1

INTRODUCTION

1.1 INTRODUCTION

Over the last twenty years, renewable energy sources have been attracting great attention due to the cost increase, limited reserves, and adverse environmental impact of fossil fuels. In the meantime, technological advancements, cost reduction, and governmental incentives have made some renewable energy sources more competitive in the market. Among them, wind energy is one of the fastest growing renewable energy sources [1].

Wind energy has been used for hundreds of years for milling grains, pumping water, and sailing the seas. The use of windmills to generate electricity can be traced back to the late nineteenth century with the development of a 12 kW DC windmill generator [2]. It is, however, only since the 1980s that the technology has become sufficiently mature to produce electricity efficiently and reliably. Over the past two decades, a variety of wind power technologies have been developed, which have improved the conversion efficiency of and reduced the costs for wind energy production. The size of wind turbines has increased from a few kilowatts to several megawatts each. In addition to on-land installations, larger wind turbines have been pushed to offshore locations to harvest more energy and reduce their impact on land use and landscape.

This chapter provides an overview of wind energy conversion systems (WECS) and their related technologies. The aim of the chapter is to provide a background on sever-

Power Conversion and Control of Wind Energy Systems. By B. Wu, Y. Lang, N. Zargari, and S. Kouro

al aspects related to this exciting technology and market trends such as installed capacity, growth rate, and costs. The details of turbine components, system configurations, and control schemes are analyzed in depth in the subsequent chapters.

1.2 OVERVIEW OF WIND ENERGY CONVERSION SYSTEMS

1.2.1 Installed Capacity and Growth Rate

Installed wind power capacity has been progressively growing over the last two decades. Figure 1-1 shows the evolution of cumulative installed capacity worldwide as of 2009 [3]. The installed capacity of global wind power has increased exponentially from approximately 6 GW in 1996 to 158 GW by 2009. The wind industry has achieved an average growth rate of over 25% since 2000, and is expected to continue this trend in the coming years. This impressive growth has been spurred by the continuous cost increase of classic energy sources, cost reduction of wind turbines, governmental incentive programs, and public demand for cleaner energy sources.

Figure 1-2 shows the cumulative installed wind power capacity of the top ten countries in the world as of 2009 [3]. Although Europe has maintained its role as the largest wind power producer as a region, the Unites States has surpassed the long-time world leader Germany by increasing its installed capacity of almost 50% in just two years. It has now an installed capacity of 35 GW, equivalent to 22.3% of the global installed capacity. Asian countries are catching up, mainly driven by the markets in China and India. In fact, China doubled its installed capacity in one year, and is expected to continue to grow at a fast pace in the next few years.

Although this sustained growth is impressive, the real challenge is to increase the share of wind power in relation to total power generation. For example, Germany generated 6.4% of its total power demand from the wind in 2009, whereas in the United States this ratio is only 1.8%. In contrast, Demark, Portugal, and Spain lead in this aspect, with over 20%, 15%, and 13% of wind power penetration, respectively.

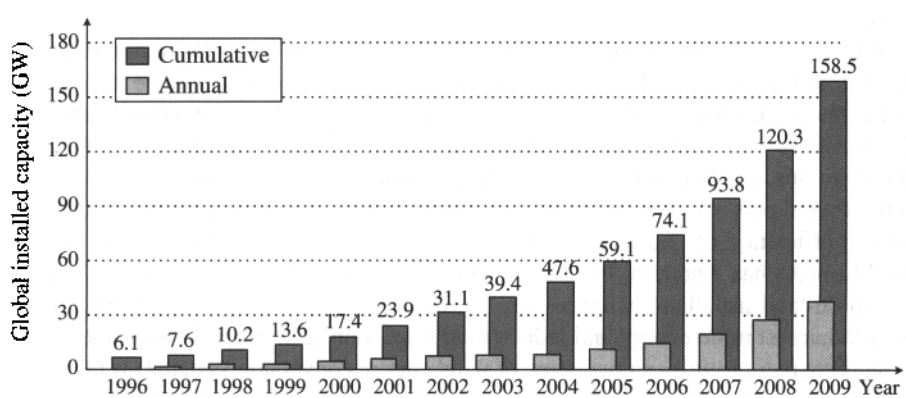


Figure 1-1. Global annual and cumulative installed wind power capacity.

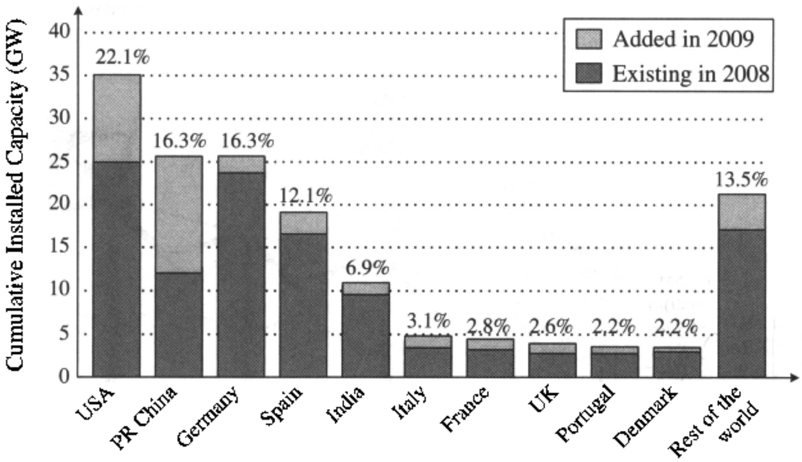


Figure 1-2. Top ten countries in cumulative installed wind power capacity as of 2009.

1.2.2 Small and Large Wind Turbines

Wind turbines range from a few kilowatts for residential or commercial use to several megawatts in large wind farms. Small-to-medium-size wind turbines are normally below 300 kW, and can be installed at homes, farms, and businesses to offset the consumption of utility power. Small wind power units can be used in combination with other energy sources such as photovoltaic power and diesel generators to form a standalone/off-grid generation system for remote areas, where access to the power grid is difficult or costly.

On the other hand, the size of large wind turbines has steadily increased over the years. The evolution in turbine size can be clearly appreciated in Figure 1-3. Starting with a 50 kW power rating and a 15 m rotor radius in the early 1980s, wind turbines can be found today up to 7.5 MW with a rotor diameter of 126 m. It is expected that a 10 MW wind turbine will be developed in the future with a turbine rotor diameter of 145 m, which is approximately twice the length of a Boeing 747 airplane.

The increase in wind turbine size implies more power output since the energy captured is a function of the square of the rotor radius. This can be observed by correlating the rotor diameter and tower height to the power rating of the wind turbines shown in Figure 1-3. Larger wind turbines often result in reduced cost since their production, installation, and maintenance costs are lower than the sum of smaller wind turbines achieving the same power output.

1.2.3 Stand-Alone and Grid-Connected Applications

The wind turbines can operate as stand-alone units of small power capacity to power villages, farms, and islands where access to the utility grid is remote or costly. Since the power generated from the wind is not constant, other energy sources are normally

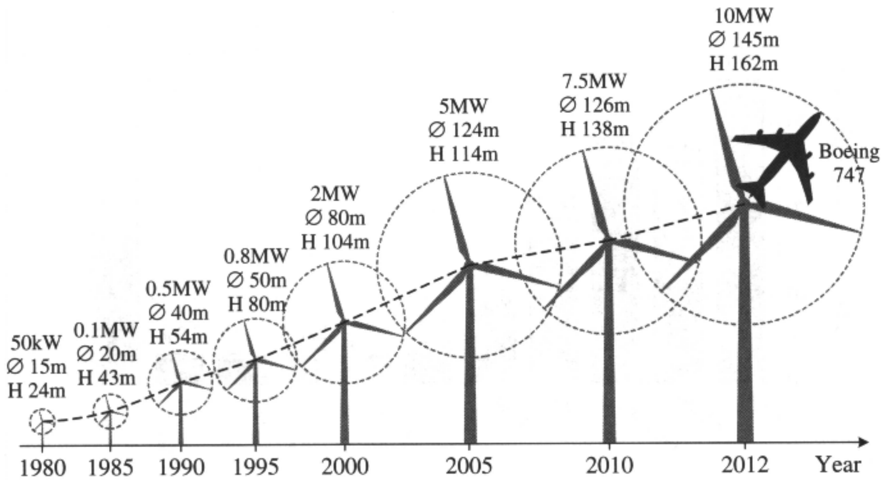


Figure 1-3. Evolution of wind turbine size (Ø: rotor diameter; H: tower height).

required in stand-alone systems. It is common that a stand-alone wind energy system operates with diesel generators, photovoltaic energy systems, or energy storage systems to form a more reliable distributed generation (DG) system [4]. Due to its limited applications, stand-alone wind power constitutes only a small fraction of the total installed wind capacity in the world.

The majority of wind turbines operating in the field are grid-connected, and the power generated is directly uploaded to the grid. As most generators operate at a few hundred volts (typically 690 V), transformers are used to increase the generator voltage to tens of kilovolts, for example, 35 kV, for wind farm substations. This voltage is stepped up further by the substation transformer, which connects the wind farm to the grid as shown in Figure 1-4.

1.2.4 On-Land and Offshore Applications

Large capacity wind farms have traditionally been placed on land for several reasons: easy construction, low maintenance cost, and proximity to transmission lines. On the other hand, offshore wind farms are also commercially viable. One of the main reasons for the offshore wind farm development is the lack of suitable wind resources on land. This is particularly the case in densely populated areas such as in some European countries. Another important reason is that the offshore wind speed is often significantly higher and steadier than that on land. Considering that the energy obtained by wind turbines is proportional to the cube of the wind speed, the turbines can capture more energy when operating offshore. Moreover, the environmental impact, such as audible noise and visual impact, is minimal in offshore applications. These factors are the primary drivers for the development of offshore wind turbine technology.

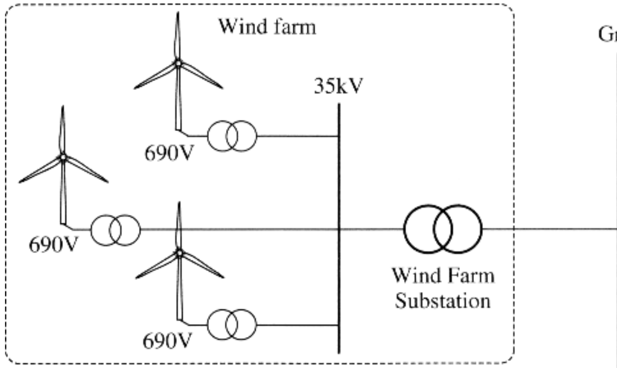


Figure 1-4. Example of a grid-connected wind farm.

Although offshore turbine prototypes can be found around the world, only a limited number of countries (mostly in Europe) have operational offshore wind farms. The biggest players in this area are the United Kingdom, Denmark, and the Netherlands, as shown in Figure 1-5 [5]. Although the total European offshore capacity of 2056 MW as of 2009 accounts for only 1.3% of total installed wind power capacity, offshore wind energy is a fast-growing market, as shown in Figure 1-6 [5]. The installed capacity increased from less than 0.1 GW in 2000 to more than 2 GW in 2009.

In addition, offshore wind resources are enormous. For instance, the offshore wind resources in Europe are several times the total European electricity consumption [6]. Some offshore wind farms scheduled to be commissioned in the near future will reach a capacity of more than 1 GW each. Examples of on-land and offshore wind farms are given in Tables 1-1 and 1-2, respectively, where the location, number of turbines, turbine size, suppliers, and production dates are provided. The photographs of some of these wind farms are shown in Figure 1-7.

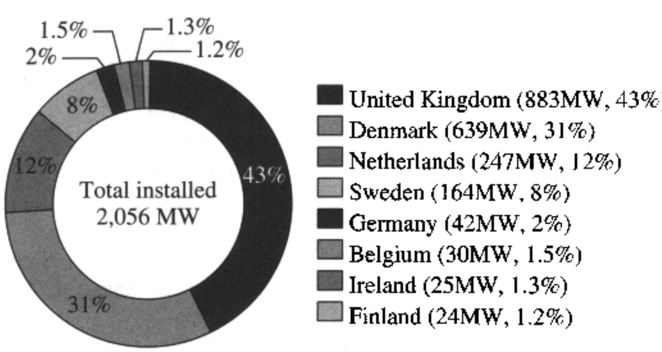


Figure 1-5. Installed European offshore wind power capacity as of 2009.

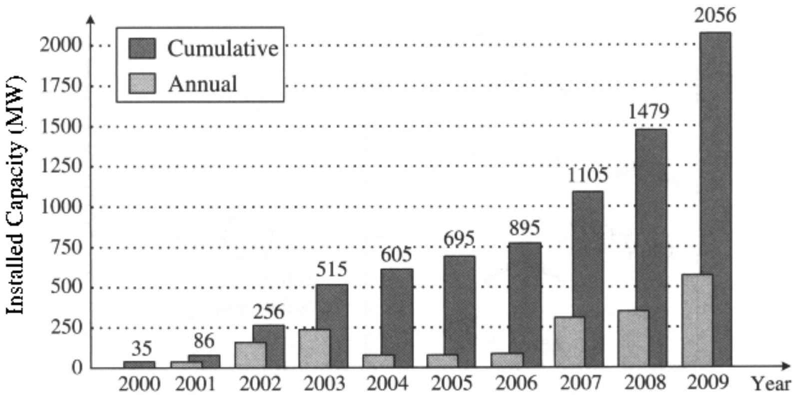


Figure 1-6. Annual and cumulative installed European offshore wind power capacity.

Table 1-1. Examples of on-land wind farms

Parameter	Roscoe	Whitelee	Bowbeat
Location	Texas, USA	Glasgow, Scotland	Moorfoot Hills, Scotland
Number of turbines	627	140	24
Power rating	781.5 MW	322 MW	31.2MW
Area	404.7 km^2	72.52 km^2	
Turbine model/supplier	Mitsubishi 1000A, GE, and Siemens	Siemens 2.3 MW	Nordex N60
Production date	2009	2009	2002

Table 1-2. Examples of offshore wind farms

Parameter	London Array	Horns Rev	Nysted/Rodsand I
Location	London, UK	Jutland, Denmark	Lolland, Denmark
Distance from shore	20 km	14–24 km	10.8 km
Number of turbines	341	80	72
Power rating	1 GW	160 MW	166 MW
Area	245 km^2	20 km^2	26 km^2
Internal bus voltage	33 kV	34 kV	33 kV
Turbine model/supplier	Siemens SWT-3.6	Vestas V80 2MW	Siemens SWT-2.3
Transmission line	150 kV subsea cable	150 kV subsea cable	132 kV subsea cable
Offshore substations	Two	One	One
Production date	2012 (expected)	2002	2003

(a) Bowbeat wind farm (photo courtesy E.ON)

(b) Rodsand I wind farm (photo courtesy E.ON)

Figure 1-7. Examples of on-land and offshore wind farms.

The increase of turbine power capacity and reduction of maintenance costs are crucial for offshore wind farms. The average power rating of installed offshore wind turbines was around 2.9 MW as of 2009 [5], and the power rating of the generators for offshore applications is expected to increase in the next decade. To reduce the maintenance cost, direct-driven wind turbines using low-speed permanent magnet synchronous generators (PMSGs) is a viable technology. The maintenance costs for these turbines are reduced due to elimination of the gearbox and brushes. For offshore wind farms, the foundation and transmission cable add significantly to the total project costs. A comparison summary of on-land and offshore farms is given in Table 1-3. The wind resources, capital/maintenance costs, and energy production are the critical factors to be considered in the development of offshore wind farms.

Table 1-3. Comparison between offshore and on-land wind turbines

	Description	On-land	Offshore
Resources	Wind speed	Adequate	Higher and steadier
	Limits in available land/area	Yes	No
Power transmission	HVDC/HVAC	Location dependent	Required
Environmental impact	Visual impact	Yes for nearby residents	No
	Acoustic noise	Yes for nearby residents	No
Operation	Access	Convenient	Inconvenient
	Erosion	Low	High
	Capital cost	Low	High
	Maintenance cost	Low	High
	Energy production	Good	Better

1.2.5 Costs of Wind Energy Conversion Systems

The cost of electricity from wind power has declined steadily over the past two decades. When the first utility-scale turbines were installed in the early 1980s, wind-generated electricity cost $0.3 per kWh. Today, wind power plants can generate electricity for $0.07 to $0.12 per kWh [7]. Compared with other clean energy resources, such as photovoltaic (PV) energy and solar thermal energy, wind energy is one of the most economically viable renewable energy resources, as illustrated in Figure 1-8 [8]. Note that for a given energy source, the cost for energy production is not constant, but varies with the power rating, operating condition, location, and technology used.

Table 1-4 gives the cost breakdown of a typical 2 MW wind turbine [9]. Around 75% of the total cost is directly related to the turbine, which includes rotor blades, gearbox, generator, power converters, nacelle, and tower. The other costs include grid connection, foundation construction, land rent, electric installation, and road construction.

One of the most effective methods for reduction in cost of per installed kilowatt is to increase the turbine size. As the swept area covered by the rotor blades grows proportionally to the square of the blade length, there is a favorable nonlinearity between the blade length and the captured wind power. A clear example has been given in Figure 1-3, in which a 50 kW wind turbine in 1980 had a rotor diameter of 15 m, and the turbine size was increased to 7.5 MW in 2010 with a rotor diameter of 126 m. The turbine rotor diameter and the power rating have been increased by 8.4 and 150 times, respectively. The increase in the power rating is also facilitated by the increase in tower height for larger turbines.

Table 1-5 gives typical costs for 10 kW, 50 kW, and 1.7 MW wind turbines installed in the mid-2000s [10]. The cost per installed kilowatt for these turbines was

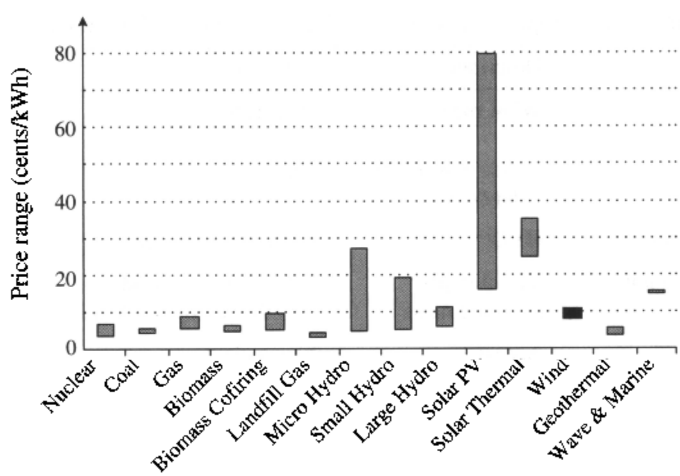


Figure 1-8. Cost range of different energy sources.

Table 1-4. Cost breakdown of a typical 2 MW wind turbine

Component	Share of total cost, %
Turbine	75.6
Grid connection	8.9
Foundation	6.5
Land rent	3.9
Electric installation	1.5
Consultancy	1.2
Financial costs	1.2
Road construction	0.9
Control systems	0.3

$5760, $3300, and $1680, respectively. Obviously, the larger the wind turbines, the lower the cost per kilowatt installed. This also explains the rapid development of large megawatt turbine technology in the past years.

The total cost of wind energy systems is also affected by the location of wind turbines. Offshore wind turbines are normally more costly than on-land turbines mainly due to higher turbine installation and power transmission costs. Figure 1-9 gives an estimated cost of offshore and on-land turbines from year 2000 to 2020 [11]. With the technological advancements, total cost of both offshore and on-land turbines will decrease in the coming years. Although the offshore wind turbines cost more than the on-land turbines, the greater energy output of offshore turbines can compensate for the higher initial costs. This is one of the reasons making offshore wind power generation attractive.

1.3 WIND TURBINE TECHNOLOGY

The wind turbine is one of the most important elements in wind energy conversion systems. Over the years, different types of wind turbines have been developed [12]. This section provides an overview of wind turbine technologies, including horizontal/vertical-axis turbines and fixed/variable-speed turbines.

Table 1-5. Costs of small and large wind turbines installed in the mid-2000s

Item	Small wind turbine		Large wind turbine
Rated output power	10 kW	50 kW	1.7 MW
Turbine cost	$32,500	$110,000	$2,074,000
Installation	$25,100	$55,000	$782,000
Total installed cost	$57,600	$165,000	$2,856,000
Total cost per kW installed	$5,760	$3,300	$1,680

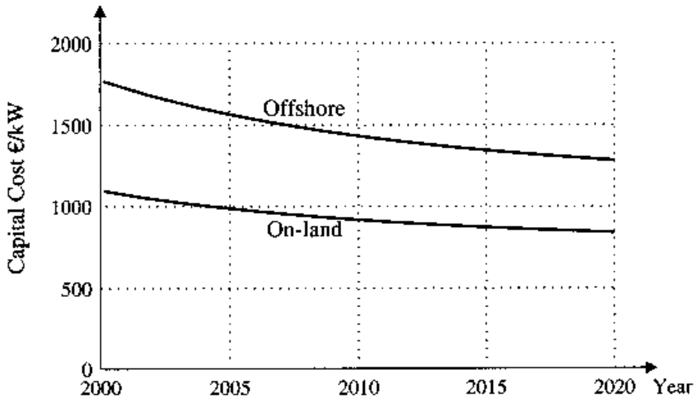


Figure 1-9. Comparison of total installed costs for on-land and offshore wind energy systems.

1.3.1 Horizontal- and Vertical-Axis Wind Turbines

Wind turbines can be categorized based on the orientation of their spin axis into horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) [12], as shown in Figure 1-10.

In horizontal-axis wind turbines, the orientation of the spin axis is parallel to the ground as shown in Figure 1-10a. The tower elevates the nacelle to provide sufficient

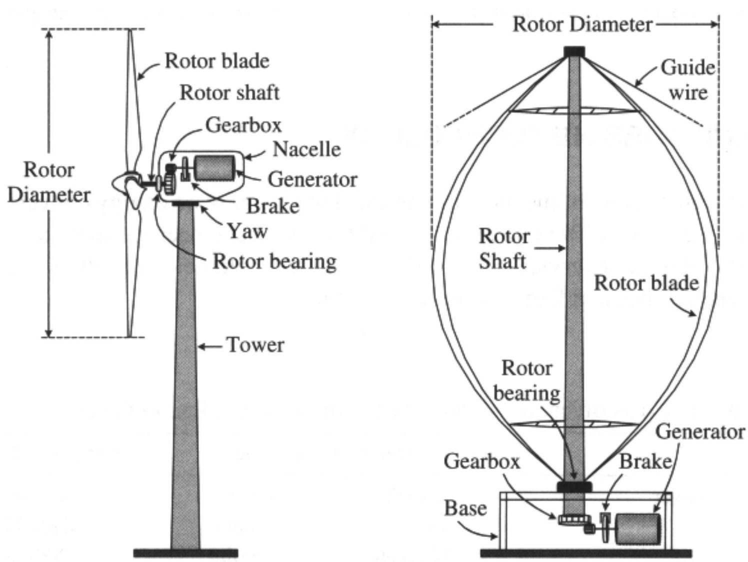


Figure 1-10. Horizontal- and vertical-axis wind turbines.

space for the rotor blade rotation and to reach better wind conditions. The nacelle supports the rotor hub that holds the rotor blades and also houses the gearbox, generator, and, in some designs, power converters. The industry standard HAWT uses a three-blade rotor positioned in front of the nacelle, which is known as upwind configuration. However, downwind configurations with the blades at the back can also be found in practical applications. Turbines with one, two, or more than three blades can also be seen in wind farms.

In vertical-axis wind turbines, the orientation of the spin axis is perpendicular to the ground. The turbine rotor uses curved vertically mounted airfoils. The generator and gearbox are normally placed in the base of the turbine on the ground, as shown in Figure 1-10b. The rotor blades of the VAWT have a variety of designs with different shapes and number of blades. The design given in the figure is one of the popular designs. The VAWT normally needs guide wires to keep the rotor shaft in a fixed position and minimize possible mechanical vibrations.

A comparison between the horizontal- and vertical-axis turbine technologies is summarized in Table 1-6. The HAWT features higher wind energy conversion efficiency due to the blade design and access to stronger wind, but it needs a stronger tower to support the heavy weight of the nacelle and its installation cost is higher. On the contrary, the VAWT has the advantage of lower installation costs and easier maintenance due to the ground-level gearbox and generator installation, but its wind energy conversion efficiency is lower due to the weaker wind on the lower portion of the blades and limited aerodynamic performance of the blades. In addition, the rotor shaft is long, making it prone to mechanical vibrations. It is these disadvantages that hinder the practical application of vertical-axis turbines for large-scale wind energy conversion. Horizontal-axis turbines dominate today's wind market, especially in large commercial wind farms.

Table 1-6. Comparison between horizontal- and vertical-axis wind turbines

Turbine type	Advantages	Disadvantages
HAWT	• Higher wind energy conversion efficiency • Access to stronger wind due to high tower • Power regulation by stall and pitch angle control at high wind speeds	• Higher installation cost, stronger tower to support heavy weight of nacelle • Longer cable from the top of tower to ground • Orientation required (yaw control)
VAWT	• Lower installation cost and easier maintenance due to the ground-level gearbox and generator • Operation independent of wind direction • Suitable for rooftops (stronger wind without need of tower)	• Lower wind energy conversion efficiency • Higher torque fluctuations and prone to mechanical vibrations • Limited options for power regulation at high wind speeds

1.3.2 Fixed- and Variable-Speed Turbines

Wind turbines can also be classified into fixed-speed and variable-speed turbines [13]. As the name suggests, fixed-speed wind turbines rotate at almost a constant speed, which is determined by the gear ratio, the grid frequency, and the number of poles of the generator. The maximum conversion efficiency can be achieved only at a given wind speed, and the system efficiency degrades at other wind speeds. The turbine is protected by aerodynamic control of the blades from possible damage caused by high wind gusts. The fixed-speed turbine generates highly fluctuating output power to the grid, causing disturbances to the power system. This type of turbine also requires a sturdy mechanical design to absorb high mechanical stresses [14].

On the other hand, variable-speed wind turbines can achieve maximum energy conversion efficiency over a wide range of wind speeds. The turbine can continuously adjust its rotational speed according to the wind speed. In doing so, the tip speed ratio, which is the ratio of the blade tip speed to the wind speed, can be kept at an optimal value to achieve the maximum power conversion efficiency at different wind speeds [12].

To make the turbine speed adjustable, the wind turbine generator is normally connected to the utility grid through a power converter system [13]. The converter system enables the control of the speed of the generator that is mechanically coupled to the rotor (blades) of the wind turbine. As shown in Table 1-7, the main advantages of the variable-speed turbine include increased wind energy output, improved power quality, and reduced mechanical stress [14]. The main drawbacks are the increased manufacturing cost and power losses due to the use of power converters. Nevertheless, the additional cost and power losses are compensated for by the higher energy production.

Furthermore, the smoother operation provided by the controlled generator reduces mechanical stress on the turbine, the drive train and the supporting structure. This has enabled manufacturers to develop larger wind turbines that are more cost-effective. Due to the above reasons, variable-speed turbines dominate the present market.

1.3.3 Stall and Pitch Aerodynamic Power Controls

Turbine blades are aerodynamically optimized to capture the maximum power from the wind in normal operation with a wind speed in the range of about 3 to 15 m/s. In

Table 1-7. Advantages and drawbacks of fixed- and variable-speed wind turbines

Speed mode	Advantages	Disadvantages
Fixed speed	• Simple, robust, reliable • Low cost and maintenance	• Relatively low energy-conversion efficiency • High mechanical stress • High power fluctuations to the grid
Variable speed	• High-energy conversion efficiency • Improved power quality • Reduced mechanical stress	• Additional cost and losses due to use of converters • More complex control system

order to avoid damage to the turbine at a high wind speed of approximately 15 to 25 m/s, aerodynamic power control of the turbine is required. There are a number of different ways to control aerodynamic forces on the turbine blades, the most commonly used methods being pitch and stall controls [2].

The simplest control method is the passive stall control, in which the blades of the turbine are designed such that when the wind speed exceeds the rated wind speed of about 15 m/s, air turbulence is generated on the blade surface that is not facing the wind. The turbulence reduces the lift force on the blade, resulting in a reduction in captured power, which prevents turbine damage. Since there are no mechanical actuators, sensors, or controllers, the power control by passive stall is robust and cost-effective. The main disadvantage of this method is the reduction in power-conversion efficiency at low wind speeds. Passive stall is normally used in small-to-medium-size WECS.

Pitch control is normally used for large wind turbines. During normal operating conditions with the wind speed in the range from 3 to 15m/s, the pitch angle is set at its optimal value to capture the maximum power from the wind. When the wind speed becomes higher than the rated value, the blade is turned out of the wind direction to reduce the captured power [12]. The blades are turned in their longitudinal axis, changing the pitch angle through a hydraulic or electromechanical device located in the rotor hub attached to a gear system at the base of each blade. As a result, the power captured by the turbine is kept close to the rated value of the turbine.

In cases in which the wind speed is higher than the limit of about 25 m/s, the blades are pitched completely out of the wind (fully pitched or feathered), and thus no power is captured. This method is effective in protecting the turbine and the supporting structure from damage caused by strong wind gusts. When the blades are fully pitched, the rotor is locked by a mechanical brake, and the turbine is in the parking mode. The major disadvantages of pitch control include the extra complexity and cost due to the pitch mechanism, and the power fluctuations during strong wind gusts due to slow pitch-control dynamics.

Another aerodynamic power control method is active stall control, which is essentially a pitch-control mechanism with the difference that the angle of attack of the blade is turned into the wind, causing stall (turbulence on the back of the blade), instead of being turned out of the wind. Active stall mechanism is an improvement over the passive stall, and can improve the power conversion efficiency at low wind speeds and limit the maximum captured power in high wind gusts. However, as with pitch-controlled WECS, it is a complex system. Active stall methods are normally used in medium-to-large-size WECS.

1.4 WIND ENERGY CONVERSION SYSTEM CONFIGURATIONS

The generator and power converter in a wind energy conversion system are the two main electrical components. Different designs and combinations of these two components lead to a wide variety of WECS configurations [13], which can be classified into three groups: (1) fixed-speed WECS without power converter interface, (2) WECS using reduced-capacity converters, and (3) full-capacity converter operated WECS.

1.4.1 Fixed-Speed WECS without Power Converter Interface

A typical configuration of WECS without a power converter interface is illustrated in Figure 1-11, where the generator is connected to the grid through a transformer. A squirrel cage induction generator (SCIG) is exclusively used in this type of WECS, and its rotational speed is determined by the grid frequency and the number of poles of the stator winding. For a four-pole megawatt generator connected to a grid of 60 Hz, the generator operates at a speed slightly higher than 1800 rpm. At different wind speeds, the generator speed varies within 1% of its rated speed. The speed range of the generator is so small that this system is often known as a fixed-speed WECS, as mentioned earlier.

A gearbox is normally required to match the speed difference between the turbine and generator such that the generator can deliver its rated power at the rated wind speed. This configuration requires a soft starter to limit high inrush currents during system start-up, but the soft starter is bypassed by a switch after the system is started. During normal operation, the system does not need any power converter. A three-phase capacitor bank is usually required to compensate for the reactive power drawn by the induction generator.

This wind energy system features simplicity, low manufacturing/maintenance costs, and reliable operation. The main drawbacks include: (1) the system delivers the rated power to the grid only at a given wind speed, leading to low energy conversion efficiency at other wind speeds; and (2) the power delivered to the grid fluctuates with the wind speed, causing disturbances to the grid. Despite its disadvantages, this wind energy system is still widely accepted in industry with a power rating up to a couple of megawatts. Examples of practical fixed-speed WECS are given in Table 1-8.

1.4.2 Variable-Speed Systems with Reduced-Capacity Converters

Variable-speed operation has a series of advantages over fixed-speed wind systems. It increases the energy conversion efficiency and reduces mechanical stress caused by wind gusts. The latter has a positive impact on the design of the structure and mechanical parts of the turbine and enables the construction of larger wind turbines. It also re-

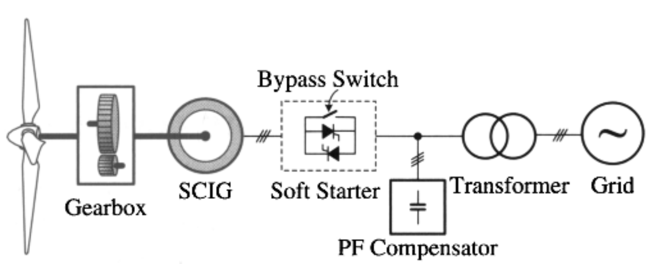


Figure 1-11. Wind energy conversion system without power converter interface.

Table 1-8. Example of commercial fixed-speed WECS

Parameter	Vestas V82-1.65
Power rating	1.65 MW
Turbine diameter	82 m
Numbers of blades	3
Turbine speed	14.4 rpm
Wind speed (cut-in/rated/cut-out)	3.5/13/20 m/s
Generator	SCIG
Gearbox	Planetary/helical stages
Pitch/stall mechanism	Active stall

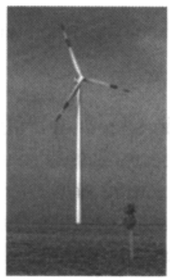


Photo courtesy Vestas Wind Systems A/S.

duces the wear and tear on the gearbox and bearings, expanding the life cycle and reducing the maintenance requirements. The main drawback of variable-speed WECS is the need for a power converter interface to control the generator speed, which adds cost and complexity to the system. However, the power converter decouples the generator from the grid, which enables the control of the grid-side active and reactive power [13].

Variable-speed WECS can be further divided into two types based on the power rating of the converter with respect to the total power of the system: reduced-capacity power converter and full-capacity power converter. The variable-speed WECS with reduced-capacity converters are only feasible with wound-rotor induction generators (WRIG) since variable-speed operation can be achieved by controlling the rotor currents without the need to process the total power of the system. There are two designs for the WRIG configurations: one with a converter-controlled variable resistance, and the other with a four-quadrant power converter system.

Wound Rotor Induction Generator with Variable Rotor Resistance. Figure 1-12 shows a typical block diagram of the WRIG wind energy system with a variable resistance in the rotor circuit. The change in the rotor resistance affects the torque/speed characteristic of the generator, enabling variable-speed operation of the turbine. The rotor resistance is normally made adjustable by a power converter. The speed adjustment range is typically limited to about 10% above the synchronous speed

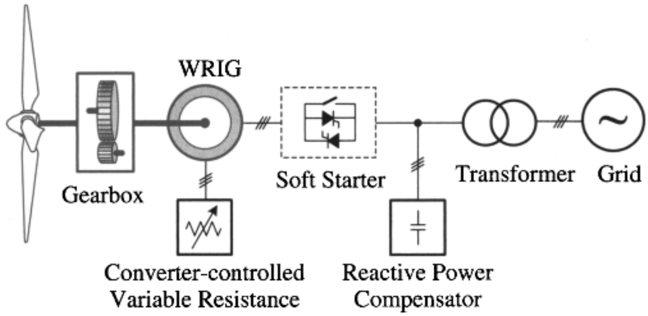


Figure 1-12. Variable-speed configuration with variable rotor resistance.

of the generator [15]. With variable-speed operation, the system can capture more power from the wind, but also has energy losses in the rotor resistance. This configuration also requires a soft starter and reactive power compensation. The WRIG with variable rotor resistance has been in the market since the mid 1990s with a power rating up to a couple of megawatts. A practical example of this configuration and its respective parameters are given in Table 1-9.

Doubly Fed Induction Generator with Rotor Converter. A typical block diagram of the doubly fed induction generator (DFIG) wind energy system is shown in

Table 1-9. Example of commercial WECS with variable rotor resistance

Parameter	Vestas V80-1.8US
Power rating	1.8 MW
Turbine diameter	80 m
Turbine speed	15.5 or 16.8 rpm
Wind speed (cut-in/rated/cut-out)	4/15/25 m/s
Generator	WRIG
Gearbox	Planetary/parallel axle
Pitch/stall mechanism	Pitch

Photo courtesy Vestas Wind Systems A/S.

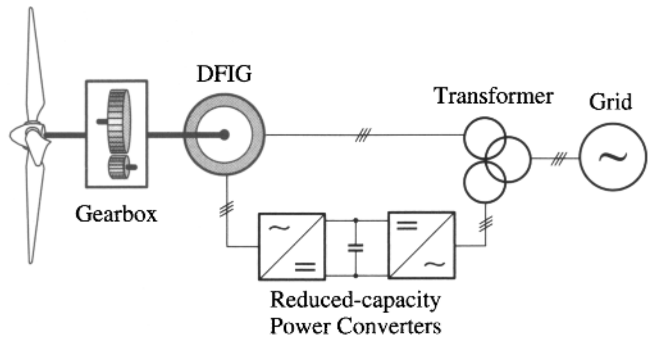


Figure 1-13. Variable-speed configuration with reduced-capacity converters.

Figure 1-13. The configuration of this system is the same as that of the WRIG system except that (1) the variable resistance in the rotor circuit is replaced by a grid-connected power converter system, and (2) there is no need for the soft starter or reactive power compensation. The power factor of the system can be adjusted by the power converters. The converters only have to process the slip power in the rotor circuits, which is approximately 30% of the rated power of the generator, resulting in reduced converter cost in comparison to the wind energy systems using full-capacity converters [13]. Examples of this configuration are given in Table 1-10.

The use of the converters also allows bidirectional power flow in the rotor circuit and increases the speed range of the generator. This system features improved overall power conversion efficiency, extended generator speed range (±30%), and enhanced dynamic performance as compared to the fixed-speed WECS and the variable resistance configuration. These features have made the DFIG wind energy system widely accepted in today's market.

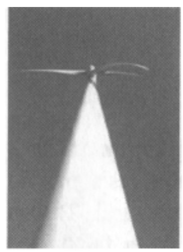
1.4.3 Variable-Speed Systems with Full-Capacity Power Converters

The performance of the wind energy system can be greatly enhanced with the use of a full-capacity power converter. Figure 1-14 shows such a system in which the generator is connected to the grid via a full-capacity converter system [13]. Squirrel cage induction generators, wound rotor synchronous generators, and permanent magnet synchronous generators (PMSG) have all found applications in this type of configuration with a power rating up to several megawatts. The power rating of the converter is normally the same as that of the generator. With the use of the power converter, the generator is fully decoupled from the grid, and can operate in full speed range. This also enables the system to perform reactive power compensation and smooth the grid connection. The main drawback is a more complex system with increased costs.

It is noted that the wind energy system can operate without the need for a gearbox if

Table 1-10. Examples of commercial DFIG WECS

	Model		
Parameter	Nordex N100	Vestas V90	Repower 5M
Power rating	2.5 MW	3 MW	5 MW
Turbine diameter	100 m	9 0m	126 m
Turbine speed	9.6 ~ 14.9 rpm	8.6 ~ 18.4 rpm	7.7 ~ 12.1 rpm
Wind speed (cut-in/rated/cut-out)	3/13/20 m/s	3.5/15/25 m/s	3.5/14/25 m/s
Generator	6-pole WRIG	4-pole WRIG	6-pole WRIG
Gearbox	Planetary/spur stages	Planetary/helical stages	Planetary/spur stages
Pitch/stall mechanism	Pitch	Pitch	Pitch


Photos courtesy (from left to right) Nordex, Vestas Wind Systems A/S, and REpower Systems AG.

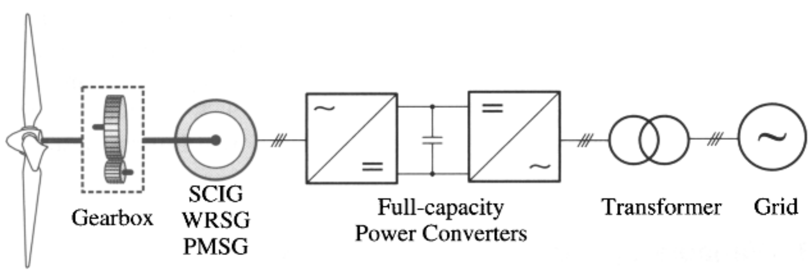
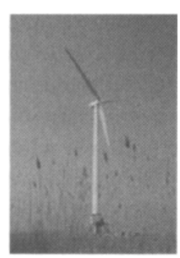


Figure 1-14. Variable-speed configurations with full-capacity converters.

a low-speed synchronous generator with a large number of poles is used. The elimination of the gearbox improves the efficiency of the system and reduces initial costs and maintenance. However, a low-speed generator has a substantially larger diameter to accommodate the large number of poles on the perimeter, which may lead to an increase in generator and installation costs.

Examples of commercial full-capacity power converter operated WECS with geared and gearless designs are listed in Table 1-11, where the system power rating, turbine speed, generator type, and power converter topology are provided. Some of the

Table 1-11. Examples of variable-speed configurations with full-capacity converters

	Model		
Parameter	Enercon E-82E3	Vestas V-112	Avantis AV928
Power rating	3 MW	3 MW	2.5 MW
Turbine diameter	82 m	112 m	93.2 m
Turbine speed	6 ~ 18.5 rpm	4 ~ 17.7 rpm	6 ~ 18 rpm
Wind speed (cut-in/ rated/cut-out)	na/na/28–34 m/s	3/12/25 m/s	3/11.3/25–30 m/s
Gearbox	Gearless (direct drive)	Planetary/spur stages	Gearless (direct drive)
Generator	Multipole WRSG	PMSG	120-pole PMSG
Converter system	Diode + boost + 2L-VSC	na	4-quadrant 2L-VSC
Pitch/stall mechanism	Pitch	Pitch	Pitch
			
Parameter	Clipper Liberty 2.5	Siemens SWT 3.0-101	Goldwind 2.5 PMDD
Power rating	2.5 MW	3 MW	2.5 MW
Turbine diameter	100 m (C-100 model)	101 m	99.8 m
Turbine speed	9.6 ~ 15.5 rpm	6 ~ 16 rpm	6.5 ~ 14.5 rpm
Wind speed (cut-in/ rated/cut-out)	4/na/25 m/s	3/13/25 m/s	3/13.5/25 m/s
Gearbox	Distributed gearbox	Gearless (direct drive)	Gearless (direct drive)
Generator	4 x PMSG	Multipole PMSG	Multipole PMSG
Converter system	4 × diode + 2L-VSC	4-quadrant	diode + boost + 2L
VSC			
Pitch/stall mechanism	Pitch	Pitch	Pitch
			

Photos courtesy (left to right, top to bottom) ENERCON GmbH, Vestas Wind Systems A/S, Avantis, Clipper Windpower Inc., Siemens Wind Power A/S, and Goldwind.

most common converter topologies used for this type of WECS include two-level voltage source converter (2L-VSC) in back-to-back configuration, diode-bridge rectifier plus DC-DC boost stage and 2L-VSC, and three-level neutral point clamped converter (3L-NPC) in back-to-back configuration.

1.5 GRID CODE

Grid codes have been developed and enforced in many countries for many years. They ensure applications of uniform standards for power systems and provide a framework for manufacturers to develop their equipment. Grid codes are usually based on the experience acquired through the operation of power systems and may vary from one utility to another. Differences in various grid codes also stem from regional and geographical conditions. However, the key elements in the different grid codes remain similar across the globe since their ultimate goal is to ensure safe, reliable, and economic operation of the power system.

Due to the rapid development of renewable energies and their integration into the grid, the grid codes in many countries have been updated to address issues related to renewable energy power generation [16]. According to the updated grid codes, wind farms tend to be considered as power generation plants, which should perform in a similar manner to conventional power-generation plants. The main elements in the grid codes include fault ride-through requirements, active/reactive power control, frequency/voltage regulation, power quality, and system protection. The following subsection only provides a brief overview of fault ride-through requirements and reactive power control.

1.5.1 Fault Ride-Through Requirements

Grid disturbances such as severe voltage dips caused by short-circuit faults can lead to power-generating units disconnected from the grid, which may cause instability in the grid. To avoid this, the grid code requires power-generating units to remain connected and continuously operated even if the voltage dips reaches very low values. The depth and duration of the voltage dips are usually defined by a voltage–time diagram. Figure 1-15 shows an example of low-voltage ride-through (LVRT) requirements during grid faults, where V_N is the nominal voltage of the grid [17]. Above the limit line, a power-generating system must remain connected during the fault even when the grid voltage falls to zero with duration of less than 150 ms. The system is allowed to be disconnected from the grid only when the voltage dips are in the area below the limit line. The grid codes also require the system to supply a certain amount of reactive current to support the grid voltage during the fault [18]. It is noted that the limits and ranges for the LVRT requirements vary with the grid operators in different countries, but they all share a common background and purpose. Most WECS equipped with full-capacity converters are capable of meeting the requirements.

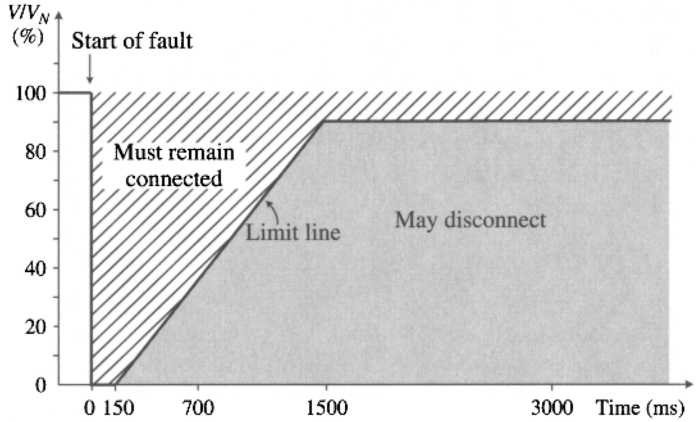


Figure 1-15. Example of grid requirements for low-voltage ride-through.

1.5.2 Reactive Power Control

Like the conventional power plants, wind turbines or wind farms are required to provide reactive power to the grid. Figure 1-16 shows an example of the range of the reactive power versus the active power for a power-generating unit [16]. Take a large megawatt wind turbine as an example. When the wind turbine deliveries the rated active power (1 pu) to the grid, it should be able to produce a maximum reactive power of ±0.33 pu to support the grid voltage. This corresponds to a 0.95 lagging and leading

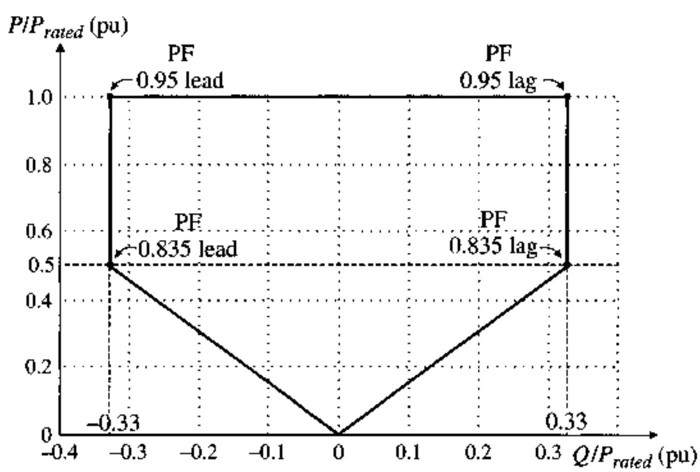


Figure 1-16. Example of reactive power requirements during system normal operation.

power factor, respectively. Similarly, when the wind turbine produces an active power of 0.5 pu, it should be capable of providing a reactive power up to ±0.33 pu, which corresponds to a 0.835 lagging and leading power factor, respectively. This requirement can be fulfilled by a properly designed variable-speed WECS. Note that the reactive power requirements given in Figure 1-16 are only examples, and different requirements may be specified in various grid codes across the globe.

1.6 SUMMARY

This chapter provided an overview of wind energy conversion systems. The basic concepts, facts, current state, and market trends of wind power technology were presented. The fundamentals of wind energy systems were discussed, including standalone and grid-connected operations, on-land and offshore applications, horizontal- and vertical-axis wind turbines, fixed- and variable-speed operations, stall and pitch angle controls, and grid codes. The technical background provided in this chapter complements the in-depth analysis of wind energy systems covered in the other chapters of the book.

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