Electrical characterization and modeling of PVDF thin-film for application in piezoelectric energy harvesting

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Abstract. Based on the necessity for cleaner and renewable energy and the growing global demand, energy harvesting stands out increasingly in this scenario. This technique is notable for the possibility of converting some types of energy that are generally neglected into electrical energy that can be used to power low-consumption electronic devices. In this context, piezoelectric materials demonstrate excellent applicability due to their ability to convert kinetic energy into electrical energy. Although these concepts and principles of conversion have been known for a long time, their use has increasingly grown in recent years. Thus, the present work objectively focuses on the electrical characterization of a thin-film piezoelectric sensor of Polyvinylidene Fluoride (PVDF) and a computational modeling of its behavior in LTSpice® software as a preliminary step of a study aimed at the development of a piezoelectric energy harvester (PEH). Consequently, this work allows for identifying and analyzing the intrinsic needs of the project, contributing to the optimization of the PEH performance.

1. Introduction

Indisputably, considering the recent environmental and political developments, such as 'The Paris Agreement' – on climate change [1] – and 'REPowerEU' – on new European Union guidelines 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, 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 emerges for these scenarios as an accessible and cheap option with the potential to make the electronic systems self-sufficient in the future, thanks to continuous technological advances and innovations that can still be achieved over the years, as in the history of solar energy, which 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 the 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 emerges as the most 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 direct, in which the material generates electrical energy when subjected to a mechanical stress (deformation), or inverse, 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 composites can be used [9].

In the case of kinetic energy captured from environmental vibrations using piezoelectric energy harvesters (PEHs), the focus of this work, a previous piezoelectric modeling is necessary to understand the behavior of the material in the time and frequency domains, with a view to 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 10 nF to 500 pF, 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.

For all this, it is understood the importance of electrically characterizing piezoelectric films and modeling them in terms of the equivalent electrical circuit, which can be simulated in software such as LTSpice®, allowing designing more efficient rectifying circuits, which 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 PVDF thin-film for application in piezoelectric energy harvesting, followed by its electrical modeling via LTSpice® software.

Concerning structure, this work is organized in this introduction that 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 the focus of section 5.

2. PVDF Sensors

Due 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.

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, as a result 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 that 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 – piezoelectric, for example, which converts vibrational kinetic energy into electrical energy; and (iv) electronic systems – such as power electronics and circuits for control, management and energy storage [15]. 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 aforementioned information, an electrical characterization of the PVDF piezoelectric generator was performed.

3. Electrical characterization of PVDF thin-film

This section presents the electrical behavior of a commercial PVDF thin-film sensor when subjected to frequency variations (electrical characterization) and its computational modeling, obtained by an Impedance Analyzer and reproduced in the LTSpice software, with the aim of previously developing an efficient rectifying circuit, to be used in conditions of low mechanical frequency arising from energy harvesting.

3.1. Impedance Analyzer Characterization

In order to better understand the behavior of a PVDF thin-film sensor for application in piezoelectric energy harvesting and computationally modeling 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 – model LDT0-028K, from TE Connectivity (Figure 1) – and an Impedance Analyzer – model E4990A, from KEYSIGHT.

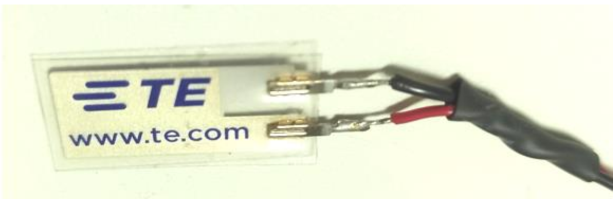

Figure 1. Piezoelectric film sensor – LDT0-028K

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 the 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 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 Analyzer, 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. The equipment model used allows the user to choose how and which parameters will be displayed on the screen, which can be (i) impedance module and phase; (ii) real part and imaginary part (resistance and reactance); (iii) resistance and capacitance; and (iv) among others.

Methodologically, a pair of wires was soldered to the terminals of a PVDF thin-film sensor and connected to the Impedance Analyzer. Thus, at the input terminal, an alternating voltage was applied with 500 mV amplitude and a frequency range between 100 Hz and 1 kHz. In addition, as it is understood that the internal impedance of the piezoelectric sensor is capacitive and not inductive in nature [16], 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) [17].

3.2. Spice 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 specificity of the PVDF sensor through electrical characterization, we sought to computationally model an equivalent electronic circuit that describes the behavior of this sensor. For this, the "Equivalent Circuit Analysis" function of the Impedance Analyzer 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 behavior was chosen and computationally modeled 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 10 pF to 10 nF. This was the case of the PVDF sensor used in the electrical characterization, which resulted in a capacitive behavior because the measured capacitance was a value of approximately 512 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 6.7 % 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 behavior), 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 modeling. Some studies model the piezoelectric sensor as a simple capacitor [18–22] in parallel with a current source, but this research sought a more elaborate model based on the electrical characterization done with the Impedance Analyzer. Thus, the equivalent circuit of the PVDF thin-film sensor featured in this work is shown in Figure 2.

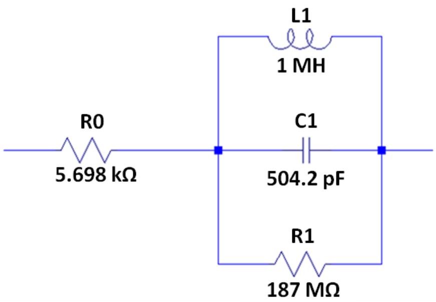

Figure 2. Equivalent circuit of PVDF piezoelectric sensor model in LTSpice.

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 microampere), as shown in Figure 3.

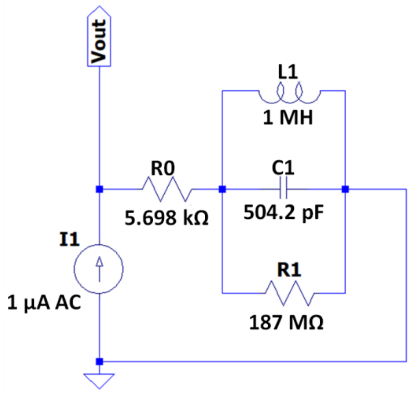

Figure 3. Equivalent circuit of PVDF piezoelectric sensor model coupled to a current source. in LTSpice.

Thereby, it was possible to find the circuit transfer function, shown in Figure 4. By analyzing 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 behavior, the modeled circuit is designated as resonant, with a resonant frequency of approximately 7 Hz. Furthermore, as the voltage amplitude at the terminals decreases for frequencies greater than resonance, the behavior is analogous to that of a low-pass filter.

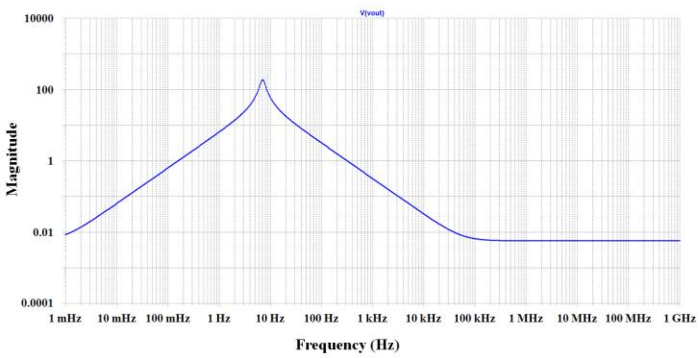

Figure 4. Circuit transfer function.

Additionally, the circuit in Figure 3 was connected in parallel with a 10 MΩ resistor (R_{osc}) 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 with the resistor not connected and Figure 5(b) with the resistor connected. Also aiming to obtain a voltage response as a function of time at the resonant frequency, the current source was configured as a sinusoidal function.

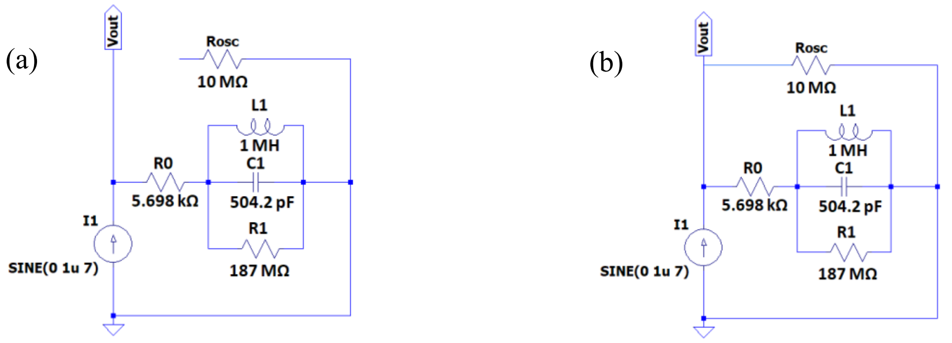

Figure 5. Circuit representing the coupling to an oscilloscope with 10 MΩ input impedance: (a) Not connected; (b) Connected.

As far as the circuit where the resistor is not connected is concerned, 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.

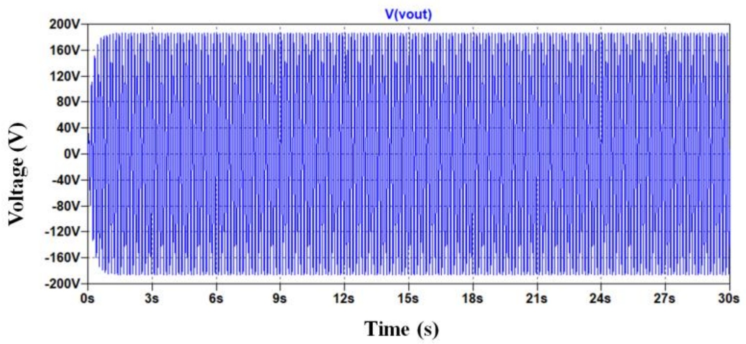

Figure 6. Voltage signal as a function of time for the circuit without the 10 MΩ resistor.

In turn, 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.

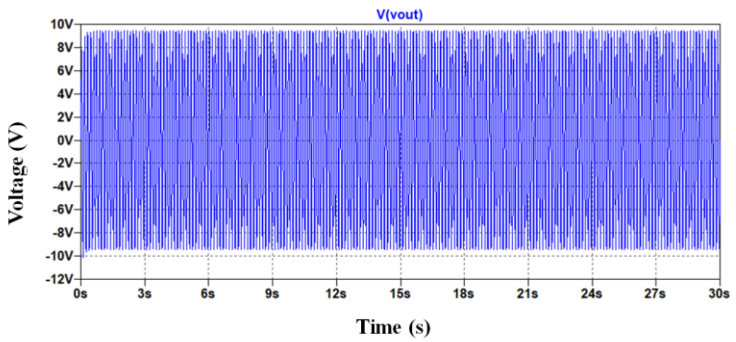

Figure 7. Voltage signal as a function of time for the circuit with the 10 MΩ resistor.

In summary, in addition to the configuration of the equivalent electronic circuit being more specific, allowing its future its application and integration with more complex circuits, capable of better predicting the behavior of an energy harvest, the modeling using the 10 MΩ resistor has an important utility 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 modeling of this circuit in LTSpice enabled the analysis of the PVDF sensor at frequencies lower than 20 Hz (impedance analyzer 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 – consequently, the demand for electricity grows. 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 (nowadays, they reach gigawatts), 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 with 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 gradually more 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 behavior when subjected to frequency variations. The capacitance obtained was approximately 512 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 modeling of the behavior of the characterized piezoelectric sensor was carried out in the LTSpice software. In addition, an AC analysis was performed. Thus, the modeling enabled the quantitative estimate of the energy generated by the piezoelectric sensor from the signal measured on the oscilloscope.

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 identifying and analyzing the intrinsic needs of the project, contributing to the optimization of the PEH performance.

Finally, as a suggestion for future work, it is expected to use the computational modeling of the piezoelectric sensor to develop an efficient rectification circuit that compensates for the high sensors impedance (reactance) under conditions of low mechanical frequency arising from energy harvesting.

Acknowledgments

The authors are grateful for the financial support of the development agencies CNPq, CAPES, FINEP, and FAPERJ. This work was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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