Chapter 5

Wind Energy, Functionality and technical advances

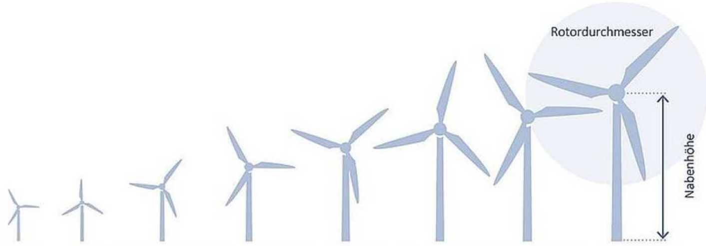
5.1 Introduction

The wind turbine uses the wind energy - more precisely the power contained in the wind - and converts this first into mechanical energy with the wind rotor and then into electrical energy via a generator.

The total efficiency of a typical wind turbine (WT) is currently almost 50% at the design point. The wind turbine is designed for the most uniform possible energy supply, which does not focus on the maximum output but on the optimal energy yield. This also means that the system has to adapt to the changing wind conditions. In the case of modern wind turbines and wind farms, integration into the grid is at the center of technical development. Today, the wind farm must make a contribution to a stable and secure power supply in terms of security of supply.

5.1.1 Technical development: Increased performance in wind turbines

In the last few decades the technical development and with it the growth in size of the wind turbines have developed rapidly. The onshore wind turbines installed in Germany in recent years have an average rotor diameter of around 120 m, an average nominal output of 3 MW to 3.5 MW and a hub height of 100 m to 160 m with a nominal output of 5 MW and a diameter of around 160 m. This means that the nominal output has doubled in the past ten years.



	1980	1985	1990	1995	2000	2005	2015	2020
Max. Nennleistung (kW)	30	80	250	600	1.500	3.000	7.000	12.000
Max. Rotordurchmesser (m)	15	20	30	46	70	90	130	220
Überstrichene Rotorfläche (m²)	177	314	707	1.662	3.848	6.362	13.273	38.000
Max. Nabenhöhe (m)	30	40	50	78	100	105	150	150
Max. Jahresenergieertrag (MWh/a)	35	95	400	1.250	3.500	6.900	15.000	67.000

Werte für Anlagen onshore und offshore

Figure 5.1: Increase in performance in wind turbines

5.2 Energy conversion

Wind energy is the kinetic energy of moving air (from the Greek kinesis = movement). When converting into electrical energy by a wind turbine, the energy of the wind must first be converted into mechanical rotational energy via the rotor blades, which then supplies electrical power via a generator. The conversion of the kinetic energy of the wind into electrical energy is subject, like all energy conversions, to energetic "losses". Physically speaking, no more than 59% of the power can be extracted from the wind (see Betz and power extraction). In addition, there are aerodynamic losses due to friction and turbulence on the rotor blade. Around ten percent more losses are caused by friction in the bearings and the gearbox as well as in the generator itself, in the converters and the cables as electrical losses.

5.2.1 Kinetic energy

Every moving mass m (body, liquid or gas) contains kinetic energy Ekin. It is equal to half the mass of the body times the square of the speed v. For wind turbines, the moving mass is the air that flows through the rotor surface of the wind turbine.

$$E_{kin} = \frac{1}{2}mv^2 \tag{5.1}$$

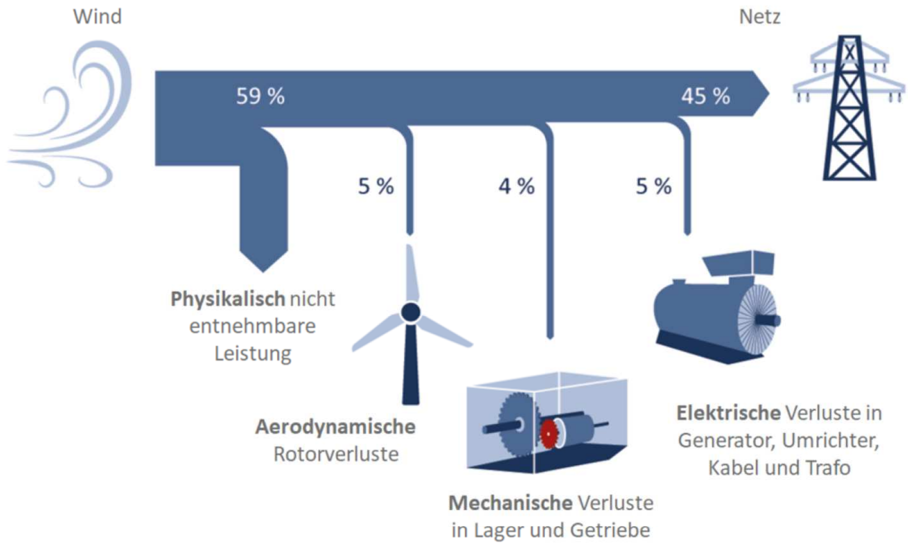


Figure 5.2: Energy flow diagram

5.2.2 Energy and performance

The air throughput, also called mass flow ?, which flows through the area of a wind energy rotor covered by the rotor blades (so-called rotor plane) in a certain time can be calculated by multiplying the rotor area, air density and wind speed:

$$\dot{m} = A\rho v \tag{5.2}$$

The power P is equal to the energy E per unit of time. This results in the power of the wind:

$$P_{wind} = \dot{E}_{kin} = \frac{1}{2}mv^2 \tag{5.3}$$

Since the air throughput is proportional and the energy of the wind depends on the square of the wind speed, the power of the wind depends on the third power of the speed.

$$P_{wind} = \frac{1}{2}\rho\pi R^2 v^3 \tag{5.4}$$

Thus the decisive factor for the performance of the wind is its speed. If the wind speed increases threefold, the power is $3x3x3 = 27$ times greater. The density of the air has a linear influence on the performance. Cold air is denser than warm air, so a wind turbine delivers approx. 11% more power at the same wind speed, e.g. at $-10°C$ than at $+20°C$. Since the density of the air also depends on the ambient pressure, high and low pressure areas as well as the altitude of the location have an influence on the performance and yield of a wind turbine.

5.2.3 Mechanical performance

The mechanical power P_{mech} on the rotating shaft of the rotor is determined by the product of torque M and rotor angular speed ω or speed n:

$$P_{mech} = M\omega = M\frac{2\pi}{60}n \tag{5.5}$$

5.2.4 Electrical power

The driven generator converts the mechanical power into electrical power, which is determined by the product of current I and voltage U. The law of induction applies here, which describes the coupling of electrical and magnetic quantities. In the generator, the induced voltage acts on an electrical conductor moving in a magnetic field. In the case of a motor, this results in the force acting on a current-carrying conductor in the rotating magnetic field.

5.3 Wind turbines with a vertical axis of rotation

Today most commercially used wind turbines rotate around a horizontal axis. However, there are other types in which a wind turbine also rotates around a vertical axis. In principle, vertical axes can be divided into drag and lift runners.

5.3.1 Vertical resistance runners

The oldest known wind turbines in the world are vertical wind turbines built since 1700 BC. They originated in the areas of what is now Iran and Afghanistan. Ruins of ancient Persian windmills can still be seen today.

These resistance runners work through a half-shaded rotor. A wall protects one half of the wind rotor. The wind blows through the other open half and thus drives the rotor.

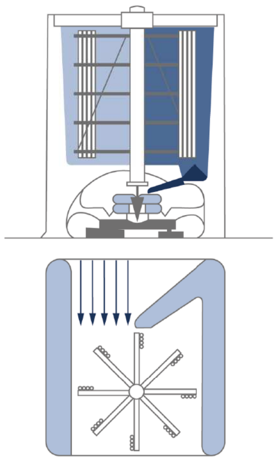


Figure 5.3: Persian windmill

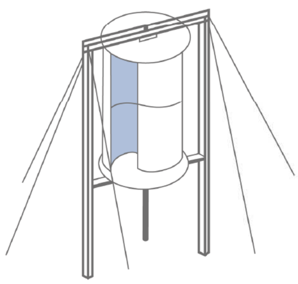


Figure 5.4: Savonius rotor

5.3.2 The Savonius rotor

The Savonius rotor is the best known rotor with a vertical axis because of its simple construction. It has a very low performance coefficient of 0.15. This means that it can draw a maximum of 15 percent of the kinetic energy of the wind.

It is only used for specific applications (low power with high torque, start-up at low wind speed, etc.). These applications are, for example, small pump systems, rotating advertisements, fans on delivery vans or toys.

5.3.3 The cup cross anemometer

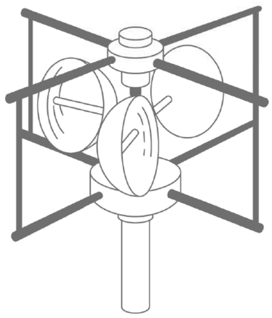


Figure 5.5: Cup cross anemometer

The cup cross anemometer is not used for energy generation because it has a very low power coefficient of cP.max ? 0.08. It is mainly used to measure wind speeds.

Since a closed hemisphere has a lower drag coefficient cW than an open hemisphere, the cup anemometer rotates. However, it can only record the horizontal component of the wind and works independently of the wind direction.

5.3.4 Vertical lift runners

The Darrieus rotor

A modern rotor with a vertical axis that works on the principle of lift is the Darrieus rotor. This was invented in 1925 by the French George Darrieus (born September 24, 1888 in Toulon, France; July 15, 1979) and patented in the USA in 1931.

A Darrieus rotor consists of several (usually two to four) vertical blades that are curved on an arc and are attached to a vertical axis of rotation.

Figure 5.6: Darrieus rotor

Depending on the angular position, these experience a variable flow and buoyancy force during rotation, so that there is no uniform torque. The maximum power coefficient is slightly lower than that of lift runners with a horizontal axis. Darrieus rotors may not start up or start up very poorly by themselves. When starting, the generator could work as a motor and bring the rotor up to speed or there is another aerodynamic start-up aid.

H-Darrieus rotor

Figure 5.7: H-Darrieus rotor

This variant of the Darrieus has straight rotor blades that are attached to the vertical shaft via a bracket. In small wind turbines with low power (¡10 kW), Darrieus rotors with straight rotor blades are very common because they are easy and inexpensive to build.

5.4 Wind turbines with a horizontal axis

Wind turbines with a horizontal axis of rotation are distinguished in the position of the rotor to the tower in leeward and windward rotors:

- With the leeward rotor, the rotor runs in the wind direction behind the tower.
- With windward winds the rotor runs in the direction of the wind in front of the tower.

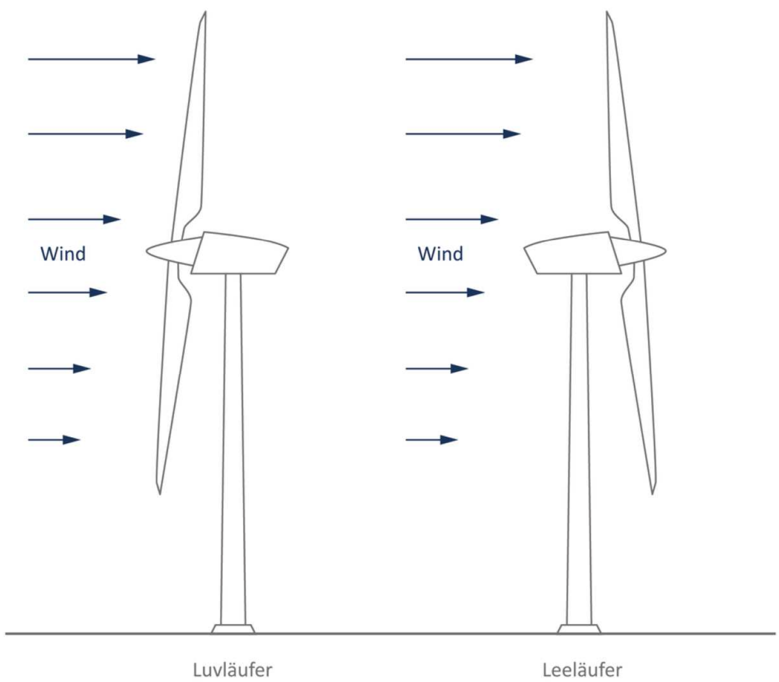


Figure 5.8: Windward and leeward runners

The advantage of the leeward runners is the possibility of passive wind direction tracking. This means the alignment of the wind energy installation according to the wind direction, which is ideal when the flow onto the rotor plane is perpendicular. In the case of historical windmills, the wind was initially tracked by hand by the windmill. Wind direction tracking has been automatic since the middle of the 18th century. A distinction is made between passive systems, which generate the drive force for tracking the wind direction from the wind, and active systems with external electrical or hydraulic auxiliary energy.

With leeward runners, the wind automatically puts the wind turbine in the correct position. It is therefore a passive wind direction tracking system. This saves the costs and weight of a wind direction tracking system. However, the problem with wind energy plants without active wind direction tracking is the twisting out of the cables if the plant tracks too often in one direction of rotation.

Larger systems such as the GroWiAn (1983) with active wind tracking were also built as leeward runners. Another disadvantage of a leeward runner is the problem of the tower shadow. Because of the periodic movement of the rotor blade due to the turbulent flow in the tower wake (or "tower shadow"), there are greater noise emissions as well as fluctuations in performance and additional loads for the rotor blades. The tower shadow is particularly problematic for large systems.

With the increasing size of wind turbines, almost all wind turbines have been constructed as windward winders since the 1990s. Since then, leewards have only been used in small wind turbines.

5.4.1 Market distribution of leeward and windward runners

In small wind turbines, because of the much lower inertia forces and because of the cost savings for wind direction tracking, passive leewards can also be found. The wind turbine concept has established itself in wind turbines over 10 kW.

Year until	leeward	windward
1988	7%	93%
1989	18%	82%
1990	8%	92%
1991	5%	95%
1992	4%	96%
1993	2%	98%
1994	1%	99%
after 1995	0%	100%

5.5 Resistance and buoyancy runners

5.5.1 Resistance runner

A resistance runner takes power from the wind according to the resistance principle and converts it into mechanical power. An area A is opposed to the wind. This reduces the wind flow, creating a force that pushes the surface in the direction of the wind.

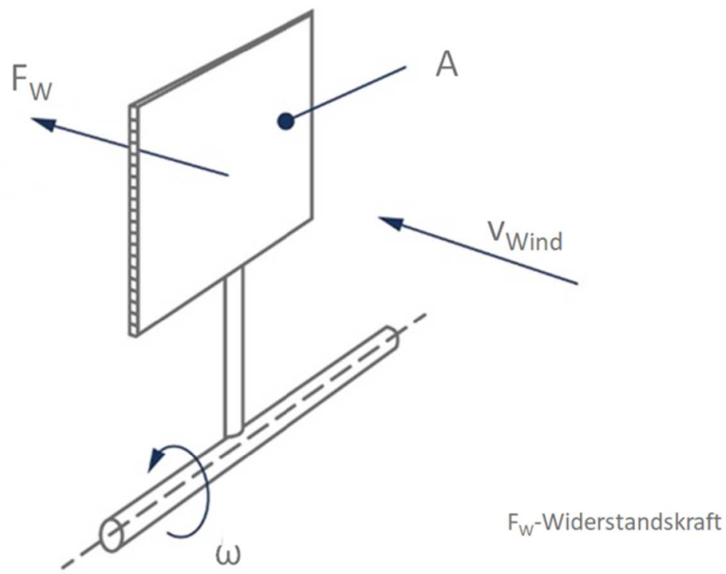


Figure 5.9: Air resistance as a driving force

The drag force F_W is proportional to the square of the wind speed v, the area A, the drag coefficient c_W of the body and the air density ρ in kg/m^3.

The drag coefficient c_W (W for drag) is a measure to characterize the air resistance of the body and is often determined in a wind tunnel.

$$P_{wind} = c_W \frac{1}{2} \rho A v^2 \tag{5.6}$$

The lower the drag coefficient, the lower the air resistance. For example, c_W assumes a value of 1.11 for a circular plate across the wind, 1.10 for a square plate, and 0.45 for a sphere.

Resistance runners have a maximum speed of 1. This means that the blade can only move as fast as the wind. As a result, a resistance rotor also has a low coefficient of performance ($c_{P.W}$, max = 19%) and is therefore not used for commercial electricity generation.

Typical representatives of resistance runners are old Persian windmills, as well as a cup cross anemometer, which is used to measure wind speeds.

5.5.2 Buoyancy runner

In modern wind turbines, the rotor blades are moved by the principle of aerodynamic lift. When the wind hits a rotor blade, air is carried along above and below the blade. The flow is diverted downwards. This creates a negative pressure (suction side) above the sheet and an overpressure (pressure side) below the sheet. This pressure difference generates a lift force F_A which, by definition, is always perpendicular to the flow and which drives the rotor blade and thus sets the rotor in rotation.

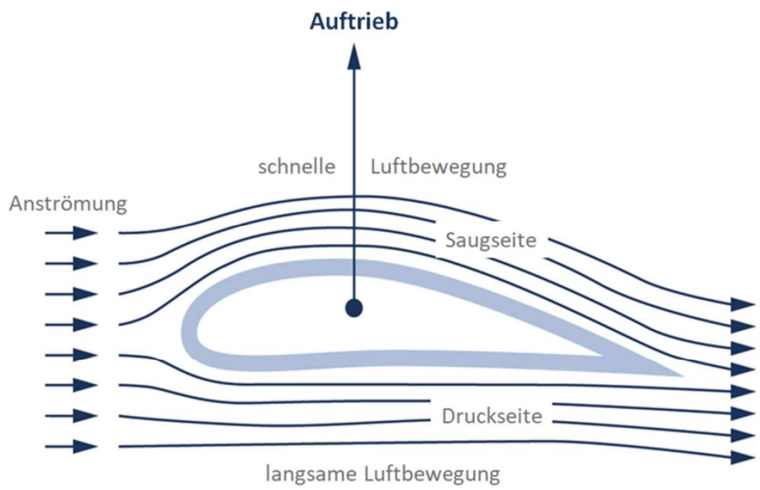


Figure 5.10: Buoyancy principle

Lift runners can have horizontal or vertical axes. The maximum performance coefficient c_p for buoyancy runners is theoretically 59% (see Betz theory) and is therefore much higher than for drag runners. Real wind turbines achieve a $c_{p,max}$ value of 45% to 52%.

The lift force increases with the square of the wind speed v, with the wingarea A, the air density ρ and the lift coefficient c_A. The following applies to the buoyancy force F_A:

$$P_{wind} = c_A \frac{1}{2} \rho A v^2 \quad (5.7)$$

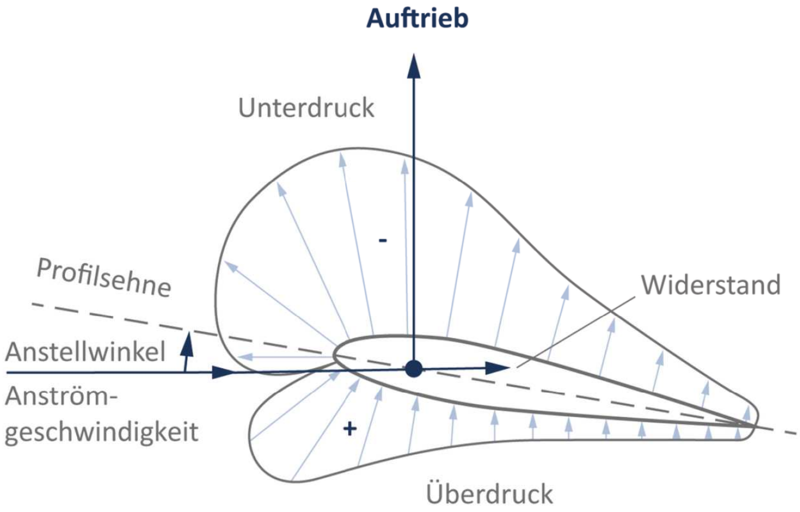


Figure 5.11: Air pressure on a blade

The area A is the size of the wing and is equal to the width or profile length times the profile depth of the blade (distance between the leading edge and the trailing edge). The lift coefficient c_A depends on the pitch α_A. By adjusting the pitch, the lift force can be controlled and the rotor power can be regulated (see power control).

The drag force F_W caused by friction on the surface also occurs in buoyancy runners, but remains very small at a low pitch (20 to 100 times lower than the lift force). It is always oriented in the direction of flow. From an pitch of around 20 degrees, the resistance begins to increase significantly.

5.5.3 Glide ratio

The glide ratio ϵ is the ratio between the lift coefficient c_A and the drag coefficient c_W and determines the quality of the blade.

$$\epsilon = \frac{c_A}{c_W} \tag{5.8}$$

The glide ratio depends on the blade profile and the pitch. The greater the glide ratio, the lower the drag losses, the faster the blade and the better the efficiency. Good profiles for wind turbines achieve a glide ratio of 60 and more.

5.6 Betz theory and power withdrawal

A wind turbine cannot completely convert the kinetic energy of the wind into mechanical rotational energy. In 1920, the German physicist Albert Betz (1885-1968) calculated the optimally achievable power conversion for an idealized wind turbine.

In doing so, he made the following simple consideration: The power is drawn off by reducing the flow velocity. If the wind is not delayed at all, no power can be drawn from it. However, if it is delayed too much, the throughput $\dot{m}$ becomes low. In the extreme case ($\dot{m} = 0$) this leads to a "clogging of the flow".

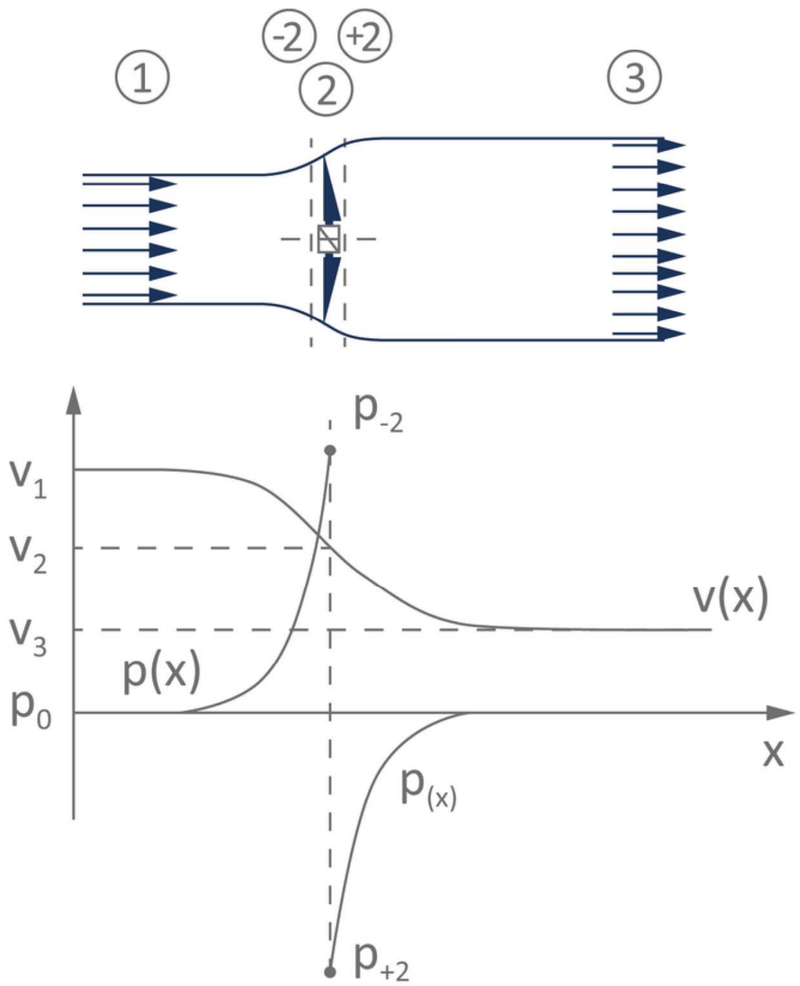


Figure 5.12: Expansion of the flow conduit

Betz came to the conclusion that if the wind speed after the rotor plane is only 1/3 of the speed in front of the rotor plane, optimal power extraction is possible. With this ratio, the aerodynamic efficiency, the power coefficient $c_P = \frac{16}{27} \approx 0.59$. This means that a maximum of 59% of the power available in the wind can be extracted by an ideal wind turbine. However, this performance coefficient only applies to lift runners.

Resistance runners also draw power from the wind. With them, the maximum performance coefficient is a significantly lower value of $c_P = 0.19$.

This results in the maximum power that can be drawn from the wind:

$$P_{wind} = \frac{1}{2}\rho\pi R^2 v^3 \cdot \frac{16}{27} \tag{5.9}$$

The question now is how a rotor blade has to be built in order to extract this power. For each ring section dr, Betz determined the optimal blade depth $t(r)$ as a function of the number of blades z, the speed ratio λ, the lift coefficient c_A of the selected profile and the radius R of the rotor.

The optimal rotor blade depth t results as a function of the radius r:

$$t(r) = \frac{1}{z}\frac{1}{c_A}\frac{8}{9}\frac{2\pi R}{\lambda\sqrt{(\frac{r}{R})^2\lambda^2 + \frac{4}{9}}} \tag{5.10}$$

According to this formula there is theoretically an optimal sum of all blade depths of the rotor blades. Several blades consequently mean a division of the depth over z blades.

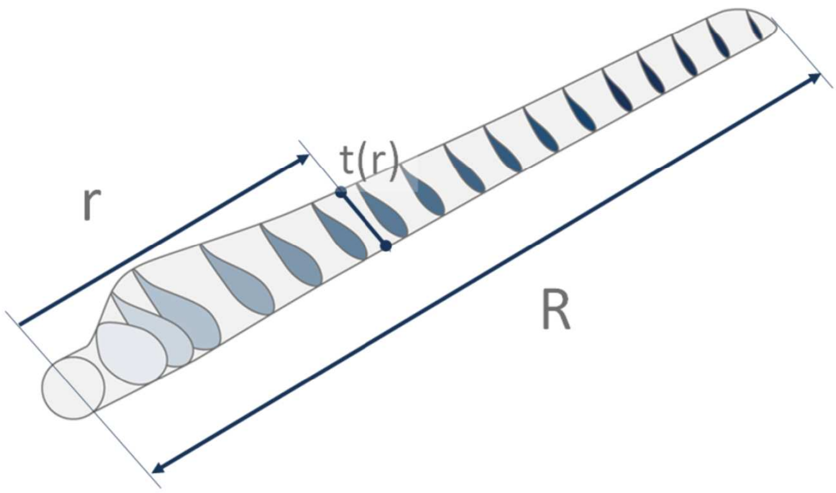


Figure 5.13: Profile depth

Betz assumed that the air flow would maintain a purely axial direction even after the wind turbine. In reality, however, this is not the case, as the flow behind the wind turbine is always subject to swirl, so there is a rotary movement of the air column flowing out.

Schmitz took these losses into account in his calculations. The swirl losses depend on the high speed number. They are very high for slow runners, but remain low for fast runners. Therefore, Betz's considerations for modern wind turbines, which are fast-moving, largely agree very well.

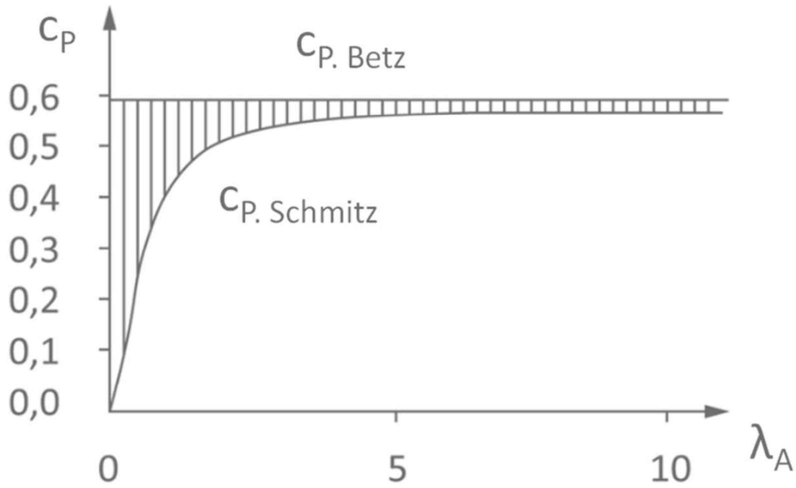


Figure 5.14: Performance coefficient c_P as a function of the speed ratio λ according to Betz and Schmitz

Both theories, Betz and Schmitz, do not take into account the blade tip losses (tip losses) at the tips of the wings. These must also be taken into account when dimensioning a system.

5.7 Aerodynamics of wind turbines

5.7.1 Aerodynamics on the rotor blade

The maximum achievable lift force of a rotor blade and consequently the optimal performance of the wind energy installation depends on the flow velocity c of the air on the rotor blade, more precisely on the rotor blade profile. This approach velocity c is not to be confused with the wind velocity v_1. It results from the vectorial relationship between the wind speed in the rotor plane v_2 (which is $\frac{2}{3}$ of the undisturbed wind speed v_1) (see Betz theory) and the circumferential speed u, which is caused by the rotation of the rotor blade.

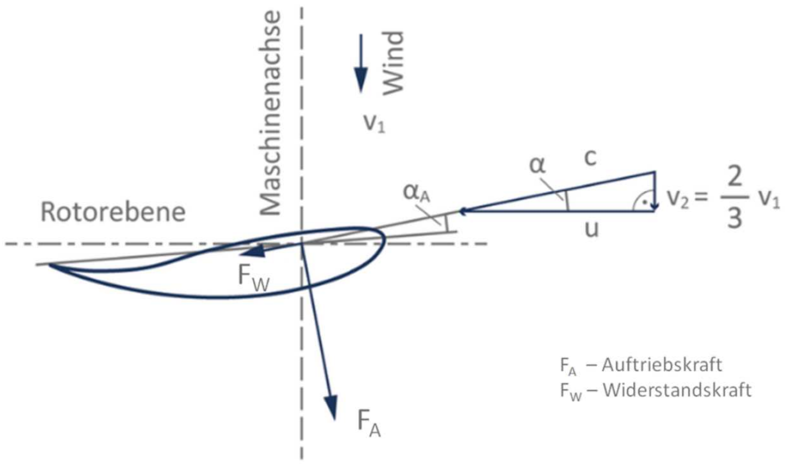


Figure 5.15: Wind triangle on the profile

The circumferential speed u increases linearly with the distance to the rotor hub, so the flow velocity on the blade also increases linearly from the inside to the outside. In order to do justice to the different approach velocities, a suitable profile and optimal installation position is found for each section of the rotor blade dr (also called blade element). In the rotor plane, this results in an annular section with the width dr.

A high glide ratio plays an important role, especially in the area of the blade tip. In the interior of the rotor blade, the flow velocity c is significantly lower. This requires thicker profiles here. This also meets the strength requirements, since the greatest loads occur at the leaf root. This means that the profile is getting slimmer towards the blade tip.

5.7.2 Tip Speed Ratio

An important parameter for the aerodynamic design of the rotor blades is the tip speed ratio λ. It indicates the ratio of the blade tip speed (peripheral speed $u = \omega \cdot R$) to the undisturbed wind speed v_1.

Since the inflow speed also increases with the high-speed number λ, the rotor blade profiles are different for high-speed and low-speed runners. Westernmills for pumping water, which are slow runners with $\lambda_A = 1$, use curved plates as rotor blades. For electricity-generating wind turbines that have a high speed ratio ($\lambda_A = 5 to 9$), high lift profiles are used (λ_A: high speed

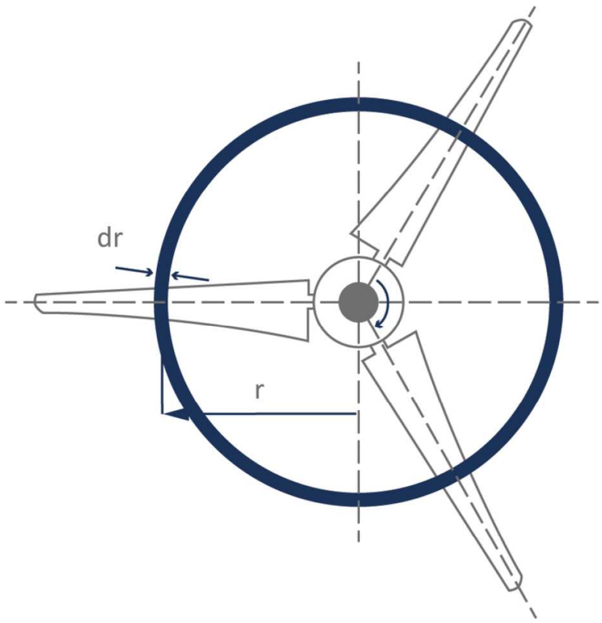


Figure 5.16: Ring cross section of the rotor surface

number in the design point).

$$\lambda = \frac{u}{v_1} = \frac{\omega R}{v_1} = \frac{\frac{2\pi}{60} n R}{v_1} \tag{5.11}$$

5.7.3 Determination of the torsion of the rotor blade

With the distance to the rotor axis, not only does the value vary, but also the direction of the flow c and thus also the lift force, which always acts perpendicular to the flow direction. In order to achieve the same angle of inflow (angle between inflow and chord) at each point along the rotor blade on each blade element, the rotor blade must be twisted.

Aerodynamic losses occur on the rotor blade through friction on the profile surface as so-called profile losses and through the pressure equalization at the blade tip, the tip losses. The rotation induced in the outflowing column of air, the wake twist (twist losses), result in further aerodynamic losses. While the theoretical maximum rotor efficiency is around 59% power (see Betz), real wind energy rotors achieve an efficiency of around 50%.

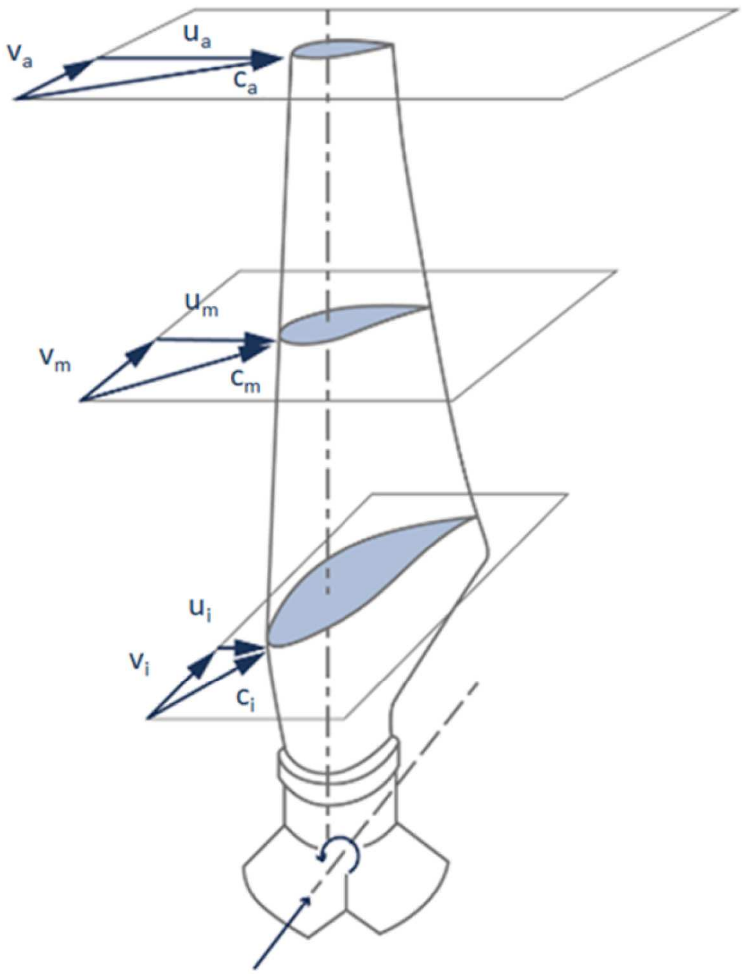


Figure 5.17: Twisting of a rotor blade

5.8 Power limitation and regulation

A wind turbine rotates on the rotor blades due to the lift force of the wind. The wind power increases with the third power of the wind speed (see energy conversion). Usually, from a wind speed of around $9[m/s]$ to $12[m/s]$, the rotor power resulting from the lift force is limited by aerodynamic measures in order not to exceed the specified nominal power, as otherwise overloading and material damage could occur. A distinction must be made here between pure safety measures to limit the power: in the case of small wind turbines, for example, braking through generator short-circuit and the power control of large wind turbines, which ensure a constant power output up to the shutdown of the system in a storm (approx. $25[m/s]$).

In the case of wind turbines feeding into the grid, the power limitation or power control on the rotor is implemented using the main concepts of stall and pitch.

5.8.1 Power limitation due to stall

The stall control is the simplest and the oldest control system and was developed in the 1950s by Johannes Juul (1887-1969) in Denmark (prototype: Gedser system 1957).

The most important prerequisite for a stall-regulated wind energy installation is the operation of the rotor at a constant speed, that is to say at a constant peripheral speed. This is implemented with the help of an asynchronous generator that is permanently coupled to the mains frequency and thus runs at a fixed speed.

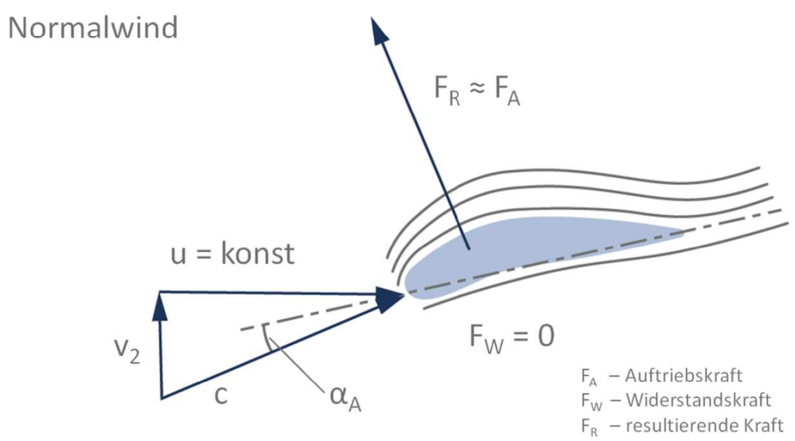


Figure 5.18: Stall during normal wind speed

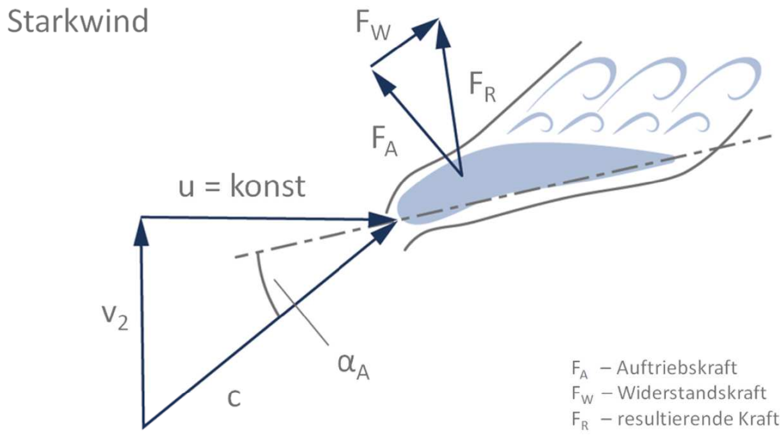


Figure 5.19: Stall during strong wind speed

As can be seen in the picture above, the pitch angle α_A depends on the wind speed v. At high wind speeds, the pitch angle becomes so large that the air flow can no longer follow the profile geometry on the suction side (top of the profile). There is a stall. This leads to a poorer performance coefficient of the rotor blade and less kinetic energy is converted into mechanical rotational energy. The system is operated in the range of the nominal output.

This principle of power limitation has a certain inertia so that the point in time or the situation at the profile section of flow interruptions cannot be precisely specified. Short-term gusts therefore lead to power peaks. But since the speed is constant, these power fluctuations are converted into a higher torque in the drive train.

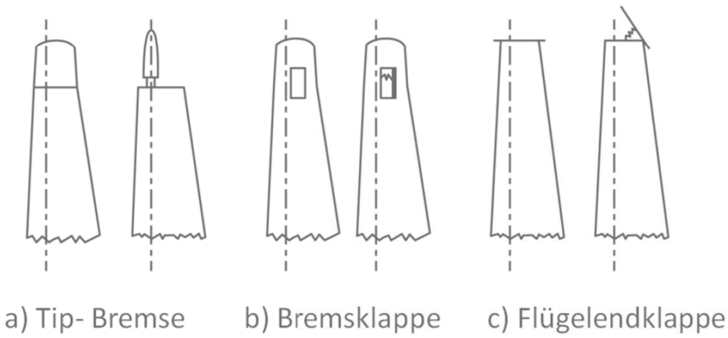


Figure 5.20: Types of brake flaps: a) rotatable blade tip, b) flap in the wing, c) hinged end plate

In order to reduce these fluctuations in output, the stall effect is actively generated in some systems with higher nominal outputs (PNom¿ 1 MW) by adjusting the angle of the rotor blade. By turning the rotor blade around the longitudinal axis, a larger angle of attack is set.However, this active stall control could not prevail because, like a pitch system, an adjustment system for the blades has to be installed and there is still higher loads in the drive train of the wind turbine.

In order to protect the rotor of the stall-regulated wind energy installation against overspeed even in the event of a load shedding, centrifugally actuated adjustable blade tips, so-called tip brakes, are used.

5.8.2 Power limitation by turning the rotor blades (pitch)

In pitch-regulated wind turbines, the power is regulated by rotating the rotor blades. Here, the leading edge of the rotor blade is turned into the flow c (so-called vane position). The lower pitch angle α_A leads to lower lift forces and thus to lower performance.

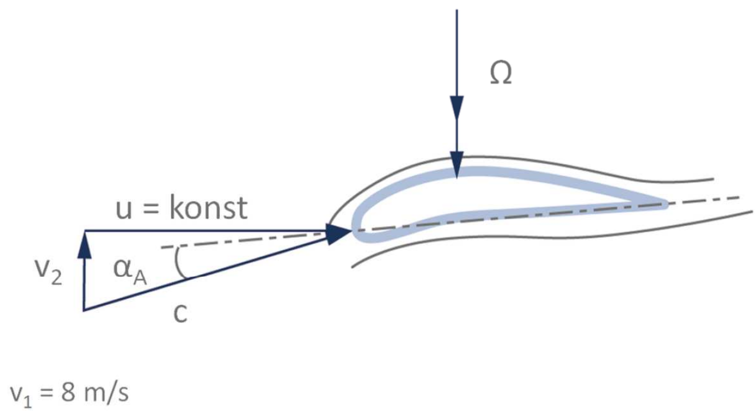


Figure 5.21: Pitch control in normal wind

With this principle, the output is adjusted to the wind speed by twisting the blades (regulating the pitch angle). The working position for the best power take-off is, by definition, the pitch angle = 0°. Adjustment leads to a reduction in the power output:

- When the wind is very weak (less than 2.5 m / s), the wind turbine does not produce any electricity: the wind is too weak to drive the rotor shaft. The blades are rotated in the so-called flag position (pitch angle = 90°). The wind turbine stands still or rotates very slowly, which is called spin mode.

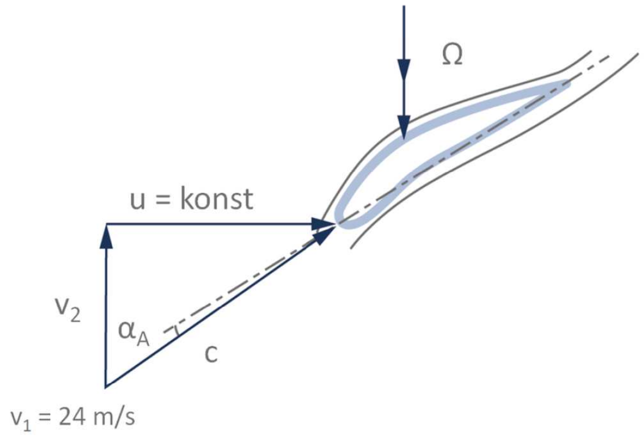


Figure 5.22: Pitch control in strong winds

- With normal wind (2.5$[m/s]$ to 12$[m/s]$) the wind turbine rotates and produces power, but the wind is still too weak to achieve the nominal output of the system. The pitch angle is 0°, the rotor blades are in the optimal working point. As much of the wind power as possible is converted into mechanical energy. As the wind speed increases, so does the speed (speed-variable operation) in order to keep the high-speed speed constant and thus the degree of efficiency optimal.

- In strong winds (12$[m/s]$ to 25$[m/s]$) the offered wind power is too great and the system has to be limited in its power output. The system is then "pitched". The pitch angle increases with the wind speed (from 0° to approx. 30°) and the lift force is influenced in such a way that the power output of the wind turbine remains constant at nominal power.

- In a storm (from 25$[m/s]$) the wind is so strong that the wind turbine has to be switched off in order to avoid possible damage. The pitch angle is almost 90°; the blades are in the flag position.

The blades are twisted using the pitch system. Since it is designed as a separate and independent system for each rotor blade, they can be viewed as three primary brakes. To safely shut down the system from all states, it is sufficient to adjust just one rotor blade, which is brought into the flag position (position in the direction of the wind).

5.8.3 Other power regulations for small wind turbines

Another option that is used in small wind turbines ($P_{nom} < 10kW$) is to turn the nacelle out of the wind. This is mostly done by the thrust on a side vane (transverse vane) or on the rotor itself.

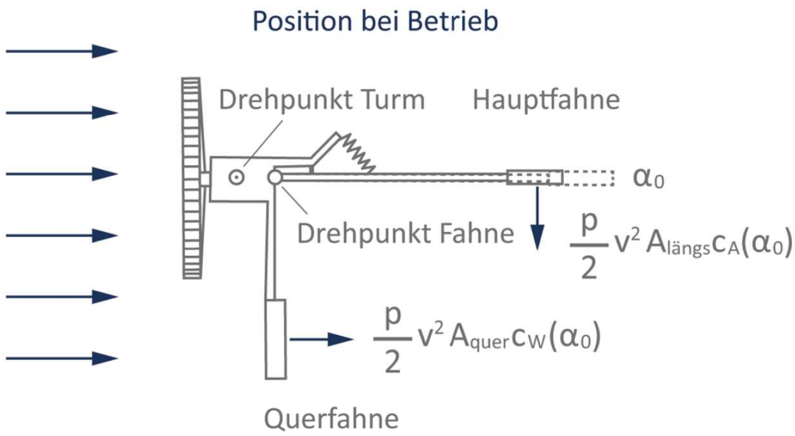


Figure 5.23: Two-flag rule of a Westernmill. Normal operation

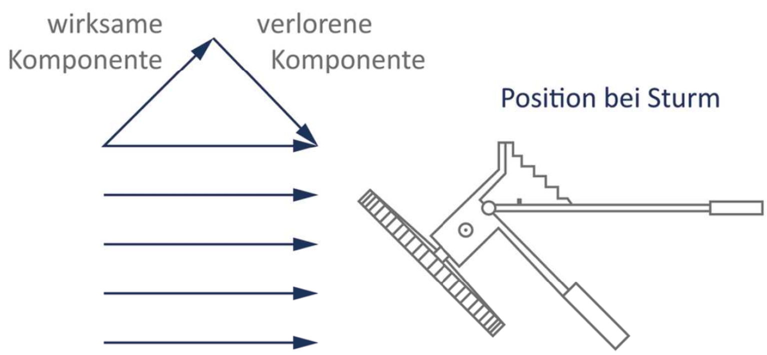


Figure 5.24: Two-flag rule of a Westernmill. In strong winds

5.9 Wind tracking

All wind turbines with a horizontal axis must always be aligned according to the wind direction in order to be able to use the wind energy optimally through a vertical flow onto the rotor plane. A basic distinction is made between passive systems, which generate the drive force for tracking the wind direction from the wind, and active systems with external electrical or hydraulic auxiliary energy.

5.9.1 Passive systems - wind vane, wing rosettes

In the case of historical windmills, the wind was initially tracked by hand by the windmill. The first automatic wind direction tracking system was developed in the middle of the 18th century and made the miller's work a lot easier. From now on, the mills were equipped with so-called wing rosettes. These were installed in such a way that the nacelle aligned with the wind without external energy. A gear with a very high reduction ratio (up to $1:4000$) connects the nacelle and the wing rosette. Wing rosettes or wind roses were also used in small electricity-generating wind turbines.

Another passive way of aligning the systems with the wind is wind tracking through independent tracking of leeward runners and wind vanes for windward runners. These are only used in very small wind turbines (up to around 10 meters rotor diameter and / or $12kW$ rated power).

For small wind turbines, the wind vane is the usual form of passive wind tracking. This is mounted in the direction of the machine axis behind the system and turns the system in the (approximate) direction when the wind direction changes.

5.9.2 Active systems

Azimuth motors

All modern wind turbines are automatically tracked by active systems with azimuth drives. The wind direction tracking is guaranteed by hydraulic motors or electric motors. The wind direction is determined by sensors (wind vane or similar) and transmitted to the actuators by a controller.

The nacelle is aligned with the wind by up to eight gear motors. Switch-on times, duration and direction of rotation of the motor are controlled by a wind direction sensor with the appropriate software. In addition, brakes are mounted on the tower rim, which are only released when the wind direction

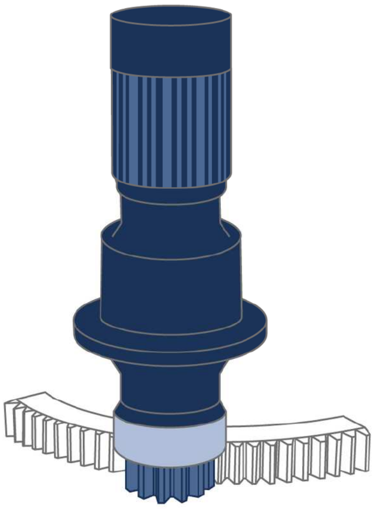


Figure 5.25: Yaw drive - Bosch-Rexroth

changes. Without these brakes, the gears would wear out heavily in the event of wind fluctuations and gusts.

5.9.3 Loading and twisting of the cables

In some cases it can happen that the nacelle rotates several times in the same direction. In order not to twist the power cables inside the wind turbine too much, the nacelle should not turn more than 2 to 3 times in the same direction. The system control therefore controls the position of the nacelle and, if necessary, ensures that the nacelle rotates in the opposite direction in order to untwist the cable. This is often done when the wind is weak and there is no wind. Every now and then you can see a carousel ride.

5.10 Machine house and drive train

5.10.1 Nacelle

The machine house, also known as the nacelle, consists primarily of the tower ring as a connection to the tower and the machine carrier. The drive train is mounted on this in the classic design. Furthermore, all other sub-systems such as the control, hydraulics and cooling are also housed in the nacelle. The housing usually consists of GRP or aluminum.

Drive train

The power-transmitting rotating components from the rotor to the generator are referred to as the drive train of the wind turbine. The rotor, usually consisting of three rotor blades and the hub, converts the aerodynamic power into mechanical power from the rotating rotor shaft (see energy conversion). On the one hand, this must be stored and, on the other hand, it transmits the rotary movement to the gearbox or, in the case of gearless systems, directly to the generator. Further components are clutches and brakes, as well as the generator itself, which transforms the mechanical power into electrical power.

The entire drive train is protected against environmental influences in the nacelle. A distinction is made primarily between drive trains with and without gearbox, according to the bearing and the arrangement of the main components.

Dissolved design

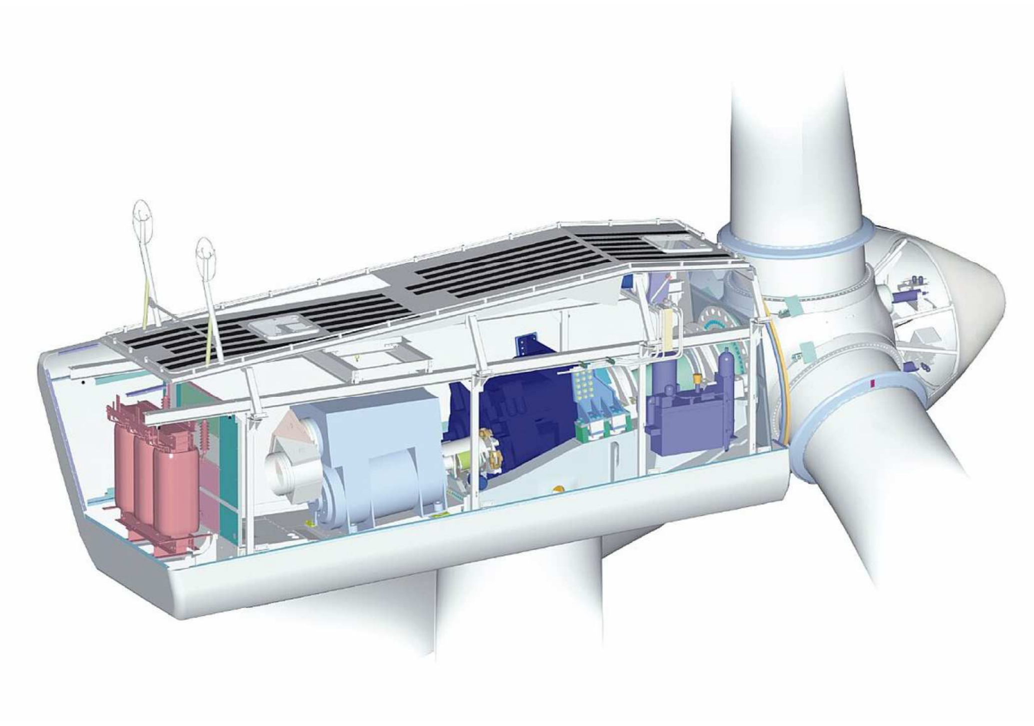


Figure 5.26: Separate design with double fed induction generator and rotor side converter

Separate designs have a separate bearing with two bearings (fixed and loose bearings) and a freely accessible gear that is integrated on the slow shaft as well as on the fast shaft with a coupling each.

Partly integrated design

Figure 5.27: Partly integrated design

A partially integrated design is used when part of the bearing is integrated into the gearbox and supported by the gearbox housing. This is the so-called three-point mounting.

Integrated design

The integrated design dispenses with free shafts, bearings and couplings. All functions are integrated in the gearbox or, in the case of gear-less systems, in the rotor-generator unit.

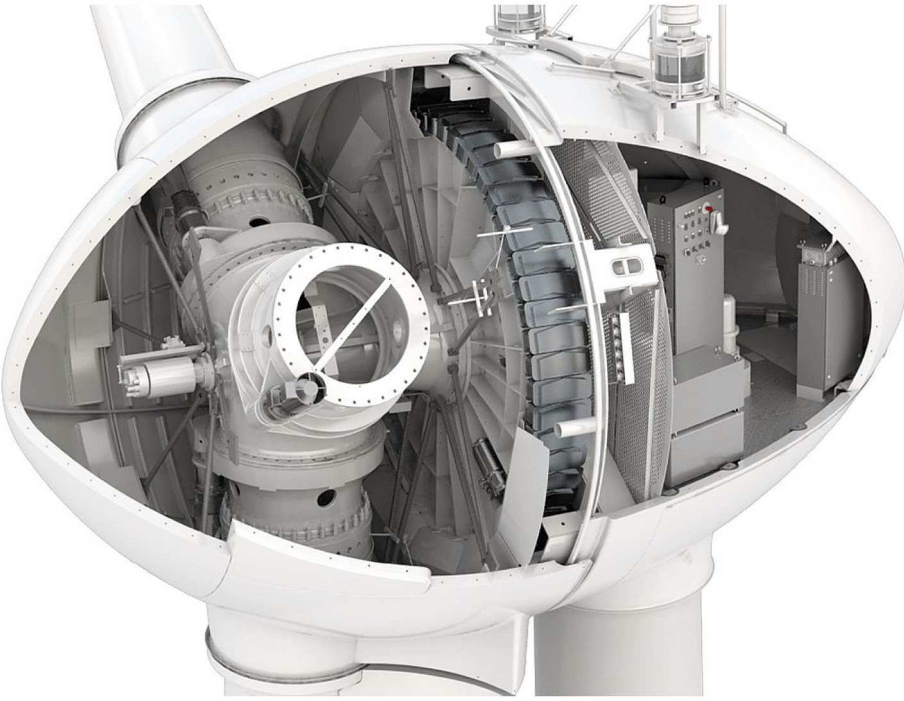


Figure 5.28: Integrated design with permanent magnet synchronous generator

5.10.2 Gearboxes for wind turbines

The vast majority of wind turbine manufacturers use gears that change the speed and torque between the wind rotor and the generator. The rotor shaft rotates slowly with a very high torque and the generator rotates very quickly with a low torque.

The rotor speed of a multi-megawatt wind turbine depends on the high-speed speed and is in the range of six to 20 revolutions per minute. In order to achieve good efficiency and to be able to adapt to the mains frequency (usually $50Hz$ or $60Hz$) and also to reduce the size of the generator, the generator speed must be much higher than that of the rotor shaft. The generator speed is in the range between 900 and 2000 revolutions per minute.

The size of a gear unit is determined by the necessary gear ratio between the rotor and the generator shaft. In order to achieve transmission ratios of this order of magnitude, several gear stages are installed in series. Gear ratios of around 1 : 100 are common for large systems.

The efficiency of the gearbox of a wind turbine is very high (around 98%). Since the power transmitted is enormous in large wind turbines (several megawatts), the losses are also relatively large. The resulting losses are mostly heat losses and the gearbox or the lubricating oil in the gearbox must therefore be cooled. This takes place via an oil-water or oil-air heat exchanger, which dissipates the resulting heat to the outside.

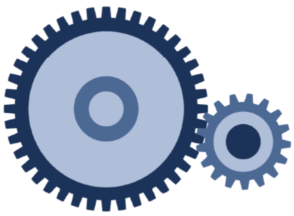


Figure 5.29: Spur gear with maximum 1 : 5 gear ratio

Spur gear

Spur gears are designed from two parallel gears. A large gear is coupled to a slow shaft and drives a small gear at a higher speed. The transmission ratio (speed of the fast shaft by the speed of the slow shaft) remains lower than 1 : 5, i.e. the fast shaft rotates at most five times faster than the slow shaft. In order to increase this transmission ratio, several spur gear stages can be coupled. Pure spur gears are now only cost-efficient for very small wind turbines. They were used in old wind turbines with a nominal output of up to $500kW$.

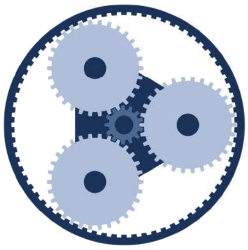


Figure 5.30: Spur gear with high efficiency

Planetary gear

Planetary gears are built with three different types of gears: the slow shaft, which is coupled to the rotor shaft, is called a ring gear (on the outside, dark blue) and has internal teeth. In the middle is the sun gear, which is coupled to the fast shaft of the generator. These two gears are connected by three (or more) planet gears (center, light blue). The planet carrier (also called a bridge) can be fixed or movable.

The efficiency is higher than that of the spur gear ($> 99\%$ per stage). The noise level is lower and the dimensions are significantly smaller. Because of these advantages, all large wind turbines are equipped with at least one planetary stage.

5.10.3 Coupling

In principle, the generator could be flanged directly to the gearbox so that a longer drive shaft of the generator is not required (see integrated concept).

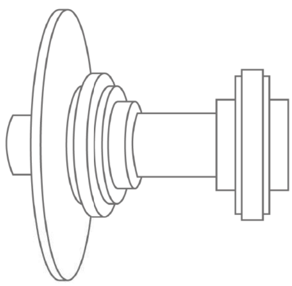


Figure 5.31: Elastic coupling

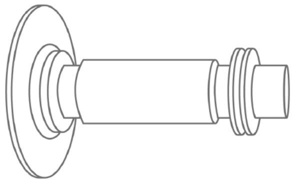


Figure 5.32: Leakage-current isolated coupling

However, the rigid connection from the gearbox to the generator is not without its problems. The drive train chain is always subject to certain deformations. This property makes flexible connecting elements between the components indispensable in order to avoid additional loads in the drive train from lateral forces and bending moments.

The accessibility of the back of the gear unit or the front of the generator must be guaranteed by a certain distance from one another. For these reasons, as a rule, detachable and flexible connection couplings are built into the high-speed shaft. The coupling often has an overload protection device to protect the gearbox and generator.

5.10.4 Brake

The mechanical brake can only be found as a service brake in wind turbines with lower rated outputs. For higher powers, the mechanical brake is only designed as a holding brake. A wind turbine is mainly braked aerodynamically by adjusting the blades. Adjusting a single blade is sufficient to completely brake the wind turbine. In stall systems, this is usually done using rotatable blade tips (tip brakes) and in pitch-controlled systems by rotating the entire rotor blade.

There are also mechanical disc brakes. These are only used to fix the rotor blades, as well as for emergency shutdowns and manual stops during maintenance and repairs. In the case of smaller systems, the brake can be mounted on the slow shaft as well as on the fast shaft (after the gearbox). The advantage of braking on the slow shaft is that the transmission is not stressed during the braking process.

In larger systems (more than $600kW$ rated power) the torque on the slow shaft is too great, so the brake must be installed on the generator side on the fast shaft, which has a lower torque.

Figure 5.33: Disc brake

5.10.5 Generator

The generator is an energy converter and converts the mechanical energy of the rotor into electrical energy.

Types

There are essentially three different types of generator for wind generators:

1. synchronous generator
2. asynchronous generator
3. double-fed asynchronous generator

Generated electricity

Large wind turbines produce three-phase alternating current like any electrical power plant. The voltage depends on the power class of the wind turbine:

- $120V$ to $240V$ for small systems (1.5 to $10kW$)
- $400V$ for medium-sized systems (up to $500kW$), or for gear-less wind energy systems
- $690V$ for large systems (from $600kW$)

This voltage is increased to $20kV$ to $110kV$ using a transformer, depending on the local mains voltage. The transformer can be located in the nacelle, in the tower or in a small building next to the system.

The majority of the systems built are equipped with generators, the frequency of which is variable. This current must then be adapted to the desired frequency with the help of a converter ($50Hz$ in Europe).

Cooling the generator

The efficiency of a generator is between 96% and 98%. Since the transmitted power is very high, the resulting losses (mostly as heat losses) must be dissipated to the outside. This takes place via cooling. Generators of smaller wind turbines (output less than $1MW$) are air-cooled. At higher outputs, the effectiveness of the air cooling reaches its limits and the generator has to be water-cooled. Since the generator is the largest heat generator, the cooler is usually attached directly to the generator.

With high outputs, only gear-less wind turbines can be air-cooled due to the size of the ring generator used.

Classic asynchronous generators dominated the market until the 1990s. These are very cheap, robust and low-maintenance, but can only work in a narrow speed range, which allows little or no adaptation to the wind conditions. They are only optimally designed for one wind speed (typically around $8[m/s]$). In addition, the mechanical components are more heavily loaded due to the fixed speed (see Danish concept). Another feature is that they can be connected directly to the grid (they do not need a converter), but they load the grid with reactive current, which the grid operator is reluctant to see and charges system services for.

Another concept is the use of a synchronous generator. This can work in a wide speed range and adapt to the wind conditions. However, the electricity generated must be adapted to the grid frequency by a converter. Synchronous generators are mainly used in gear-less wind turbines (see concepts with synchronous generators).

In 1996 a new concept came on the market that uses a double-fed asynchronous generator. This can work in a wide speed range. Only part of the electricity generated needs to flow through a converter. This concept is relatively low-loss and is nowadays often used in systems with gearboxes (see concept with double-fed asynchronous generator).