PART I

INTRODUCTION TO WIND POWER GENERATION

CHAPTER 1

INTRODUCTION

In this chapter, an overview of wind power generation and the evolution of wind power systems are briefly introduced, and the challenges and trends in wind power generation are discussed.

1.1 GLOBAL WIND POWER DEVELOPMENT

1.1.1 Global Environment Challenge and Energy Crisis

Nowadays, the human society consumes a huge amount of electricity every year. It is reported by the U.S. Energy Information Administration (EIA) that the global net electricity consumption has grown from 10,395 TWh in 1990 to 20,567 TWh in 2015 [1]. Since most of the electricity is generated from fossil fuels, the increase of the electricity net consumption will lead to large greenhouse gas emissions, and this may cause global warming. The Earth's average surface temperature has risen about 0.74°C for the period 1906–2005, which may cause the sea level rise, widespread melting of snow and ice, or some extreme weather challenges. Furthermore, burning of fossil fuels will produce dust and other chemical materials harmful to humans.

On the other hand, the fossil fuel reserves are limited and unsustainable. Oil will be exhausted in a few decades, followed by natural gas, and coal will also be used up in 200–300 years. The energy crisis brought by the exhaustion of fossil fuels is a long-range challenge for human beings. Many efforts have been made worldwide to try to find an alternative energy.

1.1.2 Renewable Energy Development

Renewable energy is defined as the energy that comes from resources that are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. Typically, the renewable energy includes wind power, photovoltaic (PV) power, hydropower, biomass power, and ocean power. As renewable energy is reproducible and has a low footprint of CO_2, it is regarded as a favorable solution to both the global environment challenge and energy crisis. Rapid deployment of renewable energy has been reported in recent years. Global renewable energy policy

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Advanced Control of Doubly Fed Induction Generator for Wind Power Systems, First Edition.
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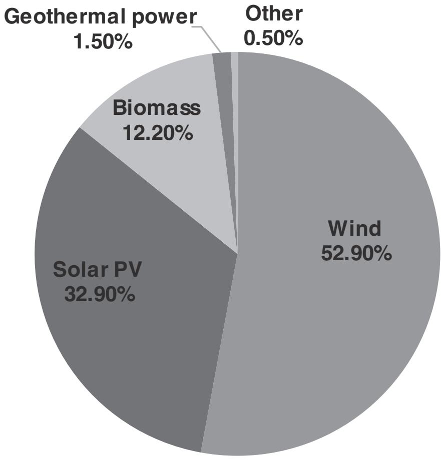


Figure 1.1 Worldwide capacity share of different non-hydro renewable powers by the end of 2016 [2].

multistakeholder network REN21 estimated that by the end of 2016, 30% power generation capacity will come from renewable energy and renewable energy will account for about 24.5% of global electricity generation [2]. Nowadays, the biggest renewable energy generation is from hydropower. However, since the location requirement of the hydropower is limited to lakes or rivers, the worldwide growth of hydropower has become slower in the recent years, which indicates that hydropower is very close to its capacity limit.

The non-hydropower renewable generation, including wind, PV, and biomass, has been growing very fast in the last 10 years. The non-hydropower renewable generation capacity reached 921 GW by the end of 2016, compared to 85 GW in 2004 [2]. The worldwide capacity share of different non-hydro renewable powers by the end of 2016 can be found in Figure 1.1. It is found that wind power has the largest capacity share among the non-hydropower renewable generations. Wind power has reached 56.8% of the non-hydro renewable power capacity.

1.1.3 Wind Energy Development

The wind power generation is regarded as the most widely used non-hydro renewable energy generation. It has a high reserve and is renewable and clean. Besides it produces almost no greenhouse gas emissions. Now at least 83 countries around the world are using wind power to supply their electricity grids [3]. The capacity of wind power installation has grown rapidly for the past 15 years. The statistics show the worldwide total wind power capacity has grown from 24 GW in 2001, to about 487 GW in 2016 [3], as shown in Figure 1.2. China leads the accumulated wind power installation, followed by the United States, Germany, Spain, Indian, etc., as shown in Figure 1.3.

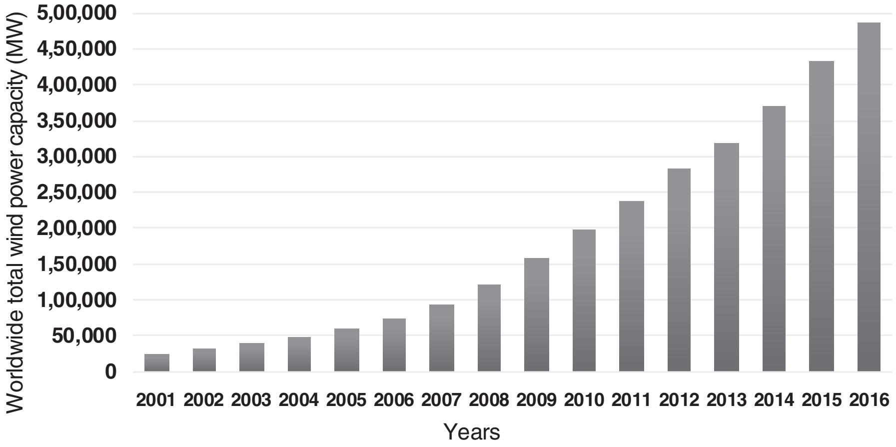


Figure 1.2 Worldwide total wind power capacity from 2001 to 2016 [3].

At the same time, the wind power share in the mix of the power supply also increased in the world, especially in some European countries. In 2014, Denmark set a new world record by reaching a wind power share of 39% in the domestic power supply [4]. Spain has wind power share of more than 15% [5]. Worldwide, the wind energy production has reached around 4% of total worldwide electricity usage in 2014 [6].

1.2 EVOLUTION OF WIND POWER SYSTEM

With the increasing penetration of wind power into the grid, the technology of the wind power generation has undergone a rapid development. One of the typical features is the changing of the wind power system structures. Modern wind power systems are more efficient, more reliable and more intelligent than before.

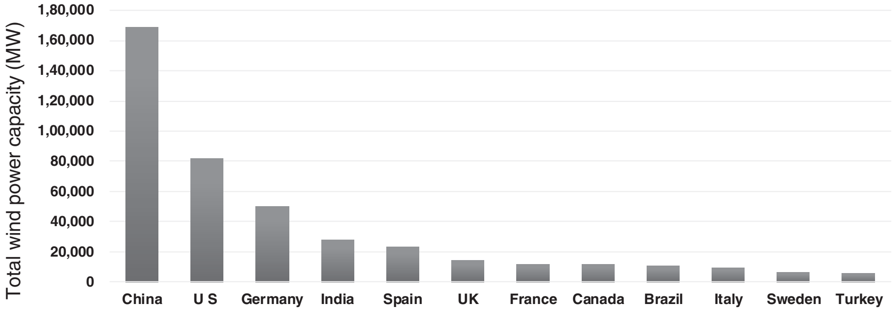


Figure 1.3 Accumulated wind power installation versus countries, end of 2015 [3].

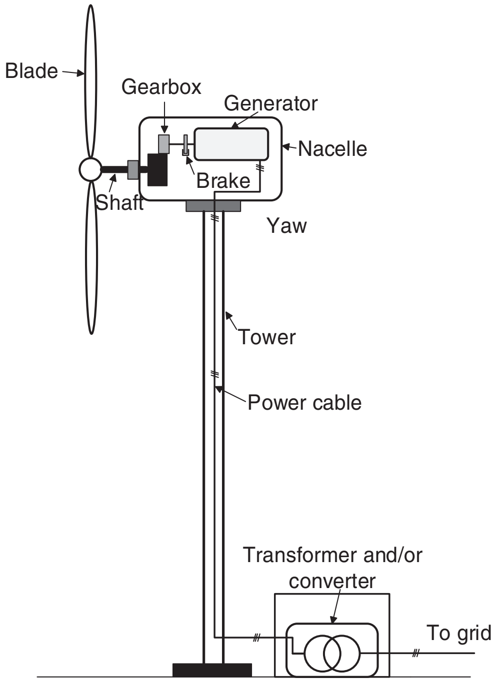


Figure 1.4 Structure of a wind turbine system.

1.2.1 Basic Structure of a Wind Turbine

The mostly used wind turbine is the horizontal wind turbine as shown in Figure 1.4. The blade, the shaft and the nacelle of the wind turbine are installed on a high tower. The blade rotates under wind flow and the wind energy is captured and converted into the mechanical energy in the shaft. The rotating angular speed of the shaft is increased using the gearbox so that it is compatible with the generator. The mechanical energy originated from the wind is converted into electric energy by the generator. Then the electricity is transmitted to the power electronic converter on the ground via the power cable, which is connected to the transformer in the grid. The nacelle provides space for components such as the shaft, the gearbox, and the brake on the tower, and can also target the turbine toward the wind flow direction by the action of the yaw.

1.2.2 Power Flow in the Wind Turbine System

The function of the wind power generation system is to harvest the kinetic energy of the wind flow, convert it into the electrical energy and finally feed into the grid. The configuration of the wind turbine system (WTS), which is composed of the wind turbine, the gearbox, the generator, the power converter, as well as the transformer, can be simplified as shown in Figure 1.5.

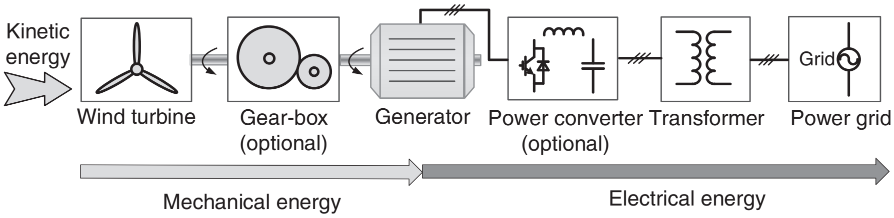


Figure 1.5 Basic configuration of wind power generation system.

Wind Turbine: The kinetic energy in the wind is collected by the wind turbine, and it is converted into mechanical energy on the shaft of the wind turbine. The early wind turbines normally rotate at an almost fixed speed, while the modern wind turbines can adjust the rotation speed with the variations in wind speed in order to increase the wind energy harvesting efficiency [34].

Gearbox: The gearbox is used to adjust the rotating speed of the shaft and make it compatible with the generator. In some cases, for example, in directly driven wind power system with multiple-pole synchronous generators, the gearbox may not be used.

Generator: The generator converts the mechanical energy on the shaft into electrical energy. In different types of WTS, the generator can be caged generator (CG), doubly fed induction generator (DFIG), or permanent magnet synchronous generator (PMSG).

Power Converter: The power converter works as an interface between the generator and the power grid. It converts the original electrical energy from the generator, which may be unstable with respect to amplitude or frequency, into the relatively stable electrical energy, which is more accepted by the power grid. On the other hand, the power converter also controls the generator to cooperate with the wind turbine to achieve better energy harvesting efficiency.

Transformer: The transformer is used to step up the output of the power converter (normally around 690 V) to a higher voltage, and transfers the wind power to the distribution or transmission power lines.

1.2.3 Fixed-Speed Wind Turbine System

The fixed-speed WTSs emerged in the 1970s and were widely used during the 1980s and 1990s. The shaft of the wind turbine is operated at a fixed angular speed, independent of the wind speed. The scheme of the fixed-speed WTS is shown in Figure 1.6. The generator operates with a fixed rotor speed corresponding to the grid frequency. It is directly connected to the grid by a transformer.

The advantage of the fixed-speed WTS is its simplicity of structure. It has a drawback that it cannot realize maximum wind energy tracking according to the variations in the wind speed. Reactive power consumed by the generator needs to be compensated by the capacitor bank. Further, it has no grid fault support capability, which is now needed by the grid operator. It also has higher mechanical stress for the wind turbine.

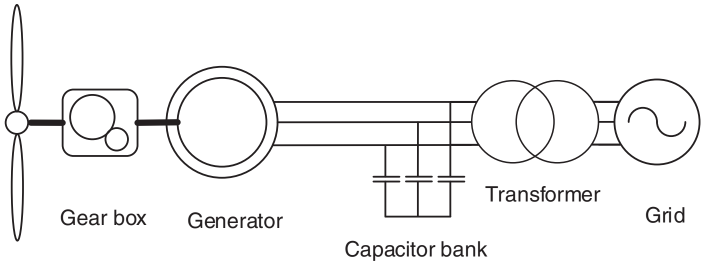


Figure 1.6 Scheme of a fixed-speed wind turbine system.

1.2.4 Variable-Speed Wind Turbine System

The variable-speed WTS is widely used nowadays. Different from the fixed-speed WTS, the variable-speed WTS is able to adjust the rotor speed when the wind speed changes to realize the maximum wind energy harvesting.

The scheme of a variable-speed wind turbine is shown in Figure 1.7. The wind power is captured by a pitch-controlled wind turbine and sent to the generator. The generator is connected to the grid by a power electronic converter. The variable-speed operation of the WTS is achieved by the power electronic converter.

The power electronic converter controls the rotor speed of the generator so that the shaft speed of the blade adjusts when the wind speed changes to realize the highest wind energy harvesting.

When the wind turbine reaches the speed limit or the electric limit, either the mechanical angular speed or electric power can be limited by controlling the power electronic converter. Besides, it can also realize soft start for the wind turbine so that there is less power surge to the grid. When the grid fault happens, the variable-speed WTS can help the grid recover from the fault by feeding reactive power to the grid. The power electronic converters may provide ancillary services to the grid.

Power electronics has been bringing in significant performance improvements for the WTSs. It not only increases the energy yield and reduces the mechanical stress, but also enables the WTS to act like an ideal power source friendlier to the utility [38].

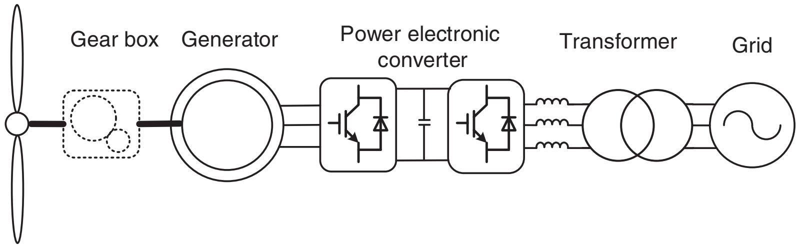


Figure 1.7 Scheme of a variable-speed wind turbine system.

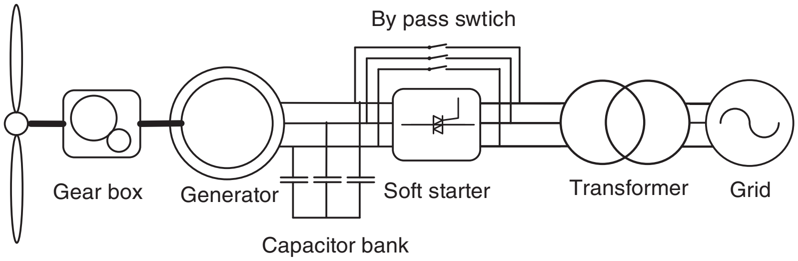


Figure 1.8 Fixed-speed wind turbine with a soft starter.

1.3 POWER ELECTRONICS IN WIND TURBINE SYSTEMS

1.3.1 Power Electronics in Fixed-Speed Wind Turbine System

For the fixed-speed WTS, usually induction machines are used as the generator. Connecting a large induction machine to the power system will cause a large power surge to the utility with a very high inrush current, which results in disturbances to the grid. To limit the starting current of the induction machine, a thyristor soft starter is used in the fixed-speed WTS, as shown in Figure 1.8. The starting current is reduced by gradually increasing the voltage applied to the generator to the grid voltage. The soft starter, based on thyristor technology, typically limits the RMS value of the inrush current to less than two times the rated current of the generator. Once the starting process is over, all thyristors are kept in the on-state. Since the thyristor has a voltage drop when it is conducting and causes power loss, a mechanical switch is used to bypass the thyristor soft starter when the WTS finishes the starting process. Besides reducing the impact on the grid, the soft starter also effectively reduces the torque peak associated with the inrush current during the starting, which is helpful to relieve the mechanical stress on the gearbox.

1.3.2 Power Electronics in Variable-Speed Wind Turbine System

In variable-speed WTSs, the power electronic converter plays an important role as the interface between the WTS and the grid. Two most popular variable-speed wind turbine configurations are DFIG and synchronous generator (SG). The DFIG wind system equipped with partial-scale power converter is dominating the market while the WTS with SG with full-scale power converter has grown in recent years.

1.3.2.1 Doubly Fed Induction Generator

WTSs with DFIG has been used extensively since 2000 and is the most adopted solution nowadays. As shown in Figure 1.9, a back-to-back converter is used in the DFIG system. The stator windings of the DFIG are directly connected to the power grid, while the rotor windings are connected to the back-to-back converter [30]. In this configuration, both the frequency and the current amplitude in the rotor windings

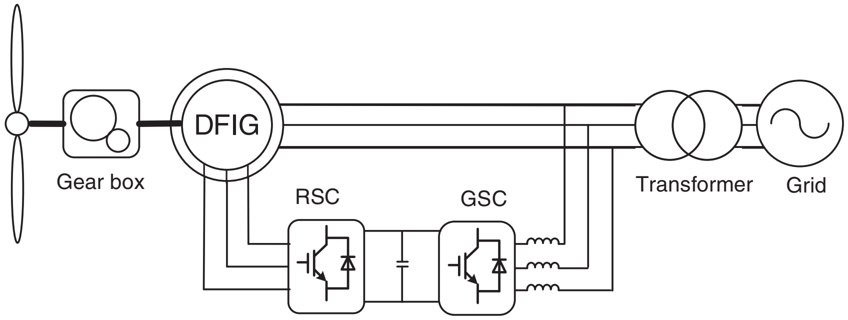


Figure 1.9 Variable-speed wind turbine with a partial-scale power converter and a doubly fed induction generator.

can be freely regulated so that the rotor speed can be changed in a wide range and wind energy harvesting capability is enhanced. Besides, it can realize soft start for the wind turbine and provide the grid fault ride-through ability. It can also reduce the mechanical stress to the wind turbine.

In addition, the DFIG has a special feature that it only needs a back-to-back converter with about 30% capacity of the wind turbine, which is an economical solution at an earlier stage of wind power development when the cost of the power converter was more critical [36–37].

The two-level pulse-width-modulation voltage-source-converter (2L-PWM-VSC) is the mostly used converter topology so far for the DFIG-based wind turbine concept as the power rating requirement for the converter is limited [41]. Normally, two 2L-PWM-VSCs are configured in a back-to-back structure in the WTS, as shown in Figure 1.10, which is called 2L-BTB for convenience. Advantages of the 2L-BTB solution include the full power controllability (four-quadrant operation) with a relatively simple structure and fewer components, which contribute to well-proven robust/reliable performances as well as the advantage of lower cost [29].

1.3.2.2 Asynchronous/Synchronous Generator with Full-Scale Power Converter

The second important configuration that has become popular for the newly developed and installed wind turbines is shown in Figure 1.11. It introduces a full-scale power converter to interconnect the power grid and stator windings of the generator. The reliability enhancement due to the elimination of slip rings and simpler or even

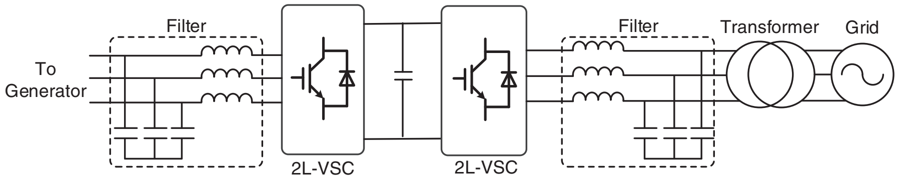


Figure 1.10 Two-level back-to-back (2L-BTB) voltage source converter for a wind turbine.

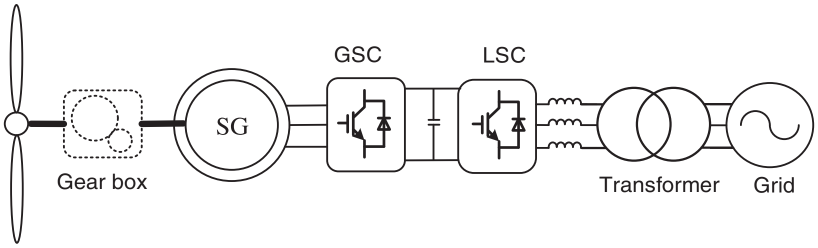


Figure 1.11 Variable-speed wind turbine with a full-scale power converter and synchronous generator.

eliminated gearbox, full power and speed controllability, and better grid support capability are the primary advantages compared to the DFIG-based concept. However, there are some drawbacks such as the high cost of PMSG, the need for a full-power BTB converter as well as the higher power losses in the converter. Instead of PMSG, wound rotor synchronous generator, etc., can be used as the generator.

1.4 CHALLENGES AND TRENDS IN FUTURE WIND POWER TECHNOLOGY

In this section, several emerging technology challenges for the future WTSs are addressed. The discussions will mainly focus on technology issues of power electronic converters in the WTS with respect to cost, reliability, grid integration, new power electronics circuits, etc.

1.4.1 Lower Cost

Cost is one of the most important considerations for the technology which determines the feasibility of certain energy technologies to be widely used in the future. In order to quantify and compare the cost of different energy technologies, levelized cost of energy (LCOE) index is generally used [7]. LCOE represents the price at which the electricity is generated from a specific energy source over the whole lifetime of the generation unit. It is an economic assessment of the cost of the energy-generating system including initial investment, development cost, capital cost, operations and maintenance cost, the cost of fuel, etc. LCOE can be defined in a single formula as [8]:

$$\mathrm{LCOE} = \frac{C_{Dev} + C_{Cap} + C_{O\&M}}{E_{Annual}} \tag{1.1}$$

Here, the initial development cost C_{Dev}, capital cost C_{cap}, and the cost for operation and maintenance $C_{O\&M}$ are first levelized to annual average cost over the lifetime of the generation system, and then divided by the average annual energy production in the whole lifetime E_{Annual}. In order to reduce the cost of energy, one effective way is to reduce the cost of development, capital, operation, and maintenance, and the other

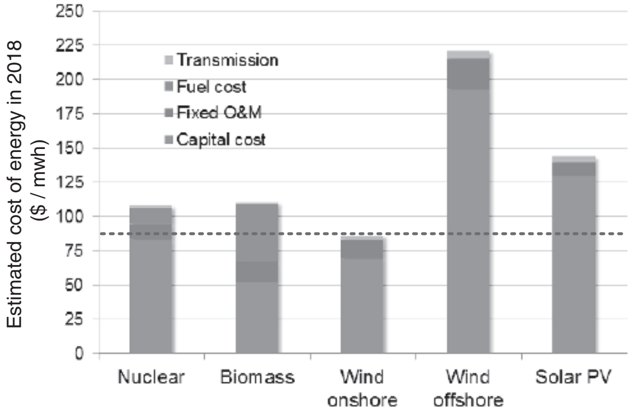


Figure 1.12 Estimated levelized cost of energy for several renewable energy technologies in 2018 [10].

effective way is to increase the lifetime of the generation system. As an example, the LCOE for offshore wind power of Denmark and the United Kingdom is between 140 and 180 EUR/MWh in 2010 according to the studies carried by [9], and this number is expected to be reduced by 50% by 2020 to a range between 67 and 90 EUR/MWh, providing an increase in the lifetime of wind turbines from 20 to 25 years, and other significant cost reductions are achieved.

Figure 1.12 shows another example of US-estimated LCOE for several promising renewable energy technologies in 2018 [10]. It can be seen that the cost distribution of different technologies varies a lot, where the onshore wind power still shows cost advantages compared to other renewable energy sources. It can be also expected that in the United States, the capital cost may still be dominant for most of the renewable energy technologies for the next decade.

As more power electronics are introduced to the energy system to improve the performances of power generation, the cost of the power electronics becomes more important. In the WTS, cost considerations impose challenges for the design and the selection of power electronics.

For instance, the needs for higher power capacity and full-scale power conversion will increase the cost for power semiconductors, passive components, and corresponding thermal management. Due to the limited space in the nacelle, higher power density for the power converters leads to extra cost for the design. Besides, remote locations of the wind turbines increase the cost for installation and maintenance, which demands high reliability, modularity, and redundancy of the system.

1.4.2 Larger Capacity

The size and power generation capacity of the wind turbine has been gradually increasing over the last decades and will be continuously increasing in the future, as shown in Figure 1.13 [11].

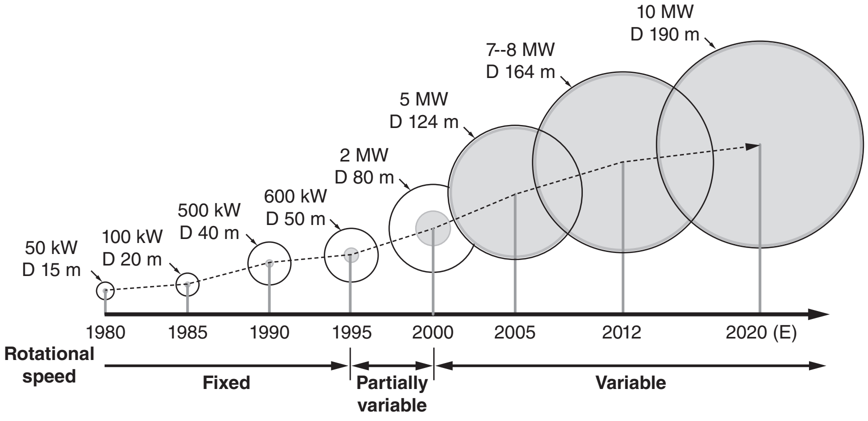


Figure 1.13 Development of wind turbines between 1980 and 2020 (estimated) [11].

Many of the major wind turbine manufacturers have developed high-power and large-scale wind turbine products. Some of the wind turbine product lines of the top wind turbine manufacturers are shown in Table 1.1.

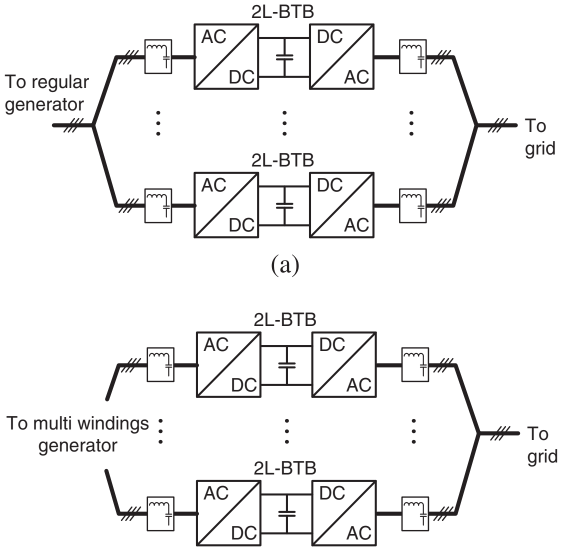
To deal with the growing power capacity, multicell converter topologies have been developed by connecting conventional 2L-BTB converters in parallel or in series. Two of the most adopted multicell solutions are shown in Figure 1.14. One of the advantages of this multicell configuration is that standard and proven converter technologies can be used for higher power capacities. Also, redundancy and modular characteristics can be achieved in this configuration. Such a solution is the state-of-the-art for wind turbines above 3 MW [12, 13] and will likely be utilized in larger-scale wind turbines in the future.

1.4.3 Higher Reliability

The growth of total installation and increasing capacity of the wind turbine make the failures of wind turbines costly. The failures of WTS will not only cause stability problem to the power grid due to the sudden absence of a large amount of power capacity, but also results in high cost for maintenance. In addition, it will cause

TABLE 1.1 Wind turbine product lines of the top wind turbine manufacturers in 2015 [11]

Manufacturer	Rotor diameter (m)	Power range (MW)
Goldwind (China)	70–121	1.5–3
Vestas (Denmark)	90–136/164	1.8–3.45/8
GE Wind (USA)	83–137/150	1.7–3.8/6
Siemens Wind (Denmark/Germany)	101–142/154	2.3–4/6–8
Gamesa (Spain)	80–132/132	2–3.3/5
Enercon (Germany)	44–141	0.8–4.2



(a)

(b)

Figure 1.14 Multicell converter topologies with parallel connected two-level back-to-back converters: (a) with regular generator; (b) with multiwinding generator.

reduction of annual energy production and thus increase the LCOE. As a result, reliability is a critical design consideration for the next generation wind turbine.

The complex nature of wind speed makes the mission profiles of the wind turbines very complicated. The large wind speed fluctuations may cause thermal cycles which is the main cause of the failures of power electronics components [14–16]. The relationship between the characteristics of thermal cycling and the failures of power semiconductors has been extensively studied, and it is found that the lifetime of power semiconductor will be shorter under thermal cycles with higher fluctuation amplitudes and mean values [11]. With the complicated mission profiles of wind turbines, the power semiconductors in wind power systems may experience many thermal cycles ranging from 15°C to 90°C, and they may cause lifetimes to drop below 20 years according to the life time models for power semiconductor devices [16].

Many efforts have been made to investigate new modeling and testing approaches to evaluate the lifetime consumption of power semiconductors and to apply appropriate control methods to improve the expected lifetime of power semiconductor devices. Reliability improvement of power semiconductors by means of condition monitoring has become a recent focus of research. Many studies have been performed to investigate online condition monitoring methods for wire-bonded power IGBT modules. The on-state voltage drop of the IGBT module has been the most used indicator for condition monitoring [17–22]. However, most of the solutions are dedicated to specific applications or need structure modifications of the power module.

Therefore, making the condition monitoring methods more intelligent and applicable to general applications will be the goal of improvement in the future.

1.4.4 The Application of New Power Semiconductor Devices

Currently, a majority of wind power generators in the market are rated at 690 VAC. Voltage rating for switching devices is 1700 V or 1200 V [23, 24]. SiC MOSFET, JFET, and Schottky barrier diode (SBD) of such voltage ratings are technically mature and commercially available. In [24], SiC devices of 1200 V and 1700 V ratings from the same manufacturer are compared to the state-of-the-art IGBT modules of the same voltage ratings. According to the analysis, a large amount of switching loss reduction can be achieved by applying SiC and hybrid devices.

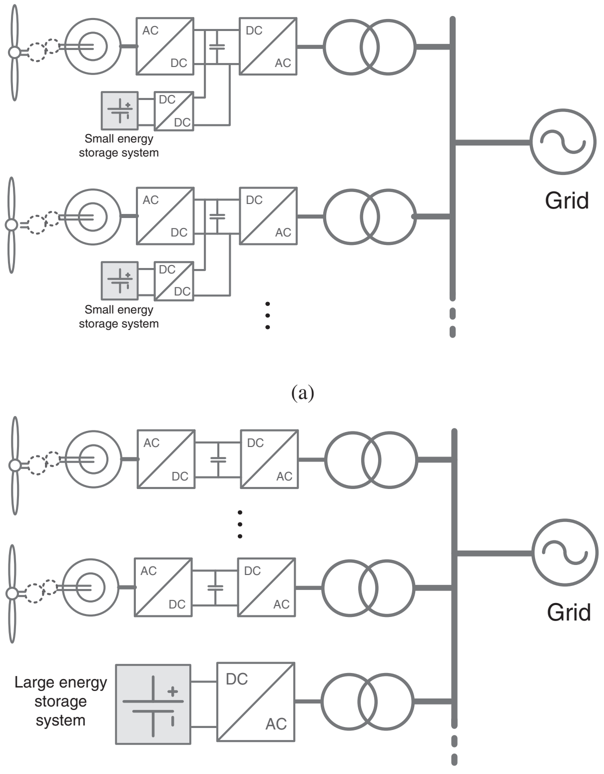
In [25] and [26], application of SiC MOSFETs and Schottky diodes are investigated in a 1.5 MW full-scale back-to-back converter adopting the two-level topology used for wind power generation based on permanent magnet generator. The 1.5 MW converter is assumed to be composed of ten SiC-based converters that each has twenty 1700 V/10 A SiC MOSFETs in parallel or an Si-based converter with two 1700 V/1200 A IGBT modules in parallel. Since at present, SiC devices with the suitable current rating are not available, a large amount of small-scaled SiC devices are paralleled in this calculation which is unrealistic in practical application. However, as the technology matures, high-current rated SiC MOSFET modules will be developed in the near future. Nevertheless, the calculation results are helpful to give us a glimpse at the advantage of SiC MOSFET in efficiency improvement.

Presently, SiC devices still cost much higher than their Si counterparts. Some studies have used SiC diodes to substitute the free-wheeling diodes in the conventional IGBT modules to form hybrid devices. In [27], an SiC diode module and an IGBT module are used to form a hybrid phase leg. According to the analysis, the inverter adopting the Si IGBT/SiC clamping diode hybrid devices has about 0.6% efficiency increase compared to all-Si IGBT inverter. This is a very cost-effective solution with significant improvement in efficiency and relatively low extra cost. Taking the cost into consideration, hybrid devices may be the compromise between efficiency improvement and cost in the near future.

1.4.5 More Advanced Grid Integration Control

In order to reduce the impact of the wind gust and ensure the security and stability of grid operation, the wind turbines or wind farms are preferred to be configured as distributed generation networks. Its power flows and electrical behaviors are different compared to the traditional centralized generation networks [28, 41]. Therefore, the protection schemes of the future grid utilities with more wind power penetration should be also changed. It results in a more distributed protection structure and may allow the islanding operation of some wind turbine units as microgrids [31].

Moreover, with the growing proportion of wind power in the power grid, more advanced grid requirements are needed. In the case of shutting down of transmission networks, the WTSs may need the abilities to black start [32].



(a)

(b)

Figure 1.15 Potential energy storage configurations for wind power plants to enable virtual power plant operation: (a) distributed energy storage and (b) centralized energy storage.

In order to achieve these more advanced features of grid interconnection, some energy storage systems may be needed for future wind turbines and wind farms. The storage system can be configured locally for each wind turbine unit, as shown in Figure 1.15a, or be configured centrally for several wind turbines/wind farms, as shown in Figure 1.15b. Such WTSs with energy storage will also be ready to operate as a primary controller and may operate as a virtual synchronous machine [39].

1.4.6 Configurations of Wind Power Plants

As the wind power capacity grows, large wind farms which consist of many wind turbines are being developed. These wind farms may have significant impacts to the grids, and therefore they will play an important role in the power quality and the control of the power grid systems. The power electronics technology is again an important part of both the system configurations and the control of the wind farms in order to fulfill the growing grid demands [35]. Some existing and potential configurations of the wind farms are shown in Figure 1.16.

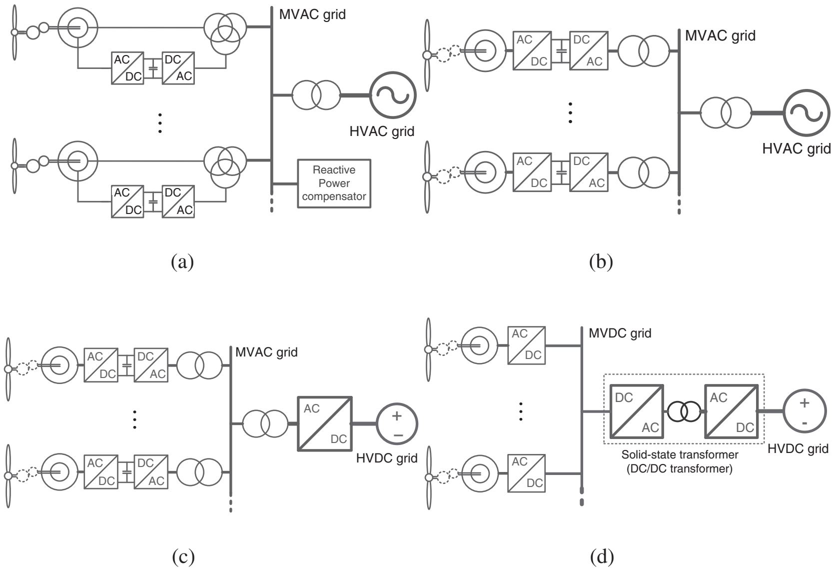


Figure 1.16 Potential wind farm configurations with AC and DC power delivery: (a) Doubly fed induction generator system with AC grid; (b) full-scale converter system with AC grid; (c) full-scale converter system with transmission DC grid; (d) full-scale converter system with both distribution and transmission DC grids.

A wind farm equipped with DFIG-based WTSs is shown in Figure 1.16a. Such a wind farm system is in operation in Denmark as a 160 MW offshore wind power station. It is noted that due to the limitation of the reactive power capability, a centralized reactive power compensator like STATCOM may be used in order to fully satisfy future grid requirements [39].

Figure 1.16b shows another wind farm configuration equipped with a WTS based on full-scale power converter. Because the reactive power controllability is significantly extended, the grid-side converter in each of the generation unit can be used to provide the required reactive power individually, leading to reactive power compensator-less solutions.

For long-distance power transmission from an offshore wind farm, HVDC may be an interesting option because the efficiency is improved and no voltage compensators are needed. A typical HVDC transmission solution for wind power is shown in Figure 1.16c, in which the medium AC voltage of the wind farm output is converted into a high DC voltage by a boost transformer and high voltage rectifier.

Another possible wind farm configuration with HVDC transmission is shown in Figure 1.16d, where a solid-state transformer (or DC/DC transformer) is used to convert the low/medium DC voltage from each wind turbine output to the medium/high DC voltage for transmission, thus a full DC power delivery both in the distribution and transmission grid can be realized. It is claimed in that the overall efficiency of the power delivery can be significantly improved compared to the configuration shown in Figure 1.16c—mainly because of fewer converters and transformers in this DC transmission system. It can be a future solution for large wind farms to increase the overall efficiency of power delivery [33, 40, 42].

1.5 THE TOPICS OF THIS BOOK

This book will focus on the advanced control of the DFIG wind power system, which is realized by the power electronic converters and aims at better grid integration performance. This book is divided into following four parts:

Part I (Chapters 1–3) will provide the basic knowledge of wind power technology. The related grid codes for wind power generator will be introduced. It will make the reader in related areas much easier to understand the following content.

Part II (Chapters 4 and 5) will evaluate the dynamic model of DFIG wind power system and the vector control scheme of the DFIG, which includes the most widely used control strategies nowadays.

Part III (Chapters 6–10) will aim at the advanced control of DFIG under the non-ideal grid, including the grid voltage harmonic distortion and the grid voltage unbalanced. The dynamic model of the DFIG and converter under grid voltage harmonic distortion, and the grid voltage unbalanced will be introduced. The stator harmonic current control is introduced in order to suppress the stator lower-order harmonics. The DC-fluctuations control of the GSC can suppress the DC-bus fluctuations under the unbalanced grid.

Part IV (Chapters 11–13) will introduce the grid fault ride-through of the DFIG WTS such as LVRT of DFIG, the smart thermal derating control of DFIG system, etc. The control strategy for DFIG under recurring faults is also investigated.

In Part V (Chapter 14), a DFIG test bench is introduced. It is helpful for the reader to understand how the real system is built and can be a guide to building a small-scale test bench in a laboratory.

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