A Review of Wind Energy Conversion Systems

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***Abstract*—In the last decade, wind energy as a renewable energy source has become increasingly popular, and the establishment of large-scale wind energy conversion systems (WECS) and its connection to the electricity grid has become common. However, conventional power systems are not directly compatible with the characteristics of wind turbines. In this article, different topologies and classification of wind turbine systems are examined and different wind energy conversion systems are discussed. The article focuses on the speed-based, output-based, generator-type-based and orientation-based classification of WECS. The typical structure and information of WECS are explained in detail. Fixed and variable WECS are compared and contrasted in the context of network stability. An overall review and comparison of different wind turbine generators in WECS are discussed. Finally, the balance problem for different wind turbine energy conversion systems in the grid network is presented and possible different mitigation methods and solutions are suggested.**

***Index Terms*—balance problem, energy conversion systems, grid connected system, wind energy, wind turbine.**

I. INTRODUCTION

There are numerous renewable energy sources in use today. Wind, geothermal, and solar energy are the main sources of energy [1]. Renewable energy sources are energy sources that are free, safe, and endless. Wind energy is a very important energy type in the renewable energy category, and its use has expanded dramatically in the last decade.

In comparison to solar energy, wind energy is used at a much lower rate. However, in the next years, it is predicted to rise at a rapid rate. In 2019, 60.4 GW of wind generating capacity was installed around the world. Compared to the facilities in 2018, there has been a 19% increase and historically it has been regarded as the second-best year for wind energy infrastructure. The total capacity for wind energy globally is now over 651 GW, an increase of 10% compared to 2018. Wind energy usage was expected to increase more than 10% with new 76 GW wind energy conversion systems (WECS) installation [2]. However, there has been a negative impact of COVID-19 on wind energy installations the past two years [3].

Different energy type sources are utilized differently. For example, geothermal energy sources use the potential energy of water. In these sources, the potential energy is initially converted to kinetic energy followed by conversion to mechanical energy that is in turn converted to electric energy [4]. Solar energy in other types is used in two different methods basically. The liquid is heated with solar energy and the energy form is converted to kinetic energy form that is converted to mechanical form before finally getting converted to the electric energy [5]. Another method is photon energy usage. Photon energy is converted to electric energy directly with the utilization of photo-voltaic panels (PV) [6]. In addition, solar energy is used indirectly as well. Currently, it is one of the widely used renewable energy sources and indirectly is associated with wind energy sources as well. For example, the sun heats the earth directly or indirectly. The air that expands due to the heat becomes lighter than the cold air. The warm air exchanges with the cold air and the potential energy created in the process changes the kinetic energy structure in the environment. The wind is produced naturally following this phenomenon. This energy is used in similar conversation methods. A very basic method is to wind the kinetic energy structure. Kinetic energy is converted to electric energy structure by the utilization of an electric generator [7]. However, the investment and initial setup cost of wind turbine is higher than that of solar PV panels. Solar energy usage requires the use DC/AC converters for PV groups. Additionally, the PV panels produce lesser power and can be used directly in DC systems. Furthermore, PV panel groups can connect to each other in other applications. In this way, it can generate high power and high voltage. Inverters can help generating high voltage and high-power converted to the AC source, and can connect to the grid system directly.

Wind energy generally is used with the help of generators. In this method, mechanical energy is converted to electric energy. But, wind energy directly cannot be converted to electric energy and requires conversion to mechanical energy through flags. This mechanical energy is used by the generator to generate electricity. Thus, the created voltage is tuned to the grid voltage value with the help of transformer. After that electricity energy becomes usable energy for consumers. A basic wind turbine structure is presented in the Figure 1.

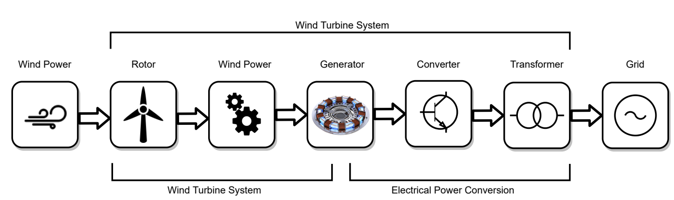

Fig. 1. Wind turbine system structure.

Energy demand has been increasing at an annual rate of about 2% every year. About 80% of the usual load demand has been supplied from fossil fuel [8]. The safety concerns and the over use of non-renewable energy sources have led to strategic targets for renewable energy sources such as wind energy. Many countries have set ambitious strategic targets [9], [10].

The remainder of the article is structured as follows. Section II provides a comprehensive review of the wind turbine topologies. The different criteria based classification of wind energy conversion systems are discussed. A focused comparison is drawn between the fixed, partly fixed, and variable speed wind energy turbines in this section. Section III presents the balance problem encountered in the wind turbine system network. Finally, the conclusions are drawn in Section IV.

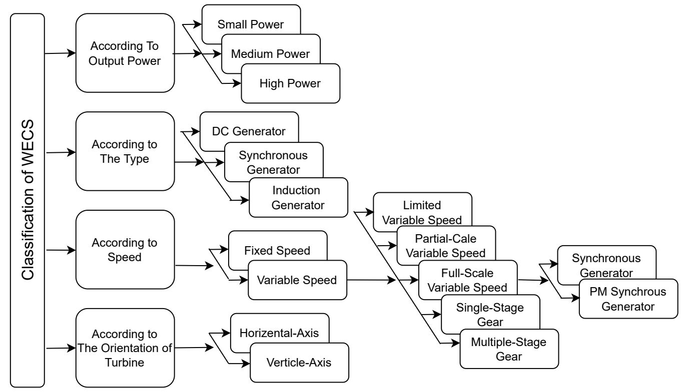

Fig. 2. Wind turbine system classifications.

II. Wind Turbine Topologies

In this section, the classifications of the wind turbine systems are discussed. The wind turbine systems utilize wind power and generate electrical energy. These systems capitalize the merits of wind energy that include renewability, low cost, and legitimacy. However, wind power is unpredictable owing to the intermittent flow of wind. Wind power fluctuations generate the power balance problem. To overcome this problem, Wind power conversion systems are used in different generator types. Generators need a power control structure before yielding energy to the system. In this case, the WECS utilizes different active and reactive control methods to control the power.

Wind energy, among the renewable energy sources, requires higher installation capacity and can yield high output in terms of electricity generation after hydraulic, thermal, and nuclear energy [11]. Therefore, site selection is very crucial for this type of energy generation. Wind speed and wind quality are other two critical factors for power generation from wind. Because a small change in wind speed can cause large changes in the energy generated. Therefore, the most preferable sites for wind turbines are locations without turbulence. Because turbulence makes wind turbines less productive and influences the turbine's overall operability and efficiency. Wind turbulence is brought on and affected by the friction between the air and the ground surface of the earth. Depending on the surface to air friction, the wind may be more or less turbulent.

Turbines are classified into different types based on the output power capacities, speed variability, equipment type, production methods used in generating electrical energy from wind, and according to the orientation turbine. These differences arise generally due to dissimilar wind speeds of regions where the power plants are installed, the network fed by the turbines, the power control systems held by the turbines, and the generator types used in the turbines. The different classifications of wind turbine systems are presented in Figure 2. As shown in Figure 2, the output power-based classes of wind turbine systems are small, medium, and high power classes. The generator-type classifies the turbine systems into DC generator, synchronous generator and induction generator types of wind turbines. According to speed, different classes include fixed and variable speed types that are further categorized into subclasses. According to the orientation of turbine, the wind turbine types include horizontal-axis and vertical-axis types. These are described in further detail in subsequent subsections.

A. Speed-based WECS classification

Wind energy turbines can generate electric energy with different turbine systems. This subsection focuses on fixed speed, partly variable speed, and variable speed wind turbines. The merits and limitations of these turbine systems are discussed as follows.

1) The Fixed Speed WECS: In fixed-speed wind turbines, the speed of the rotor is fixed above a certain wind speed by a gearbox. During operation, the rotor speed is kept constant irrespective of the wind speed. It has an inductive generator directly connected to the mains with a soft-starter and capacitor group to reduce reactive power compensation in wind turbine systems [12]. The fixed speed wind turbine systems typically employ standard squirrel-cage induction generators (SCIG). Their costs are low because there are no power electronic devices utilized in the turbine system [13]. Added advantages are system simplicity, and robustness. However, these turbine systems have a few disadvantages mentioned as follows. The wind turbine system is linked to the grid directly and any sudden wind speed changes create mechanical stress in the gearbox. This limits the power quality control and calls for exorbitant mechanical construction to eliminate the high stress. Furthermore, the wind turbine rotor is not turned to the optimum wind speed. This leads to poor wind energy conversion efficiency. The basic structure of fixed speed squirrel cage induction wind turbine system is illustrated in Figure 3 [14].

The following faults and problems can be observed in fixed speed wind turbines symmetrical 3-phase, unbalanced faults (2-phase and 1-phase), breaker re-closings, phase interruptions, operation under unbalanced system voltages [16].

2) Partly Variable Speed WECS: These are wind energy conversion systems whose rotor speed is partially fixed when

TABLE I
WIND TURBINE SYSTEM COMPARISON [15]

Turbine Type	Fixed Speed	Partly Variable Speed	Variable Speed				
Generator	SCIG	WRIG	PMSG	SG	SCIG	DFIG	SRG
Active power control	Limited	Limited	Yes	Yes	Yes	Yes	Yes
Reactive power control	No	No	Yes	Yes	Yes	Yes	Yes
Wing control	Stop-up/Tilt	Tilt	Tilt	Tilt	Tilt	Tilt	Tilt
Converter power	Unavailable	Small	Full Scale	Full Scale	Full Scale	Full Scale	Full Scale
Speed range	Fixed	Limited	Wide	Wide	Wide	Wide	Wide
Transmission type	HVAC	HVAC	HVAC/HVDC	HVAC/HVDC	HVAC/HVDC	HVAC	HVAC/HVDC
Network fault resistance	Weak	Weak	Durable	Durable	Durable	Durable	Durable
Power transfer efficiency	Less	Low	High	High	High	High	High
Control difficulty	Easy	Easy	Medium	Complex	Complex	Complex	Easy
Generator cost	Cheap	Cheap	Expensive	Expensive	Cheap	Cheap	Cheap
Converter cost	Unavailable	Cheap	Expensive	Expensive	Expensive	Cheap	Expensive
Weight	Light	Light	Light	Heavy	Light	Light	Light
Maintenance	Easy	Easy	Easy	Easy	Easy	Difficult	Easy

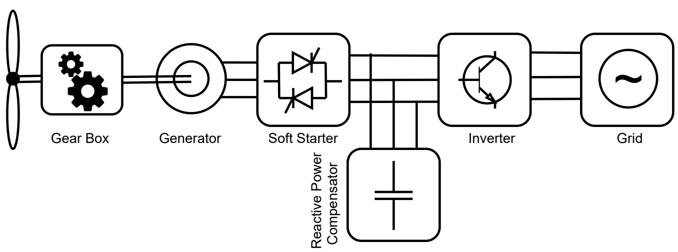

Fig. 3. Fixed speed squirrel cage induction WECS (SCIG).

compared to fixed WECS or variable WECS. These turbine systems consist of a wind blade, gear box, generator, rectifier, and inverter parts. Similar to fixed speed WECS, the generator winding is directly connected to the grid in partly variable speed WECS or sometimes, a partial scale frequency converter is used [17]. The used generator type is the squirrel cage induction generator (SCIG). The typical structure of partly variable speed WECS is depicted in Figure 4.

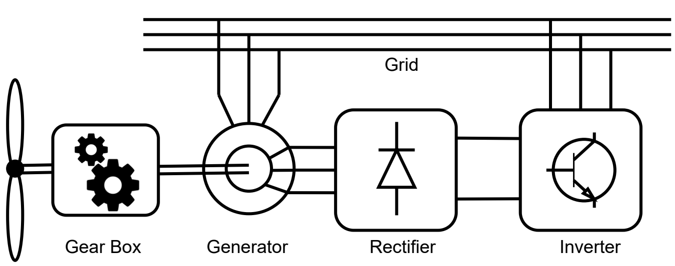

Fig. 4. Partly variable-speed WECS (WRIG).

Partly variable-speed WECS is connected to the grid through generator. In this case, the rotor speed is limited. The gearbox can damage the case of winding change and its network fault resistance is very weak. Additionally, the grid can affect this changing status. Reactive power control is not made with partly variable WECS and the power transfer efficiency is low.

3) Variable Speed WECS: Variable-speed wind turbines are systems that are connected to the grid through a power electronic converter, usually using an asynchronous or synchronous generator. The employment of power electronic converter facilitates the WECS to function at variable speed. The variable speed allows for the yielding of more power when compared to fixed speed WECS. Additionally, the power converter compensates for the reactive power and allows for a smooth grid connection. At the present time, commercial usage in modern wind turbine systems involves variable speed wind turbine systems [18]. There are many advantages of variable speed wind turbine system when compared to fixed speed wind turbine system. Wind turbine speed is adjusted for optimum energy produced according to wind velocity. This characteristic enhances the efficiency of variable-speed WECS when compared to fixed speed WECS. The mechanical pressure and losses are maintained low with the help of the system's power regulation [19], [20]. Hence, the mechanical design can be lighter which in turn can reduce the design cost. The variable speed WECS yield regulated power output and thus, enhances overall power quality and island mode operation capability. Variable speed wind generator system requires complex converters. These increase the operation and maintenance cost. Due to the improvement in power electronics and reduced product costs in the recent years, variable speed wind turbine systems are attractive systems compared to other types [21]. The variable-speed WECS can employ different generator types. The main generator types include squirrel cage induction generator (SCIG), permanent magnet synchronous generator (PMSG), wound rotor induction generator (WRIG), synchronous generator (SG), double-fed induction generator (DFIG), and switched reluctance generator (SRG) [15]. Variable speed wind turbine systems mainly consist of propellers blade, gearbox, generator, AC to DC converter, and a DC/AC converter (inverter) for grid connection. The general structure of variable speed WECS is depicted in Figure 5.

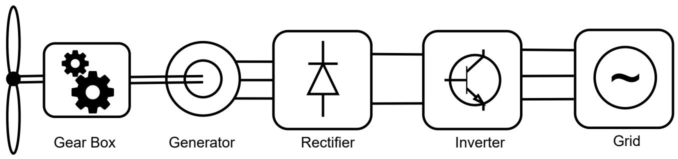

Fig. 5. Variable speed wind turbine system (PMSG).

The difference between different speed-based WECS, as utilized in current huge wind turbines and the typical speed-based operation, are summarized in the following:

1) The grid voltage cannot be regulated in fixed speed operation.
2) Fixed speed operation have low control over reactive power [22].
3) Variable speed operation below rated power can allow enhanced energy yield.
4) Variable speed capability above rated power can substantially relieve loads.
5) The variable speed operation moderates pitch system duty and diminishes output power variability.

B. Output power-based WECS classification

The wind energy conversion systems can be classified based on the output power generated by the systems. This subsection presents such output power-based WECS classes as follows.

a) Small size WECS (less than 2 kW): Small size WECS are wind turbines used for micro-scale electricity generation as opposed to commercial wind farms. Typically, small size WECS are of low power capacities and are utilized in remote applications. They are preferred in areas such as boats, caravans, chalets, and camping areas depending on the place of consumption. It can be small in size and small in power as low as 50W of power delivery.

b) Medium Size WECS (between 2kW and 100 kW): Such wind turbines can reach a capacity of one hundred kilowatts per square meter. These wind turbines are mostly built for residential and local use. The generation and the use of energy occur by converting it through various circuit elements. Due to the variable wind speed, it is preferred to not be used by direct mains feeding but to be used with energy storage units in order to avoid grid irregularities.

c) Large Size WECS (more than 100 kilowatt): The square size of large size WECS is suitable for generating power for distribution networks. Due to the high dimensions of this type of wind turbines, the installation costs are high. They are connected to the central network by grouping them with the help of various connection types. There are many wind turbine farms with very high power volumes. Their high power generation, and the sudden and unexpected variations in wind speed can cause grid irregularities relative to the grid connection point.

C. Generator type-based WECS classification

According to different types of generators used in the wind energy conversion systems, these are categorized into the following:

a) D.C. Generators: A direct current generator is a mechanical and rotating device that outputs electricity with one-way voltage and current. The DC generators operate on the same principle as that of synchronous generators. The magnetic field is on the stator that comprises of permanent magnets and is either generated by stator magnets or by the DC in field coils. And, the armature winding is on the rotor. As the wind turbine rotates, the generator coils are fostered with voltage at the rate of change over time of the magnetic flux. Considering the variability of the wind speed, the coil flux oscillates in form with zero mean value causing the variability in the induced voltage.

The armature rotates allowing the induced current to pass through a commutator or slip rings. There are carbon brushes connected to the commutator and the electrical power is yielded to the output terminals through these brushes. The generated electromotive force (emf) output is directly proportional to the speed of rotation and magnetic flux. The control of the generated emf is normally achieved with the help of a converter and by the regulation of the DC in the field.

DC generators are rarely used in wind generation systems because of the elements that rub like brushes and wear out over time and the need to control the direct current. The application of DC Generator type WECS include low power demand conditions where load is in close proximity to the wind energy conversion systems, heating applications, and charging batteries.

b) Induction Generators: There are different types of generators used in WECS, especially. Synchronous and induction generators have matching stator winding arrangement and this gets energized by the rotating magnetic field. However, the rotor winding arrangement is dissimilar in these two type of generators. The induction generator rotor conventionally uses the arrangement such as wound rotor or squirrel cage. The synchronous generators are required to be synchronized with the electrical grid before they produce energy and before they are connected. However, the asynchronous generators or induction generators can be directly connected to the electrical grid and be directly driven by the turbines at any flexible speed that changes with wind speed. Compared to the asynchronous generator, the synchronous generator is superior to the asynchronous generator in terms of weight, cost in terms of not requiring a DC supply, durability, and low maintenance costs due to its brushless nature. They are also safe against overloads and short circuits. It is used with static power converters to manage the output voltage and frequency of the induction generator.

c) Synchronous Generators: In wind turbine systems where synchronous generators are used, rotor speed needs to be controlled due to changes in wind speeds. In addition, synchronous generators are used in conjunction with gearboxes, dampers (or springs) for multi-directional coupling and reducing variable speed upwind turbulence. In addition, synchronous generators are more difficult to supply in different sizes and power than asynchronous generators due to non-availability of sizes, limited number of manufacturers and the lack of generator diversity. The synchronous generators are more expensive according to power price comparisons. One of the most prominent features of synchronous generators is that these have reactive power that these may or may not need in power systems.

D. Orientation type based WECS classification

The orientation type based classification is based on the orientation of the axis of rotation or the rotor shaft. The two classes are horizontal axis WECS and vertical axis WECS. The two types of WECS are illustrated in Figure 6 and are described as follows.

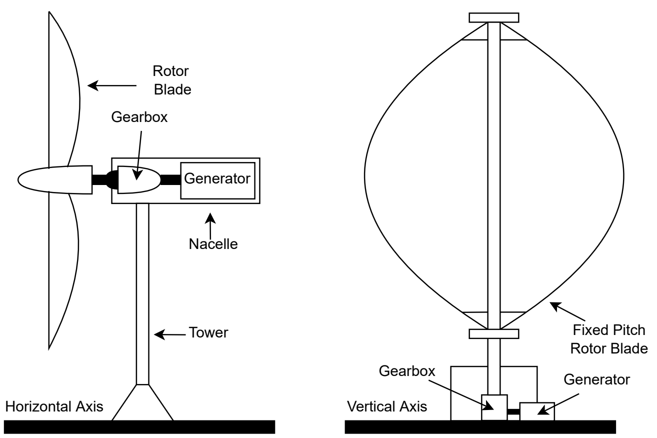

Fig. 6. Horizontal and Vertical Axis Wind Energy Conversion Systems.

a) Horizontal Axis WECS: Horizontal axis turbines are the turbines with axis of rotation horizontal to the ground surface and in line or parallel with the wind flow. The commercial wind turbines today mostly fall under the class of horizontal axis. The horizontal axis WECS work on the principle of lift. As the wind flows and interacts with the rotor blades, there is a lift force acted upon the rotor by the wind and this causes the rotation of the rotor. The speed of rotation depends on the design features and the rotor size. There is a low speed main shaft that rotates first and this passes the rotation to the high speed main shaft through a gearbox. It is known that the generator requires high speed and this is made possible by the gear trains. The generator converts the mechanical form of energy into electrical energy. The merits of horizontal axis turbines are high efficiency, high reliability, high rate of capacity, and consistency. These turbines are self-starting and in case of storms, the blades can tilt the rotor to eliminate damage. The demerits include that the turbines are heavy, the towers are required and that makes the cost go higher, difficult installation, high noise, high maintenance cost, and these turbines do not yield well in turbulent or inconsistent winds.

b) Vertical Axis WECS: The wind turbine does not have the appearance of a propeller as its axis of rotation or rotor shaft is vertical or at minimum traverse to the ground surface or the wind stream. It is produced for experiments rather than for commercial use. Since they can be placed on the ground, the need for towers and tower costs are eliminated. Since the system can be used without turning to the desired wind direction, they do not need a rudder system. Vertical axis WECS can operate in environment with intermittent and slow wind ground-level positions which are unfitting for horizontal axis WECS. However, their efficiency and reliability are lower than horizontal axis wind turbines [23]. There are different types of vertical axis WECS such as Darrieus and Savonius.

In Darrieus type WECS, there are two vertically placed blades in the vertical axis wind turbine. The blades are arranged to form an ellipse approximately with the turbine shaft long axis. The rotational movement occurs due to the effect of the wind and the difference in pulling force between the concave and convex surfaces of the wings. Due to its structure, Darrieus type wind turbines achieve twice the torque per revolution. Considering that the wind blows from one direction; the power delivered by the turbine creates a sinusoidal curve [24].

Savonius type WECSs are in the form of a combination of two or three bucket-like sections. The most common is the case with two scoops and has an "S" shape. In the Savonius turbine, the fluid follows a turbulent path on the concave blade and rotational flows occur here. These rotating flows reduce the performance of the Savonius turbine, so they are not used much in electricity generation. They are mostly used as anemometers for water pumping and wind measurements [25].

The comparison of different wind turbine systems are tabulated in Table I.

III. Balance Problem in Turbine System

The variable wind speed characteristic in wind turbine systems creates power balance problem in the network. This problem can be alleviated with a solution that involves improving wind speed, reducing speed variability, and providing highly accurate energy forecasts for areas with wind turbines. Additional solutions can be providing backup power from other production units, effective load management, and use of energy storage technologies [26].

The main shortcoming of the wind turbine system is the power balance problem and there are a high number of different methods to solve this problem. The power systems have capability of high wind power penetration. The reliability and security of such power systems should be ensured. A factor Fault Ride Through (FRT) is required and there are several ways to enhance the FRT capability, WECS stability, reliability, and security. A few of the methodologies include, but are not limited to the following: fast power control in wind energy conversion systems, and dynamic reactive power injection. Furthermore, Flexible AC Transmission System (FACTS) devices deal with the real time control or compensation of reactive power and the reduction of voltage dip. Wind turbine systems can add a new protection method and control system, also can use a fast-response energy storage system.

The impact of irregular rise and fall of wind power on system regulation and stability is other crucial consideration. Large offshore wind energy conversion systems might add significant power fluctuations into power systems [27], and such power irregularities might affect interconnected and adjacent power systems if the power irregularities are not suitably handled.

IV. Conclusion

The paper presented different wind turbine topologies and discussed different classes of wind energy conversion systems. A detailed review of the speed-based WECS classification such as fixed speed, partly variable speed, and variable speed turbine systems is presented. The specifications, merits, and demerits of all classes of WECS have been compared. Furthermore, the adverse effects to the grid of the improper handling of power fluctuations in the wind turbine systems have been mentioned in the article and different problem-solving methods to mitigate the grid balance problem have been explained for grid-connected wind turbine systems.

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