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OPERATIONAL ASPECTS IN VERTICAL AXIS WIND TURBINES

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ABSTRACT

The need for energy is growing and wind is a resource that has seen increased use worldwide in recent years, especially since it allows energy production without major environmental impacts. Vertical axis wind turbines represent a versatile and innovative technology for harnessing wind energy. While they are not yet as commonly used for large-scale wind farms as horizontal-axis turbines, they offer unique advantages in urban environments, low-wind conditions, and specific applications where wind direction varies. As technology improves, VAWTs may become a more prominent part of the global renewable energy mix.

KEYWORDS: seismic action, seismic isolation, damping, displacement, velocity, energy dissipation, vibration period

1. INTRODUCTION

Wind energy represents the process of harnessing the kinetic energy of the wind and converting it into usable power through wind turbines. It is one of the most sustainable and rapidly growing sources of renewable energy worldwide, playing a crucial role in the transition to cleaner energy systems.

Wind turbines are the primary technology used to convert wind energy into electricity and the basic process involves air masses movement carrying kinetic energy and when it hits the blades of a wind turbine, it causes their rotational movement.

The mechanical energy conversion is made by the spinning blades turning a rotor connected to a generator. This mechanical energy is converted into electrical energy by the generator.

The electricity generated is sent through cables to the grid or directly to consumers.

There are two main types of wind turbines constructed as horizontal-axis wind turbines (HAWT) which are the most common in large wind farms. The other types are represented by vertical-axis wind turbines (VAWT) which have blades arranged vertically and can operate in turbulent wind conditions, but they are less common due to their lower efficiency.

Wind energy can be broadly categorized into onshore wind energy which is the more common and widely deployed form of wind energy. Wind farms are located on land where wind speeds are higher and more consistent.

Offshore wind energy is a newer approach while offshore wind farms are located in bodies of water, typically on the continental shelf where turbines can take advantage of stronger and more consistent winds. However, they are more expensive to install and maintain.

The main advantages of wind energy are related to the fact that it is a renewable resource while wind is an inexhaustible resource and its use doesn't deplete natural resources, presents low operating costs because once a wind turbine is installed, its maintenance and operational costs are relatively low. The wind itself is free, making it cost-competitive with fossil fuels in some areas.

Reduction in carbon emissions are registered while wind energy does not emit greenhouse gases during operation, making it a critical solution for combating climate change.

Wind energy is scalable, from small residential turbines to large wind farms and wind energy sector is a major source of new jobs, ranging from turbine manufacturing to maintenance and research.

The challenges are directed towards intermittency while wind is not always predictable and turbine energy production depends on wind speed. This can lead to fluctuations in electricity generation, making it challenging to provide a constant power supply.

Some communities find wind turbines unsightly or disruptive due to the noise they generate and this can create opposition to wind farm developments.

Large-scale wind farms can require significant land space and there are concerns about the impact of turbines on wildlife, especially birds and bats.

Although operational costs are low, the initial capital investment for wind farms, especially offshore, can be very high.

Larger and more efficient turbines as advances in turbine design have led to larger turbines with greater capacity and efficiency and based on the latest research new turbine models can generate more electricity from lower wind speeds.

Offshore wind farms are being developed using floating turbines, which can be installed in deeper waters where traditional bottom-fixed turbines are not feasible.

Innovations in smart grid technology and energy storage (such as batteries) are helping to solve the intermittency problem by storing excess energy when wind speeds are high and supplying it when demand is high.

As of 2023, China is the largest producer of wind energy, with the United States and Germany following closely behind, the International Renewable Energy Agency (IRENA) reports that the global installed capacity of wind power has exceeded 800 GW.

Offshore wind energy is expected to grow significantly in the coming years, with countries like the UK, China and Germany investing heavily in this area.

The future of wind energy looks promising, driven by technological advancements, the global push to combat climate change and the falling costs of installation and operation.

Wind energy will increasingly be integrated with solar and other renewable energy systems to create a more reliable and sustainable energy grid.

As the technology matures, offshore wind energy is expected to become a major contributor to the global energy mix, particularly in countries with access to strong coastal winds.

Advances in storage technology, such as large-scale batteries and hydrogen storage, will help mitigate the intermittency issue and provide a more stable energy supply.

2. VERTICAL AXIS TURBINES

Vertical axis wind turbines represent a versatile and innovative technology for harnessing wind energy. While they are not yet as commonly used for large-scale wind farms as horizontal-axis turbines, they offer unique advantages in urban environments, low-wind conditions, and specific applications where wind direction varies. As technology improves, VAWTs may become a more prominent part of the global renewable energy mix.

Vertical axis wind turbines (VAWTs) are a type of wind turbine where the axis of the rotor is perpendicular to the ground, as opposed to the more common horizontal axis wind turbines (HAWTs), where the axis is horizontal. This design offers specific advantages, especially in certain location conditions and for particular uses.

There are several types of VAWTs, but the most common ones are represented by Savonius, Darrieus and Giromill types.

The Darrieus design (figure 1) is the most well-known and features curved or straight blades arranged in a shape similar to an “H.” The blades are attached to a vertical structure. This type of turbine is self-starting, meaning it doesn’t need an external force to begin rotating, performs well in consistent wind conditions, is durable and offers good performance in urban or crowded areas.

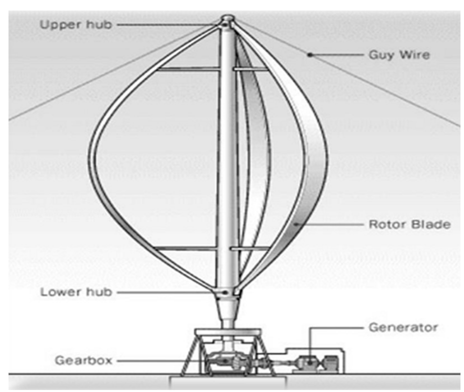

Fig. 1. Darrieus 4 MW turbine mounted in Quebec Canada

The Savonius design is a simpler type of VAWT, consisting of two or more scoops or semi-cylindrical blades that capture the wind (figure 2). Savonius turbines are less efficient than the Darrieus type but are very simple and easy to build. They are highly stable and easy to construct, being suitable for areas with variable wind speeds and for small-scale applications like battery charging.

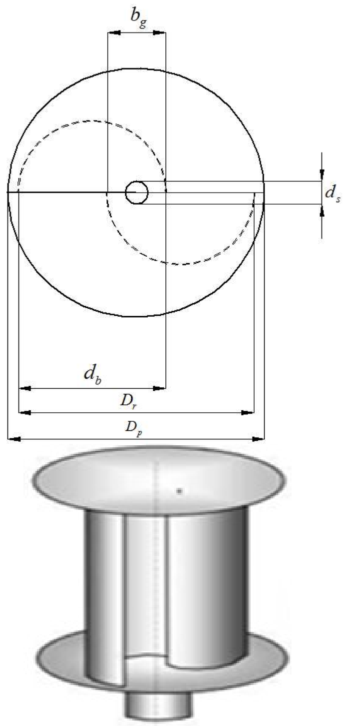

Fig. 2. Savonius turbine model

The Giromill is a variant of the Darrieus, featuring a "curved-blade wheel" design (figure 3). It is more stable than the Darrieus and performs well even in conditions of variable wind speeds. Works well in areas with constant winds and can operate efficiently in smaller or constrained spaces.

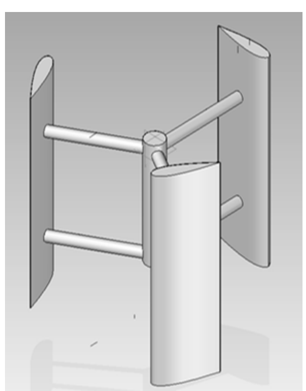

Fig. 3. Giromill turbine model

One of the biggest advantages of VAWTs is their ability to capture wind from any direction, unlike HAWTs that need to be oriented into the wind and this property makes VAWTs more versatile.

VAWTs are more suitable for locations where wind direction and speed vary. Due to their compact design and ability to be placed closer to the ground, they are ideal for urban settings or areas with limited space. VAWTs generally have fewer exposed moving parts, making them safer and easier to maintain compared to HAWTs. They do not require a complex mechanism to track wind direction, which can reduce the need for maintenance and repair. Regarding the operation VAWTs typically generate less noise and fewer vibrations than horizontal-axis turbines, making them more suitable for residential and urban environments. The vertical design allows them to be more easily integrated into the urban landscape without negatively affecting the area’s aesthetic and their smaller size allows them to be used for energy production in individual buildings without taking up significant space.

3. EFFICIENCY PARAMETERS FOR WIND TURBINES

VAWTs are generally less efficient than HAWTs. In particular, Darrieus turbines are efficient only at high wind speeds, while Savonius turbines are less effective at capturing wind energy.

VAWTs are a good option for generating small amounts of energy, such as powering homes or small commercial buildings, particularly in areas with variable winds or space constraints.

Due to their compact design and ability to operate in variable wind conditions, VAWTs can be installed on rooftops in urban environments, allowing buildings to generate their own electricity locally.

VAWTs are useful in remote or off-grid locations, where there is no infrastructure for energy supply and where wind conditions may be inconsistent.

Considering the turbine diameter, the swept area of the turbine is calculated:

$$A = \pi \left(\frac{d}{2} \right)^2 \tag{1}$$

While the power output is calculated using the formula:

$$P = \frac{1}{2} \left(\rho \cdot A \cdot v^3 \cdot C_p \right) \tag{2}$$

where:

P - power output of the turbine (W);

ρ - air density (1,225 kg/m³ at sea level);

A - the swept area of the turbine blades (m²);

v - the wind speed (m/s);

Cp - the power coefficient.

The power coefficient measures how efficiently a turbine converts wind energy into mechanical energy, with a maximum value of 0.593 based on the Betz limit.

For the efficiency calculation, it should be noted that efficiency is normalized by the Betz limit using:

$$E = 100 \cdot \left(\frac{P}{P_{\max}} \right) \tag{3}$$

where $P_{\max}$ represents the maximum theoretical power.

The equation provides efficiency in percentage, where the maximum theoretical power is calculated for each wind speed.

The rotor torque is calculated as:

$$T = \frac{P}{\omega} \tag{4}$$

where ω is the angular velocity of the turbine's rotor, which depends on the rotor speed.

Rotor speed is calculated using the Tip-Speed Ratio (TSR):

$$n = \frac{v}{v_{TSR} \cdot d} \tag{5}$$

where n is the rotor speed in RPM, v is the wind speed, v_{TSR} is the tip-speed ratio and d is the diameter of the turbine [1-5].

4. OPERATION ANALYSIS RESULTS

In order to highlight the power output and comparative differences between onshore and offshore turbines, values that are specific to the operation of both types of turbines are considered.

The operational analysis focused on vertical axis wind turbines show their performance and efficiency variation with wind conditions.

The offshore VAWTs generally have better performance (higher power output and efficiency) because they are designed to handle stronger and more consistent winds.

The onshore VAWTs produce less power and have slightly lower efficiency due to smaller swept areas and more variable wind speeds.

Main parameters for VAWT consider the definition of air density and specific wind speeds. The analysis focus is on two types of VAWTs offshore type with a diameter of 20 meters, power coefficient Cp=0.30 and onshore VAWT with a diameter of 15 meters, power coefficient Cp=0.25.

The offshore VAWT generates more power at higher wind speeds compared to the onshore VAWT, as the swept area is larger and wind conditions are generally more consistent offshore (figure 1).

The results for the highest wind speed (12 m/s) show the difference in power output and efficiency between offshore and onshore VAWTs (figure 2).

Regarding the efficiency, the offshore VAWT shows higher efficiency at higher wind speeds, although VAWTs generally have lower efficiency than HAWTs due to the design (figure 3).

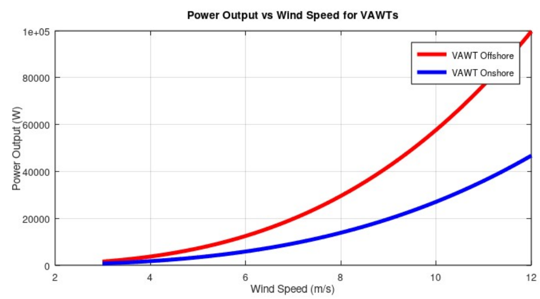

Fig. 1. VAWTs power output based on wind speed

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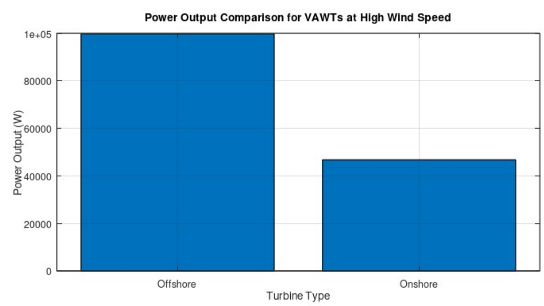

Fig. 2. VAWTs power output at high wind speed

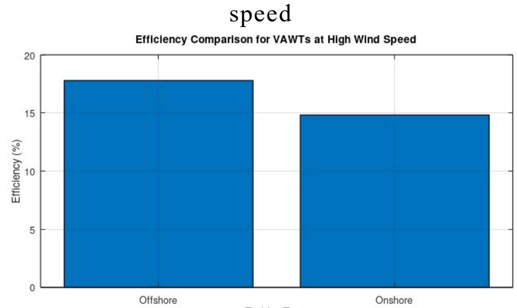

Fig. 3. VAWTs efficiency at high wind speed

For the wind speed increase, the rotor speed (RPM) also increases, but it will be limited by the turbine design in terms of tip-speed ratio (figure 4).

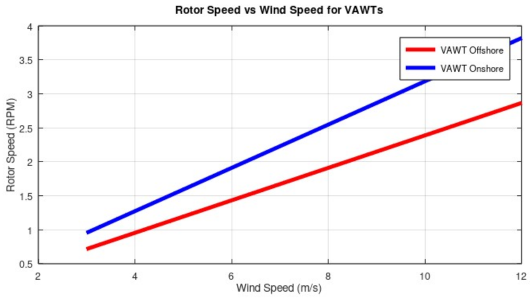

Fig. 4. VAWTs rotor speed based on wind speed

The torque value increases with wind speed, but is higher for turbines with larger diameters (offshore) (figure 5).

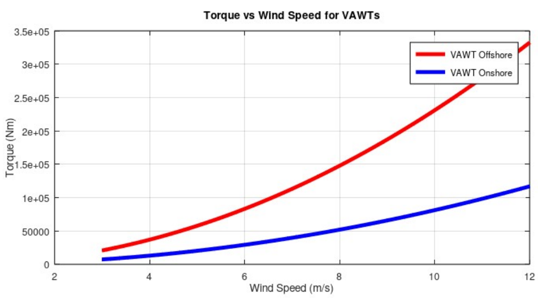

Fig. 5. VAWTs torque based on wind speed

An operational analysis for three main representative types of vertical axis wind turbines (VAWTs), the main important parameters such as power output, efficiency, torque, rotor speed are considered.

The constructive models are represented by Darrieus, Savonius and Giromill VAWT.

Key operational parameters are power output, as the amount of electrical power generated by the turbine, efficiency as the turbine conversion percentage of the kinetic energy from the wind into usable electrical power, torque as the rotational force produced by the turbine blades, rotor speed (RPM) as the speed at which the turbine blades rotate and swept area by the rotor blades, which is a key determinant of power generation.

	Turbine type		
Parameter	**Darrieus**	**Savonius**	**Giromill**
Rotor diameter [m]	10	10	10
Swept area [m2]	78.54	100	78.54
Power coefficient (Cp)	0.40	0.20	0.35
Tip speed ratio (TSR)	3-7	0.8-1.2	2-5
Torque output	Low-Medium	High	Medium
Starting torque	Low	Very high	Medium
Efficiency (%)	35-40	15-25	30-35
Optimum wind speed [m/s]	6-25	3-10	5-20
RPM Range [RPM]	100-400	10-80	50-300
Best usage	Large scale power High wind speed	Low wind speed Urban applications Water pumping	Hybrid use Medium wind speed

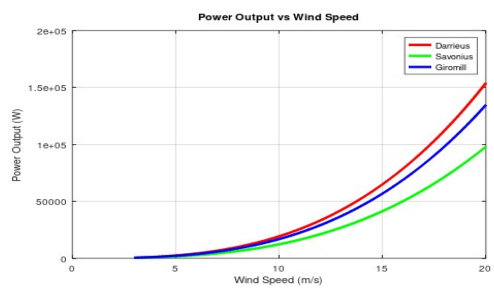

Fig. 6. VAWT power output based on wind speed values

Darrieus rotor generates the most power at higher speeds, Savonius rotor provides lower power output with the ability to start producing power at lower wind speeds, while Giromill rotor performs between the two other rotor types (figure 6).

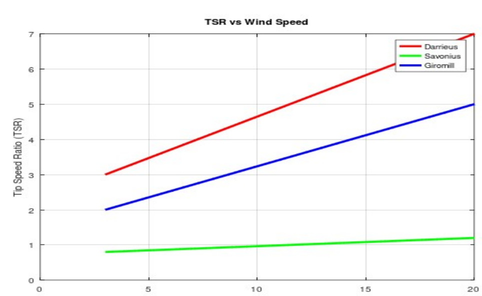

Fig. 7. VAWT tip speed ratio (TSR) based on wind speed values

Darrieus provides a higher TSR indicating higher rotor speed, Savonius has a much lower

TSR, meaning it rotates slower (figure 7).

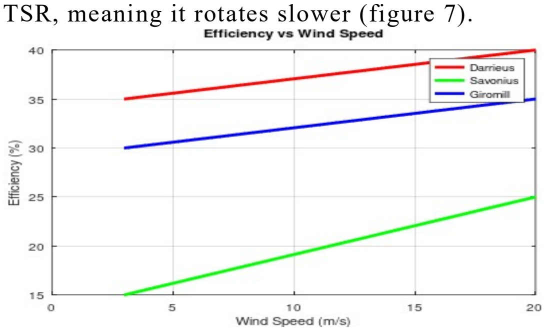

Fig. 8. VAWT efficiency based on wind speed values

Darrieus reaches the highest efficiency (up to 40%), Savonius has the lowest efficiency (15-25%), while the Giromill rotor type is in the range of 30-35% (figure 8).

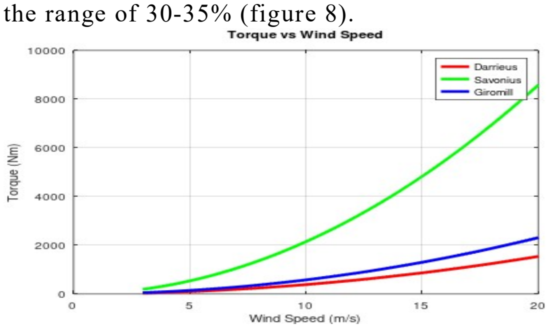

Fig. 9. VAWT torque based on wind speed values

Darrieus and Giromill rotors provide higher efficiency than Savonius rotor, while Savonius rotor has a lower efficiency because it relies on drag. Regarding the torque based on wind speed the Savonius rotor produces more torque, making it suitable for low-speed, high-torque applications like water pumping in agriculture applications (figure 9). Darrieus and Giromill rotors produce less torque but operate efficiently at higher wind speeds.

5. CONCLUSIONS

Unlike traditional Horizontal Axis Wind Turbines (HAWTs), which dominate large-scale wind farms, VAWTs offer distinct advantages, particularly in urban and small-scale applications.

The key advantages of VAWTs are related to omnidirectional operation that can capture wind from any direction without the need for yaw mechanisms. There are effective in urban and complex terrain where wind flow is unpredictable, with lower installation and maintenance costs, since key components are near the ground, servicing is easier. They are more suitable for rooftop or distributed energy systems compared to large and noisy HAWTs.

Regarding the rotor constructive type, the Darrieus turbines are more efficient but require higher wind speeds and external startup mechanisms. Savonius turbines generate high torque at low speeds, making them suitable for urban and off-grid applications but with lower efficiency.

Giromill turbines offer a balance between efficiency and torque, making them a viable alternative for small-scale electricity generation.

The Future of VAWTs is related to hybrid designs combining Savonius (for startup torque) with Darrieus for efficiency in order to improve overall performance.

Integration with urban infrastructure is also in development trends including smart buildings, highways and rooftops where conventional wind turbines are impractical.

The advanced composite materials will be used for optimized blade designs aiming to enhance efficiency and durability.

VAWTs are not a replacement for HAWTs but a complementary technology suited for specific locations.

The choice of rotor type depends on wind conditions and application requirements considering Darrieus for high efficiency, Savonius for low-speed reliability and Giromill as a balanced alternative.

As cities and industries move toward decentralized renewable energy, VAWTs will play a crucial role in sustainable energy solutions.

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