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# A Comprehensive Topology Review and Comparative Analysis of Wind Energy Conversion Systems

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**Abstract:** ***Wind energy conversion systems (WECS) have emerged as vital contributors to the global renewable energy portfolio, offering a promising solution to mitigate the challenges posed by fossil fuel dependence and climate change. This review paper presents a comprehensive analysis of various aspects related to wind energy conversion systems, encompassing their technological evolution, operational principles, challenges, and future prospects. The paper commences by tracing the historical evolution of wind energy utilization, from traditional windmills to modern wind turbines equipped with advanced aerodynamics and control mechanisms. An overview of different types of wind turbines, such as horizontal-axis and vertical-axis configurations, sheds light on their unique design considerations and operational characteristics. Key components of WECS, including rotor blades, drivetrains, generators, and control systems, are examined in detail. The interplay between these components in optimizing energy capture, conversion, and transmission is elucidated, highlighting the importance of holistic system integration. Operational and environmental challenges faced by wind energy systems are addressed, encompassing issues like intermittency, grid integration, noise, and visual impact. The paper emphasizes the significance of effective grid management strategies and innovative energy storage solutions to ensure the reliability and stability of wind-generated power.***

**Keywords:** wind energy, wind energy conversion systems, wind turbines, renewable energy, grid integration, technology, challenges, advancements, sustainability

## 1. Introduction

Wind energy holds immense significance as a pivotal pillar in the global pursuit of sustainable and clean energy sources. Its importance is multifaceted and far-reaching, touching upon environmental, economic, and technological aspects. It is a clean and renewable resource that generates electricity without emitting harmful greenhouse gases or pollutants. Its utilization contributes significantly to reducing carbon emissions, climate change, and improving air quality. By displacing conventional fossil fuel-based power generation, wind energy plays a crucial role in curbing the adverse effects of global warming and minimizing environmental degradation [1].

The evolution of wind energy conversion systems (WECS) has been a remarkable journey driven by technological innovation and the imperative for sustainable energy solutions. From their humble origins as ancient windmills used for basic mechanical tasks, wind energy systems have undergone significant transformation. The late 19th century marked a pivotal shift with the creation of the first electricity-generating wind turbine, sparking the transition from mechanical to electrical power generation [2]. The 20th century saw the utilization of wind turbines for remote applications, while the 1970s oil crises reignited interest in renewables, propelling research and development efforts. Advancements in aerodynamics in the 1980s led to the introduction of horizontal-axis wind turbines (HAWTs), greatly improving energy capture efficiency [3-4]. The 21st century witnessed exponential growth, propelled by larger turbine designs, offshore wind farms, and smart technologies. Wind power is likely to supply 8% of worldwide power by 2035 up from just 1% in 2008[5]. According to IRENA, the wind power growth has taken a sharp trajectory from 2011 to 2022 as projected in Fig. 1[6].

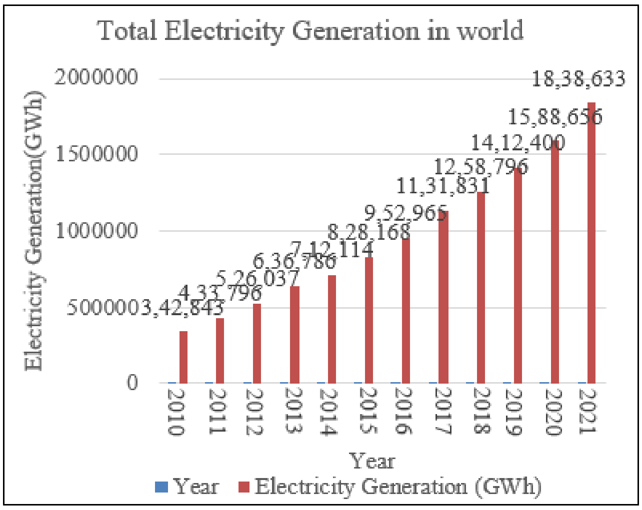


**Figure 1:** Global wind power growth from 2010 to 2021 (IRENA)

The pursuit of efficient wind energy conversion has driven substantial technological advancements. From aerodynamic designs and efficient turbine blades to smart grid integration and energy storage solutions, wind energy has paved the way for innovation and progress in various fields, ultimately benefiting a range of stakeholders in academics and in industry. The electrical aspects of wind energy have been discussed in a range of papers [7]-[9]. Today, ongoing innovations focus on increasing efficiency, reducing costs, and addressing challenges through concepts like vertical-axis turbines, floating systems, and advanced grid integration. Various authors [10-11] have critically compared the specifications, merits, and demerits of all classes of WECS. Recently, different power electronic converters techniques have been evolved for smooth connection with the electricity grid. [12]-[14]. The employment of power converters permits variable wind speed action of wind turbine, and helps in improving power output also. To integrate large wind power into electricity grid, a number of interrogations arise which includes design and operation of the power system, grid connection of wind power and power quality.

The adverse effects of inappropriate handling of power in the wind turbine systems connection to the grid have been discussed in various papers [15]-[16]. Authors in [17]-[18] suggested various problem-solving methods to eliminate the grid balance problem. This paper offers a comprehensive assessment of various wind energy conversion system (WECS) topologies, encompassing their distinct configurations, operational principles, technological innovations, and future potential. Emphasis is laid on the pivotal role of wind energy in mitigating climate change and fostering energy security. The diverse range of WECS topologies is subsequently explored, covering both established and emerging designs. This includes an in-depth examination of traditional fixed-speed and variable-speed configurations, as well as advanced multi-generator

## 2. Wind Turbine

A wind turbine turns kinetic energy of wind into electrical energy using the force applied on the blades by the gust of wind.

### 2.1 Key Components

Wind Energy Conversion Systems (WECS), commonly known as wind turbines, consist of several key components shown in Fig. 2 that work together to capture and convert wind energy into usable electricity. Here are the main components and their functions:

- **Rotor Blades:** The rotor blades are aerodynamically designed to capture the kinetic energy of the wind. Made of glass fiber reinforced plastics which are lightweight and durable, the blades are attached to the rotor hub. They rotate as the wind flows over them, transferring the wind's energy into rotational motion.
- **Rotor Hub:** The rotor hub connecting the rotor blades to the main shaft, facilitates their rotation. The hub is a central structure where the blades are mounted. It transfers the rotational motion from the blades to the main shaft.
- **Shaft:** The main shaft transmits the rotational energy from the rotor to the generator. It is a large, sturdy, and hollow metal shaft that extends from the rotor hub into the nacelle. It connects to the rotor hub at one end and the generator at the other end.
- **Nacelle:** The nacelle houses crucial components that convert the rotational motion into electrical energy. It is a large, enclosed structure positioned at the top of the wind turbine tower. The nacelle encompasses the generator, gearbox, control systems, and other auxiliary components required for turbine operation and maintenance.
- **Generator:** The generator converts the mechanical rotational energy into electrical energy. It consists of electromagnets and conductive coils. As the main shaft rotates, it spins the rotor of the generator, inducing a flow of electrons and producing electrical energy through electromagnetic induction.
- **Gearbox:** The gearbox increases the rotational speed of the rotor to harmonize with the desired speed of the generator. The gearbox is a complex arrangement of gears that transmits the relatively slow rotation of the rotor to a faster rotation suitable for the generator. It optimizes the energy conversion process and ensures efficient generator operation.
- **Control Systems:** The control systems monitor and regulate various aspects of the wind turbine's operation for optimal performance and safety. Control systems include sensors, software, and electronic components that monitor wind speed, direction, turbine speed, and other parameters. They adjust the turbine's blade pitch angle, yaw angle, and generator output to maintain safe operation and maximize energy capture.
- **Tower:** The tower provides structural support, elevating the turbine to capture stronger and less turbulent winds at higher altitudes. Typically constructed from steel or concrete, the tower is a tall structure which supports the nacelle and rotor assembly. It ensures the turbine is positioned at an optimal height to capture the most energy from the and direct-drive alternators.

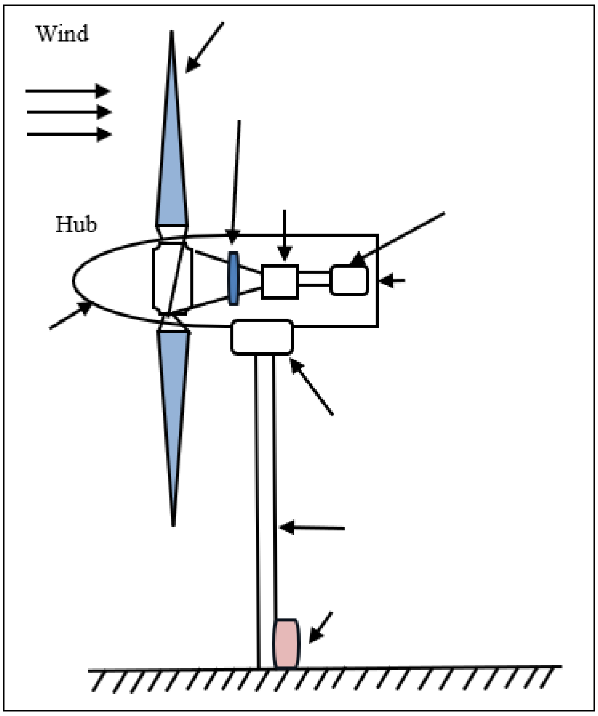


**Figure 2:** Components of a Wind Turbine

These key components work together in a coordinated manner to harness wind energy efficiently. As the wind blows past the rotor blades, blades rotate turning the main shaft connected to the generator. The generator then converts the rotational motion into electrical energy, which is either used on-site or


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transmitted to the electrical grid for distribution. Control systems monitor and adjust the turbine's operation to optimize energy capture, ensure safe operation, and protect the turbine from extreme weather conditions [19].

### 2.2 Types of Wind Turbine

There are two distinct designs for harnessing wind energy to generate electricity: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT).

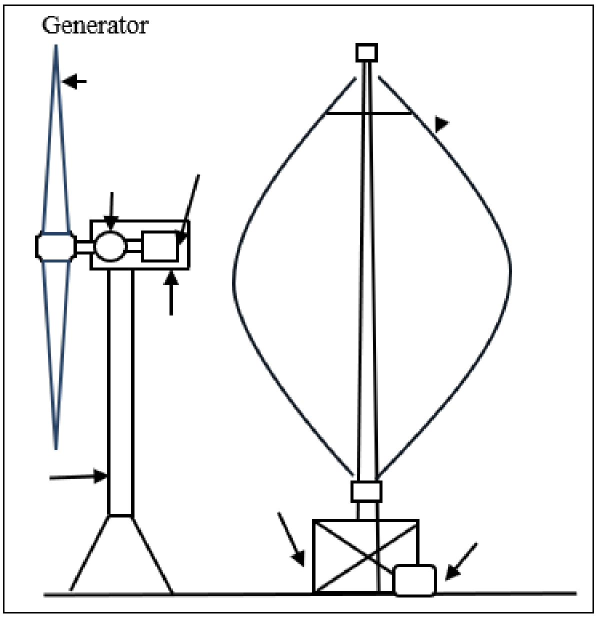



**Figure 3:** (a) Horizontal Axis Wind Turbine (b) Vertical Axis Wind Turbine

HAWTs are the more commonly recognized wind turbine design, with a horizontal rotor shaft and blades that rotate like a propeller. They typically face the wind directly, allowing for efficient capture of wind energy.

VAWTs have a vertical rotor axis, resembling an eggbeater or a helix. Unlike HAWTs, they are omni-directional, meaning they can seize wind from any direction. The schematic of Horizontal and Vertical Axis Wind Turbine is shown in Fig. 3(a) and Fig 3(b) respectively.

**Table 1:** Comparison of Horizontal and Vertical Axis Wind Turbine

| Parameter | Horizontal Axis Wind Turbine (HAWT) | Vertical Axis Wind Turbine (VAWT) |
|---|---|---|
| Design and Orientation | Horizontal rotor shaft perpendicular to the ground and parallel to the wind direction. | Vertical rotor shaft and the rotor blades rotate around a vertical axis. |
| Blades | Blades can with aligned the wind direction through a yaw mechanism allowing them to take advantage of the maximum wind energy available. | VAWTs can capture wind from any direction without necessitating the need for a yaw mechanism. |
| Wind Capture Efficiency | Higher wind capture efficiency compared to VAWTs | Lower wind capture efficiency due to their design, as some parts of the rotor blades may experience lower wind speeds compared to others. |
| Cut-in speed | Require higher wind speeds typically around 3 to 4 m/s | Require speeds around 2 to 3 m/s. suitable for areas with variable wind conditions. |
| Size and Scalability | Commonly used in large-scale wind farms and can reach heights of several hundred ft. | More compact and can be installed at lower heights, making them suitable for various settings and installation options. |
| Noise and Aesthetics | Produces more noise due to the higher rotational speeds and larger blade sizes. | Produces less noise due to lower rotational speeds and smaller blade sizes |
| Utility and Applications | Due to higher output, used in utility-scale wind farms. | used in smaller-scale or distributed applications, such as residential, commercial, or off-grid setups. |
| Maintenance and Serviceability | Easy maintenance | require more complex maintenance procedures due to their placement closer to the ground. |
| Efficiency and Power Output | Offers higher output and efficiency compared to VAWTs. | Offers lower output and efficiency compared to VAWTs. |

Both HAWTs and VAWTs contribute to the diversification of renewable energy sources, with their own niches of applications as defined in Table 1. The choice between the two depends on factors like wind conditions, available space, energy needs, and project goals. As renewable energy technology evolves, both turbine designs continue to be researched and refined, contributing to the global shift towards sustainable energy solutions.

### 2.3 Fixed speed and variable speed turbine

A fixed-speed wind turbine is a type of wind energy conversion system where the generator is directly linked to the grid and maintains a constant rotational speed, regardless of the wind's velocity. In this design, the generator's speed is determined by the frequency of the grid, and the turbine blades are positioned at a fixed angle with respect to each other.[20]. Key characteristics of fixed-speed wind turbines includes simplicity and operational stability but possess limited control over speed resulting in efficiency limitation.

A variable-speed wind turbine adjusts its rotational speed to match the prevailing wind conditions, optimizing energy capture and overall efficiency. Variable-speed turbines incorporate power electronics to facilitate this adjustment. Key features of variable-speed wind turbines include optimized energy extraction, grid support, power electronics applications, better control over speed and complex configuration [20].

## 3. Power Available in the wind

The power available in wind can be written as:

$$P = \frac{1}{2}\rho A s^3$$

Where P is power(watts)
$\rho$= air density (kg/m$^3$); the density of air at sea level and at room temperature is 1.3 kg/m$^3$
A= cross section area of gust of wind passing through in square metre (m$^2$) and s is the velocity of wind in m/sec.

It is to be noted that wind speed increases with height above the ground. This effect is modeled using a power law equation:

$$V_H = V_{10}\left(\frac{H}{10}\right)^{\alpha}$$

where $V_H$ = wind speed at some height Z (m)
$V_{10}$= wind speed at height of 10 m
$\alpha$ is an exponent that accounting for the atmospheric conditions and the geographical terrain.

According to the Betz criterion, a turbine can notionally capture a maximum of 59% of the total available power in the wind. However, this criterion does not provide any insights into the dynamic rotational state required for achieving this maximum power condition. In the event of a stationary wind turbine, the power extracted by the turbine will diminish if the blades are positioned too closely together.

## 4. Wind Turbine Generators

While consensus remains elusive in both academic and industrial circles regarding the top wind turbine design, there exist three prominent categories of wind turbines utilized for converting wind energy: direct current (DC), synchronous, and asynchronous generators. Philosophically, each of these types can operate at either a fixed or variable speed. Given the unpredictable nature of wind speeds, it is advisable to run wind turbines at variable speeds. This approach helps reduce physical strain on the turbine blades and the drive train, as recommended by reference [24]. The transition toward variable-speed turbines has gained momentum due to their ability to optimize energy capture, facilitate superior grid integration, and enhance overall efficiency in harnessing wind power. This progress underscores the ongoing advancements within the wind energy sector aimed at improving its effectiveness as a green energy source.

### 4.1 DC Generator

The wind turbine DC generator configuration, depicted in Fig. 4, includes an (IGBT) inverter, a power controller, and a transformer before it links with the grid. In the case of shunt DC generators, the field current, and consequently, the magnetic field, increase with the rise in operational speed. The definite speed of the wind turbine hinges on the balance between the torque at the shaft and at the load side. The rotor is equipped with conductors wound around an armature, which are connected to a commutator. Electrical output is collected through brushes that establish contact with the commutator, enabling the conversion of produced AC power into a DC output. It's noteworthy that these systems necessitate regular maintenance and tend to be quite costly due to the presence of commutators and brushes, as referenced in [25]. These turbines exhibit a distinct design and are primarily employed in low-power demand applications and in events where the load is located in close proximity to the turbine.

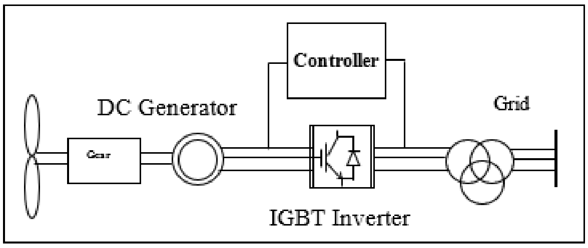



**Figure 4:** DC Generator WECS

### 4.2 Synchronous generator

Synchronous wind turbine generators (WTGs) have the flexibility to utilize either constant or DC excitations. Consequently, they are categorized as Permanent Magnet Synchronous Generators (PMSGs) or Electrically Excited Synchronous Generators (EESGs) depending on the type of excitation. When the turbine's rotor is driven by wind, three-phase power is generated in the stator. It is further connected to the power grid through transformer and power electronics converter.

In the event of fixed-speed generators, keeping the rotor speed precisely at the synchronous speed is essential to preserve synchronism. Deviations from this speed would result in a loss of synchronism [26].

The reactive power of a synchronous wind turbine generator is adjusted over the field circuit required for electrical excitation. In addition to this, synchronous WTGs generally exhibit low damping. This necessitates the incorporation of additional damping elements in the drive train.

Integrating synchronous WTGs into the power grid entails a delicate operation to synchronize their frequency with that of the grid. Furthermore, they are typically more intricate, costly, and vulnerable to failures as compared to induction generators. The schematic of PMSG is depicted in Fig. 7.

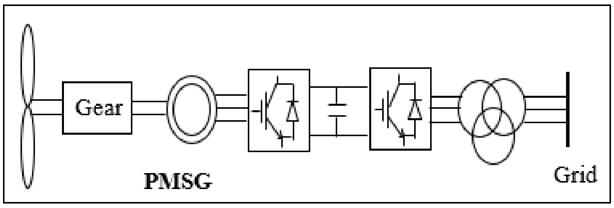



**Figure 5:** Synchronous Generator WECS

### 4.3 Asynchronous generator

Induction machines are significantly used in wind turbine applications. When three phase supply is fed to the rotor, a rotating field is set up in the air gap. When rotor rotates at a speed other than synchronous speed, the rotor circuit is energized due to production of slip. Induction Generators are categorized into two types i.e. fixed speed and doubly fed induction generator incorporating squirrel cage rotor and wound rotor respectively.

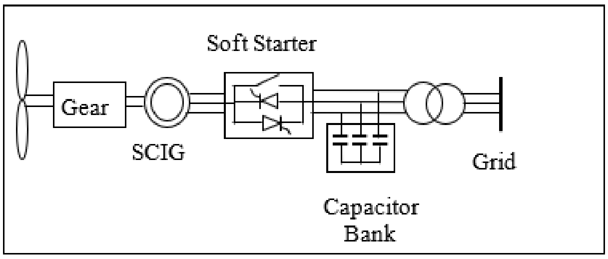
**a) Squirrel Cage Induction Generator (SCIG):**
The Squirrel-cage Induction Generator (SCIG) is directly linked to the transformer. The turbine's rotational speed remains constant or very close to the electrical grid frequency. When the turbine shaft surpasses the electrical grid frequency, resulting in a negative slip, it generates real power. In situations where wind speed undergoes abrupt changes, the mechanical inertia of the drive train restricts the rate at which electrical output can change [27]. To address reactive power requirements, a capacitor bank is employed, and a soft starter is utilized to ensure a smooth connection to the electrical grid. The system configuration is depicted in the Fig. 6(a).

**b) Wound Rotor Induction Generator (WRIG)**
Wound rotor induction generator is connected to the transformer in a manner similar to SCIG type wind generator. In addition, a variable resistor is also connected in the rotor circuit as shown in Fig. 6(b). A power electronics circuit is external to the rotor circuit. The speed characteristics of the generator changes with the change in resistor thus providing acceleration. The variable resistors intend to control the rotor side currents thereby maintaining constant power in the event of changing conditions, and therefore able to handle the machine's dynamics during grid disturbances [28]. The speed range is very narrow accompanied with poor control of active and reactive power.

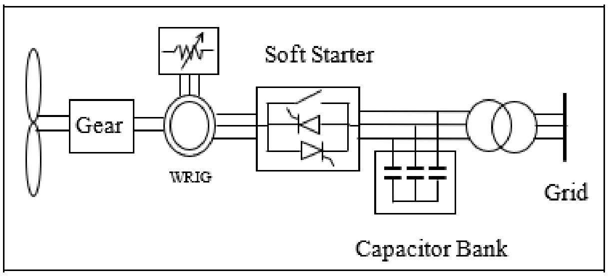
**c) Doubly Fed Induction Generator (DFIG)**
Doubly Fed Induction Generator (DFIG) incorporates adjustable frequency ac excitation in the rotor circuit. As illustrated in Fig. 6(c) the stator is connected directly to the grid while the rotor is connected through a two-way converter. This rotor-side converter and the grid side converter are connected back-to-back thus exchanging power directly with the grid.

These converters provide control over the rotor circuit's frequency, current, and phase angle shifts. Induction generators of this type can operate effectively across a wide slip range. Consequently, they offer several advantages of enhanced energy output, overcoming mechanical stress, reduced power fluctuations, and the ability to manage reactive power.

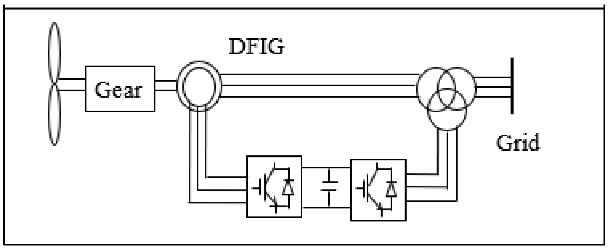
In the case of induction generators, the terminal voltage is not controllable (and hence reactive power). The reactive power is supplied either by the grid or additional capacitors [29-30]. These generators are susceptible to voltage instability, and the use of capacitors to improve power factor can potentially lead to self-excitation. Moreover, damping effects can result in power losses within the rotor, and or sustained fault currents.




(a) Fixed speed wind turbine




(b) Limited variable speed wind turbine




(c) Full variable speed wind turbine

**Figure 6:** (a) Fixed speed wind turbine (b) Partial variable speed wind turbine (c) Full variable speed turbine

A comparison of the wind turbine generator topologies has been made and shown in Table 2.

**Table 2:** Comparison of Wind Turbine Generators [31].

| Performance -Indicator | DC Generator | Induction generator | | Synchronous Generator | |
|---|---|---|---|---|---|
| | | FSIG | DFIG | Electro-magnet | PMSG |
| Speed | Variable | Fixed | variable | variable | Variable |
| Voltage variation | High | High | low | low | Low |
| Controllability | Low | Low | low | low | High |
| Active/Reactive power Control | No | capacitor banks | grid/capacitors | excitation | Separate |
| Grid support capability | Poor | Poor | good | average | very good |

| | | | | | |
|---|---|---|---|---|---|
| Damping | No | Within | within | external | External |
| Application | low power applications, local loads | small wind turbine | moderately sized turbines | | large wind turbine |
| Cost | Low | Low | medium | medium | very high |
| Reliability | Poor | Medium | high | high | High |

## 5. Conclusion

The paper has provided a comprehensive overview of wind energy conversion systems, highlighting their significance in the global transition toward sustainable and renewable energy sources. Through a thorough analysis of electrical, mechanical and aerodynamical aspects, we have gained valuable insights into the state of the art in wind energy conversion. The paper highlighted the concept of maximum power extracted from the wind turbine and the other factors affecting it. A comparison between various types of wind turbines is made and the advantages of horizontal axis wind turbine over vertical axis wind turbine is discussed considering various performance indicators.

The rapid advancements in wind turbine technology have led to increased efficiency, reliability, and cost-effectiveness, making wind energy an attractive option for electricity generation. The paper presented a deep insight into the configuration of various wind turbine generators and their suitability to various applications. Although there is no consensus over the best wind turbine generator topology, the review paper presented how the DFIG configuration is utilized in most of the applications. The integration of advanced control strategies and grid management techniques has improved the stability and reliability of wind power systems though, challenges such as intermittency, grid integration, and environmental concerns remain, and ongoing research and innovation are crucial to address these issues.

Looking forward, the future of wind energy conversion systems appears promising. Continued research into novel materials, advanced turbine designs, and energy storage solutions will likely lead to further improvements in efficiency and energy production. Moreover, the global obligation to reducing greenhouse gas emissions and combating climate change reinforces the importance of wind energy as a clean and sustainable energy source.

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