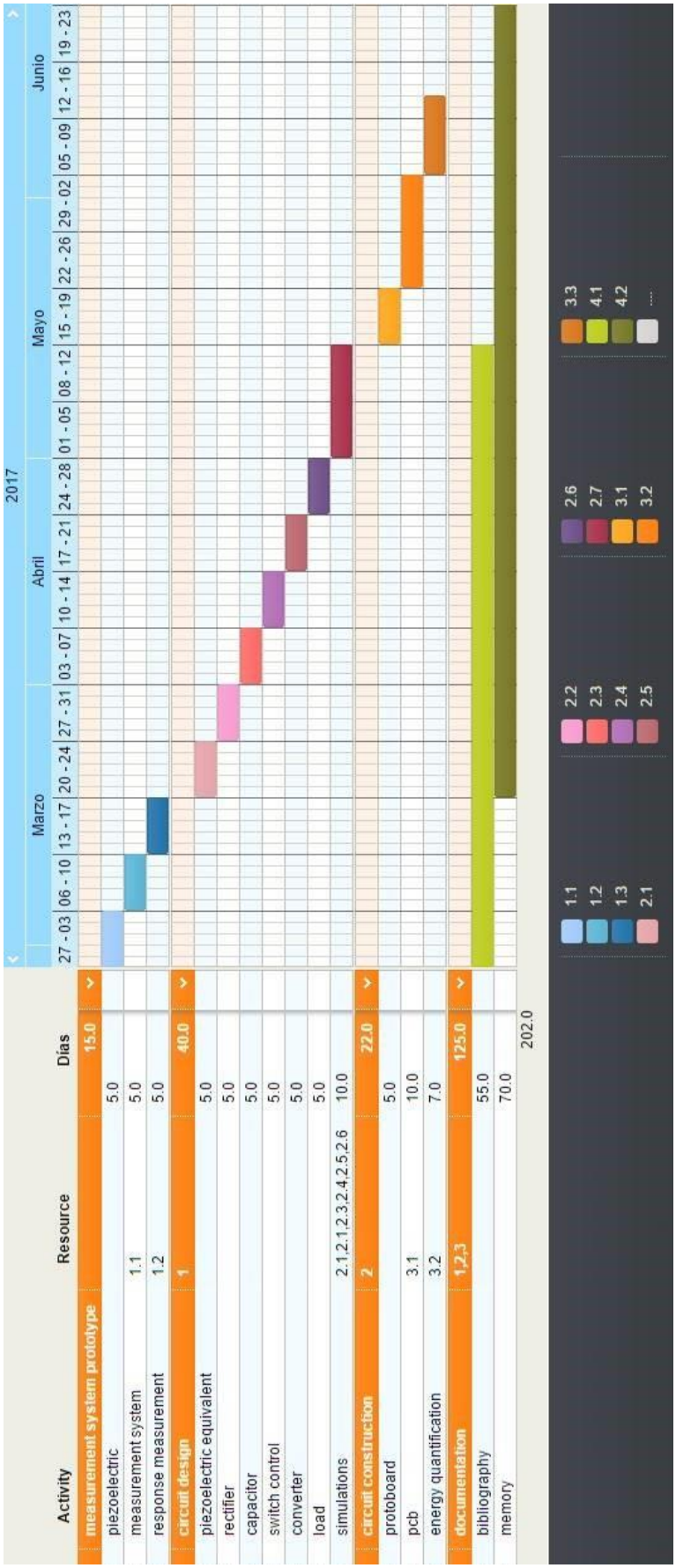

Figure 1: Project Gantt diagram

2. State of the art of the technology used or applied in this thesis:

This section contains a brief explanation of the technological devices that have been used in this project, those that have been considered and the ones that have been finally selected. The choice of appropriate components to maximize the recovered energy has been a large part of this project work, so here it is not explained each device that has been studied but only those that have been believed more appropriate. There are also explained some related articles that have helped to realize the project since they are about existing projects about energy harvesting.

2.1. Piezoelectric transducer

2.1.1. Piezoelectricity

Piezoelectricity is a method that takes advantage from the phenomenon that occurs in some crystals when they are subjected to mechanical strains. The material deformation causes an electric polarization so it allows to use the charge on its surface. This effect also occurs inversely, a material can be deformed by applying an electric potential, but this project is focused on the production of electrical energy.

2.1.2. Piezoelectric film

A piezoelectric film is based on a polymer with the piezoelectric effect as previously explained.

Taking in mind the mobility that the piece has to have for this application a film piezoelectric will be used, it has the necessary flexibility to realize the movement which we verified that generates greater electrical current. In this project, we used the DT2-028K/L w/rivets (Ref. [4])

Figure 2: Piezoelectric film DT2-028K/L w/rivets

2.1.3. Equivalent electric circuit

The piezoelectric equivalent electric circuit can be modelled as an alternate current source with a capacitor in parallel.

Figure 3: Piezoelectric equivalent electric circuit

The value of the simulation parameters of the device depends on the geometry of this device and its material.

2.2. Review of the Literature of Piezoelectric Energy Harvesting Circuits

This section makes reference to the chapter 11 of *Piezoelectric Energy Harvesting* (Ref. [3]), where are reviewed some of papers from the literature of piezoelectric energy harvesting circuits.

2.2.1. AC-DC Rectification and Analysis of the Rectified Output

Here it's explained the standard circuit used to rectify de AC output of the piezoelectric, one-stage energy harvesting interface, this circuit consist of a piezoelectric connected to a full-wave rectifier a smoothing capacitor and a resistive load. From this circuit there are provided a estimation of the harvested power

$$P = \frac{4R\Theta^2\omega^2}{\left(2C_pR\omega + \pi\right)^2}u_0^2$$

Where Θ is the effective piezoelectric coupling coefficient, ω the resonance frequency, u_0 vibration amplitude and C_p the smoothing capacitor.

2.2.2. Two-Stage Energy Harvesting Circuits: DC-DC Conversion for Impedance Matching

This part proposes using a DC-DC converter after the AC-DC converter since the rectified voltage is not constant and to achieve the maximum power transfer. After estimating the converter efficiency, it is concluded that one-stage interface can have a higher efficiency than he two-stage if an optimal voltage level is chosen for the energy storage device because the DC-DC converter consumption might cancel the advantages of the two-stage interface.

2.2.3. Synchronized Switching on Inductor for Piezoelectric energy Harvesting

In this section the effect of the electromechanical coupling in the system is analysed. This circuit adds a switch and an inductor in series connected in parallel with the piezoelectric and the rectifier bridge. The operation of the modification of the circuits consists of close the switch during the first half of the vibration period and open it during the other half, that way during the second half period the piezoelectric voltage is inverted. Finally the average power delivered to the load now is

$$P = \frac{4R\Theta^2\omega^2}{\left[(1-q_1)C_pR\omega + \pi\right]^2}u_0^2$$

Where $q_1 = e^{-\frac{\pi}{2Q_1}}$ and Q_1 the inversion quality factor.

In this project we use the One-stage rectifier on capacitor approach, due to its simplicity and ease of implementation.

2.3. Related projects

2.3.1. Optimized Piezoelectric Energy Harvesting Circuit using Step-Down Converter in Discontinuous Conduction Mode

This article (Ref. [2]) is about maximize the harvested power using a step-down DC-DC converter, the study is based on finding the duty cycle that allows the converter transfer the energy optimally. Some piezoelectric equations are presented, since piezoelectric can be modelled as a sinusoidal current source in parallel with a magnitude of polarization current I_P, it is shown that the DC component of the output current of the rectifier and the output power of the piezoelectric are

$$< i_o >= \frac{2I_P}{\pi} - \frac{2V_{rect}\omega C_p}{\pi}$$

$$< \boldsymbol{P(t)} >= \frac{\boldsymbol{2V_{rect}}}{\boldsymbol{\pi}}(\boldsymbol{I_P - V_{rect}\omega C_P})$$

Where V_{rect} is the rectifier output voltage, C_P the piezoelectric electrode capacitance and ω the resonant frequency of the mechanical host structure.

The duty cycle relates the output to the input as follows

$$V_{out} = \frac{D}{D+T_1}V_{in}$$

$$I_{out} = \frac{V_{out}T_s}{2L}(D+T_1)T_1$$

Where T_1 is the time that the transistor is off, from the power conservation principle $P_{in}=P_{out}$ and with the previous equations input current of the converter is

$$I_{in} = \frac{D^2}{2Lf_s}(V_{in} - V_{out})$$

The power produced by the piezoelectric can be expressed as the product of the rectifier voltage and the converter input current

$$P_{in} = \frac{D^2}{2Lf_s} \frac{\left(\frac{2I_P}{\pi} - \frac{2\omega C_P}{\pi} V_{out}\right)\left(\frac{2I_P}{\pi} + \frac{D^2}{2Lf_s} V_{out}\right)}{\left(\frac{D^2}{2Lf_s} + \frac{2\omega C_P}{\pi}\right)}$$

Finally to maximize P_{out} the duty cycle results

$$\boldsymbol{D_{opt} = \sqrt{\frac{4V_{rect}\omega L C_P f_s}{\pi(V_{rect} - V_{out})}}}$$

2.3.2. Design of Internal Startup Circuit for Implantable Pacemakers using Energy Harvesting Technique

This paper (Ref. [1]) deal with the need to change pacemakers batteries, this supposes a surgical process so to avoid it it's proposed power up the pacemaker with harvesting thermal energy. System ordinary operation consists on the steady-state boost converter generates a clock phase and pre-startup circuit is not needed, in case of the steady-state boost converter output voltage falls out of range the startup boost converter would return to perform the previous task.

2.4. Signal conditioning circuit

As a first research on energy harvesting, project introduction is a study on existing technology related to piezoelectricity and its conditioning. Figure 4 shows the necessary modules to use the energy from the piezoelectric to supply a load.

Figure 4: Energy harvesting circuit modules

2.4.1. Piezoelectric element

The first module is the piezoelectric element, it provides an alternating current dependent on the forces acting on the piezoelectric, so this signal will be discontinuous and the rest of the modules have to be prepared to work with this feature

2.4.2. AC-DC rectifier

Since piezoelectric gives an alternating current it's necessary to rectify the signal to provide a stable DC voltage to the load. Received signal amplitude can be very low, so this element has to be able to rectify this type of signals with sufficient efficiency to make the most of it.

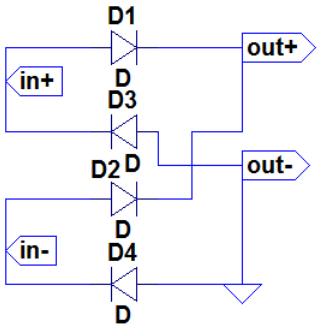

Figure 5: Diode bridge rectifier

2.4.2.1. Diodes bridge rectifier

This electronic circuit converts alternate current into direct current. The bridge works in two simple steps:

1) During the input signal positive half cycle, diodes 1 and 4 are working while 2 and 3 are in break, so signal flows from in^+ to out^+.
2) In the other half cycle, diodes 2 and 3 connect in^- to out^+, so the negative signal becomes positive at the output.

Through this process, at the output is obtained the signal showed in Figure 3.

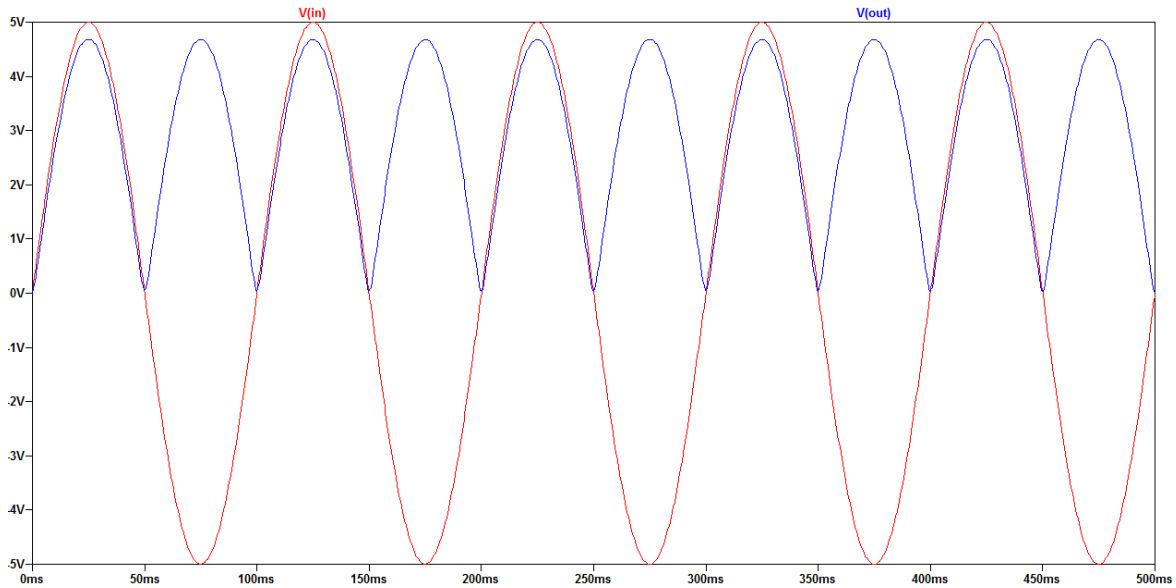

Figure 6: Rectified signal with diodes bridge

Finally, to obtain a DC signal a capacitor is included, which is charged and maintains a stable voltage value.

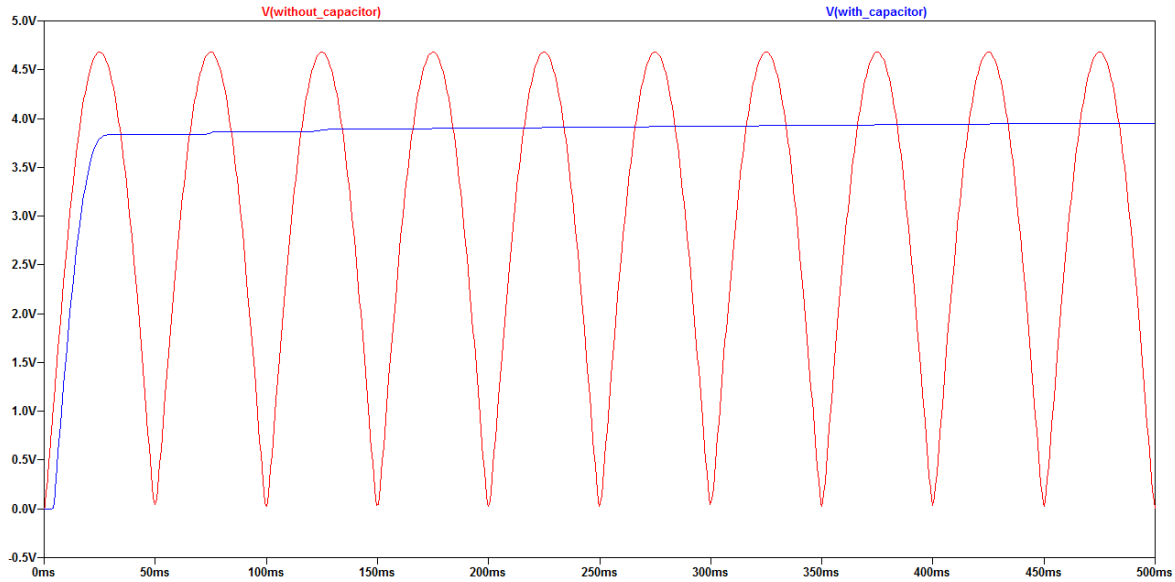

Figure 7: Rectified signal with diodes bridge and capacitor

The characteristics of the diodes and capacitor used determine certain aspects of the similarity between waves. The threshold voltage of the diode is the main limitation in the rectifier behaviour. The lower the threshold voltage, the closer will be the rectified output to the input. It is necessary to take into account also the diodes break down voltage depending on the amplitude of the input.

2.4.2.2. Transistors bridge rectifier

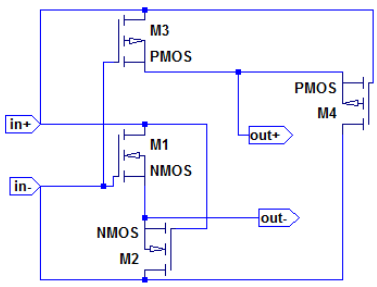

Figure 8: Transistors bridge rectifier

The operation mode of this rectifier is analogous to the diodes bridge, M3 and M1 acts like diodes 1 and 4, and M2 and M4 like diodes 2 and 3. PMOS and NMOS transistors are used to allow the current flow in both bridge paths depending on the input voltage, a capacitor is included at the output too to obtain the DC signal.

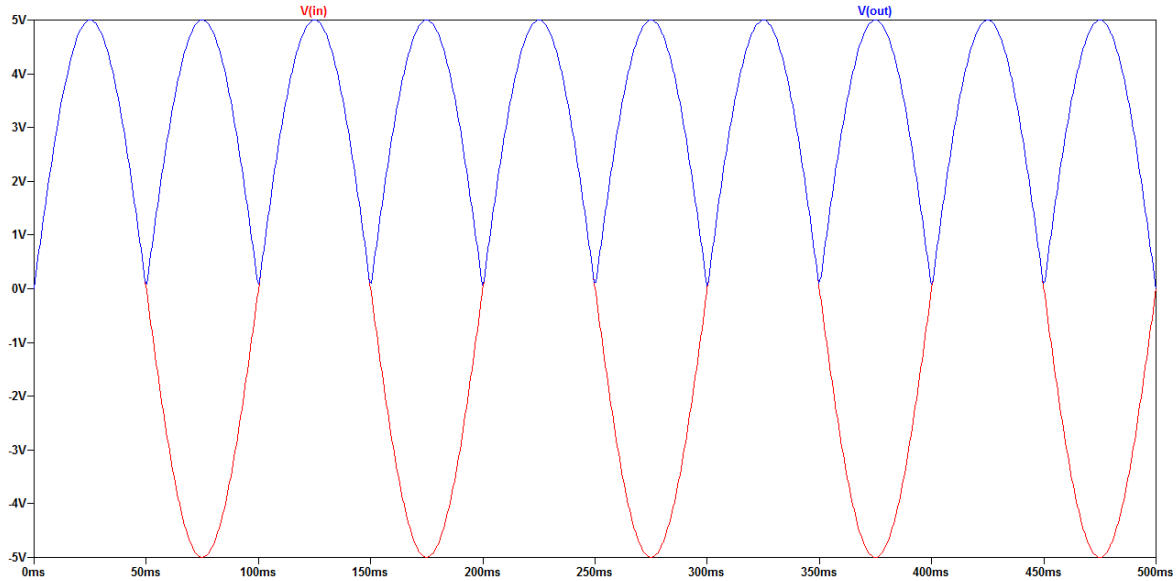

Figure 9: Rectified signal with MOS bridge

Transistor characteristics determine the rectifier operation as in previous case, threshold voltage, internal resistance, etc.

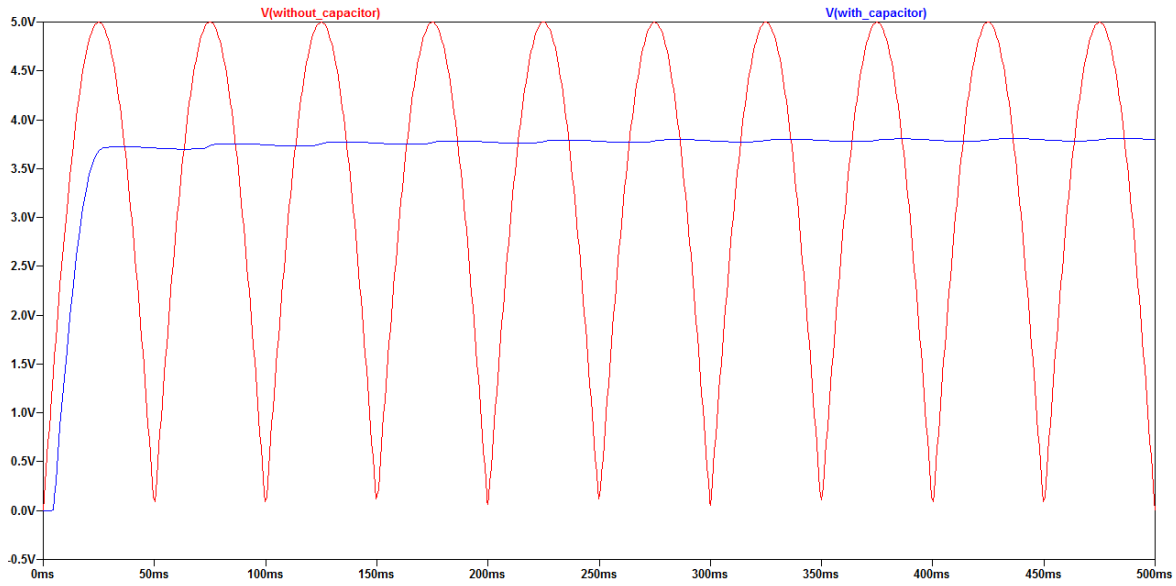

Figure 10: Rectified signal with MOS bridge and capacitor

2.4.3. Dicontinuous power management

It will be necessary to accumulate the energy in a capacitor until it's enough to supply the load. This process must be done optimally, depending on the type of load. It has to keep in mind the time required during the load has to be supplied, the time intervals in which the load operation has to be implemented and the voltage level needed.

Specifically in this project, the energy available is found in a capacitor which in open circuit is charged and accumulates energy and when it's connected it transmit the energy and it's discharged, thus is needed a device that acts like a smart switch, that connects the capacitor when it has enough energy accumulated. For this function is used a

comparator because this device is activated when in its input there is as minimum a determined voltage level. Specifically it is used a comparator with hysteresis because it allows to choose a connection voltage level and a disconnection voltage level which is lower, so the capacitor stops supplying energy and is recharged again. Thus, power is provided during a determined interval fixed by the hysteresis levels.

This type of comparator is a more complex version of the simple comparator, positive feedback is added and a voltage divider to choose the voltage range of the hysteresis. This comparator output takes the value of the positive voltage supply when the input voltage reaches the set upper limit (V_{upper_limit}), and takes the negative voltage supply when the input reaches the set lower limit (V_{lower_limit})..

Figure 11 shows how the output changes depending on the difference between the

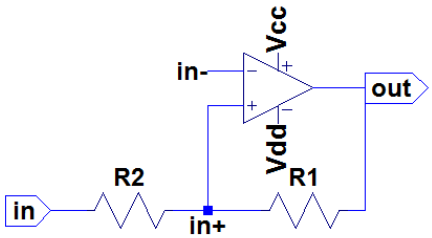

Figure 11: Comparator with hysteresis

amplifier inputs for a random resistors values. The relations between hysteresis voltage limit and resistors values are:

$$V_{lower_limit} = V_{in}^{-}\frac{R_1 + R_2}{R_2} - V_{dd}\frac{R_1}{R_2}$$

$$V_{upper_limit} = V_{in}^{-}\frac{R_1 + R_2}{R_2} + V_{cc}\frac{R_1}{R_2}$$

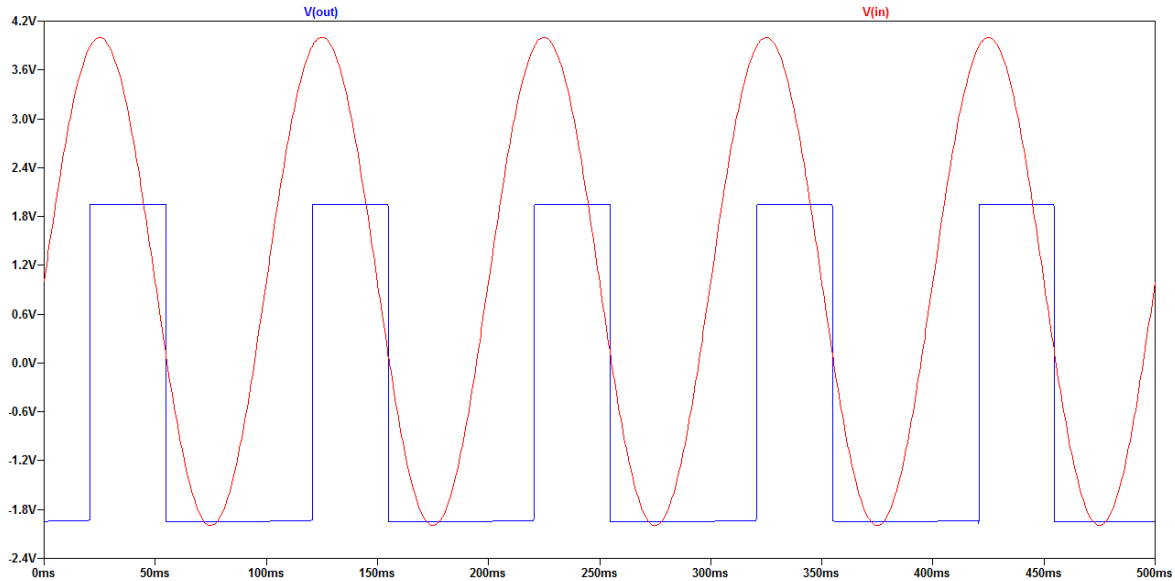

Figure 12: Output and input of a comparator with hysteresis

In our case the input signal is not a sinusoid, so the comparator will not activate periodically while the signal is maintained within a voltage range. In our circuit the input

signal is the voltage of a capacitor, so the comparator will be activated when the capacitor reaches a certain value and it will remain active while the capacitor is discharged (in case the voltage that charges the capacitor isn't be able to avoid the discharge) and will be disabled when the capacitor voltage is below a other certain value to allow it to be reloaded.

2.4.4. Load

A single piezoelectric is not able to provide a lot of energy, so the load has to be chosen accordingly.

3. Methodology / project development:

In this chapter there are explained all the processes that have been followed throughout this project, in the same order that they have been developed. At the beginning is done a study of energy harvesting circuits with a piezoelectric, from this the main project parts are obtained. After defining the parts of the circuit that will be necessary, the theoretical and simulation work begins, this include test with the piezoelectric to determine its behaviour and its equivalent for simulations, the rectifier choice, the search for a way to accumulate the recovered energy and the choice of the load to supply with the energy achieved.

All simulations are done with LTspice [10] and the provided library of components.

3.1. Piezoelectric Film Characterization

The first step was to check the current you get with different forces on the piezoelectric, after trying different ways it was proved the movement that most current induces is when one piezoelectric tip remains fixed and the other makes a movement like a pendulum. At higher vibration frequency greater amplitude of the signal generated, at the intermediate speed at which the piezoelectric can be moved (approximately 1 Hz), was obtained an amplitude of 1 V on the oscilloscope input resistance. To find the exact parameters of the equivalent circuit that brings this signal, the circuit was simulated with current source different values until finding a similarity. The parallel capacitor was previously measured so it's set to 25 nF and the oscilloscope resistance is 1 MΩ.

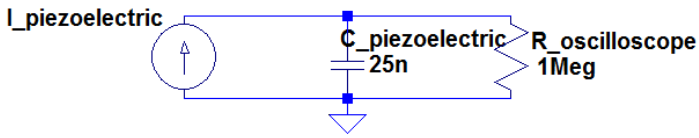

Figure 13: Piezoelectric equivalent circuit

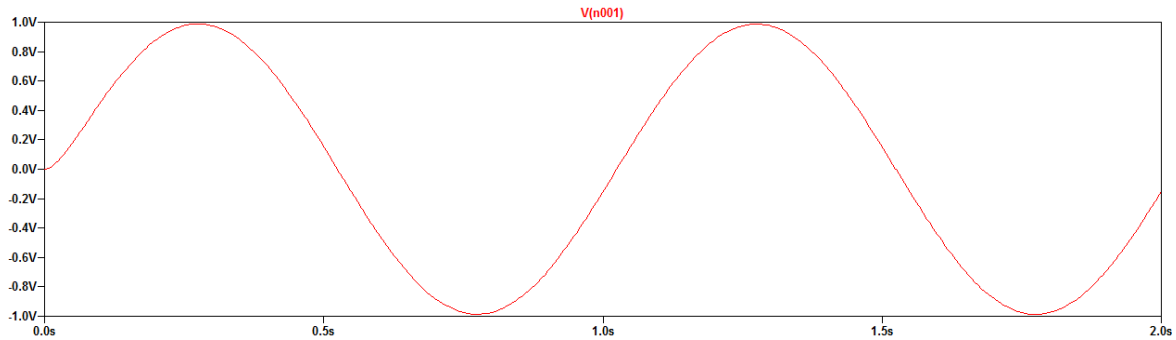

Figure 14: Piezoelectric equivalent with 1 µA amplitude and 1 Hz frequency current source

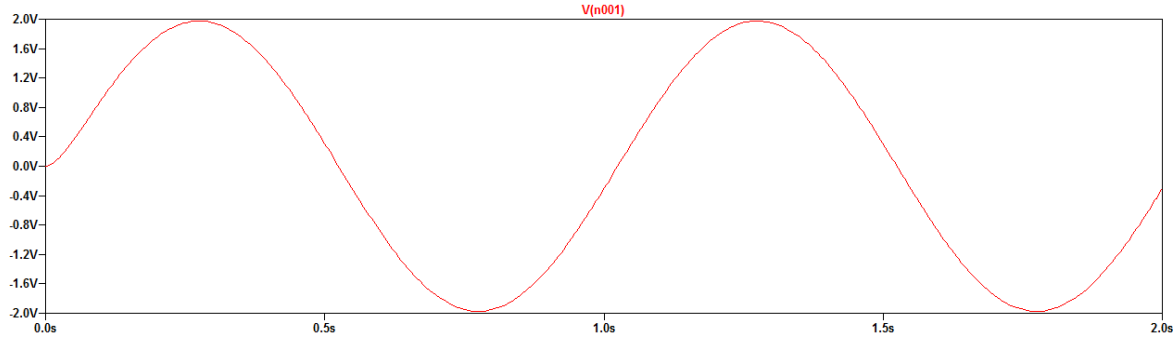

Figure 16: Piezoelectric equivalent with 2 μA amplitude and 1 Hz frequency current source

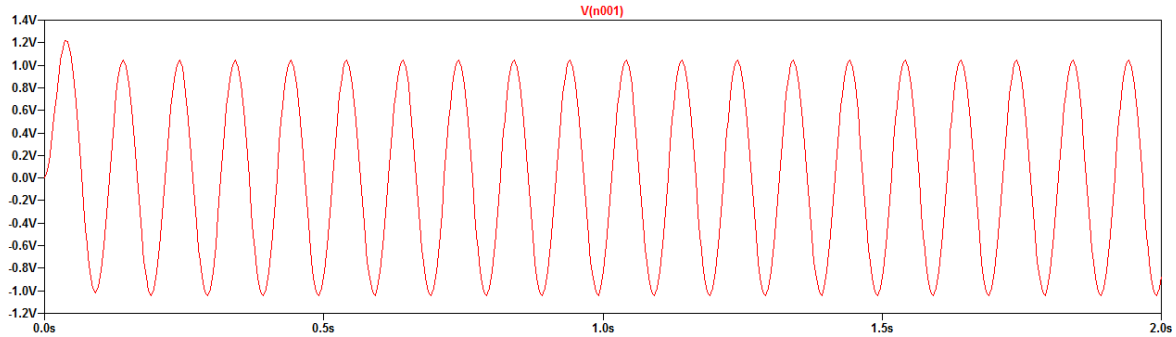

Figure 15: Piezoelectric equivalent with 2 μA amplitude and 10 Hz frequency current source

After some tests, result more similar was obtained with a current source with 1 μA amplitude and 1 Hz frequency

3.2. Rectifier selection

There are some elements to implement the bridge, it's necessary pick one that brings the rectifier work under conditions induced by piezoelectric. As options there are some diodes types and transistors, several of each with different characteristics were tested:

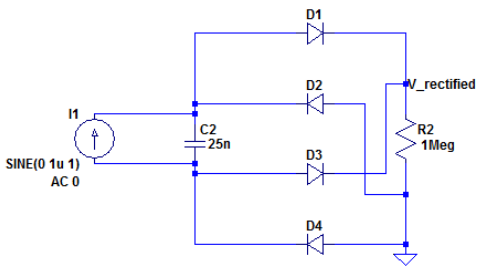

Figure 17: Rectifier bridge with silicon diodes circuit

3.2.1. Rectifier bridge with silicon diodes

- 1N914: Average forward current 0.7 A, Breakdown voltage 75 V

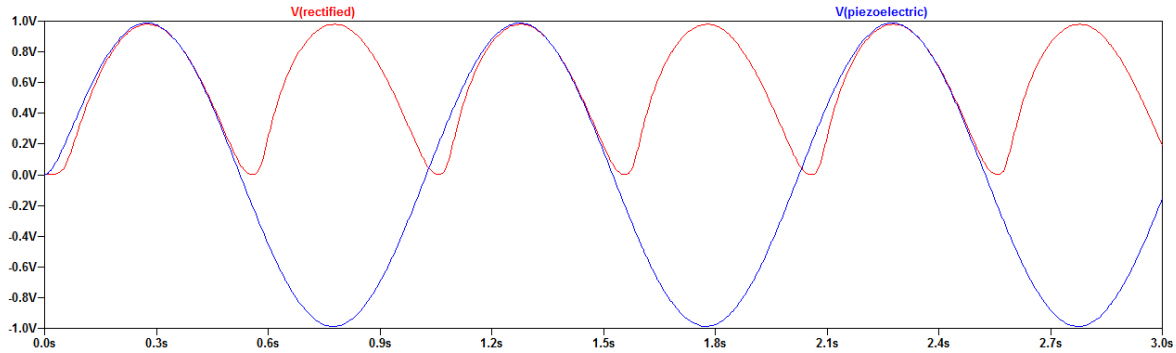

Figure 18: Rectified voltage with 1N914 diodes

- RRE02VS4S: Average forward current 0.7 A, Breakdown voltage 400 V

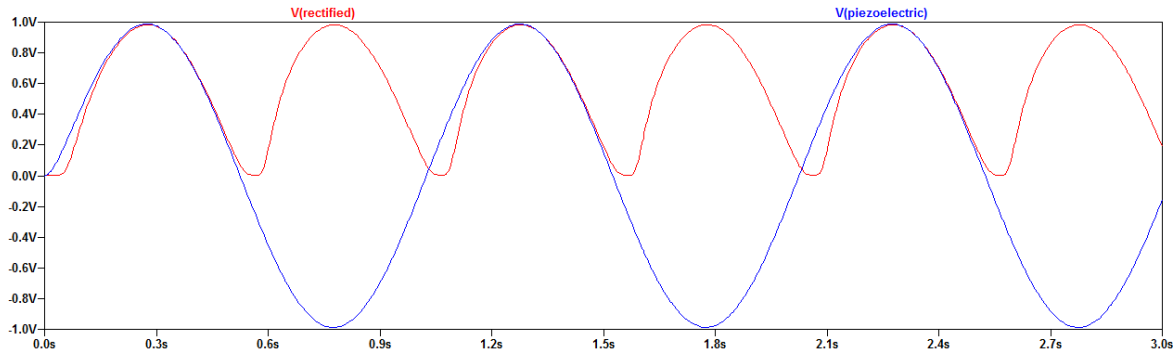

Figure 19: Rectified voltage with RRE07S4S diodes

3.2.2. Rectifier bridge with zener diodes

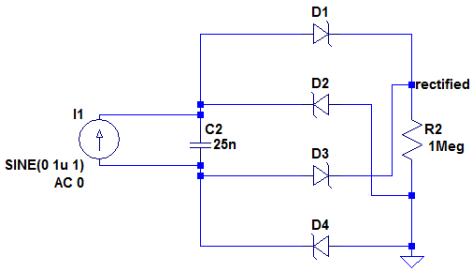

Figure 20: Rectifier bridge with zener diodes circuit

- BZX84C6V2L: Breakdown voltage 6.2 V

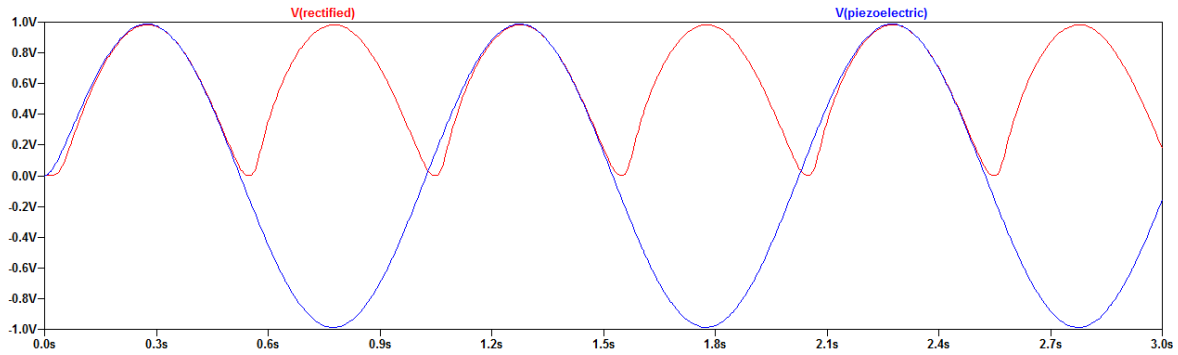

Figure 21: Rectified voltage with BZX84C6V2L diodes

- 1N5373B: Breakdown voltage 68 V

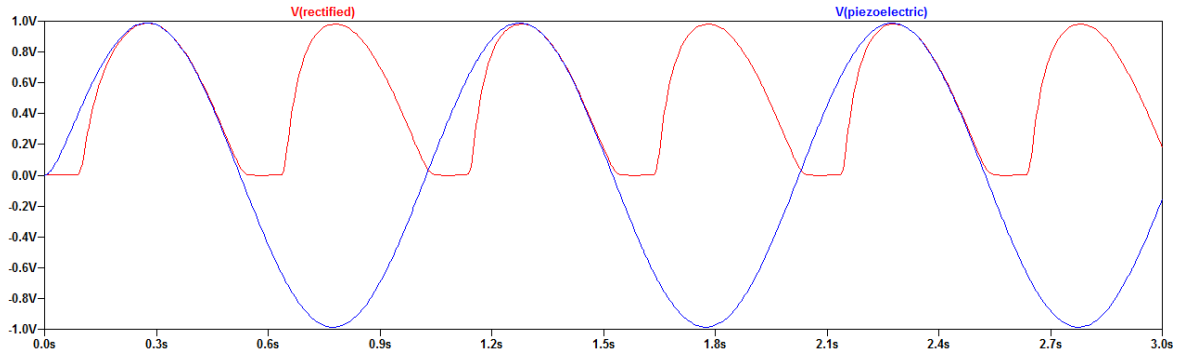

Figure 22: Rectified voltage with 1N5373B diodes

3.2.3. Rectifier bridge with Schottky diodes

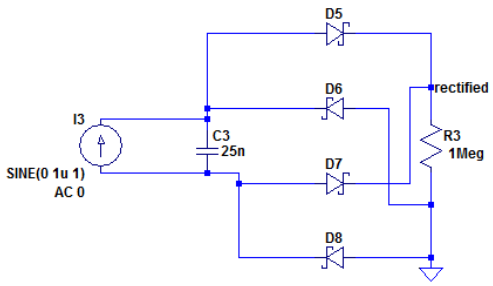

Figure 23: Rectifier bridge with Schottky diodes circuit

- BAT54: Average forward current 0.3 A, Breakdown voltage 30 V

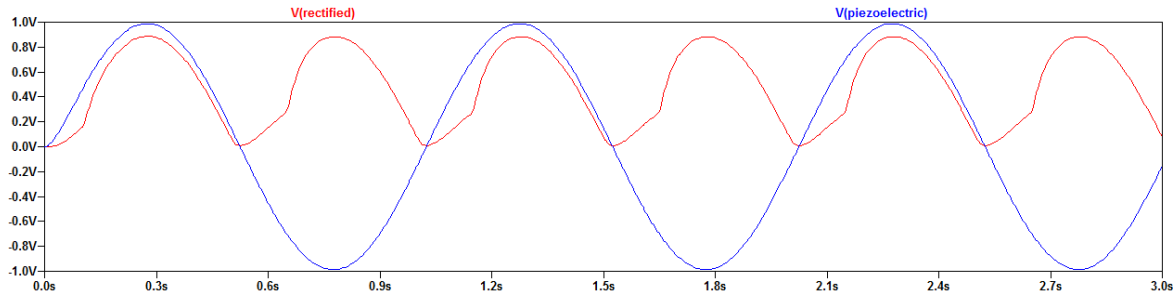

Figure 24: Rectified voltage with BAT54 diodes

- 1N5819: Average forward current 1 A, Breakdown voltage 40 V

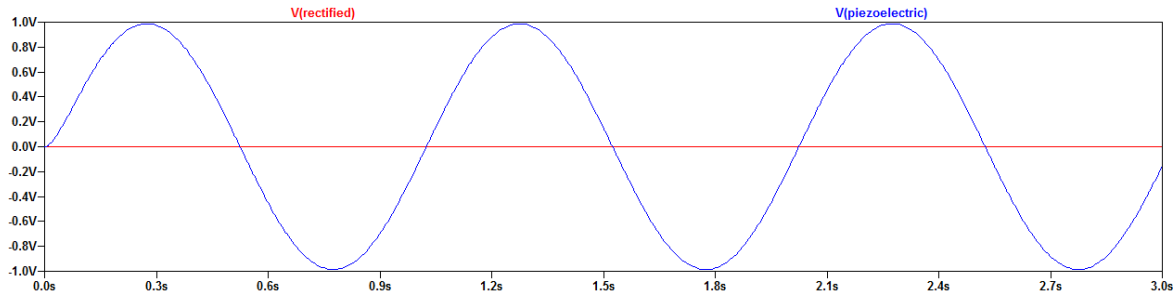

Figure 25: Rectified voltage with 1N5819 diodes

- MBR0520L: Average forward current 0.5 A, Breakdown voltage 20 V

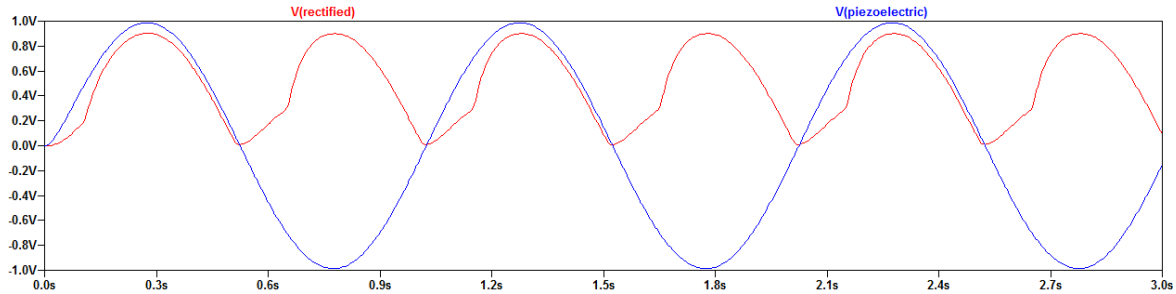

Figure 26: Rectified voltage with MBR0520L diodes

- BAT46WJ: Average forward current 0.25 A, Breakdown voltage 100 V

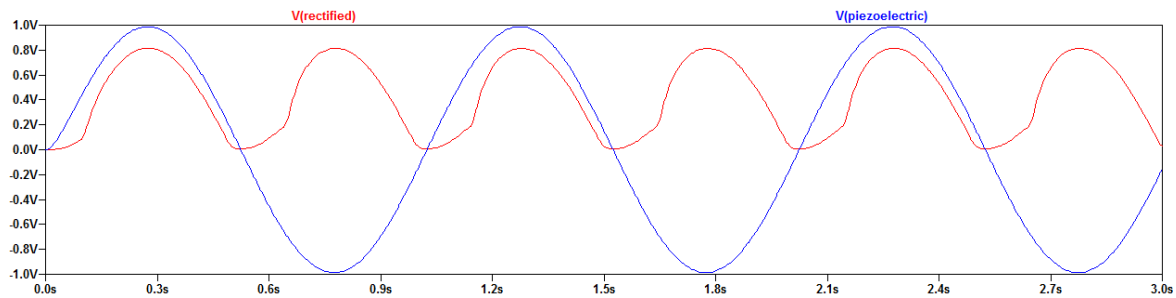

Figure 27: Rectified voltage with BAT46WJ diodes

3.2.4. Rectifier bridge with MOS transistors

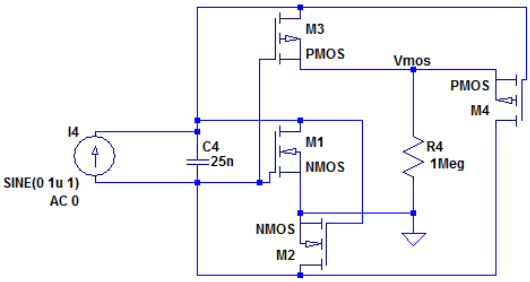

Figure 28: Rectifier bridge with MOS transistors circuit

- PMOS FDS4435: Rds 25 mΩ, Vds -30 V. NMOS Si7336ADP: Rds 2 mΩ, Vds 30 V.

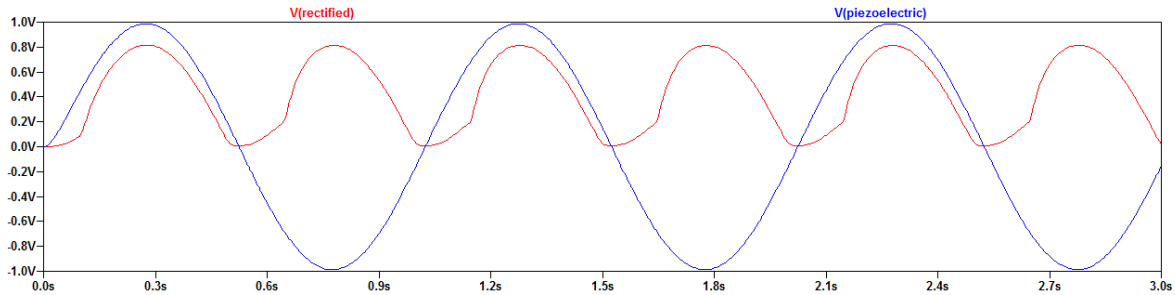

Figure 29: Rectified voltage with FDS4435 and Si7336ADP transistors

- PMOS Si4465DY: Rds 9 mΩ, Vds -8V. NMOS Si4866DY: Rds 5 mΩ, Vds 12V.

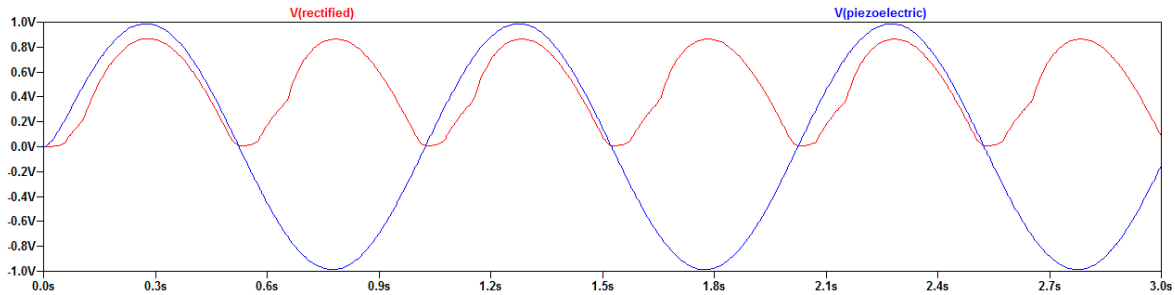

Figure 30: Rectified voltage with Si4465DY and Si4866DY transistors

- PMOS FDC5614P: Rds 105 mΩ, Vds -60V. NMOS FDS6961A: Rds 140 mΩ, Vds 30 V.

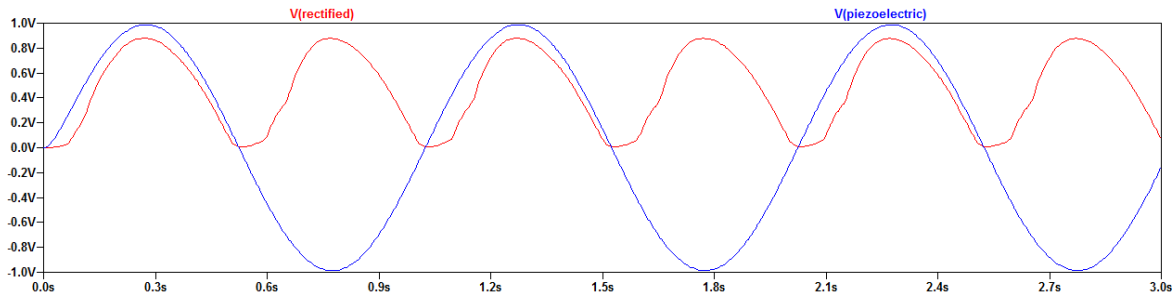

Figure 31: Rectified voltage with FDC5614P and FDS6961A transistors

- PMOS IRF7404: Rds 40 mΩ, Vds -20V. NMOS IRFH5250: Rds 1 mΩ, Vds 25 V.

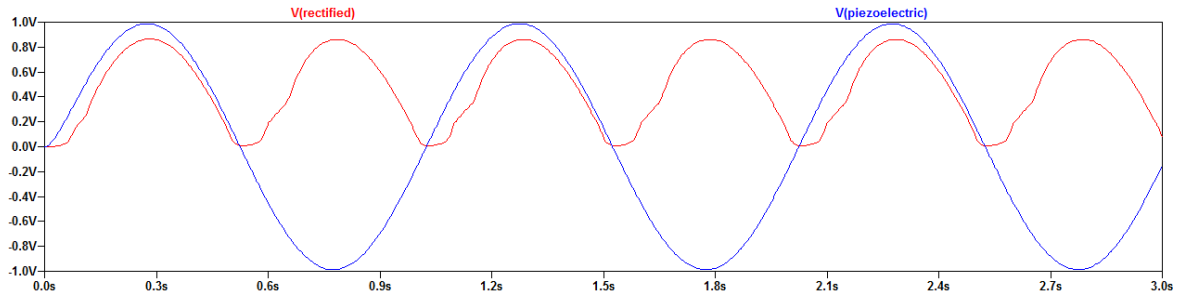

Figure 32: Rectified voltage with IRF7404 and IRFH5250 transistors

After the bridge is included a capacitor to obtain a DC voltage.

From these graphs, the best options are BZX84C6V2L for diode bridge and PMOS IRF7404, NMOS IRFH5250 for MOS bridge.

3.2.5. DC voltage

Finally it's necessary to include a capacitor at the output of the rectifier to obtain the DC voltage, this is again verified only in the two best options previously obtained. First the optimum value of the capacitor is sought.

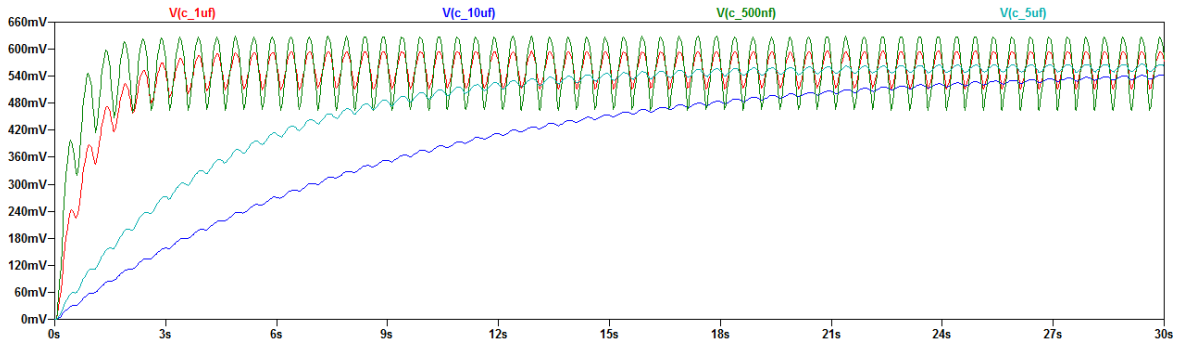

Figure 33: DC rectified voltage with diodes and different capacitor values

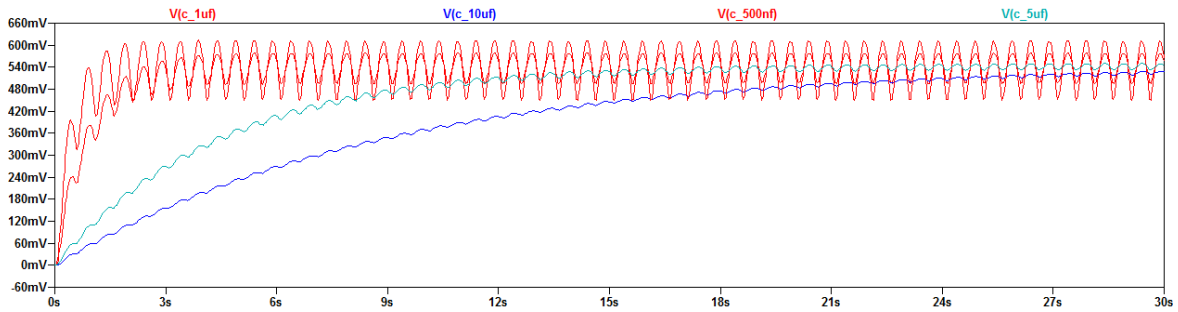

Figure 34: DC rectified voltage with MOS transistors and different capacitor values

Since best option is between 1 and 10 µF, a 5 µF capacitor will be used. Last testing is to compare what DC voltage rectified is better.

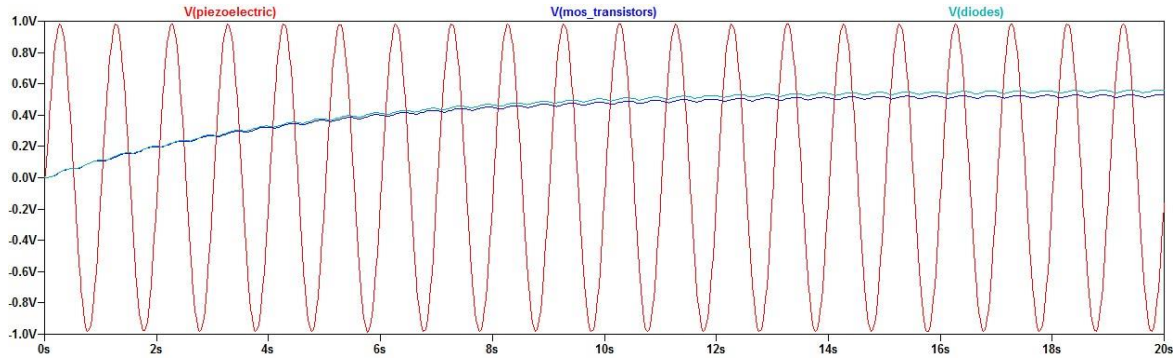

Figure 35: DC rectified voltage with a 5 µF capacitor comparison

Diodes bridge rectifier gives a better response, a slightly higher amplitude, so chosen rectifier for de circuit is the one composed by BZX84C6V2L diodes and a 5 µF capacitor.

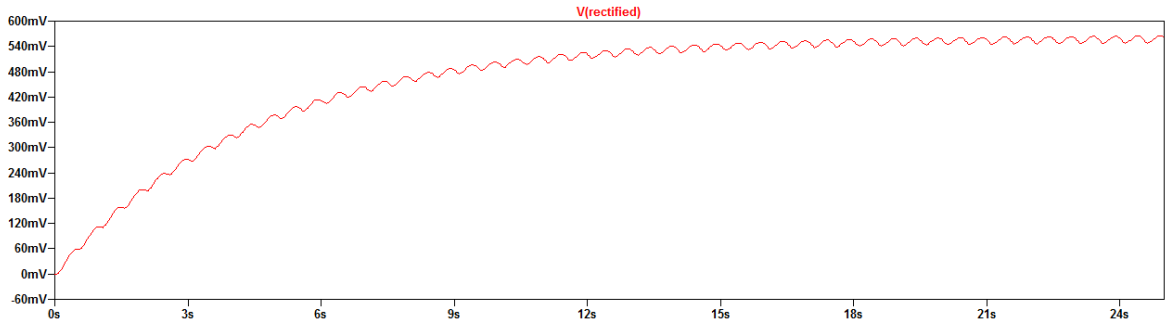

Figure 36: Rectified DC voltage with BZX84C6V2L diodes and a 5 µF capacitor

With this choice is obtained the signal that shows figure 36, the capacitor charges to approximately 0.5 V with a load of 1 MΩ connected permanently. The obtained voltage is much higher, on the order of 3-4V when higher load resistances, on the order of 100 MΩ, are used.

3.3. Comparator design and simulation

After getting the voltage rectified is necessary control how to manage it. When something is connected to the rectifier output the capacitor will start to discharge, so this section is about this connection control. First of all it is necessary to know the required characteristics of the signal that will be used to supply the load, therefore choose at this point which type of load is going to be used, or choose the minimum specifications that is wanted to achieve. Since this project is about knowing the amount of energy that can be obtained with this system and not to supply a particular system, the second option seems more correct.

As a first check, a simple simulation with a voltage controlled switch is performed, varying the switching times of the switch.

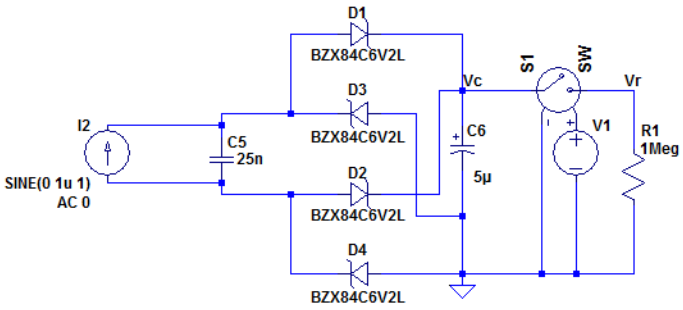

Figure 37: Circuit with a voltage controlled switch

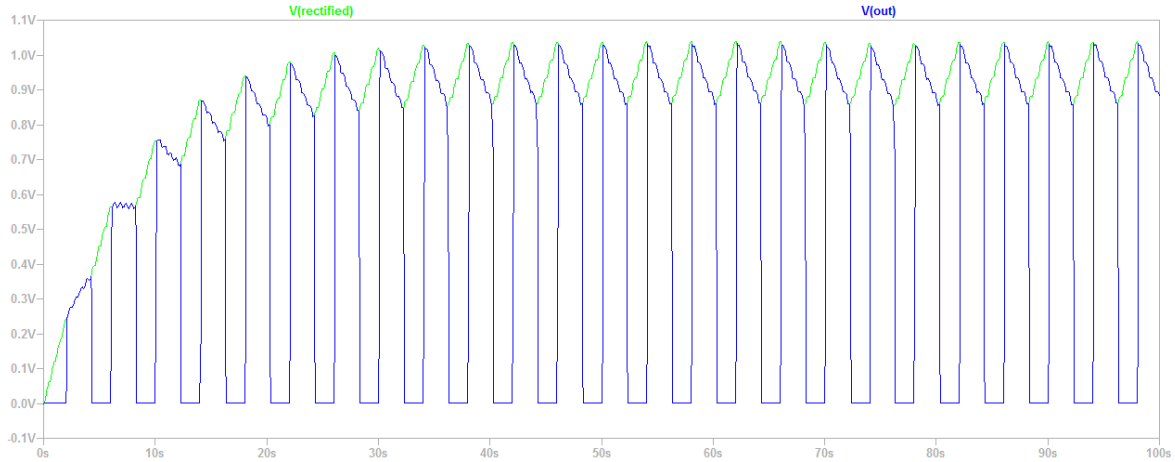

Figure 38: Rectified and output voltages with Ton 2 s Toff 2 s

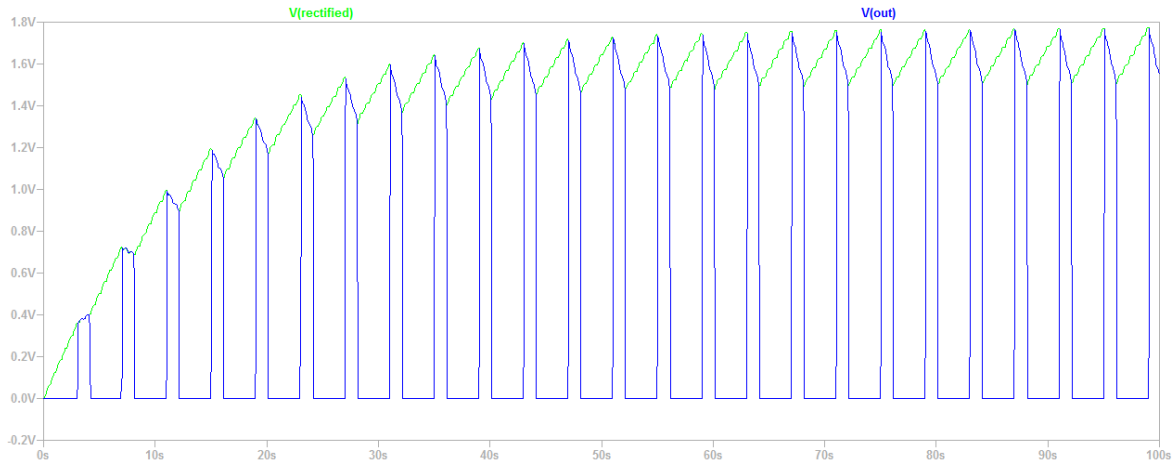

Figure 39: Rectified and output voltages with Ton 1 s Toff 3 s

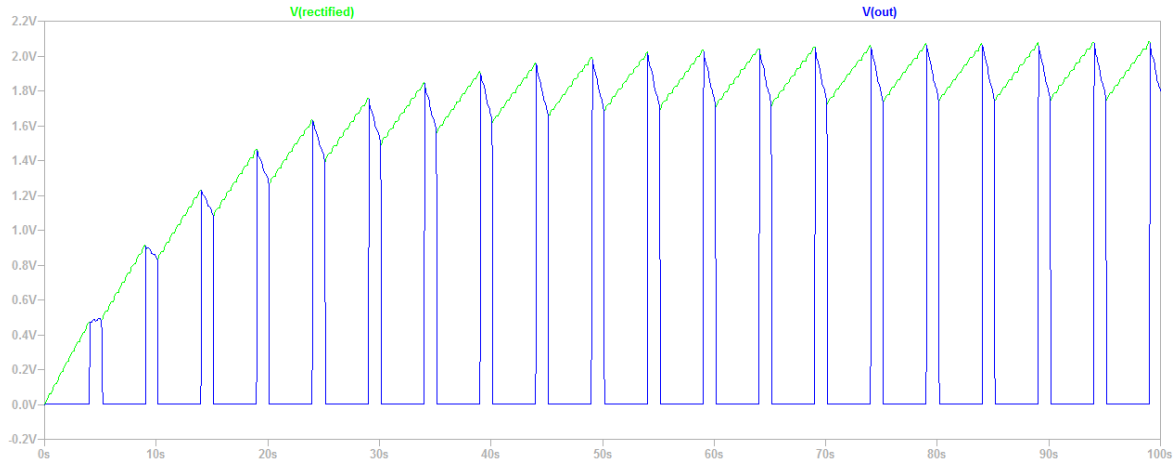

Figure 40: Rectified and output voltages with Ton1 s Toff 4 s

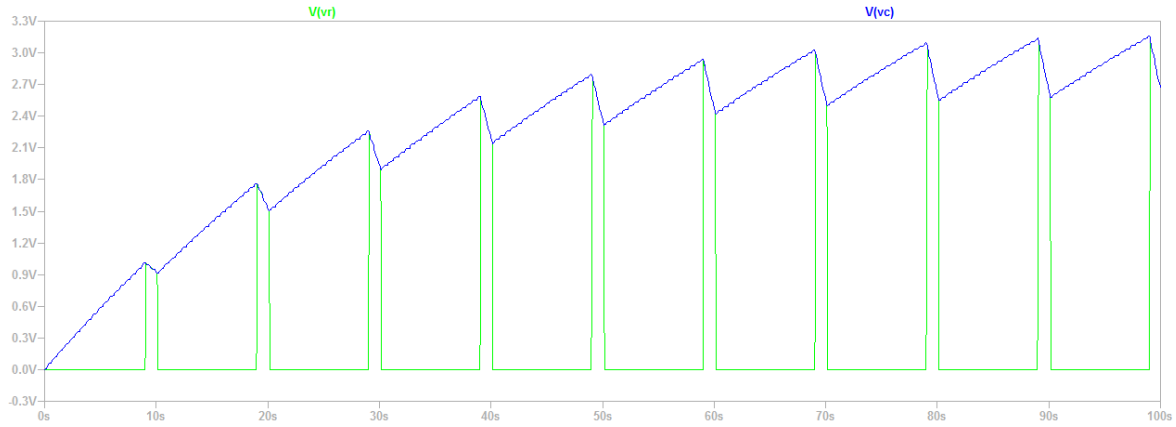

Figure 41: Rectified and output voltages with Ton 1 s Toff 9 s

From these tests it is checked that it is possible to obtain a high voltage level leaving enough time to charge the capacitor, before deciding certain specifications for the design about voltage level and work times, it is necessary to find a way to implement the switch.

The way in which it's decided to implement the switch is using a comparator with hysteresis, thus, adjusting the hysteresis levels, the capacitor will be allowed to charge up to a higher level than necessary to supply the load and therefore, the load is being supplied for a time long enough to perform its function.

The first step was to choose a comparator with a minimum supply voltage according to the voltage that is obtained from the piezoelectric in a coherent time. After checking the specifications of several similar comparators, LTC1450 is chosen given its low power consumption, less than 6 µA, with a minimum supply voltage of 2 V.

As a first approximation, the simulation was performed using voltage sources both to supply the component and to the input, to check the actual minimum values at which it works correctly.

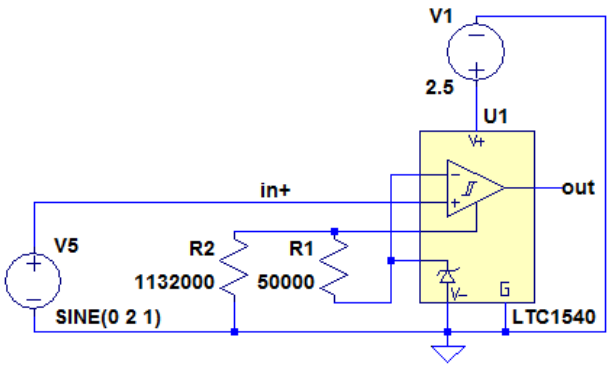

Figure 42: LTC1540 comparator with voltage sources

With this simulation it was found that at least a 2.5 V DC source was required to power the component, as input of the comparator it was used a sinusoidal source of 2 V amplitude.

Resistors compose a voltage divider to obtain the hysteresis input from the reference voltage that brings the LTC1540 itself, the hysteresis voltage band is equal to twice the voltage difference between reference voltage and hysteresis input. The value of chosen resistor give as a result a 95% of reference voltage.

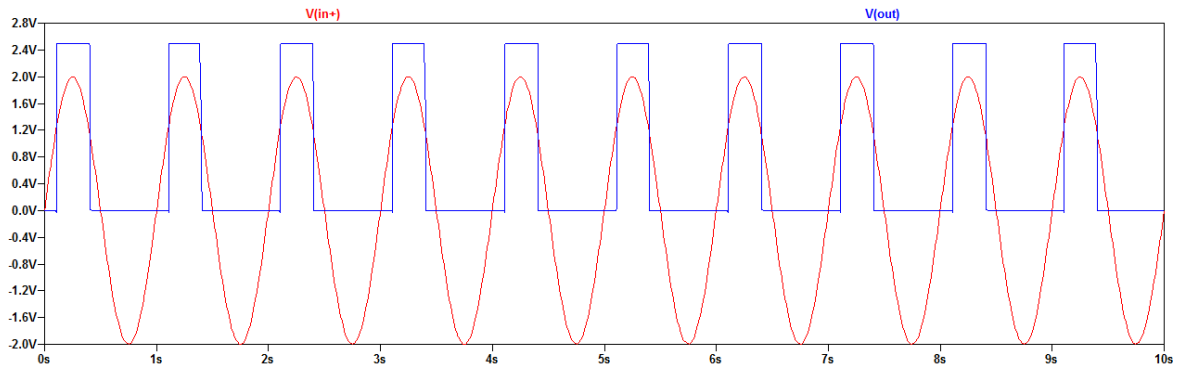

Figure 43: Comparator positive input and output

In the previous image it can be appreciated the hysteresis voltage band, although this is not really wide the lower level is clearly below, and the voltage level that the output adopts, nearly the supply voltage.

Next simulation is performed connecting the signal obtained from the piezoelectric to the input of the comparator

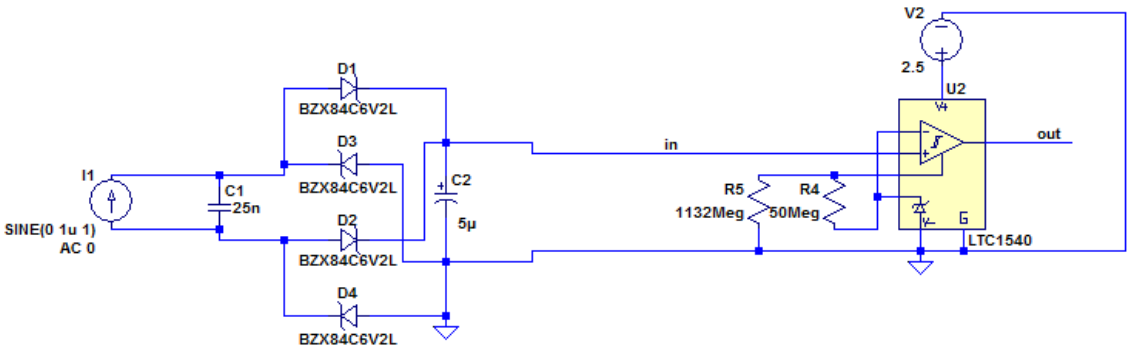

Figure 44: Comparator with rectified piezoelectric voltage at the input

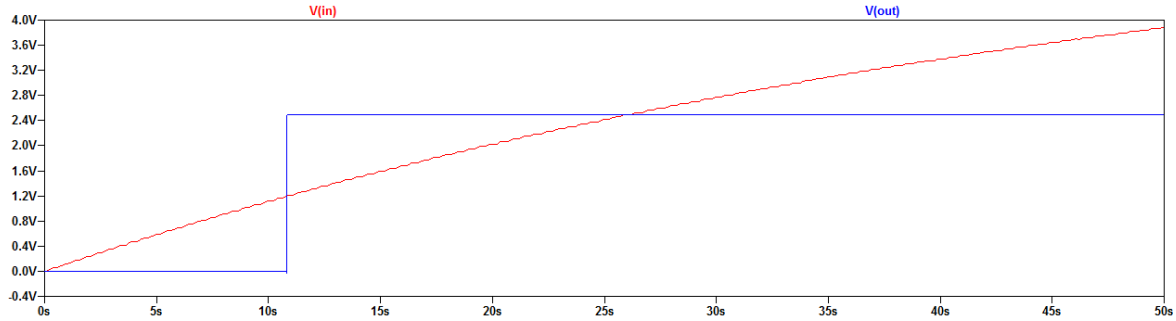

Figure 45: Comparator output and rectified piezoelectic voltage

Finally to supply the complete circuit only with the energy collected, simulation is performed connecting the rectified signal as comparator power supply and testing different combinations of components values. Note that R3 is the load resistor.

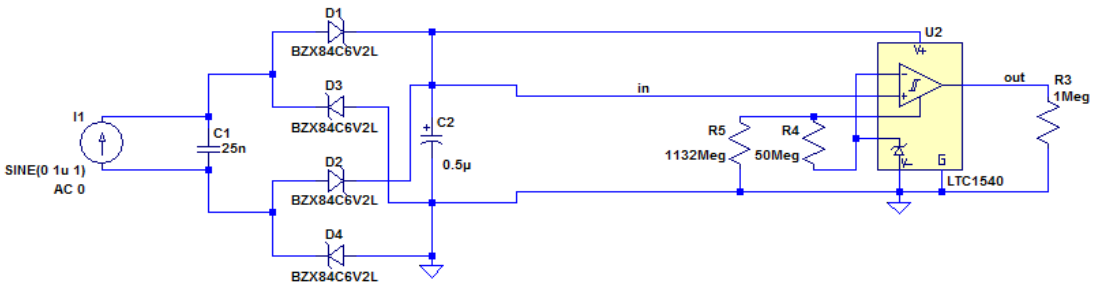

Figure 46: Comparator with rectified piezoelectric voltage as a supply voltage and input

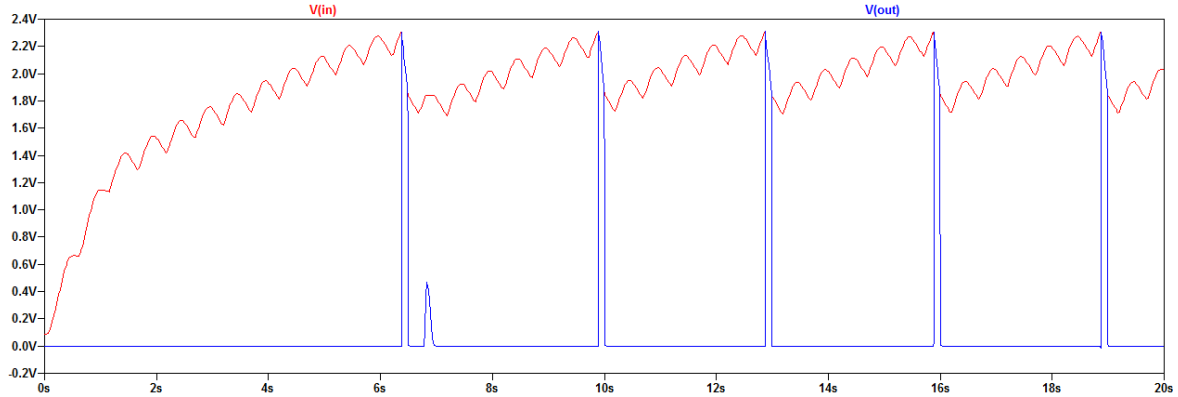

Figure 47: Comparator input and output with R3 1 MΩ and C2 0.5 µF

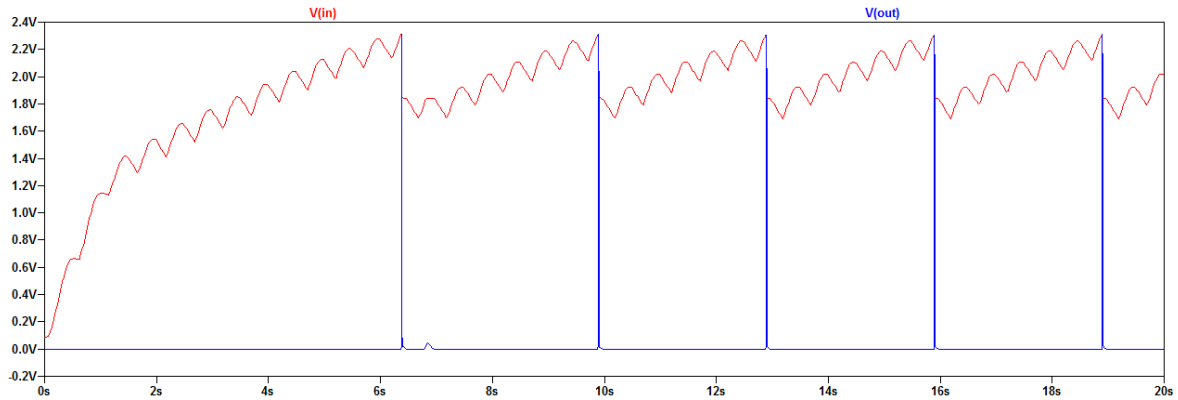

Figure 48: Comparator input and output with R3 100 kΩ and C2 0.5 µF

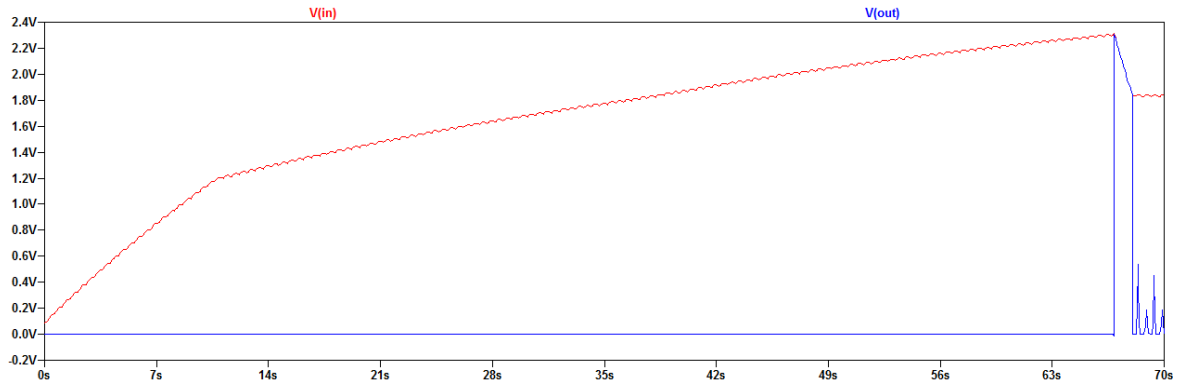

Figure 49: Comparator input and output with R3 1 MΩ and C2 5 µF

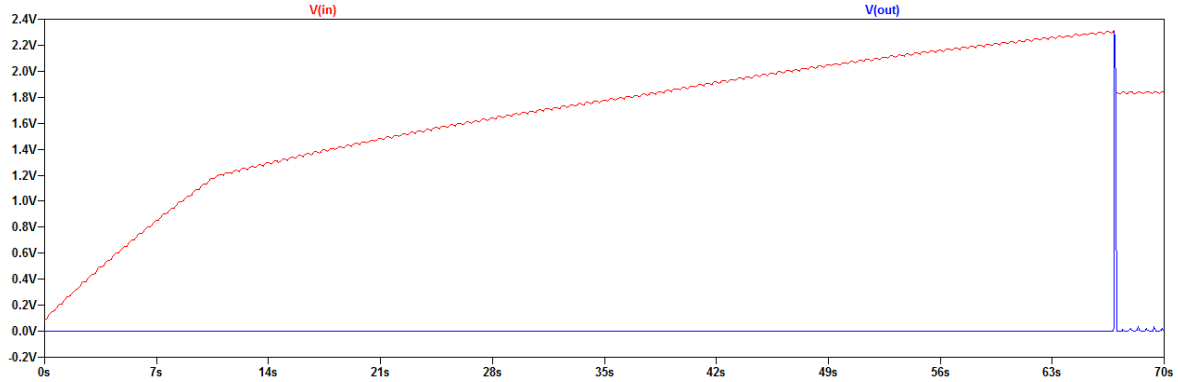

Figure 50: Comparator input and output with R3 100 kΩ and C2 5 µF

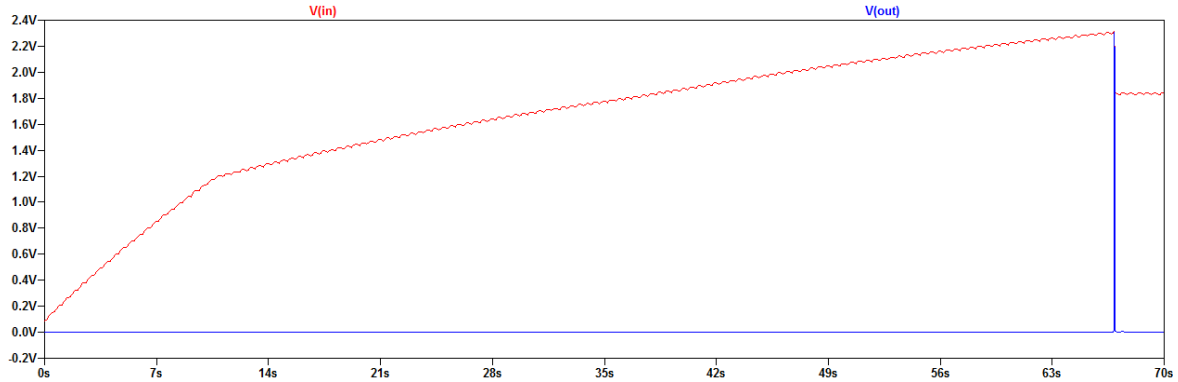

Figure 51: Comparator input and output with R3 10 kΩ and C2 5 µF

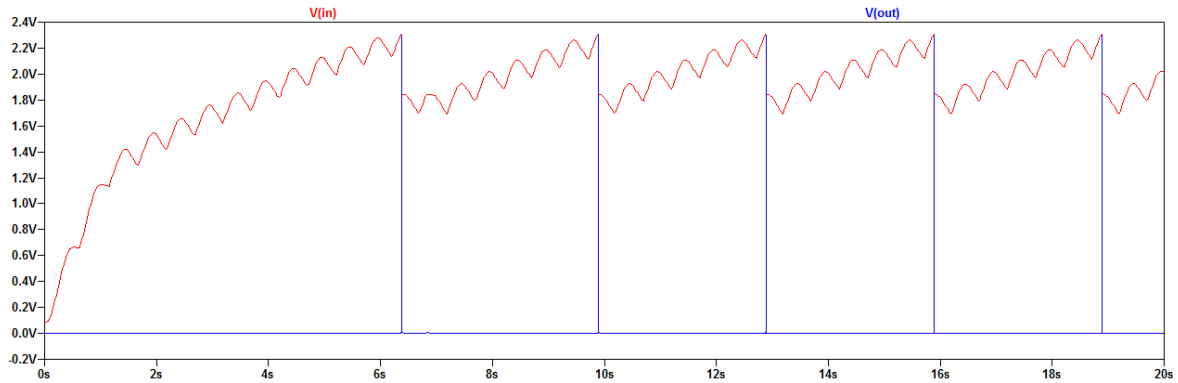

Figure 52: Comparator input and output with R3 10 kΩ and C2 0.5 µF

Changes in component values cause changes in output current, time while the output is active and period of activation of the output signal, the following table summarizes this parameters according to component values

R3 (load)	C	Current	Voltage	Period	Pulse duration
10 k	0.5 µF	210 µA	2.3 – 1.85 V	3 s	1.2 ms
10 k	5 µF	210 µA	2.3 – 1.85 V	∞	12 ms
100 k	0.5 µF	21 µA	2.3 – 1.85 V	3 s	11 ms
100 k	5 µF	21 µA	2.3 – 1.85 V	145 s	0.1 s
1 M	0.5 µF	2.1 µA	2.3 – 1.85 V	3 s	0.1 s
1 M	5 µF	2.1 µA	2.3 – 1.85 V	∞	1.1 s

Once all necessary circuit simulations have been performed and the theoretical behaviour is already known, a component is selected to check the real operation. It's decided to connect a temperature sensor to the output, the MAX6613 which operates over a 1.8 V to 5.5 V supply voltage and with a typical current consumption of 7.5 µA.

3.4. Preliminary measurements

3.4.1. PCB design and fabrication

Among all the components previously analysed, a final set was selected for implementation, corresponding to the circuit schematic shown below. A PCB was designed and fabricated to measure the obtained waveforms and compare them to previous simulation results.

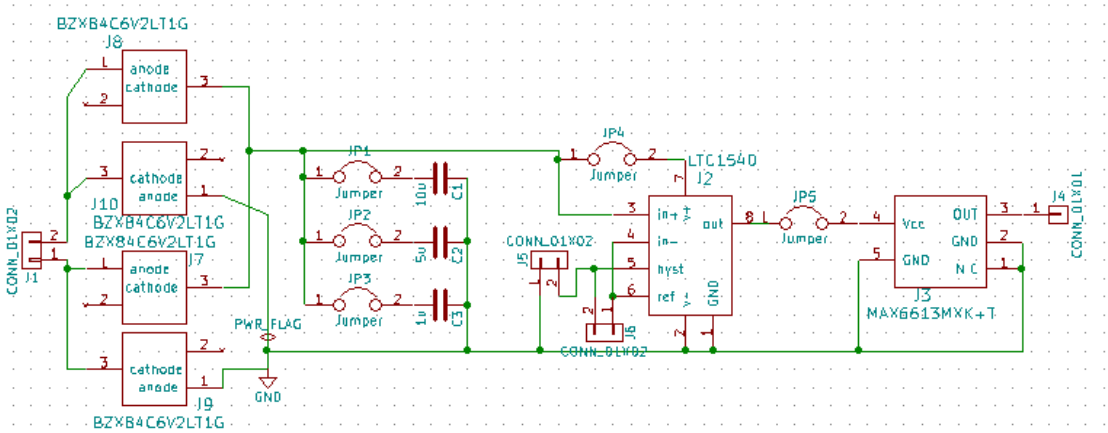

Figure 53: Designed PCB schematic

After design the PCB, which layout is included in the annex, some operation tests were performed. The design was made keeping in mind the different options considered in simulations to be able to know how simulated results are close to the real.

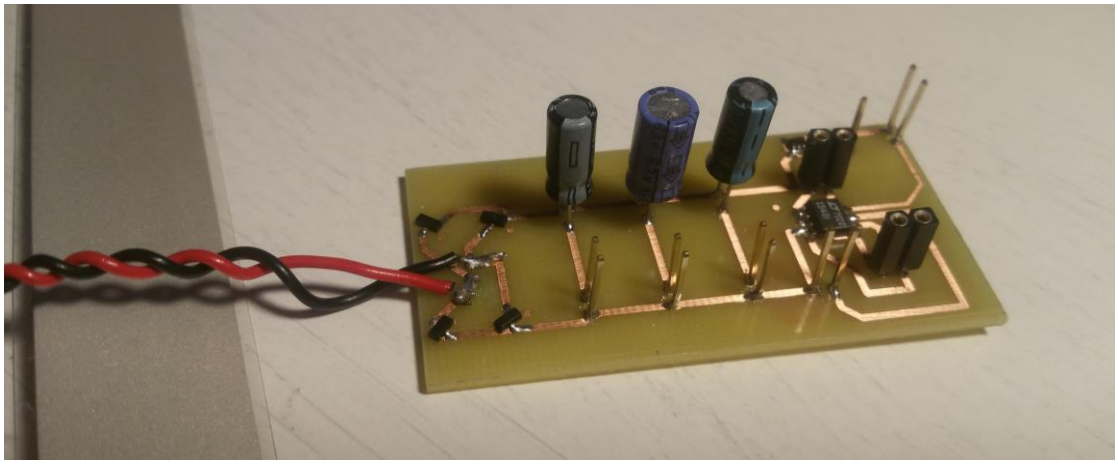

Figure 54: Designed PCB

3.4.2. Piezoelectric response

First test consists of measure the voltage provided by the piezoelectric once it's connected to the rest of the circuit, the different ways of taking the measure vary in frequency of vibration and from which point of the piezoelectric the movement is realized, it must have to keep in mind that all tests are done with a oscilloscope, so all results are conditioned to its 1 MΩ input resistance.

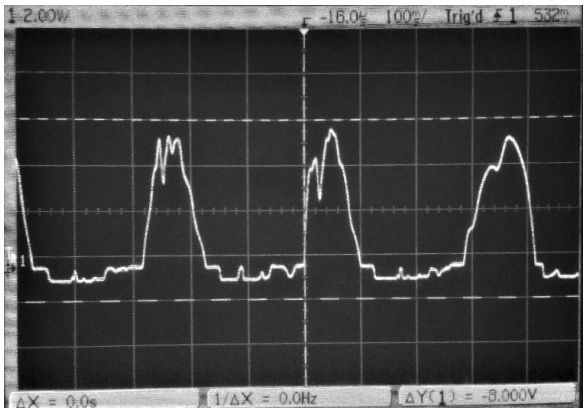

Figure 55:Piezoelectric generated signal, high frequency from the end

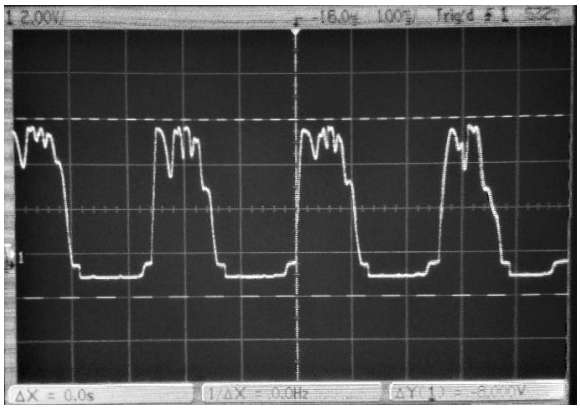

Figure 56: Piezoelectric generated signal, high frequency from the middle

The first pair of pictures correspond to the signal generated by the piezoelectric when it is submitted to a 4 Hz vibration frequency, difference between them is from where is the vibration generated, in the first case the piezoelectric is clamped from one end and in the other picture from the middle.

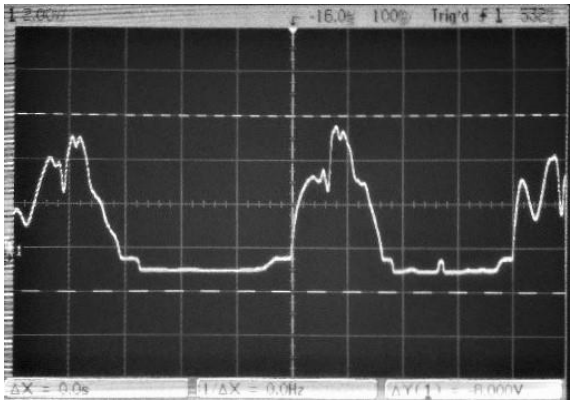

Figure 57: Piezoelectric generated signal, low frequency from the end

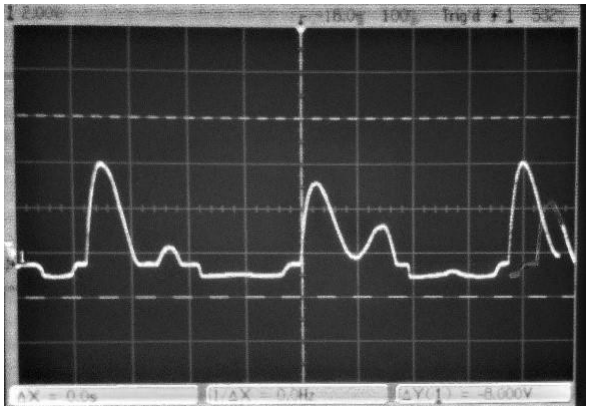

Figure 58: Piezoelectric generated signal, low frequency from the end

In this case, the piezoelectric is submitted to a 2.5 Hz vibration frequency and the difference between pictures is the same than in the previous case. Considering these measures have been taken on the input resistance of the oscilloscope (1 MΩ) and the oscilloscope scale is set to 2 V/divison, making a sufficiently effective movement on the piezoelectric can almost be obtained 6 μA current peaks.

3.4.3. Rectifier output measures

The following tests were done by connecting only the accumulation capacitor, alternating between 1 μF, 5 μF and 10 μF.

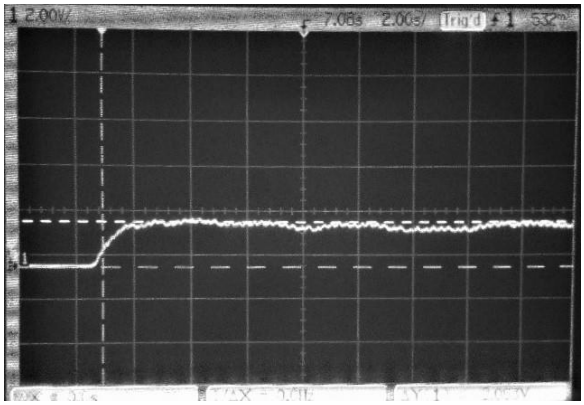

Figure 59: 1 μF Capacitor voltage with low frequency

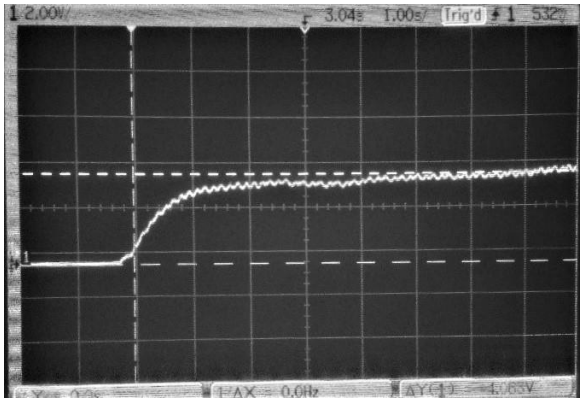

Figure 60: 1 μF Capacitor voltage with middle frequency

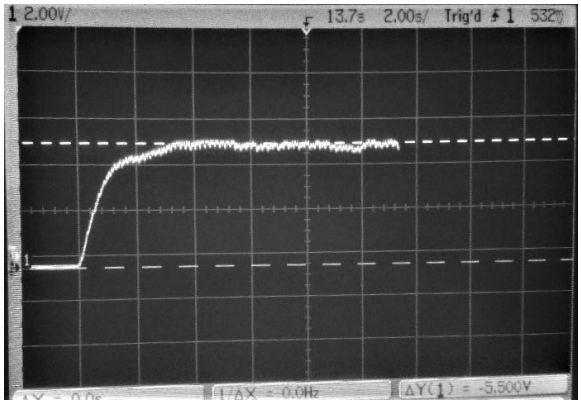

Figure 61: 1 µF Capacitor voltage with high frequency

This group of pictures belong to the 1 µF capacitor, varying the vibration frequency from lowest to highest within approximately the margins previously commented. It can be proved how in this case the capacitor charges quickly and until a high voltage level.

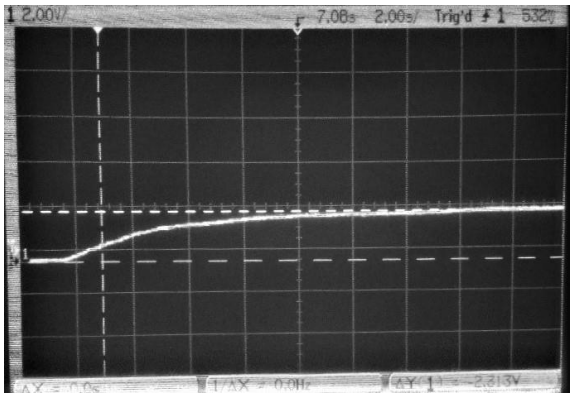

Figure 62: 5 µF Capacitor voltage with low frequency

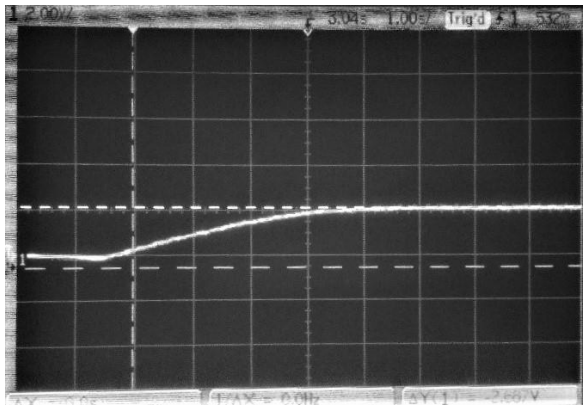

Figure 63: 5 µF Capacitor voltage with middle frequency

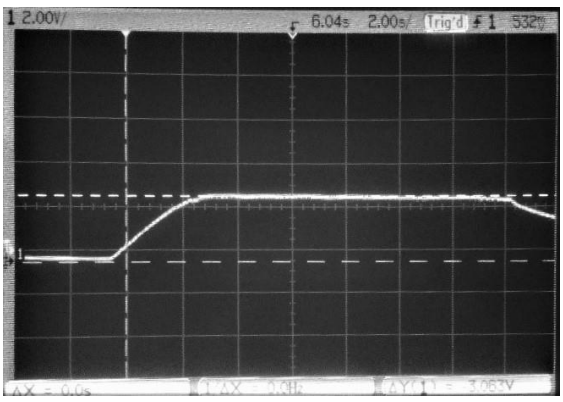

Figure 64: 5 µF Capacitor voltage with high frequency

The second group of pictures belong to the 5 uF capacitor, under the same conditions the voltage level that is reached is much lower and more slowly.

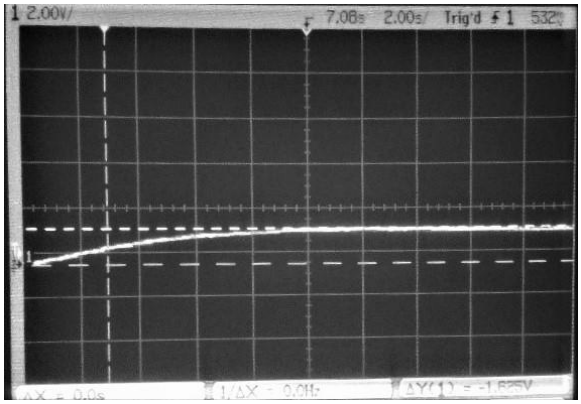

Figure 65: 10 µF Capacitor voltage with low frequency

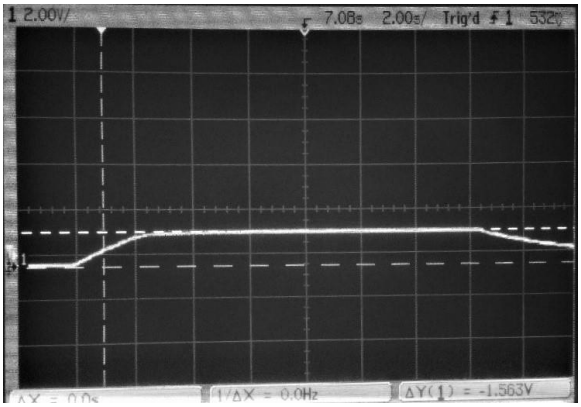

Figure 66: 10 µF Capacitor voltage with middle frequency

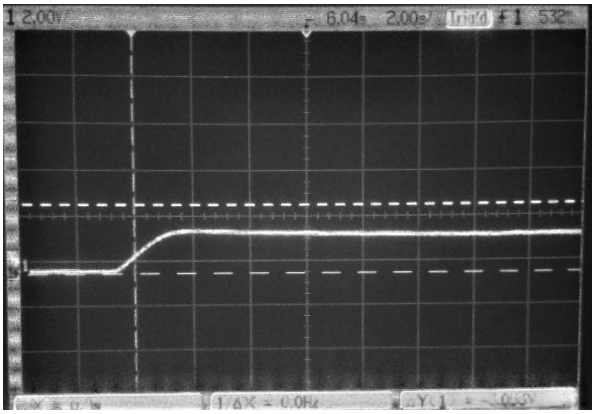

Figure 67: 10 µF Capacitor voltage with high frequency

The last pictures correspond to the 10 uF capacitor, which already is suspected is going to be the worst option given the worst performance that it present.

With these tests is verified that the most suitable capacitor is 1 µF, which with a high frequency of vibration can reach approximately 5.5 V in 3 seconds. As has been shown in previous tests vibration frequency doesn't affect the amplitude of the signal generated by the piezoelectric but modify its frequency, so for high vibration frequencies the capacitor charges faster and to higher voltage because at low vibration frequency the high discharge velocity of the capacitor doesn't allow charge it more.

3.4.4. Comparator output measures

Even though for now it seems that the 1 µF capacitor is the best option, this is which has a faster discharge, so the following tests are done with the others too, now the comparator is connected, therefore the complete signal conditioning circuit is tested. In all the following pictures channel 2 belong to the comparator output and channel 1 to the capacitor voltage.

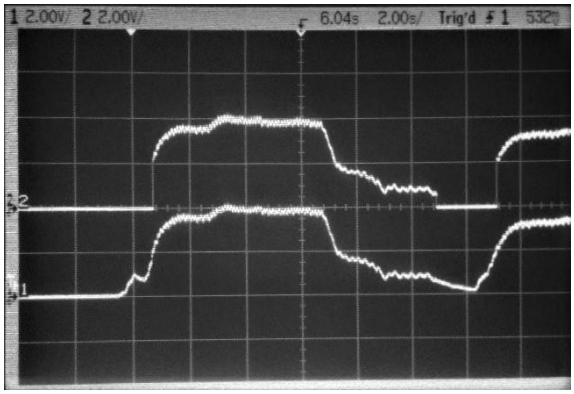

Figure 68: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 10 MΩ and C2 1 μF

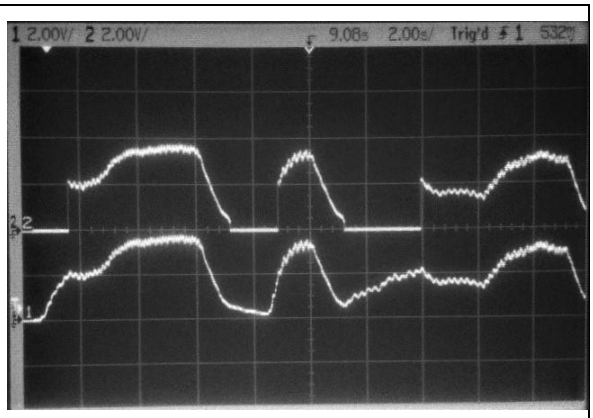

Figure 69: Capacitor voltage (1) and comparator output (2) with J5 500 MΩ, J6 100 MΩ and C2 1 μF

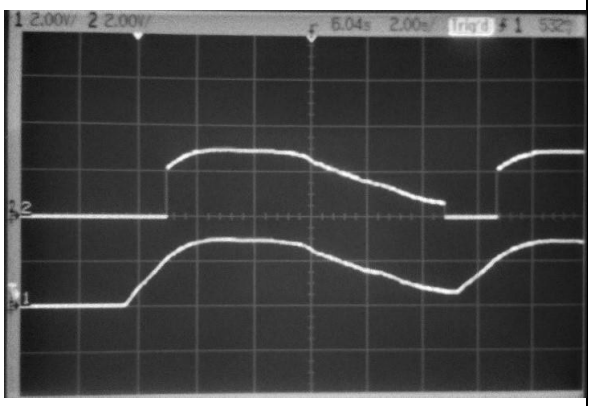

Figure 70: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 10 MΩ and C2 5 μF

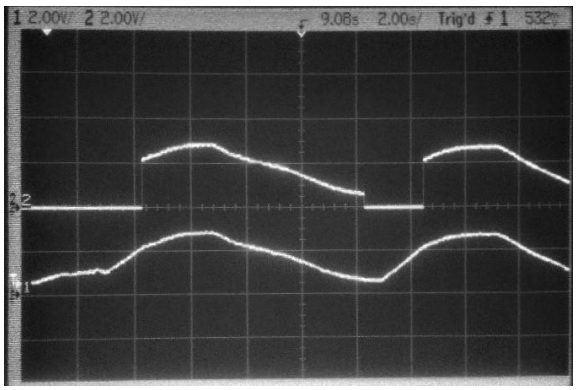

Figure 71: Capacitor voltage (1) and comparator output (2) with J5 500 MΩ, J6 100 MΩ and C2 5 μF

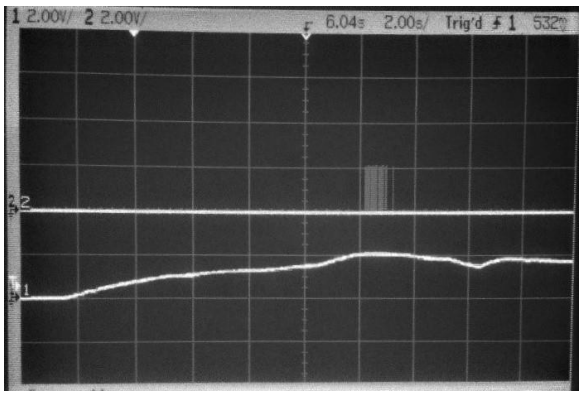

Figure 72: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 10 MΩ and C2 10 μF

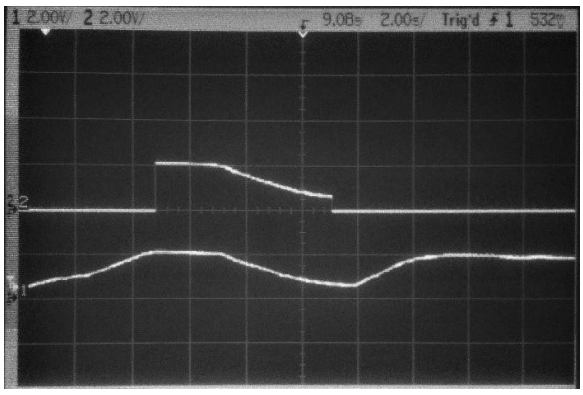

Figure 73: Capacitor voltage (1) and comparator output (2) with J5 500 MΩ, J6 100 MΩ and C2 10 μF

Each row of pictures belong to the 1, 5 and 10 μF in this same order, the first column it's with the comparator resistors combination of 1 GΩ and 10 MΩ and the second with 500 MΩ and 100 MΩ, in each case the greatest resistance correspond to the J5 component in the scheme and the other to the J6

From these tests it's verified that the comparator is activated when its supply voltage reaches 2 V, as it's specified in its datasheet although in the simulations seemed that it will require 2.5 V. Again it seems that the best option is the 1 µF and that the comparator remains active while its supply voltage is higher than 1 V.

3.4.5. Sensor output measures

The last test check capacitor voltage, comparator output and temperature sensor output once all components are connected. In all the following pair of pictures, first belong to the capacitor voltage (channel 1) and to the comparator output (channel 2) and second to the temperature sensor output (channel 1) and to the comparator output (channel 2).

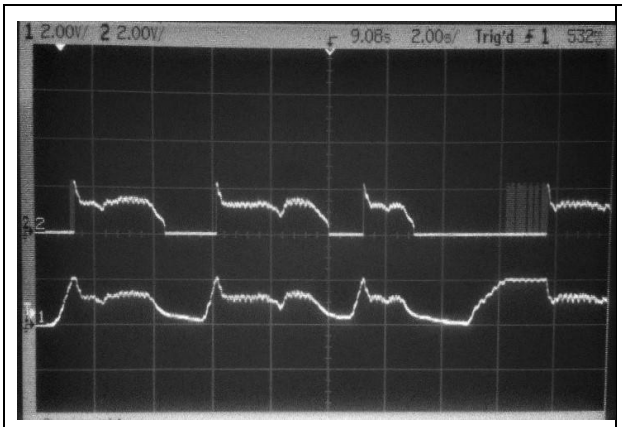

Figure 74: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 10 MΩ and C2 1 µF

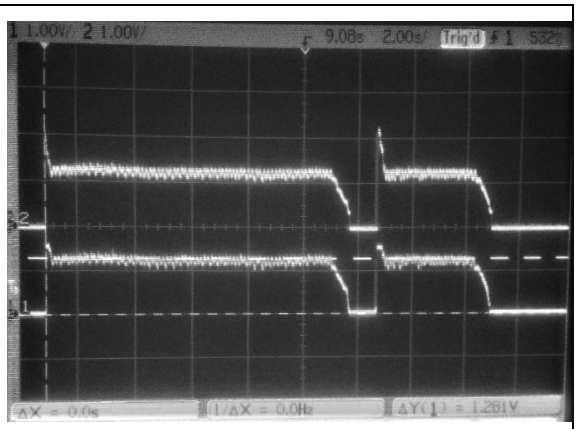

Figure 75: Comparator (1) and sensor output (2) with J5 1 GΩ, J6 10 MΩ and C2 1 µF

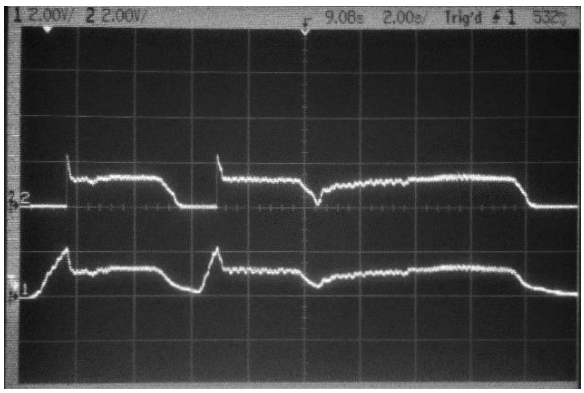

Figure 76: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 100 MΩ and C2 1 µF

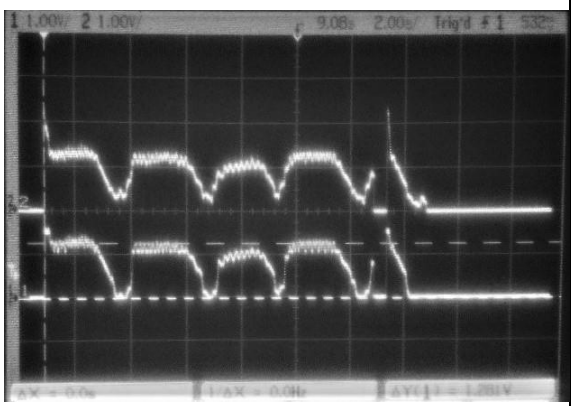

Figure 77: Comparator (1) and sensor output (2) with J5 1 GΩ, J6 100 MΩ and C2 1 µF

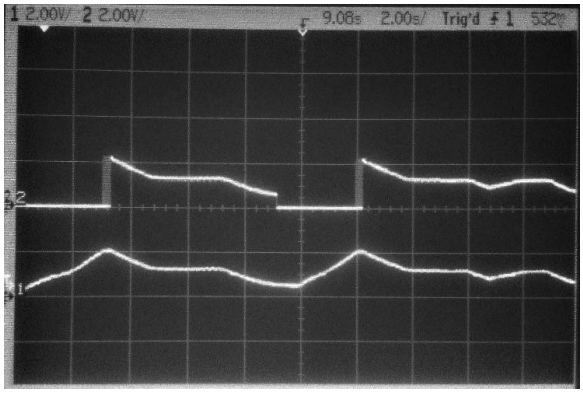

Figure 78: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 10 MΩ and C2 5 μF

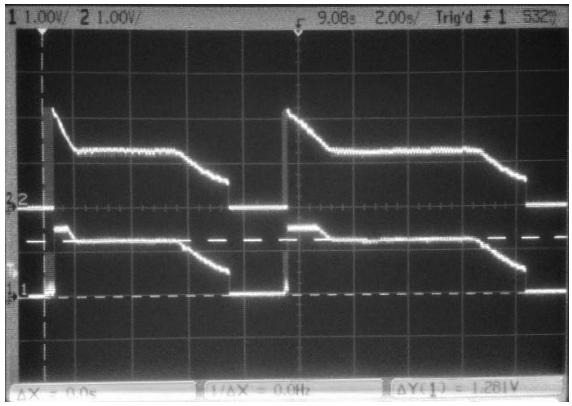

Figure 79: Comparator (1) and sensor output (2) with J5 1 GΩ, J6 10 MΩ and C2 5 μF

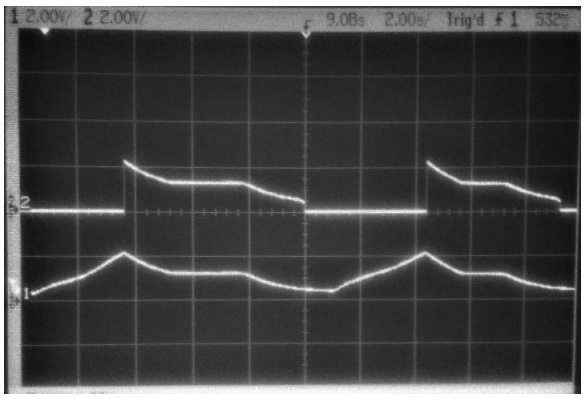

Figure 80: Capacitor voltage (1) and comparator output (2) with J5 1 GΩ, J6 100 MΩ and C2 5 μF

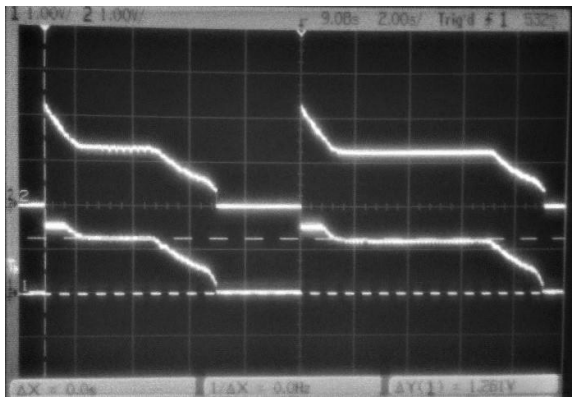

Figure 81: Comparator (1) and sensor output (2) with J5 1 GΩ, J6 100 MΩ and C2 5 μF

These tests have been performed only with 1 and 5 μF capacitors since it has previously been proved that the 10 μF capacitor is not a useful option. First four pictures correspond to the 1 μF capacitor, the first row with the 1 GΩ and 10 MΩ combination, and the second with the 1 GΩ and 100 MΩ combination, the other four pictures belongs to the same combinations but with the 5 μF capacitor.

Given this tests has been realized using 1MOhm impedance probes, there is a lot of distortion on the results because these include additional resistive loads on the circuit, but in conclusion it is proved that the temperature sensor does not work correctly under approximately 1.5 V supply voltage, according to what the datasheet specifies.

4. Results

After the actual limitations that have been found with previous tests, results are taken with all circuit components connected and with the 1 GΩ and 10 MΩ comparator resistors combination, in this case only one probe is used to reduce the load in the system.

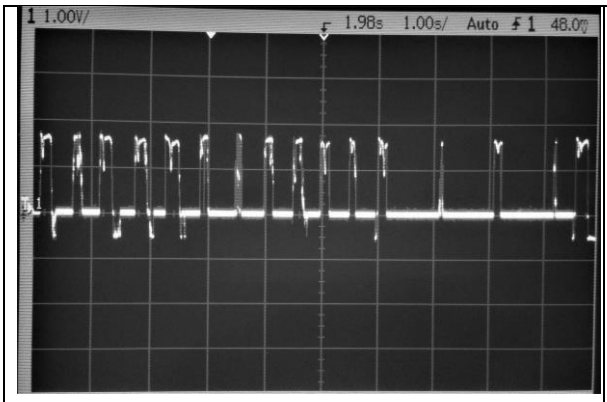

Figure 82: Piezoelectric generated signal with 2 Hz vibration frequency

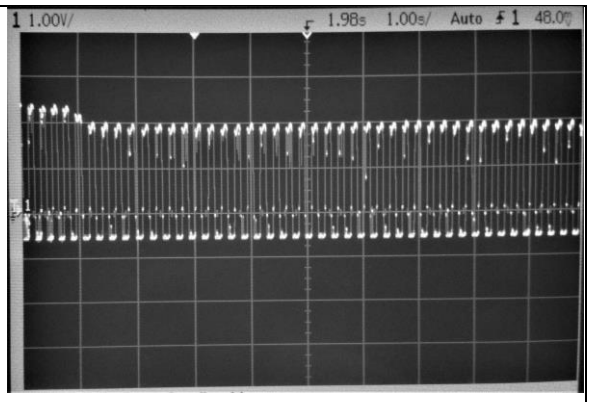

Figure 83: Piezoelectric generated signal with 4.5 Hz vibration frequency

In previous tests this voltage level almost reached 6 V with the rest of the components disconnected, now with all the circuit active it reaches 2 V, which corresponds to the supply voltage when the comparator and sensor are activated.

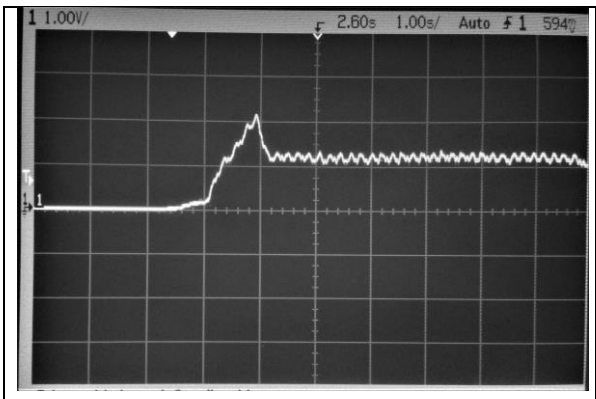

Figure 84: 1 µF capacitor voltage with 2 Hz vibration frequency

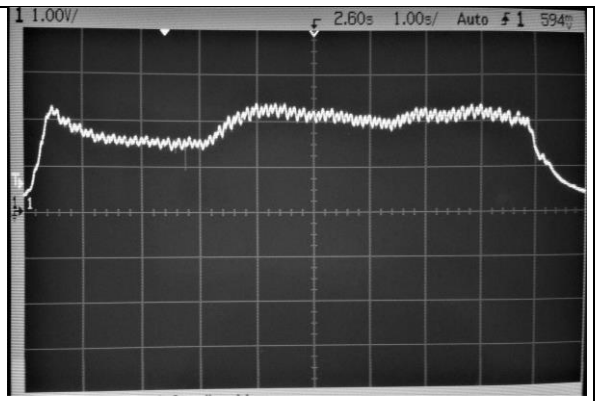

Figure 85: 1 µF capacitor voltage with 4.5 Hz vibration frequency

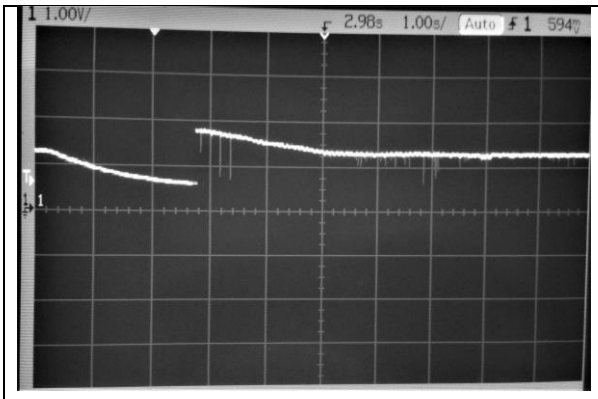

Figure 86: 5 µF capacitor voltage with 2 Hz vibration frequency

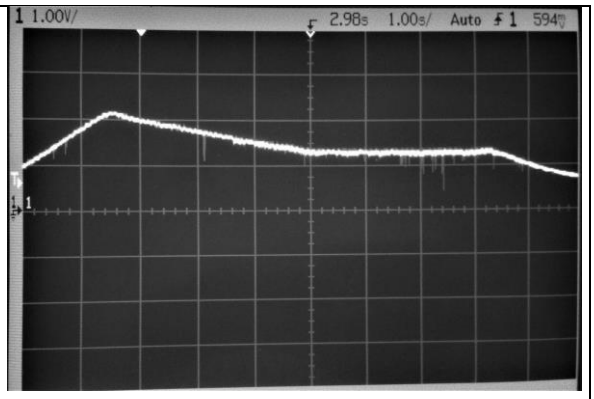

Figure 87: 1 µF capacitor voltage with 4.5 Hz vibration frequency

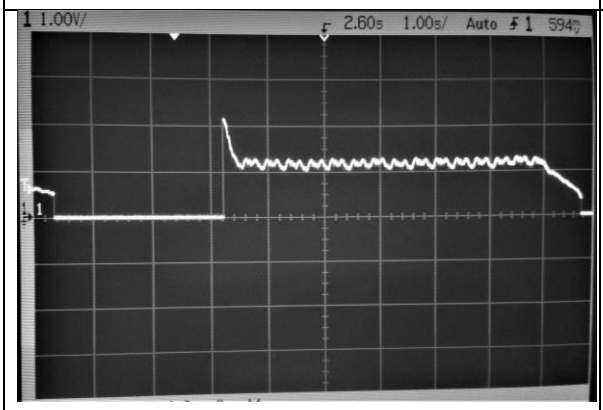

Figure 88: Comparator output with C2 1 µF and 2 Hz vibration frequency

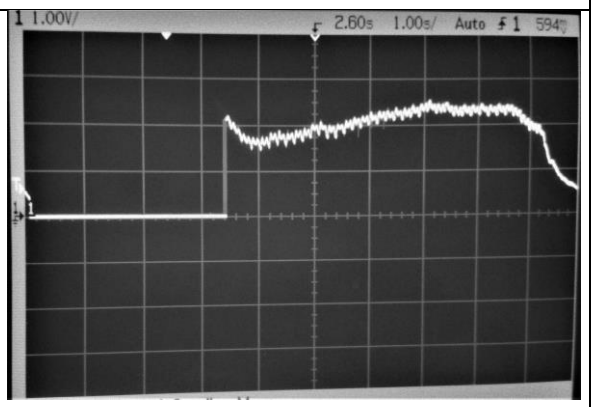

Figure 89: Comparator output with C2 1 µF and 4.5 Hz vibration frequency

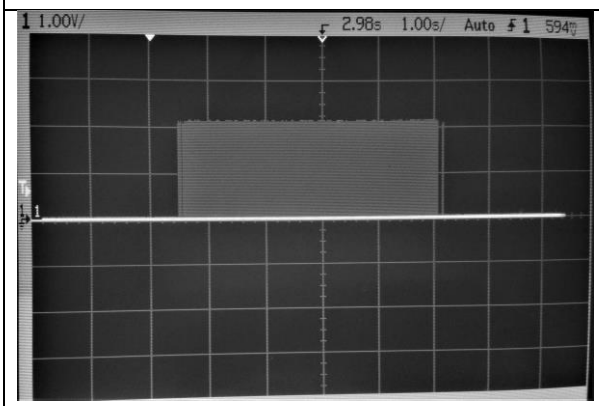

Figure 90: Comparator output with C2 5 µF and 2 Hz vibration frequency

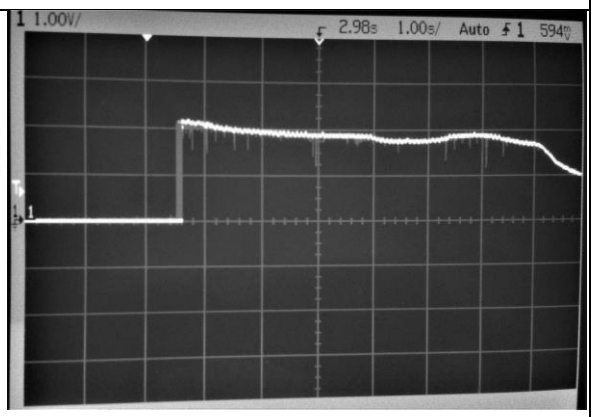

Figure 91: Comparator output with C2 5 µF and 4.5 Hz vibration frequency

With all circuit components connected is evident that the system works only with the options which produce more energy, with 1 and 5 µF and high vibration frequency.

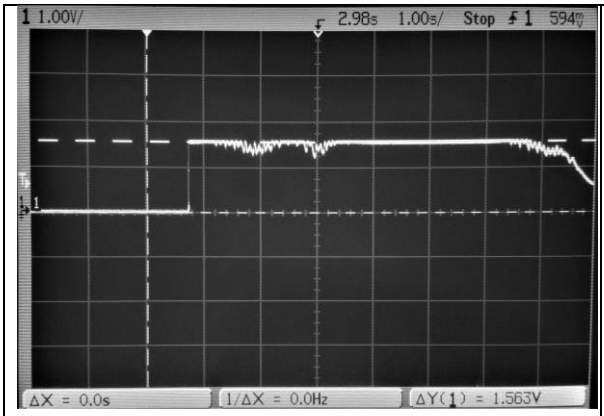

Figure 92: Sensor output with C2 1 µF and 4.5 Hz vibration frequency

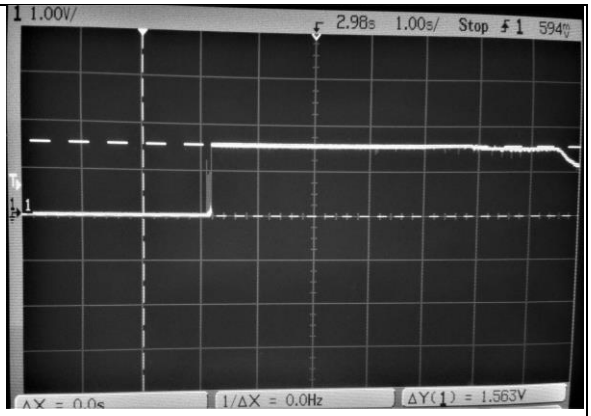

Figure 93: Sensor output with C2 5 µF and 4.5 Hz vibration frequency

Finally the last pictures belong to the temperature sensor output when the vibration frequency is nearly the high value that has been considered during the test, with the 1 µF and the 5 µF capacitors.

The temperature sensor datasheet gives the linear approximation to determine the temperature in function of the output voltage

$$T\,[°C] = \frac{1.8455 - V_{OUT}}{0.01123}$$

Following this equation and with the value of the temperature sensor output obtained at the test, we obtain a temperature of 25 °C which is exactly the temperature under these tests have been realized.

5. Budget

Article	Quantity	Unitary price	Total Price
Zener diodes BZX84C6V2LT1G	4	0.136	0.544
Comparator LTC1540IS8#PBF	1	3.72	3.72
Temperature sensor MAX6613MXK+T	1	0.928	0.928
Piezoelectric DT2-028K/L w/rivets	1	-	-
Resistor MCF 0.25W 10M	1	0.0573	0.0573
Resistor RNX-3/81G00FNL05	1	4.87	4.87
Junior engineer work	300 (hours)	15	4500
Total			4514.6193

6. Conclusions and future development:

As the main conclusion of the project it has to be noted that the designed system is able to supply energy to a temperature sensor continuously. This continuous powering has been obtained under a frequency larger than 4 Hz, which does not correspond to natural body movement. At 2 Hz it is observed (Fig. 90) a discontinuous activation of the power supply. This means that for these lower levels of mechanical excitation, the sensor can be operated discontinuously, as long as the voltage is maintained for sufficient time.

With respect to the influence of storage capacitance, it was shown that with 5 µF the best results were obtained. With 1 µF the supply voltage is not sufficiently stable to provide a reliable temperature output. The test with 10 µF did not produce good results.

From the sensor consumption current (7.5 µA), its supply voltage provided by the comparator (2 V approximately) and its correct operation demonstrated in the results section, it can be calculated that the system is able to deliver a power of 15 µW.

The power level can be increased if more piezoelectric films are connected in parallel with the same mechanical excitation. In this way, as a future development, it can be studied the possibility to design more complex systems, for example, involving a low power microcontroller and e-Ink display [11], such that temperature or other sensor output reading can be displayed without static power consumption.

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[6] Comparator LTC1540IS8#PBF http://www.farnell.com/datasheets/1575751.pdf?_ga=2.187329384.132370299.1498698481-246720399.1496759099

[7] Temperature sensor MAX6613MXK+T http://www.farnell.com/datasheets/2002140.pdf?_ga=2.43716581.132370299.1498698481-246720399.1496759099

[8] Resistor MCF 0.25W 10M http://www.farnell.com/datasheets/1716725.pdf?_ga=2.43716581.132370299.1498698481-246720399.1496759099

[9] Resistor RNX-3/81G00FNL05 http://www.farnell.com/datasheets/2049132.pdf?_ga=2.216688214.132370299.1498698481-246720399.1496759099

[10] LTspice, http://www.linear.com/designtools/software

[11] Eink display, http://www.pervasivedisplays.com/products/271#aurora-ma-v230

Appendices:

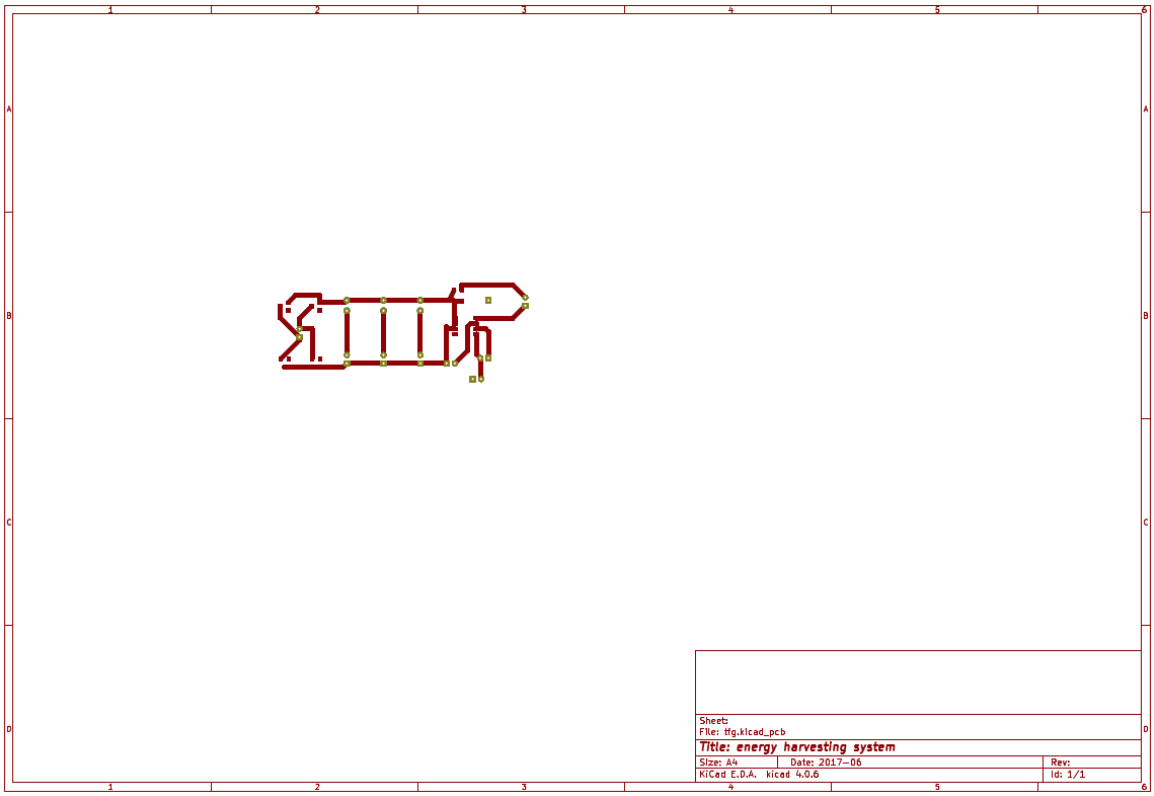

Figure 94: PCB layout