Piezoelectric Assisted Vertical Axis Wind Turbines

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Abstract

Wind power is typically exemplified by large horizontal axis wind turbines (HAWT) that can take up acres of space, yet for most densely populated urban areas, these turbines are not practical. Vertical axis wind turbines (VAWT) have long been overshadowed by traditional HAWT; however, VAWT are much more compact, and it has been shown that an array of VAWT has a much larger energy density per square kilometer than that of HAWT. Yet in low wind conditions, VAWT are unable to create a substantial amount of energy. This issue can be addressed with the use of piezoelectric ceramics. These ceramics can convert the energy harvested from vibrations into usable electrical energy. After embedding piezoelectric ceramics in the blades of VAWT, the energy output of the turbine can then be measured and compared to that of a non-piezoelectric assisted VAWT. This comparison will determine if the implementation of piezoelectric ceramics is an effective solution to the mechanical limitations of VAWT. If the piezoelectric assisted vertical axis wind turbine is found to produce more energy than the non-piezoelectric assisted vertical axis wind turbine, the implementation of piezoelectric ceramics could prove to be a feasible solution for densely populated environments.

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Introduction

With the imminent threat of global warming, the world must turn towards alternate methods of energy production in order to reduce harmful greenhouse gases. Wind turbines are one of the most popular commercially available sources of renewable energy production. However, typical wind turbines, known as horizontal axis wind turbines (HAWT), are incredibly large and almost impossible to implement in a densely populated urban area. Therefore, we must turn to another type of wind turbine, known as a vertical axis wind turbine (VAWT), for wind power in these urban areas. We can further the impact of these turbines by embedding piezoelectric ceramics in the blades of the turbine. These ceramics are able to convert vibrations from the wind into usable electrical energy, increasing the overall power output of the turbine. With these new turbines, wind power can be a more feasible renewable energy option for urban areas.

Literature Review

Piezoelectricity was first discovered in the late 1800s by Jacque and Pierre Curie, the brothers found that when a crystal was deformed it produced a although the discovery was celebrated, the study of piezoelectricity was not pursued until later in the 20th century.[1, 2] Later in the 1900s, piezoelectric research took off and it has been gaining speed since. Piezoelectric are materials that are able to convert mechanical stress into usable energy, the reverse process is also possible, converting electrical energy into mechanical energy.[3, 4] The piezoelectric effect is when the crystalline structure of a material deforms, causing a dipole which can concert the applied

mechanical energy into electrical energy.[5] The various piezoelectric materials are characterized by specific piezoelectric constants, which describe the individual characteristics of each material.[6, 7] Piezoelectric materials are commonly found in industrial settings, however the usability of piezoelectric is constantly improving, pushing piezoelectric into more common settings.[8]

Piezoelectric efficiency is a widely studied topic. Research has shown that the energy output from piezoelectric materials depends on a plethora of factors, including temperature and material specific piezoelectric constants.[9, 10] These piezoelectric constants dictate how much energy is able to be harvested from a piezoelectric material, as well as how much stress the specific material can tolerate before breaking.[11, 12] The most effective method for maximizing energy output from vibrations is using the resonance frequency of the piezoelectric.[13, 14] These factors can maximize the electrical energy harvested from mechanical energy, and they can also maximize the mechanical energy that can be harvested from applying a voltage to the piezoelectric.[15, 16]

Recent research has focused mainly on the makeup of piezoelectric materials. Most commercially available piezoelectric materials contain a structure called lead zirconate titanate, also called PZT.[17] However, PZT is dangerous to inhale, therefore, research is now being focused on finding a lead-free alternative for PZT.[18, 19] The success of this research has opened a plethora of doors for piezoelectricity, discovering safer and more efficient materials.[20, 21] One of these materials is a polymer containing zinc-oxide, a less toxic material, but still semi-dangerous.[22, 23] The most promising topic is the creation of 3D printed piezoelectric materials, allowing researchers to design their own materials, controlling the size and shape of the piezoelectric.[24, 25] With this material research, there is also research focused on recycling

piezoelectric materials, and how to keep this renewable energy method carbon neutral.[26] With these new types of piezoelectric materials, there are also new application methods for piezoelectric materials, the most notable being the creation of a wearable piezoelectric, which uses the body movement to create energy.[27, 28] These thin piezoelectric materials open a new area of research on piezoelectric polymers.[29, 30]

Piezoelectric materials continue to be implemented in a multitude of items. Any item that can be stressed, deformed, or compressed can be used with piezoelectric materials. In Los Angeles, researchers are investigating the possibilities of a piezoelectric road, where the cars driving will compress piezoelectrics in the road to create energy.[31] Piezoelectrics can also be added to even simpler objects, such as a chin strap, which can create energy when the wearer is chewing.[32] Touch screen cell phones are also being investigated for piezoelectric applications.[33] In the medical world piezoelectric materials are used every day in imaging machines.[34, 35] These machines are used so frequently, researchers have begun to 3D print the necessary piezoelectrics.[36] Expanding on the use for imaging purposes, researchers have begun investigating applications for piezoelectrics in other medical capacities, most recently they have been used in catheters as pressure sensors.[37] The many uses and applications of piezoelectrics are constantly growing with new research.

Vertical axis wind turbines (VAWTs) have commonly been overlooked due to the success of the horizontal axis wind turbine (HAWT), however with recent improvements, the VAWT is catching up to its horizontal competitor.[38] Initial research into VAWTs showed VAWTs to be more much more mechanically complex and harder to correctly construct, which led to multiple deadly large scale mechanical failures, effectively ending VAWT research.[39] However, today's VAWTs are smaller than their predecessors, this improvement has led to a

more complete understanding of the turbine mechanics.[40] Eliminating the danger of mechanical failure, the new VAWTs have slowly become larger and larger, continuously increasing the power output.[41] These VAWTs now have a higher energy density than a traditional HAWT, and are also able to produce power regardless of wind direction, which is a large improvement over the HAWT.[42] However, these VAWTs are more difficult to stop once moving.[43] With the many recent improvements in VAWT design, the turbines are now able to compete with the HAWT, however more research is needed to determine which method is superior.[44]

The idea of combining piezoelectrics and vertical axis wind turbines is an increasingly popular research topic in renewable energy. There have been multiple models proposed, with each improving on the last.[45, 46] These models have only been small scale, yet they have proven the feasibility of the idea.[47] Yet these small scale turbines have proven to be an improvement on the original VAWT.[48] These designs have been successful, however the high cost of the turbine is preventing more noteworthy improvements.[49] Upon analysis, these designs have produced a higher than expected power output.[50]

Current Technology

VAWTs work by using a rotor set transversely to the wind to convert the centripetal force generated by the wind into harvestable energy. This form of wind turbine comes with several distinct advantages over traditional horizontal axis wind turbines (HAWTs). VAWTs can operate independently of the wind direction and can withstand high turbulences, even where the wind speed and strength can change quickly and often. VAWTs also generate far less noise than HAWTs, having a low noise level of between 600 and 1200 Hz.[51] This is closer to the frequency

of natural background noise than horizontal axis wind turbines (HAWT) meaning that as a person distances themselves from a VAWT, the noise dissipates faster than it would with a HAWT. This low noise level is key for usage in a highly populated area.

Aesthetically, these turbines are far more visually appealing than its horizontal counterpart, making it a much more attractive choice for populated areas. The turbines generator can be placed on the ground, resulting in easier installation and maintenance of the turbine. However, if the VAWT is located close to the ground, it will be unable to take advantage of higher wind speeds at higher altitudes. This can be resolved by installing the turbines on the roofs of buildings, where there is a much higher wind speed.

In terms of energy, the output is largely dependent on the size and location of the turbine. A relatively small VAWT can generate about 3000 kWh per year, or about a third of a typical homes energy use.[52] Although VAWTS may not be the primary source of renewable energy, these turbines can be very effective in supplementing a home or buildings energy usage.

VAWTs are also very economically viable. A typical set up of vertical axis wind turbines has a power density three times greater than HAWTs, this means that for the same amount of space, VAWTs can generate three times the power. A typical VAWT can range in price from several hundred to several thousand dollars depending on the size, whereas a horizontal axis wind turbine is on the scale of a hundred thousand dollars. VAWTs also have very low maintenance costs, as the turbine and generators proximity to the ground means greater accessibility and ease of maintenance. When the turbine reaches the end of its lifespan, the majority of the turbine components are able to be recycled and repurposed, increasing the positive environmental impacts by the VAWT.[53]

There are multiple varieties of VAWTs, Savonius, Darrieus, H-Darrieus, and Helix shape, as shown in Figure 1 below. While all of these VAWTs operate with the same general mechanism, there are slight variation between them. The most common VAWT design is the Savonius turbine, these turbines are not typically used for energy harvesting, instead they are used a very high torque to drive pumps. The Darrieus and H- Darrieus turbines are the most popular VAWT designs for energy harvesting, the only difference between the two being the blade shape, however, these turbines can produce an incredibly large torque while rotating, which increase the possibility of mechanical failure. This shortcoming was remedied with the creation of the Helix shape VAWT, this design was meant to withstand these torques and prevent any mechanical failures.

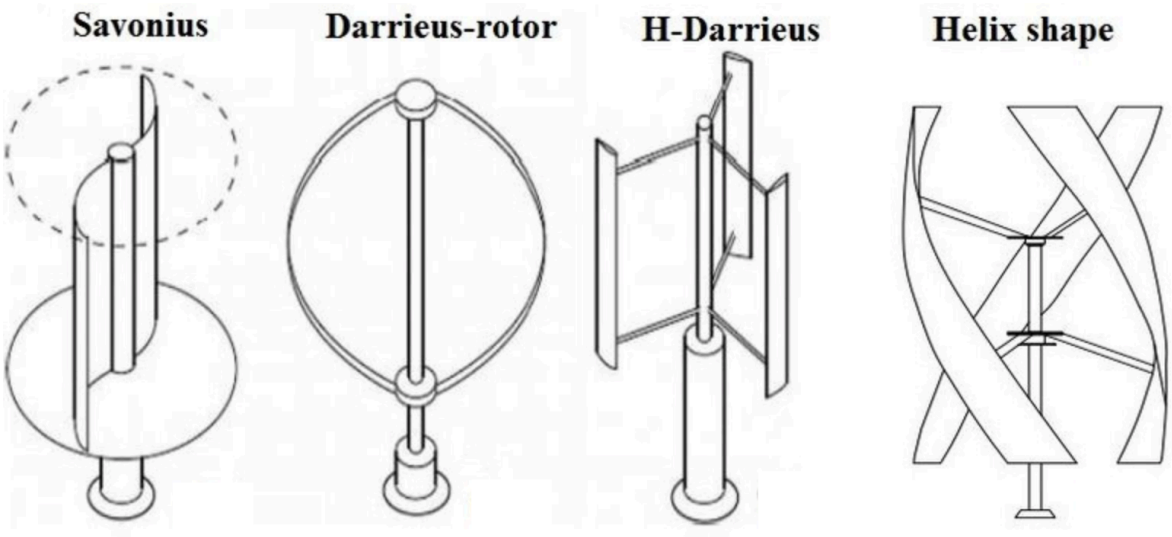

Figure 1. Types of common VAWTs. Adapted from Castellani F., Astolfi D., Peppoloni M., Natili F., Buttà D., and Hirschl A. (2019). "Experimental Vibration Analysis of a Small-Scale Vertical Wind Energy System for Residential Use." Machines. 7. 35. 10.339

Proposed Improvements

In order to increase the overall energy production of the VAWT, piezoelectric ceramics can be embedded within the blades of the turbine. These ceramics, made from lead zirconate titanate, commonly known as PZT, are able to convert the mechanical energy of the turbine blades vibrating in the wind into usable electrical energy.

First, we must determine which type of VAWT is most suited for the addition of piezoelectric ceramics. The Savonius design is not intended for energy harvesting purposes, so it would not be suitable for the piezoelectric ceramics. The other VAWT designs, Darrieus, H-Darrieus, and Helix, are all intended for energy harvesting so any of these designs could be outfitted with piezoelectric ceramics. However, because of the C-shaped blades in the Darrieus design, it would be very difficult to embed the ceramics within the blades, and the ceramics would be highly susceptible to damage. Therefore, we can focus our piezoelectric endeavors on the H-Darrieus and Helix VAWT designs.

In the case of the H-Darrieus design, we can easily add piezoelectric ceramics to the turbine blades. The blades are flat and provide a solid shape for the piezoelectric ceramics to be added, as shown in Figure 2 below.

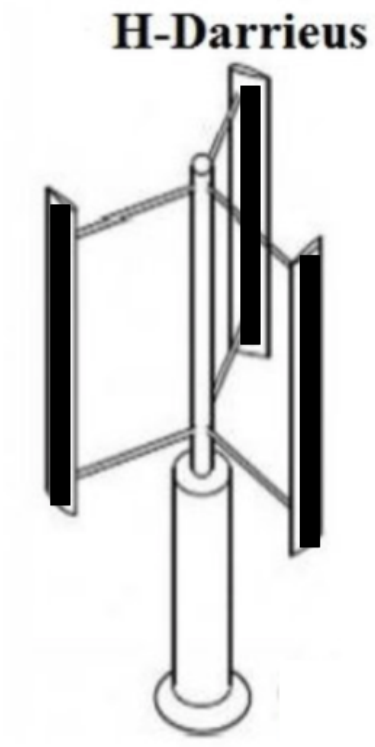

Figure 2. Proposed H-Darrieus design piezoelectric assisted VAWT, potential piezoelectric ceramics are in black. Adapted from Castellani F., Astolfi D., Peppoloni M., Natili F., Buttà D., and Hirschl A. . (2019). "Experimental Vibration Analysis of a Small-Scale Vertical Wind Energy System for Residential Use." Machines. 7. 35. 10.339

For the Helix design, the piezoelectric implementation is more difficult. The blades are curved, which makes it much harder to embed the piezoelectric ceramics. For this design, the blades would have to at slightly more perpendicular at the ends for the ceramics to fit, as shown in Figure 3 below. Because of the curved shape of the blades, the ceramics would have to be concentrated at the end of the blades, which would lower the overall efficiency and energy output of the turbine.

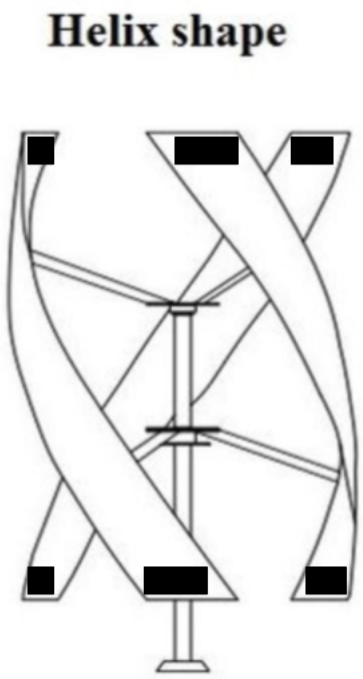

Figure 3. Proposed Helix design piezoelectric assisted VAWT, potential piezoelectric ceramics are in black. Adapted from Castellani F., Astolfi D., Peppoloni M., Natili F., Buttà D., and Hirschl A. . (2019). "Experimental Vibration Analysis of a Small-Scale Vertical Wind Energy System for Residential Use." Machines. 7. 35. 10.339

Overall, the most promising deign for a piezoelectric assisted VAWT is the H-Darrieus design. This design offers the largest area for piezoelectric ceramics to be embedded, without compromising the overall effectiveness of the VAWT. With this design, the turbine can provide more energy than a turbine without the piezoelectric ceramics, the exact amount of energy produced would be the next step in this research endeavor.

Further Research

Although it could not be completed due to the current world situation, the intention of this research was to determine how much energy a piezoelectric assisted vertical axis wind turbine could produce in comparison to a typical vertical axis wind turbine. The experimental goal was to measure the power output from a tradition H-Darrieus VAWT and compare this value with the power output from a piezoelectric assisted VAWT. The turbines would be 3-D printed, with the Piezoelectric assisted VAWT having piezoelectric ceramics embedded in the turbine blades. Both turbines would be subjected to the same wind conditions to observe the power outputs and observe how the overall turbines behavior in the various wind conditions.

Conclusions

Unfortunately, the intended experiment could not be completed due to the coronavirus pandemic, but there is great promise for further research into this technology. The implementation of piezoelectric assisted vertical axis wind turbines could help increase renewable energy in urban and densely populated areas, providing a much cleaner alternative for fossil fuels.

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