

Chapter 2

Wind Turbines

2.1 Introduction

Wind turbines generate electricity by harnessing the power of the wind. A wind turbine works the opposite of a fan (a fan uses electrical power to work). The energy in the wind turns the blades around a rotor. The rotor is connected to the main shaft, the low-speed shaft. The drive train including the gears increases the rotational speed. The high-speed shaft is connected to a generator which creates electricity. The schematic layout of a land-based wind turbine is shown in Fig. 2.1.

Based on the Rankine–Froude theory, the power (P) generated by a wind turbine can be written in the following form:

$$P = \frac{1}{2} \rho_{air} C_p A_s V_{Rel}^3 \quad (2.1)$$

in which ρ_{air} is the air density, C_p is the power coefficient, A_s is the swept area of the wind turbine rotor and V_{Rel} is the relative wind velocity. This simple relation between the wind speed and power shows that 10% increase in the relative wind velocity results in a 33% increase in produced power.

2.2 Nacelle

The nacelle is located at the top of the tower (see Fig. 2.2). The nacelle is connected to the rotor and it supports several components, such as the generator and the drive-train. For megawatt (MW) wind turbines, the nacelle is large, and some nacelles are large enough for a helicopter to land on.

The wind energy captured by the rotor is converted to electricity at the nacelle. The conversion of wind kinetic energy to electrical energy is done at the rotor nacelle. Hence, the rotor nacelle assembly is the most important part of a wind turbine.

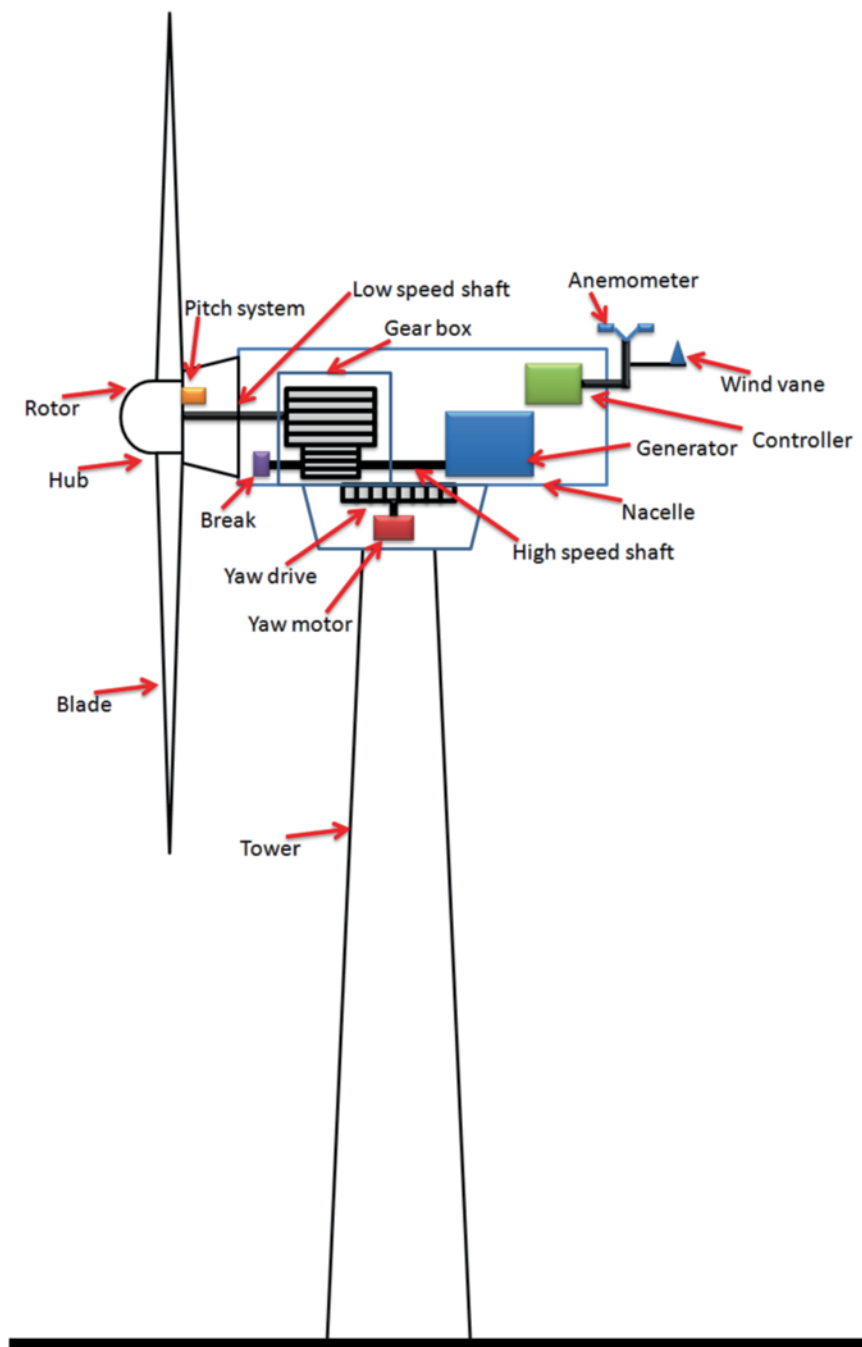


Fig. 2.1 Wind turbine components

Fig. 2.2 Nacelle of a wind turbine. (Courtesy of Paul Anderson (Anderson, Nacelle of Turbine Tower No 26—geograph.org.uk—824692.jpg, 2011b). This file is licensed under the Creative Commons Attribution-Share Alike 2.0 Generic license)



The drivetrain is a series of mechanical components, such as gears, bearings and shafts. Gearless wind turbines exist as well. However, the most developed wind turbines have gears. In a drivetrain, first is the main shaft which is connected to the rotor (hub and blades). The main shaft supports the rotor. The rear of the main shaft is connected to the slow-rotating side of the gearbox. The gearbox increases the rotational speed, e.g. 100 times.

The next component after the gearbox is the electrical generator. The generator's construction is linked to whether or not the nacelle design includes a gearbox. In front of the generator is a large disc brake that has the ability to keep the turbine in a stopped position (Lorc-website 2011).

Three-phased electrical power is generated, which must then be transformed to the higher voltage (HV) of the grid. For each phase, there is a transformer, which is placed usually at the back of the nacelle (Muljadi and Butterfield 1999).

The power cable transfers generated electricity from the generator to the grids. The cable is located in the tower. As the nacelle yaws, the cable twists to face the wind direction. The control system counts the number of cable twists to ensure that the cable is kept within defined and safe limits.

2.3 Hub

Current state-of-the-art wind turbines are using pitch-controlled variable-speed generators (E. Muljadi and C.P. Butterfield 1999). This means the pitch angle of the blades are changed to optimize the produced power. The hub is a part for the pitchable blades and their bearings, as it is clear in Fig. 2.3.

The blades are mounted on special bearings, which allow the blades to pitch, i.e. to change their angle relative to the hub while they are still in the rotor plane. The blades angle of attack (relative to the wind) can accordingly be optimized. So, the

Fig. 2.3 Hub. (Courtesy of Paul Anderson (Anderson, Hub of Turbine No 23—geograph.org.uk—837248.jpg, 2011a). This file is licensed under the Creative Commons Attribution-Share Alike 2.0 Generic license)



blades produce the maximum lift for a variety of wind speeds without stalling. Also, the blades are feathered to maintain the rated power when the wind velocity gets high. Fast pitching of the blades to zero degrees provides an effective means to stop the turbine (Lorc 2011).

2.4 Blades

The core of conversion of kinetic energy of wind to rotary-mechanical energy is the blade (see Fig. 2.4). A blade has an airfoil shape which directs the wind forces to the turbine low-speed shaft. Three-bladed horizontal-axis wind turbine is typical. However, downwind turbines with two blades are also used. The airfoil changes the airflow streamlines and creates pressure differences. This difference of pressure over the blade creates lift force, which is a driving force that creates torque in the wind turbine rotor. Keep in mind that drag forces appear as well, which are resistant forces and should be overcome by the structure components. The main shaft (low-speed shaft) should take these drag forces and transfer them to the nacelle base and consequently to the bottom of the tower. So, the structure should be capable of handling the drag forces together with the lift forces. The lift and drag forces are dependent on some parameters, such as the shape of the blade, the surface area, the wind speed and the angle of attack.

A symmetrical airfoil creates no lift forces when the angle of attack is zero. However, if the angle of attack is more than zero, lift occurs as a consequence of the pressure difference between the two surfaces. This discovery was made by Bernoulli and published in 1738 (Bauman 2007). Bernoulli's equation is simply a relation between static and dynamic pressure. The total pressure is assumed to be constant. Hence, when the dynamic pressure (related to the wind speed) increases, the static pressure decreases at the top of the airfoil surface. This makes a force perpendicular



Fig. 2.4 Wind turbine blades. (Courtesy of Jacopo Werther (Werther 2013). This file is licensed under the Creative Commons Attribution-Share Alike 2.0 Generic license)

to the streamlines, which is called lift. Aerodynamics will be discussed in a separate chapter of this book.

Current design solutions usually make use of three blades. However, two blades is another option. In theory, more blades over the same swept area should produce more power, but experience has shown that a design with many blades forces the wind to go around the rotor rather than through its swept area where energy can be harvested. The advantages of more than three blades are generally less than the additional costs (Lorc 2011).

2.5 Pitch System

The pitch system feathers the blades above the rated wind speed. The controller decides how much the actuators need to turn the blades. As it was mentioned earlier, it is necessary to feather the blades and control the blade angle of attack. The relative angle between the incoming wind and the blade chord should be controlled by a controller. The pitch system applies the controller's commands and feathers the blades (Jonkman et al. 2005).

The angle of attack is dependent on the wind speed, the rotational speed, and the distance from the blade root. Depending on the incoming wind velocity, there is an optimal angle of attack allowing the rotor to deliver maximum power to the main shaft. The modern wind turbine must therefore continually adjust the pitch in order to maximize energy production (Muljadi and Butterfield 1999).

Currently, the wind turbines have a collective pitch system which feathers all the blades with a same angle. Individual blade pitching can be applied in future turbines to improve the power production. Smart blades with adjustable angles of attack through the blades may be applied in a longer term. In smart-blades design, each blade is divided to several segments and each segment has its own pitching servomechanism.

Fig. 2.5 Hydraulic pitch system. (Courtesy of Wikimedia commons (KarleHorn 2010). This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license)



Blades of older wind turbines were directly connected to the hub with a fixed angle that could reflect the best design and power production. Those wind turbines had no pitch control system. Hence, if the winds were strong, the blades with fixed angle would stall as the angle of attack would increase by increasing the wind speed. This had a positive effect on the survivability of the wind turbine and could protect the wind turbine components, such as the blade and the tower. However, this could reduce the amount of generated electricity. Hence, the turbine's maximum rated production could only be reached within a narrow range of wind speeds in stall-regulated wind turbines.

Active pitch control in modern wind turbines helps to harness energy in lower wind speed and increases the range of wind speed in which the rated power is captured. At high wind speeds, the blades pitch to smaller angles of attack and the rated power is maintained. This improves the survivability of the wind turbine in such harsh conditions. Meanwhile, the power production is increased.

Depending on the turbine size, the energy needed for the servomotor to feather the blades varies. For a 2.5-MW turbine, around 60 kW (roughly 2.5% of the rated power) is used. However, the gained energy from the active control of such a turbine is significant compared to the servomotor's electric consumption. Both hydraulic (Fig. 2.5) and electric systems (Fig. 2.6) can be used to feather the blades. In offshore wind industry, the hydraulic system is the dominant option.

As it was mentioned, the blades are mounted on hub bearings; hence, they can be feathered. Actuators mounted inside the hub can adjust the angle of attack based on the commands coming from the central controller unit. In emergency shutdown or fault conditions, sudden feathering of the blades can be used to stop the turbine. This is an aerodynamic break in which the angle of attack is set rapidly to zero to neutralize the wind forces on the blades.

Safety requirements include a pressurized tank to store sufficient energy to stop the turbine if the central electric system fails. In some turbines, an electrical pitch system is applied, in which the blades are feathered by gearmotors. Safety

Fig. 2.6 Electric pitch system. (Courtesy of geograph.org.uk (Anderson, Interior of the hub of Turbine No 3, 2008b). © Copyright Paul Anderson and licensed for reuse under this Creative Commons Licence)



requirements include an emergency circuit with a battery to be activated in fault conditions, i.e. when the central electric system fails.

2.6 Main Shaft

The high-speed shaft is connected to the gearbox and transmits the mechanical power of the rotor to the generator. The low-speed shaft drives the high-speed shaft through gears. The main shaft (low-speed shaft) has important functions (see Fig. 2.7). It supports the rotor (hub and blades), as well as transmits the rotary motion of the rotor and torque moments to the gearbox and/or generator. The thrust loads are taken by the shaft and transmitted to the nacelle and to the top of the tower. The low-speed shaft (main shaft) is a massive part usually built from forged or

Fig. 2.7 Main shaft. (Courtesy of geograph.org.uk (Anderson, Gearbox, Rotor Shaft and Disk Brake Assembly, 2008a). © Copyright Paul Anderson and licensed for reuse under this Creative Commons Licence)



cast iron. New materials such as carbon-fiber-reinforced polymer (CFRP) are introduced to reduce the main-shaft weight, saving several tons in the complete nacelle (windpowermonthly.com 2012).

2.7 Gearbox

The gearbox (Fig. 2.8) connects the low-speed shaft to the high-speed shaft and increases the rotational speeds. For turbines, e.g. of 1 MW, the rotational speed of the rotor is about 20 rotations per minute (rpm). The gearbox increases the rotational speed by a ratio of about 90 times to get the rotational speed of the high-speed shaft to reach about 1800 rpm. The corresponding values for a large turbine, e.g. 5 MW (REpower 5M machine), are around 12.1, 97 and 1173.7 rpm, for rotor rotational speed, gearbox ratio and high-speed shaft rpm, respectively.

A wind turbine may need a gear system depending on its generator type. Some wind turbines do not need a gearbox and they are gearless (direct drivetrain). Gearbox design in a wind turbine is tightly linked to the choice of generator. Electric generators need high rotational speed input. However, the rotor of a wind turbine is rotating relatively slow. Hence, a gearbox system is needed to increase the rotational speed of the input torque. The low-speed shaft (main shaft) is connected to the hub and delivers the torque to the gearbox. The gear systems, which consist of several types of gears, increase the rotational speed roughly 100–200 times for MW turbines (depending on the type and scale of the turbine). The high-speed shaft is connected to the generator.

The main shaft speed is dependent on the blade tip speed and the length of the blades. Hence, longer blades result in slower rotation of the main shaft as it is needed to keep the tip speed subsonic. The power is a multiplication of rotational speed and torque. When a gearbox increases the rotational speed, it simultaneously decreases the torque. MW turbines have multi-pole generators, e.g. four-pole generators. In general, the less complicated is the generator; the more complicated should be the gear system. Usually, a gear system consists of both planetary and parallel gear stages.

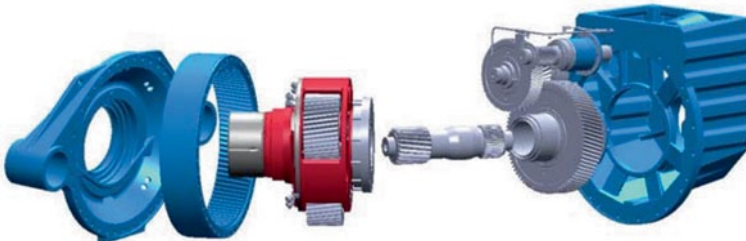


Fig. 2.8 Exploded view of GRC gearbox components. (Courtesy US Department of Energy, US Government 2014)

The gearbox is a mechanical system subjected to variable dynamic loads. The gearbox downtime is relatively high, especially for offshore units as the accessibility and availability are subjected to weather windows and environmental conditions. Hence, efforts have been made to make gearless turbines and connect the main shaft directly to the generator. However, this choice poses a considerable challenge to the generator design, significantly increasing the number of poles, complexity, size and price of this component (Lorc 2011). Hybrid concepts may be used as well including smaller gear ratios and less complex generators.

The Japanese company Mitsubishi Heavy Industries (MHI) is testing a 7-MW offshore wind turbine with a hydraulic drivetrain (mhi-global.com 2013). This avoids the need for a mechanical gearbox. Dozens of hydraulic cylinders around the main shaft compress the hydraulic fluid, which drives the hydraulic motors, and the hydraulic motors drive the generator. The advantages of such a design are expected to be considerable, ranging from less overall weight to using less expensive generators and discarding the gearbox (mhi-global.com 2013).

2.8 Generator

The generator is the main electrical part of the turbine that produces 60-Hz alternating current (AC) electricity, and it is usually an off-the-shelf induction generator. Relatively high rotational speed is required by most generators to produce electricity. There are gearless wind turbines, in which the idea is to remove the gears, and the turbines operate with “direct-drive” generators that operate at lower rotational speeds and do not need gearboxes. The gearbox is a costly (and heavy) part of the wind turbine, and removing it can have some advantages. However, more research is needed to investigate and develop a mature gearless turbine. Currently, the market is dominated by turbines using gears.

Induction generators were used in the first generation of wind turbines. Induction generators did not have any speed control that needed to match the frequency of the grid (hence, they were inexpensive). Using induction generators requires that the rotation should be speeded up. This means that the rotational speed of the turbine should be almost constant. Since the slip of the generator resulted in the speed range.

Modern wind turbines are designed for variable rotational speeds to maximize the power production and reduce the loads. This is done in a variety of ways using different generator principles and converter technologies. The introduction of a new generation of high-voltage, high-speed power electronic components allow a wide range of variable-speed operation for very-large-scale machines (Carlin et al. 2003).

In 1979, the designers set up a trade-off between a synchronous generator with a frequency converter in the stator circuit and a doubly fed asynchronous (induction) machine with a frequency converter in the rotor circuit. The doubly fed system was chosen (Carlin et al. 2003). The classic doubly fed induction generator was sufficient for the newer and larger turbines because of efficiency and relatively low

converter cost. The Vestas V80/V90 2–3-MW turbines and the Repower 5–6-MW turbines use doubly fed generators (Lorc 2011).

2.9 Control

To optimize the functionality of a wind turbine, a control system is used. The controller increases the power production and limits the loads on the structural parts. Modern wind turbines apply active control to achieve the best performance. The control system consists of a number of computers which continuously monitor the condition of the wind turbine and collect statistics of operation from sensors. The controller constantly optimizes the energy production based upon a continuous measurement of mainly wind direction and speed (Muljadi and Butterfield 1999). The controller actively controls the yaw system, the blade pitch system and the generator.

The produced power is highly linked to the swept area. Hence, it is very important that the turbine rotor be straight into the coming wind. Any deviation results in reduction of power. The yaw system turns the nacelle and the rotor based on received information from the central controller. As mentioned earlier, the pitch system feathers the blades to adjust the angle of attack. The controller monitors and adjusts the angle of attack based on the wind direction and wind speed measurements.

To ensure that the produced energy is correctly sent to the electrical grid, a fast control of the generator should be performed as the electric current is alternating with a high frequency, e.g. 50 Hz. Novel control concepts have been proposed with the goal of making distribution networks more flexible by introducing active control mechanisms. Active control is expected to help with maintaining the stability of the power grid even after disturbances, loss of equipment or other unforeseen situations, by undertaking proactive actions to preserve the stability of the power network (Bouhafs and Mackay 2012).

There are several types of sensors to measure wind characteristics such as speed and direction. The simplest one is a cup anemometer. It just measures the wind speed. It is highly fragile and does not work in cold areas as it usually ices in such harsh conditions.

Most turbines are equipped with an ultrasonic anemometer, which sends high-frequency sound waves “crossover” between the four poles, and from this it detects the phase shifting in the received signals. On the basis of this information, wind direction and velocities are calculated (Anderson et al. 2008).

LIDAR (light detection and ranging) systems are able to provide preview information of wind speed, direction and shears at various distances in front of the wind turbines. This technology provides the way for new control concepts such as feed forward control and model predictive control to increase the energy production and to reduce the loads of wind turbines. LIDAR detects coherent light reflected from the air molecules in front of the turbine and thus can predict the wind before it hits the rotor. With the LIDAR system, the wind turbine can react to changes (for example a gust) before it hits the turbine (Schlipf 2012).

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