Palacký University Olomouc
Faculty of Science
Joint Laboratory of Optics and Institute of Physics of the Czech Academy of Sciences

BACHELOR THESIS

Electronic systems for energy harvesting from piezo-elements

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Olomouc 2018

I declare that I carried out this bachelor thesis independently under the supervision of
doc. RNDR. Jiří Pechoušek, Ph.D. and only with the cited sources, literature and other professional sources.

In Olomouc ……………….

...………………………......¨
Jan Bizoň

I would like to express my sincere gratitude to my supervisor doc. RNDr. Jiří Pechoušek, Ph.D. for his guidance, patience and motivation. Furthermore, I would like to thank Mgr. Michal Dudka for advice concerning electronics.

Bibliografická identifikace:

Jméno a příjmení autora	Jan Bizoň
Název práce	Vývoj a využití systému pro získávání a ukládání energie z piezoprvků
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Abstrakt	Tato práce se zabývá získáváním energie z obnovitelných zdrojů, zvláště pak z piezo-elektrických prvků. Vysvětluje pojem Energy Harvesting a čeho se týká. Co je piezo-elektrický jev a jak funguje. V práci se testuje komerční obvod pro Energy Harvesting a uvádí i měření přes jednoduchý Energy Harvesting obvod. Posuzuje jaký vliv mají na piezoprvek veličiny jako frekvence či amplituda.
Klíčová slova	Energy Harvesting, Obnovitelné zdroje energie, Piezo prvky, piezo-elektřina
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Abstract	This thesis deals with energy harvesting from renewable sources, especially from piezo-electric elements. Explains the term Energy Harvesting a what it is about. What is piezo-electric effect and how does it work. In this thesis is testing of commercial Energy Harvesting system and shows measurement of simple Energy Harvesting System. Establishes the influences of frequency and amplitude of piezo element.
Keywords	Energy Harvesting, Renewable energy resources, piezo-element, piezo-electricity
Number of pages	30
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Contents

Introduction

Nowadays the mineral resources, which are often used as a source of energy, are nearly deplenished. That leads to the need for sustainable or renewable source of energy. Renewable energy sources include wind power, solar power, hydropower, tidal power, geothermal energy, biofuels and the renewable part of waste. The portion of energy from these sources in gross final energy consumption was 17 % in EU in 2016 [1]. Piezo-electricity is less known sustainable energy source, but with great potential.

Piezo-electricity can be used to power sensors or small devices just from mechanical vibrations. The mechanical vibrations are all around us, so the energy resource, that can be transformed into electricity is practically inexhaustible. It can be parasitic effect on a machine or noise from cars passing by or other undesirable vibration and piezo-element can transform it into useful energy. Methods for energy harvesting from piezo-electricity need to be developed, because it would be a waste of resource, that can be transformed into electrical energy, which is so demanded nowadays.

The commercial energy harvesting systems are already being sold, but how effective are they? Are they worth the money or is it easier and cheaper to build your own energy harvesting system? How does the frequency and amplitude of deformation of piezo-element affect the harvested energy? How can we define how good is piezo-element? All that should be answered in this thesis.

1. Theoretical section

1.1. Energy harvesting

Energy harvesting, power harvesting or energy scavenging are terms, that we use to name a process, in which we acquire energy from renewable resources. This energy can be harvested from many different sources such as light, wind, mechanical vibrations, electromagnetic variations or temperature. Harvesting process takes ambient energy and turns it into electrical energy [2].

1.1.1. Energy harvesting process

The harvested energy from all renewable sources can be stored for later use. This process is illustrated in Figure 1.

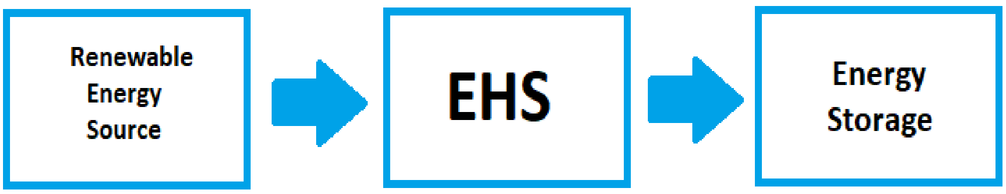


Figure 1: Diagram of the energy harvesting process

Also this energy can be used immediately by connecting the EHS to a device. EHS connected like this is able to influence or eliminate usage of power supplies especially in low-energy wireless devices or inaccessible sensors. These devices and sensors get timeless energy supply and can work almost forever, because their service life is limited only by service life of single components and not by exhaustion of power supply [3]. Device like that can be placed anywhere, even in dangerous or sensitive environments.

1.2. Renewable resources

Renewable resources of electric or thermal energy are resources, that renew themselves. The greatest source of these types of energy are thermonuclear fusions happening in the Sun. Thermal radiation from the Sun heats the air, water and Earth itself. That causes air movement and sea currents. Another source is movement of the Moon, which causes high tides and low tides of seas and oceans. All renewable energy sources are considered inexhaustible, but it is just because the time until they are deplenished is counted in billions of years [4].

1.2.1. Solar energy

Solar energy is radiant heat and light from the Sun that is harnessed using a range of technologies like photovoltaics or solar heating. It is relatively well-spread over the globe offering clean, inexhaustible, abundant and climate-friendly energy source for the mankind [5].

Photovoltaics, also known as solar PV, are a method for generating electricity using solar cells. A solar cell is a device that converts light directly into electricity using the photoelectric effect (Fig. 2). It is the emission of electron when photons of light beam strike the material. The first solar cell was constructed by Charles Fritts in the 1880s [6]. In 1931 a German engineer, Dr. Bruno Lange, developed a photo cell using silver selenide. The prototype selenium cells converted less than 1% of incident light into electricity, but scientists recognized importance of this discovery and researchers Gerald Pearson, Calvin Fuller and Daryl Chapin created the crystalline silicon solar cell in 1954, which had the efficiency around 5 % [6]. In the last decade researchers are trying to make solar cells from perovskite structure compound. The efficiency of these cells increased more than five times in the last decade, making perovskite solar cells the fastest-advancing solar technology to date [7].

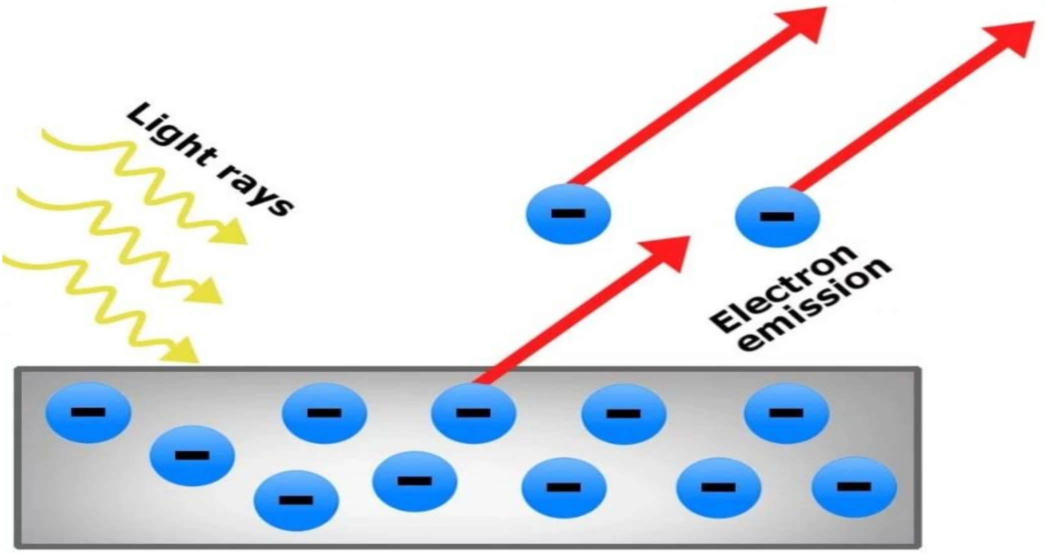


Figure 2 – Photoelectric effect (Taken from [8])

Single solar cell does not produce that much electric energy, so they are typically wired together into one solar panel. More solar panels can be wired together to make and solar array (Fig. 3). This way it produces much more electricity.

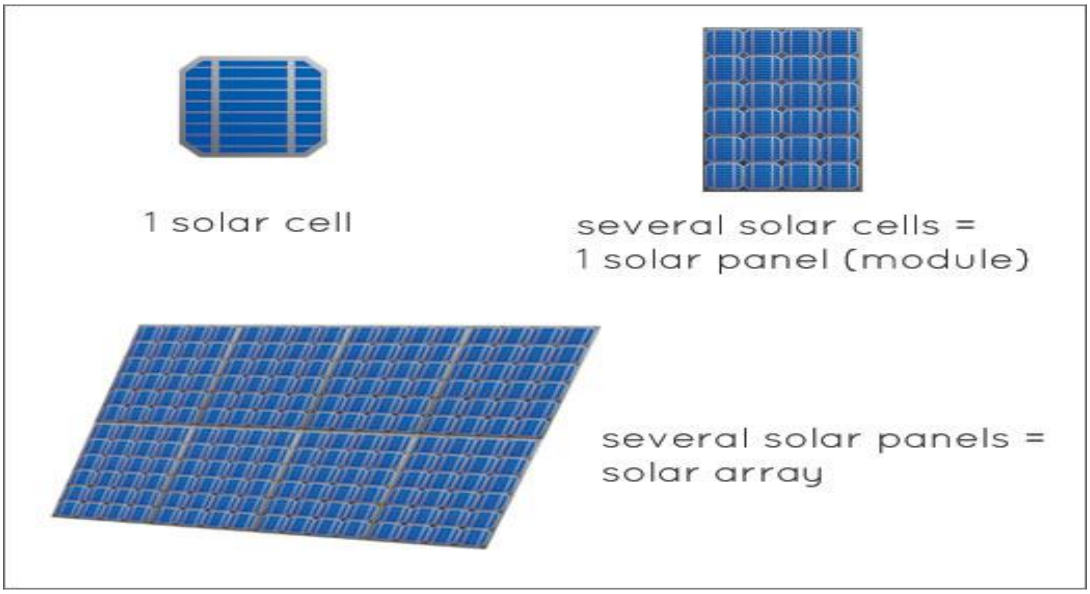


Figure 3 – Solar cells combinations (Taken from [9])

There are two possible configurations – serial and parallel. If connected in series the electrical voltage of each cell adds up, but the electric current stays the same. In parallel configuration the currents add up, but voltage stays the same. Each solar cell should have the same amount of current if connected in series or the same amount of voltage in parallel configuration to avoid damaging other cells [10].

In 2014 Czech Republic had the 6th highest watt per capita made from solar energy in the European Union [11].

1.2.2. Wind energy

Kinetic energy of moving air masses is possible to use in many different heights above the face of the Earth. The wind energy is being used since ancient times as drive force for sailing boats or as water pumps drives or windmills (Fig. 4).


Figure 4 – Windmill in Buckinghamshire (Taken from [12])

This wind machinery was powered by blades covered with canvas [4]. It converts the energy of wind into rotational movement. This technology of harnessing the wind energy is nowadays overcome, but the principle of harvesting energy from wind energy is still evolving and is being vastly used.

Current wind power plants consist of four main parts (Fig. 5): Rotor, generator/alternator, device for measurement and regulation and building part. Rotor converts the energy of wind into mechanical energy. Generator/alternator transforms mechanical energy in electric one. The device for measurement and regulation provides automatization of the whole power plant and building part holds the thing up.

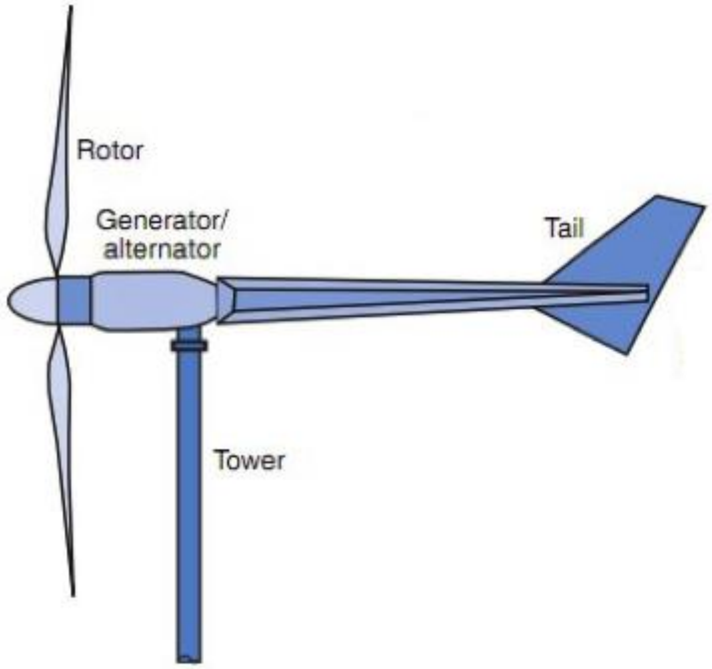


Figure 5 – Main parts of wind power plant (Taken from [13])

1.2.3. Hydropower

Mankind uses hydropower from ancient times. Water wheels were built to power many different machineries, watermills, etc. Type of the watermill determines how effective is the transformation of hydropower into energy. They are transforming kinetic energy, but can also transform potential energy if the water falls from certain height on the wheel.

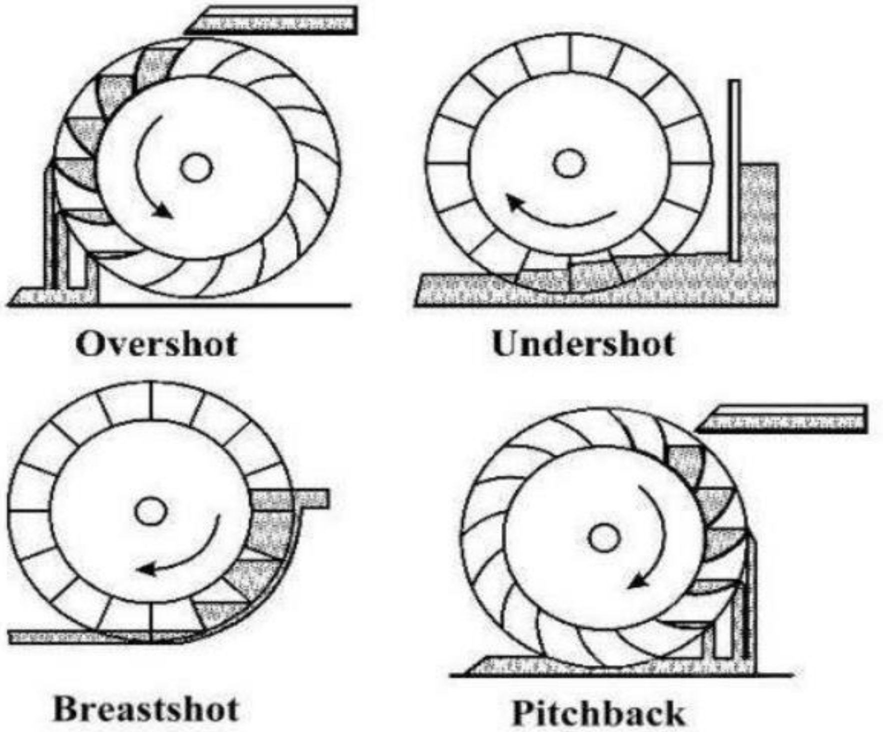


Figure 6 – Types of waterwheels (Taken from [14])

Overshot	water enters the buckets at the top
Undershot	water flows underneath the wheel
Breastshot	water enters the buckets at about the middle of the wheel
Pitchback	water enters the buckets at the rear of the wheel beneath the penstock

Water is about 800 times denser than the air, so even a slow flowing stream of water can yield considerable amount of energy. Usage of hydropower started by building water dams and reservoirs and is still popular. The largest hydroelectric water dam is Three Gorges Dams in China (Fig 7). It generates around 22,5 GW of electric energy, which is 1,5 GW more than all power plants in Czech Republic combined [15].

Figure 7 – Three Gorges Dams in China on Yangtze River
(Taken from [16])

Wave power and tidal power are another two types of hydropower with great future potential. Wave power captures the energy of surface waves on the ocean and tidal power converts kinetic energy of tides. Unfortunately building of those power plants harvesting energy from tides or waves is very expensive, so they are not widely employed commercially yet.

In 2015 hydropower generated 16.6 % of the world's total electricity and 70 % of all renewable electricity [17].

1.2.4. Piezo-electricity

It has been almost 140 years since piezo-electric effect was first observed by Pierre and Jacques Currie [18]. They were conducting series of experiments with crystals of tourmaline, quartz, topaz, Rochelle salt and cane sugar. During these experiments they observed new phenomenon, which was later named piezo-electric effect by Wilhelm Gottlieb Hankel [19].

In 1917 Paul Langevin found first practical use for piezo-electric effect [20]. He used reverse piezo-electric effect in the first submarine detector utilizing quartz crystal. This detector works on the principle of echolocation. Device emmites pulses of sound and then it detects the echoes. From the time it takes to the sound to travel to an object and back to detector and known velocity of sound under water, it calculates the distance between object and device. This device is also known as SONAR.

It took over one hundred years since the first observation for someone to start thinking about energy harvesting from mechanical vibration using piezo-elements to power microsystems [21].

As the response to applied material stress some solid materials (such as crystals, certain ceramics, biological matter like bone etc.) accumulate in electric charge [22]. This phenomenon is called piezo-electricity. The word piezo means “pressure”, it was derived from Greek *piezen*, which has a meaning of “squeeze, to press tight “[23].

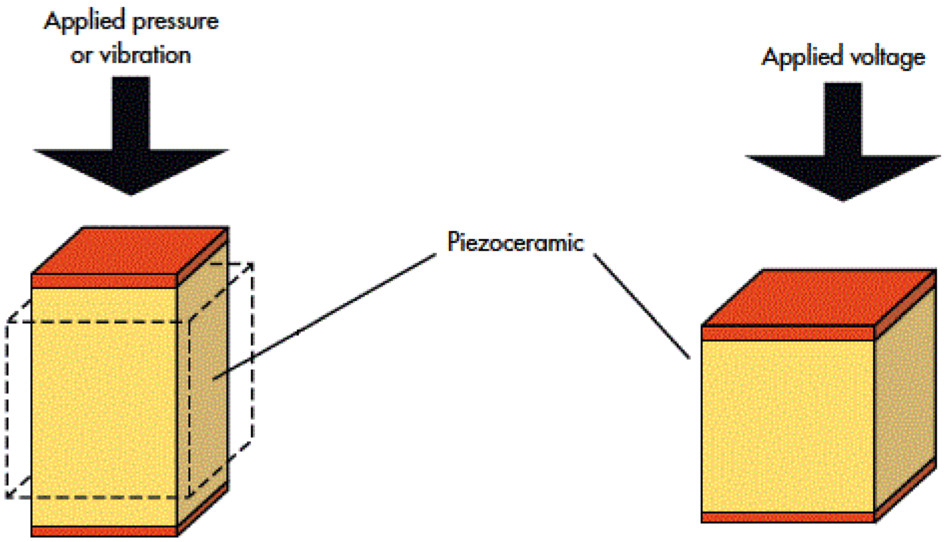


Figure 8: Deformation of the piezoceramic leads to voltage production and vice versa. Source [24]

When voltage is delivered to piezo-electric material, it responds with deformation proportional to the quantity of voltage. This phenomenon is called converted piezo-electric effect. It has a broad field of use and is used in many things, which surround us nowadays. For example in modern loudspeakers, it is part of the apparatus, which converts electrical impulses into sound. The alternating voltage with certain frequency is sent to piezo-element, which starts vibrating on the frequency and creates a sound or a tone. As long as the voltage can be altered, the sound can change, resulting in sound, which can be heard coming out of loudspeakers. Next it is used in piezo-electric resonators, which can be used for example in SONAR as we found out earlier. And last but not least small piezo-electric crystals are utilized in fine mechanics, where is need for really small shifts or movements, which can be achieved with small amount of voltage coming into these small crystals. Shifts in order of micrometres are possible with piezo-electric crystals. In addition to this there is a second type of piezo-electricity manifested by the same materials.

The piezo-electric material also works in the opposite way. When the stress is applied periodically to piezo-electric material (for example with the use of oscillator) it responses by making alternating voltage. This kind of voltage then can be harvested if rectified. The simple energy harvesting circuit is consisting from piezo-generator with bridge rectifier and capacitor. The rectifier transforms alternating voltage into rectified voltage (Fig. 9), which can be used to charge up energy storage [25] or to power a device directly.

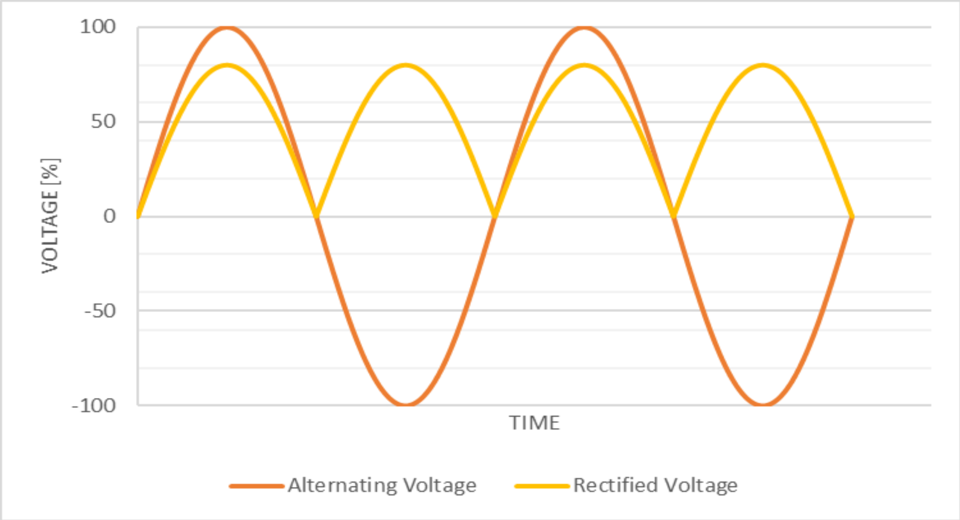


Figure 9 – Alternating voltage before rectifier and rectified voltage with 80% efficiency

Piezo-electric materials are suitable for high frequencies in order of hundreds or thousands of hertz. They produce high voltage, but for low frequencies the impedance is high, resulting in low current [26].

Yet there is an effort to make wearable power supplies. Throughout our daily activities, a significant amount of power is spent. Harvesting this energy can be used to generate power for electronics [27]. For this purpose, the concept of “smart fabric” was researched [28]. With different amounts of conductive material, the resistance can be adapted, so other components can be sewn into the fabric. Next step was to generate electrical power while walking. For this reason, piezo-electric actuators can be placed inside the sole of shoe [29].

Another direction of research is about sensors powered by piezoelectricity. These sensors are mostly used in transport. Piezo-elements are mostly used as sensing elements. Piezo-electric sensors can be placed on distinct areas of the train wheel, where they are changing the displacements on the surface into electricity. In the cars they are used as knock sensors, detecting irregular combustions of the engine or they can be used as accelerometers [30]. Sensors using piezo-electricity can be used as well as seismic detectors [31], using piezo-element to measure vibration and record the changing electricity output from piezo-element.

2. Experimental section

2.1. Materials

2.1.1. Measuring card

All the communication between PC and outside devices is mediated by the measuring card NI CB–68LRP from National Instruments (Figure 10). This card is a low-cost termination accessory with 68 screw terminals for easy connection of field input and output signals to 68-pin data acquisition products. It includes one 68-pin male connector for direct connection to 68-pin cables. The connector blocks feature standoffs for use on a desktop or mounted in a custom panel. The CB-68LP has a vertical mounted 68-pin connector. The CB-68LPR has a right-angle mounted connector and is used with the CA-1000 [32].

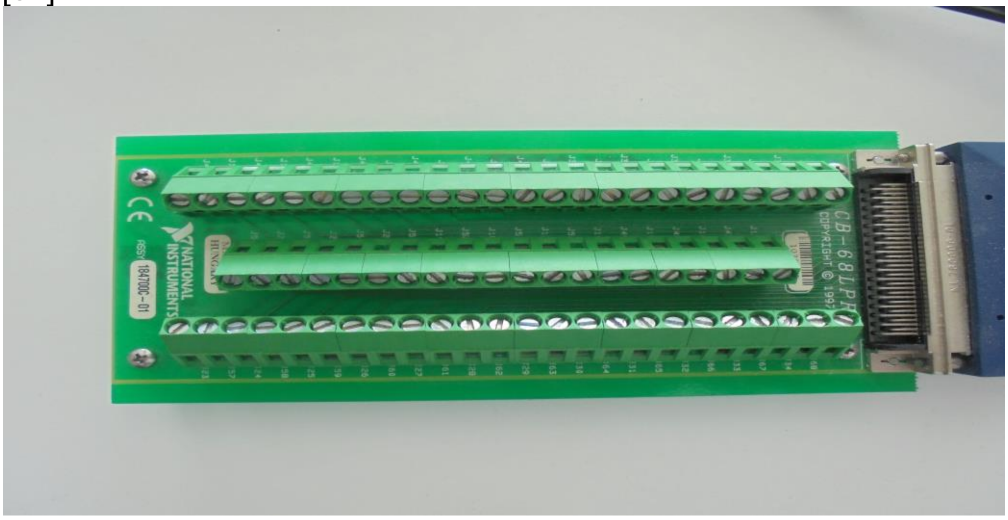


Figure 10 - Measuring card NI CB-68LRP

2.1.2. Oscillator

The oscillator (Fig. 11) was borrowed from Department of Experimental Physics. It was used to put stress periodically to piezo element. It was set up, so the screw on the right side of the oscillator in the figure would touch the piezo-element, resulting in deformation of the element, when the oscillator started oscillating.

a) 

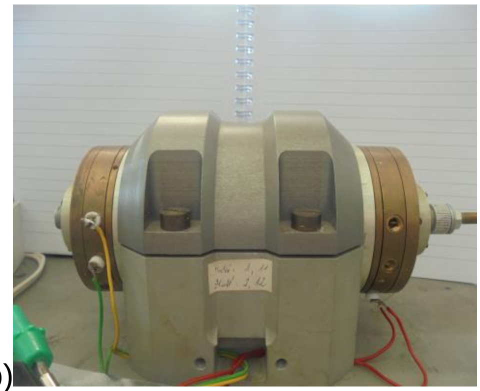
b) 

Figure 11 – Oscillator: a) view from above, b) front view

The screw, which is in contact with the piezo-element is made of metal. This could cause loss of electric energy generated from the element, because the material of the screw was made from conductive material. The need to electrically isolate the screw from the piezo-element led to the search for suitable insulating component. The suitable component (Fig. 12) was printed from plastic on department's 3D printer. The screw fits into the hole on the bottom of the component (Fig. 12.c). On the top is a narrow cylinder, which minimizes the area of contact.

a) b) c)

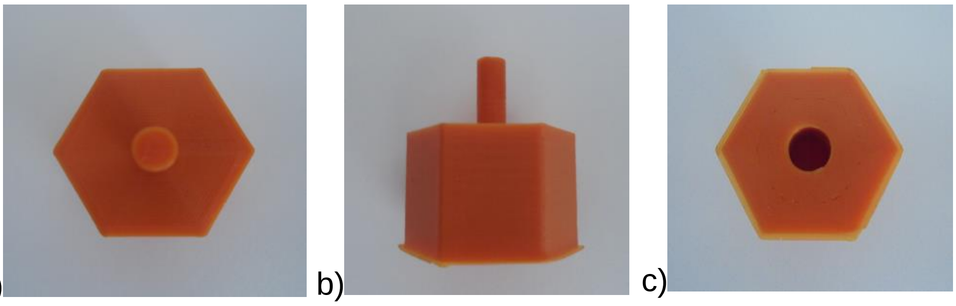


Figure 12 – Insulating component: a) Top view, b) front view, c) bottom view

2.1.3. Piezo-element

The piezo-element was chosen to be KPS 100 from Kingstate. It was used for all measurements in this Bachelor Thesis. It consists of bigger metal disc with diameter 50mm, concentric smaller disc made from piezo crystal and black plastic ring into which, the bigger disc is attached. To bigger and smaller disc are soldered two separated wires. Black wire is connected to the bigger disc and red wire to the smaller disc (Fig. 13).

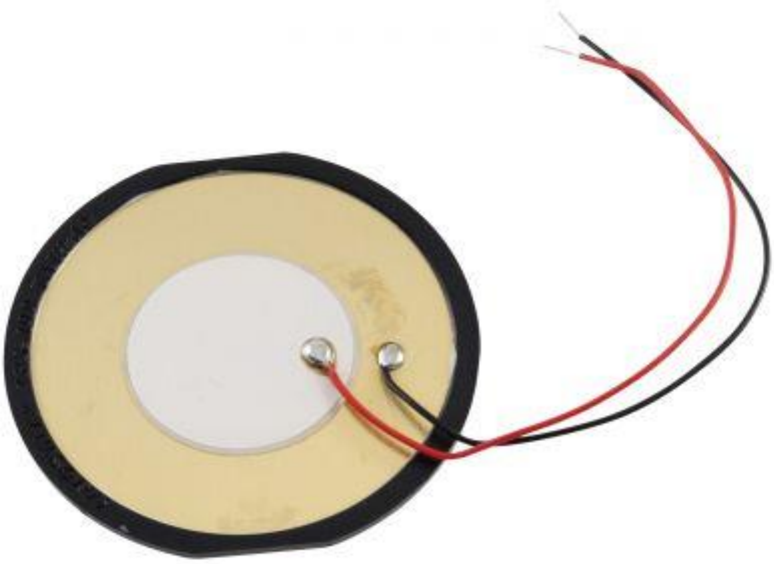


Figure 13- Piezo-element KPS 100 (Taken from [33])

2.1.4. Energy storage

After considering many types of energy storages, capacitor was chosen. More specific type of capacitor was chosen by trial and error method. The main criterion was the highest capacity, which could be charged in a reasonable time. Another requirement occurred, when the commercial circuit was chosen. It needs at least 5 V to release regulated 3.3 V, which could power some small device. In the end capacitor with the capacity of 2200 μF and 16V was chosen (Fig. 14).

Figure 14 – Used capacitor

2.2. *Circuits*

2.2.1. Commercial Energy Harvesting Circuit

The commercial EH circuit was chosen after search for a circuit, which was made especially for energy harvesting from piezo-elements. After search the Sparkfun Energy Harvester Breakout – LTC 3588 was chosen (Fig. 15). In the description and datasheet was the information that it uses the LTC3588 Piezo-electric Energy Harvester from Linear Technologies. It offered the possibility to select regulated output voltages and promised high efficiency harvesting.

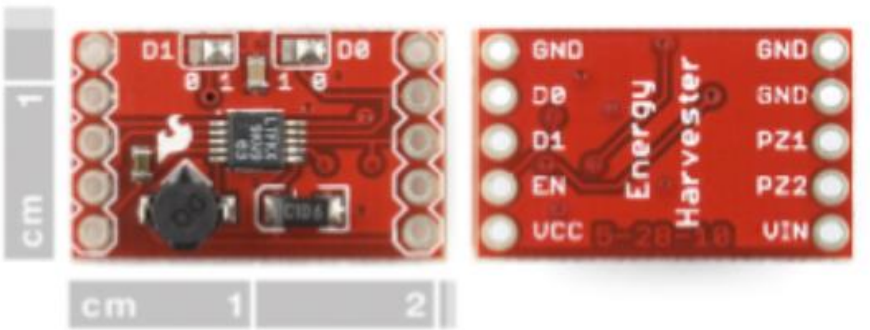


Figure 15 – Commercial EH Circuit (Taken from [34])

It wasn't just simple EH circuit, it had the special piezo-electric energy harvester built in (Fig. 16), so the harvesting would be effective.

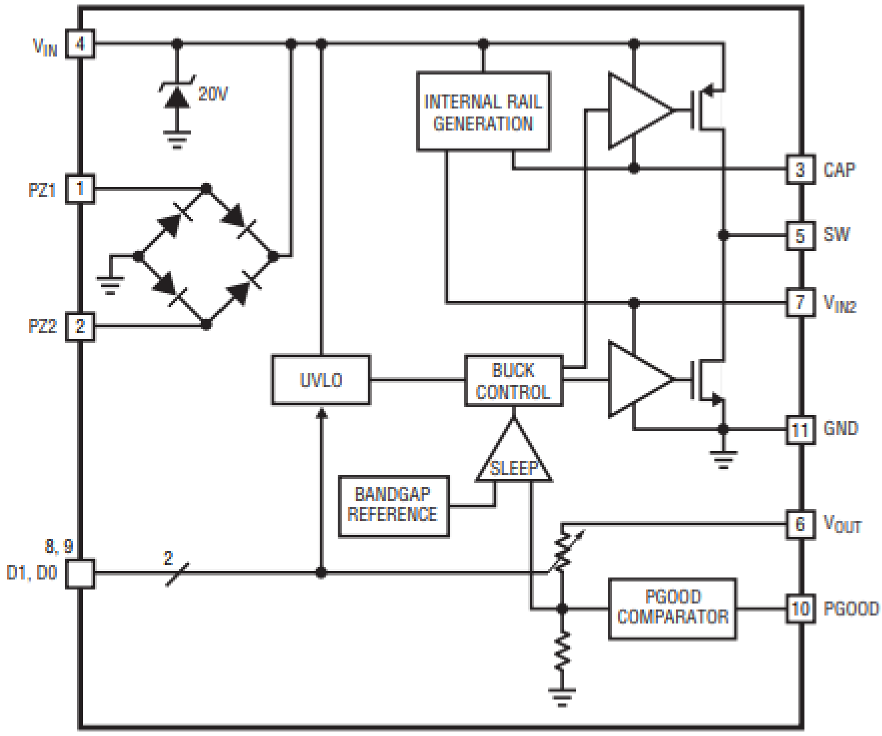


Figure 16- Block diagram of the LTC3588 (Taken from [35])

The piezo-electric energy harvester has 10 accessible pins, each with different function.

V_{IN}	Rectified Input Voltage. A capacitor on this pin serves as an energy reservoir and input supply for the buck regulator.
PZ1	Input connection for piezo-electric element or other AC source (used in conjunction with PZ2)
PZ2	Input connection for piezo-electric element or other AC source (used in conjunction with PZ1)
D1, D0	Output Voltage Select Bit. D1 or D0 should be tied high to V_{IN} or low to *GND* to select desired V_{OUT}.
CAP	Internal rail referenced to V_{IN} to serve as gate drive for buck PMOS switch. A 1µF capacitor should be connected between *CAP* and V_{IN}.
SW	Switch Pin for the Buck Switching Regulator. A 10µH or larger inductor should be connected from *SW* to V_{OUT}.
V_{IN2}	Internal low voltage rail serves as gate drive for buck NMOS switch. Also serves as a logic high rail for output voltage select bits *D0* and *D1*. A 4,7µF capacitor should be connected from V_{IN2} to *GND*.
GND	Ground. The Exposed Pad should be connected to continuous ground plane on the second layer of the printed circuit board by several vias directly under the LTC3588-1.
V_{OUT}	Sense pin used to monitor the output voltage and adjust it through internal feedback.
PGOOD	Power good output is logic high when V_{OUT} is above 92 % of the target value. The logic high is referenced to the V_{OUT} rail.

2.2.2. Simple Energy Harvesting Circuit

This circuit (Fig. 17) was built with the single intention of charging up capacitor from piezo-element. The bridge rectifier that was used has upper voltage limit of 500 V and costs around 4 CZK. It is Silicon Bridge Rectifier B250R from Diotec Semiconductor.

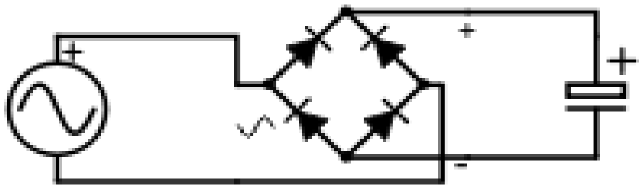


Figure 17 – Simple EH Circuit

2.3. Control program

The whole program that allows the communication between PC and National Instruments measuring card was made in Labview from National Instruments.

2.3.1. User interface

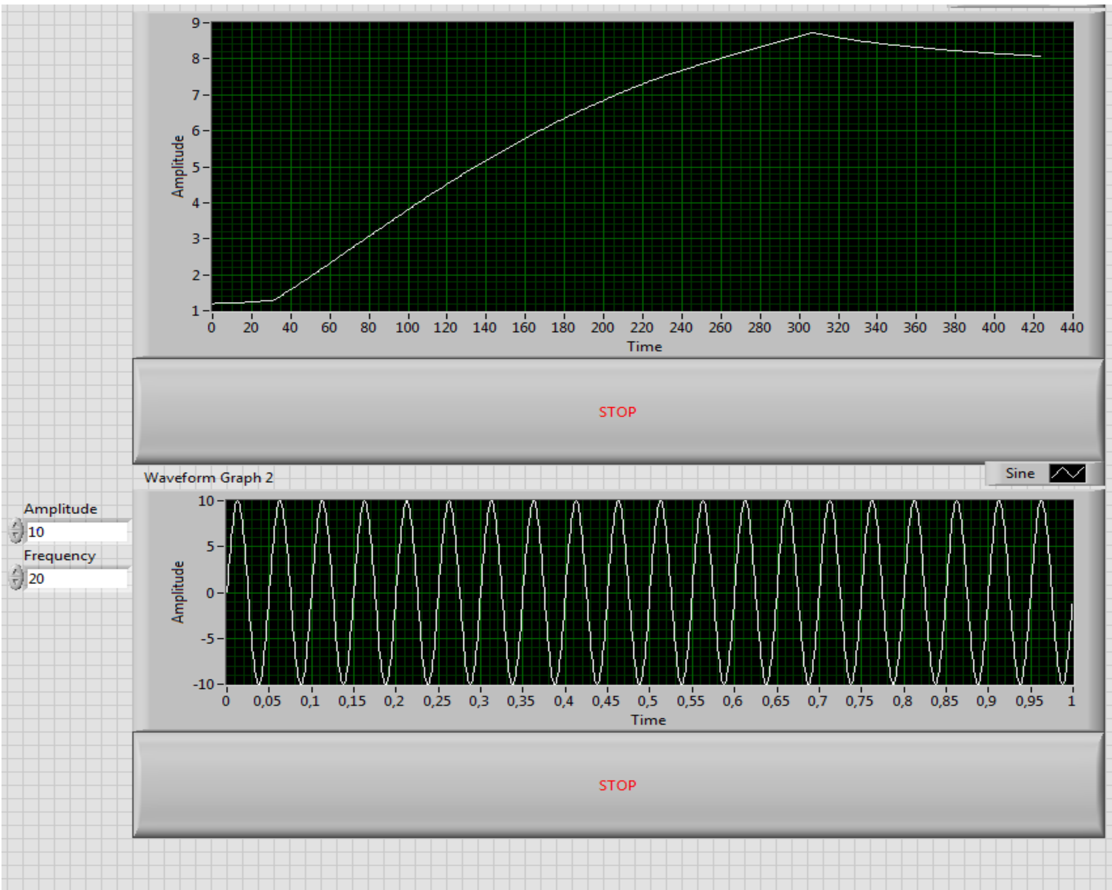


Figure 18 - Front panel of the program

The program uses front panel to communicate with user. Front panel (Fig. 18) shows in the upper part of the picture the first diagram. This diagram represents the change of voltage on the capacitor through the time. Right under this diagram is the first stop button, which when clicked on, ends the measurement. In the lower part of the picture is second diagram, which shows frequency and amplitude of the oscillator, which is periodically pressuring the piezo element. Next to it are two indicators/ controllers, where user can change values of the amplitude and frequency. Bellow the diagram is the second stop button, which allows stopping the oscillator from oscillating without interrupting the whole measurement.

2.3.2. Oscillator control

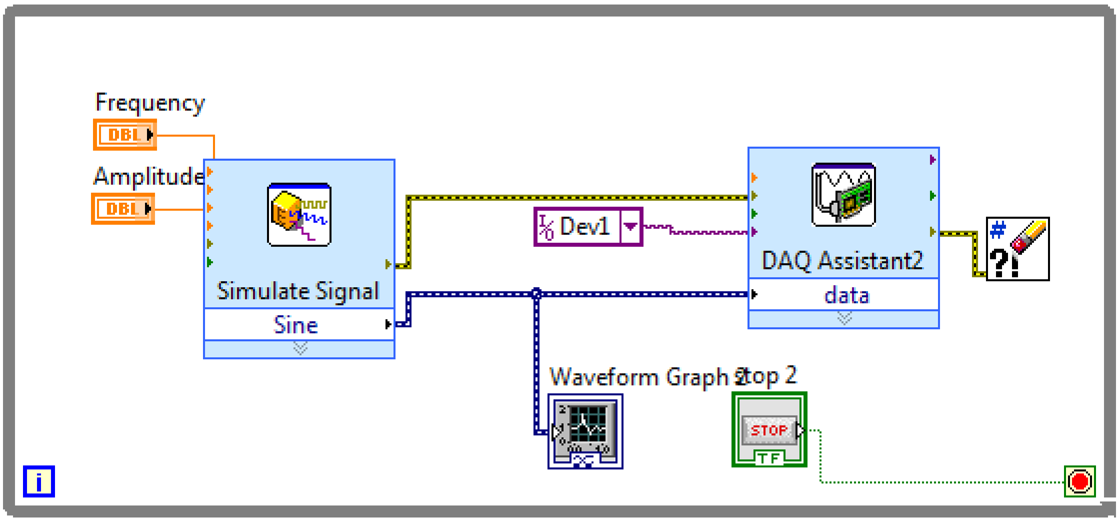


Figure 19- Oscillator control

Code (Fig. 19) allows the user to control properly the oscillations of the oscillator from PC. This part of the program generates signal output.

While loop	Putting code into this loop allows to stop only the oscillator without interfering with the rest of the program. It is being represented by the grey rectangle around.
DAQ Assistant2	Allows the communication between the PC and measuring card. The card sends signal with certain amplitude and frequency to the oscillator. The amplitude of signal commands how much it should move and the frequency how fast it should move.
Simulate signal	Creates defined type of signal. There is a choice between basic types of signal (e.g. sine, square) or the signal user can design.
Waveform graph	Shows how the simulated signal looks like before sent to the card.

Stop Ends the while loop, resulting in stopping the oscillators movements.

Frequency Allows the user to change the frequency of oscillation.

Amplitude Allows the user to change the amplitude of oscillation.

Dev1 Indicates which device is controlled by the code. Here Dev1 is the measuring card connected to the PC.

Clear error When an error would appear, this function automatically removes it. In this code was this function used because after some time, a dialog window would appear, which caused the oscillator to stop moving, until enter was pressed. After pressing enter the oscillator continued to move. By clearing all errors, even this dialog window was removed and the oscillator could oscillate continuously.

2.3.3. Voltage measurement

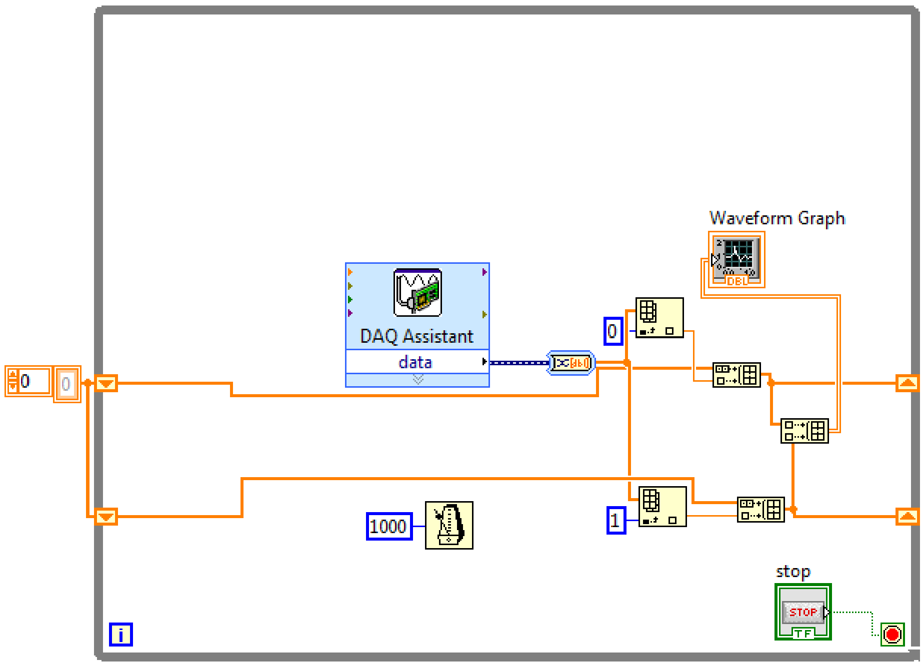


Figure 20- Data collecting

Code (Fig. 20) shows the dependence of voltage on capacitor to time. Data are shown in real time in the upper graph in front panel from where they can be later exported to file. This part of the program processes input voltage.

While loop Allows to continuously collect and show data in real time. When this loop is stopped, the measurement stops. It is being represented by the grey rectangle around.

DAQ Assistant	Allows the communication between the PC and measuring card. The card measures voltage on the capacitor a then sends signal with the value to the PC.
Waveform graph	Shows the change of voltage on capacitor in real time.
Stop	Ends the while loop, resulting in stopping the measurement.
Wait until	Makes the PC to read data only once in the set time.

The rest of the code is doing two things. Firstly it changes time axis, because the *waveform graph* normally shows time in the format HH : MM: SS DD/MM/YYYY. After the change the time axis starts with zero ends with the last second of the measurement. And secondly it allows user to show dependency of voltage on time, if needed.

3. Data analysis

3.1. Charging with commercial circuit

The commercial circuit was used through all the tests of the measuring program. Unfortunately, data were not acquired, because at the moment when was time to acquire data from measurements, the circuits didn't handle the voltage from piezo-element and its connections were burned.

3.2. Charging with simple circuit

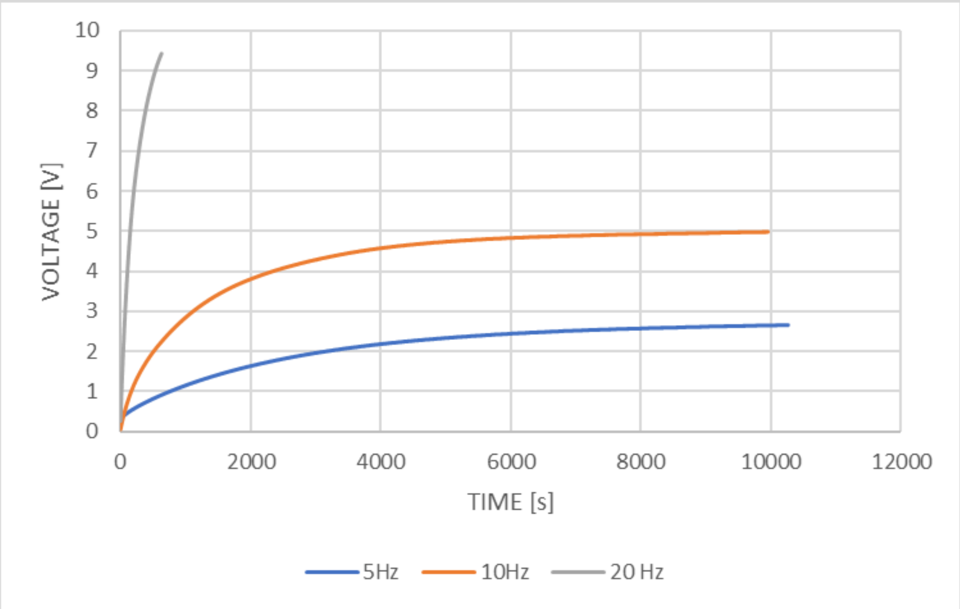


Figure 21 – Charging the capacitor with different frequencies

3.3. Self-discharge of capacitor

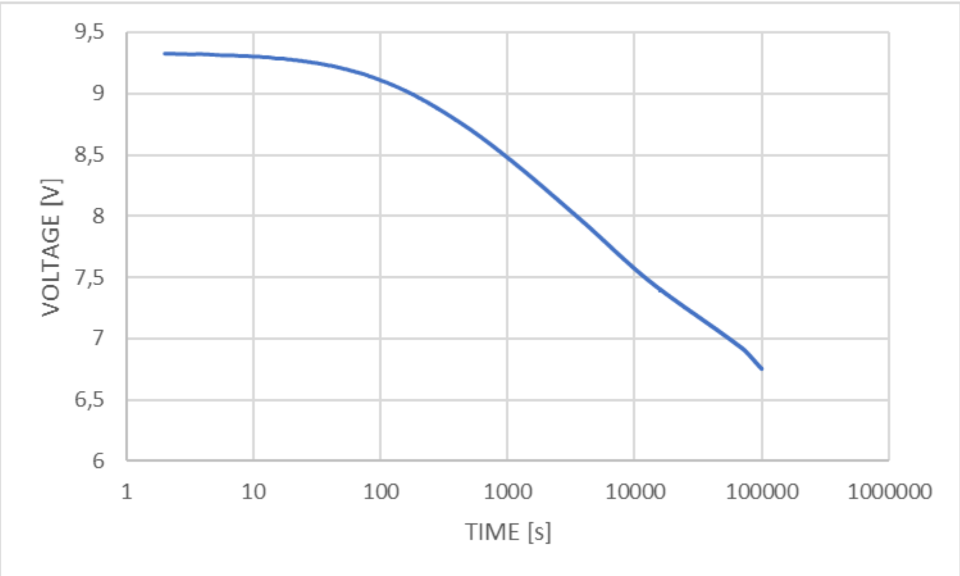


Figure 22 – Self discharge of capacitor

Conclusion

Circuit that was made especially for energy harvesting from piezo-elements Sparkfun Energy Harvester Breakout – LTC 3588 failed to provide any useful data. With the price over 600 CZK it is inconceivable, that this circuit had no overvoltage protection. Especially when it is well known that piezo-elements can generate high voltage. And this circuit was burned in low frequency application.

Fortunately enough, the simple energy harvesting circuit provided us with enough data. For circuits, which consist only from bridge rectifier for 4CZK, it is quite worthy substitution. It can be established that the charging curve (Fig. 21) is probably equal to exponential curve and the higher the frequency and/or amplitude the faster the charging of capacitor is conducted. The self-discharge curve (Fig. 22) of capacitor is similar to logarithmic curve.

With the possibility of repeating the measurements, piezo-elements can be changed and after series of measurements under the same conditions, the quality of different piezo-elements can be compared. The piezo-element, which produces more energy, while it is equally deformed as a different one is better for energy harvesting. When new piezo-electric material will be developed, it can be compared to the best ever measured like this. It is an easy way of how to relatively soon, after developing a new material, figure out if the new material is better.

In the future the development of more efficient materials will continue. The need for more renewable energy will drive these researches. It will find use in wearable electronics, and if more efficient materials occur, it has definitely the potential to replace the batteries in phones and other small electronics.

List of Used Sources

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List of Abbreviations

EHS – Energy Harvesting System
EH – Energy Harvesting
SONAR – Sound Navigation And Ranging

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