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Wind Turbines Control Trends and Challenges: An Overview

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Abstract

Wind turbines (WTs) create electricity by utilizing the energy of the wind. As a result, wind turbine control and cost-effective operation were studied. The control system offers a long service life, maximum energy output, and safety. On control methods and control strategies, various ways for limiting and optimizing energy consumption were discussed. Integration of wind power may compromise the stability of the transient system. Asynchronous induction generators cannot handle the quantity of reactive power generated in wind energy applications. WTs are usually constructed to withstand inclement weather but not for high speeds or torque. Strong aerodynamic torques or rotational speeds are capable of destroying WT blades. To prevent this, WTs always have a cutout speed over which the turbine will be stopped by its brakes. When excessive wind speeds endanger the safety of the turbines, the WT employs a range of control techniques. As a result, all WTs are constructed using a power control method. This can regulate pitch and stall. Passive or active stall control can be applied to the WT. Therefore, this study analyzed the associated technologies, the maintenance of wind turbines, the cost, the many types of wind turbine controllers, and the negative effects and roadblocks unique to the wind energy industry.

Keywords: Consumption, Control methods, Energy, Renewable energy, Wind turbine.

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1. Introduction

The increase in global energy consumption and hazardous gas emissions from traditional fossil fuels have made it imperative for every nation to improve the proportion of renewable energy such as wind turbines (WTs) in its energy balance [1]. Wind turbines harness the wind's energy to generate electricity. Variations in the axis of rotation, the number of blades, the control surfaces, and the kind of generator are among the most common characteristics of wind turbines (Figure 1) [2]. The control literature has thoroughly explored three blades of upwind-facing horizontal axis wind turbine (HAWT); an active yaw system adjusts the blades vertically and perpendicularly in response to changes in wind direction

to establish rotor-blade alignment [3]. HAWTs are extensively scrutinized due to their market dominance and incorporation of active controls. Recently, wind turbines have become one of the most significant new sources of grid capacity in the United States [4]. As the number of wind turbines increases, it becomes increasingly vital to implement effective control systems. Independent systems operators (ISOs) desire additional control over turbine operations in a growing number of instances. It is anticipated that wind turbines will play a crucial role in ISOs' attempts to provide a continuous and dependable electricity supply [5].

All generators must contribute to maintaining the grid's voltage and frequency and reducing current harmonics. This harmonic is the first time wind turbines and farms have been classified as a positive load instead of a negative one, and the rest of the system has had to adapt to this very variable supply [6].

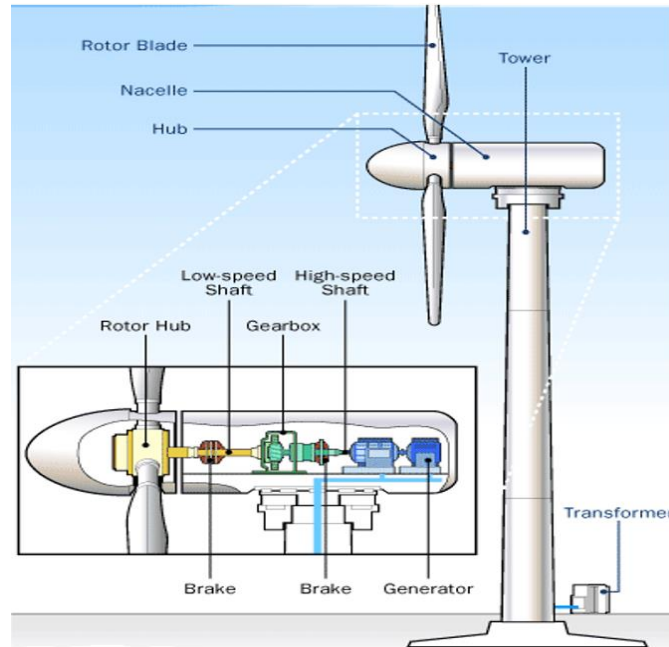


Figure 1. Wind turbine.

If reliability is achieved, active load reduction measures must be included in turbine control for wind turbines. Consequently, the equilibrium between usability and resilience can be adjusted in real time [7]. The gap between high-level profit maximization and low-level turbine control cannot be bridged in a single step. As a result, we recommend that the behavior of the turbine be modified by utilizing dependability control. Each turbine experiences specific loads despite being subjected to identical wind farm inflow circumstances. This study provides an overview of wind energy controllers that incorporate fatigue loads and energy production asset points. The wind turbine's real-time controller can be set using structural load data (Figure 2) [8].

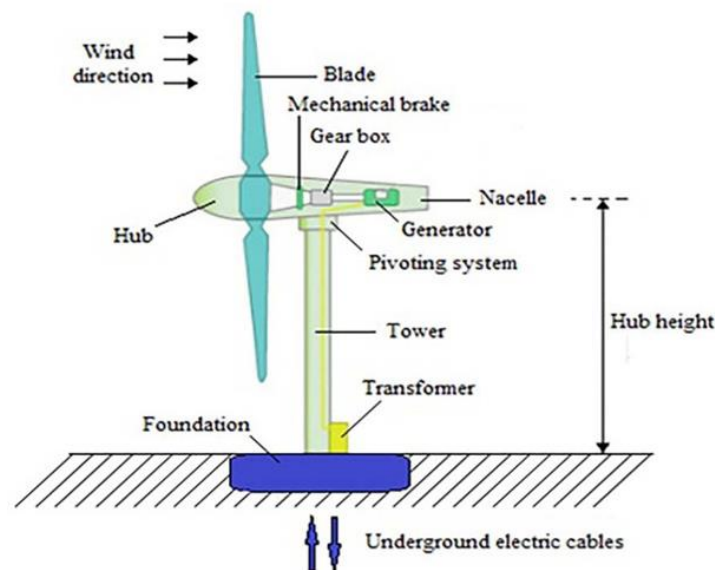


Figure 2. Overview of wind turbine.

Even though other articles have carefully studied the various control approaches linked with wind systems, few research works have comprehensively reviewed the numerous control strategies associated with wind systems [9]. MPPT procedures and WT pitch angle controls are two of the most recently explored control methods. Song et al. [10] did not discuss wind turbine pitch control despite investigating WT pitch angle controllers. The classification of WT operating regions is omitted by Jiang et al. [11]. Kumar et al. [12] did not discuss the pitch angle controller when discussing pitch control methods; therefore, this paper addresses a key gap. The study also focuses on the connection between the power electronics and the WT grid. This article analyses the essential control concepts and methods/techniques for wind turbine control systems due to the significance of wind turbine control to their cost-effective and efficient operation. In addition to assuring a long service life, the control system ensures safe operation and maximizes energy output. When striving to limit and optimize energy consumption, the generator's speed and the turbine's rotational speed are the two most crucial aspects to consider—the Control Methods and Control Strategies sections of this article detail the implementation of various strategies.

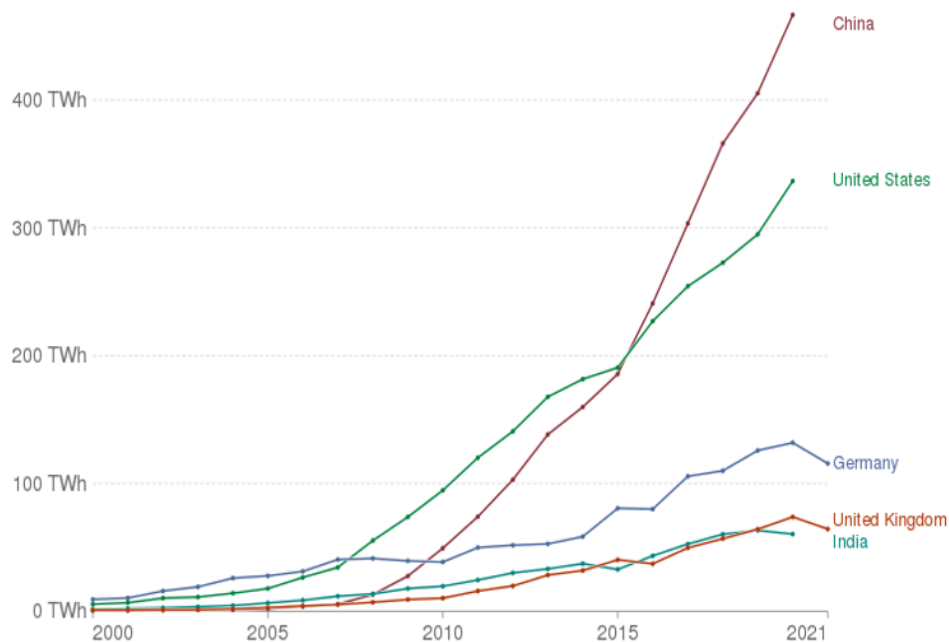


Figure 3.
Wind power generation.

2. Overview of Wind Turbine Advancements in the 21st Century

Since 2000, wind power's average compound annual growth rate (CAGR) has increased by more than 21 percent (Figure 3). In 2010, the annual increases in conventional power capacity in several locations surpassed expanding renewable energy capacity. Wind power has been the second most prominent renewable energy technique for many decades, after hydropower. At the end of 2018, onshore wind energy generated 542 gigawatts (GW) of global installed capacity. Onshore wind power is one of the most cost-effective ways to add new production capacity to the grid. Since 2010, global onshore wind installations have decreased by 22% compared to 2017, as China and India's low-cost constructions have spurred a substantial surge in deployment [5].

The North Sea and the adjacent Atlantic Ocean account for 90 percent of the world's offshore wind capacity. China contributed to over three-quarters of the world's new offshore wind capacity increases in 2016, with the United Kingdom and Germany each responsible for nearly a third (29 percent) of that total (22 percent). In the coming years, efforts to increase deployment to North America and Oceania will commence. As the offshore wind industry grows, many nations establish offshore deployment objectives [13].

Europe has long been the driving force behind the global deployment of wind power. In 2010, the region accounted for more than half of the world's onshore installations. However, other regions, particularly China, have experienced a CAGR of approximately 27%. China has almost a third of the global installed capacity and has surpassed Europe's onshore wind industry by 2018 (Figure 2) [14]. The European Union (EU) financed a record amount of new wind generation capacity in 2018 when 16,7 GW of projects received a Final Investment Decision (FID). In 2018, funding for onshore wind farms averaged \$1.54 million per megawatt (MW), while financing for offshore wind farms averaged \$2.50 million per MW. Approximately 29.4 billion US dollars (USD) were invested in new wind farms.

Wind energy costs have decreased mostly as a result of wind turbine innovations. Increases in wind turbines' rotor diameter and hub height enable the machines to generate more electricity in areas with lower wind speeds, larger rotors with lower specific power can be advantageous. In 2018, much more wind turbines were installed than in 2015, when 3.3 MW were installed. General Electric company's (GE's) most recent onshore turbine technologies range in power output from 4.8 MW to 5.3 MW. Siemens-5.8 Gamesa's MW turbine with a 170-meter rotor diameter is currently the largest offshore turbine available [15].

The most expensive components of an offshore wind farm are the turbines (including towers), foundations, grid connection to land, and installation. The turbines account for around 45 percent of the total installation expenses for offshore wind power. As a result of technological advances, the price of wind turbines continues to decrease. In 2018, the overall installation cost was 5 percent less than in 2010 due to China's shallow coastal seas (5–25 m from shore); Europe has higher total installation costs than China. By 2030 and 2050, the weighted average offshore wind turbine installation costs are projected to increase from \$1 700 to \$3 200/kW and from \$1 400 to \$2 800/kW, respectively [16].

After reaching a record high of USD 27.6 billion in 2016, worldwide offshore wind investment dropped to USD 18.9 billion in 2017 and is predicted to rebound to USD 19.4 billion in 2018. In 2018, China accounted for more than fifty percent of worldwide offshore wind investments, investing \$11.4 billion in thirteen new offshore wind projects. The Chinese government has approved 6,7 GW of offshore wind power and around USD 18 billion for development in 2019 [17].

Wind energy's intermittent nature can be mitigated by combining it with other renewable electricity sources, such as solar PV, hydropower, and storage technology, when resources are few. This would aid in addressing the intermittent issue. In 2012, the State Grid Corporation of China and Build Your Dreams (BYD) erected the world's first hybrid project [18], which featured the world's first lithium-ion energy storage capacity unit. A maker of wind and solar turbines has announced its intent to construct a 43.2 MW plant with 2 MW battery storage. The global hybrid solar-wind energy market will reach USD 1.5 billion by 2025, with a CAGR of around 8.5% over the forecast period. The rise of solar-wind hybrid systems in China is anticipated to continue. Several governments have already adopted hybrid initiatives to address grid integration issues, and more are anticipated to do so in the future [8].

In the presence of low-cost renewable power generation, the energy transition's success hinges on integrating considerable amounts of VRE into power systems at the lowest possible cost. Approximately 10% of the G20 countries' current electricity generation comes from renewable sources. Denmark had 53 percent of the global VRE burden in 2017; South Australia had 48 percent; while Lithuania, Ireland, Spain, and Germany all had VRE burdens above 20 percent. China, India, and the United States, the world's three largest power systems, are projected to account for more than 10 percent of annual VRE generation over the coming decade. India's VRE generation capacity was 7.7 percent in 2017 and 2018 and was on track to meet the 2019 goal of 9 percent. In 2017, 76 percent of the United States' electricity was generated by wind and solar power [19].

In 2018, wind turbines were worth 50,3 billion dollars, followed by rotor blades at 15 percent, gearboxes at 7 percent, and generators at the remainder of the market (USD 50.3 billion). European makers of wind turbine technologies control a sizeable piece of the global industry. In 2018, 37 different manufacturers installed 20,641 wind turbines worldwide (Figure 4).

In 2018, 1.16 million people were employed in the global onshore and offshore wind industry. Compared to the solar PV industry, most wind jobs are concentrated in fewer countries. North America and Europe accounted for less than a quarter of the global wind employment (each with slightly more than half a million jobs) (10 percent). China retained its position as the world's largest wind market in 2018, accounting for 44 percent of global wind employment (510 000 jobs) (Figure 4). The United States ranked second after Germany with 114 000 wind jobs at the end of 2018, an increase of 8%. Europe will be the third-largest onshore wind market behind China and the United States in three decades. As of 2018, 161 GW of onshore capacity had been installed. The region contains an estimated 13,900 GW of land-based wind power. Europe's northern and central regions and the United Kingdom are good for onshore installations [20].

Particularly, blade, drivetrain, and control technologies developments may result in larger, more reliable turbines with increased capacity ratings. The size of wind turbines has increased dramatically during the past few decades—at the end of 2018, the installation of offshore wind turbines with rotor diameters of approximately 150 meters. In 2018, European offshore wind farms with turbines with power outputs ranging from 3.5 MW to 8.8 MW were commissioned [2].

Significant milestones in the wind sector development have been reached, such as founding renowned wind energy organizations and installing new wind turbines. In 2020, renewable energy sources such as wind turbines and solar panels will be less expensive than the cheapest fossil fuels [21].

Two essential concerns are replacing wind turbines nearing the end of their operational lifespans and repowering existing projects to extend their operational lifespans. The initial socioeconomic gains can be amplified by replacing aging components with newer ones and performing system-level maintenance and upgrades. Regulation or politics have not yet launched a repowering initiative. It is economically viable to replace older wind turbines in particular markets, even if they can last for many more years [22]. In addition, repowering enables the most advanced turbines in places with the best onshore wind resources. The rising demand for wind turbines and related technology represents a tremendous opportunity for investors. China's onshore wind industry will undoubtedly experience an increase in demand for key components and raw materials in the next decades, both domestically and internationally. Due to the cost-competitiveness of onshore wind compared to fossil fuel production sources, China will be able to develop large-scale, subsidy-free projects by 2021. Second, wind farm developers may benefit from grid expansion and infrastructure enhancements [4].

Advancements in wind turbines, wind farm development, and operations and maintenance contribute to the decline in offshore wind farm electricity prices. As a result of the development of new turbines, larger wind farms can generate more electricity. Compared to smaller turbines with narrower swept areas, larger turbines with broader swept areas can generate more energy with the same supply quality.

We anticipate that these technological advances will continue beyond 2022 [3]. Industry professionals are developing designs for 15 MW turbines, and 20 MW turbines are anticipated. These turbines are anticipated to have greater capital costs per megawatt capacity than conventional turbines due to their superior energy production and reduced capital

expenditure (CAPEX) for foundations and installation. If dependability and maintenance are enhanced, operating expenses (OPEX) and energy production could be reduced further. Fewer basic structures would be necessary to maintain the production capacity of a wind farm [23].

On the other hand, these turbines would have taller blade tips, making them more visually intrusive if positioned near the coast. Technological developments in wind turbine foundations, which enable access to stronger wind resources, are among the most critical factors accelerating the adoption of offshore wind. Commonly, 40-meter-deep, 80-kilometer-distance turbines are installed today [24]. In waters less than 60 meters deep, monopile or jacket foundations are employed to anchor these turbines to the seafloor. This is a severe disadvantage, as there are few shallow-water locations in some of the most promising offshore wind markets, such as Japan and the United States [25].

Due to the changing nature of wind and solar resources, the power system must undergo significant modifications in light of the growing contribution of variable renewable energy (VRE) in numerous markets. Efforts must be made to safeguard grid stability and reliability as the amount of variable renewable energy production rises. As well as minute-by-minute adjustments to the grid's operation and management, seasonal solar and wind output variations necessitate minute-by-minute modifications [11].

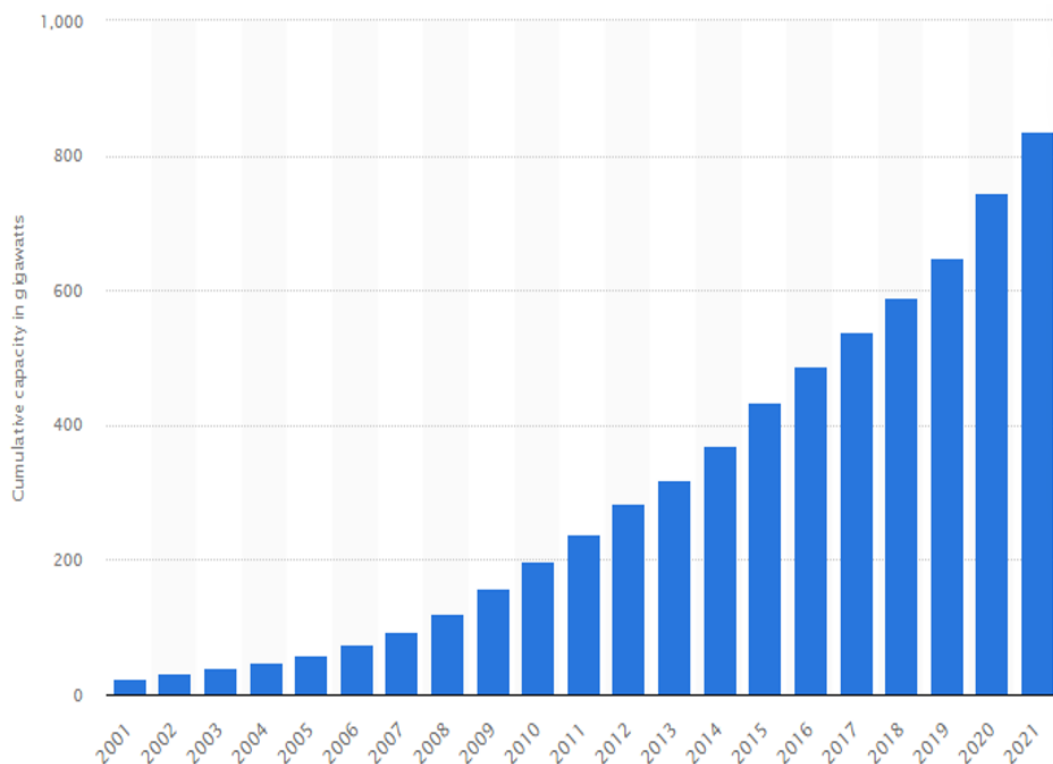


Figure 4.
Global advancement in Wind turbine.

3. Challenges of Wind Power Regarding Power System Stability

Kooten and Timilsina [3] define "stability" as the capacity of a power system, under typical operating conditions, to maintain or recover an acceptable equilibrium state. A disturbance could be caused by generators, loads, wires, transformers, or a failure. There is angular stability, which ensures that the generator maintains synchronization to supply electricity. The relationship between the rotor angle and power angle determines this stability. Regarding stability, transient stability refers to stability that accounts for major system disturbances, whereas small signal stability accounts for disturbances of lesser scale. Problems with tiny signal stability arise when the operating parameters of a power system alter, and the system's oscillations are inadequately muted [26].

Regarding the frequency stability of a system, think in terms of tens of tenths of a minute or less. Loss of generation is a frequent cause of frequency instability because it causes an imbalance between the load and generation. Inadequacies in the system, such as sluggish control actions and lack of protective coordination, may impact frequency stability [5]. One or more of the bus voltages of the power system falls continuously, causing the protective devices to cause the power system to fail. Voltage collapses when a power system fails to balance the demand and supply of reactive power [4].

Once upon a time, wind power plants were the only means of generating electricity. The utility operators are familiar with how these generators react to a disturbance because they have dealt with it numerous times [27]. When wind energy was originally introduced, induction generators were utilized to create electricity due to their inexpensive cost, extended service life, and variable speed operation. When wind energy was originally introduced, worries regarding its impact on the overall stability of a power system were minimal. The growing tendency of wind power integration may harm transient system stability (Figure 5) [21].

In wind power applications, asynchronous induction generators have a poor capacity to control the quantity of reactive power generated. In a surge in generator input torque and subsequent voltage reductions above the Point of Common Coupling (PCC) threshold limit, reactive power demand could lead to insufficient feeder control and consequent voltage collapse [14]. Induction generators with a fixed speed incorporate reactive power compensators to fulfill the high network demand for reactive power. Reactive power is supplied by power electronics devices in the case of variable-speed generators. The critical clearing method is commonly utilized for transient stability tests. Excitation systems and voltage source static var compensators such as a static synchronous compensator (STATCOM) have been implemented to increase the ride-through performance of generators [28].

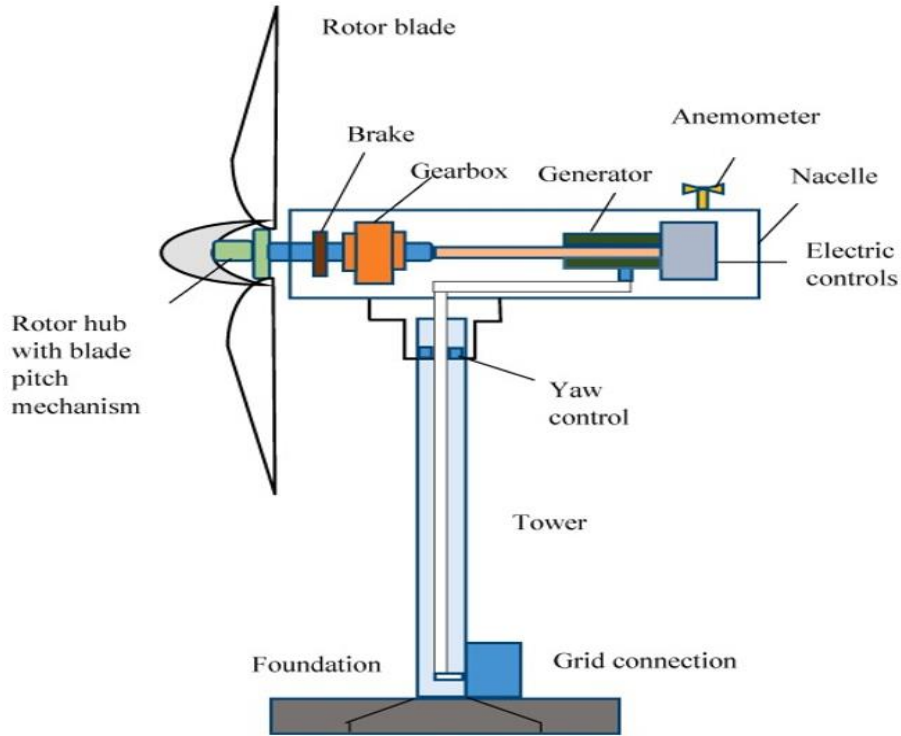


Figure 5. Challenges and advancement of WT.

4. Wind Turbine Control Method

WTs are often constructed to withstand poor weather conditions, although they are not intended for exceptionally high speeds or rotating torque. If the WT blades are subjected to strong aerodynamic torques or rotational speeds, they can be broken apart. WT blades always contain a cutout speed over which the brakes will bring the turbine to a stop to avoid this issue [1]. When high wind speeds pose a hazard to the turbines, the WT employs a range of control techniques to ensure the turbines' safety prior to the cutout speed. Consequently, all WTs employ a power control strategy in their construction. With this, either pitch control or stall control can be achieved. WT stall control can be classified as either passive or active [29]. As seen in Table 1, this study identifies different wind turbine controller methods in association with previous studies.

Table 1. Comparisons of different controllers.

S/N	Method	Ref
1.	Real-Time Stall Power controller	[17]; [21]; [30-32]
2.	Pitch Controller	[13-16]; [33]
3.	Collective Pitch Controller	[14]; [21]
4.	Individual Pitch Controller	[15]; [21]
5.	Electric Pitch Controller	[13]; [16]; [33]
6.	Hydraulic Pitch Controller	[16]; [33-36]
7.	Robust Controller	[14]; [16]; [30]; [31]; [37]
8.	User Interface Computer Controller	[14]; [17]; [30-32]; [37]
9.	Conventional Controller	[17]; [33]; [37]
10.	Hybrid Controller	[6]; [23]; [28]; [31]; [38]; [39]
11.	Maximum Power Point Tracking (MPPT) Controller	[1]; [10]; [31]; [39-41]
12.	Operational Controller	[20]; [40]; [42]

4.1. Maximum Power Point Tracking (MPPT) Controller Methods

WT systems implement MPPT control algorithms to maximize the amount of wind energy gathered. When the wind speed exceeds the wind generator's rated speed, overload and surge protection are provided for wind generators using MPPT algorithms. The optimal MPPT algorithm for WTs is determined by user proficiency and skill. There are pros and downsides to each algorithm [2]. DPC and IPC are the two major MPPT algorithm types investigated in this study.

Pustina et al. [15]; Do and Söffker [30]; Tavner et al. [43] carried out in-depth investigations on the different MPPT algorithms. Hill-climb Search (HCS), optimal relation based (ORB), and incremental conductance (INC) are all direct power control (DPC) based approaches for obtaining maximum power point tracking. Several algorithms in this category utilize the HCS due to its versatility and simplicity. It is feasible to achieve optimal torque control (OTC) by employing three MPPT algorithms based on IPC: power signal feedback (PSF) and maximum power point tracking [1]; [10]; [31]; [39-41].

HCS requires no prior understanding of WT features. The local maximum of a function can be determined using this method. The implementation is carried out utilizing a duty-cycle-controlled by direct current to direct current converter (DC-DC converter). In this MPPT technique, the duty cycle is altered discretely, and the slope of the objective function is watched until it reaches zero [39].

The HCS method has various downsides, such as recognizing the wrong wind direction to attain the highest power point when the wind direction changes rapidly. As a remedy, a modified HCS algorithm was created by Hosseini et al. [41] which is capable of producing consistency between track speed and control efficiency to resolve the issue of incorrect directionality under variable wind conditions. Calculate the distance between the operating point and the ideal curve to calculate the direction and amplitude of the next disturbance.

Applying the ORB-based MPPT algorithm must be a perfect relationship between WT output power, DC voltage, current, and speed. This algorithm has a significant advantage over conventional MPPT algorithms in tracking speed. With this MPPT approach, speed sensors and look-up tables are unnecessary because the system curve has already been constructed. Following the MPP requires an awareness of typical curves between turbine power and direct current at varying wind speeds [10].

Regardless of sensor needs or wind turbine and generator settings, INC algorithms decrease system costs and increase dependability. This method provides benefits in terms of nonlinearity, dynamic reaction, and ease of implementation. The slope of the power-speed relationship establishes the operating point of the MPPT [40]. Regarding speed-power characteristics, positive and negative sloping curves have operating points on opposite ends of the spectrum. This method becomes unstable as wind conditions shift and turbine inertia changes. When addressing the issue of instability, Apata and Oyedokun [40] introduce the fractional-order INC algorithm (FO-INC). The MPP is monitored with a configurable step size for rapidly changing feasible wind conditions to minimize unnecessary power losses.

A power-speed curve that already exists can also be used to construct the ideal power. The controller decreases the difference between the actual and ideal power. Due to the need for an exact estimation of the optimal power coefficient and tip speed ratio, this approach has several limitations [31].

To maximize wind energy output, algorithms that utilize the tip speed ratio (TSR) maintain the ratio of blade tip speed to rotor speed at a maximum value regardless of wind variations. The difference between real and ideal values must be supplied into a feedback controller to be effective. To reduce inaccuracy, the controller reduces the generator's speed. A torque/power reference is established based on the speed deviation, which is then changed to reduce the speed deviation. Despite its simple implementation and excellent efficiency, the TSR-based MPPT controller has a high operating cost. As previously stated, the MPPT method has a significant problem [40].

To maintain the generator's optimal torque, a controller can determine a maximum power reference based on the actual torque using an error signal. This method is straightforward, efficient, and surprisingly rapid. There is a disadvantage inherent in the inability to assess wind speed directly. As a result, the reference signal will not reflect changes in wind speed [21].

4.2. User-Interface Computer Controller

The controllers can respond rapidly and precisely to environmental changes that may impact the wind energy system using artificial intelligence techniques. These controllers typically employ metaheuristic algorithms, Artificial neural networks (ANNs), and Fuzzy logic controls (FLCs). Fuzzy logic controls are gaining popularity among WTs due to their adaptability and user-friendliness [17]; [21]; [32]; [37]. The effectiveness of a fuzzy logic controller is determined by the user's comprehension of the controller. Due to FLC's memory needs, WT control is highly constrained. Lara et al. [13] discovered that adopting an FLC-based controller improved the microgrid's performance. Comparing this technology to the battery storage method for microgrid frequency deviation control demonstrates its simplicity. An FLC study of a low-speed wind system can be accomplished by creating a reference power using WT and subtracting it from the actual generator power. This method's high price tag is a downside. According to Apata and Oyedokun [22], this controller was developed to compensate for wind speeds below average by adjusting output based on wind velocity.

ANN serves as a control approach for various control systems. Possible inputs include rotor speed, output torque, wind speed, pitch angle, and terminal voltage. A WT controller based on ANN permits maximum output at wind speeds above the rated speed. Using ANN techniques, it is also possible to estimate the nonlinear properties of the WT [17]; [30].

When the wind speed is moderate, metaheuristic pitch angle controllers based on evolutionary algorithms can maintain system stability. When adjusting the generator's speed, it is customary to employ a control signal based on the reference speed [17]; [22].

4.3. Robust Controller

Several authors [14]; [16]; [37] have investigated the robust pitch angle controller. With this controller, it is reasonable to assume that it is highly effective, responsive to uncertainty, and stable. The negative aspect of this controller's control mechanism is its intricacy. A second issue with the pitch controller is a rise in mechanical stress caused by rapid changes in control variables. To deploy trustworthy controllers, one must have a thorough understanding of the mechanical model of the WT system. Integrating feedback, feedforward, and sliding-mode control (SMC) in WT systems improves pitch angle control stability [14]; [30]; [31]; [37].

4.4. Conventional Controller

The majority of wind energy systems are conventional. A proportional–integral–derivative controller (PID) and a proportional–integral (PI) are commonly utilized to govern the rotor speed and output power. They are appropriate for smaller WT systems. Pitch angle is normally determined by conventional controllers using wind speed, generator power, and rotor rotation speed. Extensive research has been conducted regarding traditional controls. Despite the controllers' usability, accurate wind speed measurements are impossible. In other words, this controller is extremely responsive. Traditional controllers that regulate pitch angle based on rotor speed and generator power are the most efficient and trustworthy [33]; [37].

A classical controller can improve the performance of a nonlinear system through gain scheduling. This approach lowers the aerodynamic torque effect of changing pitch angles. As the controller gain rises, the system's sensitivity falls. Therefore, controller gain scheduling improves control system dependability [17].

4.5. Operational Controller

WT systems can be better managed with the emergence of power electronic interfaces, especially when connecting with the utility grid. Both grid-side and machine-side converters require a power electronic system interface to handle WT systems. The GSC guarantees that the WT system is effectively integrated into the grid by regulating the dc-link voltage and minimizing power losses. DPC and voltage-oriented control (VOC) are examples of GSC variants [40]; [42].

Using the DPC approach, the active and reactive power of the WT system may be properly regulated. Absent are pulse width modulation blocks and an inner current control loop. Reactive power must be zero to have a power factor of one [20]. The primary benefit of this control is reducing calculation time and system complexity. Despite the diversity of parameter modifications, the DPC system is dynamic and resistant to uncertainty. The DPC's high power factor results from its straightforward algorithm and architecture [40].

VOC resembles field-oriented control with a converter when utilized on the machine side. Both approaches utilize dual-loop control, but VOC tries to reduce power ripple while enhancing power quality [34]. Using an internal current control loop and an external PI control loop in the dc-link voltage and current control loops allows for synchronized reference frame control. The DC connection voltage is sensed immediately to respond rapidly and perform consistently. This method incurs a total harmonic distortion penalty when the line voltage is distorted [11].

Machine side converter (MSC) is responsible for harvesting the highest amount of wind energy possible by regulating the variable speed functioning of the WT system. When a wind turbine's rotor speed is set to its maximum level, energy output and system stability are enhanced. The MSC uses direct torque control (DTC) and field-oriented control (FOC) technology. The dynamic performance of both control strategies is remarkably comparable [44].

Two of FOC's key characteristics are direct control of current and utilization of the entire line current for torque generation. This control mechanism is implemented using dual-loop control. The speed and location of the rotors regulate the outside loop, while the synchronous reference frame governs the inner loop [32]. Setting the d-axis to zero makes it possible to lower stator current to an absolute minimum, which minimizes the related electromagnetic torque. The q-axis of stator current regulates the electromagnetic torque.

A change of the reference frame, such as the FOC, is unnecessary for the DTC approach, which employs a single outer loop control. If required, the switching pulse of the converter can be determined from the flux angle. Managing torque and power enhances the system's responsiveness and simplifies it. Additionally, it eliminates rotor speed sensors, has a faster response time and does not need a current regulation loop. In contrast, the oscillating torque and current wave constrain the performance evaluation of the direct torque controller. The disadvantage of direct torque control is that it requires a consistent switching frequency [45].

4.6. Hybrid Controller

A hybrid pitch controller combines the advantages of both types of pitch controllers. This gadget was created to overcome the constraints of the standard controller to maximize the overall capabilities of the WT system [6]; [39]. The controller's capabilities permit a reduction in system complexity and improved system stability. The fundamental advantage of this controller for nonlinear systems is that it provides a dependable solution, while the principal disadvantage is that it increases the cost of the entire system [38].

4.7. Real-Time Stall Power Controller

Passive management's apparent failure led to active power control for stalling—blades with adjustable pitch and an integrated battery. With pitchable blades and active power control mechanisms, these closely resemble pitch-controlled WTs. Fixed-speed WTs that operate in high-wind situations and larger WTs with at least 1 MW ratings can take advantage

of this capacity. By gently pitching them, WT blades may generate a large amount of torque in low-wind conditions. Instead of decreasing lift and rotation speed by decreasing the angle of attack, WT active stall control increases the angle of attack [17]; [21]; [31]; [33].

Active stall control permits greater control over the WT's power output at the beginning of a wind gust than passive stall control. Active stall management is superior to passive stall control because it permits the WT to sustain rated power under all scenarios of strong wind. The rotor blades of a wind turbine with passive stall control tend to enter a deeper stall as wind speed increases, decreasing electrical output [13]; [15]; [17]; [37].

4.8. Pitch Controller

In pitch-controlled WTs, electronic controllers continuously check the WT's output power. The blades are turned away from the wind to prevent the turbine from creating too much energy. By aligning the blades with the wind, energy consumption can be decreased. The WT blades can be positioned to capture the same amount of electricity as wind turbines to reduce power loss. The torque and rotational speed can be decreased by altering the pitch angle of WT blades dynamically. Due to high wind speeds and aerodynamic torques, this management method frequently minimizes equipment damage [15]; [36]; [40]; [46].

The distinction between WT pitch controls and stall controls becomes evident at high speeds. In systems that use active blade pitch modification to vary aerodynamic thrust or turbine rotational speed, the aerodynamic design of turbine blades is crucial for high wind speeds. Pitch-controlled systems, in contrast, can produce a continuous energy output above the maximum wind speed [34]; [47]. Wind turbine blades (WT) can be utilized in pitch control and stall management. The mode of operation changes when the WT blades are rotated. When the WT active stall control is enabled, the lift force of the turbine blades is decreased by actively stalling them. Individual pitch control (IPC) and group pitch control (GPC) are the two strategies usually used for WT collective pitch control (CPC). Both electric and hydraulic controllers apply to both control systems [1]; [36]; [48].

4.9. Collective Pitch Controller

In most commercial wind turbines (WTs), collective pitch control is accomplished using the same control for every WT blade. If independent servomechanisms exist, the pitch of each WT blade will be the same. Using standard proportional-integral (PI) equations to regulate rotor speed limits the amount of wind energy that may be captured. The variable under control is the collective pitch of the blades, which differs from the reference rotor speed [14]; [21]; [48].

There have been numerous inquiries into the CPC as Kim et al. [14] discovered that CPC efficiently regulated WT. Although CPC systems were initially utilized for PI control with gain scheduling, they are currently being investigated. Uncertainty modeling has resulted in the creation of adaptive and robust methods. A CPC strategy for rejecting WT disturbances is presented by Kim et al. [14]. This adaptive approach was examined to determine if it might prevent the excitation of modal WT subsystems in turbulent wind conditions. The assumption that all WT blades have identical physical attributes and are consequently subjected to identical aerodynamic loads during operation is a significant error in the CPC method. As a result, the rotor disc is subjected to unbalanced loads, which increases the WT's stress and the chance of failure [48].

4.10. Individual Pitch Controller

By altering the pitch angle on an individual basis, it is possible to lessen mechanical loads. The IPC is a relatively recent addition to the WT family in pitch control. Despite years of development, it has not yet been applied commercially in WTs. Future WTs with larger and more flexible blades will support this research. Utilizing this method for analyzing tower displacement can reduce fatigue-related damage and load [21]. As implied by the name, each WT blade is controlled by its sensors. By modifying the pitch angle of IPC's products, structural vibrations can be mitigated. Because IPC in WTs requires additional sensors and separate pitch orders for each blade, WT control systems are multiple-input multiple-output (MIMO). For WTs with blades equipped with separate pitch actuators, the reliability of the sensors is a significant consideration when employing this technology [11]; [47]; [49].

4.11. Electric Pitch Controller

Electromechanical actuators manage the WT blade in the electric pitch controller. The gearbox design incorporates pitch control devices for blackouts and energy storage. Without a backup power source, installation is prohibitively costly. There have been numerous investigations on electrical pitch angle controllers. The regular pitch controller, the soft computation pitch controller, the robust pitch controller, and the hybrid pitch controller were investigated and compared [1]; [26]; [33]; [49].

4.12. Hydraulic Pitch Controller

An accumulator tank provides linear movement of the wind turbine blades for the hydraulic pitch controller, which uses a hydraulic actuator. The WT's hydraulic pump nacelle generates rotational energy for the blades. Hydraulic pitch controls have been the focus of various experiments. Studies [46-50] in the last few years, however, have centered on a detailed dynamic analysis and the most effective control approaches, hydraulic pitch controller models, and reliability. According to this study, hydraulic pitch changes sustain WT output power by reducing variances in powertrain torque. In addition, online fault compensation solutions can determine the incidence of an issue in real time [34-36].

Hydraulic pitch controls are more robust to nonlinear aspects of wind speed than electromechanical pitch controls. This controller's initial installation cost is cheaper than an electromechanical controller [12]. Another notable characteristic of this WT's control system is its ability to operate without external power sources in emergency control circumstances. Aside from that, it is highly resistant to vibrations and quite trustworthy. The hydraulic controller's fundamental drawback is its exorbitantly expensive running and maintenance expenses [36].

5. Evaluation of Advanced Wind Turbine Controller

Research in wind energy has focused largely on safety, reliability, cost reduction, and power quality improvement. Effective control mechanisms must be built to manage a wide range of objective concerns to fulfill these aims.

Installing and maintaining wind turbines that can endure extreme weather and sea conditions is simpler than turbines that cannot. In order to bypass road/rail travel constraints, the supply chain will need to construct production and assembly sites near the coast over the next decade. Wind turbine manufacturers are also developing offshore wind turbines that float [37]. Floating wind turbines can be carried and connected to the seafloor since they can be constructed and maintained on land. Enhanced condition monitoring systems, lighter-than-average rotors, and taller, more innovative towers are just a few advancements that hint at a prosperous future for innovation. Patents and innovations will decrease component weight, production costs, transport and assembly, monitoring and control, turbine reliability (integration), grid integration, and performance maximization. The most ambitious research and development (R&D) objective for 50-MW offshore wind turbines is to develop rotor blades longer than 200 meters. This design is 2.5 times longer and six times more powerful than existing turbines and blades [5]; [17]; [23]; [24]; [47]; [49]; [50].

Cost and turbine technology are crucial factors to consider when adopting a control approach. Fixed-speed WTs have significantly increased WT deployments in Africa and around the world. For WTs with a set speed, passive stall control has been replaced by active stall control, which is more efficient and less costly [42]. If residing in a location with high wind speeds, it is highly suggested that the variable-speed wind system include pitch control. Pitch control for Due to the emergence of big variable-speed WTs, the prevalence of WTs is growing. In WT systems, electrical or hydraulic controllers may be employed. There has been some debate on whether the controller is superior. They believe that electric pitch controllers are better for the environment than hydraulic pitch controllers because hydraulic fluids cannot leak under high pressure [17]; [18]; [22]; [29].

In contrast, hydraulics requires a continuously operating pump, which increases the risk of energy waste. This pump is required to maintain high oil pressure and be prepared to rotate the rotor blades at any moment. Electric pitch controls, in contrast, are susceptible to battery and capacitor failure. An electric pitch control system's battery life per charge is two and three years. The electric pitch controller is more suitable for use in cooler climates. As temperature drops, the viscosity of hydraulic oil falls [16]; [19]; [21]; [45].

Therefore, the hydraulic controller is suitable for usage in regions with warmer climates, such as Africa. In warmer climates, electric pitch controllers can be implemented. In addition, the hydraulic system's quickness and dependability merit recognition. Due to the low cost of the hydraulic fluid used to adjust the pitch, the system's oil consumption is modest. Although hydraulic systems are more challenging to diagnose, they are less complicated to maintain [29]; [51]; [52].

However, it is possible to control the pitch of WT systems with a hybrid controller. The turbine blades are rotated electrically by a hybrid pitch control controller, while the failsafe systems that protect the blades are controlled hydraulically. Due to the hybrid control system's reliance on a hydraulic system for failsafe power, oil leakage is less likely because pitch control is mostly powered by electricity, reducing energy costs [9]; [53].

Multiple WT subsystems' structural loads must be decreased. If the IPC is properly explored, it can significantly reduce the stress on the rotor blades. IPC can reduce fluctuations in wind turbine output power, stabilizing output and improving grid quality, whereas CPC can be used to regulate rotor speed at high wind speeds. Multiple control strategies can simultaneously minimize structural loads on WT subsystems. However, these tactics cannot be employed simultaneously. Ongoing research into wind energy system optimization and intelligent control should enhance WT control in future IPC tests [16]; [32]; [54].

Multiple techniques exist for determining the optimal WT frequency, making it difficult to select an MPPT technique. These strategies' complexity, convergence speed, and performance requirements must be investigated in depth. In contrast to DPC-based algorithms, IPC-based TSR and PSF algorithms are simpler to build and execute more quickly. The disadvantage is that mechanical wind power is maximized rather than electrical power. As it does not directly monitor wind speed, the OTC method is less efficient than the TSR algorithm, albeit faster [11]; [17]; [52]. The reference torque does not instantly reflect changes in wind velocity. Although the TSR algorithm permits a rapid response to fluctuating wind conditions, its implementation is expensive; therefore, the WT system will be expensive. The performance and complexity of the PSF algorithm are comparable to those of the OTC. DPC approaches are more dependable, cost-effective, and memory-efficient. These algorithms can correctly evaluate available electric power sources without prior wind speed information. Due to their lower performance in variable wind situations, DPC algorithms have a limited application area. Currently, wind energy system designers and engineers cannot identify the optimal MPPT method for a WT installation due to a lack of approaches or criteria. Additional research may be required to determine the most suitable MPPT method for a specific application [38-40]; [53].

Due to LIDAR's high expense, its use in WT control has been limited for nearly four decades. It has been suggested that LIDAR-based feedforward control be added to the baseline control system to improve pitch control. An initial objective is to create independent feedforward controllers that incorporate wind data as an input and compensate for control

system interruptions caused by wind. This device measures wind speed using sensors before the wind reaches the WT. It has time to react when it receives output control signals from the WT. In order to prevent uneven pressures on rotor blades, it is possible to initiate pitch actuation in large WTs with enormous blades. Even though this technology has been around for a while, it has been exhaustively investigated and is essential for the future regulation of WTs [1, 2, 26]. Model predictive control (MPC) is predominantly utilized to regulate Light Detection and Ranging (LIDAR) systems. Rule optimization takes future conditions into account. These upcoming conditions can be predicted using LIDAR data on the wind speed in front of the rotor. LIDAR can be used to implement feedforward control. LIDAR-assisted control can improve low-rated activities, although additional control actions are required. For the previously described pitch control, LIDAR readings may be superior. Currently, LIDAR cannot be used commercially in WTs, demanding substantial study [17]; [43]; [50]; [52].

Utilizing intelligent rotors for the control of WTs is a recent innovation. Future WTs will be lighter because of the research conducted in this vital field. The WT blades are equipped with sensors, actuators, and embedded intelligence to achieve this objective. Instead of pitch angle control, each WT rotor blade is controlled by an individual actuator. In other words, this results in an intelligent, quick-response rotor. As active load management devices, trailing edge flaps, micro tabs, active blade twists, and boundary layer control have all been proposed. Intelligent rotors are being considered as a substitute. On the other hand, intelligent rotors would assist pitch control systems [4]; [9]; [12]; [35].

6. Conclusion

An assessment of the trend and challenges of wind power was undertaken in this study by examining the associated technology, maintenance of wind turbines, cost, different types of wind turbine controllers, and detrimental consequences and obstacles unique to the wind industry. It has been proved that wind turbines can supply sufficient electricity to meet the needs of transmission system operators. However, the full potential of wind turbines was examined. Although more research is required, the literature describes different strategies for dealing with the various controller forms. Future wind turbines will feature larger rotors constructed from novel materials, allowing them to catch more energy. It is anticipated that the amount of waste generated by wind turbines at the end of their service life will increase dramatically and must be managed responsibly.

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