1
Introduction

1.1 Motivation

Wind energy is an increasingly important source of renewable energy. Presently, most wind turbines are installed on land. However, lack of available land area as well as the need for good and stable wind conditions have stimulated the development of offshore wind turbines. Moving offshore has also allowed for a considerable increase in the size of wind turbines; presently, 10–15 MW turbines are the state of the art, while even larger turbines are under development. Moving offshore involves new challenges, both with respect to the design for the offshore environment as well as for the installation, operation and maintenance of the turbines.

The first offshore wind farm, Vindeby, Denmark, was installed in 1991 in a water depth of approximately 4 m. The 11 turbines had a rated power of 0.45 MW each. The technology used for the early offshore wind turbines was the same as for the land-based turbines, only that the tower was "elongated" to provide support for the structure through the water column. The early development of offshore wind turbines resembles that of the offshore oil and gas industry in the 1940s to 1960s. The technology used offshore was very similar to the technology used on land. To compensate for the "new" wet environment, the equipment was placed upon a simple platform, or substructure. In the beginning, the installations were made in water depth of less than 10 m. As the industry moved, step by step, into deeper waters and the size of the wind turbines increased, the same basic design was applied and the technology was extrapolated. However, a significant shift in technology has occurred through the introduction of floating platforms, which have required a rethinking of the complete design.

As the size of individual wind turbines as well as wind farms increases, and as wind farms are located further from shore, in deeper waters and in harsher environments, new technologies are needed. Modification of land-based technology is not sufficient. To design and operate offshore wind turbines, a real multidisciplinary approach is needed. The disciplines comprise meteorology, aerodynamics, hydrodynamics, structural dynamics, material technology, cybernetics, power electronics and several others related to environmental impact, logistics and economics.

1.2 Content of the Book

The focus of the present book is on some key issues that make offshore wind turbines different from land-based wind turbines.

Understanding the offshore environment – the wind and wave conditions – is key to understanding the dynamics of offshore wind turbines. Therefore, a description of the marine atmospheric boundary layer and classical wave theory is given in Chapter 2. Some basic wave statistics are also included in this chapter.

For the sake of completeness, the aerodynamic principles behind a wind turbine are dealt with in Chapter 3. Classical approaches such as the Betz limit and the beam element momentum (BEM) method are described. Further, the dynamic response of the wind turbine, which becomes more important as the size of the turbine increases, is discussed. In addition, vortex methods are described in some detail, which may represent an intermediate and efficient step between the classical BEM and more complete RANS[1] or LES[2] methods for analyzing the aerodynamics of wind turbines.

In Chapter 4, various offshore support structures are discussed. There has been continuous development of new support structures in the last decades. Still, the monopile is the most frequently used substructure.[3] Various jacket structures and tripods are also used. In more recent years, the development of floating support structures has gained speed. The world's first multimegawatt floating offshore wind turbine, Hywind Demo, was installed off the west coast of Norway, at Karmøy, in 2009. A 2.3 MW turbine was used on this test unit. In 2017, the first floating offshore wind farm was installed off the east coast of Scotland. The wind farm consists of five turbines, each of 6 MW. The support structure is of the Hywind brand.

To provide a background for the dynamic analysis of wind turbines, Chapter 5 is included to summarize some simple classical dynamics of linear systems.

The basic principles for computing wave loads on fixed support structures are covered in Chapter 6. The focus is on slender vertical structures, but the principles behind the theory of computing wave loads on large-volume structures of general shape are also included. Further, some issues related to wave forces in steep waves

[1] Reynolds-averaged Navier–Stokes equations. [2] Large eddy simulation.
[3] See Chapter 4 for a further description of the various concepts as well as definitions of wind turbine components such as the nacelle, tower, support structure, substructure and foundation.

https://doi.org/10.1017/9781009341455.002 Published online by Cambridge University Press

are included. These issues are important to estimate extreme loads as well as fatigue effects due to waves.

Wave loads and wave-induced dynamics of floating support structures are covered in Chapter 7. Here, some classical approaches based upon slender body assumptions and linear theory are outlined in detail. Such methods are computational-efficient and may thus be useful in, for example, optimization processes. To compute the rigid body dynamics of a floating body, the mass, damping and inertia matrices must be established. Each of these matrices are discussed and the restoring effects of mooring lines are examined in some detail. Finally, the need for a motion control system for floating wind turbines is discussed.

Marine operations are an important part of installing as well as operating a wind farm. In Chapter 8, the issues of weather windows and duration statistics are discussed and the dynamics of lifting operations from a floating crane vessel are considered in some detail. The probability of impact during a load transfer operation is discussed, as well as a simple approach for estimating the impact loads during load transfer by a crane. Issues related to wind farms are discussed in some detail in Chapter 9, in particular, simple wake models and the summation of wakes.

This book does not handle in detail the classical aerodynamic analysis of wind turbines. This may be found in textbooks such as those by Hansen (2015) or Manwell et al. (2009). Issues related to choices of material and corrosion in the offshore environment are not covered in this book. The same goes for the generation and transformation of electrical power, as well as electrical cable issues.

1.3 The Design Process

A wind turbine must be designed to fulfil several criteria related to, for example, operational conditions and extreme conditions. The various design criteria will determine which analysis is needed in the design process. In standards such as IEC 61400–3 (2009) and DNV (2021a), the criteria are formulated as limit states. A limit state is "a condition beyond which a structure or structural component will no longer satisfy the design requirements." According to the standard issued by DNV (2021a), four different "limit states" have to be considered in the design of offshore wind turbine structures.

The *serviceability limit state* (SLS) corresponds to the tolerance criteria applicable to normal use, i.e., the SLS design check should ensure that the structure works under normal operating conditions.

The *fatigue limit state* (FLS) corresponds to failure due to the effect of cyclic loading, i.e., the FLS design check should ensure that during the lifetime of the structure, the cumulative effect of cyclic loading should not damage the structure.

The *ultimate limit state* (ULS) corresponds to the maximum load-carrying resistance, i.e., the ULS design check should ensure that the structure is able to withstand the extreme loads typically experienced without damage.

The *accidental limit state* (ALS) corresponds to (1) maximum load-carrying capacity for (rare) accidental loads or (2) post-accidental integrity for a damaged structure, i.e., the ALS design check is to secure that the structure, if exposed to loads beyond the ULS level, does not collapse, and that it may survive even in damaged condition.

DNV (2021a) lists the following examples of limit states within each category.

Serviceability limit states (SLS)

- Deflections that may alter the effect of the acting forces.
- Excessive vibrations producing discomfort or affecting nonstructural components.
- Excessive vibrations affecting turbine operation and energy production.
- Deformations or motions that exceed the limitation of equipment.
- Durability.
- Differential settlements of foundations soils causing intolerable tilt of the wind turbine.
- Temperature-induced deformations.

Fatigue limit states (FLS)

- Cumulative damage due to repeated loads.

Ultimate limit states (ULS)

- Loss of structural resistance (excessive yielding and buckling).
- Failure of components due to brittle fracture.
- Loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body, e.g., overturning or capsizing.
- Failure of critical components of the structure caused by exceeding the ultimate resistance (which in some cases is reduced due to repetitive loading) or the ultimate deformation of components.
- Transformation of the structure into a mechanism (collapse or excessive deformation).

Accidental limit states (ALS)

- Structural damage caused by accidental loads (ALS type 1).
- Ultimate resistance of damaged structures (ALS type 2).
- Loss of structural integrity after local damage (ALS type 2).

Prior to the design process for the support structure,[4] the site-specific environmental condition as well as the design of the rotor-nacelle assembly (RNA) must be

[4] The names of the various components of an offshore wind turbine are shown in Section 1.4 and Chapter 4.

known. Based upon these, the design basis for the support structure is formulated. Several operational cases (design situations) and environmental conditions (load cases) are analyzed. These include:

- normal design situations and appropriate normal or extreme external conditions
- fault design situations and appropriate external conditions
- transportation, installation and maintenance design situations and appropriate external conditions

For each case, the load effects are analyzed and checked as to whether they satisfy the appropriate limit state. If not, the design must be modified.

To check if the structure fulfils the limit states, one has to check if the "capacity" (e.g., material strength) of the structure is sufficient to withstand the loads acting upon it. This is normally done by use of the "partial safety factor method." Formally, this is expressed by requiring that the "resistance" of the structure, R_d, shall exceed the design load effect, S_d:

$$S_d \leq R_d \tag{1.1}$$

The design load effect, S_d, is obtained from the "characteristic load" effect, S_k, by multiplying by a load factor, γ_f, $S_d = \gamma_f S_k$. For example, the characteristic load effect for a ULS is the load combination that has an annual probability of exceedance of 0.02 or less. That is, the load has a return period of at least 50 years. In an FLS, the characteristic load effect history is defined as the expected load effect time history during the lifetime of the structure.

Similarly as for the load effect, the design resistance is obtained by dividing the characteristic resistance by a material factor, γ_m, $R_d = R_k/\gamma_m$.

The load factor, γ_f, is introduced to account for uncertainties in the methods for estimating the loads as well as to account for statistical uncertainties in the loads, for example, the statistics of waves. Similarly, the material factor, γ_m, shall account for uncertainties in the capacity of the material, such as yield strength, thickness, fatigue capacity and so on. As an example, DNV (2021b) states that γ_f should be set to 1.35 for environmental loads in a ULS check, while the material factor γ_m should be set to 1.10 for the strength of steel tubular members (DNV, 2021a). The load and material factor will vary depending on load case considered and failure mode.

For FLS checks, several issues must be accounted for. The fatigue capacity of a steel material depends upon the steel quality, plate thickness, corrosion protection and weld geometry and quality, as well as accessibility for inspection of critical details. With all these factors included and using a characteristic load time history, the cumulative fatigue damage during the lifetime of the structure should be less than one half to one third of the damage causing failure.

1.4 The Layout of Wind Turbines

The function of a wind turbine is to convert the kinetic energy in the wind to rotational energy. Rotational energy was in the past used for grinding ("windmills") or pumping water. Today, rotational energy is converted to electric energy by an electrical generator. Various design principles of wind turbines exist and some features of the main ones are discussed briefly in the following sections.

1.4.1 Horizontal-Axis Wind Turbines

The horizontal-axis wind turbine (HAWT) is the most frequently used wind turbine. In Figure 1.1 (left), an illustration of the layout of a HAWT is given. Both on land and offshore, a HAWT is mounted upon a slender tower. In most cases the rotor consists of three blades mounted on an almost horizontal axis. The axis may have some tilt to avoid collision between the blades and the tower during rotation. The rotor is usually mounted on the upwind side of the tower. Each blade has the profile of an aerofoil. How this works is described in Chapter 3.

Wind blowing into the rotor makes the rotor rotate. Considering the aerodynamics of large rotors, the optimum rotational speed is too low for a standard electrical generator to be efficient. Therefore, a gear is mounted between the rotor shaft (the

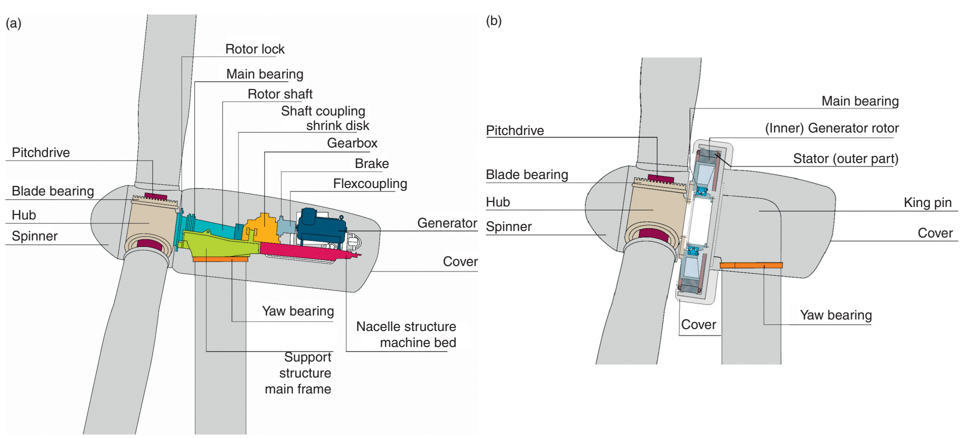

Figure 1.1 Illustration of the main components in a geared wind turbine (left) and a direct-drive turbine (right). Reproduced with permission of Fraunhofer IWES. Source: Wenske (2022).

https://doi.org/10.1017/9781009341455.002 Published online by Cambridge University Press

low-speed shaft) and the generator shaft (the high-speed shaft), with a gear ratio that may be in the order of 100. A four-pole generator should run at 1500 revolutions per min to generate 50 Hz AC power. Thus, if the rotational speed of the turbine is 15 revolutions per min, a gear ratio of 100 is needed. Several multimegawatt turbines are now equipped with so-called *direct-drive* generators, illustrated in Figure 1.1 (right). A direct drive implies that the gear is removed and a generator with a large diameter and many poles along the circumference is used. The generator used is frequently a permanent magnet generator. The many poles secure a sufficiently efficient generation of electrical power even if the rotational speed is low. The frequency of the AC power generated does not normally fit the grid frequency. The AC current is therefore converted to DC current and back to AC with the correct frequency and phase.

The rotor blades are mounted to the rotor hub. In the hub, a mechanism for twisting or pitching the rotor blades is located. The pitching of blades is used to control the power and reduce the loads on the rotor at high wind speeds. The shafts, gear, generator, control system and power converter systems are assembled in a housing denoted the nacelle. The rotor and nacelle assembly, frequently denoted the RNA, is located on top of the tower. A weathervane is mounted on the top of the nacelle, by which the direction of the wind is measured. The RNA may rotate on top of the tower so that the rotor heads into the wind; this is accomplished by the yaw mechanism. The operation of a modern wind turbine relies upon several systems that control rotational speed, blade pitch and yaw angle.

As discussed in Chapter 3, the three-bladed upwind turbine illustrated in Figure 1.1 has many advantages. However, two-bladed designs exist as well. A two-bladed rotor is lighter and has a higher optimum rotational speed than a three-bladed turbine. Therefore, the required gear ratio is lower. A three-bladed rotor has a beneficial dynamic property as the mass moment of inertia is independent of which axis in the rotor plane is considered. This contrasts with a two-bladed rotor, which has very large difference in the mass moment of inertia about the axis coinciding with the blade axis and the axis normal to the blade axis. This difference in inertia may trigger unfavorable dynamic loads.

Downwind rotors also exist. By locating the rotor on the downwind side of the tower, the collision issue between blades and tower is solved. However, every time a blade passes the leeward side of the tower, it moves into a wind shadow, causing severe dynamic loads. Downwind rotors may, under certain conditions, be self-correcting with respect to wind direction. In that case, the yaw mechanism required for the upwind turbine may be avoided.

1.4.2 Horizontal-Axis Multirotors

The size of horizontal-axis wind turbines has steadily increased. In the 1980s, wind turbines with a rated power of 50 KW and a rotor diameter of 15 m were common. Currently, turbines with a rated power of 15 MW and more and a rotor diameter in the order of 250 m are the state of the art. The power that can be extracted by a wind turbine is proportional to the area swept by the rotor, i.e., proportional to the diameter squared. However, the bending moment in the blade root will increase by approximately the cube of the rotor diameter. The same goes with the mass. It may thus be assumed that increased mass, large deformations and large and heavy units (blades, generator) to be handled during installation and maintenance will at some point limit the size of turbines. So far, this has not happened, but alternative designs have been proposed to address the upscaling challenge. Wind turbine designs with two or more rotors mounted on the same tower have been built (van der Laan et al., 2019). Also, offshore, floating wind turbine concepts with serval rotors mounted upon the same hull have been proposed (Jamieson, 2017). These designs span from using two rotors to large arrays using in the order of 100 rotors. The arguments for having many smaller rotors rather than one large rotor are related to costs of energy and ease of handling. It may also be argued that the complete production and assembly line is simpler and faster.

1.4.3 Vertical-Axis Turbines

As the name states, the blades of a vertical-axis wind turbine (VAWT) rotate around a vertical axis, as shown in Figure 1.2. In addition to the two principles shown in Figure 1.2, designs with helical-shaped blades exist. The cross-section of each blade is shaped like an aerofoil, thus creating a lift force on the blade section, driving the rotation. Drag-based systems also exist. The differences between lift-based (aerofoil) systems and drag-based systems are discussed in Chapter 3. An important difference is that drag-based systems are far less efficient than lift-based systems.

The main advantages of a VAWT are that most of the technical equipment, including the generator, may be placed at ground level, and that the turbine works independent of the wind direction. Generally, a VAWT has lower efficiency than a HAWT. The reason for this is mainly related to the angle of attack for the blades. This angle varies during the rotation, thus, the angle of attack most of the time is not optimum. Further, when the blade is moving at the downwind side of the rotor, it is moving in the wake of the upwind blade, causing reduced efficiency and larger dynamic loads due to the increased turbulence. However, for smaller turbines – e.g., “rooftop” versions – a VAWT may be an attractive solution.

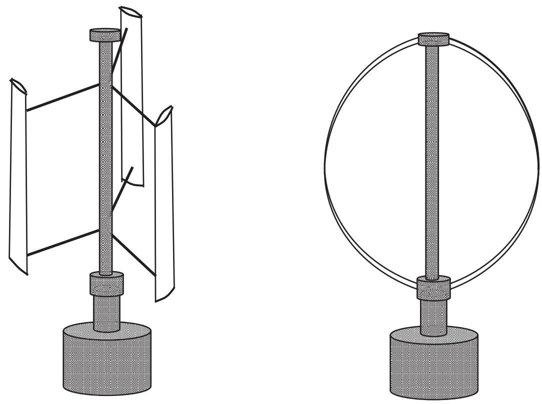

Figure 1.2 Vertical-axis wind turbines. "H-shaped" type (left) and Darrieus ("eggbeater") type (right).

1.4.4 High-Altitude Wind Power Devices

High-altitude wind power devices (HAWP) use wind forces to stay high above ground level and at the same time extract energy. The systems are inspired by kites. A kite, or a wing, is connected via a line to a drum on the ground. As the kite is flying, it is forced into a special motion pattern, for example, a figure-eight pattern, as illustrated in Figure 1.3, or a circular pattern. By allowing the drum to rotate, the line is little by little released from the drum and the combination of the tension in the line and rotational velocity of the drum creates mechanical power, driving an electrical generator. When the full length of the line is out of the drum, a "home-flying" mode is activated; the kite descends and the line is wound up on the drum under low tension. Power is thereby produced as the kite flies up, while a small amount of power is used when it flies back "home."

As an alternative to extracting power when the kite flies up and tensions the line, other concepts equip the kite, or rigid wing, with small wind turbines that extract wind power while the system is flying at a steady pattern at high altitude. The Makani system[5] is an example. The power is transferred via the line down to ground level. Such a system can in principle produce power continuously.

The main idea behind HAWP devices is to utilize the strong and steady wind of high altitudes. These devices operate several hundred meters above ground level. However, at the present stage of development the systems are not commercial and do not deliver power at the megawatt scale.

[5] The Moonshot Factory. n.d. "Makani: Harnessing Wind Energy with Kites to Create Renewable Electricity." www.x.company/projects/makani/ (accessed November 3, 2021).

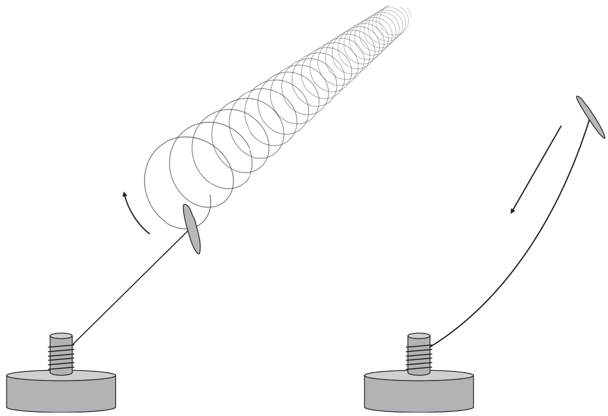

Figure 1.3 Simplistic view of a kite connected to a drum, with an indication of the flying pattern when power is produced (left) and when flying back (right).

Exercises Chapter 1

1. Describe the main differences between HAWT and VAWT. Why can the rotor blade of a VAWT not work at an optimum angle of attack all the time?
2. Consider a H-shaped VAWT, as illustrated in Figure 1.2. Assume the angular velocity of the blades is given by ω and the incident wind speed is U. Derive an expression for the angle of attack as a function of the angular position of the rotor blade. (See Chapter 3 for definition of the angle of attack.) Ignore induced velocities.
3. Consider a Cartesian coordinate system with one axis oriented along the axis of rotation of the rotor and the two other axes in the rotor plane. Show that the mass moment of inertia of a three-bladed wind turbine is independent of which axis in the rotor plane is considered.