

## 1

## Status of Wind Power Technologies

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### 1.1 Wind Power Development

Although wind power has been utilized by humans for more than 3000 years, the history of wind power for electricity production is only 120 years long.

In July 1887, Professor James Blyth (1839–1906) of Anderson's College, Glasgow built the first windmill for the production of electricity at Marykirk in Kincardineshire, Scotland [1]. The windmill was 10 m high, and was used to charge accumulators to power the lighting in the cottage. Around the same period, a wind turbine was designed and constructed in the winter of 1887–1888 by Charles F. Brush (1849–1929) in Cleveland, USA [2]. The rotor of Brush's wind turbine was 17 m in diameter and had 144 blades. The rated power was 12 kW. It was used either to charge a bank of batteries or to operate up to 100 incandescent light bulbs and various motors in Brush's laboratory.

A pioneer of modern aerodynamics, Poul la Cour (1846–1908) of Askov, Denmark, built the world's first wind tunnels for the purpose of aerodynamic tests to identify the best shape of the blades for turbines. Based on his experiments, he realized that wind turbines with fewer rotor blades were more efficient for electricity production. He designed the first four-blade wind turbine in 1891 [3].

The developments in the 20th century can be divided into two periods. From 1900–1973, the prices of wind-powered electricity were not competitive. The gradual extension of electrical networks and the availability of low-cost fossil fuels lead to the abandonment of wind turbines. Wind turbine generators (WTGs) were mainly used in rural and remote areas. Although several wind turbines in the hundred-kilowatt class were manufactured and installed for testing, due to high capital costs and reliability problems, they were not widely adopted.

The two oil crises in 1973 and 1979, with supply problems and price fluctuations for fossil fuels, spurred the adoption of non-petroleum energy sources. As an alternative to fossil fuels, wind power was once again put on the agenda. European countries and US government started to invest in research into large commercial wind turbines. The world's first multi-megawatt wind turbine was constructed in 1978, and pioneered many technologies now used in modern wind turbines. From 1975 through to the mid-1980s, NASA developed 3.2 MW and 4 MW wind turbines. Although they were

sold commercially, none of these were ever put into mass production. When oil prices declined, electricity generated by wind power became uneconomical and many manufacturers left the business.

At the beginning of the 21st century, although fossil fuels were still relatively cheap, concerns over energy security, global warming, and eventual fossil fuel depletion increased, and this led to an expansion of interest in renewable energy. The wind power industry has since achieved rapid development.

From the point of view of global capacity, according to statistics from the Global Wind Energy Council (GWEC), the global annual and cumulative installed wind capacities for the past ten years are as illustrated in Figures 1.1 and 1.2, respectively. In 2015, the global wind power industry installed 63.5 GW of capacity, representing annual market growth of 22%. By the end of 2015, the total installed capacity reached 432.4 GW, representing cumulative market growth of 17%. As estimated by International Energy Agency (IEA), that figure will reach 2016 GW by 2050, representing 12% of global electricity usage [5].

From the point of view of development in each country, more than 83 countries around the world were using wind power on a commercial basis by 2010. The top ten

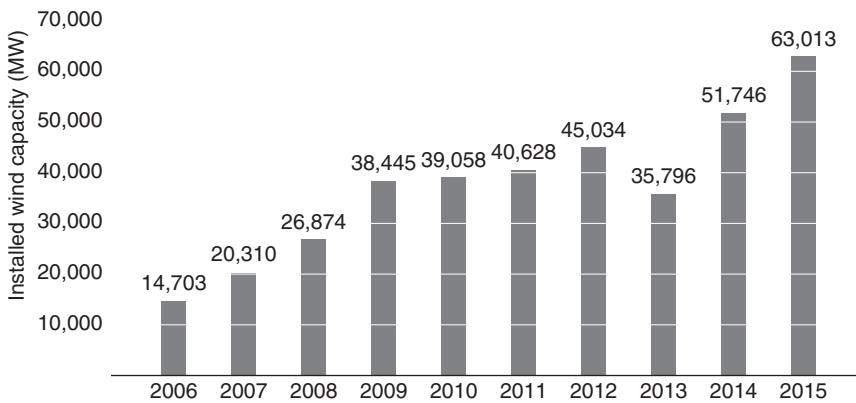


Figure 1.1 Global annual installed wind capacity 2005-2015 [4].

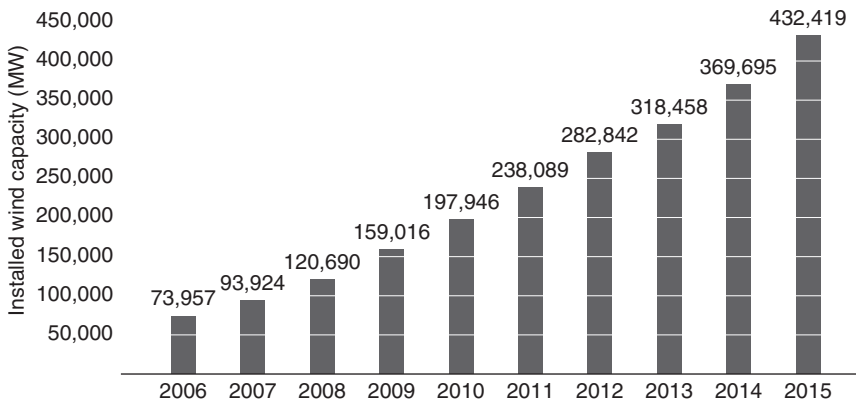


Figure 1.2 Global cumulative installed wind capacity 2005-2015 [4].

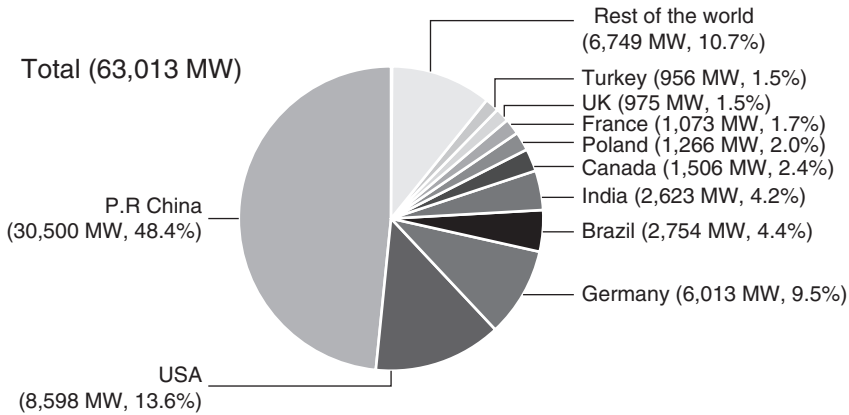


Figure 1.3 Newly installed capacity during 2015 [4].

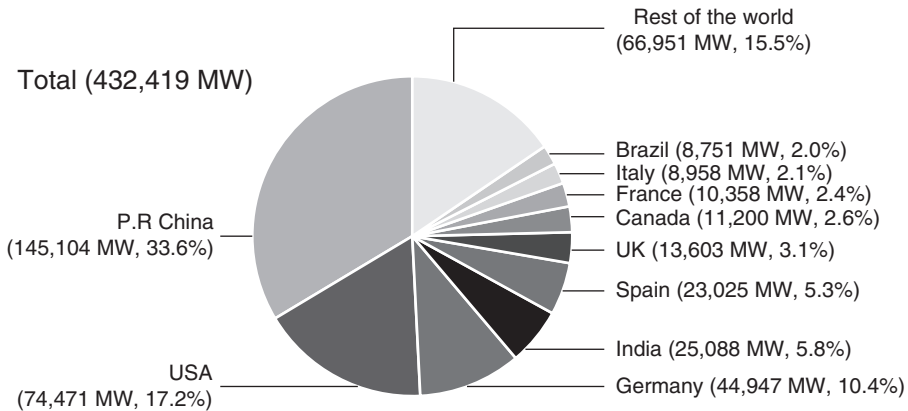


Figure 1.4 Cumulative capacities at 2015 [4].

countries in terms of 2015-installed and cumulative wind power capacities at 2015 are illustrated in Figures 1.3 and 1.4, respectively. More than half of all new installed wind power was added outside the traditional markets of Europe and North America. Asia has been the world's largest regional market for new wind power development, with capacity additions of 33.9 GW. China maintained its leadership position. China accounted for nearly half of the installations (48.4%) and its total wind power reached 145.1 GW.

In many countries, relatively high levels of wind power penetration have been achieved. Figure 1.5 presents the estimated wind power penetration in leading wind markets [6]. The installed capacity is estimated to supply around 40% of Denmark's electricity demand, and between 20% to 30% in Portugal, Ireland, and Spain, respectively. Denmark has a even more ambitious target of 50% by 2020. In the United States, 5.6% of the nation's electricity demand is estimated to be covered by the wind power. On a global basis, the contribution of wind power is estimated to be around 4.3% [6].

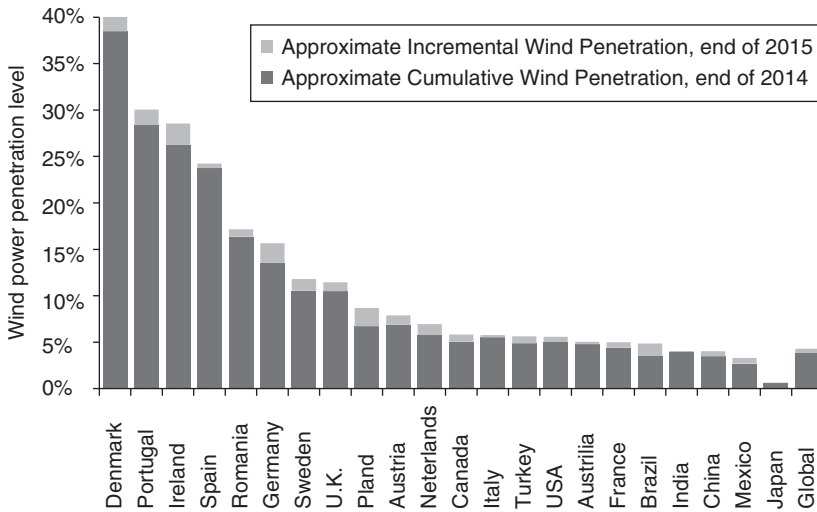


Figure 1.5 Wind power penetration in leading wind markets in 2014~2015 [6].

## 1.2 Wind Turbine Generator Technology

As at 2015, the largest wind turbine is the 8 MW capacity Vestas V164, for offshore use. By 2014, over 240,000 commercial-sized wind turbines were operating in the world, and these met 4% of the world’s electricity demand. WTG-based wind energy conversion systems (WECS) can be divided into the following four main types [7, 8].

### 1.2.1 Type 1

Type 1 generators are directly grid-connected induction generators (IGs) with fixed rotor resistance. An example is the squirrel cage induction generator (SCIG). As illustrated in Figure 1.6, the wind turbine rotor (WTR) is connected to the IG via a gearbox (GB). Most Type 1 WTGs are equipped with mechanically switched capacitor (MSC) banks, which provide reactive power compensation. As the protection device, the main

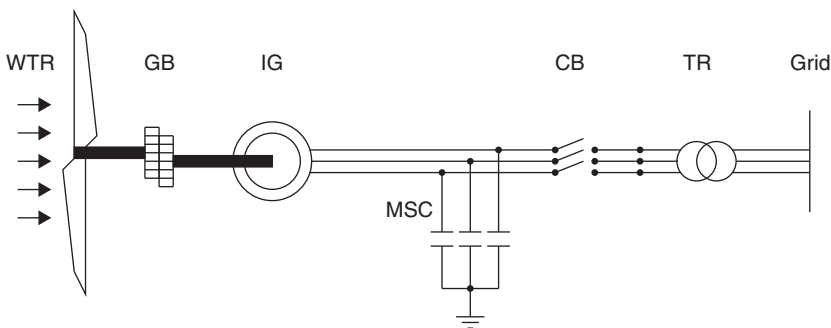
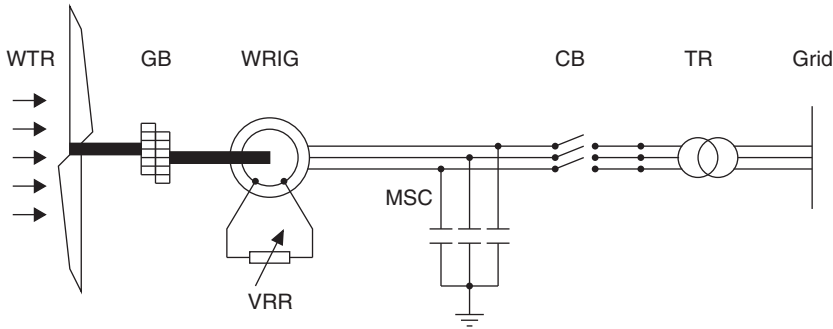


Figure 1.6 Structure of Type 1 WTG [8]. Refer to main text for explanation of acronyms.



**Figure 1.7** Structure of Type 2 WTG [8]. Refer to main text for explanation of acronyms.

circuit breaker (CB) disconnects the generator and capacitor from the grid in the event of a fault. Through a step-up transformer (TR), the WTG is connected to the grid.

Because of the direct connection to the grid, the IG operates at its natural mechanical characteristic, with an accentuated slope (corresponding to a small slip, normally 1–2%) from the rotor resistance [7]. The rotational speed of the IG is close to the synchronous speed imposed by grid frequency, and is not affected significantly by wind variation.

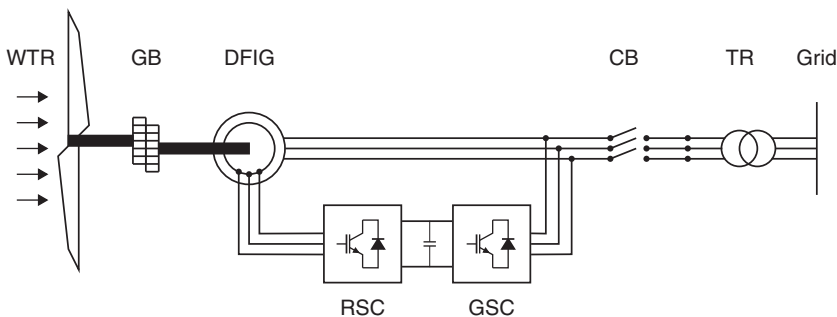
### 1.2.2 Type 2

Type 2 generators are directly grid-connected IGs with variable rotor resistance (VRR).

Figure 1.7 illustrates the general structure of a Type 2 WTG. As an evolution of Type 1 WTGs, using regulation through power electronics, the total (internal plus external) rotor resistance is adjustable. In this way, the slip of the generator can be controlled, which affects the slope of the mechanical characteristic. The range of dynamic speed variation is decided by the additional resistance. Usually, the control range is up to 10% over the synchronous speed.

### 1.2.3 Type 3

Type 3 generators are double-fed induction generators (DFIGs). As illustrated in Figure 1.8, the DFIG is an induction generator with the stator windings connected



**Figure 1.8** Structure of Type 3 WTG [8]. Refer to main text for explanation of acronyms.

directly to the three-phase, constant-frequency grid and the rotor windings connected to back-to-back voltage source converters (VSCs), including a rotor-side converter (RSC) and grid-side converter (GSC) [9]. They are decoupled with a direct current (DC) link. Conventionally, the RSC controls the generator to regulate the active and reactive power, while the GSC controls the DC-link voltage to ensure DC voltage stability.

The power flow of the stator is always from wind turbine to grid. However, the power flow of the rotor is dependent on the operating point:

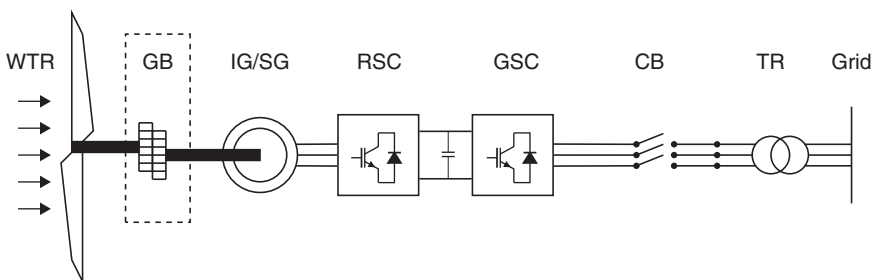
- If the slip is negative (over-synchronous operation), it feeds power into the grid.
- If the slip is positive (sub-synchronous operation), it absorbs power from the grid.

In both cases, the power flow in the rotor is approximately proportional to the slip. By regulation of the generator behaviour through the GSC controller, the rotation speed is allowed to operate over a larger, but still restricted range (normally 40%).

#### 1.2.4 Type 4

Type 4 WTGs have the wind turbine connected fully through a power converter. Figure 1.9 shows the general structure of Type 4 WTG. The generator type can be either an induction generator or a synchronous generator. Furthermore, the synchronous generator can be either a wound-rotor synchronous generator (WRSG) or a permanent-magnet synchronous generator (PMSG). Currently, the latter is widely used by the wind turbine industry. The back-to-back VSC configuration is used. The RSC ensures the rotational speed is adjusted within a large range, whereas the GSC transfers the active power to the grid and attempts to cancel the reactive power consumption [7].

The PMSG configuration is considered a promising option. Due to its self-excitation property, it gives high power factors and efficiency. As it is supplied by permanent magnets, a PMSG does not require an energy supply for excitation. Moreover, since the salient pole of a PMSG operates at low speeds, the gearbox (Figure 1.9) can be removed. This is a big advantage of PMSG-based WECS, as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multipole PMSGs (DD-PMSGs) with large diameters.



**Figure 1.9** Structure of Type 4 WTG [8]. Refer to main text for explanation of acronyms.

### 1.2.5 Comparison

These four WTG types can also be classified into two categories according to the rotor speed control criterion: fixed-speed wind turbines (FSWTs), including Type 1, and variable-speed wind turbines (VSWTs), including Types 2–4 [10].

FSWTs have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems. They are well-proven in operation. Moreover, they can naturally provide the inertial response. However, as FSWTs have limited controllability of rotational speed, the captured aerodynamic efficiency is restricted. Due to the fixed-speed operation, mechanical stress is important. All fluctuations in wind speed are transmitted into mechanical torque and then, as electrical fluctuations, into the grid.

Due to the regulation of rotor speed within a larger range, VSWTs, especially Types 3 and 4, are highly controllable, allowing maximum power extraction over a large range of wind speeds. In addition, the active and reactive power control can be fully decoupled and implemented separately, and they are therefore more flexible. VSWTs dominate the marketplace, especially in the megawatt class. Due to the electrical decoupling between the generator and the grid, they cannot contribute to the power system apparent inertial as conventional synchronous generators [11]. However, the inertial response can be emulated by an additional power or torque loop [12–15].

### 1.2.6 Challenges with Wind Power Integration

Due to the inherent variability and uncertainty of the wind, the integration of wind power into the grid has brought challenges in several different areas, including power quality, system reliability, stability, and planning. The impact of each is largely dependent on the level of wind power penetration in the grid [16].

#### Impact on Power Quality

Power quality is evaluated as a deviation from the normal sinusoidal voltage and current waveforms in power system network. Power quality distortions of a power system include flickers and harmonic distortions.

Flickers are periodic voltage and frequency variations, typically of between 0.5 and 25 Hz. The oscillatory output power produced by WTGs can cause flickers in a power system. Fluctuations due to the tower shadow and turbulence effects in the wind may cause flickers too. The IEC 61400-21 standard furnishes a measurement procedure to calculate the flicker impact of wind turbines.

Harmonics can be injected on both the generation and consumer sides. On the consumer side, harmonics are caused by non-linear loads. On the generation side, sources of harmonics include flexible alternating current transmission systems (FACTS), such as reactive power compensators and power electronics devices. The power electronic converters used by VSWTs are considered sources of harmonics.

#### Impact on System Reliability

The uncertainty of wind generation will increase the requirement for operating reserve, which will in turn increase generation costs. When the wind penetration level is low, the wind power fluctuation is comparable to existing load fluctuations. Committed conventional generators, such as thermal or hydro units, have sufficient load-tracking capability, so no additional operating reserve is required. However, load balancing becomes

challenging at high wind-power penetration levels. An extra reserve of 3–6% of the rated capacity of the wind plant is required at 10% wind penetration and 4–8% for 20% wind penetration.

### Impact on System Stability

**Frequency stability** Conventional synchronous generators can provide inertia response, which plays a significant role in stabilizing system frequency during a transient scenario. The inertia value dictates the frequency deviations due to a sudden change in the generation and load power balance. It affects the eigenvalues and vectors that determine the stability and mode shape of the transient response [17].

The contributions to the system inertia of WTGs are dependent on the WTG type. Due to the direct connection of the power system, fixed-speed induction generators can provide inertia response. Modern VSWTs, whose rotation speed is normally decoupled from grid frequency by a power electronic converter, may decrease the system inertia [18]. With high wind power penetration, this decrease aggravates the grid frequency instability.

**Voltage stability** Many power system faults are cleared by the relay protection of the transmission system, either by disconnection or by disconnection and fast reclosure. There is a short period with a voltage drop beyond a specified threshold, followed by a period when the voltage returns. Previously, when the voltage dip occurred, the wind turbine was simply disconnected from the grid. When the fault was cleared and the voltage returned to normal, the wind turbine was reconnected. When the wind power penetration level is low, the impact on system stability is limited. However, with high levels of wind penetration, if the entire wind farm is suddenly disconnected while at full generation, the system will lose further production capability [17]. This can lead to a further large frequency and voltage drop and possibly complete loss of power. It is very important to maintain the connection of WTGs when there are disturbances in the network. Therefore, modern WTGs are required to have the fault ride-through (FRT) capability by grid codes.

Since large wind farms are mainly located in areas far from load centres, the short-circuit ratio (SCR) is small [19], and the grid at the connection point is weak. Voltage fluctuations caused by the intermittent power of the wind farms are large.

### Impact on System Planning

As wind resources are often located far from load centres, it is critical to develop sufficient transmission to transport wind power to load centres. Old transmission lines must be updated. On the one hand, transmission planning processes are highly dependent on regional politics. The generation capacity, transmission location and load size are different from one place to another. These disparities make the development of transmission for wind power contentious and complex. On the other hand, in order to transfer variable and unpredictable wind power, new requirements for transmission technology arise [20].

Microgrids are considered as an alternative vision of the future grid, with energy generated and consumed locally. They can significantly reduce the long-distance energy transmission requirement and transmission losses. The electricity grid could be conceptualized as a collection of independent microgrids [20].



### 1.3 Conclusion

There is potential for wind energy to play an important role in future energy supply. With the development of wind turbine technology, wind power will become more controllable and grid-friendly. It is desirable to make wind farms operate as conventional power plants. To achieve this objective, more advanced control strategies for both wind turbines and wind farms are required.

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