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Review Article

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Review on Energy Harvesting from Wind-Induced Column Vibrations: Theories, Mechanisms, and Applications

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Abstract

This paper presents an extensive review of energy harvesting from the column vibrations of wind turbines under the influence of wind. The study investigates the underlying theories, mechanisms, and potential applications of such a system. By tapping into the vibrational energy otherwise dissipated in wind turbines, the study proposes an innovative approach to enhance renewable energy generation. Furthermore, the potential benefits of the technology, such as powering remote sensors, vibration damping, structural health monitoring, and increasing wind turbine efficiency and lifespan, are discussed. While the study acknowledges the promise of such an approach, it also emphasizes the need for further research to optimize and integrate these systems effectively into the renewable energy landscape.

Keywords: Wind turbine, Energy harvesting, Column vibration, Structural health monitoring, Remote sensors, Wind energy efficiency.

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1. Introduction

The escalating interest in renewable energy sources over recent years marks an essential shift in our approach to energy consumption, spurred by mounting environmental concerns and the urgent pursuit of sustainable alternatives to fossil fuels. This dynamic transformation found its roots in the 1970s energy crisis, which catalyzed the renewable energy revolution [1]. Within the realm of renewable energy, wind power has emerged as a leading player. By the conclusion of 2017, worldwide wind turbine installations surged dramatically, reaching an impressive 539 GW—reflecting a noteworthy increment of 126% compared to figures from 2011 [2]. An increasing proportion of these installations are offshore, deliberately distanced from coastlines to optimize the exploitation of abundant wind resources [2].

Wind turbines, an integral part of the wind energy infrastructure, are primarily categorized into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs), predicated on their rotating axis orientation [3]. HAWTs, with blades spinning on a horizontal axis and oriented perpendicular to the wind flow, command the utility-scale wind turbine market. A testament to their dominance is the ongoing constructions of massive turbines like the Haliade-X 12 MW offshore wind turbine, boasting a tower height of 150 meters and a rotor diameter of 220 meters [2].

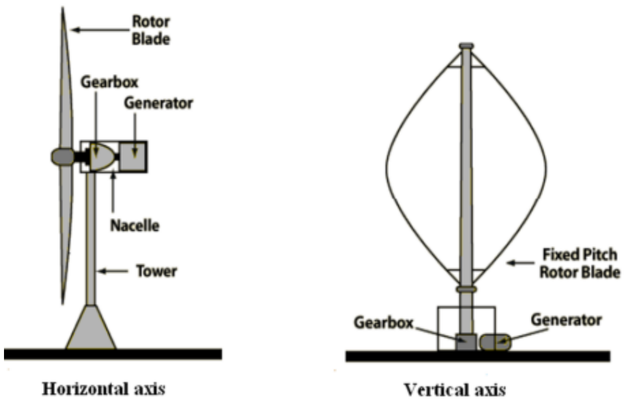

Fig. 1 Vertical axis and horizontal axis wind turbines [3]

Despite the advances, large-scale wind turbines—those with blade lengths exceeding fifty meters [4]—face significant challenges regarding safety and maintenance. These enormous composite blades, usually made from a lightweight composite of balsa wood and fiberglass [5], bear cyclic loading and are prone to fatigue, cracks, and damage caused by various environmental conditions like ice accumulation, lightning strikes, and bird strikes [6,7]. Blade failure can have devastating consequences, causing additional damage to other blades, internal turbine components, or neighboring wind turbines. The remote locations of these installations, often in difficult terrains or harsh seas, amplify inspection and maintenance challenges. Furthermore, the towering heights of these turbines introduce another layer of complexity to maintenance procedures. Therefore, addressing these challenges is critical to ensure the safety, reliability, and cost-effectiveness of wind turbines [8].

Due to their light-weight and high-strength structure, wind turbines are highly flexible and weakly damped, making them vulnerable to dynamic excitations from wind and wave loads. These external forces continually impact offshore wind turbines throughout their operational life. In seismically active regions like the western United States and China, home to numerous wind farms, earthquakes present an additional source of vibration [9]. These excessive vibrations can impede the conversion of wind energy into electricity, decrease the fatigue life of structural components, and potentially lead to catastrophic turbine collapses [10]. The resultant damage to sensitive components, such as the gearbox and generator housed in the nacelle, can prove highly expensive [11]. Consequently, it is critical to mitigate these unwanted vibrations to ensure the structural safety and operational longevity of wind turbines.

Historically, various strategies have been employed to control excessive vibrations in engineering structures exposed to external forces [12–14]. Damping control systems are broadly divided into passive, active, hybrid, and semi-active categories [15]. A passive control system dissipates the energy derived from the primary structure without requiring any external energy. In contrast, an active control system, akin to a dynamic positioning system in offshore vessels, supplies energy to prevent undesirable motion or achieve specific motion patterns, necessitating considerable external energy. A semi-active control system requires minimal energy input to adjust the parameters of a passive control system, such as the frequency of a tuned mass damper or the damping effect of a magneto-rheological damper. Hybrid methods combine the features of both active and passive control devices [6, 16]. Understanding the operation and optimization of these control systems will be pivotal for harnessing the full potential of wind energy in the face of operational challenges. The advent of modern electronics marked a turning point for energy harvesting, driving it into the limelight. With the progressive evolution of technology, devices became smaller and more power-efficient. Concurrently, it became increasingly feasible to fuel such devices solely with ambient energy by incorporating a small-scale energy harvester, thereby setting the stage for its widespread adoption [17].

1.1. Detailed exploration of energy harvesting strategies

Energy harvesting, alternatively termed energy scavenging, is a discipline that revolves around the conversion of ambient energy into usable electrical power. The methodology encompasses a broad range of potential energy sources, including the kinetic energy of moving or vibrating structures, radiant energy emitted from sunlight, and thermal energy derived from heat sources. The defining feature of an energy harvesting device lies in its capability to capture and transform the otherwise dissipated energy from its surroundings, causing negligible interference with its host structure or environment.

Energy harvesters have made their mark across a diverse array of applications, such as powering rechargeable batteries, monitoring automotive tire air pressure, operating unmanned vehicles, powering embedded and implanted medical sensors, and facilitating structural health monitoring. The techniques employed for energy harvesting span a spectrum of methodologies, including photovoltaic, thermoelectric, piezoelectric, magnetostrictive, electrostatic, and electromagnetic approaches [18].

Photovoltaic energy harvesters capitalize on solar radiation to generate electrical energy, whereas thermoelectric energy harvesters convert thermal energy into electrical power [19]. Piezoelectric energy harvesting engages the principle of generating an electric field which, in turn, produces a voltage when a piezoelectric material is subjected to stress [20, 21]. Magnetostrictive materials, when deformed, generate a magnetic field that can induce a voltage across an adjacent conductive coil [22].

Electrostatic energy harvesters' function by modulating the capacitance of a pre-charged capacitor in response to vibrations of the host structure. This variable capacitor operates as a current source, supplying power to an electrical circuit [23]. Alternatively, electromagnetic energy harvesters, also known as induction energy harvesters, induce a voltage across a coil of wire by moving a permanent magnet, thereby supplying energy to an electrical circuit [24-26].

In the contemporary technological landscape, electromagnetic energy harvesting has garnered substantial attention due to its extensive applicability in engineering domains to produce electricity. Furthermore, it exhibits great potential for enhancing the performance and reliability of wind turbines by tapping into their vibrational energy. By transforming this vibrational energy—considered an unwanted byproduct—into usable power, it opens up avenues for improved operational efficiency and maintenance of wind turbines, adding another layer of sustainable innovation to renewable energy harvesting.

1.2. Electromagnetic energy harvesting

The foundation for harvesting electromagnetic energy was laid by 19th-century scientists such as Hans Oersted, Joseph Henry, Michael Faraday, James Maxwell, and Heinrich Hertz. Their work has shed light on the interaction between magnetic and electric fields, encapsulated in Maxwell's equations. Among these laws, Faraday's law of induction determines how a changing magnetic field creates an electric field. The relative motion of the permanent magnet and the conducting coil generates an electrical potential (voltage) across the ends of the coil, a principle that Faraday used for the first time in an electric generator. The figure below shows the connection of the harvester to the wind turbine tower for the purpose of causing the relative motion of the magnet and the coil

Presently, this principle is harnessed in various power generation modalities, including fossil fuels, nuclear power, hydroelectric power, and wind turbines, converting ambient energy into electricity. Comprehensive reviews of different electromagnetic energy harvesting strategies have been provided by Arnold [27] and Mitcheson [28].

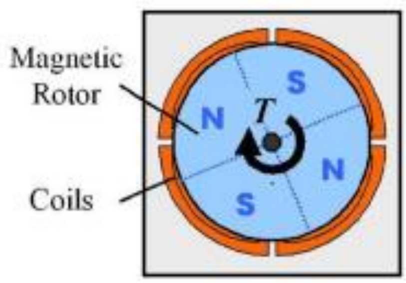

Fig. 2 Rotational device driven by continuous rotational power [27].

Inductive energy harvesters employ several strategies to achieve relative velocity between the coil and the magnet. These can be categorized into linear, rotational, and pendulum harvesters, as well as those that utilize beams. In a linear harvester, the magnet moves in a straight line relative to the coil. Rotational harvesters deploy magnets mounted on a rotating rotor with stationary coils positioned around the rotor. In pendulum harvesters, the magnet moves relative to a stationary coil, while beam-utilizing harvesters attach a magnet or a coil to an elastic beam.

Pioneering research by Williams and Yates [29] involved modeling a rudimentary linear energy harvester consisting of a proof mass and a rigid frame connected by a spring. They depicted the electromagnetic energy harvester as a dashpot, exerting a force on the mass proportional to its relative velocity to the frame. When the rigid frame oscillated, some of the mechanical energy of the moving proof mass was transferred through the harvester to a load resistor.

Their findings suggested that enhancing the natural frequency or deflection of the proof mass would increase the device's power output to the load resistor. Theoretically, a harvester with a volume of 25 mm3 could generate 0.1 mW at 330 Hz from a deflection of 50 μm. Building on this concept, Williams et al. [30] constructed a linear micro-generator. The 25 mm3 device featured a permanent magnet connected to a polyimide membrane suspended above a gold coil. The device yielded up to 0.3 μW at 4.4 kHz from a displacement of 0.5 μm.

Zuo et al. [31] explored a linear electromagnetic energy harvester designed for car suspensions. This regenerative shock absorber absorbed vibrations triggered by road irregularities and vehicle accelerations and decelerations. The shock absorber was capable of generating 16 to 64 W from a suspension velocity of 0.25 m/s to 0.5 m/s. Other researchers have investigated linear generators for harvesting ocean wave energy, where a floating buoy connected to a generator on the seabed moves vertically due to wave action, causing magnets on a rod to induce the generator's coils. Prudell and Brekken [32] developed a model of a 1 kW generator using this concept.

Rotational energy harvesters have also been a focus of research. These devices typically require a mechanism to transform the linear motion of a vibrating structure into rotational motion. Due to their lack of displacement limitations compared to linear harvesters, rotational harvesters can achieve higher power densities. However, rotational generators tend to operate at higher frequencies than their linear counterparts. An early example of an electromagnetic energy harvester is the Seiko Kinetic self-powered wristwatch, which was first unveiled at the 1986 Basel Fair [33]. The watch utilized an eccentric mass on the rotor of a miniature electric generator, which was rotated by the wearer's movements, negating the need for winding the watch's mainspring or replacing the battery. Yeatman [34] explored the maximum power density of spinning and gyroscopic energy harvesters, concluding that rotational devices can achieve higher power densities than linear energy harvesters, albeit at the expense of requiring low parasitic damping. If a torsion spring is used to connect the rotating mass to a rigid frame, it should possess a high angular range.

Trimble et al. [35] investigated a simple generator comprising a rotating mass hung by a torsion spring. Magnets mounted on the rotating mass moved relative to coils located on the rigid housing. The 80 cm^3 prototype device was capable of producing over 200 mW at a resonance frequency of 16 Hz and an angular acceleration of 150 rad/s^2. Pendulum-based induction harvesters generate rotational motion using linear vibrations and can generate power even when installed on a spinning structure.

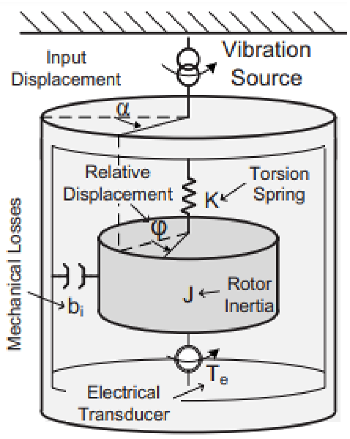

Fig. 3 Lumped parameter model of the harvester [35].

Another variant of electromagnetic harvesters attaches a magnet or a coil to an elastic beam. El-hami et al. [36] analyzed a micro-scale harvester composed of a U-shaped bracket and a magnet assembly positioned on a cantilever beam. The oscillating magnets on the bracket moved relative to a coil fixed to a stationary frame. From a 25 μm excitation amplitude, the 240 mm3 device generated 0.53 mW at a resonance frequency of 322 Hz. Yang et al. [37] examined a system that employed three magnets affixed to an elastic beam with clamps on both ends. The device harvested energy at 369 Hz, 938 Hz, and 1184 Hz, the first three natural frequencies of the beam. With a 14 μm excitation amplitude, the device produced 3.2 μW at the second natural frequency.

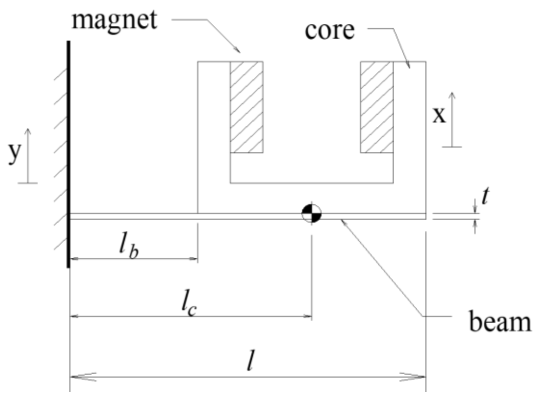

Fig. 4 Labelled drawing of beam/magnet assembly [36].

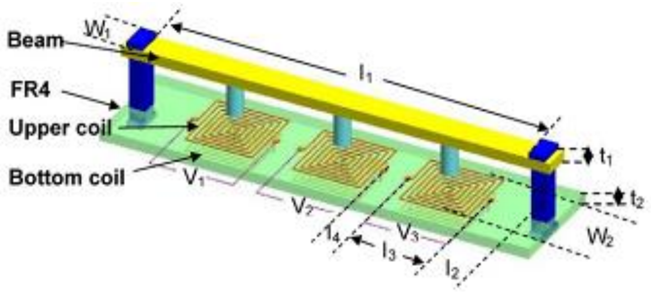

Fig. 5 Schematic drawing of the FR4 energy harvester [37].

Challa [38] probed a hybrid energy harvesting method that combined electromagnetic and piezoelectric techniques, using a magnet on the tip of a piezoelectric cantilever beam. The 35 cm3 device generated a total of 332 μW from both harvesting methods at a resonance frequency of 21.6 Hz. In a similar vein, Yang et al. [39] analyzed a 222 mm3 cantilever harvester that produced a combined output of 176 μW at 310 Hz under acceleration.

Future research should prioritize vibration energy sources, as they hold potential for powering not only small-scale devices but also energy-intensive apparatus in sectors like transportation, infrastructure, and human movement. Vibration energy harvesting entails capturing energy from undesirable environmental vibrations. Various forms of ambient vibration are emitted from sources such as wind, vehicle motion on bridges, and operation of machinery in industrial settings and structures. These residual energies can be perceived as potential and yet wasted energy sources. By harnessing smart materials and diverse energy harvesting methods, this vibrational energy can be converted into electrical energy. As it is derived from natural and industrial environments, it can be referred to as "free energy." Hence, vibration is an appealing energy source for powering small devices, involving the harnessing of moving waves on solid materials. To convert mechanical to electrical energy, vibrations must be coupled with a generator using seismic mass inertia.

2. Theory of column vibrations and wind energy harvesting

Understanding column vibrations is pivotal when examining structures like wind turbines that are subjected to constant dynamic forces. A vibrating column, or more generally, a beam, is a classic problem in structural dynamics, governed by the equation of motion represented by Euler-Bernoulli beam theory [40]

where A is the cross-sectional area, I is the moment of inertia of the cross-sectional area, E is the modulus of elasticity, ρ is the mass per unit of volume and v (x, t) is the transverse deflection at the axial location x and at the time t.

According to this theory, a beam's deflection is dependent on the applied load, the properties of the beam material, its geometric attributes, and its support conditions. For wind turbines, these applied loads originate from wind and wave action [41].

Vibrations in a column can be broadly categorized into free and forced vibrations. Free vibrations occur when the column vibrates at its natural frequency, in the absence of any external force, once it is disturbed from its equilibrium position. Conversely, forced vibrations occur when the column vibrates under the influence of continuous external forces at their frequency [42]. Understanding these vibrational dynamics is critical for designing efficient vibration damping and energy harvesting systems.

A column under wind action often experiences fluctuating forces, leading to forced vibrations and instigating a cycle of vibration energy that is mostly wasted as heat due to structural damping. However, this wasted energy can be harvested and transformed into electrical power using an energy harvester. In the context of wind turbines, vibrational energy harvesting can serve a dual purpose. Firstly, it can enhance the total energy output of the turbine by converting vibration energy into electrical power. Secondly, it can serve as a passive damping mechanism, reducing structural vibrations and improving turbine longevity [43].

Energy harvesting from column vibrations can be achieved through various mechanisms like electromagnetic, piezoelectric, or electrostatic techniques, as detailed in the previous section. For example, an electromagnetic energy harvester can be designed to couple with the column's vibration mode shapes. Such a design would entail a magnet moving relative to a coil in response to the column vibrations, inducing a voltage across the coil due to Faraday's Law of electromagnetic induction [44].

The performance of an energy harvester under variable environmental conditions is a crucial consideration. Harvesters need to function efficiently under a range of wind speeds and direction changes that affect the vibration behavior of the column [45]. Therefore, a thorough understanding of column vibrations under wind influence is vital for optimizing the design and performance of energy harvesters and realizing the potential of this technology for sustainable power generation [46].

From the perspective of wind turbines, this concept is not only attractive from an energy efficiency standpoint but also presents a promising solution to address maintenance and operational challenges related to vibrations. However, realizing this potential requires a detailed understanding of the intricate relationships between wind action, column vibrations, and energy harvesting principles [47]. Therefore, more research is required to establish effective strategies for harnessing vibrational energy in wind turbines, which could have significant implications for the wind energy sector.

3. Mechanisms of energy harvesting from column vibrations under wind influence

The energy harvesting mechanisms that exploit column vibrations under wind influence fall into three main categories: electromagnetic, electrostatic, and piezoelectric methods.

3.1. Electromagnetic energy harvesting

Electromagnetic energy harvesting is a popular and well-researched method due to its versatility and robustness. In this context, it involves the relative movement of a magnet and coil due to column vibrations, leading to changes in the magnetic field and generating an electromotive force (EMF) according to Faraday's law of electromagnetic induction [48]. A simple electromagnetic energy harvester may consist of a coil attached to the column and a magnet attached to a mass that moves relative to the coil due to the column's vibrations. This mechanism can produce significant power outputs, particularly when the harvester is tuned to the column's natural frequency, and the vibrations are large [49].

3.2. Electrostatic energy harvesting

Electrostatic energy harvesting, also known as capacitive energy harvesting, operates on the principle of variable capacitance. This method involves a variable capacitor, with one plate attached to the column and the other plate free to move relative to the first plate due to the column's vibrations. This movement alters the gap between the plates, leading to changes in the capacitance and producing energy. Despite the need for an initial charging source, electrostatic energy harvesting can be extremely efficient and provides excellent power density, making it suitable for low-frequency, high amplitude vibrations like those experienced by wind turbines [50].

3.3. Piezoelectric energy harvesting

Piezoelectric energy harvesting leverages the unique property of certain materials to generate an electric charge in response to mechanical strain. When these materials are integrated into a vibrating column structure like a wind turbine tower, the cyclic strain resulting from the wind-induced vibrations generates an electric charge across the piezoelectric material. This charge can then be collected and transformed into usable electric power. Due to their solid-state nature, piezoelectric harvesters are durable and able to operate over a wide range of frequencies, making them particularly well-suited to unpredictable, variable conditions such as wind [46].

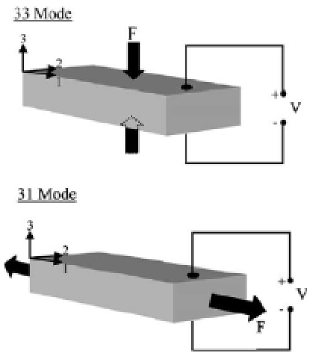

Fig. 7 Illustration of −33 mode and −31 mode operation for piezoelectric material [46].

To realize the full potential of these energy harvesting mechanisms, they need to be optimized for the specific characteristics of the column vibrations and the wind conditions. This optimization may involve tuning the natural frequency of the harvester to match the dominant frequency of the column vibrations, utilizing advanced materials to maximize energy conversion efficiency, or using sophisticated control strategies to adapt to variable wind conditions. By integrating these advanced energy harvesting mechanisms into wind turbine structures, it is possible to harness a significant portion of the otherwise wasted vibrational energy, contributing to the overall efficiency and sustainability of wind energy systems.

3.4. Applications of energy harvesting from column vibrations under wind influence

The unique aspect of harvesting energy from column vibrations under wind influence lies in the wide range of applications that can be derived from such a technique, which extends across various industrial domains. These applications span from providing power to remote sensors and reducing structural vibrations, to enhancing the overall efficiency and life span of wind turbines.

3.4.1. Enhancing remote sensor operation through vibration energy harvesting

Wind turbines are frequently installed in remote and hard-to-access regions such as offshore sites or atop mountains to take advantage of uninterrupted wind flow. While these locations are ideal from an energy production standpoint, they pose significant challenges for maintenance and operational monitoring [20]. This is where remote sensors come into play. These devices perform critical roles in ensuring optimal turbine performance, tracking weather conditions, and monitoring the structural integrity of the turbines. However, to fulfil these roles effectively, these sensors necessitate a reliable, continuous power source—a requirement that can prove challenging given the remote locations of the turbines.

Vibration energy harvesting technology emerges as a robust solution to this challenge, offering a means to supply power to these remote sensors autonomously [51]. By capitalizing on the vibrational energy inherent in the operation of wind turbines, these harvesting devices convert mechanical oscillations into usable electrical energy. This energy can subsequently be used to power the sensors responsible for monitoring the turbines.

The autonomous powering of sensors achieved through vibration energy harvesting carries several significant benefits. Firstly, it eliminates the dependence on external power sources, which can be logistically difficult and expensive to deliver to remote turbine locations. Secondly, it reduces the need for regular battery replacements, a task that requires intensive labor and resources due to the inaccessibility of the turbines [52].

Moreover, harnessing the energy of column vibrations under wind influence can yield continuous power supply for the sensors, as wind turbines are subject to near-constant vibrations during operation. This ensures the uninterrupted operation of the sensors, facilitating real-time monitoring of the turbines [53]. By leveraging the energy that would otherwise be dissipated as heat or sound, this method of powering also enhances the overall energy efficiency of the wind turbine system.

Lastly, the implementation of vibration energy harvesting technologies for powering remote sensors also contributes to sustainability efforts. By reducing the consumption of batteries and minimizing the need for transportation to these remote sites for maintenance, this approach aligns with the broader goals of reducing carbon footprint and promoting green energy solutions.

3.4.2. Optimizing wind turbine performance and lifespan through energy harvesting

Energy harvesting technologies, specifically those that leverage vibrational energy, can play a pivotal role in augmenting the efficiency of wind turbines. The vibrational energy, often regarded as a by-product or waste energy in the operation of wind turbines, is a source that can be tapped into to augment the primary power output [54]. This comes into play especially during periods of low wind speeds when the turbine's power generation may be inadequate. Energy harvesting technologies can convert the vibrational energy into supplementary electrical power, boosting the overall efficiency of the wind turbine during such times.

Beyond mere power augmentation, vibration energy harvesting has a significant role in enhancing the longevity of wind turbines. Wind turbines, especially their blades and towers, are subjected to continuous and cyclic vibrations during their operation. These repetitive vibrational stresses are a leading contributor to structural fatigue and eventual failure. By harnessing and thereby reducing these vibrations, energy harvesting devices effectively mitigate the cyclical stresses on the turbines [55].

The consequence of reduced stress on the structural elements is a lower rate of wear and tear, resulting in an extended operational life for the wind turbines. The damping effect provided by the energy harvesters could translate into fewer instances of breakdowns, less frequent maintenance needs, and lower repair costs. It contributes to a more sustainable and cost-effective operation of wind turbines in the long run, aligning with the broader goal of renewable energy sector to maximize energy output while minimizing maintenance and operational costs [56].

Energy harvesting thus emerges not just as a supplementary power generation method, but also as a vital tool for vibration damping and structural health monitoring. By fulfilling these multiple roles, it can significantly enhance the operational efficiency, structural integrity, and overall lifespan of wind turbines [57].

3.4.3. Dual utility of energy harvesting: vibration damping and structural health monitoring

Beyond their role in generating electricity, energy harvesting devices confer additional benefits, particularly in enhancing the overall stability and structural integrity of wind turbines. These devices function as vibration dampers, reducing the vibration amplitudes and associated stress levels within the wind turbine structure [58]. They achieve this by drawing energy from the vibrational motion of the turbine columns, effectively transforming potentially damaging mechanical energy into useful electrical power.

The dual functionality of energy harvesting—generating power and damping vibrations—opens up avenues for designing robust and resilient wind turbines. Such design versatility can be crucial for turbines installed in regions that experience high wind speeds, seismic activities, or other forms of environmental stress [59]. In such contexts, energy harvesters can help alleviate structural wear and tear, enhancing the longevity and reliability of these massive renewable energy structures.

Adding another layer to their utility, energy harvesting devices can play a significant role in structural health monitoring (SHM) systems. SHM systems have become increasingly crucial in maintaining the structural integrity of wind turbines, as they provide real-time, continuous feedback on the condition of the structures. Energy harvesters contribute to these SHM systems by serving as vibration sensors. By monitoring the output of the energy harvesting devices, changes in the structural vibrations—an early indicator of potential structural faults or failures—can be promptly detected [60].

Moreover, the harvested energy can be used to power the SHM systems themselves, further enhancing their efficiency and autonomy. This results in a synergistic relationship between energy harvesting and structural health monitoring, where each support and reinforces the other [61].

Finally, with the integration of advanced machine learning and data analysis techniques, the vibration data collected from these energy harvesters can be used to predict and prevent potential turbine failures. Such proactive approaches to maintenance can lead to significant cost savings and improved turbine performance [62].

4. Results and discussion

The wide-ranging, multi-faceted discussion embarked upon in this study serves to underscore the immense potential of energy harvesting from column vibrations of wind turbines under wind influence. It opens the door to a paradigm shift in how we perceive and address the challenges associated with wind turbine operations. By providing a comprehensive exploration of the relevant theories, mechanisms, and applications, this paper has systematically highlighted the potential of energy harvesting technology to enhance wind energy's sustainability and efficiency.

The theoretical underpinnings of vibration energy harvesting have been painstakingly explored, emphasizing the principle of transforming mechanical vibrations into usable electrical power [31,32]. Unearthing these theoretical concepts has proven to be instrumental in gaining a firm understanding of how such a process can be harnessed to provide sustainable power to remote systems, mitigate unwanted vibrations, and enhance structural health monitoring.

This study further examined the mechanisms by which energy can be harvested from wind-induced column vibrations [34-36]. These mechanisms hinge on the intelligent exploitation of wind turbines' intrinsic characteristics – their lightweight, high-strength structures, their susceptibility to wind and wave loads, and their vibrations under these influences. While these characteristics might traditionally be viewed as challenges or drawbacks, they provide us with a unique opportunity to harvest otherwise wasted energy. This transformative perspective is a testament to the power of innovative engineering solutions that redefine the boundaries of renewable energy generation.

Moreover, the study examined real-world applications of such energy harvesting technology, with a particular emphasis on powering remote sensors and enhancing the structural integrity of wind turbines [39, 41-43]. These are not mere theoretical postulations but tangible, practical implications with the potential to revolutionize wind turbine operation and maintenance.

The use of vibration energy harvesting for powering remote sensors could be a game-changer, reducing dependency on external power sources or frequent battery replacements [39, 40]. It presents a sustainable solution to monitor and maintain turbines stationed in inaccessible or harsh environments, serving as a testament to the technology's practical utility.

Moreover, the dual functionality of energy harvesting devices as vibration dampers opens up new avenues for enhancing the structural integrity of wind turbines [41, 42]. Such an approach not only ensures the generation of supplemental electricity but also contributes to the overall stability of these renewable energy structures. Additionally, the potential of these devices in structural health monitoring systems signifies a proactive strategy in maintaining wind turbines, a step forward in moving from reactive to preventative maintenance [43, 45].

Furthermore, by reducing wear and tear on turbines, energy harvesting technologies effectively extend their operational lifespan, resulting in more efficient and cost-effective wind energy production [46, 47]. The financial and environmental implications of such efficiency cannot be overstated in a world increasingly grappling with energy demands and climate change.

In conclusion, this study reveals energy harvesting from column vibrations under wind influence as a multifaceted solution capable of addressing several challenges plaguing the wind energy sector. The theoretical exploration, coupled with the detailed examination of mechanisms and real-world applications, underlines the immense potential of this technology. The findings illuminate how such an approach could redefine the boundaries of renewable energy production, making wind energy not only more efficient but also more sustainable. The discussion propels the dialogue on renewable energy generation to newer, uncharted territories, inviting further exploration and innovation in this exciting field.

Yet, like any groundbreaking study, the journey does not end here. More research is necessary to delve deeper into other potential applications and to optimize the energy harvesting process. As the technology continues to evolve, the potential for harnessing more renewable energy sources will undoubtedly expand, bringing us closer to a truly sustainable future.

5. Conclusion

The present study investigated energy harvesting from the column vibrations of wind turbines under wind influence. Through an in-depth analysis of the theoretical principles, associated mechanisms, and potential real-world applications, this study has showcased the considerable potential and far-reaching implications of such an approach in renewable energy generation.

In theory, the transmutation of mechanical vibrations into functional electrical power offers a new avenue for augmenting renewable energy resources. By capturing and converting vibrational energy that would otherwise be dissipated, a new perspective on energy efficiency and sustainability is brought to the forefront.

In terms of mechanisms, this research underscores the idea that wind turbines, which are often viewed as susceptible to wind and wave loads, could instead be considered as unique platforms for energy harvesting. Through this innovative lens, we see challenges turned into opportunities, providing new ways to utilize the inherent characteristics of wind turbines.

Applications of this technology demonstrate tangible, real-world implications. Energy harvesting for powering remote sensors could significantly enhance the monitoring and maintenance of wind turbines, particularly those located in remote or challenging environments. Furthermore, these mechanisms' role as vibration dampers could result in substantial improvements in structural health and stability.

As a sustainable and innovative solution, the approach discussed in this paper signifies a considerable leap towards enhancing wind turbine efficiency and lifespan. By harvesting vibrational energy, we can supplement power output, reduce wear and tear, and thus prolong the operational life of wind turbines.

However, like any scientific endeavor, this study opens up as many questions as it answers. While the potential for energy harvesting from column vibrations under wind influence is clear, many intricacies need to be explored further. For instance, the optimization of energy harvesting systems for different types of wind turbines, the incorporation of these systems in turbine design, and their potential impact on turbine manufacturing costs are all crucial areas for further study.

Moreover, as the global renewable energy landscape evolves, it is important to consider how this technology could be integrated with other renewable energy systems or how it might be adapted for other applications outside of the wind energy sector.

In conclusion, energy harvesting from column vibrations under wind influence presents a promising direction for enhancing the sustainability and efficiency of wind energy. This study is an essential stepping stone on the path to a more sustainable energy future, paving the way for further research and innovation in this exciting field. As we continue to explore the potential of this technology, we inch closer towards our shared goal of a world powered by sustainable and efficient renewable energy sources.

References

[1] C. C. Ciang, J-R Lee, and H-J Bang, "Structural health monitoring for a wind turbine system: a review of damage detection methods", Measurement science and technology, Vol. 19, Issue 12, 2008. https://doi.org/10.1088/0957-0233/19/12/122001

[2] Global Wind Energy Council (GWEC). Global wind report-Annual market update 2017, GWEC, 2018.

[3] M. E. H. Al-Kharbosy, "Enhancement Protection and Operation of The Doubly Fed Induction Generator During Grid Fault", Ph.D. thesis, South Valley University, 2012. https://doi.org/10.13140/RG.2.2.16718.25925

[4] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development", National Renewable Energy Laboratory, (NREL), Technical Report NREL/TP-500-38060, 2009.

[5] C. Pitchford, B. L. Grisso, and D. J. Inman, "Impedance-based structural health monitoring of wind turbine blades", Health Monitoring of Structural and Biological Systems 2007, Vol. 6532, 2007. https://doi.org/10.1117/12.715800

[6] H. Zuo, K. Bi, and H. Hao. "A state-of-the-art review on the vibration mitigation of wind turbines", Renewable and Sustainable Energy Reviews, Vol. 121, 2020. https://doi.org/10.1016/j.rser.2020.109710

[7] F. Xie, and A-M. Aly. "Structural control and vibration issues in wind turbines: A review", Engineering Structures, Vol. 210, 2020. https://doi.org/10.1016/j.engstruct.2019.110087

[8] A. Awada, R. Younes, and A. Ilinca, "Review of Vibration Control Methods for Wind Turbines", Energies, Vol. 14, Issue 11, 2021. https://doi.org/10.3390/en14113058

[9] E. I. Katsanos, S. Thöns, and Ch. T. Georgakis, "Wind turbines and seismic hazard: a state-of-the-art review", Wind Energy, Vol. 19, Issue 11, pp. 2113-2133, 2016. https://doi.org/10.1002/we.1968

[10] J-Sh.Chou, and W-T Tu. "Failure analysis and risk management of a collapsed large wind turbine tower", Engineering Failure Analysis, Vol. 18, Issue 1, pp. 295-313, 2011. https://doi.org/10.1016/j.engfailanal.2010.09.008

[11] L. D-Osorio, and B. Basu, "Unavailability of wind turbines due to wind-induced accelerations", Engineering Structures, Vol. 30, Issue 4, pp. 885-893, 2008. https://doi.org/10.1016/j.engstruct.2007.05.015

[12] B. F. Spencer Jr, and S. Nagarajaiah, "State of the art of structural control", Journal of structural engineering, Vol. 129, Issue 7, pp. 845-856, 2003. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:7(845)

[13] R. Kandasamy, F. Cui, N. Townsend, Ch. Ch. Foo, J. Guo, A. Shenoi, and Y. Xiong, "A review of vibration control methods for marine offshore structures", Ocean Engineering, Vol. 127, pp. 279-297, 2016. https://doi.org/10.1016/j.oceaneng.2016.10.001

[14] M. Rahman, Z. Ch. Ong, W. T. Chong, S. Julai, and Sh. Y. Khoo, "Performance enhancement of wind turbine systems with vibration control: A review", Renewable and Sustainable Energy Reviews, Vol. 51, pp. 43-54, 2015. https://doi.org/10.1016/j.rser.2015.05.078

[15] Ch. Huang, "Structural health monitoring system for deepwater risers with vortex-induced vibration: Nonlinear modeling, blind identification, fatigue/damage estimation and vibration control", PhD thesis, Rice University, 2012.

[16] M. Ghassempour, G. Failla, and F. Arena, "Vibration mitigation in offshore wind turbines via tuned mass damper", Engineering Structures, Vol. 183, pp. 610-636, 2019. https://doi.org/10.1016/j.engstruct.2018.12.092

[17] I. Sil, S. Mukherjee, and K. Biswas, "A review of energy harvesting technology and its potential applications", Environmental and Earth Sciences Research Journal, Vol. 4, Issue 2, pp. 33-38, 2017. https://doi.org/10.18280/eesrj.040202

[18] B. Pozo, J. I. Garate, J. Á. Araujo, and S. Ferreiro, "Energy harvesting technologies and equivalent electronic structural models", Electronics, Vol. 8, Issue 5, 2019. https://doi.org/10.3390/electronics8050486

[19] J. R. Farmer, "A comparison of power harvesting techniques and related energy storage issues", PhD thesis, Virginia Tech, 2007.

[20] S. P. Beeby, M. J. Tudor, and N. M. White, "Energy harvesting vibration sources for microsystems applications", Measurement science and technology, Vol. 17, Issue 12, 2006. https://doi.org/10.1088/0957-0233/17/12/R01

[21] M. Iqbal, and F. U. Khan, "Hybrid vibration and wind energy harvesting using combined piezoelectric and electromagnetic conversion for bridge health monitoring applications", Energy conversion and management, Vol. 172, pp. 611-618, 2018. https://doi.org/10.1016/j.enconman.2018.07.044

[22] L. Wang, and F. G. Yuan, "Energy harvesting by magnetostrictive material (MsM) for powering wireless sensors in SHM", Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007, Vol. 6529, p. 652941, 2007. https://doi.org/10.1117/12.716506

[23] E. O. Torres, and G. A. Rincon-Mora, "Electrostatic energy harvester and Li-Ion charger circuit for micro-scale applications", 49th IEEE International Midwest Symposium on Circuits and Systems, Vol. 1, pp. 65-69, 2006.

[24] Q-l. Cai, and S. Zhu, "Enhancing the performance of electromagnetic damper cum energy harvester using microcontroller: Concept and experiment validation", Mechanical Systems and Signal Processing, Vol. 134, 2019. https://doi.org/10.1016/j.ymssp.2019.106339

[25] T. G. Larsen, Z. Zhang, and J. Høgsberg, "Vibration damping of an offshore wind turbine by optimally calibrated pendulum absorber with shunted electromagnetic transducer", Journal of Sound and Vibration, Vol. 505, 2021. https://doi.org/10.1016/j.jsv.2021.116144

[26] B. S. Joyce, J. Farmer, and D. J. Inman, "Electromagnetic energy harvester for monitoring wind turbine blades", Wind Energy, Vol. 17, Issue 6, pp. 869-876, 2014. https://doi.org/10.1002/we.1602

[27] D. P. Arnold, "Review of microscale magnetic power generation", IEEE Transactions on magnetics, Vol. 43, Issue 11, pp. 3940-3951, 2007. https://doi.org/10.1109/TMAG.2007.906150

[28] P. D. Mitcheson, "Analysis and optimisation of energy-harvesting micro-generator systems", PhD thesis, Department of Electrical and Electronic Engineering, Imperial College London, University of London, 2005.

[29] C. B. Williams, and R. B. Yates, "Analysis of a micro-electric generator for microsystems", Sensors and Actuators A: Physical, Vol. 52, Issue 1-3, pp. 8-11, 1996. https://doi.org/10.1016/0924-4247(96)80118-X

[30] C. B. Williams, C. Shearwood, M. A. Harradine, P. H. Mellor, T. S. Birch, and R. B. Yates, "Development of an electromagnetic micro-generator", IEE Proceedings-Circuits, Devices and Systems, Vol. 148, Issue 6, pp. 337-342, 2001. https://doi.org/10.1049/ip-cds:20010525

[31] L. Zuo, B. Scully, J. Shestani, and Y. Zhou, "Design and characterization of an electromagnetic energy harvester for vehicle suspensions", Smart Materials and Structures, Vol. 19, Issue 4, 2010. https://doi.org/10.1088/0964-1726/19/4/045003

[32] J. Prudell, M. Stoddard, E. Amon, T. K. A. Brekken, and A. V. Jouanne, "A permanent-magnet tubular linear generator for ocean wave energy conversion", IEEE Transactions on Industry Applications, Vol. 46, Issue 6, pp. 2392-2400, 2010. https://doi.org/10.1109/TIA.2010.2073433

[33] Seiko, "Seiko Kinetic", http://www.seikowatches.com/technology/kinetic/

[34] E. M. Yeatman, "Energy harvesting from motion using rotating and gyroscopic proof masses", Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 222, Issue 1, pp. 27-36, 2008. https://doi.org/10.1243/09544062JMES701

[35] A. Z. Trimble, J. H. Lang, J. Pabon, and A. Slocum, "A device for harvesting energy from rotational vibrations", Vol. 132, Issue 9, 2010. https://doi.org/10.1115/1.4002240

[36] M. El-Hami, P. Glynne-Jones, N. M. White, M. Hill, Stephen Beeby, E. James, A. D. Brown, and J. N. Ross, "Design and fabrication of a new vibration-based electromechanical power generator", Sensors and Actuators A: Physical, Vol. 92, Issue 1-3, pp. 335-342, 2001. https://doi.org/10.1016/S0924-4247(01)00569-6

[37] B. Yang, Ch. Lee, W. Xiang, J. Xie, J. H. He, R. K. Kotlanka, S. P. Low, and H. Feng, "Electromagnetic energy harvesting from vibrations of multiple frequencies", Journal of micromechanics and microengineering, Vol. 19, Issue 3, 2009. https://doi.org/10.1088/0960-1317/19/3/035001

[38] V. R. Challa, M. G. Prasad, and F. T. Fisher, "A coupled piezoelectric-electromagnetic energy harvesting technique for achieving increased power output through damping matching", Smart materials and Structures, Vol. 18, Issue 9, 2009. https://doi.org/10.1088/0964-1726/18/9/095029

[39] B. Yang, C. Lee, W. L. Kee and S. P. Lim, "Hybrid energy harvester based on piezoelectric and electromagnetic mechanisms", Journal of Micro/Nanolithography, MEMS and MOEMS, Vol. 9, Issue 2, 2010. https://doi.org/10.1117/1.3373516

[40] W. Weaver Jr, S. P. Timoshenko, D. H. Young, Vibration problems in engineering, John Wiley and Sons, 1991. ISBN: 978-0-471-63228-3

[41] C. Davidson, M. J. Brown, B. Cerfontaine, T. Al-Baghdadi, J. Knappett, A. Brennan, C. Augarde, W. Coombs, L. Wang, A. Blake, D. Richards, "Physical modelling to demonstrate the feasibility of screw piles for offshore jacket-supported wind energy structures", Géotechnique, Vol. 72, Issue 2, pp. 108-126, 2022. https://doi.org/10.1680/jgeot.18.P.311

[42] S. S. Rao, Mechanical Vibrations, 6th edition, Pearson Editions, London, UK. 2017.

[43] I. Antoniadou, N. Dervilis, E. Papatheou, A. E. Maguire, K. Worden, "Aspects of structural health and condition monitoring of offshore wind turbines", Philosophical Transactions of the Royal Society A, Mathematical, Physical and Engineering Sciences, Vol. 28, 2015. https://doi.org/10.1098/rsta.2014.0075

[44] M. Faraday, "V. Experimental researches in electricity", Philosophical transactions of the Royal Society of London, Vol. 122, pp. 125-162, 1832.

[45] Z. Hameed, Y. S. Hong, Y. M. Cho, S. H. Ahn, C. K. Song, "Condition monitoring and fault detection of wind turbines and related algorithms: A review", Renewable and Sustainable energy reviews, Vol. 13, Issue 1, pp. 1-39, 2009. https://doi.org/10.1016/j.rser.2007.05.008

[46] S. R. Anton, H. A. Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)", Smart materials and Structures, Vol. 16, Issue 3, 2007. https://doi.org/10.1088/0964-1726/16/3/R01

[47] K. Leahy, C. Gallagher, P. O'Donovan, D. T. O'Sullivan, "Issues with data quality for wind turbine condition monitoring and reliability analyses", Energies, Vol. 12, Issue 2, 2019. https://doi.org/10.3390/en12020201

[48] N. G. Stephen, "On energy harvesting from ambient vibration. Journal of sound and vibration", Vol. 293, Issue 1-2, pp. 409-425, 2006. https://doi.org/10.1016/j.jsv.2005.10.003

[49] H. A. Sodano, G. Park, D. J. Inman, "Estimation of electric charge output for piezoelectric energy harvesting", Strain, Vol. 40, Issue 2, pp. 49-58, 2004. https://doi.org/10.1111/j.1475-1305.2004.00120.x

[50] D. Guyomar, A. Badel, E. Lefeuvre, C. Richard, "Toward energy harvesting using active materials and conversion improvement by nonlinear processing", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, Vol. 52, Issue 4, pp. 584-595, 2005. https://doi.org/10.1109/TUFFC.2005.1428041

[51] A. Khaligh, P. Zeng, C. Zheng, "Kinetic energy harvesting using piezoelectric and electromagnetic technologies—state of the art", IEEE transactions on industrial electronics, Vol. 57, Issue 3, pp. 850-860, 2009. https://doi.org/10.1109/TIE.2009.2024652

[52] S. Roundy, P. K. Wright, J. Rabaey, "A study of low-level vibrations as a power source for wireless sensor nodes", Computer communications, Vol. 26, Issue 11, pp. 1131-1144, 2003. https://doi.org/10.1016/S0140-3664(02)00248-7

[53] R. Elfrink, T. M. Kamel, M. Goedbloed, S. Matova, D. Hohlfeld, Y. Van Andel, R. Van Schaijk, "Vibration energy harvesting with aluminum nitride-based piezoelectric devices", Journal of Micromechanics and Microengineering, Vol. 19, Issue 9, 2009. https://doi.org/10.1088/0960-1317/19/9/094005

[54] S. Sukumaran, S. Chatbouri, D. Rouxel, E. Tisserand, F. Thiebaud, T. Ben Zineb, "Recent advances in flexible PVDF based piezoelectric polymer devices for energy harvesting applications", Journal of Intelligent Material Systems and Structures, Vol. 32, Issue 7, pp. 746-780, 2021. https://doi.org/10.1177/1045389X20966058

[55] D. Zhu, M. J. Tudor, S. P. Beeby, "Strategies for increasing the operating frequency range of vibration energy harvesters: a review", Measurement Science and Technology, Vol. 21, Issue 2, 2009. https://doi.org/10.1088/0957-0233/21/2/022001

[56] D. Clemente, P. Rosa-Santos, F. Taveira-Pinto, "On the potential synergies and applications of wave energy converters: A review", Renewable and Sustainable Energy Reviews, Vol. 135, 2021. https://doi.org/10.1016/j.rser.2020.110162

[57] M. O. Hansen, "Aerodynamics of Wind Turbines, Earthscan from Routledge", 3rd Edition, Taylor and Francis Group, London, UK, 2015. ISBN 9781315769981 https://doi.org/10.4324/9781315769981

[58] Z. Wang, L. He, X. Gu, S. Yang, S. Wang, P. Wang, G. Cheng, "Rotational energy harvesting systems using piezoelectric materials: A review", Review of Scientific Instruments, Vol. 92, Issue 4, 2021. https://doi.org/10.1063/5.0039730

[59] H. Liu, J. Zhong, C. Lee, S. W. Lee, L. Lin, "A comprehensive review on piezoelectric energy harvesting technology: Materials, mechanisms, and applications", Applied Physics Reviews, Vol. 5, Issue 4, 2018. https://doi.org/10.1063/1.5074184

[60] H. B. Radousky, H. Liang, "Energy harvesting: an integrated view of materials, devices and applications", Nanotechnology, Vol. 23, Issue 50, 2012. https://doi.org/10.1088/0957-4484/23/50/502001

[61] V. Giurgiutiu, Structural health monitoring of aerospace composites, 1st Edition, 2015. ISBN: 9780124104419

[62] J. P. Lynch, K. J. Loh, "A summary review of wireless sensors and sensor networks for structural health monitoring", Shock and vibration digest, Vol. 38, Issue 2, pp. 91-130, 2006. https://doi.org/10.1177/0583102406061499