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Electrical characterization and modelling of polyvinylidene fluoride thin film for application in piezoelectric energy harvesting

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ABSTRACT
The search for clean and sustainable energy sources has increased dramatically in recent years. As a result, research into Energy Harvesting (EH) technology has become increasingly important. EH allows powering low-consumption electronic devices by converting types of energy that are commonly neglected into electrical energy. In this scenario, piezoelectric materials stand out due to their property of converting kinetic energy into electrical energy. Therefore, this article aims to focus on the electrical characterization of a Polyvinylidene Fluoride (PVDF) piezoelectric transducer and a computer modelling of its behavior using the LTspice® software, as well as its coupling to an EH power management chip (LTC3588-1), as the initial phase of a research project aimed at developing a piezoelectric energy harvester (PEH).

Section: RESEARCH PAPER

Keywords: renewable energy; vibration energy; PEH circuit design; piezoelectric sensors; measurement

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1. INTRODUCTION

Indisputably, considering the recent environmental and political developments, such as the Paris Agreement on climate change [1] and REPowerEU, the new European Union guidelines outlined as a result of the energy crisis caused by the war between Russia and Ukraine [2], as well as the already established actions related to the adoption of low-carbon energy systems, aiming at continued progress in the field of decarbonization and driven by the necessity for a global energy transition [3], it can be affirmed that the search for new renewable energy generation technologies is on the rise.

In this context, Energy Harvesting (EH) emerges for these scenarios as an accessible and cheap option, with the potential to make electronic systems self-sufficient in the future, thanks to continuous technological advances and innovations that can still be achieved over the years. This was the case, for example, with solar energy: its exploitation began with the discovery of the Becquerel effect/photovoltaics in 1839 [4] and needed a lot of scientific evolution to reach the current technological status, considering aspects such as improving the efficiency of energy conversion and reducing production costs in volume [5].

Fundamentally, energy harvesting has been widely explored in its various existing forms, such as wind (wind energy), light (solar energy), heat (thermal energy), electromagnetic fields (radio frequency/microwave energy), and mechanical vibrations (kinetic energy). Among these, energy harvesting from mechanical vibrations is particularly promising because it is present everywhere and does not depend on climate and/or season [6].

In terms of vibrational energy harvesting, there are some energy conversion methods that can be used. The electromechanical coupling can be done through piezoelectric, electromagnetic, electrostatic, triboelectric, or magnetostrictive energy harvesting mechanisms [6]-[8].

Conceptually, piezoelectricity can be used directly, in which the material generates electrical energy when subjected to a mechanical stress (deformation), or inversely, when an electric field is applied and, in response, the material produces mechanical energy. Furthermore, this effect is driven only by the intrinsic polarization of the material, so a wide range of materials, such as inorganic, organic and composite materials, can be used [9].

In the case of kinetic energy captured from environmental vibrations using Piezoelectric Energy Harvesters (PEHs), which is the focus of this work, a preliminary piezoelectric modelling is necessary to understand the behaviour of the material in the time and frequency domains, aiming at designing circuits that can maximize the collected energy, bearing in mind that the technique itself is based on the direct piezoelectric effect [10].

In practical terms, when it comes to PEHs, some energy demands are not complied with due to some specific aspects, such as (i) the fact that the kinetic energy is intrinsically time-varying (non-continuous), generating alternately positive and negative voltages, thus, as the final application typically depends on a direct voltage (either stored in a capacitor, at the output of a voltage regulator, or used to charge a battery), it is necessary to adopt rectifying circuits (AC-DC conversion) [11]; (ii) the other aspect concerns the intrinsically capacitive nature of piezoelectric materials [12], with typical values in the range of 500 pF to 10 nF, a capacitance value that is directly proportional to the area of the piezoelectric material and inversely proportional to its thickness. As the environmental mechanical vibrations typically have low or very low frequencies, in the range of 1-30 Hz [13], the capacitive reactance is very large, which makes the coupling to the rectifying circuits much more challenging.

All of this highlights the importance of electrically characterizing piezoelectric films and modelling them in terms of the equivalent electrical circuit, which can be simulated using software such as LTspice®, allowing the design of more efficient rectifying circuits that compensate for the high impedance (reactance) of the sensors. Therefore, objectively, this work focuses on an initial phase of a study applied to the development of PEHs, consisting of a preliminary electrical characterization of a commercial Polyvinylidene Fluoride (PVDF) thin film for application in piezoelectric energy harvesting, followed by its electrical modelling via LTspice® software (version 17.0.36.0, Analog Devices).

Concerning the structure of this paper, the introduction addresses issues intrinsic to the topic of energy harvesting. In Section 2, key concepts of the use of PVDF sensors in energy harvesting are presented. In Section 3, the characterization and simulation methodologies carried out are presented. In Section 4, the results are presented and discussed. Finally, conclusions and recommendations for future work are presented in Section 5.

2. PVDF SENSORS

Thanks to its characteristics, such as high piezoelectric coefficient, excellent stability, and desirable flexibility, PVDF has become one of the most promising and studied polymeric materials for kinetic energy harvesting purposes [14]–[17].

Derived from the PVDF dipoles orientation, piezoelectricity is the main property required for this type of application. It is known that this polymer has five phases, which can be identified as α, β, γ, δ, and ε, with β being the most electroactive, because of all dipole moments pointing in the same direction, that is, being parallel. Thus, PVDF sensors that predominantly have the β-phase crystalline structure present the highest piezoelectric responses [14].

Another important aspect related to energy harvesting and the PVDF piezoelectric sensor is the capacitive reactance value which responds inversely to frequency and capacitance. So, as the mechanical frequencies available around the harvester and the piezoelectric sensor capacitance are low, and as the capacitance is low, the reactance value is high, impairing the generation of more energy.

Typically, a system for energy harvesting from a vibration source comprises (i) a mechanical system, which is basically an external excitation; (ii) movement transmission and amplification mechanisms; (iii) a transducer, for example, piezoelectric, which converts vibrational kinetic energy into electrical energy; and (iv) electronic systems, such as power electronics and circuits for control, management, and energy storage [18]. Therefore, electronic circuits are extremely important for the performance and efficiency of these energy harvesters, as they are responsible for processing and conditioning the signals generated by the transducers and for transforming the energy in an adequate way to feed other electronic elements. Furthermore, with the objective of maximizing the efficiency of the energy harvesting process, it is necessary to choose the appropriate components of the electronic circuit, as well as the values of their respective magnitudes. Thereby, considering the above information, an electrical characterization of the PVDF piezoelectric generator was performed.

3. ELECTRICAL CHARACTERIZATION OF PVDF THIN FILM

This section presents the electrical behaviour of a commercial PVDF thin-film sensor when subjected to frequency variations (electrical characterization) and its computational modelling, obtained by an impedance analyser and reproduced in the LTspice software, with the aim of computationally testing the LTC3588-1 power management chip for energy harvesting under low mechanical frequency conditions.

3.1. Impedance characterization of the PVDF

In order to better understand the behaviour of a PVDF thin-film sensor for application in piezoelectric energy harvesting and computationally modelling an electronic circuit that is equivalent to this sensor, an electrical characterization was carried out. For this, the following components were used: a piezoelectric film sensor (Figure 1), LDT0-028K (TE Connectivity), and an impedance analyser, E4990A (Keysight Technologies).

This type of sensor is made up of a PVDF polymer film (28 μm thick) with silver ink electrodes deposited on the mylar substrate (polyester with 125 μm thickness) by serigraphy (screen printing) technique. In addition, it has two crimped contacts. This thin-film sensor acts as an accelerometer or vibration sensor when positioned like a cantilever beam with one end fixed and

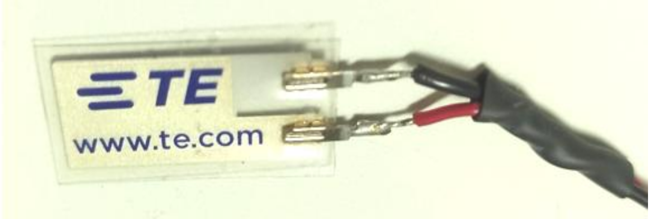

Figure 1. Piezoelectric film sensor – LDT0-028K.

one end free. Thus, as the piezoelectric film is flexed at the free end, i.e., it is displaced from its mechanical axis, an electrical charge is generated within the PVDF, which can be measured by an electronic circuit.

Concerning the impedance analyser, one of its possible functions is the quantification of the capacitance of a sensor, a preliminary parameter of interest in this article. Basically, the systematic operation of this equipment makes it possible to carry out a scan within a previously determined frequency range, applying an input voltage to the sensor and measuring the current at the output, or it is also possible to perform the inverse procedure. Then, from this, some parameters can be estimated, such as impedance, resistance, and reactance.

Methodologically, a pair of wires was soldered to the terminals of a PVDF thin-film sensor and connected to the impedance analyser. Thus, at the input terminal, an alternating voltage was applied with 500 mV amplitude (a voltage value that is neither too high, to avoid damaging the transducer, nor too low, to prevent a noisy signal) and a frequency range between 100 Hz and 1 kHz (this range was chosen to avoid interference from the 60 Hz electrical grid in Brazil, and because higher frequencies are unnecessary for typical low-frequency EH applications).

In addition, as it is understood that the internal impedance of the piezoelectric sensor is capacitive and not inductive in nature [19], the model chosen to present the parameters resulting from the signal produced by the equipment was a resistance in parallel with a capacitance and some other passive components, aiming to corroborate this capacitive performance and to compare the value obtained with that provided by the manufacturer (480 pF) [20].

3.2. LTspice model derived from the characterization

As a fundamental part of energy harvesting, an electronic circuit needs to be properly designed so that it can read the low values of the input parameters (from the harvested energy) and also be able to store this energy. So, after validating the characteristics of the PVDF sensor through electrical characterization, we sought to computationally model an equivalent electronic circuit that describes the behaviour of this sensor. For this, the "Equivalent Circuit Analysis" function of the impedance analyser was used, which provides a total of seven circuit models—four models with three electronic components and three models with four electronic components. In addition to the configurations of these equivalent circuits, the equipment also estimates the values of its electronic elements, such as capacitors, inductors, or resistors. Thus, the model that best adjusted the characterized sensor behaviour was chosen and computationally modelled in LTspice®, which is a software that helps in the study of electronic circuits. Therefore, in this research, it was used as an analysis methodology.

4. RESULTS AND DISCUSSIONS

As expected, and mentioned previously, piezoelectric materials are intrinsically capacitive, with capacitance values ranging in magnitude from 500 pF to 10 nF. This was the case of the PVDF sensor used in the electrical characterization, which resulted in a capacitive behaviour because the measured capacitance was a value of approximately 500 pF that varied very little with frequency. Additionally, when comparing this value with that provided in the sensor datasheet—provided by the manufacturer (TE Connectivity)—a relative capacitance difference of 4.2 % was obtained.

Conceptually, when considering an alternating current source (characterizing the piezoelectric generator) in parallel with a capacitor (representing the energy losses due to the capacitive behaviour), the capacitive reactance (X_C) is inversely proportional to the sensor capacitance and the source frequency (f). Therefore, the greater the value of f, the smaller the X_C, consequently, the smaller the energy losses. However, for piezoelectric energy harvesting, the mechanical energy is concentrated in the low frequencies (as previously presented, in the range of 1 Hz to 30 Hz). Because of that, and principally to the low capacitance values, the reactance will be high—representing large losses.

Possibly, a way to attenuate this effect of energy losses would be to choose piezoelectric sensors with a higher capacitance value, which would be equivalent to an increase in frequency. Thus, the importance of computational modelling. Some studies model the piezoelectric sensor as a simple capacitor [21]–[25] in parallel with a current source, but this research sought a more elaborate model based on the electrical characterization done with the impedance analyser. Thus, the equivalent circuit of the PVDF thin-film sensor featured in this work is shown in Figure 2.

Based on this equivalent electronic circuit configuration, an AC analysis was carried out, coupling the circuit obtained to a current source (representing the charge generated by the piezoelectric film, in this case, a current of 1 mA), as shown in Figure 3.

Thereby, it was possible to find the circuit transfer function, shown in Figure 4. By analysing this transfer function, it is observed that the output voltage generated at the piezoelectric sensor terminals grows with increasing frequency, reaching a peak around 7 Hz, and then decreases. As a result of this overall behaviour, the modelled circuit is designated as resonant, with a resonant frequency of approximately 7 Hz. Furthermore, as the voltage amplitude at the terminals decreases for frequencies

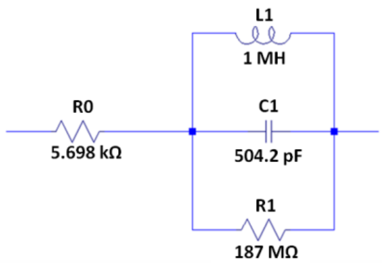

Figure 2. Equivalent circuit of PVDF piezoelectric sensor model in LTspice.

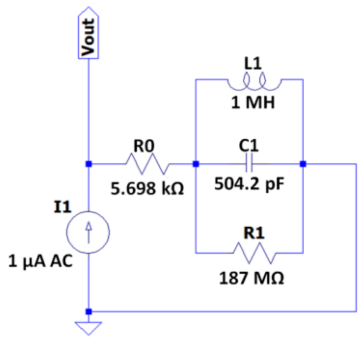

Figure 3. Equivalent circuit of PVDF piezoelectric sensor model coupled to a current source in LTspice.

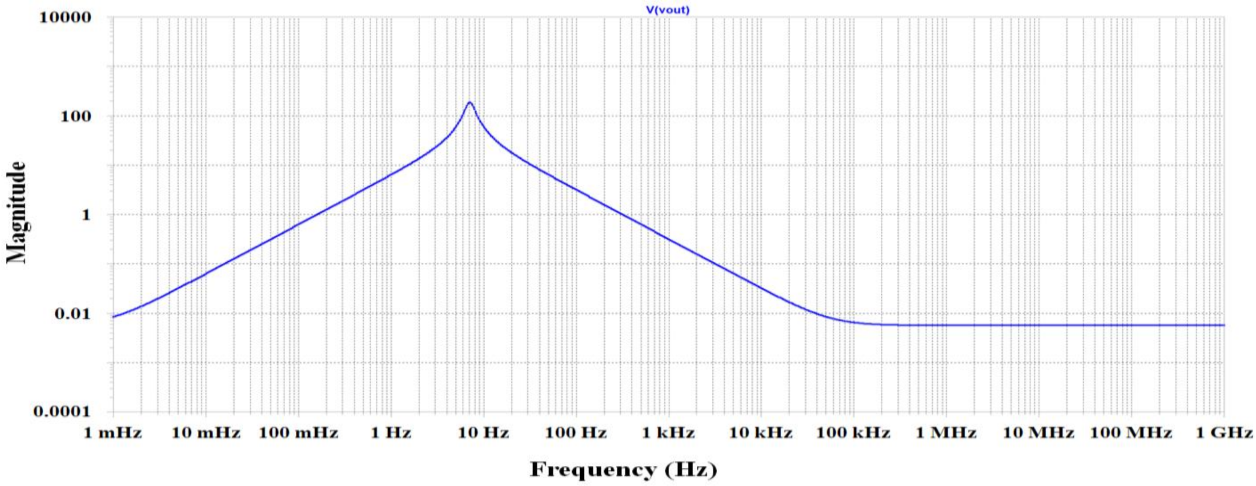

Figure 4. Circuit transfer function.

greater than resonance, the behaviour is analogous to that of a low-pass filter.

It is important to note that the simulation uses a current source in parallel with the impedance (Z), so the output voltage is given by $Z \cdot I$. As the current is constant, a maximum voltage indicates maximum impedance, meaning higher losses—thus reinforcing the previous statement.

Additionally, the circuit in Figure 3 was connected in parallel with a 10 MΩ resistor (Rosc) that represents the input impedance of an oscilloscope, thus making it possible to simulate and observe the effect of this coupling—Figure 5(a) shows the circuit without the resistor connected and Figure 5(b) with the resistor connected. Also, to obtain a voltage response as a function of time at the resonant frequency, the current source was configured as a sinusoidal function.

With regard to the circuit where the resistor is not connected, the amplitude of the output signal is approximately 180 V (Figure 6). Thus, this would be a typical voltage signal observed by a rectifying circuit connected to the output of the PVDF film.

On the other hand, when the resistor is connected, this amplitude decreases significantly to 9 V (Figure 7), simulating what would happen in practice when observing a signal generated on the oscilloscope from the piezoelectric sensor.

Furthermore, in order to assess the behaviour of the sensor integration with an EH power supply, the circuit in Figure 3 was connected to the LTC3588-1 circuit [26]—the computer modelling that is available from Analog Devices (Figure 8a) [23]. In summary, the chosen EH power supply has a full-wave rectifier and two capacitors: one input (C1) and one output (C2), with capacitance values of 5 μF and 47 μF, respectively. In addition, the circuit is configured to provide an output voltage equivalent to 1.8 V (pins D0 and D1 connected to the ground - GND).

Figure 8(b) shows the results of the input voltage (V_{in}), output voltage (V_{out}), and PGOOD (power good output) curves. Thereby, it is possible to observe that the responses obtained corroborate the specifications of the LTC3588-1. In other words, when the input voltage reaches around 4.5 V, the switched-mode power supply is activated. Consequently, the output capacitor begins to charge. However, as this occurs, the input capacitor slightly discharges, causing the supply to switch off. Then, it reaches 4.5 V again, triggering the source, continuing to charge the output capacitor, and C1 suffers a brief discharge. Therefore, C1 enters this charge-discharge cycle until C2 is charged with V_{out} equal to 1.8 V.

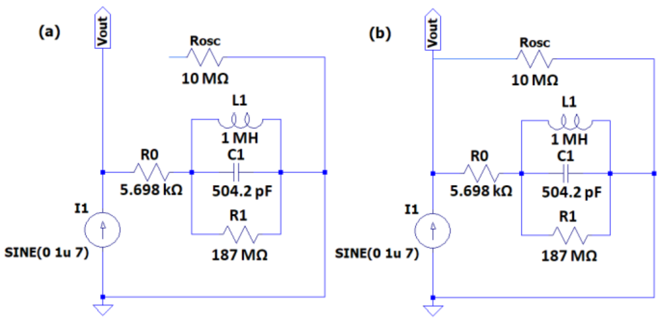

Figure 5. Circuit representing the coupling to an oscilloscope with 10 MΩ input impedance: (a) not connected, (b) connected.

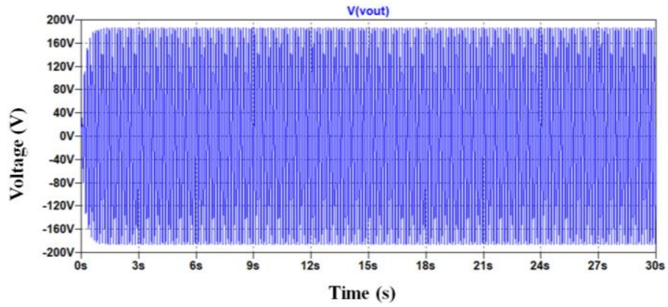

Figure 6. Voltage signal as a function of time for the circuit without the 10 MΩ resistor.

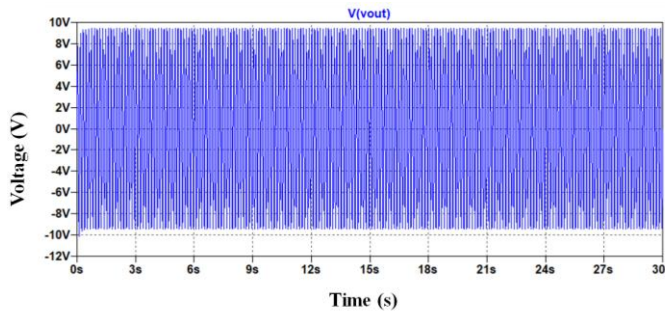

Figure 7. Voltage signal as a function of time for the circuit with the 10 MΩ resistor.

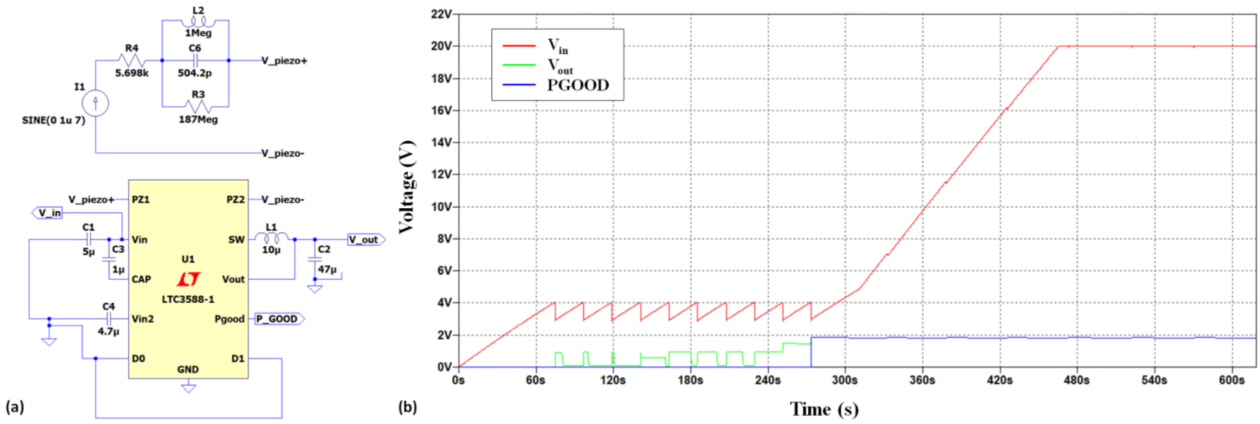

Figure 8. (a) Equivalent circuit of PVDF piezoelectric sensor coupled to the EH power supply (LTC3588-1), (b) voltage signal as a function of time for the input voltage (V_{in}), output voltage (V_{out}), and PGOOD.

After breaking this cycle, C2 is capable of obtaining a full charge, and C1 charges up to 20 V (Zener diode voltage, responsible for limiting the input voltage to 20 V, protecting the rest of the circuit). In addition, PGOOD is a pin used as an indicator to show when V_{out} reaches 92 % of its determined maximum value.

In summary, besides the configuration of the equivalent electronic circuit being more specific, allowing its future application and integration with more complex circuits and being capable of better predicting the behaviour of an energy harvesting system, the modelling that uses the 10 MΩ resistor has an important use for design purposes of PEH circuits, as it allows estimating how much is being generated by the piezoelectric sensor from the signal measured on the oscilloscope. Another point worth mentioning is that the modelling of this circuit in LTspice enabled the analysis of the PVDF sensor at frequencies lower than 20 Hz (impedance analyser measurement lower limit), consequently, allowed the observation of the peak at 7 Hz (not observed in the electrical characterization).

5. CONCLUSIONS

Over the last few years, there has been a significant increase in the daily use of electronic devices with low autonomy, such as smartwatches, headphones, digital books, digital trackers, wireless sensor networks, and routers, and consequently, the demand for electricity has grown. In addition, the search for a more sustainable and cleaner energy matrix stimulates research on this subject, and this is noted by the progressive interest in energy harvesting—which is part of this scenario as an accessible and cheap option.

Although the energies generated by these energy harvesters are relatively low (in the range of microwatts or milliwatts) when compared to those produced by solar panels (reaching gigawatts nowadays), they are sufficient to power electronic devices with low energy demand. However, it is worth noting that, for this photovoltaic generation to reach these power values and high efficiency, there were years of scientific evolution, from the discovery of the Becquerel/photovoltaic effect to the present day. So, it is envisioned that, over the years and with technological advances, energy harvesting will be a more widely disseminated technique, especially from piezoelectric materials.

In this context, this article methodologically presented an electrical characterization of a PVDF thin-film piezoelectric sensor (LDT0-28K), which allowed the corroboration of its capacitive behaviour when subjected to frequency variations. The capacitance obtained was approximately 500 pF—a low value but typical of these sensors. Thus, the main implication of this small capacitance is that the reactance will be high, representing greater energy losses at low mechanical frequencies (between 1 Hz and 30 Hz). For this reason, a computational modelling of the behaviour of the characterized piezoelectric sensor was carried out in the LTspice software. In addition, an AC analysis was performed. Thus, the modelling enabled the quantitative estimate of the energy generated by the piezoelectric sensor from the signal measured on the oscilloscope and demonstrated its applicability when coupled to an EH Power management chip (LTC3588-1).

Therefore, the widespread aspects explored in this work are part of a preliminary stage of a study aimed at the development of a piezoelectric energy harvester (PEH) and allowed the intrinsic needs of the project to be identified and analysed, contributing to the optimization of the PEH performance.

Finally, as a suggestion for future work, it is expected to experimentally corroborate the computational simulations of the piezoelectric sensor with the LTC3588-1 power management chip for energy harvesting under low mechanical frequency conditions.

AUTHORS' CONTRIBUTION

Methodology: L.d.S.G., M.C.M., K.A.R.M. and C.R.H.B.; software: L.d.S.G., M.C.M., K.A.R.M. and C.R.H.B.; validation: L.d.S.G., M.C.M., K.A.R.M,. and C.R.H.B.; formal analysis: L.d.S.G., M.C.M., K.A.R.M., and C.R.H.B.; investigation: L.d.S.G., M.C.M., K.A.R.M., and C.R.H.B.; resources: K.A.R.M. and C.R.H.B.; data curation, L.d.S.G., M.C.M., and K.A.R.M.; writing—original draft: L.d.S.G., M.C.M., and K.A.R.M.; writing—review & editing: L.d.S.G., M.C.M., K.A.R.M., and C.R.H.B.; visualization: L.d.S.G.; supervision: K.A.R.M. and C.R.H.B.; project administration: K.A.R.M. and C.R.H.B.; funding acquisition: C.R.H.B.. All authors have read and agreed to the published version of the manuscript.

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