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Wind Energy Technology and Power Braking Mechanism

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Abstract

The development of advanced power braking mechanisms for wind turbines is the focus of this study, which first examines the principles of wind energy conversion, wind turbine design, and control systems before diving into the principles of power braking mechanisms, including mechanical, electrical, and hydraulic braking systems. The study also looks at the limitations and difficulties of current braking systems and discusses new developments in the field. Wind energy has become a crucial part of the global renewable energy mix, providing a clean and sustainable source of power. This study highlights the vital role of advanced power braking systems in ensuring the safe and efficient operation of wind turbines. These systems are essential for managing the dynamic loads and high rotational speeds typical of wind energy generation. By enhancing control and stability, sophisticated braking mechanisms help prevent mechanical failures and extend turbine lifespan. The findings underscore the importance of continued innovation in braking technologies to support reliable performance and safety in modern wind turbine systems. The study's findings provide valuable insights for developing next-generation wind energy technologies. They can aid policymakers, researchers, and industry experts in making informed decisions, driving innovation, and shaping sustainable energy strategies.

Keywords: Mini wind turbine, power, site, rural India, installation, capacity, power plant

INTRODUCTION

Wind is merely the air in motion produced by the sun's energy differentially heating the earth's surface and atmosphere. One or two percent of the 1.74 x 1017 watts of energy that the sun sends to the planet each hour is converted to wind energy. Wind power is the conversion of wind energy into a useful type, such as the generation of electricity by means of wind turbines, mechanical power for the operation of wind turbines, wind pumps for pumping or draining water or sailing boats, ships, etc. [1].

The kinetic energy of the wind on the rotor blades in a wind turbine is transformed into torque to machine energy for a shaft to spin, which is transferred to the generator via the gearbox and generates electrical energy from that generator.

A wind turbine in which density of air σ, intercepting a cross-sectional zone A, of the wind front at a wind speed V generates the power to the full rated potential

$$P = \frac{1}{2} A\sigma V^3$$

The wind turbine blades are moved by the use of the theorem of Bernoulli. Figure 1 shows the streamline of the wind on the upper or longer part

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travels a greater distance from the streamline on the lower part as the wind crosses over the surface of the spinning blades. Therefore, according to Bernoulli's theorem, the upper streamline speed increases producing low pressure. This disparity in pressure results in the lifting force that raises the blade [2].

The lifting force induces the rotation of hub as blades are fixed to a plane with the hub at its centre. The hub's rotating movement is also increased by the drag force perpendicular to the lifting force. As a result, the hub's low speed shaft spins, converting the high-speed shaft into a mechanical one and changing the wind's kinetic energy. Electrical energy is produced by this production from mechanical energy. Mass, momentum and energy saving regulations are the general concepts used in the operation of a wind turbine [3]. However, certain assumptions are made in these theories:

- Air is a non-viscous ideal fluid.
- Incident flow is one-dimensional and has uniform pressure, density and speed.
- Turbine is sufficiently far from all obstacles so that their influence is worthless.
- It is considered in stationary state.

As shown in Figure 2, before the rotor is crossed, the wind speed and pressure are V_0 and P_0. As the speed reaches the rotor, it decreases and the pressure increases after moving away from the rotor (the Bernoulli principle), approaching the speed u and the minimum value of u_1. Similarly, the pressure begins at minimum P_0, following rotor crossing, until the value is reached, ΔP similar to P1. As a result of the kinetic energy transfer to mechanical energy, pressure restores its initial value, but the wind speed does not [4].

The mechanical, electrical, servo pitch, and aerodynamic subsystems are the four primary functional blocks that make up the Wind Energy Conversion System (WECS) [5]. The wind energy is transformed into mechanical energy via the aerodynamic subsystem. There are two purposes for the mechanical subsystem. Transferring torque from the rotor to the electric generator is the first function performed by the drivetrain [6]. The second is to sustain the height of the rotor and other devices while enduring the thrust force. At the generator shaft, mechanical power is transformed into electrical power by the electrical subsystem. Finally, the servo pitch subsystem requires a hydraulic or electromechanical instrument that rotates the blades (part of them) around their longitudinal axis, thus changing the pitch angle [7].

Between 2000 and 2006, global wind power increased more than quadrupled, doubling roughly every three years. Eighty-one percent comes from wind turbines in China, the U.S., and Europe. The top five nations' share of new installations decreased from 71% in 2004 to 62% in 2006, but by 2008, it had risen to 73%. Nearly 93 GW of the increased capacity was installed by 2020. With the addition of 93 GW of new installations, the total wind power capacity worldwide now stands at 743 GW. An annual reduction of 1.1 billion tons of CO_2 can be achieved with the energy production described above. This report is till 31st March 2021 [8].

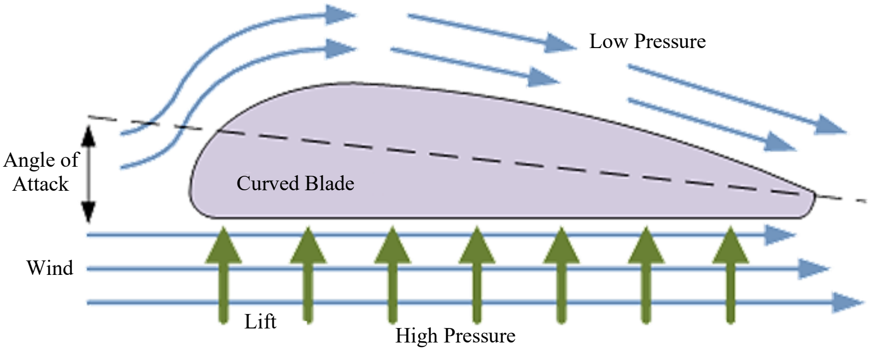

Figure 1. Lift mechanism of wind turbine blade.
Source: https://cutt.ly/ojOBPpd

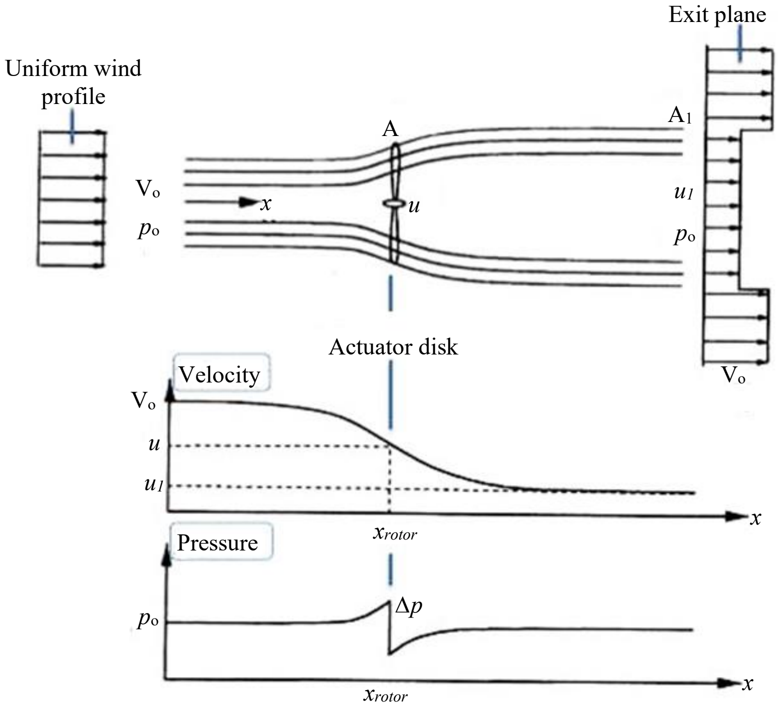

Figure 2. Changes in velocity and pressure of wind as it pass turbine blades.
Source: https://cutt.ly/tjOBnmD

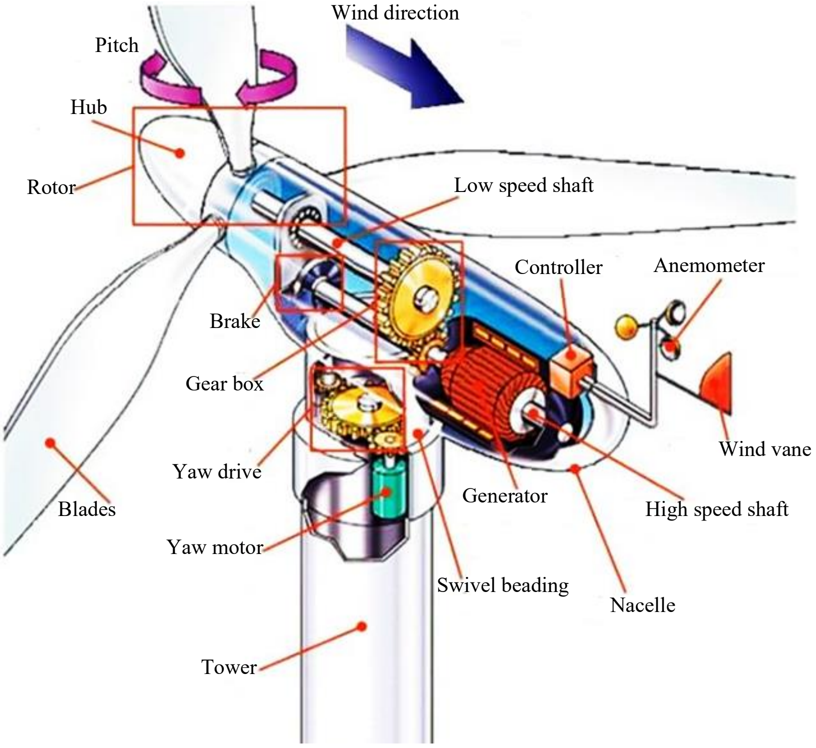

Figure 3. Energy conversion in wind turbine.
Source: https://cutt.ly/VjONu8G.

WIND TURBINE

In order to achieve a maximum output power at 15 m/s most likely wind speeds, wind turbines are optimized [9]. Designing them to run at unlikely high speeds will be inexpensive (Figure 3).

A wind turbine is also fitted with a control system. Different items considered in the design are:

- Control the wind power captured by the rated speeds.
- Maximization of partially loaded wind-harvested electricity, provided the speed and capacity constraints are met.
- To raise varying loads to ensure a certain degree of mechanical component durability.
- Meeting strict requirements of power quality (power factor, harmonics, flicker, etc.). For a wide variety of wind speeds, conversion of electrical power to an imposed grid.

The wind turbine's performance is measured by its capacity factor, which is the percentage of its rated power during a 12-month period. According to the first law of thermodynamics, wind turbine energy must be equal. The energy in wind is its kinetic energy, which depends on the wind's speed and air density. All the wind's kinetic energy cannot be transformed into mechanical energy [10]. The "energy cut" is the energy converted to mechanical energy by the turbine blades plus any energy remaining in the air after the turbine rotors are passed through [11].

A wind turbine will capture all of the wind's kinetic energy if it operates at 100% efficiency. This means that there is zero "exit" speed, that is, no wind leaves, which is not possible. German scientist Betz shows that 59.3 percent, known as the “Betz limit", is the highest efficiency a wind turbine can achieve [12].

Typical Wind Turbine Components

Wind Turbine contains following main components on which its working depends [13].

- *Blades:* Most turbines have 2 or 3 blades. The blades are lifted and set into motion by the wind blowing over them.
- *The Brake:* It is a disc brake that can be used hydraulically, electrically, or manually to stop the rotor in an emergency.
- *Processor:* At wind speeds between 8 and 16 miles per hour (mph), the controller starts the computer and shuts off its motor at approximately 55 mph. The turbines do not run at wind speeds above 55 mph, because high winds can destroy them.
- *Speedy Shaft:* A high-speed shaft transfers rotational energy between the generator and the gearbox.
- *The Generator:* Enhances the low-speed shaft's rotational speed in order to maximize generator efficiency. Normally the wind turbine supplies an induction generator generating 50 cycles AC power.
- *Gearbox:* Motorcycles attach the low-speed shaft to the high-speed shaft and raise the rotational speed from approximately 30–60 rpm to approximately 1000–1800 rpm. The gearbox is an expensive and heavy part of the wind turbine, while engineers pursue generators with 'direct-drive' operations at lower turns and without gear boxes.
- *Shaft at Low Speed:* An essential part of a wind turbine is the low-speed shaft, which joins the gearbox and rotor blades. The rotor changes the low speed wave at a rate of roughly 30 to 60 revolutions per minute.
- *The Nacelle:* The primary parts of a wind turbine, such as the gearbox, generator, low and high speed shafts, transmission box, control systems, and power brake, are housed in the nacelle.
- *Rotor:* The hub and blades are other names for the rotor. The kinetic energy of the wind is captured by the rotor and transformed into mechanical energy.
- *Tower:* The tower is a crucial component, providing the structural support needed to elevate the rotor and capture wind energy. Towers of steel, concrete or stainless steel are constructed from tubular steel. Since wind speed increases with height, taller turbines allow more energy to be collected and more electricity to be produced.
- *Yaw Drive:* To keep the rotor facing the wind, the yaw drive is utilized to shift the rotor's direction as the wind direction changes.

- *Pitch:* The angle at which the blades of a wind turbine are positioned to maximize energy harvesting is known as pitch.

Each wind turbine is made to operate within certain parameters, which are:

- *Cut-in Velocity:* The lowest wind speed at which a wind turbine starts to produce power is known as the cut-in speed. It ranges from 2.5 to 5 meters per second.
- *Speed of Rating:* The wind speed at which a wind turbine generates its maximum or rated power output is referred to as the rating speed or rated wind speed.
- *Cut Out Speed:* The cut-out speed, also known as the shutdown speed, is the wind speed at which a wind turbine automatically cuts off to avoid damage from strong winds. It ranges from 25 to 40 meters per second.
- *The Power Curve:* A wind turbine's power production as a function of wind speed is represented graphically by a power curve.

The cut-in and cut-out speeds are the turbine's operating limits [14]. The power curve is divided into three different areas. Low wind speeds are in the region I under the nominated turbine capacity. Region III is high wind speed and is powered by a rated turbine. Region II is a region of transition that primarily retains low noise and rotor torque. The power curve is used to evaluate the performance of a wind turbine, comparing its actual power output to its expected output [15, 16] (Figure 4).

POWER CONTROLS MECHANISM

A wind turbine is a complex device that cannot be manually controlled and damage to one part contributes to tremendous monetary loss. If a turbine does not restrict the power output at higher speeds, its rotors, mechanical power trains and generators can overload, causing a catastrophic fall. In the case of unlikely wind gusts, power management is also available in modern wind turbines to avoid furling [17].

Mechanical Pitch Control

Wind turbines employ a mechanism called mechanical pitch control to modify the blade angle in order to maximize energy extraction. The higher rotating speed produces centrifugal force on a weight of balancing regulation which compresses a spring. It is a spring regulated mechanism. The strength of the weight is associated with a pivot which decreases the air foil's angle to the Windstream and reduces its rotation speed. As the velocity decreases, the compressed spring helps to return the air foil to its original angle. But this approach is no longer used and is substituted for power controls [18].

PITCH POWER CONTROL

Pitch power control is a technique used in wind turbines to regulate power output by adjusting the angle of the blades. This is the way to sense the output multiple times a second by using an electronic controller.

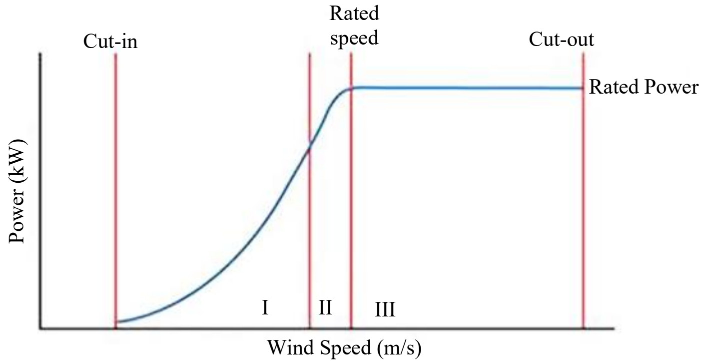

Figure 4. The power vs speed curve.
Source: https://cutt.ly/PjO0Peg

If the level of electricity goes above a specified safe level, an electrical signal either turns the blade away from the wind or activates a light [19]. There are two forms.

Active Pitch Control

The active pitch control achieves power limit over rated wind speed, spinning all or part of the blade caching around its axis, thereby reducing the angle of attack and thus the lifting coefficient. The benefits of this technique are improved energy collection, the aerodynamic braking system it offers and the reduction of intense loads when the turbine is shut down. However, its disadvantage is that it is costly.

Passive Pitch Control

Blades or joysticks are designed for twisting with pressure on the blades so that the desired timing adjustments are accomplished in high velocity winds. Although the angle of attack is lowered, the cross-sectional area is also reduced, which lowers the blade lift and rotating speed. Whenever the turbine blade is stopped, the edges face the wind. They are pitched back to their optimum position, when their strength is lower.

REGULATION OF THE PARTLY SPAN PITCH

While the majority of manufacturers prefer complete pitch controls, power control can still be completely effective, even when only 15% of the latch is pitched outside. The key advantage is that the pitch actuators have a considerable reduction in their duties and that they stay in a standstill, thus greatly reducing the variations in the blade load [20]. However, the following are the disadvantages:

- Adding the additional weight close to the tip.
- The difficulty in adapting the actuator physically within the profile of the blade.
- The high moments of bending through the tip-shaft of a blade.
- The equipment must be built.
- The need to build equipment for high radii centrifugal loads.
- The challenge of maintenance entry.

STALL CONTROL

Active Stall Control

The control device ties the blades at low velocities in measures such as the pitched control systems. But the stall-controlled system works differently when the turbine exceeds its design-rated level of power. In higher wind speeds; however, it is generally appropriate to pitch the blades back onto the paddle to keep the power output at a rated advantage. By doing this, the blade effectively remains stalled above the rated wind velocity, which reduces the cyclical changes in power output and blade loads.

It is noticed that the output level is only held at low pitch angles, so pitch rates do not have to be as high as those in positive pitch regulation. Power output can also be monitored in order to prevent over-shooting at the beginning of wind gusts of the generator.

Passive Stall Control

The shape of sheets with a fixed hub angle is simpler. When the wind speed exceeds the safe limit and the turbulent flow on the upper side of the aerofoil is replaced by laminar flow, the aerodynamic design increases the angle of attack of the aerofoil relative to the wind stream.

The resulting drag is decreased by stopping the lifting force on the blade. This is achieved without altering the geometry of the blade.

When stopped, the blade’s flat side faces the wind thanks to the progressive blade stop. The absence of moving parts in the rotor is beneficial, and helps to avoid stalled vibrations. Some of its inconveniences in aerodynamics are: a stall which can lead to incorrect predictions of power levels and blade loadings at and above a rated wind speed [21].

COMBINED PITCH-STALL CONTROL

Constant Speed Turbines: Steady-control of Pitches

The pitch setting for the blade is progressively balanced for optimum power output at any specific wind speed at low or minimum wind speeds. The blades are guided to a more negative position when the rated wind speed is attained, aerodynamic stalemate is tripped and excess power is therefore dispersed. The angle of the wind is continuously changed at higher wind speeds to retain the specified highest strength. It is straightforward and effective and runs at constant tempo.

Turbines of Variable Speed: Pitch-stall Controls

In contrast to constant turbines, the pitch setting of the blade is slowly adjusted at low and minimum wind speeds in order to ensure maximum power at any wind speed. When the rated wind speed is attained, the blades are adjusted to a more positive pitch setting, which lowers aerodynamic forces and maintains the turbine control unit's planned power output.

The angle of the wind is continuously changed at higher wind speeds to retain the specified highest strength. The benefits are low aerodynamic noise and mild blade swing.

Flap Power Control

Some wind machines have rotors with aircraft-like flaps. In this case, it is modified to increase or lower the geometry of the wing aerofoil aircraft. Controlled rubber flaps could help reduce the noise and energy output in wind turbines. It uses a control system that uses information from built-in sensors to direct the flap movement. These sensors can detect wind conditions locally along the blade. Last research shows that in wind turbines, pitching blades reduce charges by 25 to 30 percent compared to those without them, but flap addition can decrease the load by 40 percent or more [22].

YAW Organization

To reduce its turning speed and power production, the wind turbine rotor is mounted completely out of the wind; in other words, it is perpendicular to the direction of the wind, minimizing the lagoon angle. Because the winds vary fast, the wind turbine has a small average yaw angle. This system is usually used for small wind turbines of 1 kW or less.

Electrical Braking

This method uses generator dumping, where energy is converted from the wind turbine’s kinetic energy into heat from a resistance banks. This is helpful in the event that the generator's kinetic charge is abruptly decreased or is insufficient to restrict the turbine speed. Cyclic breakage slows down the blades, thus reducing the efficiency of the blades by increasing the stop-doing effect. The rotation of the turbine can thus be maintained in fast winds at a safe speed while maintaining (nominal) power output. Usually, this method is not used on large wind turbines, connected to the grid.

Mechanical Braking

The wind turbine is held back by the drum brake or a disc. However, it is only used after blade wave and electromagnetic braking have reduced speed because if used for stopping the turbine, mechanical brake would wear out easily.

In general, a wind turbine brake consisting of a steel brake disc to which one or more brake calipers are attached. Its important drawback is that the gear train experiences "braking torques". Another factor is that, because of the extent of the centrifugal stress, the material consistency of the brake discs connected to a high-speed shaft is more critical. Almost all the brake calipers are spring applied and hydraulically released, i.e., designed to fail-safely [23].

FURLING SYSTEMS

Furling is a control mechanism used in wind turbines to regulate power output and protect the turbine from excessive winds.

Tilt-Back

The body of the generator is hung behind the nacelle in these designs. The entire nacelle, the hub and blade mounting, tilts away almost vertically from the wind when the wind speed gets too high. With the wind decelerating, either the wind springs, the action on the tilted tail, or the counterweight, return to natural horizontal position. Many home-made prototypes use this process in some commercial wind generators.

Tail for Furling

The generator is horizontally mounted off centre of the lagoon. The queue is also bent and hinged in the vertical axis. The tail folds and turns the alternator away from the wind. If the wind force on the rotor is strong enough to overpower the axis generator, the rotor tends to twist, but the wind vane (tail) prevents it from misaligning. As wind speeds decrease, the tail is returned by gravity or springs to normal operating position. This system is used by many commercial and home-made designs, and has proven very reliable.

Vane for Folding

It's like the tail, except the tail boom is fixed and the hinged vane is below. It is used by many older wind loaders. The downside is that the tail and the vane are stressed more intensely by the wind, as they try to cling to the vacuum.

Flexible Blades

The blades bend back to the tower and around its main axis, thus defend themselves against speed. It works when the materials and details are right. For example, the blades must not bend back to touch the pole and they must also avoid bending during cold weather. One problem is that it's loud even before it begins to make any noise [24].

FUTURE POTENTIAL REACH

Wind energy is the most rapidly growing source of renewable energy worldwide, with an annual growth rate of 30 percent. A strong wind power future seems sure with increasingly competitive costs, rising environmental issues and a demand for a reduction in reliance on foreign energy sources. Deep water offshore and land-based systems that can run at lower wind speeds are the next frontages for the wind industry. Both advances in technology would bring new technologies in wide areas. The latest developments and trends serve as examples of this [25]. With soil-based turbines now usually 2–5 MW, and ocean-shore turbines in 5–10 MW, turbines are becoming increasingly sophisticated. Significant technological advances have already been made that allow wind power marketing. Although there is space for change. A "weather change" may occur on the market that will allow many major companies or financial organizations to benefit from the wind technology's next round of development and benefit from public interests, political and economic conditions, as well as emotional and marketing factors. It is more beneficial to squeeze the energy of traditional wind turbines, instead of making bigger and bigger devices. The use of different materials, better electronics and turbine blades can be achieved for the purpose of better wind capture. Although the latest gearbox systems should operate efficiently, direct driving mechanisms using around half as many parts are much more efficient and should minimize operating costs in the long term, thus increasing the competitiveness of electricity from wind farms. For offshore wind farms, this is particularly important because maintenance on sea is much more complicated and costly than on the land [22].

Global wind potential forecasts are high and geographically wide. The total available wind power is considerably higher than the actual use of human energy from any source. The potential commercially available 72 terawatts (TW) of wind power is compared to the global average power consumption from all sources. In many countries, ambitious goals for renewable energy supplies to diversify energy protection supplies, economic reasons such as job creation and environmental reasons, including emissions of greenhouse gases have been set [20].

CONCLUSION

Recent years have seen tremendous advancements in wind energy technology, which is now an essential part of the world's renewable energy mix. However, for wind turbines to operate safely and successfully, power braking devices must be effective. This article discussed the development of advanced power braking devices for wind turbines and an outline of wind energy technologies. The results of the study demonstrate how crucial sophisticated power braking systems are for guaranteeing the secure and effective operation of wind turbines. The findings show that new developments in braking technology, like sophisticated control systems and regenerative braking, have the potential to greatly increase wind turbine performance and dependability.

One essential renewable energy source that has several advantages and is essential to lowering the world's dependency on fossil fuels is wind energy. Because wind energy produces power without releasing greenhouse gases, it has a smaller impact on climate change. By lowering the quantity of sulfur dioxide, nitrogen oxides, and particulate matter released into the atmosphere, it lowers air pollution. Unlike conventional power plants, which use a lot of water for cooling, it uses relatively little water to run. Wind energy can reduce customers' global energy costs, especially in areas with abundant of wind resources. Braking is essential to wind energy because it keeps wind turbines operating safely and under control. In the event of an emergency or severe weather, it guards against harm to the turbine, its parts, and nearby structures. It makes controlled turbine shutdown possible, lowering the possibility of harm or damage. It increases the lifespan of turbine components by reducing stress and fatigue. It keeps the turbine from going too fast, which could lead to damage or instability. By controlling the turbine's power production and averting abrupt fluctuations, it contributes to grid stability. It improves wind turbine dependability by offering a safe and regulated shutdown method. It ensures that industry standards and legislative requirements for wind turbine operation and safety are followed.

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