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14.2 Theoretical and mathematical analysis of a bladeless wind turbine

Abstract

A groundbreaking approach to harness wind energy for sustainable power generation involves the utilization of bladeless wind turbines. Unlike traditional wind turbines equipped with rotating blades, bladeless wind turbines employ advanced technology to eliminate the need for mechanical spinning components. Nonetheless, these turbines come with certain drawbacks, such as their impact on wildlife, maintenance requirements, and aesthetic considerations. This article aims to illuminate the potential of bladeless wind turbines in transforming the renewable energy landscape by providing an overview of their principles, design, and advantages. The fundamental concept behind bladeless wind turbines revolves around harnessing kinetic energy through wind-induced oscillations and vibrations. This article underscores several essential mathematical equations while considering each topic. A slender mast or rod will oscillate and vibrate due to the wind's movement around it. Bladeless wind turbines represent a pioneering advancement in the realm of renewable energy. As the world seeks cleaner and more sustainable electricity sources, they do present challenges, yet their potential benefits in terms of environmental impact, maintenance, and aesthetics position them as a promising inclusion in the array of renewable energy solutions.

Key words

Bladeless wind turbine(BWT), working principle, renewable energy harvesting, mathematical analysis, power conversion, future applications

14.2.1 Introduction

In response to mounting environmental concerns and the urgent need to stop climate change, there has been a rise in the global drive to adopt sustainable energy sources in recent years. Because it provides a plentiful and environmentally benign source of electrical energy, wind power stands out as a feasible alternative within the area of renewable energy. Although conventional horizontal-axis wind turbines have been instrumental in capturing wind energy, they have a number of disadvantages, including noise pollution, damage to birds, and aesthetic concerns. These drawbacks have motivated the investigation of creative substitutes.

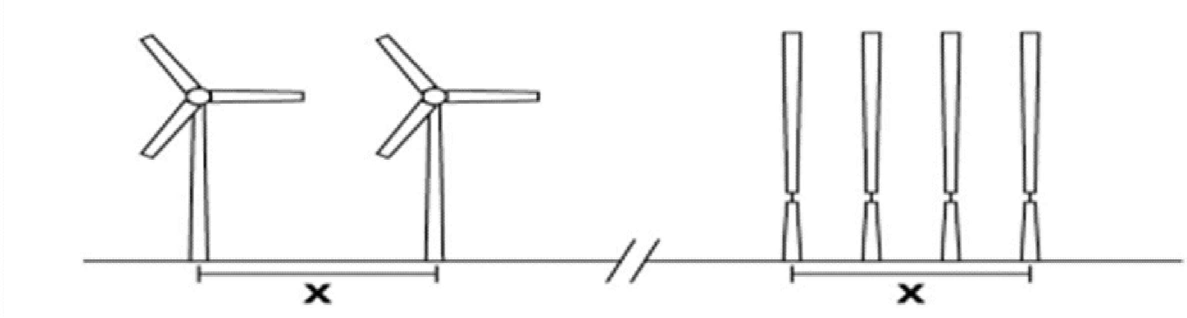
In order to overcome these challenges, the development of bladeless wind turbines has emerged as a promising new direction in the field of wind energy production. With their ground-breaking method, these cutting-edge turbines represent a substantial divergence from the conventional spinning blade concept. Bladeless turbines, which use aeroelastic flutter, vibration, or oscillation mechanisms rather than moving blades to capture wind energy, offer a number of advantages that have the potential to completely reshape the wind energy market.

This study explores the intriguing world of bladeless wind turbines and considers how they can alter the wind energy sector. We examine the basic ideas, various design approaches, practical benefits, and potential drawbacks of bladeless wind turbines with an emphasis on sustainability and environmental concerns. Our goal is to offer meaningful insights into the practicality and sustainability of bladeless turbines as a substantial component of renewable energy sources by assessing recent advancements and research in this field.

Understanding the potential and constraints of bladeless wind turbines is increasingly important for governments, investors, and researchers as the world moves toward cleaner energy sources. We might be getting closer to creating a cleaner and more sustainable energy future by utilizing the creative possibilities of bladeless wind turbines. Such a discovery could help lessen our reliance on fossil fuels and lessen the negative effects of conventional wind turbine technology on the environment. This study acts as a lighthouse, illuminating how bladeless turbines may help to increase the production of sustainable wind energy.

14.2.2 Traditional wind turbines vs bladeless wind turbines

Bladeless turbines are inherently straightforward, consisting of just a single structural component. This simplicity offers several advantages in terms of manufacturing, transportation, storage, and installation. Notably, they lack bearings, gears, or other moving parts, which makes their maintenance a straightforward process.



Comparison between bladeless and conventional wind turbines.

In comparison to bladed wind turbines, bladeless turbines have the potential to generate electricity at a 40% lower cost. Traditional wind turbines, on the other hand, are towering structures with rotating fan-like blades, a well-established technology used worldwide. In the case of traditional wind turbines, the blades capture the kinetic energy of the wind and convert it into mechanical energy, which, in turn, drives a generator to produce electricity.

The choice between bladeless and conventional wind turbines depends on factors like efficiency, environmental impact, and location-specific considerations. Conventional turbines are widely used for utility-scale power generation, while bladeless turbines may find applications in specific situations where reduced noise and visual impact are important.

14.2.3 STRUCTURE & OPERATION

The concept of vortex devices is simple, which makes them easy to produce, install, and use. They are made out of a fixed base and a free-moving cylindrical mast that oscillate perpendicular to the wind, joined by a carbon rod. The internal parts never come into contact; instead, they cooperate to create electricity.

14.2.4 ENERGY HARNESS

Pressure vortexes are created when wind swirls around an object. The wind speed affects how often these vortexes occur. The structure begins oscillating and absorbs the energy from the vortexes if it has a suitable natural resonance frequency. Vortex Shedding is an aeroelastic resonance phenomenon that happens frequently in nature.

14.2.5 ENERGY CONVERSION

Similar to a traditional alternator, our gadget generates power using induction of electricity by interacting coils and magnetic fields. It's significant that neither the usage of a gearbox nor rotation on a shaft are necessary for this method to work. The magnets also act as a "Tuning System," changing the mast's perceived elasticity constant. The range of wind speeds in which oscillations can occur is increased by this adjustment.

14.2.6 Differences between bladeless and traditional wind turbines

Although conventional wind turbines don't need as much wind as some people might think in order to function, they are less effective when there isn't any wind. By being independent, bladeless wind turbines allay this worry. Alternatives without blades perform better at producing, storing, and dispersing energy.

While bladeless designs increase energy harnessing capabilities and overall efficiency by more than 60%, traditional wind turbines can lose up to two-thirds of the wind energy they catch. Additionally, they have benefits for the environment and supply chains.

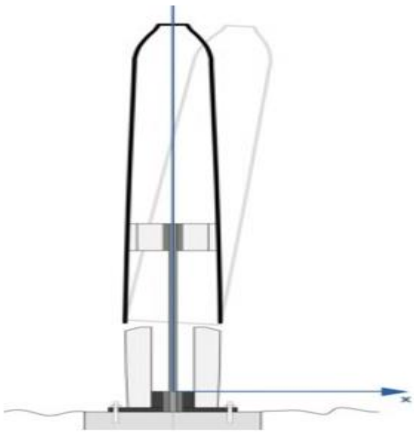
Compared to their conventional equivalents, their streamlined construction and smaller size put less strain on the extraction of raw materials. Furthermore, the lack of blades guarantees the protection of bats and birds. Instead of using traditional blades, they work by harnessing a phenomena known as the "Magnus Effect."

14.2.7 The working principles of bladeless wind turbines?

This cutting-edge device uses a vertically oriented cylinder with an elastic rod to generate power by harnessing wind-induced vortex shedding. Through the use of an alternator system, the cylinder oscillates within a wind range and generates electricity.

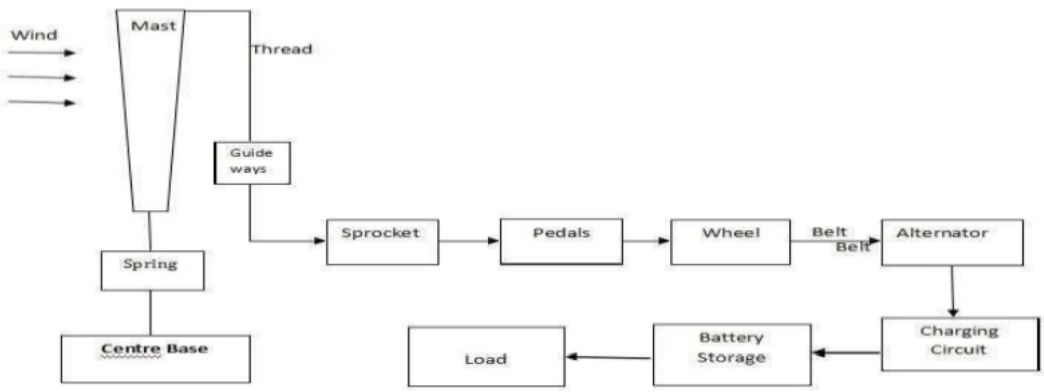
Although mostly rigid, the outer cylinder can vibrate because it is attached to the bottom rod. The maximum oscillation amplitude is present at the top of the cylinder.

Polymers reinforced with carbon and glass fibers, which are frequently used in conventional wind turbine blades, are used to build the framework. The top of the rod supports the mast, and the bottom is firmly fastened to the ground. Low energy loss during oscillation and good fatigue resistance are guaranteed by the use of carbon fiber-reinforced polymers.



Work principle.

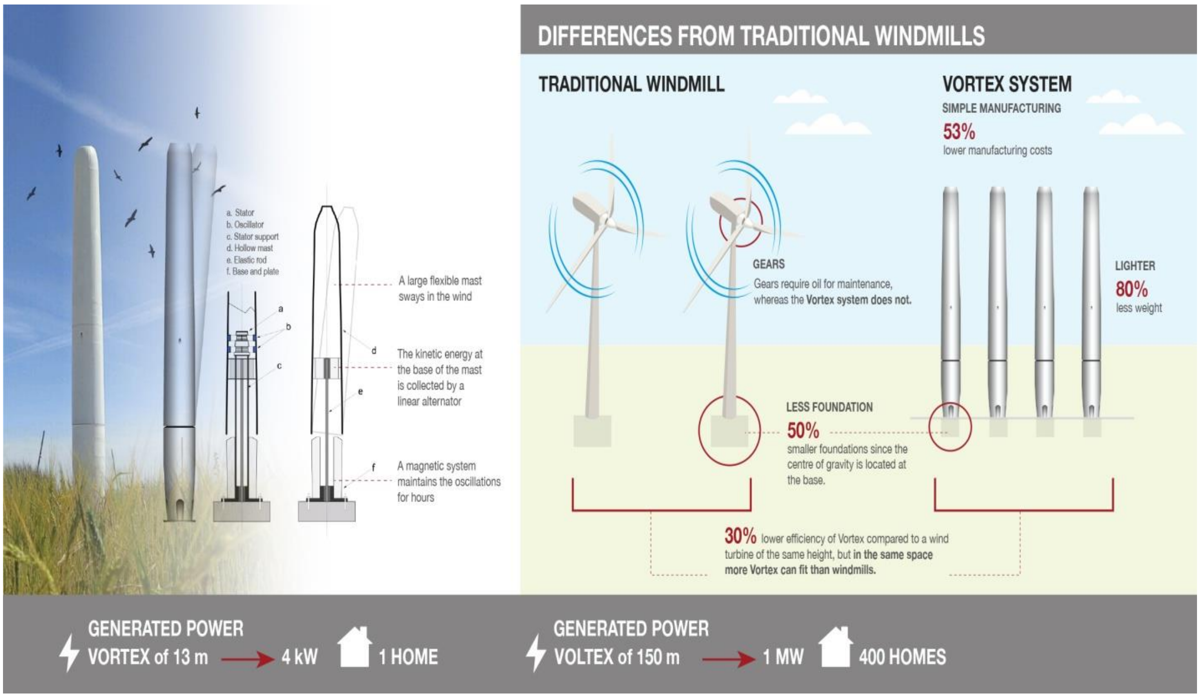
The idea behind how vortex wind turbines work is that similar forces may be used to produce power. The bladeless wind turbine is able to harvest energy from this motion, much like a traditional generator, when wind vortices align with the natural frequency of the device's structure. Although Vortex bladeless turbines may not be as power-efficient as conventional wind turbines, this efficiency loss can be made up for by the fact that more of them can be installed in the same space.



Work principle scheme.

14.2.8 POTENTIAL APPLICATIONS

Identical to solar panels, these devices have low maintenance needs and are wildlife-friendly, opening up new opportunities for wind energy in populated and protected areas. However, they are also compatible with the areas where traditional wind power installations are made. In order to provide its special qualities to large-scale production, this technology may be scaled up, whether in conventional wind farms or vast offshore regions.



These bladeless turbines are able to provide a significant amount of force while rotating up to twenty times per minute and reaching speeds of 289 km/h. Turbine blades typically experience significant deterioration over time, which is understandable given their exposure to harsh offshore weather and the erosion they experience. Three-bladed turbines are considered the most effective alternative right now, but this might not always be the case. We owe the majority of our wind energy production to the efficiency of three-bladed turbines until they become the norm.

Table 1

Dimensions for the design of bladeless Turbine

Parameter	**Dimension**
Length of each Rod	517 mm
Upper diameter of the Disc	203 mm
Lower diameter of the Disc	100 mm
Angle between each rod with horizontal	96 deg
Outer casing thickness	17mm
Outer casing outer diameter	40mm
Total number of rods	18mm

14.2.9 Bladeless mathematical model and power calculation

It was difficult to create a mathematical model because the vortex bladeless problem had not been thoroughly examined in many earlier studies. The lateral force produced by vortex shedding oscillates back and forth along the mast. It is logical to characterize this force as a harmonic in time at the shedding frequency because it is a more asinusoidal process, equation (1)

$$F(t)=F_0 \sin(\omega_s t)$$

Where vs is the frequency of vortex shedding and F_0 is the magnitude of the stimulating force. These factors are affected by the shape of the cylinder and the characteristics of the fluid, based on experiments carried out by Bearman in 1984 and revelations from Kelly in 2012. Then, using equations (2) and (3), those variables are combined in a non-dimensional form:

$$C_l = f\left(Re, \frac{D}{L}\right)$$

$$S = f\left(Re, \frac{D}{L}\right)$$

The initial parameter is the lift coefficient, defined by equation (4):

$$C_l = \frac{F_l}{\frac{1}{2}\rho u^2 DL}$$

Therefore, the exciting force can be determined using equation (5),

$$F_1(t) = \frac{1}{2}\rho u^2 DLC_l \sin(\omega_s t)$$

The second parameter is the Strouhal number and is defined by equation (6)

$$S = \frac{\omega_s D}{2\pi u}$$

The independent parameters of equations (2) and (3) are the Reynolds number, equation (7), and D/L ratio of mast:

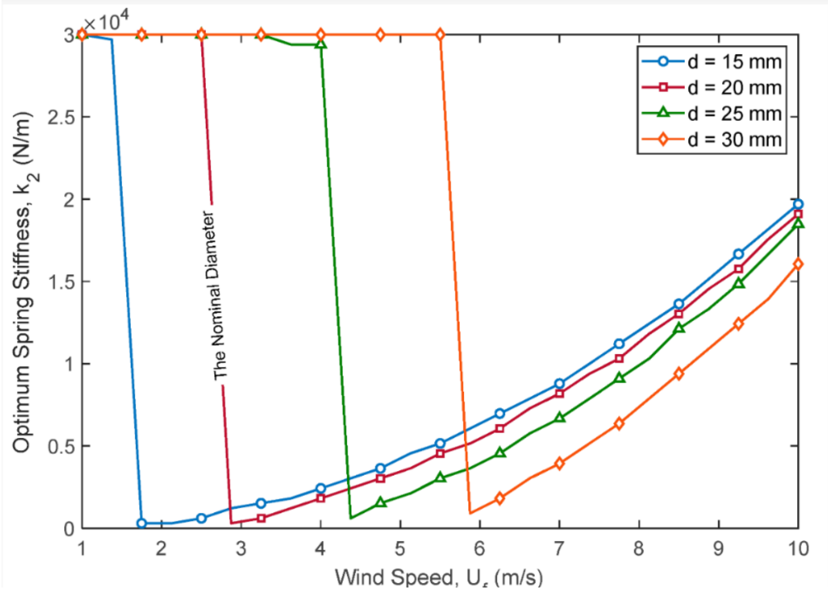
$$Re = \frac{\rho u D}{\mu}$$

The threshold wind speed normally increases with a larger beam diameter, as a first observation. The turbine becomes more stable at low wind speeds with a bigger beam diameter. Therefore, a larger wind speed is needed for the turbine to operate efficiently, which subsequently reduces the turbine's useable range.

It's also important to note that for all diameters above the threshold speed, the relationship between the optimal stiffness of the spring and wind speed follows a quadratic proportion. It is possible to determine the cantilever beam's relative stiffness, represented by the letter "k1." k_1 can be determined by

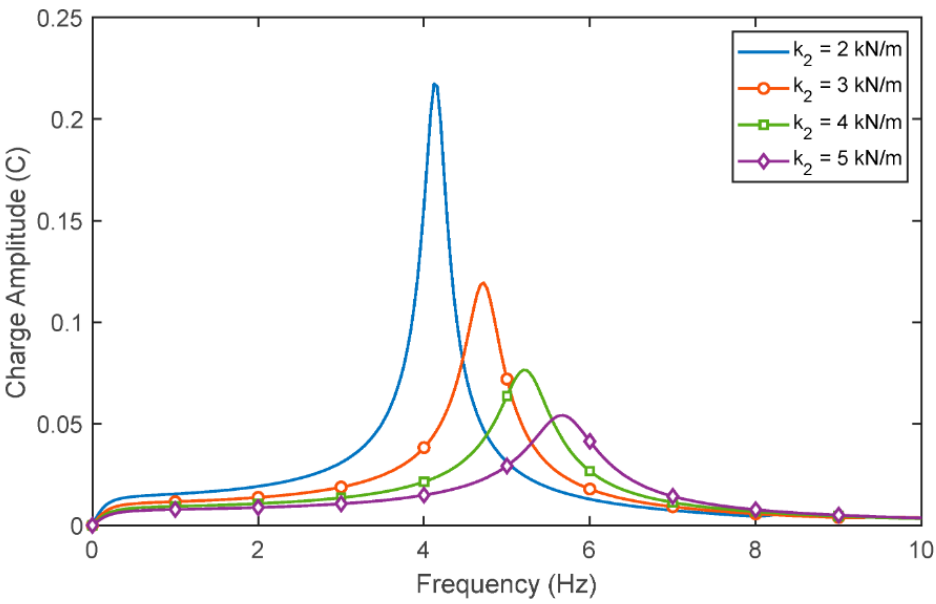
$$k_1 = \frac{3\pi}{64} \times \frac{E_b d^4}{L_b^3}$$

where E_b is the Young's modulus of the beam material, and d is the beam diameter.



Optimum spring stiffness at various diameters of cantilever beam of the tunable turbine

Following figure shows the frequency spectrum of the output charge of the turbine for different spring stiffness values. It is clear that adjusting spring stiffness allows the fundamental frequency of the turbine to be precisely regulated. The amount of electricity that can be gathered declines as the spring stiffens. This is explained by the reason that the magnet's displacement decreases significantly with high spring stiffness. The spring performs as a rigid link at extremely high stiffness levels, effectively converting the device into a typical bladeless wind turbine.



Frequency spectrum of the output charge at different values of the spring stiffness

The natural frequency of the body is calculated by using torque method.

$$fn = 0.5 \cdot \left(\left((KL^2 - 2Mc \cdot gL):4\right):I\right)$$

fn - Natural frequency,

I - Moment of inertia of conical frustum,

K - Spring stiffness,

L - Length of conical frustum,

Mc - Center of mass of conical frustum ,

G- Acceleration due to gravity.

MOMENT OF INERTIA

$$I = \left(\frac{1}{3}\right) Mc \cdot L^2$$

I - Moment of inertia of conical frustum

K - Spring stiffness. (1.219 m)

Mc - Mass of conical frustum (0.7986 kg)

G - Acceleration due to gravity. (9.81)

I = (1/3) Mc * L2 = (1/3) * 0.7986 * 1.2192 = 0.395 kg m2

SHEDDING FREQUENCY CALCULATIONS

$$St = \frac{F_s \cdot D}{U}$$

St - Strouhal No (0.2)

Fs - Shedding frequency

D - Diameter (0.2m)

U - Velocity of fluid (2.8 m/s)

St = Fs * D/ U

0.2 = Fs * 0.2/2.8

Fs = 2.8 , Therefore shedding frequency is 2.8 Hz

POWER CALCULATION

The oscillation produce by the vortex shedding is converted in to rotary motion and then into power.

$$P = KC_P\left(\frac{1}{2}\right)\rho AV^3$$

P - Power output, Kilowatts

Cp - Max Power coefficient (0.35)

P - Air density, lb/ft 3 (0.0765)

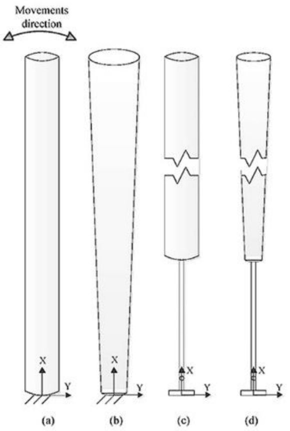
A - Rotor swept area

V - Wind speed, kmph (21.6)

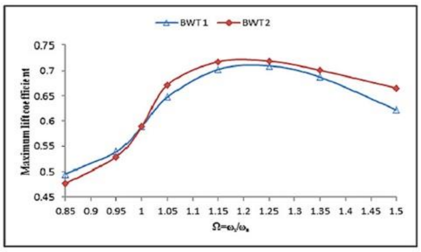
K = 0. 000133 A = πDL = 3.14 * 0.656168 * 3.999 A = 8.239ft 3

P = 0.000133*0.35*(1/2)*0.0765*8.239*(21.6)3 P = 0.1478KW P = 147.83W

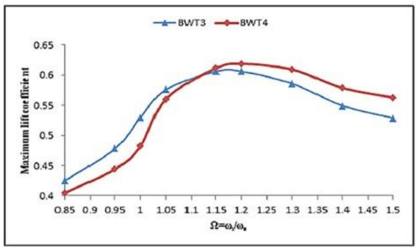
The proposed Bladeless Wind Turbines (BWTs) differ in how they are installed and how their bluff body is designed. The assessment of the power levels that can be transferred to BWTs and the comprehension of how these power levels fluctuate with variations in the free-stream air velocity are more particularly connected to these discrepancies. In order to do this, it has been decided to analyze the lateral displacement degree of freedom (DOF) of BWTs using simple mathematical dynamic models.



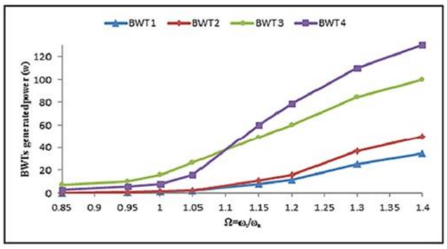
Geometrical model of the bladeless wind turbine
(a) BWT1, (b) BWT2, (c) BWT3, (d) BWT4



Lift coefficient curves of BWT1 and BWT2 versus non-dimensional frequencies Ω



Lift coefficient curves of BWT3 and BWT4 versus non-dimensional frequencies Ω



Power level transmitted to BWTs in the lock-in bound

The Vortex-Induced Vibration (VIV) bladeless wind turbines are made of a relatively long cylinder that is exposed to the airflow and can be either flexible or placed on a flexible structure. As shown in figure, there are four different BWTs that are taken into consideration, each with a unique cylinder design and mounting arrangement:

- BWT1: Features a flexible right circular cylinder.
- BWT2: Incorporates a flexible conic cylinder.
- BWT3: Utilizes a rigid right circular cylinder that's mounted on a flexible beam.
- BWT4: Employs a rigid conic cylinder mounted on a flexible beam.

14.2.10 Advantages

• Traditional wind turbines require expensive pieces such nacelles, support systems, and blades, which are essential components of bladeless wind turbines. But bladeless wind turbine does not contain from these parts.

• Bladeless turbines are incredibly light, with low centers of gravity that are located close to the ground. As a result, compared to traditional turbines, there is a significant reduction in the need for anchoring or intricate foundations, simplifying the installation procedure.

• These turbines can fit more units on the same surface area because to their lower swept areas, effectively making up for the loss in power efficiency through increased space efficiency.

• Turbines without blades are adaptable and can run on or off the grid. Additionally, they work well with hybrid wind-solar installations.

• Bladeless wind turbines are 50% less expensive than their conventional counterparts.

• In comparison to conventional wind turbines with blades, bladeless wind turbines have fewer moving parts, which lowers noise levels.

14.2.11 Disadvantages

• Bladeless wind turbines have many benefits, but they also have some significant drawbacks. Their insufficient ability to produce energy is a severe disadvantage. While bladeless wind turbines can only create a limited amount of power, conventional wind turbines can produce significant amounts of energy.

• Bladeless turbines lack the ability to alter the direction of the wind, rendering them unsuitable for regions where wind direction frequently changes.

• Because they are so dependent on wind speed, bladeless wind turbines cannot produce energy when there is little wind. Because of this, they are an unreliable source of energy, especially where the wind blows at different speeds.

• Bladeless turbine oscillations can cause a natural vibration that could be harmful to the environment and wildlife.

14.2.12 Future of bladeless wind turbines

Although three-bladed turbines have been the industry norm for producing renewable energy in recent years, there is no assurance that this will be the case in the future. Engineers are developing more practical and efficient systems for generating energy in the future, such as vertical bladed turbines for residential usage.

One of the most often proposed concepts is a turbine without blades. There are several benefits to building a turbine without blades, despite the fact that it may appear intuitive considering the resistance needed to convert wind energy into electricity. Cost and upkeep are one advantage. The running of current turbines places them under a considerable deal of stress. Turbine blades have been shown to deteriorate in quality over time, particularly when they are subjected to erosion in harsh conditions.

14.2.13 Conslusion

In conclusion, this research article has provided a comprehensive exploration of bladeless wind turbines, shedding light on their potential to reshape the wind energy industry. With a primary focus on sustainability and environmental considerations, the fundamental principles, diverse design variations, operational advantages, and potential challenges associated with bladeless wind turbines have been thoroughly examined.

The findings presented here suggest that bladeless wind turbines hold promise as a novel and potentially transformative technology in the renewable energy landscape. Their innovative design offers several advantages, including reduced maintenance requirements, lower noise emissions, and the potential for decreased environmental impact when compared to traditional bladed turbines.

Nevertheless, it is important to acknowledge that there are still critical issues that must be addressed. Scalability, efficiency optimization, and cost-effectiveness remain challenges that require continued research and development efforts.

As we navigate the global shift toward cleaner and more sustainable energy sources, bladeless wind turbines emerge as a promising candidate to play a significant role in this transition. They have the potential to contribute to a reduced reliance on fossil fuels and offer a more environmentally friendly alternative for wind energy generation.

This research serves as a valuable resource, offering insights into the feasibility and sustainability of bladeless wind turbines as a vital component of our renewable energy mix. Further innovation and collaboration within the field are necessary to fully unlock the potential of this technology and drive sustainable wind energy generation into the future.