RF CIRCUIT POWERED BY A PIEZOELECTRIC GENERATOR

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Abstract — This study presents a piezoelectric generator powering a radio frequency (RF) transmission system. The objective of the research is to propose a wireless communication system that is self-powered without using conventional batteries. Electricity is generated from the mechanical impact of a small hammer on a piezoelectric stack. An electronic circuit was developed in order to adapt the piezo-generated voltage to levels compatible with the regulatory circuits. The voltage was adjusted to operate a small low-power RF signal transmitter. A receiver circuit validated the message sent by the transmitter. This work presents the voltages produced by the piezoelectric generator and the characteristics of the electronic circuits: the power consumption, transmission response, receiving response considering data sent by the self-powered transmitter.

Keywords — Energy Harvesting, Piezoelectric Materials, Self-powering, RF Communication.

1 Introduction

Nowadays there is a constant search for renewable energy sources due to the need to supply the growing demand for electronic devices and equipment and to reduce the environmental impacts caused by non-renewable sources, such as electrochemical batteries (Anton and Sodano, 2007). Several forms of environmental energy can be converted into useful electrical energy. However, the application and availability are preponderant factors for choosing the most suitable medium for energy extraction and conversion. Among the main sources we can highlight: wind, solar, thermal and kinetic. Although all these forms of energy are available in several places, mechanical energy through vibration is quite attractive for electricity generation, since it is an inherent part of the operation of various devices and it is present in a wide range of applications, such as electric machines in industry, cars, computers or household appliances; amplitude and frequency levels vary.

Within the possibilities of converting mechanical energy into electrical energy, piezoelectric materials are distinguished providing a direct coupling between voltage and mechanical deformation. Due to the coupling between two distinct physical domains, occurring in a bidirectional manner, these materials are also known as intelligent materials. Figure 1 shows a comparison between piezoelectric materials and other types of energy sources in terms of energy density. These materials represent the major part of this research field. They are capable to produce adequate levels of electrical voltage for a direct connection to a load (Erturk and Inman, 2011).

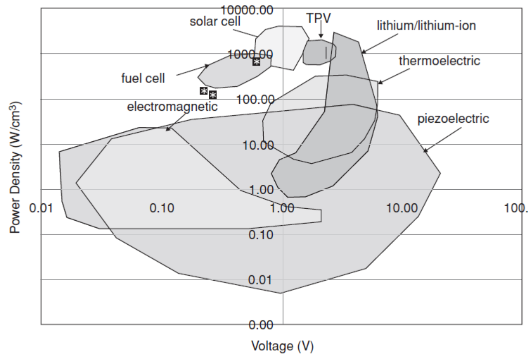

Figure 1. Comparison of energy density and generated voltage for different energy sources (Erturk and Inman, 2011).

For applications in the field of materials engineering, piezoelectrics must have high mechanical coupling, which is present for instance in Lead Zirconate Titanate piezoceramics (PZT). This material was developed by Tokyo Institute of Technology in the 1950s and has become the most widely used piezoelectric ceramic (Erturk and Inman, 2011). Such ceramics have allowed the use of this mechanism in electric power generation systems, vibration control and even structural monitoring (Patel, 2011).

Research on energy harvesting with piezoelectric material is divided in two parts, first the mechanical structures providing the coupling and second the electric circuitry conditioning the generated signal. Most devices are in beam configuration with one or two layers of piezoceramic; the beam is clamped at one point. When such a structure is excited by vibrations, an alternating electrical voltage is observed across the surfaces of the material, having the same frequency than the induced deformation (Hamilton, 2012). Roundy and Wright (2004) developed a piezoelectric generator and compared the experimental data with the mathematical model developed for a two-layered single-beam configuration (one clamped point). They reported a power density of 375 μW/cm^3 at an acceleration of 2.5 m/s^2 and a vibration frequency of 120 Hz. The electricity generated was not sufficient to power the wireless transmission system directly, but by means of a storage capacitor, the power could be transferred with a 1.6% duty cycle.

Keawboonchuay and Engel (2003) conducted research with the aim of maximizing the electrical energy generated by a piezoelectric pulse generator excited by a mechanical impact. These authors evaluated the relationship between thickness and axial area to obtain the maximum electric power. It was concluded that the output power of this type of generator increases linearly with the thickness to axial area ratio (TAR); this follows from the fact that the voltage increases at a higher rate than the current. The mechanism of the piezoelectric impact can be achieved by releasing a spring, causing a hammer to bump the piezoelectric surface generating a pressure wave which is reflected multiple times, thus creating a mechanical resonance. This translates into an oscillatory electrical voltage signal at the mechanical resonance frequency (Tan et al., 2006). Paradiso and Feldmeier (2001) developed a conditioning circuit for this type of device in order to feed an RF circuit to send a coded signal. The obtained output power was 0.5 mJ and the energy consumed for transmission of a 12-bit word was 150 μJ, with an approximately 7.5 mW peak for 20 ms. Tan et al. (2006) used a piezoelectric device impact to send a signal via RF without the use of batteries. The obtained electrical energy was 67.61 μJ, being enough to send two words of information.

This work presents the characterization of a piezoelectric generator excited by mechanical impacts; it also reports results of the transmission and receiving of RF signals.

2 Materials and Methods

This research used a piezoelectric generator excited by mechanical impacts, a circuit for signal conditioning and a load. The schematic diagrams of the proposed self-powered transmission and receiving system are shown in Figure 2.

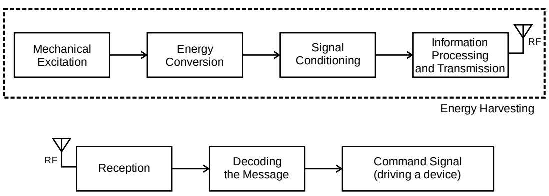

Figure 2. Diagram of the self-powered transmission and receiving system.

In this work, the mechanical excitation is achieved by pressing a button containing the piezoelectric generator in its interior. An electromagnetic transformer, a full-wave rectifier, a storage capacitor, and a low-power linear voltage regulator mediate the conversion from mechanical impact to electrical signal. The regulated electrical voltage signal feeds an encoder circuit and a RF transmitter sending a serial code. Energy is generated only when sending a code, thus no power consumption by the circuit when no message is being sent (standby mode). An RF receiver with independent power supply, tuned to the frequency of the transmitter, receives the code and triggers a load. According to the decoding protocol, code is accepted after two equal consecutive transmissions.

2.1 Measurement of the Generated Electric Voltage

The voltage produced by the piezoelectric generator under no load condition is a function of the force applied at the actuation button. Considering the impact generator used in this research, the hammer force was controlled by the defined compression of a spring, which always produces the same impact intensity. Consequently, the amplitude of the voltage generated is not affected by how the button is pressed. A resistive divider circuit with high impedance was implemented to reduce the measured output voltage to a value suitable for a common oscilloscope probe (Figure 3). The tests have been conducted with an Agilent DSO1004A oscilloscope and Agilent N2862A passive probes.

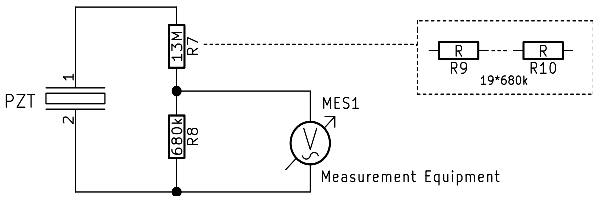

Figure 3. Circuit setup to measure the voltage generated.

When the output impedance of the generator is neglected, the voltage read across the resistor can be calculated using Equation (1).

$$V_{MES} = \frac{R_8}{R_8 + R_7} \cdot V_{PZT} = \frac{R}{R + (19 \cdot R)} \cdot V_{PZT} \cong \frac{V_{PZT}}{20} \qquad (1)$$

2.2 Signal Conditioning Circuit

Due to the high voltage and low current provided by the piezoelectric generator, the conditioning circuit contains a step-down transformer at the input stage with transformation ratio of 100: 1 and low flux leakage, because the load to be powered operates between 3.3 and 5.0 V approximately. As the piezoelectric element has capacitive characteristic, the magnetizing inductance forms an LC oscillator circuit contributing to the energy transfer. Because the output signal from the transformer is AC, a full rectifier bridge and a storage capacitor were used to provide a continuous voltage level. The storage capacitor was determined considering the need for filtering the alternating component and for reducing the value of the generated voltage. The latter fact was considered as the most important, because with increasing capacitance the impedance decreases, causing the voltage to be reduced as well. To maintain the voltage signal provided by the capacitor constant for the period of time required for signal transmission, a low-power linear voltage regulator was used. Due to the small current consumption of the load and a small voltage drop between IN and OUT, this type of circuit is more suitable than a DC- to-DC boost converter.

The integrated circuit HT7333 was used as a regulator; its characteristics are a low bias current (typical 8 µA) with an output voltage of 3.3 V, output current up to 250 mA and a maximum input voltage of 12 V. The output voltage passed across a capacitor in order to attenuate possible high frequency components. Figure 4 shows schematically the signal conditioning circuit for powering the RF circuit.

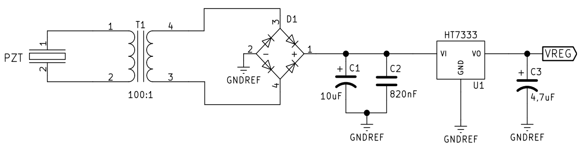

Figure 4. Conditioning circuit setup.

In order to generate the code to be transmitted, a MC145026 encoder unit was used; it converts 4 data bits and 5-bit addresses and sends them serially. Each high or low bit is encoded in eight clock pulses. A high bit is encoded in two long pulses, one high impedance state (open) represented through one longer pulse and the second shorter pulse; a low bit is encoded in two shorter pulses. The first five bits of the word refer to the address and the remaining four bits to the data. To ensure system integrity, the encoder sends a word twice with an interval of 24 clock pulses between both transfers (MC145026, 2017). When the decoder (MC145027) receives the first word it stores it and awaits the second one for comparison. If equality is verified the VT pin (valid transmission) is at a high level for a certain period of time.

The RF transmitter used was the TWS-D 434 suitable for this application due to its low power consumption. The main characteristics are: input voltage between 1.5 and 15 VDC, RF output power of 8 mW, frequency of 433.92 MHz and 5 kHz bandwidth. Figure 5 shows the circuit diagram of the encoder and RF transmitter.

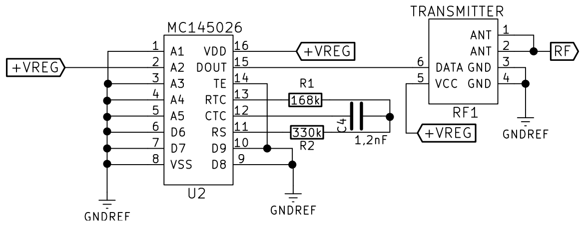

Figure 5. Encoder and RF transmitter diagram.

The transmission rate is defined by the frequency of the oscillator according to Equation (2).

$$f_{osc} = \frac{1}{(2.3) \cdot R_{TC} C_{TC}} \tag{2}$$

The received data are transferred directly to the decoder input, which is associated to the same address set in the encoder. The resistors of R4 and C6 define the end of the word and the end of the transmission. Already R3 and C5 are responsible for interpreting the high, low and open states. However, all these resistor values depend on the oscillation frequency (RTC and CTC).

Figure 6 shows the scheme of the receiver circuit for a code transmitted by the self-powered RF circuit.

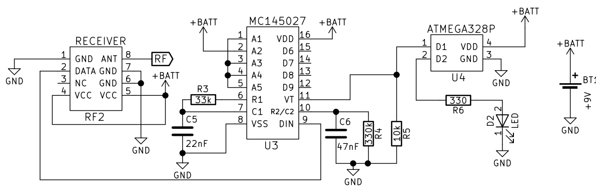

Figure 6. Decoder and receiver diagram.

The following conditions hold for calculating the resistance values (Equations (3) e (4)):

$$R_4 C_6 = 77 \cdot R_{TC} C_{TC} \tag{3}$$

$$R_3 C_5 = (3.95) \cdot R_{TC} C_{TC} \tag{4}$$

2.3 Prototype and Electronic Circuit

The piezoelectric generator used in this investigation is a commercial igniter spark generally used as a lighter. A prototype consisting of this conventional igniter inside a 3D structure was used to carry out the experimental tests. The developed prototype offers an easier way of handling the generator, besides facilitating an integration with electronics systems. The picture of the generator used in this works is presented in Figure 7, the 3D structure is on the left and the igniter is on the right. The mechanical input and the electrodes of the generator are indicated. It is described the direction of the displacement (Δ) when the system is excited.

The electronics circuits discussed before has been implemented in laboratory for experimental validation. It is shown in Figure 8 the self-power transmission system based on energy harvesting.

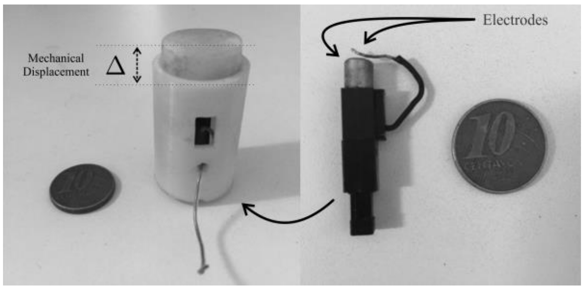

Figure 7. Pictures of the piezoelectric generator.

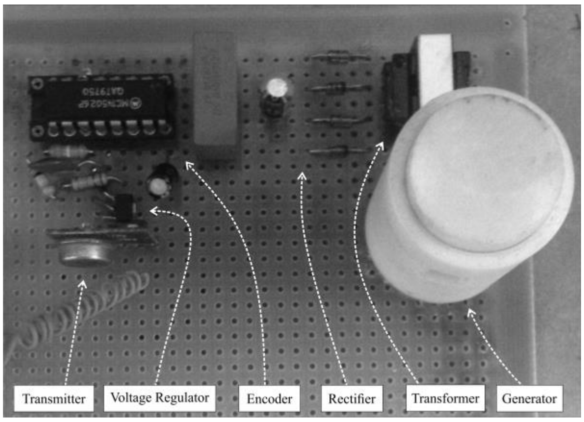

Figure 8. Self-powered RF transmission system.

3 Results and Discussions

3.1 Electrical Voltage Generated in Open Circuit

The voltage measured in open circuit mode upon mechanical impact is shown in Figure 9, multiplied with the attenuation factor of the resistive divider. A maximum voltage value of over 7 kV was observed when actuating the piezoelectric generator's button. The first 100 μs displays voltage fluctuations due to mechanical resonance. Applying a fast Fourier transform revealed the existence of a DC level and frequencies of 20 kHz and 40 kHz. These frequencies are related to the resonances of the structure of the generator.

Figure 10 shows the voltage response in the secondary winding of the signal conditioning transformer, when a piezoelectric pulse is generated in the primary winding. Due to the inductive behavior of the transformer, an LC circuit is formed with the internal capacitor of the piezoelectric generator. This is evidenced by a high-amplitude oscillation around 40 kHz which occurs due to interaction of the resonance of the mechanical structure with the electrical circuit, providing a better utilization of energy. The frequency of the transmitted signal was 600 Hz, which avoids distortion of the received signal. Signals with 10% and 70% duty cycle were tested to validate the longer and shorter pulses, just in accordance with the encoder.

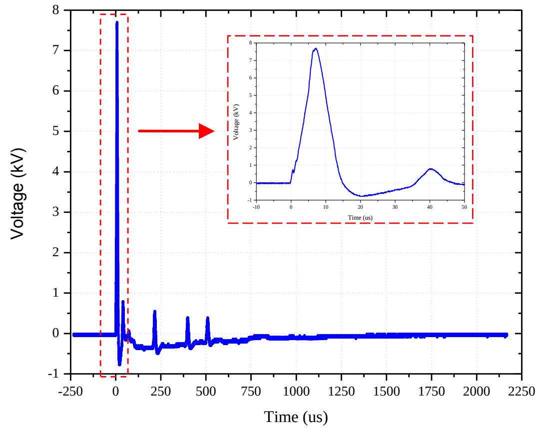

Figure 9. Voltage generated by the PZT.

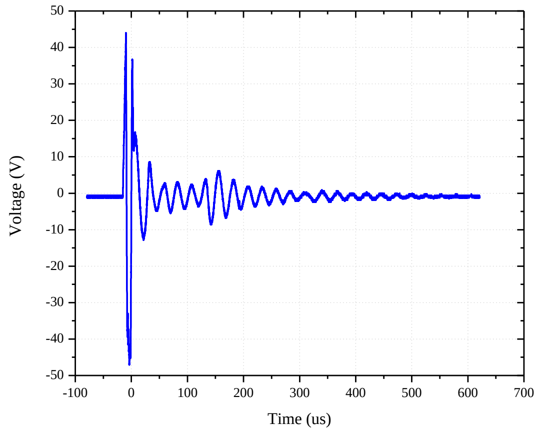

Figure 10. Voltage at low voltage side of the transformer.

The waveforms are shown in Figure 11 and 12 for two duty cycle values and a 600 Hz signal.

When sending a coded message, for instance 010000000, the transmission circuit and the encoder consumes together about 1.65 mW peak power at 3.3 V, considering an 80 ms transmission. This is equivalent to an energy input of 132 μJ, which corresponds to the consumption of a resistor of 6.6 kΩ connected as load conducting a current of 500 μA. The capacitance chosen for the energy storage after the rectifier (C1 + C2) was 11 μF, resulting in a peak voltage of 12 V, with a stored energy of approximately 800 μJ. For a load of 4.7 kΩ, the time in which the capacitor voltage reaches 3.3 V (threshold voltage of the regulator) is 80 ms; this load was considered for evaluation of the transmission behavior due its higher power consumption.

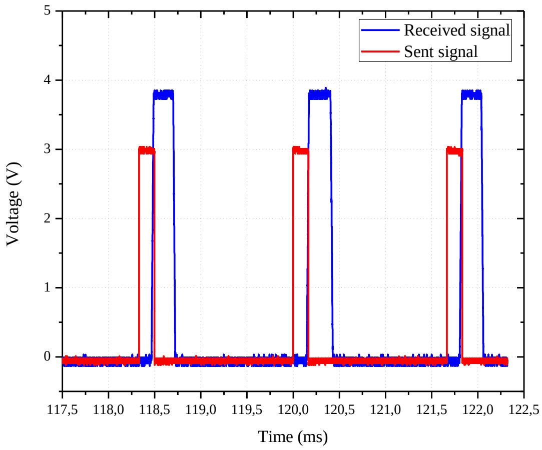

Figure 11. Transmitted signal at 600 Hz and 10% duty cycle.

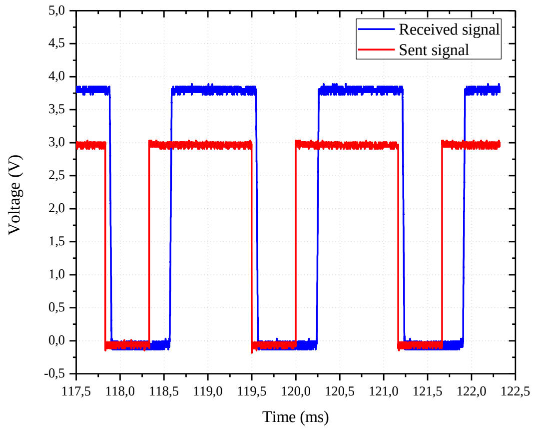

Figure 12. Transmitted signal at 600 Hz and 70% duty cycle.

Figure 13 shows the voltage decay across the capacitor under load values higher and lower than required for this application. Since the rectifier output circuit is an RC type, these curves present an exponential behavior with an increase in the time constant caused by the resistance value. This result demonstrates the load range for which the generator can transmit a message.

When the transmission circuit is powered, the data are sent immediately to the RF transmitter. A test was implemented by feeding the RF circuit with a DC voltage source to verify encryption and decryption response with conventional feeding. It is shown in Figure 14 that the first word sent was received with the second bit modified, that is, the received word is different from the sent one. Thus, only from the following two correctly interpreted words the decoder interpreted the message as valid and modified VT bit to high level. This proves the operation of the encoder and decoder.

With the RF transmitter fed by the studied generator, the message was transmitted as shown in Figure 15. The output voltage of the regulator was kept constant until close to 80 ms, the voltage starts to decay with the second word. Despite this decay, the lower voltage is still sufficient for the RF transmitter to send the third word. The first word was received with a change in the address bit, while the next two were received correctly and the decoder validated the code setting the VT pin to high.

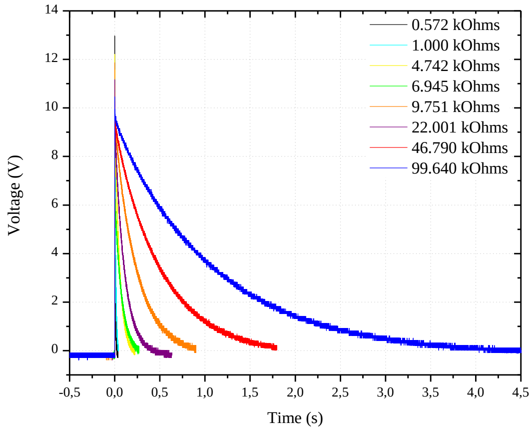

Figure 13. Decay of the regulated voltage under different load values.

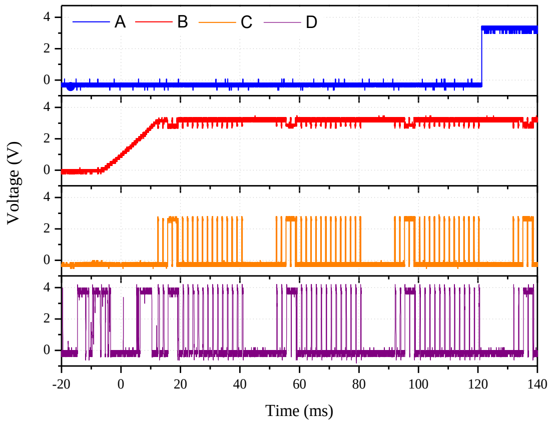

Figure 14. RF transmitted and received signals supplied for a bench power supply. A: bit VT, B: external power supply, C: sent message, D: received message.

It may be observed that the voltage decay causes attenuation of the voltage level of the sent signal. However, as the transmission was not compromised, the signal was sent without distorting the information.

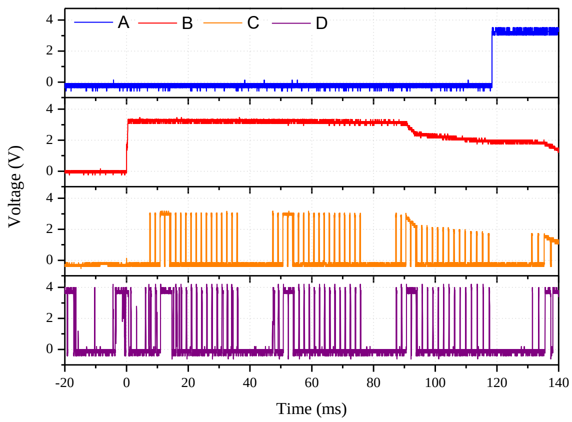

Figure 15. RF transmitted and received signals supplied for the self-powered system A: bit VT; B: regulator voltage; C: sent message; D: received message.

It is worthwhile to mention that the waveforms presented were obtained from the oscilloscope and generated by an external software.

4 Conclusions

A piezoelectric generator was designed and studied as power supply the RF circuit, and was proved to be capable for this function. A voltage generated for a relatively short time period allowed the transmitter to send the message, which was then understood by the decoder. Thus, it was possible to test and validate the self-powered device for RF transmission, without the need for batteries or any other external voltage source. A suggested application of this self-powered device would be to trigger home lighting. In this case, the light switch can be in any position without the need for the returning wire.

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