Wind Energy Technology: An Introduction

1. A brief history of the development of wind energy from antiquity until today

Since antiquity, mankind has been using wind energy; it is thus not a new idea. For centuries, windmills and watermills were the only source of motive power for a number of mechanical applications, some of which are even still used today.

Humans have been using wind energy in their daily work for some 4,000 years. Sails revolutionized seafaring, which no longer had to make do with muscle power. In 1700 B.C., King Hammurabi of Babylon used wind powered scoops to irrigate Mesopotamia.

Aside from pumps for irrigation or drainage, windmills were mostly used to ground grain. Thus, we still speak of "windmills" today, even when we are talking about machines that do not actually grind, such as sawmills and hammer mills.

Historical Dutch windmill, © Bundesverband WindEnergie e.V.

American windmill used for water pumping, © Bundesverband WindEnergie e.V.

But the wind turbines that generate electricity today are new and innovative. Their success story began with a few technical innovations, such as the use of synthetics to make rotor blades. Developments in the field of aerodynamics, mechanical/electrical engineering, control technology, and electronics provide the technical basis for wind turbines commonly used today.

Since 1980, wind turbines have been becoming larger and more efficient at rates otherwise only seen in computer technology.

2. The development of modern wind turbines since 1900

The major success story is wind turbines that generate electricity and feed it directly to the grid. They usually have two or three rotor blades, while horizontal axis, a nacelle with a rotor hub, gears, and a generator, all of which can be turned into and out of the wind. The rotor is positioned in front of the tower in the direction the wind is blowing (windward as opposed to leeward).

In 1920 and 1926, Albert Betz calculated the maximum wind turbine performance, now called the "Betz limit", and the optimal geometry of rotor blades.

In 1950, Professor Ulrich Hütter applied modern aerodynamics and modern fiber optics technology to the construction of rotor blades on the wind turbines in his experimental system.

Poul la Cour of Denmark developed a wind turbine that generated direct current. In 1958, one of his pupils named Johannes Juul developed the "**Danish Concept**," which allowed alternating current to be fed to the grid for the first time. This concept very quickly won over. Today, almost half of all wind turbines operate according to this principle.

In the 1980s, the Danes developed small turbines with a nominal output of 20 kW to 100 kW. Thanks to state subsidies, these turbines were set up on farms and on the coast to provide distributed power, with the excess power not consumed locally being fed to the power grid.

In other countries, research focused on large systems, two examples being NASA's research in the US or the German GroWiAn project. Unfortunately, these plans turned out to be too ambitious. After only a few hundred operating hours, tests at the research facilities were discontinued.

3. The physics of wind energy: what is the useful potential of wind energy?

Power is available from the kinetic energy of the mass of air moving in wind. The amount of energy that wind carries increases by a factor of two as its speed increases and is proportional to the mass of air that passes through the plane of the area swept by the rotors. As power is the product of energy (work) within a given time frame, the power of wind increases by a factor of three as the speed of wind increases. Because of the low density of air (P_{air}=1.25 kg / m3), the power density of wind is much lower than that of water power (P_{water}=1000 kg / m3), for instance. The power that can be harvested from wind is calculated in terms of the swept area -- for a horizontal axis wind turbine (HAWT), the area through which the rotor blades pass. As a result, if the diameter of the rotor blades is doubled, the power increases by a factor of four. If the wind speed then doubles, power increases by a factor of eight.

In 1920, Albert Betz demonstrated in his theory of the closed stream tube that a wind turbine can only convert a maximum of 16/27 or 59% of the energy in wind into electricity. This optimum performance cP is attained when a wind turbine's rotors slow the wind down by one third.

Current wind turbines convert up to 50% of energy in wind into electricity, thus coming very close to the theoretical limit.

4. Comparison of resistance and lift

Like some of these simple turbines with small output (up to 2 kW), historic windmills operate according to the *principle of resistance*. Here, a rotor with a vertical axis resists the wind, thus reducing wind speed. The maximum performance of such wind turbines is 12%. The performance of wind turbines based on the *principle of lift* is much greater at around 50% due to the relatively high lift-to-drag ratio.

The power coefficient (performance) of a wind turbine can be improved by optimizing the tip speed ratio (*lambda*), i.e. the ratio of wind velocity to the velocity of the tip of the rotor blade. If the tip speed ratio = 1, the rotor has many blades, generates great torque, and runs at slow speeds. If the tip speed ratio is higher, the rotor has few blades, generates less torque, and runs at higher velocity.

The performance of a rotor is not, however, relative to the number of rotor blades in principle (cf. Betz theory in the next section).

5. The aerodynamics of wind turbines

The power coefficient of a wind turbine's rotor blade is calculated according to the laws of airfoil theory. As with the wing of an airplane, air passing over a rotor blade creates an aerodynamic profile with low pressure above the wing, pulling the wing up, and overpressure below, pushing it up.

The difference in pressures exerts a lift on the wing vertical to the direction in which the wind is blowing and creates resistance in the direction of the wind (incident flow). For a wind turbine's rotor blade rotating around the rotor axis, the incident flow is the result of the geometric addition of wind velocity v and the circumferential speed u, which increases in linear fashion the longer the blade is. In other words, the lift exerted on the rotor blade is not only the result of wind velocity, but mostly out of the blade's own rotation. Speeds at the tip of the blade are thus very great. Current wind turbines have rotor tips travelling at velocities six times faster than the speed of the wind. The tip speed ratio is thus *lambda* = 6. The rotor tip can then be traveling at velocities of 60 m/s to 80 m/s.

The energy that the rotor harvests is equivalent to the lifting force in the swept area minus the resistance force in the swept area. The forces applied in the direction of the axis drive the rotor, which then not only harvests the energy of the wind, but also exerts a load on the tower and the foundation.

The Betz Theory allows us to calculate the optimal geometry of a rotor blade (thickness of blade and blade twisting).

6. Types of wind turbines

Wind turbines are categorized according to a number of criteria:

The position of the axis (**horizontal or vertical**) is obvious. Horizontal axis wind turbines (HAWTs) can be further divided into those with rotors rotating in front of the tower (windward) and those rotating behind the tower (leeward) vis-à-vis the direction of the wind. The tip speed ratio and the number of blades determine the response of the drive, and hence how the wind turbine can be used.

In modern wind turbines that generate electricity, there are different types of nacelles that turn on top of the tower to face the wind. There are turbines with gearboxes and without and nacelles whose components (bearings, gears, generator) are positioned separately or have multiple functions integrated in one component (bedding of rotor shaft in the gearbox).

Poles (generally guyed) are usually only used for small wind turbines (up to 10 kW). Free-standing towers are either steel or concrete tubular towers or pylons.

Modern wind turbines

Modern wind turbines are complex technical systems that combine the theoretical basics of a number of fields:

Aerodynamics, lightweight construction >> rotor blades, dynamics, overall system) Mechanical and plant engineering >> machines with shafts, gearboxes, bearings, brakes, and tower

Electrical engineering >> generator, frequency converter, mains connection, electrical lines

Electronics, instrumentation and controls, and computer science >> system controls, remote monitoring, sensors

Construction engineering >> foundation, access roads

Meteorology >> design, yield

7. Concepts of wind turbines to generate electricity

At present, three concepts for the feed of electricity to the power grid dominate the market. The following table provides an overview of the differences and common ground between these types.

- The "Danish concept"
- The pitch concept with a synchronous generator
- The pitch concept with a doubly fed asynchronous generator

In the Danish concept, which completely dominated the market up to the mid-1990s, the asynchronous generator "naturally" limits power production in strong wind or gusts. It restricts the speed of the system to the frequency of the power grid, so that the rotor cannot turn faster when the wind blows stronger. In this concept, the rotor blades are designed to create turbulence at a certain wind velocity, preventing the lift from accelerating rotation any further even though the blades are not themselves pitched. Johannes Juul developed this concept.

The use of an asynchronous generator also eliminates the synchronization needed for a synchronous generator. In other words, the system is simple and robust.

The pitched concepts developed from 1990 to 2000 turn the rotor blades in and out of the wind along their axis. Depending on the wind velocity, the machines run at various speeds. The blades are turned out of the wind to limit power generation when the wind becomes too strong (above 12 m/s). The blades are only turned into the wind to start the system. Under normal conditions, the turbines are run at a set optimal angle for the best power generation, with the speed of rotation increasing until nominal output is attained. From then on, the pitch of the blades is activated to keep power production constant.

In the pitch concept with a synchronous generator (concept 2), a frequency converter ensures that the fluctuations in electricity caused by the changing speed of the turbine are nonetheless fed to the grid at the frequency of the grid.

In the concepts of a doubly fed asynchronous generator (concept 3), this is not necessary for all of the electricity generated, but rather only for the share coming from the generator's rotor. As this share only makes up around 40% of nominal output, the converter can be smaller.

8. From the drawing board to a working wind turbine

Wind turbines only appear to be simple constructions. There are many steps from the draft to construction before the turbine can begin generating environmentally friendly energy in the field.

Wind is not constant, so wind turbines do not always run at nominal output. The amount of energy generated is below the amount theoretically possible. One speaks of a **capacity factor**, which is the yearly yield in kilowatt-hours divided by the product of the wind turbine's nominal output and the 8,760 hours in a year.. Depending on the location, the capacity factor can range from 30% in coastal areas with great wind to around 18% at inland locations with less wind.

It is true that wind energy is not available at all times. However, the wind energy fed to the power grid does make up part of the base load. The large number of wind turbines already installed in Germany (17,500 as of December 31, 2005) ensures that wind power is always being fed to the grid somewhere. Over large areas, some 10% of the nominal power of all wind turbines can be expected to be fed to the grid as constant output.

Wind farm Sintfeld for electricity production, one of the largest wind farms in Germany, © WWEA e.V.

In other words, conventional central power plants can actually be decommissioned and replaced by renewable energy for good. Intelligence demand management systems and the development of forecast systems for wind conditions will also help reduce the need for conventional power plant capacity.

9. Controlled power: nominal capacity and control

If we speak of a 1.5 megawatt wind turbine, we are describing the generator's maximum output -- its nominal capacity. 1.5 megawatts is equivalent to 1500 kW or 2,039 horsepower. The turbine generates that much power at a specific wind velocity. This nominal wind velocity is generally between 11 and 15 m/s (equivalent to 40-54 km/h).

Wind turbines begin generating power at the cut-on speed of around 2.5-4 m/s and cut off at wind velocity of 25-34 m/s. Modern control technology is used when wind turbines are connected to the grid to ensure a “soft”, gradual transition. If the wind is too strong, output is reduced to ensure that a constant level of power is fed to the grid. Modern turbines also switch off slowly during storms to prevent power output from disappearing suddenly. This gradual transition helps prevent disturbances in transit grids.

Control

To prevent wind turbines from overloading and to ensure that they have constant output, part of the power has to be throttled when the wind velocity exceeds nominal wind velocity. The following two principles are the most commonly used methods of controlling power output:

- **Stall control** (aerodynamic turbulence): if the wind velocity exceeds a certain limit, the rotor blades are designed to cause turbulence at the edge of the blade to limit speed. In active stall control, the pitch of the rotor blades can also be changed.
- **Pitch control**: Electronics and hydraulics are used to infinitely adjust the pitch of each blade. This reduces the lift, so that the rotor continues to generate power at nominal capacity even at high wind speeds.