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A REVIEW OF POWER HARVESTING FROM WIND TURBINES USING PIEZOELECTRIC TRANSDUCERS (2005 - 2019)

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Abstract. *The need to obtain electric energy through renewable sources, accompanied by the growing advances in technology and the development of electrical and electronic devices, has enabled the creation of new ways of extracting energy from the environment, especially for low power devices. Among the most promising methods is the Power Harvesting, using piezoelectric transducers, which when coupled to a system, can be triggered by mechanical vibration, electromagnetic devices, wind energy, etc. This work aims to gather and describe the most relevant works available in the literature on wind turbine devices using associated piezoelectric elements, during the period from 2005 to 2019. Compared mainly, its dimensions, forms of energy extraction, piezoelectric material used, maximum electric power generated, and the power density obtained by each one. By showing that for systems that require low power to operate, such as remote sensors, these devices are capable of being applied efficiently and sustainably, contributing to the available energy matrix. Although prototypes capable of generating considerable powers are also presented in comparison with similar devices.*

Keywords: *Renewable Sources, Low Power, Power Harvesting, Wind Turbine, Piezoelectric Transducer.*

1. INTRODUCTION

In recent years, several papers and scientific articles have been published, many of them describing techniques and devices capable of transforming the energy of the environment into available energy, mainly for the extraction of vibration energy using piezoelectric transducers like the works of Priya and Inman (2009), Elvin and Erturk (2013), Kaźmierski and Beeby (2011), Erturk and Inman (2011), Spies, Mateu and Beeby. (2013). Although kinetic energy is the most used, it is possible to obtain energy from other sources such as solar, thermal, through radio frequency (RF) transmitters, electromagnetic sources, among others (Di Paolo, 2017). With the recent advances in Energy Harvest research and mainly due to the reduction of the amount of energy consumed by some electronic devices, piezoelectric materials have gained space in the most diverse applications of daily life. One of the ways of obtaining energy that competes directly with piezoelectrics is the methods that use electromagnetic devices. Heywang, Lubitz, and Wersing (2008) summarize the main advantages of piezoelectric devices over electromagnetic (EM) devices. As the greatest possibility of miniaturization; there is no generation of electromagnetic noise; and piezoelectric devices are not flammable.

Khan (2016) also made comparisons of some of the scientific articles published in the literature and verified the power developed by these devices using electromagnetic, electrostatic and piezoelectric sources as a function of the size of the device. The data presented by Khan (2016) in Fig 1 show that piezoelectric materials are more efficient for generating electrical power when the devices are built on smaller scales.

2. PIEZOELECTRIC WIND TURBINES

2.1 Low Power

Focusing on devices that convert wind energy from the environment and transform it into electrical energy through the piezoelectric, several promising researches are being carried out, such as the work of Myers *et al.* (2007), which suggests the creation of a small-scale wind turbine. The structure of the wind turbine is made of ABS polymer, which uses 18 individual bimorphs (60 x 20 x 0.6 mm³) piezoelectric (APC 855) with a free length of 53 mm, having a capacitance of 170 nF and a natural frequency of 65 Hz in the free condition. The speed range of wind interest is 1.341

to 4.471 m/s, which promotes a continuous rectified power of 5 mW, with an optimum electrical resistance found in the order of 20 kΩ.

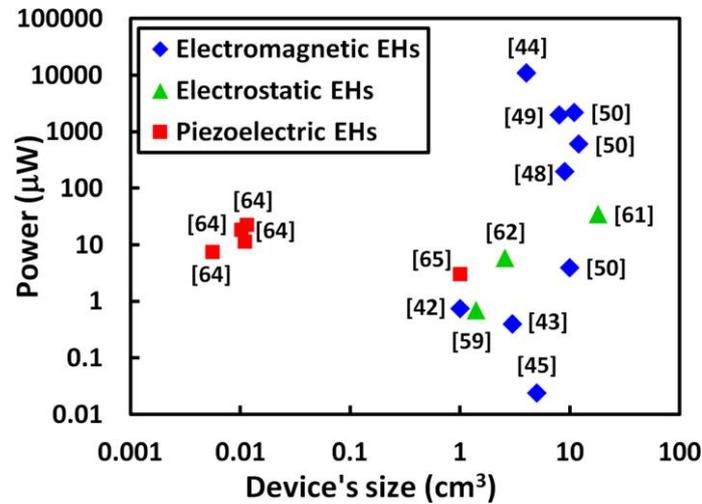


Figure 1. Comparison between different ways of obtaining electrical power as a function of device dimensions.

Tien and Goo (2010) aims to present an initial analysis on a prototype of a small-scale wind turbine that uses composite piezoelectric as a generator element of electric energy for use in urban areas. In its application, it works as a secondary vibration element of beams ($72 \times 14 \times 0.47 \text{ mm}^3$), which is excited at its natural frequency by the protrusions trapped inside the rotor, driven by the blades of the wind turbine. The first resonance frequency of the structure was calculated at 9 Hz and the wind speed range used for the experiments was 0 to 5 m/s. The electric charge generated was used to supply a 3.6 V battery with a capacity of 40 mAh. The input frequency of the generator was 9.4 Hz, producing a maximum voltage of 26 V, with an electric resistance of 80 kΩ, which resulted in a maximum power of 8.5 mW.

Luong and Goo (2012) continued the work carried out by Tien and Goo (2010), adding a magnetic exciter in the form of permanent magnets, maintaining the same structure and dimensions. Another contribution was the study of the performance of the device during the charging of a nickel hydride (NiMH) battery. In this new configuration a maximum power of 2 mW was obtained, with a distance between the magnets of 6 mm and a wind speed of 2.7 m/s. The optimal electrical resistance for this power was 100 kΩ at a voltage of 14 V with a frequency of 15 Hz. For tests using battery, the charge time for a 40 mAh battery was approximately 3 h for applications in using natural ventilation of the environment.

Khameneifar, Arzanpour and Moallem (2013) performed the analysis and design of a device for collecting energy based on the vibrations caused by the rotation of a propeller. The converter consists of a beam having a free end mass and a piezoelectric element coupled along the length of the beam, which is mounted on a rotating support. For comparison, two types of piezoelectric materials were used: Vinylidene Polyfluoride (PVDF) and Lead Titanium Zirconate (PZT). The PVDF has dimensions of $73 \times 16 \times 0.2 \text{ mm}^3$ and the beam to which it is glued has dimensions of $73 \times 16 \times 0.7 \text{ mm}^3$, while for the PZT, the dimensions are $50.8 \times 38.1 \times 0.13 \text{ mm}^3$ and the substructure has $50.8 \times 38.1 \times 0.5 \text{ mm}^3$. To adjust the natural frequency of the structure, a mass was used at the end of the beam of 48 and 65 g for PZT and PVDF, respectively. In order to compare the power generated by the two piezoelectric types, a mass of 105 g was placed in its free end. The results indicated that for this mass value, a maximum power of 6.4 mW was obtained for PZT with an electric resistance of 40 kΩ and 147 μW with an electrical resistance of 600 kΩ for PVDF. Both used an axis rotation speed of approximately 22 Hz.

Rezaei-Hosseiniabadi *et al.* (2015) presented two different topologies for a low power piezoelectric wind turbine, one with perpendicular wind flow and the other with wind flow parallel to the blades. The proposed topologies consist of a small rotor with blades, having permanent magnets (PMs) embedded and a piezoelectric beam with magnets (PM), which aims to excite the structure. The wind turbine model chosen was that of air flow parallel to the rotor axis due to its efficiency, where the piezoelectric material used in the beam was the PVDF. Finally, beam dimensions were stipulated at $31.8 \times 12.7 \times 0.508 \text{ mm}^3$ with a free length of 28.6 mm, and a resonance frequency of 146.5 Hz. Test results showed that the maximum power generated was 363 μW with an electric voltage of 3.8 V in a speed range ranging from 1.5 m/s to 20 m/s for an effective mass of 1.505 g.

Following this same concept, Rezaei-Hosseiniabadi, Tabesh and Dehghani (2016) developed another work that presents a new wind turbine topology, as well as a project optimization method to obtain the maximum available energy in the environment. The device includes a piezoelectric beam that oscillates due to its interaction with the permanent magnets (PMs) embedded in a small turbine and a magnet at the free end of the beam. The authors further showed that adding nonlinearities to the system was able to improve generator performance. A 7-blade generator was used, having

an internal radius of 15.6 mm and an external radius of 30.7 mm. The piezoelectric is bimorph type (Q220-A4-303YB) and the beam has the following dimensions, 31.8 x 12.7 x 0.508 mm³ with a mass (magnet) at its free end of 2.4 g for the adjustment of natural frequency of the system. In this test, the resistive load used was R = 33 kΩ. The maximum power density, maximum efficiency and wind shear rate are 0.59 mW/cm³, 24 % and 2.1 m/s, respectively. Considering the dimensions of the beam (generator) as parameter, we will have a maximum power obtained of 121,045 μW.

The work done by Bressers *et al.* (2010) suggests the design of a small-scale wind turbine using piezoelectric bimorphs that uses the forces generated by magnets to create mechanical oscillations in the structure. The prototype consists of a Vertical Axis Wind Turbine (VAWT) with a series of magnets mounted on the axis of rotation of the generator. The prototype assembly consists of six piezoelectric elements mounted in a swing beam configuration. The piezoelectric beams have dimensions of 60 x 20 x 0.60 mm³, with a free length of 53 mm, a resonance frequency of 65 Hz and a capacitance of 170 nF. In terms of developed power, the generator with two blades and four magnets overhung the other configurations, reaching a maximum generated power of approximately 1.2 mW at a wind speed of 4.02 m/s.

Chen, Islam, and Priya (2006) carried out a study that reports the development of a mechanism to convert wind energy into electricity using small-scale bimorph piezoelectric transducers. The total dimensions of the piezoelectric generator are 50.8 x 116 x 77 mm³. The dimensions of each piezoelectric beam are 60 x 20 x 0.6 mm³ with a free length of 55 mm. The resonance frequency and capacitance for this beam dimension is 65 Hz and 170 nF, respectively. The prototype was able to generate a maximum power of 1.2 mW at a wind speed of 5.36 m/s for a resistive load of 1.7 kΩ, with an excitation frequency of approximately 12 Hz.

Kan *et al.* (2016) developed a piezoelectric wind turbine excited by rotating magnets to extract energy from low speed winds. As shown in Fig. 2, the presented generator consists of piezoelectric transducers bonded to cantilever beams, excited by magnets embedded in a rotating disk, which composes the tubular structure of the generator together with the blades of the rotor. Its main objective was to study the influence of the number of magnets on the generated waveform and the performance of the piezoelectric beams. The piezoelectric beams measure 40 x 40 x 0.5 mm³ with a capacitance of 90 nF and an estimated damping factor of 0.02. The frequency range used was 0 - 50 Hz with a step of 0.25 Hz. The authors have shown that the number of magnets and response amplitudes depend on the number of magnets used and rotation speeds, this indicates that if many magnets are used, the results are likely to show that the response amplitudes decrease with increase the speed of rotation. The maximum variation in measured electrical voltage was 16.4 V to 37.2 V, while the maximum energy ranged from 0.16 mJ for a wind speed of 11.7 m/s to 2.24 mJ for 5, 9 m/s, respectively.

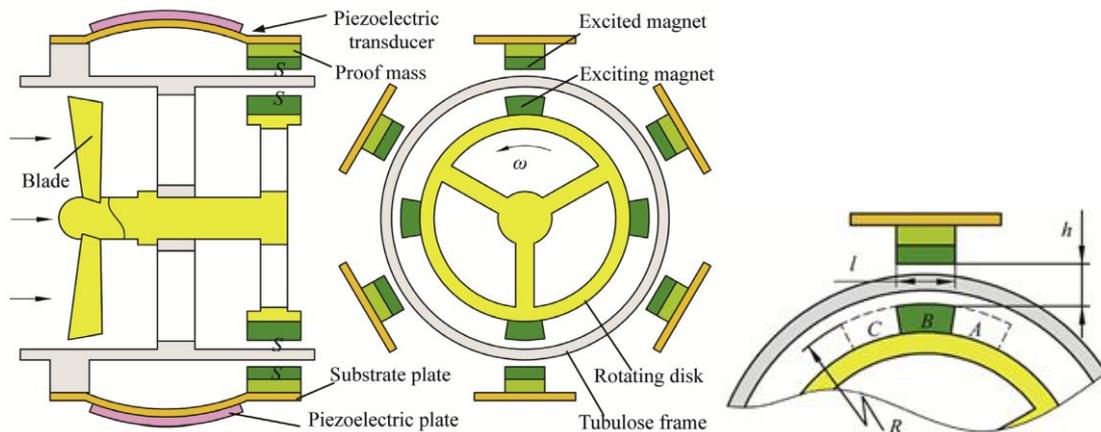


Figure 2. Structure and working principle of the piezoelectric wind turbine.

Bai *et al.* (2016) proposed the creation of a piezoelectric generator made of PVDF. The geometry that presented the best efficiency was to the triangular beam with 0.1 mm of thickness and the PVDF with the same dimensions, but with 0,05 mm of thickness. Under optimal impedance conditions and overlapping of the beams, the sum of the output power of the AC signals from the four beams separately was 0.75 mW, measured at a wind speed of 7 m/s. In the case of the use of a full wave rectification using two beams connected in parallel, an output power of the DC signals of 0.27 mW was obtained at a wind speed of 7 m/s. The optimum electrical resistance found was about 200 kΩ for each beam. The wind turbine and experimental setup are shown in Fig 3.

Priya *et al.* (2005) developed a study on a piezoelectric generator to obtain electricity through wind energy. The proposed generator was developed using 12 piezoelectric elements of the type APC855 bimorph with dimensions 60 x 20 x 0.5 mm³ and a free length of 53 mm, subject to a preload of 23.5 g. The resonance frequency and capacitance for a piezoelectric transducer of these dimensions was 65 Hz and 170 nF, respectively. Under an applied torque level corresponding to the normal wind flow with an oscillating frequency of 6 Hz, a maximum rated power of 10.2 mW was obtained for all the beams through a resistive load of 4.6 kΩ after rectifying the signal.

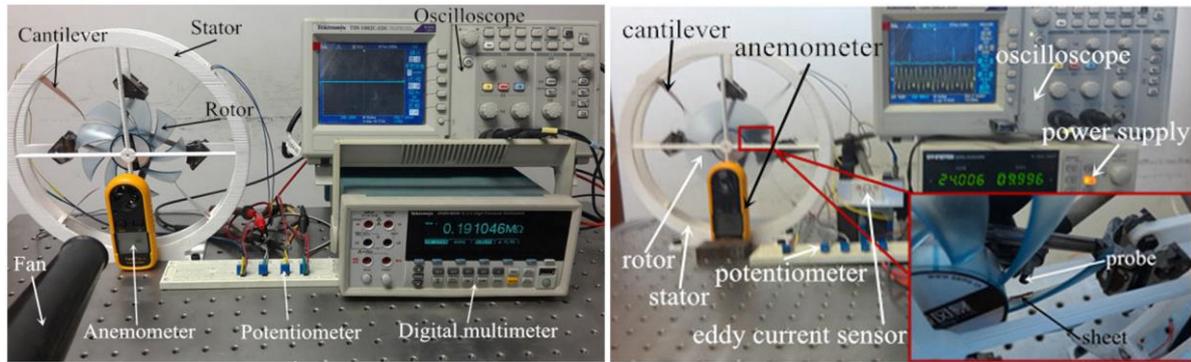


Figure 3. Experimental setup used.

A prototype proposed by Zhang *et al.* (2017) establishes a way of obtaining electric energy through wind energy using piezoelectric transducers (PVDF) using a rotational device. The generator basically consists of three beams set at one end and free at the other, with dimensions of approximately $41.5 \times 16.3 \times 0.2 \text{ mm}^3$ each, where the propeller blades rotate the shaft deforms the piezoelectric beams, generating electricity. In this case, the values of RMS maximum electrical voltage of 160.2 V and maximum electrical output power of 2.566 mW were obtained at a wind speed of 14 m/s with the use of three crimped beams.

Feng and Zhou (2017) designed and developed a prototype of an electric power generator using wind power, based on a conversion mechanism using two MFC (Macro Fiber Composite) crimped beams driven through their interaction with permanent magnets, producing vibration. The prototype has an approximate size of $110 \times 110 \times 190 \text{ mm}^3$, the MFC type piezoelectric ones have $37 \times 18 \times 0.3 \text{ mm}^3$ and the beams used have $100 \times 18 \times 0.4 \text{ mm}^3$ each, with a natural frequency of approximately 14 Hz . Although there was a divergence between the numerical and experimental results, the total electric power generated by the device was $1.38 \mu\text{W}$, with a voltage of 1.9 V at a rotation of 6 Hz . The prototype suggested by the authors is shown in Fig. 4.

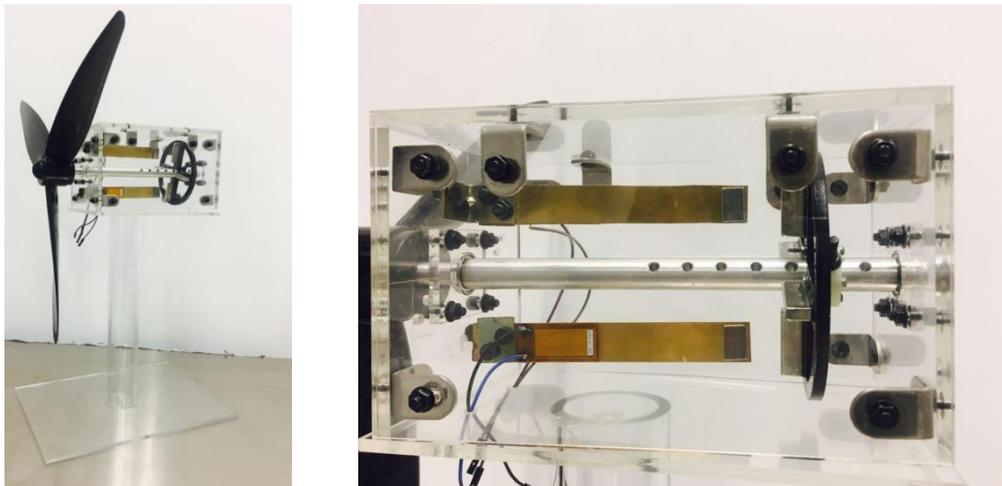


Figure 4. Wind turbine developed and its operating mechanism, showing the beams, piezoelectric and permanent magnets.

Kurt *et al.* (2017) developed and built a power converter using three rectangular bar ($41.3 \times 4.7 \times 1.5 \text{ mm}^3$) piezoelectric devices having different masses at their ends, i.e. with different resonance frequencies. These masses were selected as permanent magnets, positioned at an angular distance of 120° from each other. The maximum measured power of the generator for low wind speeds (1.75 m/s) was of the order of $0.2 \mu\text{W}$, for the closed circuit. The maximum power obtained directly at the piezoelectric terminals was approximately $3.8 \mu\text{W}$. The tests were performed for resistive loads of $1 \text{ M}\Omega$ and $100 \text{ k}\Omega$ for various wind speeds (1.6 to 3.2 m/s). The power generated by the resistive loads was stored in capacitors, after the proper rectification and conversion of the signal generated.

Kishore, Vuckovic and Priya (2014) developed a 72 mm diameter horizontal axis wind turbine prototype with a rotor with 12 equally distributed permanent magnets. Parallel to this rotor shaft were bimorph crimped piezoelectric beams with dimensions of $60 \times 20 \times 0.7 \text{ mm}^3$, with permanent magnets glued to their free end, as shown in Fig. 5. The prototype has dimensions of $100 \times 80 \times 65 \text{ mm}^3$ than in the case studied, only one piezoelectric beam was used as

energy conversion element. The maximum produced electrical power of $450 \mu W$ at a wind speed of $1,9 \text{ m/s}$ with a load of $9 \text{ k}\Omega$.

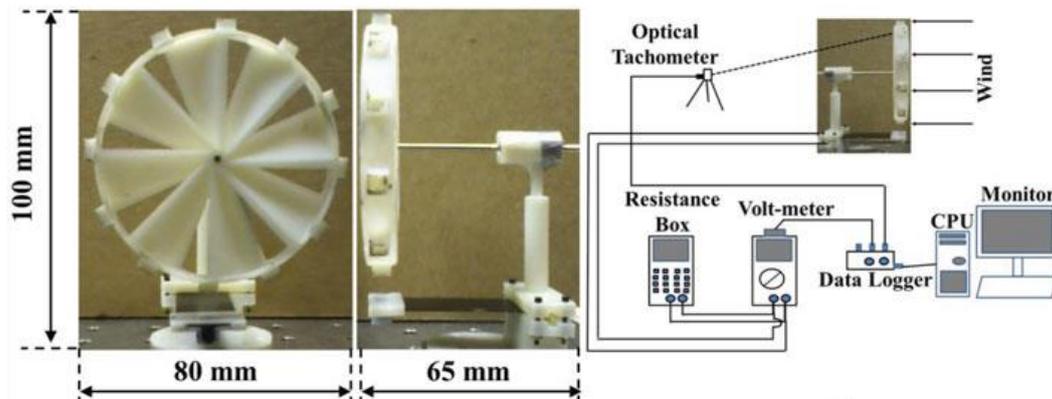


Figure 5. Wind turbine developed with its respective dimensions and experimental apparatus used in the tests.

Karami, Farmer and Inman (2012), created the prototype of a compact rotational generator using bimorph type piezoelectric transducers of nonlinear form for low wind speeds with permanent magnets at their end. The generators proposed in their tangential and radial configuration have approximate dimensions of $80 \times 80 \times 175 \text{ mm}^3$ and $75 \times 75 \times 165 \text{ mm}^3$, respectively. The devices can contain up to four bimorph piezoelectric beams simultaneously, with dimensions of $50 \times 12.7 \times 0.38 \text{ mm}^3$. For the tangential configuration indicated above, the resonance frequency of each of the beams of 16.71 Hz with a resistive load of $247 \text{ k}\Omega$ was obtained, capable of generating a maximum power in the order of 5 mW for a speed of rotation of 2 Hz with a distance between magnets of 25 mm .

Yang *et al.* (2018.a) presented an analytical and experimental piezoelectric wind turbine. The structure of the system consists of a propeller, a rotating shaft with permanent magnets attached to it and a set of stainless steel beams with piezoelectric glued on its surface, having dimensions of $38 \times 78.5 \times 0.2 \text{ mm}^3$ and $35 \times 45 \times 0.16 \text{ mm}^3$ for the beam and the piezoelectric, respectively. As in the shaft, the beam also has a permanent magnet at its free end with 13 g of mass, responsible for deforming the beam. The value of the first fundamental frequency of the system obtained analytically was 10.25 Hz . Thus, the angular speed of the rotor that obtained the best response was 650 RPM (10.50 Hz), corresponding to a wind speed of 1.94 m/s . In this configuration, the maximum electric power obtained was 3.14 mW with a distance between magnets of 20 mm . The system is presented in the Fig. 6.

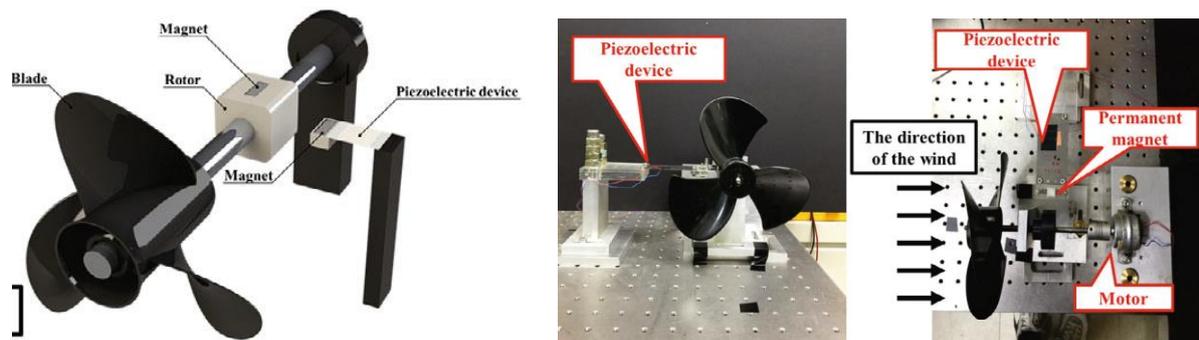


Figure 6. Schematic view of generator and experimental bench used.

The work developed by Wu and Xu (2018) proposes the development; optimization and testing of a device composed by a rotational piezoelectric transducer responsible for converting wind energy, with general dimensions of $100 \times 100 \times 65 \text{ mm}^3$. We used only a piezoelectric transducer (PZT) coupled to a base structure made of aluminum, where the excitation of the system is performed permanent magnets. With the intention of increasing the input power, the proposed generator is composed of a force amplification mechanism, responsible for transforming an input of 50 N into an output of 729.13 N . With a distance between 10 mm magnets, having a volume of 1162.32 mm^3 each, it was possible to obtain an average output power of 0.15 mW at a rotation of 100 RPM while a resistive load of $2 \text{ k}\Omega$ is connected to the system.

Bouzelata *et al.* (2018) have suggested the design and implementation of a piezoelectric wind energy harvesting (PWEH), focusing on the efficient conversion of AC to DC. The generator has three piezoelectric blades ($41.3 \times 4.7 \times 1.5 \text{ mm}^3$) placed at an angular distance of 120° from each other, with lengths of 11 cm , 12.2 cm and 14.8 cm , having a

natural frequency of 9 Hz, 11 Hz and 13 Hz, respectively. Permanent magnets were also attached at its end, which with the rotation of the shaft, causes the piezoelectric beams to be excited harmonically. The average voltage at the output of the rectifier was 40 V_{DC}, which after passing through the converter was reduced to 12 V_{DC}, operating at a speed ranging from 1.5 m/s to 8 m/s. The maximum power obtained from the sum of the three piezoelectrics was approximately 0.15 mW, equivalent to a frequency of 12 Hz with a resistive electric load of 350 kΩ at a wind speed of more than 4 m/s.

In Zhao *et al.* (2019), the authors proposed a wind powered hybrid electric power generator (WP-HWH) using magnetic devices and mechanisms for power amplification, through piezoelectric and electromagnetic transducers. The excitation of the system is carried out by four permanent magnets evenly distributed and glued to the end of the rotating arm which are connected to the axis and which in turn is driven by the force of the winds. The piezoelectric transducer (PZT-5H) has the dimensions of 40 x 10 x 1 mm³, while the base metal to which the piezoelectric is bonded has the dimensions of 40 x 10 x 0.25 mm³. As a result, it was concluded that the use of WP-HWH under rainfall conditions can generate an RMS power of 3.1577 mW with an electric resistance of 300 kΩ for the piezo and 400 kΩ for the electromagnetic generator at a speed of wind of 7.0 m/s.

Yang *et al.* (2018.b) carried out a deep research about electric energy converters using piezoelectric, identifying the main works published in the literature in recent years. Although it is not an exclusive work of wind-driven piezoelectric generators (wind turbines), it is recommended to consult them, due to the number of relevant devices and applications presented.

2.2 Medium Power

The next two prototypes to be presented differ from the other devices studied in this work, both in relation to their dimensions and in relation to the generated electrical powers; however, these works are part of the literature and due to their constructive relevance will also be presented here.

Viet *et al.* (2017) have suggested a generator that consists of drive blades connected to a rotor and a stator, secured by eight piezoelectric energy conversion devices associated with a system consisting of spring, piston and cylinder. The system is a device that operates basically through an impact-type excitation, with the generator receptacle diameter of 1 m, connected to three drive blades of length *L*. The piezoelectric bar-type has dimensions of 100 x 20 x 20 mm³. The selected rotational speed is in the range of 0 to 180 rad/s or approximately 28.65 Hz. The maximum power obtained for a wind speed of 3.5 m/s, with a blade length of 7.5 m, a rotation of 0.48 Hz and a spring constant 365 kN/m was approximately 5000 W.

Tao *et al.* (2017) have suggested the development of a system that works by converting kinetic energy from the winds in rotation of an axis. A relatively high RMS electrical power can be obtained in the 150 W band by the piezoelectric wind turbine. With the blade radius of the device measuring 1 m, a wind speed of 7.2 m/s, a spring stiffness of 40 kN/m and a developed angular speed of 7.96 Hz. The piezoelectric in the form of a rod have dimensions approximately 15 x 15 x 15 mm³ while its substructure has dimensions of 25 x 25 x 100 mm³. The device is shown in Fig. 7.

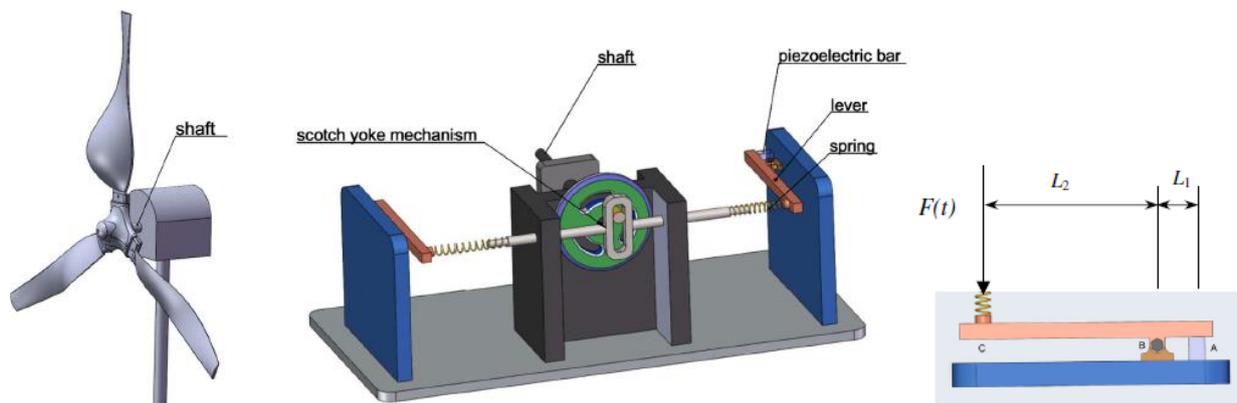


Figure 7. Schematic diagram of the device, its main parts and its drive mechanism.

2.3 Innovations in the Area

There are few studies in the literature using piezoelectric aerogenerators that approach devices developed in an innovative way, that is, different from those presented previously. However, the work of McCloskey, Mosher and Henderson (2017) deserves attention. The authors proposed as an alternative option the induction-based turbines, artificial plants containing piezoelectric elements, as in Fig. 8. They measured the power conversion capacity of the device, which was less than 10 W, although they have stated that trees of the same type, but of larger proportions, could

generate approximately 80 W through the movement of the leaves. Finally, they concluded that piezoelectric materials are unable to convert enough energy from devices with such dimensions, although other piezoelectric types can be more efficient.

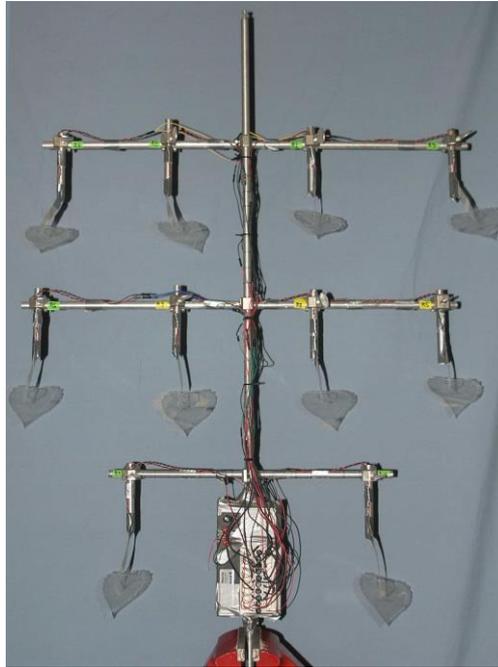


Figure 8. Piezoelectric artificial plant made of plastic and aluminum.

Another interesting way to obtain electric power using piezoelectric transducers and wind force is the concept called *Windstalk*, suggested by the New York-based architecture company called Atelier DNA (2010). The concept consists of the installation of 1203 resin posts reinforced with carbon fiber, measuring about 55 m high each device, anchored in the ground through concrete bases with a diameter ranging from 10 to 20 m, as shown in Fig. 9. The posts are 30 cm in diameter near the base and decrease with the height, like a cone trunk, reaching 5 cm in diameter at its top, where most piezoelectric plates in the form of ceramic discs were positioned. Among the disks, we have the electrodes that are connected to the power transmission cables that run the entire length of the structure. Unfortunately, the electrical power and voltage data generated were not disclosed.



Figure 9. Windstalk concept for electricity generation using piezoelectric.

3. RESULTS

In order to facilitate the comparison and exposure of the results regarding the devices studied, Table 1 was created, which shows the generators suggested by the authors, their approximate dimensions, the maximum electric power developed and the generated load density.

Table 1 – Comparative table of the studied devices.

Author	Dimensions Approx. (mm ³)	Generated Power	Generated Power Density
Priya <i>et al.</i> (2005)	60.00 x 20.00 x 0,5.00 ²	10.200 mW	17.0000 μW/mm ³
Chen, Islam e Priya (2006)	50.80 x 116.00 x 77.00 ¹	1.200 mW	0.0026 μW/mm ³
Myers <i>et al.</i> (2007)	76.20 x 101.60 x 127.00 ¹	5.000 mW	0.0051 μW/mm ³
Bressers <i>et al.</i> (2010)	60.00 x 20.00 x 0.60 ²	1.200 mW	1.6667 μW/mm ³
Tien e Goo (2010)	72.00 x 14.00 x 0.47 ²	8.500 mW	17.9416 μW/mm ³
Karami, Farmer e Inman (2012)	80.00 x 80.00 x 175.00 ¹	5.000 mW	0.0045 μW/mm ³
Luong e Goo (2012)	72.00 x 14.00 x 0.47 ²	2.000 mW	4.2215 μW/mm ³
Khameneifar, Arzanpour e Moallem (2013)	73.00 x 16.00 x 0.70 ² (PVDF) 50.80 x 38.10 x 0.50 ² (PZT)	0.147 mW 6.400 mW	0.1798 μW/mm ³ 6.6133 μW/mm ³
Kishore, Vuckovic e Priya (2014)	100.00 x 80.00 x 65.00 ¹	0.450 mW	0.0009 μW/mm ³
Rezaei-Hosseinabadi <i>et al.</i> (2015)	31.80 x 12.70 x 0.51 ²	0.363 mW	1.7693 μW/mm ³
Rezaei-Hosseinabadi, Tabesh e Dehghani (2016)	31.80 x 12.70 x 0.51 ²	0.121 mW	0.5898 μW/mm ³
Kan <i>et al.</i> (2016)	40.00 x 40.00 x 0.50 ²	2.240 mJ ⁴	2.8000 μJ/mm ³
Bai <i>et al.</i> (2016)	20.00 x 60.00 x 0.10 ^{2 3} 20.00 x 15.00 x 0.10 ²	0.750 mW	8.3333 μW/mm ³
Zhang <i>et al.</i> (2017)	41.50 x 16.30 x 0.20 ²	2.566 mW	0.0189 μW/mm ³
Feng e Zhou (2017)	100.00 x 18.00 x 0.40 ²	1.380 μW	0.0019 μW/mm ³
Kurt <i>et al.</i> (2017)	41.30 x 4.70 x 1.50 ²	3.800 μW	0.0131 μW/mm ³
Viet <i>et al.</i> (2017)	100.00 x 20.00 x 20.00 ⁵	5.000 kW	125.0000 W/mm ³
Tao <i>et al.</i> (2017)	15.00 x 15.00 x 15.00 ⁵	0.150 kW	0.0444 W/mm ³
McCloskey, Mosher e Henderson (2017)	-	0.010 kW	-
Yang <i>et al.</i> (2018.a)	35.00 x 45.00 x 0.16 ⁵	3.140 mW	12.4600 μW/mm ³
Wu e Xu (2018)	100.00 x 100.00 x 65.00 ¹	0.150 mW	0.0002 μW/mm ³
Bouzelata <i>et al.</i> (2018)	41.30 x 4.70 x 1.50 ⁵	0.150 mW	0.5152 μW/mm ³
Zhao <i>et al.</i> (2019)	40.00 x 10.00 x 1.00 ^{5 6}	3.158 mW	7.8950 μW/mm ³

¹Overall dimensions of the generator. ²Partial dimensions of the generator (beam). ³The beam that composes the system had the triangular shape, being 20 mm its greater base. ⁴Only values were supplied according to the work generated, and it is not possible to determine the electric power developed due to the lack of information. ⁵These values refer to the piezoelectric element. ⁶Hybrid generator: piezoelectric and electromagnetic.

4. CONCLUSIONS

It has been found that energy conversion devices using piezoelectric wind-driven transducers are still scarce in the literature, although most of them have satisfactory generation potential for applications involving low electrical powers involved. Enough arguments were presented to demonstrate the importance and applicability of piezoelectric aerogenerators - comparing them to their main electromagnetic competitors, having their main advantage in the size of the devices, as well as a high-power density. Thus, we can conclude from the literature that, in addition to be an in-depth subject with great potential, most of the piezoelectric wind turbines described here are not capable of generating electrical powers greater than 1 W, maintaining portability and objective which limits the large-scale commercial application of this type of system. Although many studies and research have been carried out in the area of energy conversion during the last decades, there is still a considerable distance between the design of the studied system and its relevant practical applications (Zhao *et al.*, 2019). Another barrier encountered is the low innovation presented by the authors for new devices in relation to the mechanisms of power extraction. However, the apparent possibility of obtaining devices capable of developing enough power to power small electronic circuits autonomously and using completely clean and renewable energy makes this an attractive field of research.

5. ACKNOWLEDGEMENTS

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