UNIVERSIDADE FEDERAL DE LAVRAS

LUCIANO MENDES DOS SANTOS

DEVELOPMENT OF A PIEZOELECTRIC ENERGY HARVESTING SYSTEM BY MECHANICAL VIBRATIONS AIMING TO APPLY IN AGRICULTURAL SYSTEMS

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Tese apresentada a Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, área de concentração em Instrumentação, para a obtenção do título de Doutor.

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LUCIANO MENDES DOS SANTOS

DESENVOLVIMENTO DE UM SISTEMA PIEZOELÉTRICO DE COLHEITA DE ENERGIA POR VIBRAÇÕES MECÂNICAS PARA APLICAÇÃO EM SISTEMAS AGRÍCOLAS

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“Compartilhe seu conhecimento, é uma forma de alcançar a imortalidade” *(Dalai Lama).*

RESUMO GERAL

O avanço da tecnologia em qualquer área é decorrente da necessidade e do tempo, assim sempre existirá a convivência com esse paradigma de evolução da tecnologia, um conceito relacionado à geração de energia encontra-se associado a vibrações mecânicas, conhecido como *Energy Harvesting* ou "colheita de energia", utilizando dispositivos piezoelétricos (PZT). Esses dispositivos instalados em equipamentos, que eventualmente trabalham em regime de vibração, como máquinas e veículos, podem gerar pequenas quantidades de energia a partir da piezoeletricidade, a qual refere-se a propriedade que alguns materiais possuem de gerar corrente elétrica quando submetidos a deformações mecânicas. O objetivo deste trabalho foi avaliar e caracterizar o uso de materiais piezoelétricos na colheita de energia através de vibrações mecânicas a partir de sistemas massa-mola associados a pastilhas de PZTs. Inicialmente realizou-se a caracterização de um sistema de colheita de energia composto por apenas uma pastilha de PZT associada a um sistema massa-mola. Para tal foram avaliados dois modos de tratamento do sinal gerado no sistema: um retificador de onda completa com capacitor e um módulo gerenciador de carga de uso comercial (LTC3588). O sistema massa-mola foi condicionado a operar em ressonância, cuja frequência natural foi de 16,2 Hz, sendo consideradas 5 repetições. Determinou-se a tensão, corrente e potência elétrica geradas pelo sistema, considerando-se os diferentes modos de retificação propostos. Neste contexto, observou-se uma potência média de 2,53mW para a ponte de diodo e 1,50mW para o modulo LTC3588. O sistema de retificação influencia o processo de geração de energia, sendo de fundamental importância o seu projeto e adequação ao sistema. O sistema de retificação de onda por onda completa mostrou-se mais eficiente no processo de geração de energia quando comparado ao módulo LTC3588, independentemente da variável resposta avaliada. Posteriormente, foi desenvolvido um sistema de colheita de energia composto pela associação de 25 PZTs em paralelo, série e mista (5S5P - 5 conjuntos de PZTs em série e estes conjuntos ligados em paralelo entre si e 5P5S - 5 conjuntos de PZTs em paralelo e estes conjuntos ligados em série entre si). A frequência ressonante do sistema foi de 16,2Hz, sendo avaliadas faixas de frequência superior e inferiores a frequência natural do sistema, considerando-se 5 repetições em cada cenário. Verificou-se que a associação 5P5S foi a que demonstrou melhor resultado em relação a potência gerada na frequência natural do sistema, com pico de potência média de 700mW. A frequência de excitação do sistema influenciou significativamente o processo de geração de energia, no qual as melhores frequências de excitação foram obtidas para um sistema operando em condições de ressonância. A configuração composta pela retificação de sinal por ponte de diodos em conjunto com a associação mista de pastilhas de PZT (com 5 conjuntos de 5 PZTs em paralelo e estes conjuntos ligados em série entre si), mostrou-se promissora para o desenvolvimento de sistemas de colheita de energia por vibrações mecânicas as serem empregadas em máquinas e equipamentos agrícolas.

Palavras-chave: Colheita de energia. Piezoelétrico. PZT.

GENERAL ABSTRACT

The advancement of technology in any area is due to need and time, so there will always be coexistence with this paradigm of technology evolution, a concept related to energy generation is associated with mechanical vibrations, known as Energy Harvesting, using piezoelectric devices (PZT). These devices installed in equipment, which eventually work in a vibration regime, such as machines and vehicles, can generate small amounts of energy from piezoelectricity, which refers to the property that some materials have to generate electric current when subjected to mechanical deformations. The objective of this work was to evaluate and characterize the use of piezoelectric materials in energy harvesting through mechanical vibrations from mass-spring systems associated with PZTs pellets. Initially, the characterization of an energy harvesting system composed of only one PZT tablet associated with a mass-spring system was carried out. For this purpose, two modes of treatment of the signal generated in the system were evaluated: a full wave rectifier with capacitor and a load manager module for commercial use. (LTC3588). The mass-spring system was conditioned to operate in resonance, whose natural frequency was 16.2 Hz, considering 5 repetitions. The voltage, current and electrical power generated by the system were determined, considering the different proposed rectification modes. In this context, an average power of 2.53mW was observed for the diode bridge and 1.50mW for the LTC3588 module. The rectification system influences the power generation process, and its design and adequacy to the system are of fundamental importance. The full-wave rectification system proved to be more efficient in the energy generation process when compared to the LTC3588 module, regardless of the evaluated response variable. Subsequently, an energy harvesting system was developed consisting of the association of 25 PZTs in parallel, series, and mixed (5S5P - 5 sets of PZTs in series and these sets connected in parallel to each other and 5P5S - 5 sets of PZTs in parallel and these sets connected in series with each other). The resonant frequency of the system was 16.2Hz, with frequency ranges above and below the natural frequency of the system being evaluated, considering 5 repetitions in each scenario. It was found that the 5P5S association was the one that showed the best result about the power generated at the natural frequency of the system, with an average power peak of 700mW. The system excitation frequency significantly influenced the energy generation process, in which the best excitation frequencies were obtained for a system operating under resonance conditions. The configuration composed of signal rectification by diode bridge together with the mixed association of PZT chips (with 5 sets of 5 PZTs in parallel and these sets connected in series with each other), proved to be promising for the development of energy harvesting by mechanical vibrations to be used in agricultural machinery and equipment.

Keywords: Energy harvesting. Piezoelectric. PZT.

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DOF	Single Degree of Freedom
PLA	Polylactic Acid
PZT	Lead Zirconate Titanate

SUMMARY

CHAPTER 1 GENERAL INTRODUCTION

1 INTRODUCTION

The advancement of technology in any area is due to the need of human beings, so there will always be coexistence with this paradigm of technological evolution, whether in the present or in the future. An area that has always experienced considerable advances is the energy area, both in terms of generation and consumption. In a generation, there are various sources of energy such as wind, solar, thermal, and energy generated by the movement or vibrations of structures. On the other hand, with regard to consumption, studies are based on the item economy, low consumption and rational use, which are factors that advance over time.

In our environment, there is a large amount of energy, which is wasted by industrial dynamic systems, for example, through mechanical vibrations, which can be reused by converting it into electrical energy using intelligent materials that have piezoelectric capabilities. In this context, a new concept related to energy generation is associated with mechanical vibrations, known as Energy Harvesting. From piezoelectric devices or PZT, such as Lead Zirconate Titanate, installed in equipment that eventually works in a vibration regime, it is possible to generate small amounts of energy.

The term piezo is derived from the Greek word meaning pressure. Such devices may be associated with the movement of machines, people and vehicles in which, based on piezoelectricity, the property that some minerals have to generate electric current when subjected to mechanical pressure, it is possible to conceive a renewable source of energy (GODOY; SOUZA; NEWBWE, 2014).

Piezoelectricity was discovered in 1880 by French physicists, Jacques and Pierre Curie in quartz crystals, and since then, there have been developments in studies to generate electricity. The effect consists of materials that have electrical dipoles aligned, either naturally or artificially. The voltage generated in piezoelectric materials is associated with electronic circuits, which may consist of resistors, voltage rectifiers and a device to store the energy produced, such as a capacitor or battery. According to Armendani (2016), PZT, when suffering deformations during generation, can convert a rate of up to 80% of mechanical energy into electrical energy.

In the modes of energy generation and capture, called *Energy Harvesting,* one can find four applications for its capture, namely: piezoelectric (SODANO et al., 2005; SWALLOW et al., 2008), electromagnetic (REID et al., 2005; SWALLOW et al., 2008 al., 2007; TORAH et al., 2007), thermoelectric (ROWE, 2005) and photovoltaic (LEE et al., 1994).

Currently, clean and renewable energy generation has advanced in the area of study of smart materials. NARITA et al (2018) compared devices developed by more than 20 authors, who used piezoelectric, magnetostrictive and magnetoelectric materials in their composition. Analysis of the study showed that electrical voltage, current, and power are directly dependent on the selection of materials and structures.

These materials, usually used as sensors and actuators in intelligent systems, may have adaptive characteristics, changing their shape or physical properties based on the application of electric, magnetic field, temperature or, mechanical loads. Currently, the main smart materials are: piezoelectric materials; alloys, and polymers, which have shape memory (*Shape Memory Alloys* - SMAs and *Shape Memory Polymers* - SMPs); magnetic shape memory alloys (*Magnetic Shape Memory Alloys* - MSMAs); magnetostrictive materials; and the electromagnet rheological fluids (LAGOUDAS, 2008; PRIYA and INMAN, 2009).

PZT materials are endowed with unique properties such as hardness and high density, and can be manufactured in any size and shape, in addition to almost all of them being chemically inert and inaccessible to humidity and different atmospheric conditions (Gomes, 2016). Additionally, its mechanical and electrical pins can be oriented exactly according to your application need, through the PZT polarization process.

According to Sezer and Koç (2021), there are several applications of piezoelectric energy capture in nano, micro, and mesoscale and in several fields, including transport, structures, aerial applications , intelligent systems, microfluidics and biomedicine.

Among the various research areas of the process of generation and storage of electrical energy from renewable sources, the mechanical energy of vibrations has assumed an important role, mainly due to the development of piezoelectric materials that present a great ability to generate electricity when deformed (ANTON; SODANO, 2007).

Therefore, the energy generated from piezoelectric devices can be used to power low-consumption circuits, such as those used in instrumentation and control systems in machines. Thus, considering the evolution of agricultural machinery, in terms of the use of embedded electronics and agricultural processes, mainly associated with precision agriculture and energy efficiency, there is a vast field of development and application of piezoelectric devices in the field of energy harvesting.

1.1 Theoretical framework

Currently, there are numerous ways to generate energy from renewable sources. From the discovery and development of piezoelectricity, a wide field of its application in several areas of engineering was generated. This theoretical framework will be based on topics involving the use of piezoelectric materials used in energy generation from mechanical vibrations.

Piezoelectricity is a form of energy generation that is based on obtaining an electrical potential difference from the deformation of specific materials (SOUZA, 2018). The phenomenon of piezoelectricity is observed only in solids, which generally acquire some kind of polarization when subjected to some external load (SILVA, 2010).

Liu et al. (2008) developed a piezoelectric generator based on MEMS technology, where an arrangement of piezoelectric elements presents an increase in the operating frequency range and also in the electrical output potential of the piezo structure.

According to Sezer and Koç (2021), recent efforts in research and development of piezoelectric materials and manufacturing methods at the micro and nanoscale allowed expanding the fields of application of piezoelectric technology. Piezoelectric materials such as ceramics, polymers, composites and bioinspired natural materials have been recently developed in the form of different nanostructures and thin films with satisfactory physical properties, such as high piezoelectric coefficient, flexibility, stretchability, and durability. Such properties and characteristics favored its use in emerging fields, including wireless sensor networks, IoT (Internet of Things), wearable electronics, and implantable biomedical devices.

1.2 Piezoelectric Materials (PZT)

According to Silva (2010), certain types of crystals have permanent electrical polarization, while others, especially piezoelectric crystals, only become electrically polarized when subjected to external actions and loads.

Smart materials are all types of materials that change their properties based on the variation of some physical properties. Several materials are reported in the literature that exhibits such properties, among which we can mention materials that present different couplings, such as electromechanical, magnetomechanical and thermomechanical (LAGOUDAS, 2009).

The performance of an energy harvester based on microelectromechanical devices (MEMS) from the mechanical impact was presented by Jamphuan et al (2011). Electric energy is generated by the impact of a rotating gear on the transducer, the device consists of a film of PZT and glued on a silicon beam. The tension generated by the impact on the transducer was evaluated and average power of 1.26uW was measured through a resistance of 2.7MΩ, on a gearbox at 25rpm. The stress level can be changed by using several beams on the same gearbox or by varying the rotation. A typical model for the application of magnetostrictive material to energy harvesting is presented by BERBYUK (2013) who uses a Galfenol cylinder of 6.35 mm in diameter and 50 mm in length, surrounded by 4000 coil turns and receiving a harmonic axial voltage of 55mV at a frequency of 50 Hz. Magnets were used around the device to increase the electrical voltage in the circuit, aiming at a higher output power. THONAPALIN (2021), investigated the thermomechanical effects on the electrical energy harvested from a laminated piezoelectric device, known as a thin layer unimorph ferroelectric driver, called THUNDER. Three configurations of THUNDER devices were tested over a controlled temperature range of 30 to 80 °C. Experimental results showed a detrimental effect of elevated temperature on generated voltage and harvested electrical energy. Kuang (2016), presented a wide variety of devices is the generation of up to 5.8 mW using piezoelectric material, while using a magnetostrictive material (Terfenol-D) with a structure of larger dimensions, it can generate up to 4 W (FANG, 2017).

According to Hao (2019), the first piezoelectric ceramic, BaTiO3, abbreviated as BT, was discovered in 1947. This material polycrystalline can become permanently piezoelectric after the application of an electric field, the so-called polarization process. Ceramic piezoelectric materials include Barium Lead Titanates (BaTiO3 and PbTiO3), Lead Zirconate (PbZrO3), Lead Zirconate Titanate (PZT) [Pb(Zr,Ti) O3] and Potassium Niobate (KNbO3) (CALLISTER; RETHWISCH, 2016).

Polyvinylidene Fluoride (PVDF) and its copolymers are the families of polymers with the highest dielectric constant and electroactive response, including piezoelectric, pyroelectric, and ferroelectric effects (MARTINS, 2014). According to Ferreira (2016), the most used type of piezoelectric is Lead Zirconate Titanate (PZT) which, despite its limitations regarding deformation, proves to be very efficient in the condition of generating electricity.

Piezoelectric materials can, from mechanical efforts, generate electrical charges on their surface or, inversely, from the application of an electric field, generate deformation of the material. Quartz, tourmaline, Rochelle salt and topaz crystals exhibit piezoelectric effects in their natural state (SIQUEIRA, 2018). Some of these ceramic materials (ionic crystalline) have unit cells without a center of symmetry and, consequently, have a small electric dipole, being then called ferroelectric (OLIVEIRA, 2013).

The electric dipole arises when the material is subjected to pressure, which generates a deformation in the molecule. From this disarrangement, there is a break in the balance of the gravitational centers where the positive and negative charges of the particles are, originating the dipole. According to Eiras (2014), disregarding the symmetry of the material, the piezoelectric effect can be represented by the direct mode (electrical properties) expressed by Equation 1.1 and by the indirect mode (mechanical properties) expressed by Equation 1.2.

$$D = dT + \varepsilon E \tag{1.1}$$

$$S = sT + dE \tag{1.2}$$

in which,

D= electric displacement vector (Coulomb/m ^{2});

d= piezoelectric coefficient (m/V);

T= mechanical stress (N/m ^{2});

ε = dielectric permittivity (farad/m);

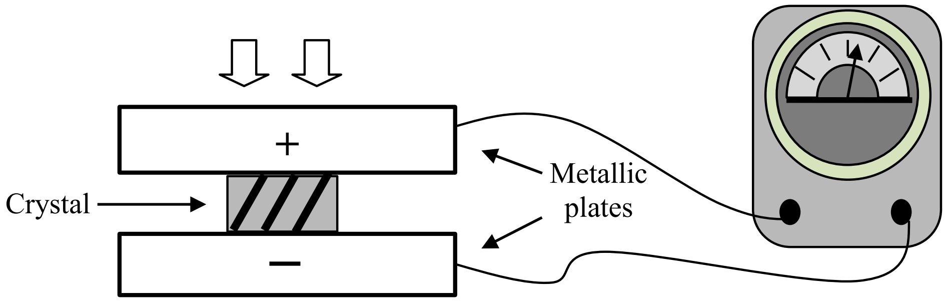
E = electric field (V/m);

S= strain (mm);

s= elastic coefficient (m ^{2}/N).

A piezoelectric material, when subjected to mechanical efforts (compression, traction, or flexion) that result in its deformation, can generate electrical energy, this condition is characterized as a direct piezoelectric effect (ALMEIDA, 2018; MINETO, 2013). Figure 1.1 illustrates this effect from the application of compression force on PZT.

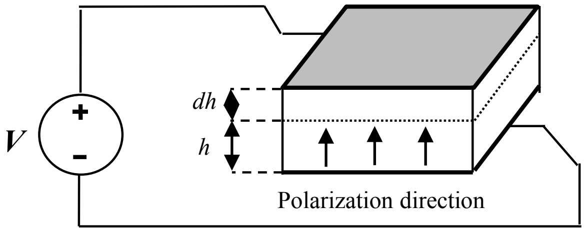
Figure 1.1 - Direct effect of power generation from piezoelectric crystals



Source: Author.

On one hand, the inverse piezoelectric effect (FIGURE 1.2) is characterized by the application of a potential difference in the polycrystalline structure, which generates the dilation of the piezoelectric material resulting in a mechanical deformation of the material (CAMARA, 2012). The effect of inverse piezoelectricity does not follow the same proportion of direct piezoelectricity, requiring a large amount of energy to promote small deformations in the material (SOUZA and RIBEIRO, 2013).

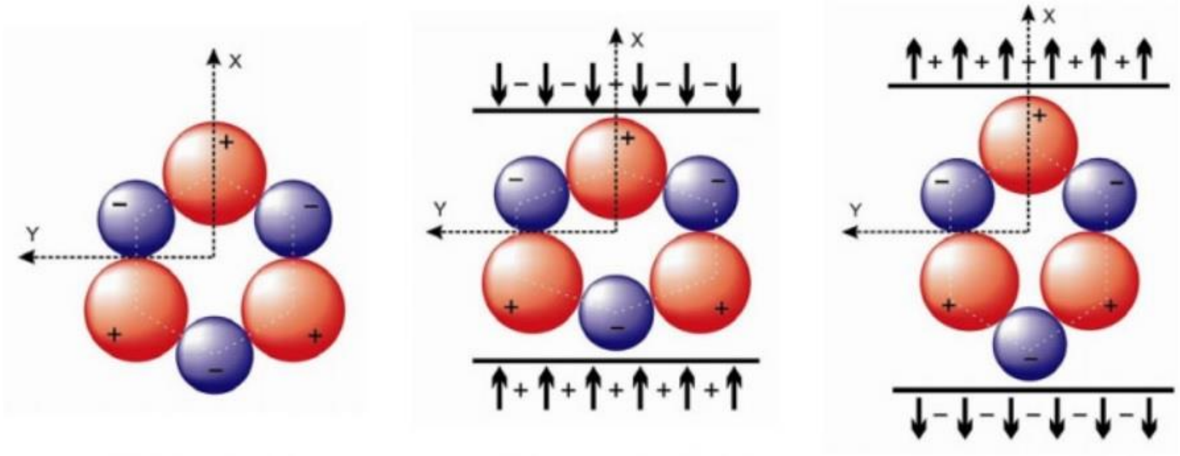
Figure 1.2 - Inverse effect in piezoelectric materials



Source: Natal (2008).

Quartz is a naturally piezoelectric material and was one of the first to be discovered, having its atomic structure constituted by a helix that extends along the Z axis with two atoms of oxygen (negative charges) and one of silicon (positive charge). Considering the XY plane, the atoms form a hexagon that has zero total electric charge, in the natural state, that is, in the absence of voltage (SIQUEIRA et al., 2018). The application of traction or compression efforts in the X or Y direction of the crystal causes an imbalance of loads leading to the generation of external electrical charges (FIGURE 1.3). On the other hand, the application of forces in the Z axis does not generate electrical charges.

Figure 1.3 - Atomic structure of quartz and its relationship with piezoelectricity from the application of compression and traction efforts.

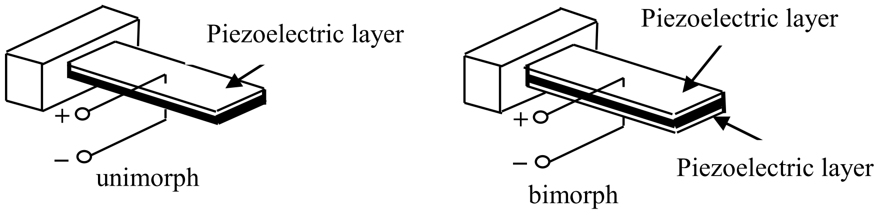


(a) Natural state (b) Compression effect (c) Traction effect

Source: Enemet (2018).

According to Ramadas (2010), PZT's can be made up of one or two piezoelectric layers, ie the Piezoelectric Unimorph Beam with thin piezoelectric layer or the Bimorth Cantilever Beam which are made up of two piezoelectric layers (FIGURE 1.4). Bimorph PZT's provide higher output energy levels.

Figure 1.4 - Schematic representation of beams with PZT unimorph and PZT bimorph



Source: Ramadass (2010).

Synthetic piezoelectric ceramics have better performing properties than quartz crystals. This type of material offers flexible dimensions and geometries due to its manufacture by sintering ceramic powders arranged via pressing or extrusion (Pereira, 2010). It is important to point out that PZT materials are endowed with unique properties such as: high hardness and density. PZT's can be manufactured in any shape or size, being chemically inert and inaccessible to moisture, in which its mechanical pin and electrical pin can be properly oriented according to the need for the application through the PZT polarization process (GOMES, 2016).

The piezoelectric material most used in the conversion of mechanical vibrations into usable electrical energy is the ceramic of Lead Zirconate Titanate (PZT), however, it is fragile, presenting limitations to deformations (RANGEL, 2014). According to Abdelkefi (2012), as an alternative for applications where the piezoelectric element can suffer large deformations and/or high vibration frequencies, researchers are using polymeric piezoelectric elements, such as *Polyvinylidene Fluoride* or Polyvinylidene Fluoride (PVDF).

1.3 Energy generation from piezoelectric materials

Piezoelectric structures have great potential for generating energy through vibrations and impacts (ALMEIDA, 2018). Different types of structures and machines can be used in this process, including bridges, buildings, aircraft, and cars (SODANO et al., 2004; ERTURK et al., 2009; ERTURK et al., 2010).

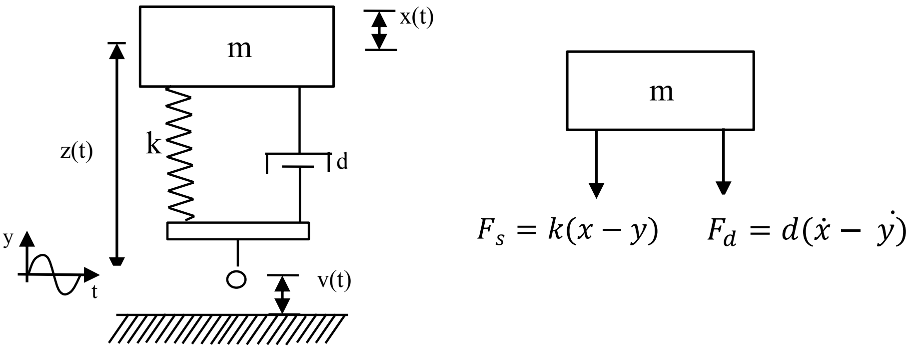
According to Pares (2006), PZT's have been used by many researchers due to their high piezoelectric coefficient, being widely applied in the conversion of mechanical energy into electrical energy. The generation capacity of current piezoelectric materials, such as Zinc Sulphide (ZnS), Sodium Chlorate (NaClO3), Magnesium Chloroborate (Mg3B7O13Cl), Lead Zirconate Titanate (PZT, PbZrTiO3), can even be 100 times more efficient than the quartz (ARMENDANI, 2016).

There are numerous types and models of PZT devices used in power generation, the basic operation consists of a brass disk with a ceramic disk based on Barium Titanate in its center (SOUZA et al., 2018). In this device, by exerting a mechanical pressure in its central region, promoting deformation, the ceramic will be contracted or expanded depending on the direction and direction of the force, which will result in the modification of its electrical polarization, that is, potential difference. The electric charge will flow from ceramics to metal and vice versa as the materials are deformed.

The operating principle of vibration transducers is based on the conversion of mechanical energy, arising from vibrations, into electrical energy. In terms of obtaining energy, piezoelectrics can be configured in numerous ways that prove to be highly useful in energy harvesting applications (Anton; Sodano; 2007). From a theoretical point of view, the development of these transducers is similar to a spring-mass system. Williams and Yates (1996) developed the first model to capture energy. The system is based on a linear spring with one degree of freedom (FIGURE 1.5), with a spring constant k and a damping factor d, both coupled to a body of mass m. Equation 1.3 which governs its motion is obtained by applying Newton's second law.

$$\vec{F} = m\vec{a} \Leftrightarrow -\left(\vec{F_s} + \vec{F_d}\right) = m\vec{a} \Leftrightarrow -k(x-y) - d(\dot{x} - \dot{y}) = m\ddot{y} \qquad (1.3)$$

Figure 1.5 - Model with one degree of freedom of a mass, damper and spring system



Source: Torres (2015).

Power generation by piezoelectricity can be done through linear and non-linear devices. One issue in power generation by piezoelectric materials is that the best performance of the device occurs when it is in resonance condition. According to Mineto (2013), if the vibration frequency is changed, the electrical power produced is drastically reduced, so in practical applications it is more difficult to achieve a scenario in which the vibration remains linear for a certain period. The main limitation of linear oscillators is that they are only suitable for stationary excitations and with excitation ranges close to the natural frequency, becoming less efficient when the ambient vibration energy is distributed over a wide spectrum of frequencies (CAETANO, 2017).

Although there are many papers published on linear piezoelectric power generators, in recent years power generation by nonlinear devices has received special attention from researchers. The great advantage of non-linear devices compared to linear ones lies in the fact that they work by capturing energy in a large frequency range of vibrations (MINETO, 2013).

Lu, Lee, and Lim (2004) report that power generation from linear devices is simpler than from non-linear devices. Liao and Sodano (2008) describe a theoretical model that provides an accurate prediction of energy generated around a single vibrating mode, the optimization of system parameters to achieve maximum efficiency is performed through numerical simulations and confirmed through an experimental model.

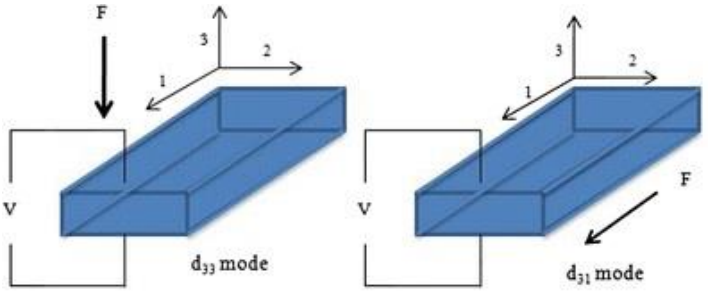
Triplett and Quinn (2009) explain that there are several electromechanical mechanisms for collecting piezoelectric energy, but the preponderance of the process occurs in piezoelectric models of nonlinear capture. According to Iliuk (2016), the advantage of the nonlinear energy capture model is the ability to convert energy over a large frequency range through vibrations.

1.4 Energy harvest from mechanical vibrations

According to Iida (2005), vibration is the oscillation that a given body performs around a fixed point, and the number of cycles of this movement that is repeating itself in a unit of time (s) is given in Hertz (Hz).

According to Priya and Inman (2009), there are two most common modes used to capture piezoelectric energy, the d33 mode for use in stack-type actuators of piezoelectric elements and the d31 mode used in the design of devices based on cantilevered beams. When the piezoelectric device is installed at the ends of the beam, we call it a bimorph configuration, in d33 mode the generated electrical voltage has the same direction as the applied mechanical stress (force). In d31 mode, the electrical stress is obtained from the direction perpendicular to the beam, and the mechanical action is applied in the axial direction, as illustrated in Figure 1.6.

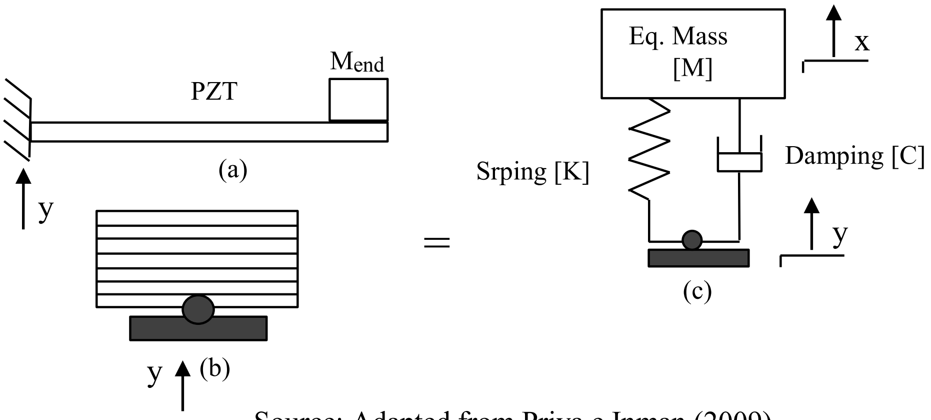
Figure 1.6 - Modes of operation of piezoelectric materials



Source: Microsystem technologies (2010)

Cantilevered beam with mass at the end is a model of energy capture device that uses the d31 mode (FIGURE 1.7a). Another model presented uses multiple layers of piezoelectric elements for energy harvesting, the PZT's are subjected to transverse vibration exciting the base, this is a configuration that uses the d33 mode presented (FIGURE 1.7b), the most common mathematical model used for representing energy capture devices is the mass-spring-damper system with lumped parameters (FIGURE 1.7c).

Figure 1.7 - Energy capture models



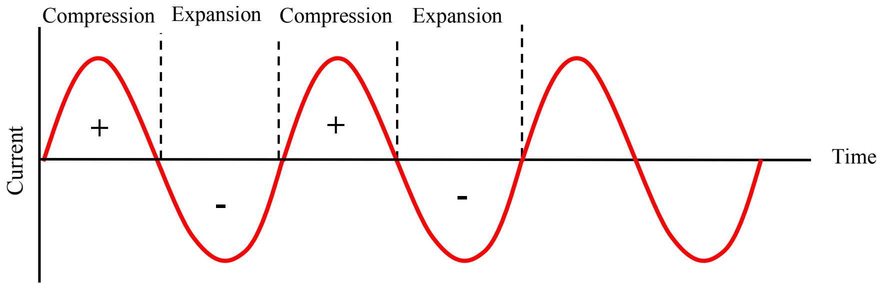
Source: Adapted from Priya e Inman (2009).

The piezoelectric device can have various shapes to achieve different vibration modes, the vibration mode will directly influence the energy capture process (GAIOTTO, 2012).

1.4.1 Conditioning of the signal generated by the PZT

According to Sousa (2016), the main limitation found in the conversion of mechanical energy into electrical energy through piezoelectricity lies in the generated power, which is relatively low, the current generated in the PZT is alternating, requiring rectification for use in electronic circuits, or for energy storage in batteries. During the operation of an energy harvesting system by PZT's subjected to mechanical vibrations, it is possible to observe the compression and expansion of the material (FIGURE 1.8), which promotes an alternation in the current generated as a function of the current effort.

Figure 1.8 - Direction of the current generated by a PZT

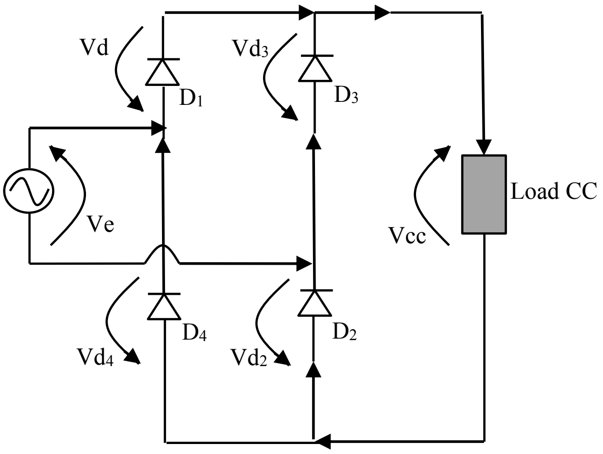


Source: Souza (2018).

To take advantage of the negative half cycle of the generated current, a rectifier bridge is used to convert the alternating current produced by the transducer into direct current, the so-called full-wave rectification (SOUZA, 2018).

The full-wave rectifier circuit shown in Figure 1.9 is developed from four diodes, which are electronic components whose property only allows the passage of current in one direction. In this rectifier circuit mode, the alternating current received at the input is converted into pulsating direct current, and a capacitor is indicated to stabilize the generated current close to the peak value of the waves that result from the direct current (ARRABAÇA and GIMENEZ, 2014).

Figure 1.9 - Full wave rectifier



Source: Author.

The disadvantage of the bridge appears in the voltage drop across the rectifier. Each time current passes through a diode, a voltage drop occurs. On silicon rectifiers, this drop is approximately 0.7V. For the case of the bridge, each half cycle will cross two diodes, resulting in a drop of 1.4V, as shown by MARTINS (2021), in the full-wave bridge rectifier, the voltage drop is even greater, as there is a loss of power over two diodes. However, rectification takes place in both half-cycles of the input signal. However, in most applications this drop is not a problem, being of concern only when it comes to voltages below 10V (MALVINO, 2014).

1.5 Hypothesis

The use of PZT pellets in power generation can be used as an alternative and renewable source of energy, aiming at obtaining more efficient systems in energy terms, in addition to its association with machines and devices used in Precision Agriculture and Agriculture 4.0.

1.6 Objectives

1.6.1 General purpose

Propose, evaluate and implement an energy harvesting system using piezoelectric materials, based on mechanical vibrations, aiming at its application in agricultural machinery.

1.6.2 Specific objectives

a) Analyze and evaluate a piezoelectric device for harvesting energy from mechanical vibrations in the laboratory;
b) Evaluate a low-cost and low-consumption electronic circuit to be applied to energy harvesting from piezoelectric devices;
c) Evaluate the functioning of the combination of piezoelectric devices regarding their ability to generate electrical power in the laboratory.

1.7 Scope of work

This work aimed to analyze the functioning of PZTs applied in power generation, as well as to define a better PZTs association model for several applications. The work is divided into xx chapters organized as follows:

Chapter 1: Presents an introduction, theoretical framework, hypothesis, objectives, and bibliographical references with an overview of the use of various configurations of piezoelectric association systems for harvesting energy from vibrations, being thus, an alternative to conventional systems (cells or batteries) to increase the energy efficiency of machines and mechanized agricultural systems.

Chapter 2: In this chapter, the characterization of PZT's applied in power generation is presente, contemplating the basic concepts of the piezoelectric effect.

Chapter 3: It presents an analysis of the association of several PZT in different combinations, as well as the use of common rectifiers and the use of a module destined to capture energy. The best association will be analyzed using statistical methods, presenting a structural configuration, candidate to supply the loss in energy generation with variations in the excitation frequency.

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CHAPTER 2 CHARACTERIZATION OF A VIBRATION ENERGY HARVESTING SYSTEM FROM PIEZOELECTRIC MATERIALS

ABSTRACT

The present study was carried out to characterize and analyze the use of piezoelectric pellets, known as lead zirconate titanate (PZT), to harvest energy through the mechanical vibrations of a spring-mass system. Through frequency sweep analysis, the natural frequency of the system was found, from which the frequency ranges to be analyzed were established. Only one PZT connected to two models of treatment of the generated energy was used in this experiment, one consisting of a full-wave rectification circuit and another consisting of a commercial charge controller module for energy harvesting (model LTC3588), were used. During the tests, the voltage, current and power parameters were analyzed. The vibration system consisted of an electromechanical vibrator controlled by a frequency inverter. The data were analyzed by statistical means to obtain a better result of the application of PZT in the generation of energy. The excitation frequency of the system significantly influenced the energy generation process, in which the best excitation frequencies were obtained for a system operating under resonance conditions. The rectification system influenced the energy generation process, and its design and suitability were of fundamental importance. The full-wave rectification system was more efficient in the power generation process than the LTC3588 module, regardless of the response variable evaluated.

Keywords: Mechanical vibrations. Resonance. Harvesting energy. Wave rectification.

1 INTRODUCTION

The energy crisis and changes in the environment have led researchers to explore alternative energy technologies. Mechanical energy is the most omnipresent and can be captured and converted into useful electrical energy. The conversion of mechanical energy from vibrations into electrical energy has increased in the last decade in efforts to meet the need for alternative energy sources, with piezoelectric transduction being the prominent mechanical mechanism (SEZER; KOÇ, 2021).

According to Sezer and Koç (2021), piezoelectric transduction has a high potential for energy harvesting due to its high electromechanical coupling factor and piezoelectric coefficient compared to electrostatic, electromagnetic and triboelectric transductions.

Mechanical vibrations can be defined as a movement of a particle or a body that oscillates around an equilibrium position that repeats itself after an interval of time. This type of phenomenon occurs commonly in dynamic systems, especially mechanical systems observed in machines and equipment (RAO, 2009). In the context of energy harvesting, there are three main types of energy generation based on mechanical vibrations: piezoelectric, electromagnetic and electrostatic (TOPRAK; TIGLI, 2014). According to Souza (2016), piezoelectric materials need to be able to deform and return to their initial state after the stimulus ceases, requiring means to increase their durability, such as the addition of polymers and manometric particles, because the materials lose their malleability due to their use.

The main limitation found in the conversion of mechanical energy into electrical energy by means of piezoelectricity is related to the power level, which can be considered relatively low, requiring the use of batteries for energy storage (SOUSA, 2016). According to Chen et al. (2010), the development of piezoelectric generators is a challenge due to their poor source characteristics (high voltage, low current, high impedance) and relatively low power. However, this type of technology can be used in different types of structures, including bridges, buildings, aircraft and vehicles (SODANO et al., 2004; ERTURK et al., 2009; ERTURK et al., 2010). Authors such as Almeida (2018) predicted that the use of piezoelectric materials in the generation of electricity will result in clean energy and can be used in highways, sidewalks and soccer fields, generating savings because conventional power supply cables are not used, thus increasing the autonomy of current electrical systems. Harrop (2019), showed in his studies that over time, energy harvesting concepts will be increasingly used for the generation of energy by trends such as the reduction of polluting gases, conservation of natural resources, access to electricity, mobility and health resources, development of underdeveloped countries and omnipresence of electronics.

Great efforts are being made by researchers in the study and development of energy extraction and storage techniques to increase the electrical potential produced by piezostructures, a set composed of structures in association with piezoelectric elements coupled to their surface (ADACHI; TANAKA, 2009; AJITSARIA et al., 2007), as well as to minimize the potential lost through AC/DC conversion (LEFREUVE, 2006; RAMADASS, 2010; SOUZA, 2011).

Technological advances over the last decade, especially those in micro and nanotechnology, have influenced the development of important electronic devices with a large reduction in size and energy consumption, and there has been an increase in the demand for self-powered systems in different applications (ZHU et al., 2009; PINNA et al., 2010; JORNET et al., 2012). Miniaturization, multifunctionality, portability, flexibility, high computational capacity and low power communication have become the general trend in the development of electronic devices (SEZER; KOÇ, 2021).

In this context, the energy generated from piezoelectric devices can be used to supply power to low consumption circuits, such as those used in the instrumentation and control of systems in machines. Thus, considering the evolution of agricultural machinery, in terms of the use of embedded electronics and agricultural processes associated with precision agriculture and energy efficiency, there have been vast developments and applications of piezoelectric devices in the field of energy harvesting. With the simultaneous reduction of the size and energy requirements for microelectronics, it is conceivable that some circuits could be directly powered with energy extracted from the environment in which the circuit operates (RANGEL, 2014), this energy could also be accumulated in batteries for storage and reintegration into the system. According to Levron (2011), it is necessary to comprehensively evaluate these energy storage devices from experiments to determine their advantages and disadvantages. Many devices, such as electrolytic capacitors, supercapacitors, and rechargeable batteries without memory, can serve as energy storage equipment that best suits the situation.

Maiwa (2016) mentioned that by combining the appropriate electronics, energy harvesting devices can be used to create a self-sufficient energy supply system. The merits of the system include replacing the power cables, replacing or supplementing the batteries and minimizing the associated maintenance costs. The main application is independent sensor networks.

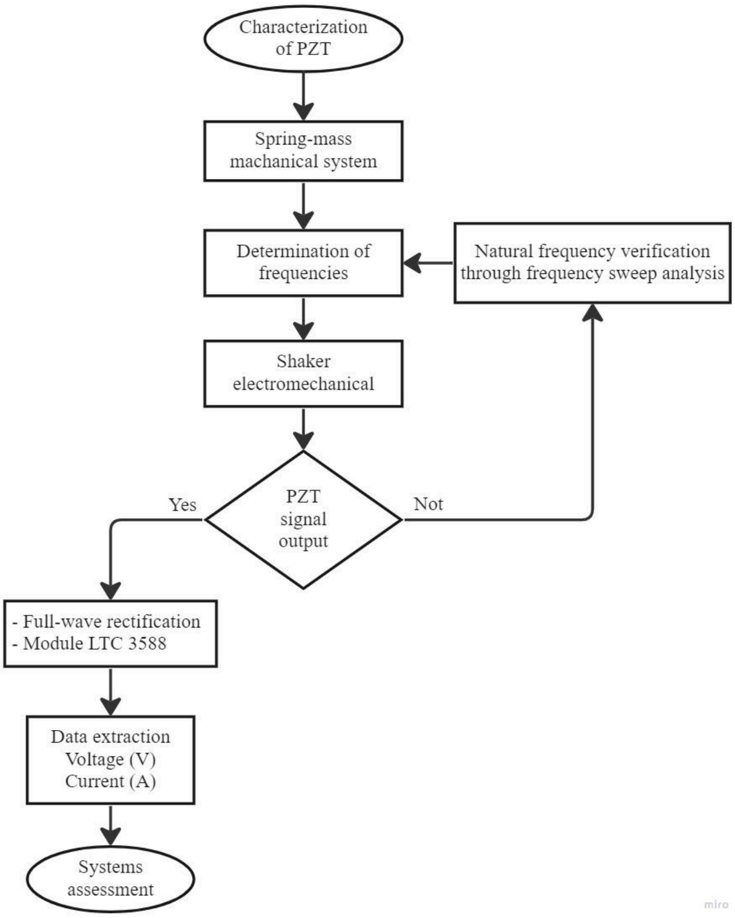
Therefore, this work was developed with the objective of characterizing piezoelectric materials, PZT pellets, aiming at their application in energy harvesting in agricultural machinery. The pellets were coupled to spring-mass mechanical systems for their potential use in energy harvesting during the operation of the machines based on the dynamic response of the system. Additionally, different wave rectification systems were evaluated to extract the maximum efficiency of the system in the energy harvesting process.

2 MATERIAL AND METHODS

Analyzes and data obtained from PZT pellet for power generation were carried out at the Electronics Laboratory of the Department of Computer Science (DCC), where the electronic circuits were developed, and at the Laboratory of Mechanical Vibrations at Department of Engineering (DEG).

The project was based on the evaluation of an energy harvesting system to be used in low consumption devices using piezoelectric materials coupled to spring-mass mechanical systems. The system is capable of supplying energy to devices with low power demand. However, based on this characterization, different associations can be configured to increase the power generation capacity of the system. The following steps were performed according to the flowchart shown in Figure 2.1.

Figure 2.1 - Flowchart with the system evaluation steps

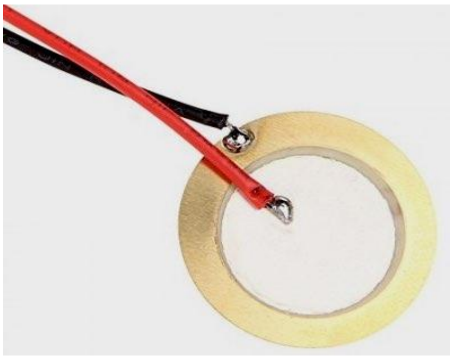


Source: Author.

2.1.1 Characterization and Analysis of the PZT

Among the numerous piezoelectric devices found on the market, an easy to acquire and low-cost model, that consists of a brass plate with a 35 mm diameter ceramic plate (Figure 2.2), was chosen.

Figure 2.2 - Illustration of the PZT pellet, which was characterized for the development of the energy harvesting system



Source: Author.

The main characteristics of the piezoelectric wafer used in the project are summarized in Table 2.1.

Table 2.1 - Main characteristics of the piezoelectric plate

Specification	Characteristics
Brand	MuRata
Model	SY-35T-3.5A1
Resonant frequency	1.8 kHz +/- 0.3 kHz
Resonant impedance	300 Ω max
Capacitance	50 nF +/- 30%
Operating temperature	-30 °C - +70 °C
Plate material	Brass
Piezoelectric material	Ceramic
External diameter	35 mm +/- 0.1 mm
Internal diameter	24 mm +/- 0.2 mm
Plate thickness	0.15 mm +/- 0.05 mm
Total thickness	0.35 mm +/- 0.05 mm

Source: MuRata (2019).

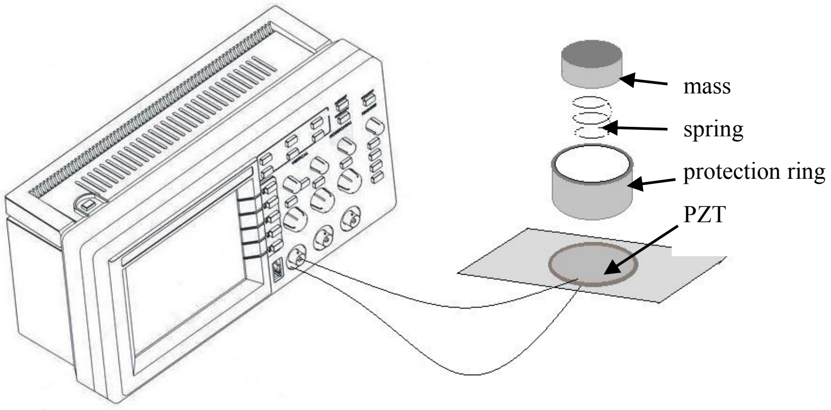
To characterize the energy harvesting device, considering its operating capacity and electrical power generation, a Tektronix TS1052B digital oscilloscope with a data storage system was connected directly to the PZT. The results of the generated voltages and currents were stored for graphical and quantitative analyses. For this purpose, the resonance frequency of the energy harvesting device, composed of the PZT in combination with a spring-mass system, was considered, and its excitation was performed by an electromechanical vibrator. The voltage and current values generated by the device were evaluated, and the electronic regulator circuit was subsequently implemented. For this characterization, five replicates were considered.

2.1.2 Mechanical system associated with the PZT

When compressed by a force, PZT pellets generate electrical energy; therefore, it is necessary to dynamically characterize the spring-mass system in association with a PZT pellet. The natural frequency (ω_n) of the set was determined from Equation 2.1, considering the spring stiffness (k) and the body mass (m), as shown in Figure 2.3.

$$\omega_n = \sqrt{\frac{k}{m}} \tag{2.1}$$

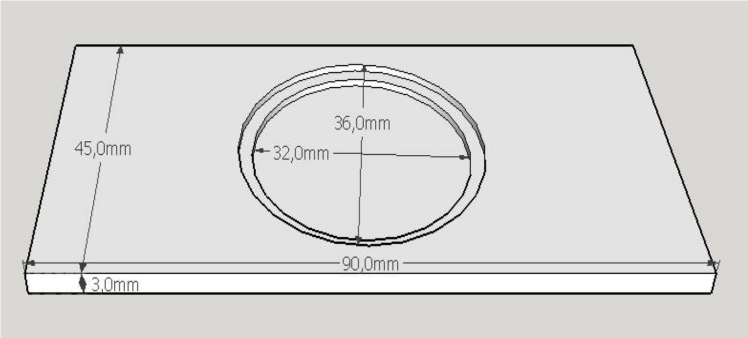
Figure 2.3 - PZT working in the spring mass system - expanded view



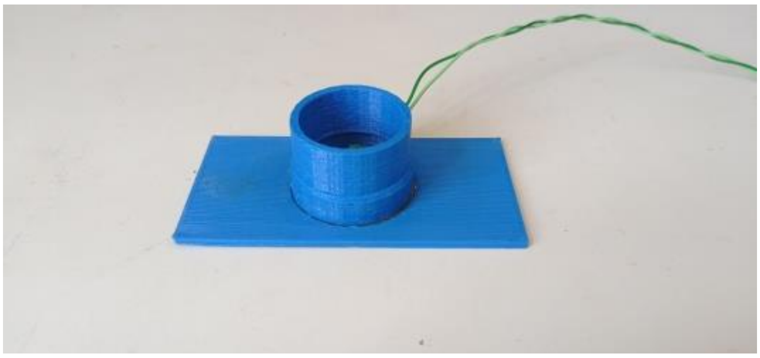
Source: Author.

To analyze and characterize the energy harvesting system, a support for the PZT pellet coupled to the spring-mass system was developed and manufactured using 3D printing with PLA material. From this support, the PZT insert was fixed only by the ends, with a greater deformation of the PZT and, consequently, a higher yield compared to supports with a completely flat base. Figures 2.4a and 2.4b show the support used for the characterization of the energy harvesting system. The body for complete analysis is shown in Figure 4c, and the mass and spring used were the same for all bases.

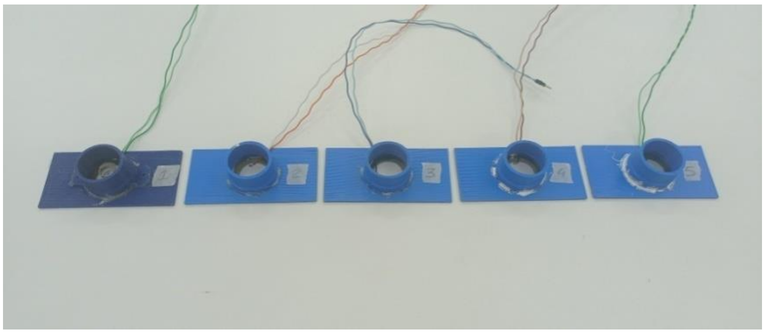
Figure 2.4 - Support base used in the characterization of the system



a) Design of the base for PZT positioning



b) Individual energy harvesting system and spring-mass system



(c) Composition of the five replicates for evaluation

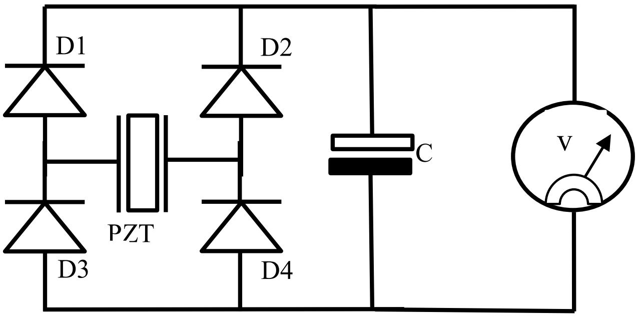
Source: Author.

2.1.3 Development of the electronic circuit for signal rectification

In this study, two circuits were proposed and evaluated for signal rectification. The first consisted of a rectification of the extracted signal associated with an electrolytic capacitor, and the second consisted of a commercially sold charge controller module manufactured by the Analog Device company (model LTC3588).

The developed electronic circuit consisted of a full-wave rectifier and a capacitor (Figure 2.5). This circuit was developed and tested to obtain the highest possible efficiency of the system because the power generated by a PZT is relatively low. Considering that the device, when subjected to mechanical vibrations, generates positive and negative voltages in the form of a sinusoid, the signal must be rectified. It is important to note that for the development of the circuit, the minimum loss of the generated voltage was taken into account and, depending on the application, it should be conditioned to a specific voltage, according to the circuit to be supplied.

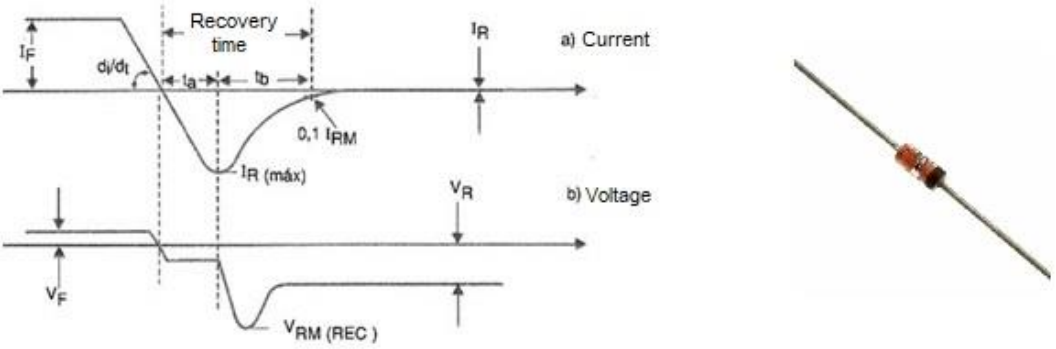
Figure 2.5 - Basic circuit of the PZT rectifier



Source: Author.

When starting from the state of full conduction in a common rectifier diode, the voltage is inverted in the next half-cycle and must pass to nonconduction. As shown in Figure 2.6a and Figure 2.6b, this process does not happen immediately; thus, is diode is encapsulated.

Figure 2.6 - Conduction time of a fast switching diode and 1N4148 diode



(a) (b)

Source: Newton C. Braga 2009 - Siemens 2008.

When the applied voltage decreases, it passes through the zero point until reaching its maximum in the reverse direction. However, diode does not stop conducting immediately. It remains in full driving in the opposite direction for a certain time and needs to “recover” from the transition that occurs. As the dynamic response of the device is high in certain applications, the 1N4148 diode, whose main characteristics are summarized in Table 2.2, was used. This diode is characterized by a high switching frequency and low conduction loss to obtain better signal rectification.

Table 2.2 - Main characteristics of the 1N4148 diode

Symbol	**Parameter**	**Value**
V_R	Reverse voltage	75 V
V_{MR}	Reverse peak stress	100 V
I_F	Rectified current (mean)	200 mA
P_{tot}	Total energy dissipation (T_{amb} = 25 °C)	500 mW
T_J	Junction temperature	175 °C

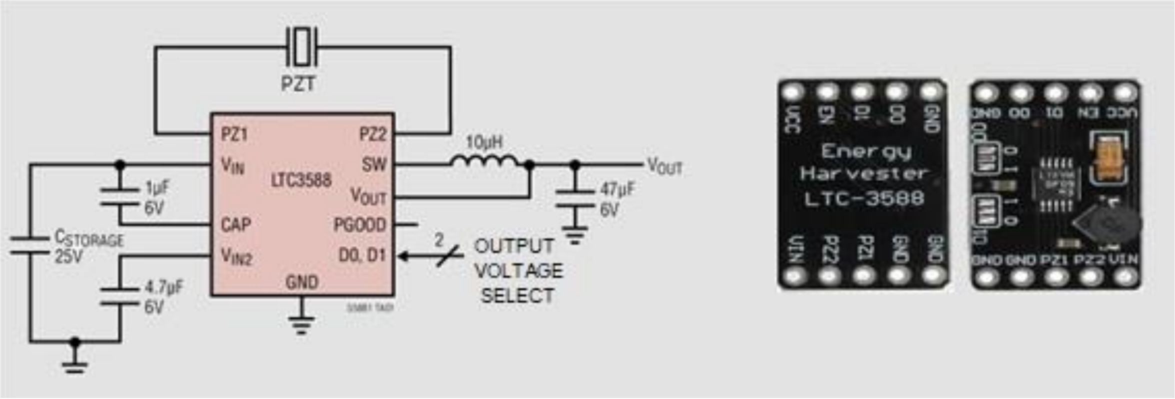
Source: Philips Semiconductor 2018.

The electrical power (P) generated was obtained by obtaining the voltage (V) and current (I) generated by the energy harvesting system using the power equation $P = V.I$.

In the circuit, under operating conditions, the current and voltage values were recorded and analyzed. To measure the current, a resistor was inserted in series with the output of the rectifiers so that the circulating current in the circuit could be measured. The voltage values were recorded on the oscilloscope together with a multimeter in the current scale (mA), which was used to measure the results.

The technical feasibility of using a module (LTC3588) to replace the developed bridge rectifier was evaluated, as this device has a low acquisition cost. The LTC3588 Energy Harvesting module is a low load manager with an internal low loss bridge rectifier together with a high efficiency buck converter, as shown in the electronic scheme and module in Figure 2.7. The LTC3588 module has several configurations according to its application. The input voltage is limited to 20 V, and the output (Vout) allows up to 4 voltage levels (1.8 V, 2.5 V, 3.3 V and 3.6 V) through the combination of pins. The maximum output current is 100 mA.

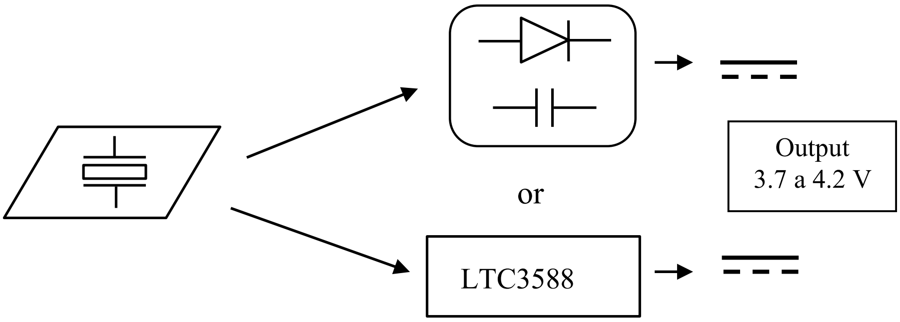
Figure 2.7 - Electronic circuit and LTC3588 module



Source: Linear Technology LTC3558.

Figure 2.8 shows the block diagram of the basic energy harvesting system composed of the PZT, rectification and filtering circuit and LTC3588 load management module, which were compared in the final process. The circuit connected to the energy generating system must have a low consumption due to the low values generated by the PZT, and any other device that considers the characteristics of the generating circuit can be coupled. Therefore, the definition of the rectification system followed criteria based on cost and performance.

Figure 2.8 - Block diagram of the basic power generation circuit

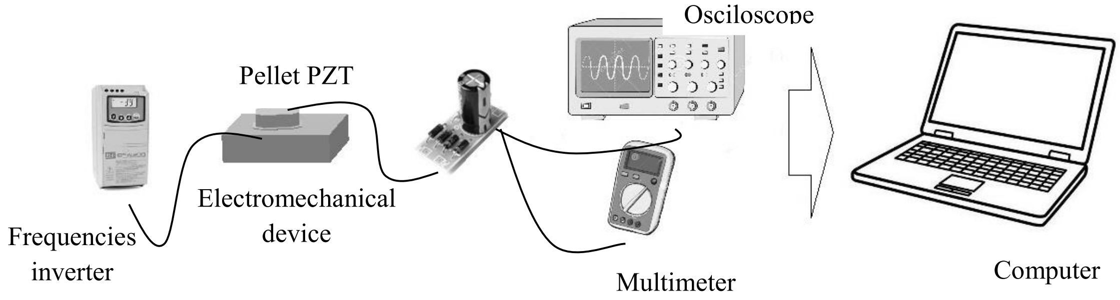


Source: Author.

2.1.4 Evaluation of energy harvest using PZTs

The initial set for analyzing the power generation capacity of PZT pellets consisted of an electromechanical vibrator with displacement of 1,0mm, controlled by a frequency inverter, which was used for the excitation of energy harvesting devices. To evaluate the response of the energy harvesting devices, a Tektronix oscilloscope was used. Figure 2.9 shows a schematic illustration of the set for PZT analysis.

Figure 2.9 - Basic configuration for PZT analysis



Source: Author.

The spring-mass system was mounted directly on the electromechanical excitation device in association with the PZT. This device was controlled by a WEG frequency inverter (model CPW300), which allowed the performance of tests at specific frequencies or even the performance of frequency scanning in preestablished ranges.

In this test, the spring-mass system was conditioned to operate in resonance, whose natural frequency was determined by Equation 1. Additionally, a frequency sweep analysis was performed with the objective of measuring the natural frequency calculated with the experimentally determined frequency, concomitantly observing the acceleration peak and the voltage peak of the system. From the natural frequency, the excitation frequencies of $0.70\omega_n$, $0.85\omega_n$, $1.00\omega_n$, $1.15\omega_n$ and $1.30\omega_n$ were considered.

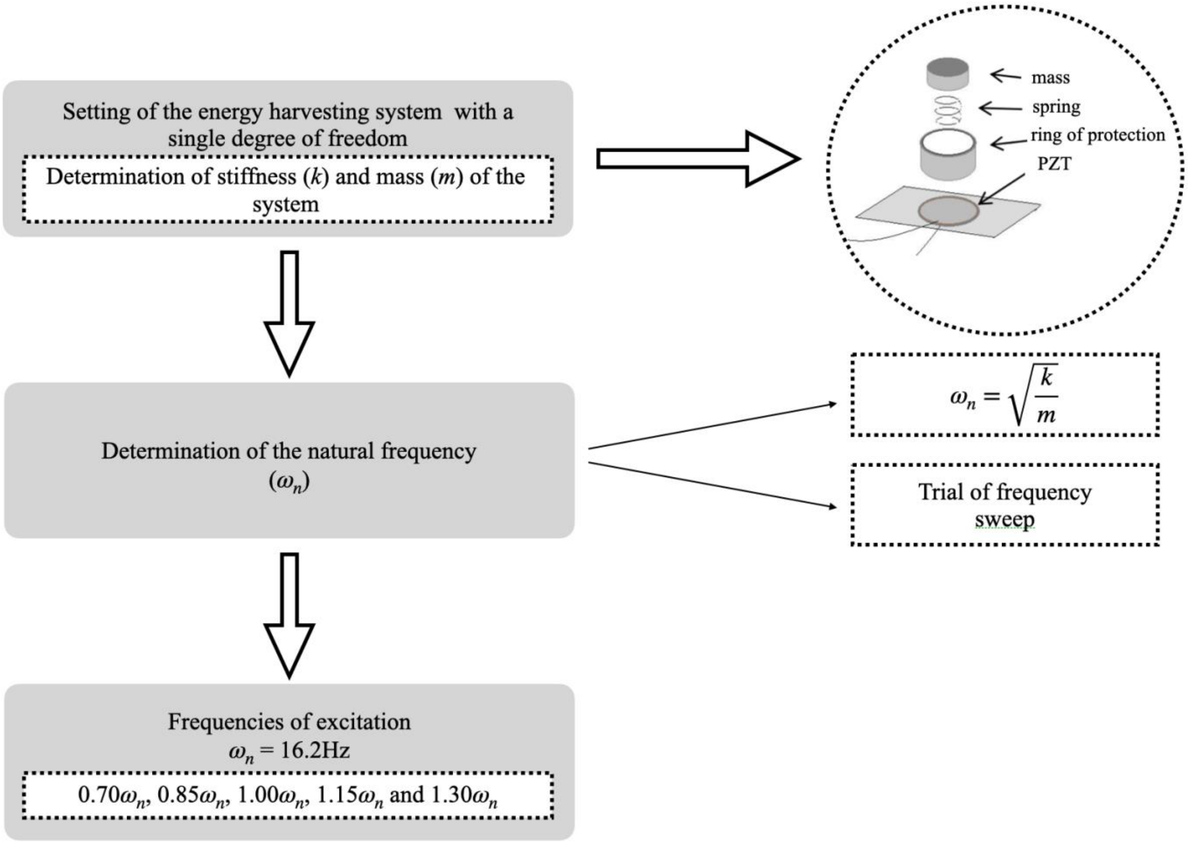
To evaluate the effect of the operating frequency of the system, in terms of the spring-mass system coupled to the PZT pellet and the signal rectification system (rectification and filtering circuit and LTC3588 load management module) under the capacity of generating energy of the system, an experiment was performed according to a completely randomized design in a 3 x 2 factorial scheme, with 5 replicates. The following response variables of the device were determined: voltage (V), current (I) and power (P).

The results were subjected to analysis of variance, considering a significance level of 5% probability. The interaction between the excitation frequency and signal rectification factors of the system was evaluated. The means of the response variables, referring to the qualitative factors, were studied using Tukey's test at 5% probability. The means of the response variables for the quantitative factors were studied through regression analysis, in which the models were selected based on the coefficient of determination, significance of the coefficients and analysis of the lack of fit of the model. R software (CORE TEAM, 2020) was used to perform the statistical analyses.

3 RESULTS AND DISCUSSION

Initially, the system was characterized in terms of its dynamic response. For this purpose, its natural frequency was determined from Equation 1, considering that it has 1 degree of freedom (DOF), as shown in Figure 2.10. Subsequently, this value was measured from a frequency scan analysis, and the natural frequency was 16.2 Hz. In this context, the evaluated frequencies were 11.4, 13.8, 16.2, 18.6 and 21.0, which correspond to $0.70\omega_n$, $0.85\omega_n$, $1.00\omega_n$, $1.15\omega_n$ and $1.30\omega_n$, respectively. The steps of this process are summarized in Figure 2.10.

Figure 2.10 - Steps to characterize the dynamic behavior of the energy harvesting system with DOF



Source: Author.

Table 2.3 shows the results of the analysis of variance considering the excitation frequency factors of the systems and the forms of rectification of the generated signal in relation to the voltage (V), current (I) and power (P) response variables. It was found that the interaction between the excitation frequency factors and the wave rectification presented significant difference, in this context the influence of this factors over the response variables was studied.

Table 2.3 - Results of the analysis of variance for the energy harvesting system with 1 DOF considering the excitation frequency (F) and wave rectification system (R) factors for the voltage, current and power response variables.

Sources of variation	**Vontage (V)**	**Current (mA)**	**Power (mW)**
Frequência (F)	F = 527.27 p = <0.001*	F = 918.29 p = <0.001*	F = 376.25 p = <0.001*
Retificação (R)	F = 34.19 p = <0.001*	F = 44.12 p = <0.001*	F = 31.15 p = <0.001*
F:R	F = 12.50 p = <0.001*	F = 15.68 p = <0.001*	F = 25.09 p = <0.001*

* Significant at 5% probability.
Source: Author.

The excitation frequency is a factor that directly influences the response variables evaluated in the study (Table 2.3). Such behavior is of fundamental importance in the process of energy harvesting and is directly reflected in the electrical power generated in the system. It can be noted that the voltage and current values are directly influenced by the frequency. Similar results were observed by Bernat-Maso (2022), who performed experimental tests on piezoelectric materials and showed that the electrical response depends on the frequency and amplitude of mechanical excitation imposed on the energy harvesting system.

Roundy (2004) stated that when piezoelectric transducers are subjected to external excitation at their natural frequency, amplification of the dynamic response will occur, resulting in maximum deformation, and, consequently, the maximum amount of energy will be generated. Additionally, according to Mota (2021), it can be identified through computer simulations that there is a proportional relationship between the amount of electrical power generated, the excitation frequency and forces.

Table 2.4 shows the models for the voltage, current and power variables as a function of the excitation frequency of the energy harvesting systems.

Table 2.4 - Models selected from the regression analysis for the variables voltage, current and power as a function of the excitation frequency (f).

Response Variable	Rectification	Model	R²
Voltage (V)	R1	$V = 1372 - 358.7f + 35.50f^2 - 1.446f^3 + 0.02232f^4$	0.97
	R2	$V = 1884 - 492.5f + 47.37.50f^2 - 1.986f^3 + 0.0306f^4$	0.99
Current (I)	R1	$I = 142.7 - 37.32f + 3.59f^2 - 0.1505f^3 + 0.002322f^4$	0.98
	R2	$I = 185.9 - 48.61f + 4.676f^2 - 1.960f^3 + 0.003025f^4$	0.99
Power (P)	R1	$P = 662.23 - 173.21f + 16.66f^2 - 0.69836f^3 + 0.01078f^4$	0.96
	R2	$P = 1125 - 294.30f + 28.30f^2 - 1.186f^3 + 0.01831f^4$	0.97

* The model coefficients were significant at 5% probability.
Source: Author.

Figure 2.11 shows the graphical results obtained from the models selected in the regression analysis (Table 4). The voltage, current and power peaks occur at a frequency of 16.2 Hz, which refers to the natural frequency of the mechanical system coupled to the PZT. Scornec (2021) obtained similar results, but in his study, the mass parameter was configured to obtain the highest possible yield during the operation of the system. He also observed that the voltage peaks occurred at a frequency of 9.9 Hz, which was dynamically characterized as the natural frequency of the system under study.

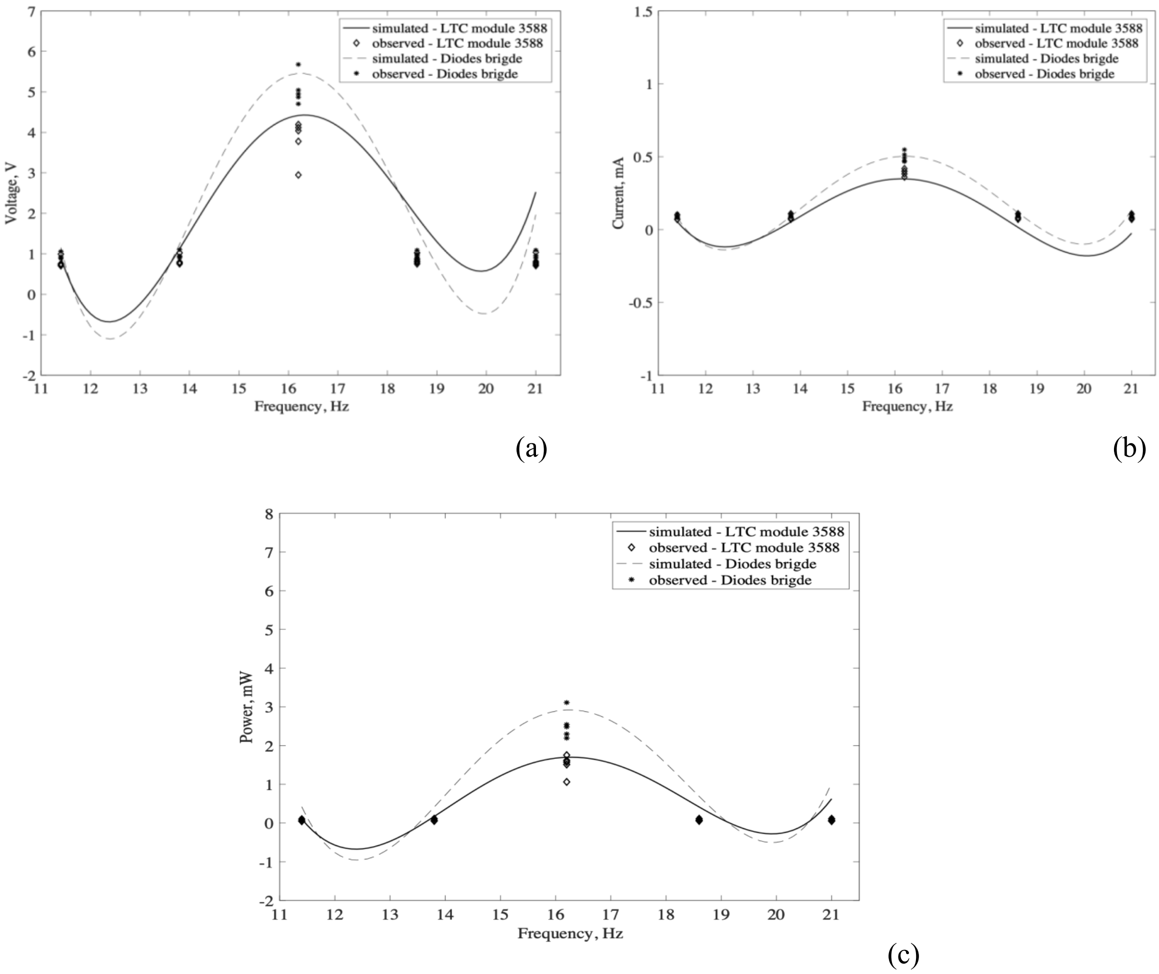
According to Rao (2009), the response of a mechanical system operating under resonance conditions is amplified by the phenomenon, which can be verified by the observed voltage, current and power peaks. Figure 2.11c shows that power peaks greater than 3 mW were observed, which reinforces the importance of adjusting the dynamic response of the system to obtain more efficient energy generation. In this context, considering the potential of developing a system to be embedded in agricultural machinery for power generation, it is important to pay attention to the configuration of the coupled mechanical system for greater power generation, as the system operates under resonance conditions.

Bertacchini (2016) developed a multisensor wireless system applied to agricultural vehicles. The data provided by the different types of wireless sensors can be used as a starting point for the implementation of an automatic system to improve the active safety of vehicles.

With this system, the author aimed to extend the useful life of the implement or trailer where the sensors were mounted. Each sensor has its own energy capture system employing the principle of mechanical vibrations in the energy harvesting process, which occurs in the environment where the sensor operates, using piezoelectric devices.

Grover (2011), in a study conducted with agricultural tractors, found that there are changes in the dynamic response of the machines as a function of the type of implement to be used in the operation. The author also observed that the vibrations in the machine frame ranged from 3.4 to 5.7 Hz, and it is possible to use the vibration to convert the dynamic response of the machine into electrical energy using piezoelectric materials. The author emphasized that the electricity generated after rectification can be directly stored or reintegrated into the system.

Figure 2.11 - Results of the voltage (a), current (b) and power (c) variables as a function of the excitation frequency of the energy harvesting system



(a) (b)

(c)

Source: Author.

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Additionally, it is possible to observe that the wave rectification by diodes bridge presented a better results than the LTC module 3588, for the evaluated variables. For power variable (Figure 2.11c), it was observed an expressive gain of power when the diodes bridge was used, this resultes indicates the potencial of this way of rectification for energy harvesting.

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Table 2.5 shows the results obtained for the mean values of voltage, current and power, considering the rectification of the signals by the LTC3588 module and by the diode bridge, which were studied using Tukey's test at 5% probability and R1 describes LTC 3588 module and R2 decribes diodes brigde wave rectification.

Table 2.5 - Tukey's test results for the mean values of voltage, current and power considering rectification by the LTC3588 module and by diode bridge

Frequency	Retification	Voltage (V)	Current (mA)	Power (mW)
11.4	R1	0.78 a	0.08 a	0.06 a
	R2	0.94 b	0.09 a	0.08 a
13.8	R1	0.83 a	0.08 a	0.07 a
	R2	0.96 a	0.09 a	0.09 a
16.2	R1	3.82 a	0.39 a	1.50 a
	R2	5.05 b	0.50 b	2.53 b
18.6	R1	0.85 a	0.08 a	0.07 a
	R2	0.98 b	0.10 a	0.10 a
21.0	R1	0.81 a	0.08 a	0.07 a
	R2	0.96a	0.09 a	0.09 a

* By Tukey's test, at a significance level of 5% probability, means followed by the same letter, in the column for each frequency and response variable, do not differ from each other.

Source: Author.

According to the results presented in Table 2.3, it was observed that for the voltage, current and power variables, the rectification system used influences the energy generation process. For both variables, it was observed that the system from the diode bridge showed a higher performance. In some applications of the LTC3588 module, the current levels need to be sufficient to activate the circuit, and thus, the module has ideal operation conditions.

It can be observed that on the resonance frequency the highest values of voltage, current and power were observed, regardless the way of rectification. However, it is important to enphasize the diodes bridge presented a higher perfomance when compared to LTC3588 module, resulting in a power generation 69% higher (Table 2.5). Studies conducted by Yuan (2018) showed that the adoption of the commercial LTC3588 device may underestimate the performance of the energy harvesting system, yielding unsatisfactory results. Additionally, the author found that when studying different types of diodes, the classic full-wave bridge showed greater efficiency in relation to the module, which confirms the results obtained in this study.

However, Heever (2013) stated that for certain applications, such as applications in nanogenerators with maximum voltage and current limits of 5 V and 1.25 μA, respectively, the LTC3588 module has better performance.

It is important to note that, despite the low power, this type of energy harvesting system is promising for use in agricultural machinery, since the dynamics of these machines during preparation and cultivation activities can be used as a source of energy excitation for energy harvesting modules. In this context, energy can be harnessed by rubber brush actuators and thus stored in supercapacitors, storage devices, portable and nonportable electrical devices, manometer valves and thermostats. This reduces the engine load and increases the fuel efficiency of an agricultural tractor, thus decreasing its operational cost (Groove, 2011).

Modern agriculture uses new processes, such as precision agriculture, to optimize workflows, and agricultural machines are equipped with various types of sensors and actuators (Muller, 2010). In his work, Agrawal (2020) mentioned that in precision agriculture, several types of sensors, including soil, humidity, temperature, wind direction, wind speed, camera, drone, etc., are used to continuously monitor the field and connect to the base station. The base station is a power-constrained device that needs to function while maintaining the energy requirements of various sensors and modules and uses energy collection to maintain energy neutrality. According to Goel (2020), in the case of wireless sensor networks (WSNs) based on precision agriculture, energy consumption can vary due to different parameters (i.e., dynamic computational overload/sensor density variations), and these conditions are not considered during collection in traditional energy collection system schemes. Therefore, the overall useful life of the network may be reduced. Energy harvesting from piezoelectric materials has great potential to be employed in this type of system since piezoelectric transduction has a high potential for energy harvesting due to its high electromechanical coupling factor and piezoelectric coefficient compared to electrostatic, electromagnetic and triboelectric transduction mechanisms (SEZER AND KOÇ, 2021). In addition to energy collection, piezoelectric materials have also been used as sensors and actuators due to their sensitive nature and their large electromechanical coupling coefficient (GODOY et al., 2014).

Roy (2022) noted that applications such as Agriculture 4.0 are increasing in rural areas based on the development of the Internet of Things (IoT). Low-cost sensors, climate data, soil information and drones are used to solve problems in real time, a new development of IoT-based precision agriculture. The range of IoT applications can vary between drone water spraying, soil recommendation for different crops, weather forecasting and water supply recommendation using genetic algorithms.

Therefore, considering the evolution of agricultural machinery and equipment, in terms of its embedded electronics, this type of system can be used to increase energy efficiency and drive associated electrical and electronic devices, including the characteristics of machines in the context of precision agriculture and Agriculture 4.0.

4 CONCLUSIONS

Under the conditions in which the work was performed, it can be concluded that:

a) The dynamic response of the system, in terms of the excitation frequency, significantly influenced the energy generation process, in which the best responses were obtained for the system operating under resonance conditions;
b) The rectification system influenced the energy generation process in energy harvesting devices from PZTs associated with mechanical systems. Its design and adequacy to the system were of fundamental importance;
c) The full-wave rectification system, the diode bridge, was more efficient in the power generation process than the LTC3588 module, regardless of the response variable evaluated.

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CHAPTER 3 DEVELOPMENT OF A VIBRATION ENERGY HARVESTING SYSTEM FOR APPLICATION IN MECHANIZED AGRICULTURAL SYSTEMS

ABSTRACT

This study was developed with the objective of characterizing piezoelectric materials, considering the combination of PZT tablets, with their application aimed towards energy harvesting in agricultural machinery. The tablets were combined in series, parallel and mixed configurations (series/parallel and parallel/series) and coupled to a mechanical mass-spring system, aiming to obtain the greatest potential in energy harvesting during its operation from the dynamic response of the system. Additionally, two energy conditioning systems, full wave rectification and commercial rectification modules, were evaluated to extract the maximum efficiency of the system in the energy harvesting process. The energy harvesting system consisted of 25 PZT pellets fixed on a PLA plate. Each pellet was associated with a spring, which was connected to only one adjustable mass, constituting a system with 1 degree of freedom. The tests were performed using an electromechanical vibrator. The voltage, current and power parameters were analyzed to characterize the energy harvesting system. From the results, it was found that regardless of the configuration used in the energy harvesting system, in terms of signal rectification and association of PZT pellets, the highest power generated occurred with the system operating in resonance conditions. The configuration consisting of the signal rectification by diode bridge together with the mixed association of PZT chips (with 5 sets of 5 PZTs in parallel which are connected in series to each other) was promising for the development of energy harvesting by means of mechanical vibrations for use in agricultural machinery and equipment.

eywords: Piezoelectricity. Signal rectification. Association of PZTs.

1 INTRODUCTION

Modern society has become dependent on the use of electricity, which has resulted in the study of new forms of energy generation, especially clean energy. Currently, the increasing technological advances in different sectors of society and the need for environmental sustainability have directly dictated the need to use alternative energies (JAMAL et al., 2015).

The advancement of micro and nanotechnology has provided important developments to electronic devices, such as the reduction in size and energy consumption and a wide variety of wireless devices (FLEMING, 2021; MASSONE et al., 2019; KIM et al., 2012). According to Lima (2019), with the digitization of rural areas and the use of technologies such as the *Internet of Things (IoT),* there are opportunities to enhance the agricultural production chain, which is being reinforced with the emergence of agriculture 4.0 and the consolidation of precision agriculture. Therefore, these technologies will be integrated into energy harvesting systems, aiming to increase their energy efficiency. In agriculture, the technological leap of machines and equipment used in the different processes is noticeable, and has occurred due to precision agriculture and, currently, due to the use of techniques, concepts and philosophy focused on agriculture 4.0.

Given the above, the need for new energy generation alternatives is noteworthy, especially piezoelectricity. The piezoelectric effect on quartz crystals was discovered in 1880 by the brothers Pierre and Jacques Curie (MOLD, 2007), the word piezoelectricity comes from the Greek and means “electricity under pressure” (piezo = pressure). According to Callister (2008), piezoelectricity is an unusual property exhibited by a few ceramic materials where polarization is induced, and an electric field is established by the application of external forces. The reversal of the signal of an external force (i.e., from traction to compression) reverses the direction of the field. According to Baldwin et al. (2011), piezoelectricity is an effect that occurs naturally in polycrystalline structures, without a center of symmetry, in which there is no common direction for the polar axes of dipoles. Thus, an electric charge is produced on the crystal surface when a mechanical compression force is applied, aligning the polar axes that were previously randomly distributed.

Minazara (2008) describes the direct piezoelectric effect as a phenomenon that takes place when a deformation is performed on the material, the energy resulting from this deformation is converted into electricity by means of a transducer, and the subsequent inverse effect, which consists of the deformation of the crystalline structure of the piezoelectric material when the application of a difference in electrical potential occurs. By applying an external force on these piezoelectric materials, an internal electrical polarization is obtained, with an intensity directly related to the symmetry of the material (TICH STRAIGHT et al., 2010).

Among the numerous research areas of the process of generation and storage of electric energy using renewable sources, the mechanical energy from vibrations has assumed an important role, mainly due to the development of piezoelectric materials that have a large capacity to generate electricity when deformed (ANTON; SODANO, 2007). Piezoelectricity has gained prominence as one of the sources of energy microgeneration from the transformation of energy which results from mechanical vibrations and deformations that are transformed into electrical energy (MOTA, 2021). The conversion of vibrations into electrical energy to power small low-power electronic components has been investigated by researchers from different fields in the last decade (SCORNEC, 2019; TOPRAK AND TIGLI, 2014; ZHU, 2011). In this context, the techniques of generation, collection and storage of this type of energy are known as *energy harvesting* or *power harvesting* (ANTON et al., 2007, BEEBY, 2006).

According to Gomes (2016), the low energy levels obtained can be considered factors that prevent their use in electronic circuits, as well as their transfer to storage in a battery. However, the application potential exists mainly for the feeding of light and remote devices of low consumption such as engines, highways and railways, which are close to vibration sources.

In this respect, research has shown that energy harvesting based on piezoelectric elements have higher energy density and great conversion efficiency through vibrations. It is noteworthy that the use of energy collection technologies, such as piezoelectric energy, is also important to reduce the dependence on batteries, which has a positive impact on the environment (TRAN; CHA; PARK, 2017; BHALLA SURESH, 2017).

According to Scornec (2019), currently connected sensors are an integral part of our daily lives and are present in the management of transportation, industrial maintenance, health, home automation and the military. Therefore, piezoelectricity can be used to replace or at least recharge the batteries needed to feed these sensors with renewable energy sources, and vibrations in mechanical systems have a high potential for energy generation.

Boby et al. (2014) emphasize in their study that the energy produced by the pressure is captured by sensors and converted into an electrical charge by piezoelectric transducers. This energy is then stored and integrated into the system of interest as a source of energy, whose application can be significantly broad, with emphasis on agriculture, domestic applications, lighting and as a source of energy for sensors in remote locations.

According to Toprak and Tigli (2014), the process of converting mechanical energy from mechanical vibrations into electrical charge is performed through the direct piezoelectric effect, without the need for external inputs to induce the conversion. The piezoelectric devices can be connected in series or parallel to ensure higher voltages (series) or currents (parallel). This will reduce the charge time of the capacitors and lead to better device functionality (SUN, 2013).

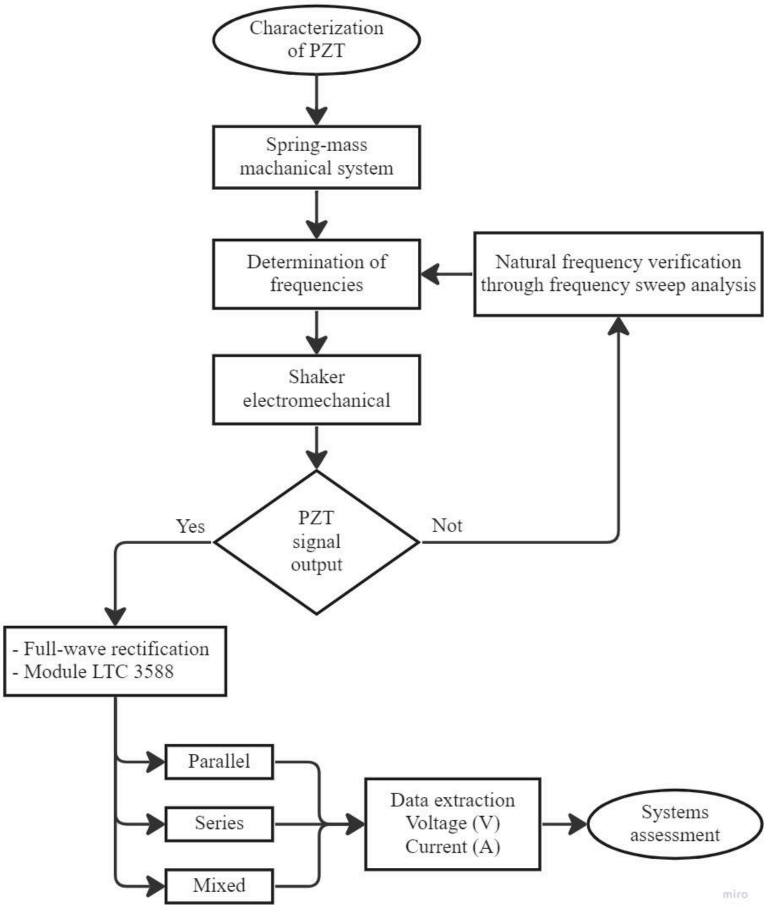
Based on the above, this study was developed with the objective of characterizing piezoelectric materials, considering the combination of PZT pellets, aiming at their application in energy harvesting in agricultural machinery. The tablets were combined in series, parallel and mixed configurations (series/parallel and parallel/series) and coupled to a mechanical mass-spring system, aiming to obtain the greatest potential in energy harvesting during its operation and using the dynamic response of the system. Additionally, two energy conditioning systems, full wave rectification and commercial rectification modules, were evaluated to extract the maximum efficiency of the system in the energy harvesting process.

2 MATERIAL AND METHODS

The analyzes and evaluations of the functioning of the combination of PZT pellets for power generation were carried out at the Electronics Laboratory of the Department of Computer Science (DCC), where the electronic circuits were developed and at the Laboratory of Mechanical Vibrations of the Department of Engineering (DEG), where analyzes of the energy harvesting device were performed with a PZT.

The study was based on the evaluation of an energy harvesting system using piezoelectric materials associated with a mass-spring mechanical system. The system can be used in low power consumption devices. Associations of piezoelectric materials in series, parallel and mixed configurations (series/parallel and parallel/series) were analyzed to increase the power generation capacity of the system. The following steps were performed, as described in the flowchart shown in Figure 3.1.

Figure 3.1 - Flowchart of the evaluation steps of the energy harvesting system considering considering the different associations of piezoelectric materials

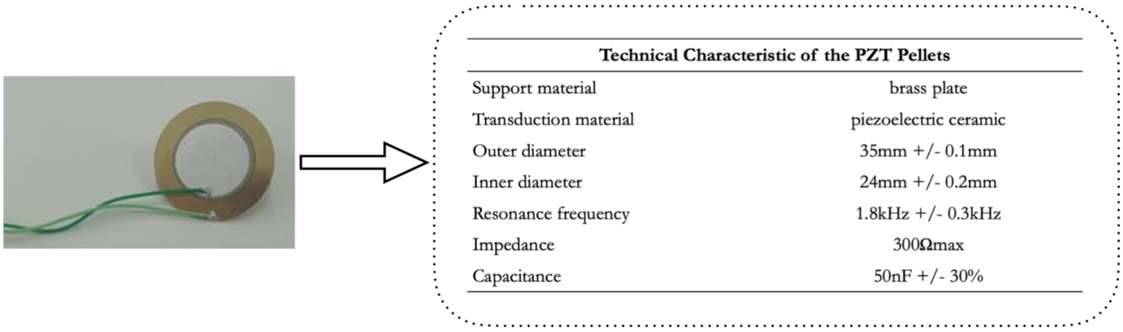


Source: Author.

2.1 Characterization of PZTs

Due to the low cost, easy commercial availability, and geometric and technical characteristics, which facilitated the assembly in different associations, we chose to use PZT inserts in this experiment (FIGURE 3.2).

Figure 3.2- PZT pellet used in the development of the energy harvesting system and its main technical characteristics



Technical Characteristic of the PZT Pellets	
Support material	brass plate
Transduction material	piezoelectric ceramic
Outer diameter	35mm +/- 0.1mm
Inner diameter	24mm +/- 0.2mm
Resonance frequency	1.8kHz +/- 0.3kHz
Impedance	300Ωmax
Capacitance	50nF +/- 30%

Source: Author.

To obtain the characteristics of the operation of the PZT tablets, considering the power generation, an apparatus consisting of a digital oscilloscope of the Tektronix brand, model TS1052B, was mounted, and was directly connected to the plate with the association of the PZTs and a module of vibration, composed of an electromechanical vibrator controlled by a frequency inverter.

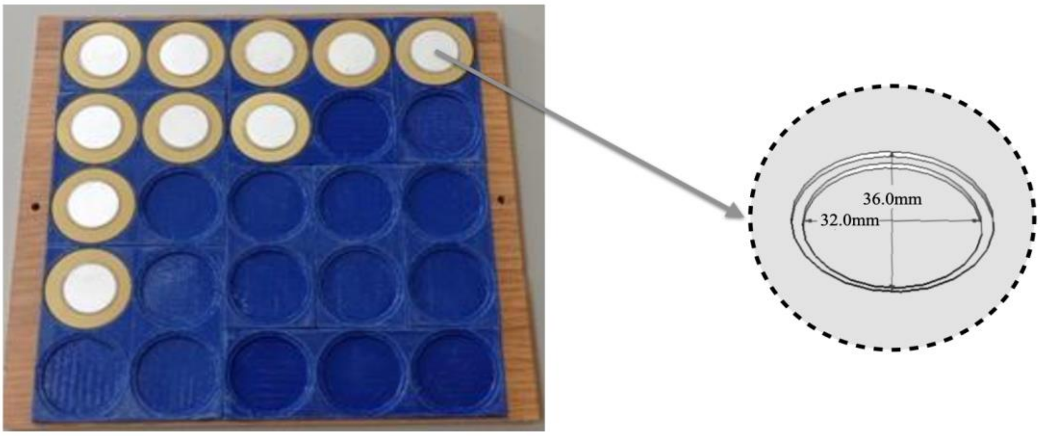
The natural frequency of the set of PZTs associated with the mass-spring system was determined, in addition to the voltage, current and power values generated by the device. Subsequently, the regulating electronic circuit for signal rectification through a diode bridge and the commercial module LTC3588 were implemented, which were evaluated for their efficiency in the energy harvesting process.

All experiments were performed considering 5 replicates to obtain greater confidence in the results.

2.2 Mechanical system associated with PZT tablets

The energy harvesting system consisted of 25 PZT pellets fixed on a PLA plate made in a 3D press (Figure 3.3a). The PLA plate has a geometry designed to receive the inserts, presenting a housing ring for the inserts (Figure 3.3b), which allowed a greater deformation (flexion) during the vibration of the mass-spring system and, consequently, a higher yield. Additionally, to give the module greater structural rigidity, it was decided to fix the PLA plate to a flat HDF (*high-density Fireboard) base,* as shown in Figure 3.3a.

Figure 3.3 - (a) Plate developed in PLA to house the PZT inserts that will be associated with the mass-spring system and (b) detail of the main dimensions of the housing of the PZT pellet



(a) (b)

Source: Author.

For the dynamic characterization of the mass-spring system, in association with the PZT insert plate, it was necessary to determine the natural frequency of the set. For this purpose, Equation 3.1 was used, considering the stiffness of the springs (k_{eq}) and body mass (m). It is important to note that the stiffness of this system was composed of the equivalent stiffness (k_{eq}) of 25 springs in parallel (Equation 3.2), linked to each PZT pellet, which were associated with only one body with adjustable mass, aiming to facilitate the configuration of the natural frequency of the system with 1 degree of freedom (DOF).

$$\omega_n = \sqrt{\frac{k_{eq}}{m}} \tag{3.1}$$

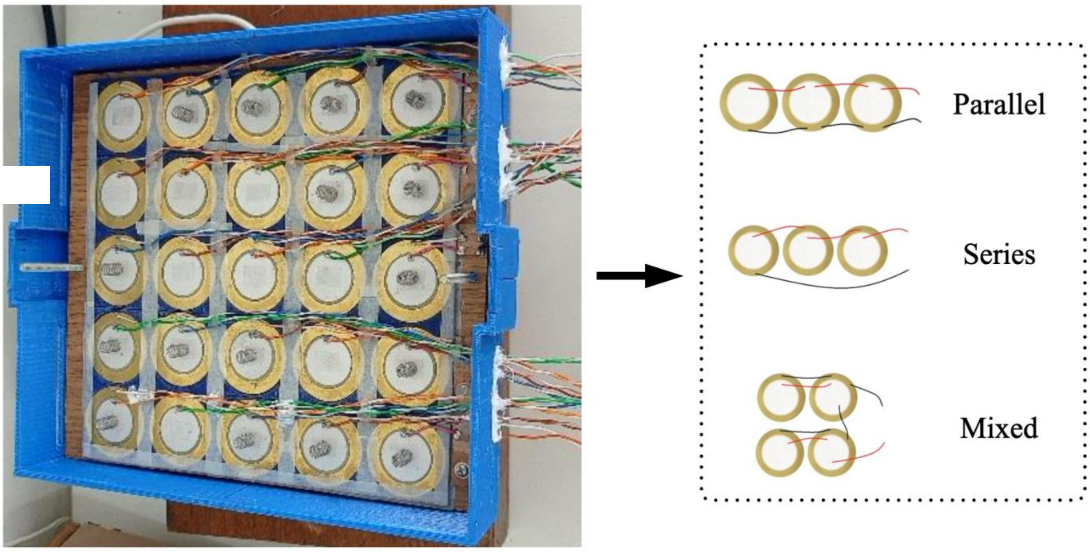
$$k_{eq} = \sum_{i=1}^{25} k_i \tag{3.2}$$

2.3 Association of PZTs

To obtain a higher yield of the energy harvesting system with respect to the generated electrical power, a study was conducted in relation to the different associations of PZTs. Figure

3.4a shows the PZT housing plate with the cabling performed in each insert. From this cabling, it was possible to establish and configure the system for tests considering the following: - the series association (25 inserts in series), described as A1; - in parallel (25 tablets in parallel), described as A2; - mixed with the configuration of 5 sets of 5 PZTs in series and these sets connected in parallel, described as A3; and - mixed with 5 sets of 5 PZTs in parallel and these sets connected in series to each other, described as A4.

Figure 3.4 - (a) PZT insert housing plate with independent cabling and (b) Simplified scheme of association of PZTs in parallel, series and mixed association.



(a) (b)

Photo: The author.

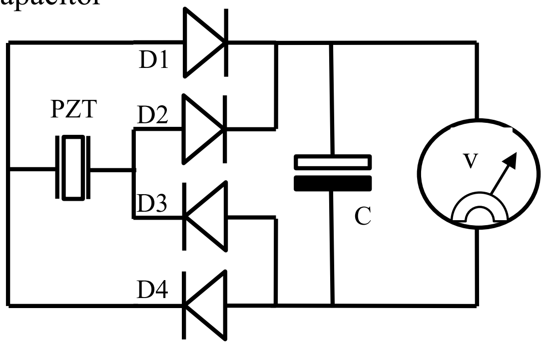
Simplified connection diagrams of the PZTs are shown in Figure 3.4b. For the association in series (A1), the voltage values are summed, and the current values maintain the lowest PZT value in the series. In the parallel association (A2), the voltage values are maintained, and the current is summed by each PZT. In the mixed association, two configurations were used: A3, in which the voltages of the 5 sets of 5 PZTs in series were summed and, subsequently, the currents of the sets in parallel were summed, and A4, in which the currents of the 5 sets of 5 PZTs in parallel were summed, and subsequently, the stresses of the sets in series were summed.

2.4 Electronic circuit for signal rectification

The set of PZTs, when subjected to mechanical vibrations, generates positive and negative sinusoidal voltages, as the signal to be used must be of direct current, there was the need for its rectification.

Two modes of rectification of the signal generated by the set of PZTs were evaluated, which basically consist of a load controller module (R1), commercially sold, manufactured by the company Analog Device, model LTC3588 *(Energy harvesting)* and a full-wave rectification system of the signal by a diode bridge (R2) connected to an electrolytic capacitor in parallel with the output. The electronic circuit is a basic full-wave rectification system with a capacitor used to stabilize the output signal (Figure 3.5). This developed circuit was tested to obtain the highest possible efficiency of the set because the power generation capacity of a PZT is relatively low. The development of the circuit took into account the voltage loss that each silicon diode presents. For this purpose, a diode with minimum voltage loss was used, which, depending on the application, should be conditioned to a specific voltage value, according to the circuit to be fed.

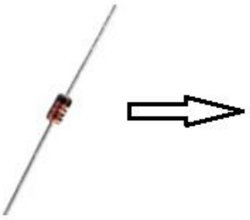
Figure 3.5 - Schematic representation of the electronic circuit for rectification of the signal generated by the energy collection system, where D1, D2, D3 and D4 are diodes and C is a capacitor



Source: Author.

As in certain applications where the vibration can be high, the dynamic response of the device must be compatible, so the diode used was the 1N4148 model, which has adequate characteristics with the proposed system (Figure 3.6). This diode is characterized by a high switching frequency and low conduction loss, obtaining better signal rectification.

Figure 3.6 - Main characteristics of diode 1N4148



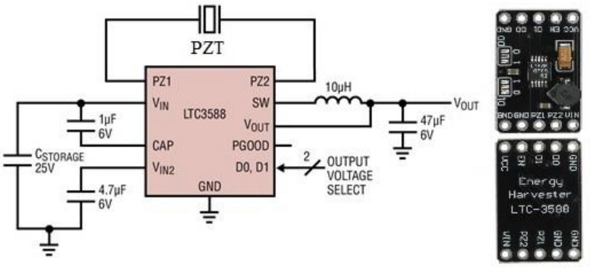
Símbolo	Parâmetro	Valor
Vr	Reverse voltage	75V
Vrm	Peak reverse voltage	100V
If	Continuous forward current	200mA
Ipot	Total power dissipation (25°C)	500mW
Tj	Junction temperature	175°C

Source: Author.

In the R2 rectification system, composed of a diode bridge (Figure 3.5), the voltage readings were obtained directly; that is, a multimeter on the voltage scale was connected directly to the rectification output of the PZT and, in parallel with the capacitor. An oscilloscope was used to record the values. To measure the current, it was necessary to place a resistor in series with the diode output to record the current in the circuit. The readings were made with a multimeter on the current scale (mA). With the data of the voltage (V) and current (I) variables, the electrical power (P) generated by the PZTs was calculated from the following relationship: P = VI

For the LTC3588 module (R1), the voltage (V), current (I) and power (P) values were determined from the same process described for the diode bridge system. This device is a load manager with its circuit already including the rectifier bridge with low voltage loss and a bulk converter that increases the output current (Figure 3.7).

Figure 3.7 - Schematic representation of the LTC 3588 module and technical characteristics

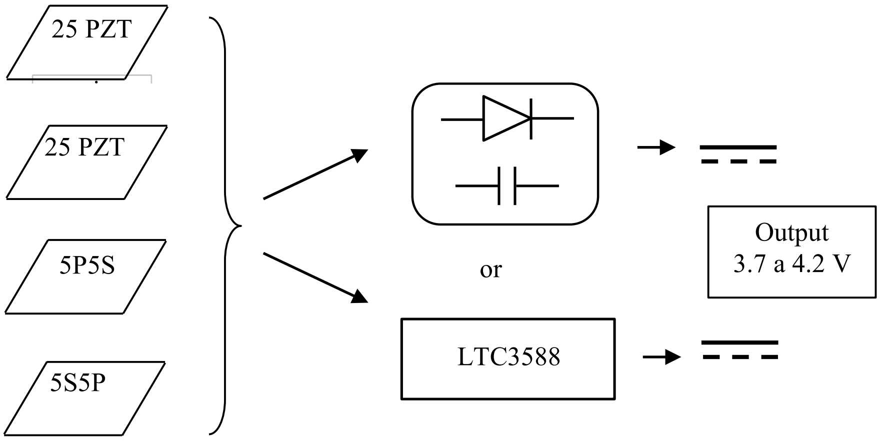


Parameter	Value
Input voltage	20V Max.
V output	1.8V- 2.5V- 3.3V- 3.6V
Current Max.	100mA

Source: Author.

Figure 3.8 shows the block diagram of the basic energy harvesting system composed of 25 PZTs, rectification circuit, filtering and LTC3588 load management module, which were compared at the end of the process. The definition of the grinding system followed the performance criteria of the system combined with its development or acquisition cost.

Figure 3.8 - Block diagram of the basic power generation circuit

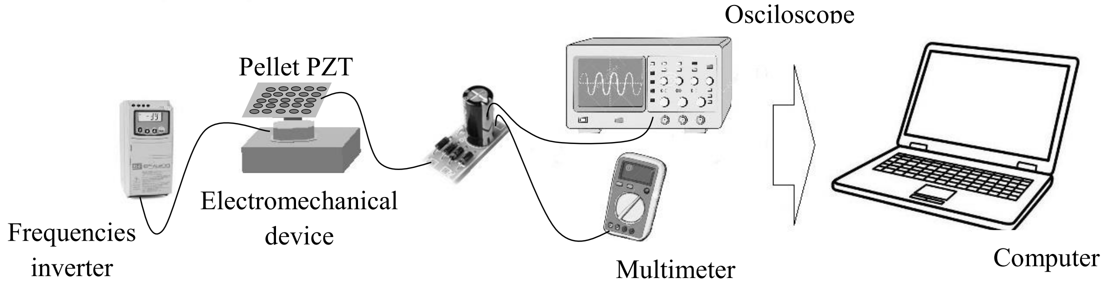


Source: Author.

2.5 Evaluation of energy harvest based on the association of PZTs

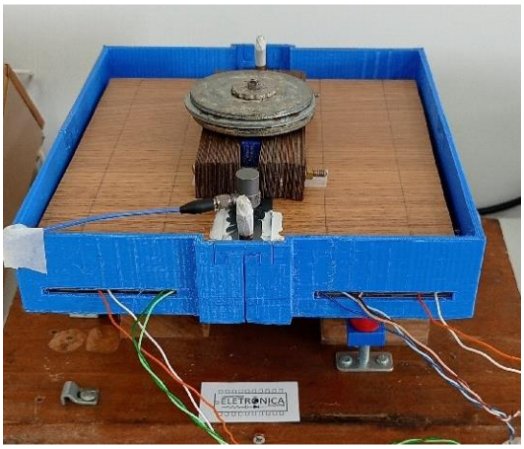
The initial set for analysis of the power generation capacity consisted of 25 PZT pellets associated with a mechanical system mounted on a PLA plate which was especially developed for this purpose. This set was excited by an electromechanical vibrator with control of the excitation frequency. It is noteworthy that this apparatus was set up to evaluate the response of the energy harvesting device (Figure 3.9). The electromechanical excitation system made it possible to perform tests at specific frequencies and perform frequency scanning in preestablished ranges (Figure 3.10).

Figure 3.9 - Basic configuration for the analysis of the energy harvesting system composed of 25 PZTs



Source: Author.

Figure 3.10 - Energy harvesting system composed of a housing plate for 25 PZT inserts, parallel spring association, adjustable mass and cabling for the grinding systems and records of response variables (voltage, current and power)



Source: Author.

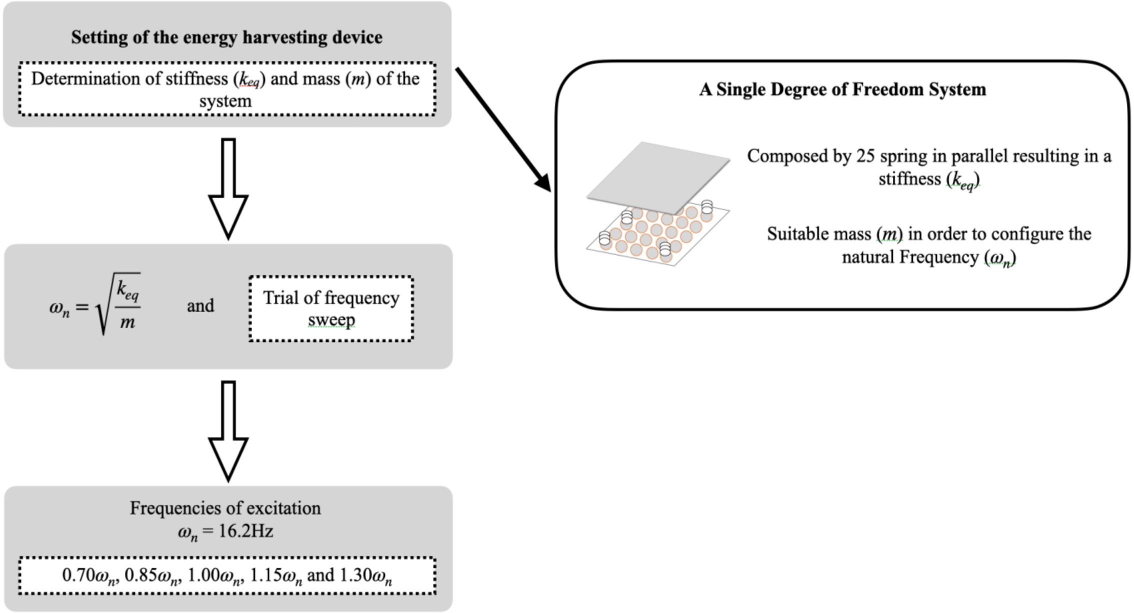
The mass-spring system was conditioned to operate in resonance, and its natural frequency (ω_n) was determined using Equation 3.1. Additionally, a frequency sweep analysis was performed with the objective of measuring the natural frequency calculated with the experimentally determined frequency, concomitantly observing the acceleration peak and the voltage peak of the system.

To evaluate the effect of the frequency of operation of the energy harvesting system, an experiment was performed according to a completely randomized design in a 5 x 4 x 2 factorial scheme, with 5 replicates. The factors studied were the excitation frequency ($0.70\omega_n$; $0.85\omega_n$; $1.00\omega_n$; $1.15\omega_n$ and $1.30\omega_n$), the association between PZT pellets (A1, A2, A3 and A4) and the rectification of the generated signal (R1 and R2), as already described and presented in the methodology. The following device response variables were determined: voltage (V), current (I) and power (P). The results were subjected to analysis of variance, considering a significance level of 5% probability. The interaction between the excitation frequency, association of PZT pellets and system signal rectification was evaluated. The means of the response variables, referring to the qualitative factors, were studied using the Tukey test at 5% probability. The means of the response variables for the quantitative factors were studied through regression analysis, in which the models were selected based on the coefficient of determination, significance of the coefficients and analysis of the lack of fit of the model. R software (CORE TEAM, 2020) was used to perform the statistical analyses.

3 RESULTS AND DISCUSSION

To improve the efficiency of the energy harvesting system from its excitation by mechanical vibrations, we sought to characterize the system in terms of its dynamic response. Its natural frequency was determined (Equation 3.1), considering that it has 1 DOF, as shown in Figure 3.11. Subsequently, by means of a frequency scan analysis, it was determined that the natural frequency was 16.2 Hz. In this context, the frequencies evaluated were 11.4 Hz, 13.8 Hz, 16.2 Hz, 18.6 Hz and 21.0 Hz. The stages of this process are summarized in Figure 3.11.

Figure 3.11 - Steps for characterization of the dynamic behavior of the Energy harvest with 1 DOF



Source: Author.

Table 3.1 shows the results of the analysis of variance considering the factors of excitation frequencies of the system, the forms of rectification of the generated signal and associations of the PZT chips in relation to the variables voltage response (V), current (I) and power (P). The interaction between the factors excitation frequency, wave rectification system and type of association showed a significant difference in relation to the variables under study.

Table 3.1 - Results of the analysis of variance for the energy harvesting system with 1 GAL considering the factors excitation frequency (F), wave rectification system (R) andtype of association (A) for the voltage response variables (V), current (I) and power (P)

Sources of Variation	**Voltage (V)**	**Current (mA)**	**Power (mW)**
Frequency (F)	F = 341.940 p = <0.001	F = 1041.000 p = <0.001	F = 268.400 p = <0.001
Association (A)	F = 258.740 p = <0.001	F = 1105.100 p = <0.001	F = 270.200 p = <0.001
Rectification (R)	F = 11.690 p = <0.001	F = 6978.800 p = <0.001	F = 543.300 p = <0.001
F: A: R	F = 68.240 p = <0.001*	F = 474.700 p = <0.001*	F = 168.600 p = <0.001*

* Significant at 5% probability
Source: Author.

For the LTC3588 module, the highest values of voltage, current and power were obtained for the frequency of 16.2 Hz, which is the natural frequency of the system (Table 3.2). According to Rao (2009), the dynamic response in systems subjected to resonance is amplified; therefore, considering the operation of the systems in resonance conditions, a greater deformation is expected in the PZT pellets. It was observed that association A2 showed a better performance in the generation of electrical power outside the resonance frequency. The A4 association showed the best response in power generation when the system was excited at its natural frequency (Table 3.2), being twice as high in terms of power generated by the A2 association.

Table 3.2 - Mean results of the voltage (V), current (I) and power (P) response variables at the different excitation frequencies and in each type of association considering ectification by the LTC module

Rectification by LTC Module												
Frequency (Hz)	Association											
	A1			A2			A3			A4		
	V	I	P	V	I	P	V	I	P	V	I	P
11.4	0.57 b	4.56 b	2.61 b	0.85 a	6.74 a	5.72 a	1.00 a	1.18 c	1.18 c	0.64 b	4.88 b	3.18 b
13.8	0.68 b	6.64 a	4.54 b	1.03 a	6.66 a	6.87 a	1.00 a	1.22 c	1.22 c	0.64 b	4.88 b	3.18 b
16.2	1.24 c	9.46 c	11.70 c	1.57 b	12.34 b	19.35 b	1.05 c	1.18 d	1.24 d	2.09 a	20.20 a	42.35 a
18.6	0.84 c	5.12 b	4.35 b	1.28 a	7.92 a	10.13 a	1.02 b	1.20 c	1.22 c	0.66 d	5.90 b	3.86 b
21.0	0.76 c	6.52 a	4.93 b	1.18 a	6.08 a	7.27 a	1.02 b	1.20 c	1.22 c	0.51 d	4.38 b	2.25 c

*According to the Tukey test, at the significance level of 5% probability, in the row and considering the same variable, means followed by the same letter do not differ.

Source: Author.

For the rectification by the diode bridge, it was observed that, regardless of the excitation frequency, association A4 showed a higher efficiency in relation to the power generation (Table 3.3). It is important to note that the power generated from the full-wave rectification was significantly higher than the power obtained from the LTC3588 module, especially when the system operated in resonance conditions, where 731.1 mW was obtained. Yuan (2018) demonstrated that the use of the LTC3588 module may underestimate the performance of the energy harvesting system, making it unsatisfactory. However, for certain applications, the LTC3588 module may have a better performance (Heever, 2013).

From the results presented in Tables 3.2 and 3.3, it was also observed that the association of the PZTs in series (A1) showed lower yield, regardless of the signal rectification. On the other hand, association A4 presented the highest powers generated for the rectification of the signal from the diode bridge.

Table 3.3 - Mean results of the voltage (V), current (I) and power (P) response variables at the different excitation frequencies and in each type of association considering the diode bridge rectification

Full Wave Rectification (RC)												
Frequency (Hz)	**Association**											
	A1(25S)			**A2(25P)**			**A3(5S5P)**			**A4(5P5S)**		
	S(v)	**I(mV)**	**P(mW)**	**S**	**I**	**P**	**S**	**I**	**P**	**S**	**I**	**P**
11.4	0.42 c	1.06 d	0.45 d	0.69 b	29.20 b	20.03 c	0.70 b	32.00 a	22.38 b	1.12 a	24.00 c	26.88 a
13.8	0.44 c	1.08 d	0.47 d	0.69 b	30.00 b	20.75 c	0.71 b	33.00 a	23.42 b	1.17 a	26.00 c	30.52 a
16.2	0.77 c	19.18 c	14.32 c	1.34 b	99.40 b	133.11 b	0.71 c	34.00 c	24.20 c	3.13 a	233.6 a	731.1 a
18.6	0.61 d	23.20 d	14.03 d	0.88 b	49.80 b	43.96 b	0.71 c	34.00 c	24.19 c	1.26 a	78.40 a	98.79 a
21.0	0.58 d	20.20 d	11.67 d	0.78 b	41.80 b	32.72 b	0.72 c	34.00 c	24.37 c	1.19 a	48.40 a	57.41 a

*According to the Tukey test, at the significance level of 5% probability, in the row and considering the same variable, means followed by the same letter do not differ.

Source: Author.

Table 3.4 shows the models selected to describe the power generated by the vibration energy harvesting system as a function of the excitation frequency, considering the different associations between the PZT tablets and the different forms of signal rectification.

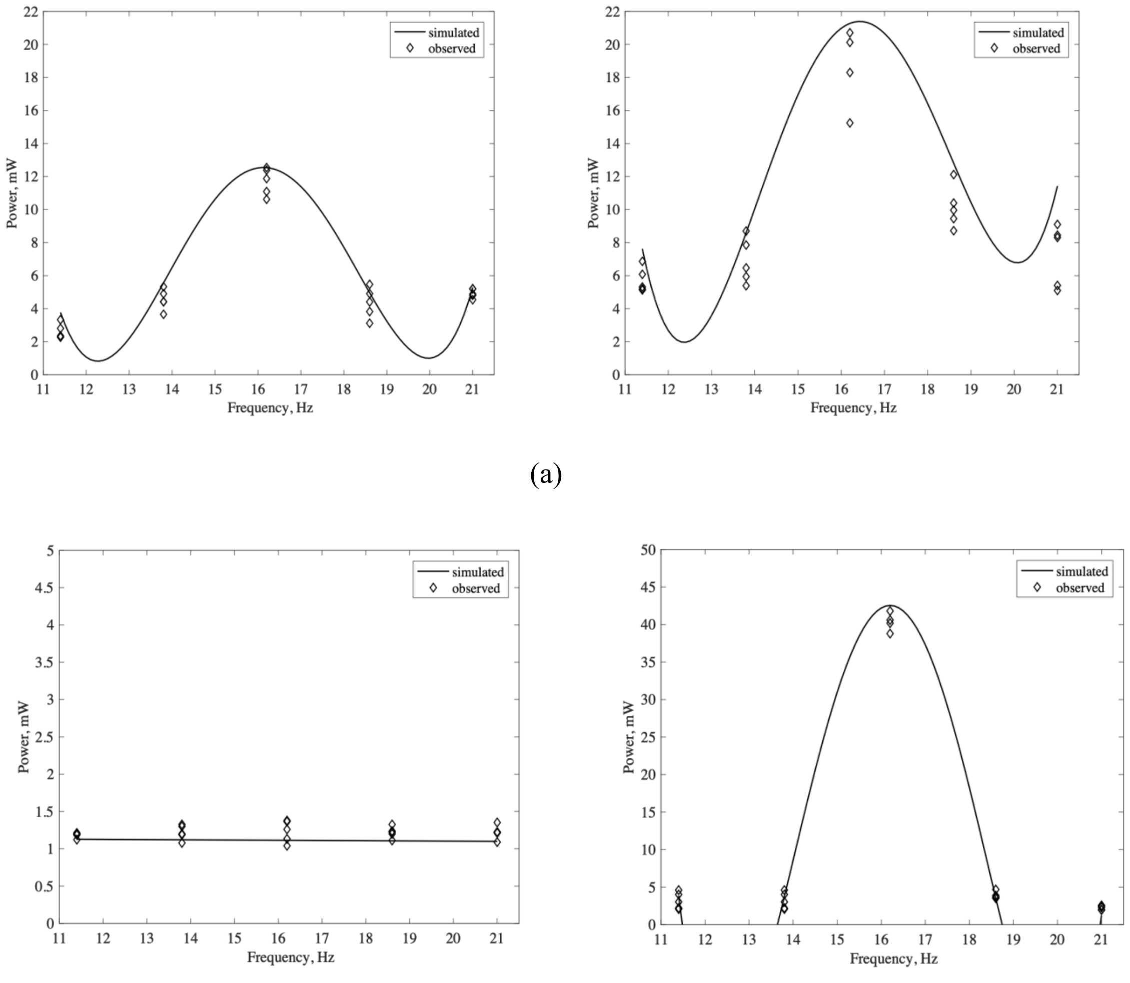
Table 3.4 - Selected models of the electrical power generated as a function of the excitation frequency considering the different types of association of the PZT pellets and the different forms of wave rectification

Association	**Rectification**	**Model**	**R^2**
A1	R1	$P = 3184 - 837.8f + 81.09f^2 - 3.418f^3 + 0.0053f^4$	0.96
	R2	$P = -16.11 + 1.50f$	0.34
A2	R1	$P = 4810 - 1252f - 119.9f^2 - 5f^3 + 0.076f^4$	0.91
	R2	$P = 46440 - 12100f + 1160f^2 - 48.43f^3 + 0.744f^4$	0.98
A3	R1	$P = 1.162 - 0.003f$	0.90
	R2	$P = 120.643 - 27.535f + 2.787f^2 - 0.120f^3 + 0.0019f^4$	0.87
A4	R1	$P = 17900 - 4680f + 449.8f^2 - 18.84f^3 + 0.290f^4$	0.98
	R2	$P = 307265 - 80248.73f + 7705.17f^2 - 322.38f^3 + 4.965f^4$	0.97

Source: Author.

Figure 3.12 shows the graphical representations of the models selected for electrical power, considering the signal rectification by the LTC3588 module. The power peaks occurred at a frequency of 16.2 Hz, under resonance conditions, except for the A3 association, which showed no significant variation (Figure 3.12c). The highest average power generated was observed for association A4 (Figure 3.12d). This result corroborates the work developed by Rangel (2014), in which a better use of the energy generated was observed in a combination of mixed PZTs, with sets in parallel and interconnected series.

Figure 3.12 - Graphical representation of the models selected for the power generated as a function of the excitation frequency and association of the PZT tablets: (a) A1 association, (b) A2 association, (c) A3 association and (d) A4 association



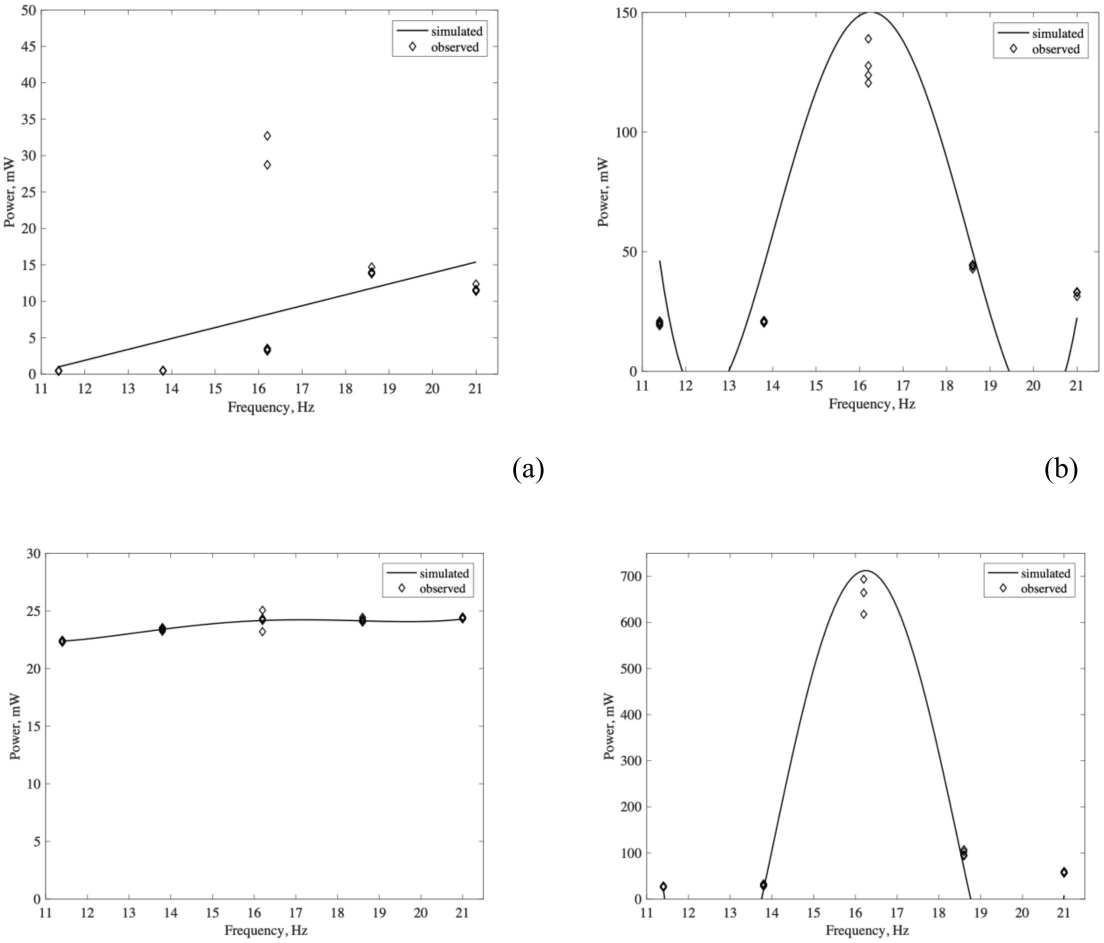
(a) (b)

(c) (d)

Source: Author.

For the rectification of the signal via diode bridge, it was observed that the associations A2 and A4 showed the highest power levels during the operation of the system, also in resonance condition (Figure 3.13). The power generated using the combination of A4 inserts is noteworthy, with the highest average generation being 731 mW (Figure 3.13d), a value significantly higher than any other configuration evaluated, even when compared to the results obtained from the rectification by the LTC3588 module. However, Heever (2013) states that for certain applications, the LTC3588 module has better performance, such as applications in nanogenerators with maximum voltage and current limits of 5 V and 1.25 μA, respectively.

Figure 3.13 - Graphical representation of the models selected for the power generated as a function of the excitation frequency and association of the PZT tablets: (a) A1 association, (b) A2 association, (c) A3 association and (d) A4 association



(a) (b)

(c) (d)

Source: Author.

It is important to highlight that these results indicate the potential of the system for energy generation, in addition to establishing that the rectification of the signal by diode bridge together with the combination of A4 pellets, can be characterized as those that presented the highest yield within the conditions in which this study was performed (Figure 3.13d).

Table 3.5 summarizes the results for the generated electrical power, considering the different types of rectification (LTC3588 module and diode bridge rectification) and the associations of the PZT pellets as a function of the excitation frequency.

Table 3.5 - Generated electrical power (mW) considering the different types of rectification (LTC3588 module and diode bridge) and the associations of the PZT pellets as a function of the excitation frequency

Treatments	**Frequencies (Hz)**				
	11.4	**13.8**	**16.2**	**18.6**	**21.0**
T1	2.61 ef	4.54 e	11.70 c	4.35 e	4.93 f
T2	5.72 d	6.87 d	19.35 c	10.13 d	7.27 e
T3	1.18 fg	1.22 fg	1.24 c	1.22 e	1.22 g
T4	3.18 e	3.18 ef	42.35 c	3.86 e	2.25 g
T5	0.45 g	0.47 g	14.32 c	14.03 d	11.67 d
T6	20.03 c	20.75 c	133.11 b	43.96 b	32.72 b
T7	22.38 b	23.42 b	19.35 c	24.19 c	24.37 c
T8	26.88 a	30.52 a	731.10 a	98.79 a	57.41 a

According to the Tukey test, at a significance level of 5% probability, means followed by the same letter in the column do not differ from each other.
We treat these with reference to the interaction between the Association (A) and Rectification (R) factors at their different levels, such that T1 = R1A1; T2 = R1A2; T3 = R1A3; T4 = R1A4; T5 = R2A1; T6 = R2A2; T7 = R2A3; and T8 = R2A4.
Source: Author.

Based on the results, it was observed that the configuration of the energy harvesting system composed of the rectification of the signal by diode bridge (R2) and the A4 association of PZT pellets (treatment T8) presented, on average, the highest powers generated regardless of the excitation frequency. However, under resonance conditions, a significantly higher result was observed, which demonstrates the potential of this configuration in the energy harvesting process. It is important to note that regardless of the treatment considered (Table 3.5), in terms of signal rectification and the combination of PZT pellets, the most promising results were obtained under resonance conditions, which is due to the amplification of the system response (Rao, 2009) and, therefore, greater deformation of the PZT pellet (TICH TM et al., 2010; MINAZARA, 2008).

It is possible to observe that the magnitudes of the powers are relatively low, which corroborates other results available in the literature (SCORNEC, 2019; GOMES, 2016). However, it is important to emphasize the potential of this type of energy harvesting system from mechanical vibrations (MOTA, 2021), especially for its use in agricultural machinery and equipment.

A configuration with a larger number of PZT pellets can result in electrical power generation responses that can be reintegrated into the system, as well as assist in the feeding of sensors (BOBY et al., 2014), commonly found in agricultural machinery, which would result in efficiency gains of the machines. Therefore, considering the nature and characteristics of the agricultural machinery and equipment used in the different current processes, combined with precision agriculture and 4.0 agriculture, there is a vast field for the development of energy harvesting systems by mechanical vibrations.

4 CONCLUSIONS

Under the conditions in which this study was conducted, it can be concluded that:

a) Regardless of the configuration used in the energy harvesting system, in terms of signal rectification and association of PZT pellets, it was observed that the highest power generated occurred with the system operating in resonance conditions;
b) The rectification of the signal from the diode bridge showed a better performance, resulting in a greater capacity of the system in the generation of electrical power;
c) The mixed combination of the pellets, with 5 sets of 5 PZTs in parallel and these sets connected in series to each other, resulted in the highest powers generated, mainly under resonance conditions;
d) The configuration consisting of the signal rectification by diode bridge together with the mixed association of PZT chips (with 5 sets of 5 PZTs in parallel and these sets connected in series to each other) was promising for the development of harvesting of energy by mechanical vibrations to be used in agricultural machinery and equipment.

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