Turbine Design II

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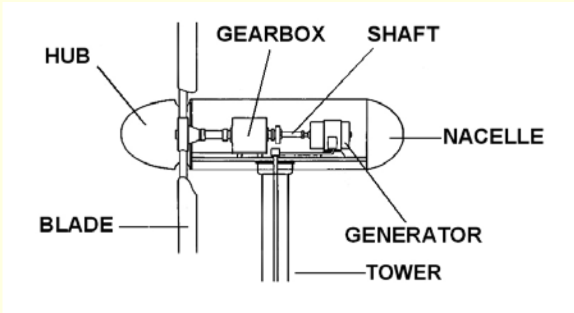
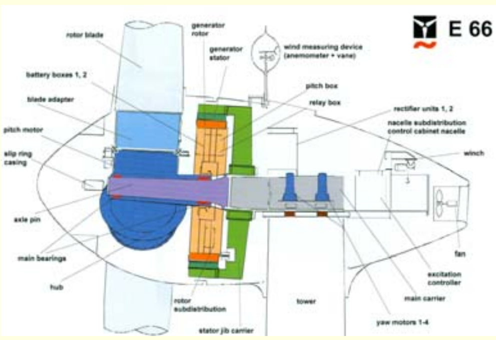
WT Major Components



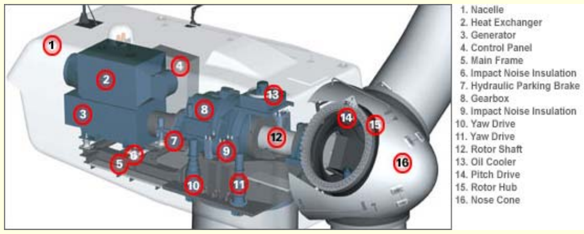
Sterzinger and Svrcek, NREP, 2004

Nacelle: Enercon 1.5MW Turbine



 T. Ackerman (2005), p.16

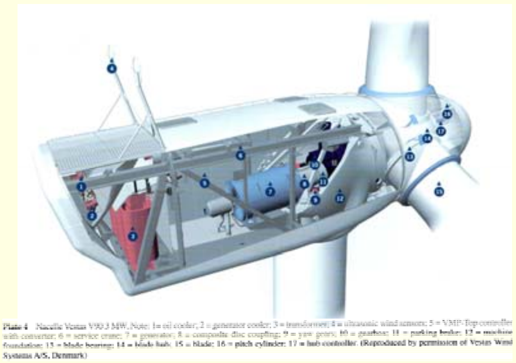
Nacelle: GE 1.5 MW Turbine



GE Turbine Information

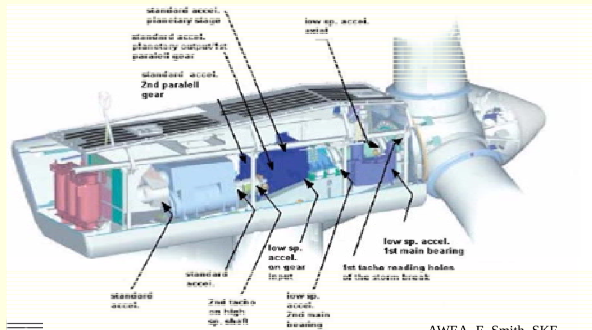
GE 1.5 MW Turbine: http://www.gepower.com/prod_serv/products/wind_turbines/en/15mw/index.htm
GE 2.5 MW Turbine: http://www.gepower.com/prod_serv/products/wind_turbines/en/2xmw/index.htm
GE 3.6 MW Turbine: http://www.gepower.com/prod_serv/products/wind_turbines/en/36mw/index.htm

Nacelle: Vestas 3 MW Turbine



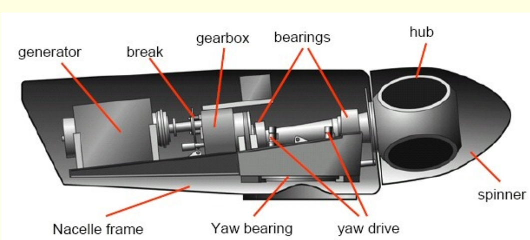
T. Ackerman (2005), p.17

Nacelle Components of Condition Monitoring Systems



AWEA, E. Smith, SKF

Drive Train



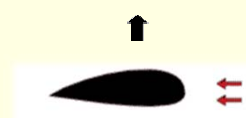
http://www.world-wind-energy.info/

Aerodynamics of Wind Turbines: Lift

What makes the rotor turn?

The answer is obvious - the wind

Lift



Difference in pressure created by the speed difference

Aerodynamics of Wind Turbines: Lift

- ✓ Principles from airplanes and helicopters, with a few other turbine-related principles, e.g.:
  - Turbines function in an environment with changing wind speeds and wind directions
  - Turbine does not fly while a plane does

Aerodynamics of Wind Turbines: Stall

Stall

Stall = the lift from the low pressure on the upper surface of the wing disappears

- ✓ Stall while fatal for aircrafts, it is deliberately used in turbine blade designs

Power Control of Wind Turbines

Turbine primary design goal: A machine producing energy at low cost

- ✓ Wind turbines are designed for maximum power output at rated wind speed, e.g., 12 m/s
- ✓ Winds that are too strong are wasted to avoid turbine damage
- ✓ Two basic ways of power control:
  - Pitch controlled wind turbines
  - Stall controlled wind turbines (passive and active)
  - Other power control approaches

Pitch Controlled Wind Turbines

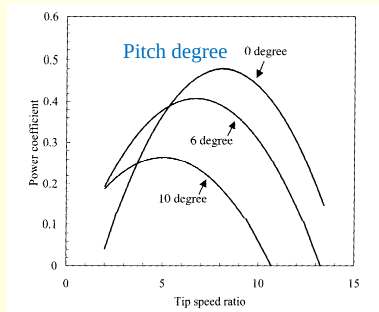
- ✓ The controller of a pitch controlled wind turbine checks the power output of the turbine several times per second
- ✓ When the power output becomes too high, the blade pitch mechanism immediately *pitches (turns) the rotor blades* slightly out of the wind
- ✓ Conversely, the blades are turned back into the wind whenever the wind drops

The rotor blades turn (are controlled) around their longitudinal axis

Pitch Drive

http://www.boschrexroth.com/BoschRexroth/business_units/brm/en/branches/wind

Pitch Controlled Wind Turbines



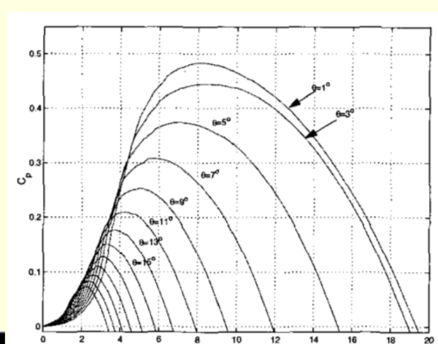
Power coefficient -Tip speed ratio λ curves for different degree of pitch

$$P = 0.5\rho\pi R^2 C_p(\lambda,\beta)v^3$$

$$\lambda = \frac{\omega R}{v}$$

S. Mathew (2006)

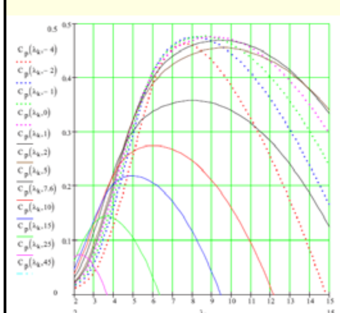
GE WT Power Coefficient



Note:

$$\theta = \beta$$

Pitch Controlled Wind Turbines



Coefficient of performance (Cp) for a modern wind turbine blade assembly as a function of tip-speed ratio (λ) and blade pitch (β, in degrees)

AWEA (2005)

Passive Stall Control Turbines

- ✓ Passive stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle
- ✓ The rotor blade profile is designed to ensure that when the wind speed becomes too high, it creates turbulence on the side of the rotor blade not facing the wind
- ✓ This stall prevents the lifting force of the rotor blade from acting on the rotor (i.e., the rotor stops)

Passive Stall Control Wind Turbines

Advantages:

The avoidance of:
- ✓ moving parts in the rotor itself, and
- ✓ a complex control system

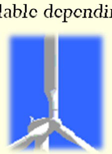
Disadvantages:

- ✓ Stall control is a complex aerodynamic design problem involving the structural dynamics of the whole turbine, e.g., avoiding stall-induced vibrations
- ✓ A two thirds of the early wind turbines installed were stall controlled

Active Stall Control Turbines

- ✓ Large wind turbines (>=1 MW) usually use active stall control mechanism
- ✓ The active stall machines use pitchable blades and resemble pitch controlled turbines
- ✓ To produce a required torque at low wind speeds, the turbines are usually be programmed to pitch the blades similar to a pitch controlled machine at low wind speeds
- ✓ Usually only a few fixed adjustment steps are available depending on the wind speed

Pitchable blades of a pitch controlled turbine



Active Stall Control Turbines

Differences: Active stall controlled vs pitch controlled turbines

- ✓ The difference is visible when the turbine reaches its rated power
- ✓ When the generator is about to be overloaded, the active stall turbine pitches its blades in the opposite direction from what a pitch controlled machine does
- ✓ The control mechanism increases the angle of attack of the rotor blades to stall the blades, thus wasting the excess of wind energy

Active vs Passive Stall Control Turbines

Advantages:

- ✓ Power output is more accurately controlled than with passive stall
- ✓ Thus overshooting the rated power is avoided at the beginning of a gust of wind
- ✓ The turbine runs almost exactly at rated power at high wind speeds
- ✓ For a passive stall control wind turbine, a rotor blades go into deeper stall at high wind speeds

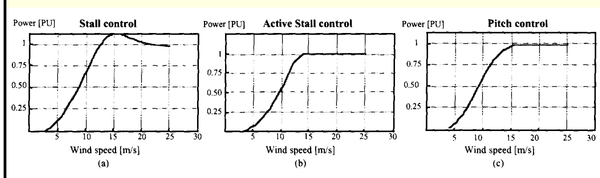
Disadvantages:

- ✓ The pitch mechanism is usually operated using hydraulics or an electric stepper motor
- ✓ Added complexity of the turbine and cost due to the blade pitch mechanism

Comparison of Power Curves

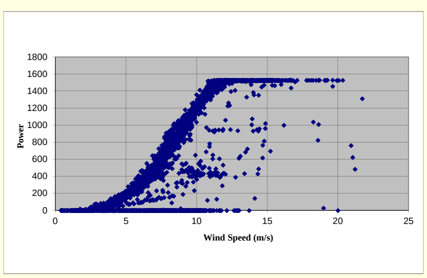
Rotor power enhancing/limiting methods:

Stall control | Active stall control | Pitch control



 Blaabjerg and Chen (2006)

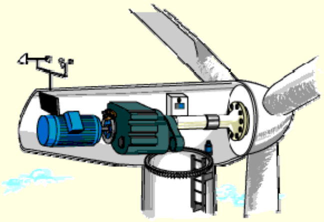
Actual Power Curve



Other Power Control Methods

- ✓ Some older wind turbines used ailerons (flaps) to control the power of the rotor - similar to aircraft using flaps to alter the geometry of the wings to provide extra lift at takeoff
- ✓ Another option is to yaw the rotor partly out of the wind to decrease the power
- ✓ The yaw control approach is used in practice for very small wind turbines (~ 1 kW) due to cyclically varying stress applied to the rotor that could damage the entire structure

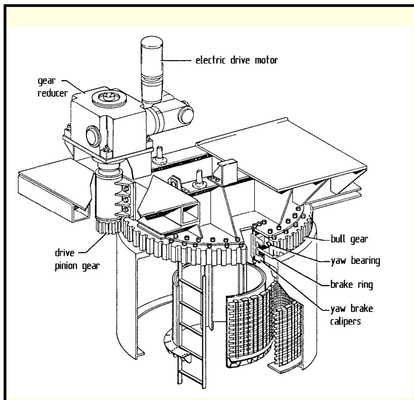
Yaw Mechanism



www.windpower.org

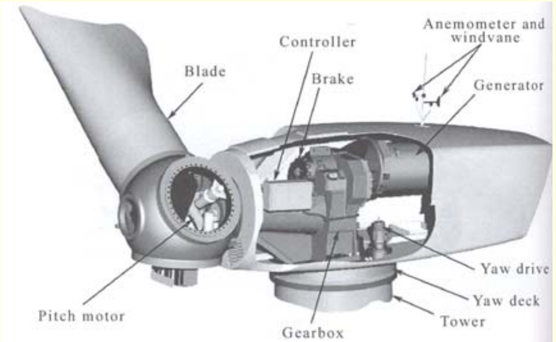
Almost all horizontal axis wind turbines use forced yawing, i.e., they use a mechanism using electric motors and gearboxes to keep the turbine yawed against the wind

Yaw Mechanism



 E. Hau (2006), p. 312

Enron Wind 750i Turbine



Yaw Mechanism

Yaw Drive
http://www.boschrexroth.com/BoschRexroth/business_units/brm/en/branches/wind

- ✓ The yaw bearing around the outer edge, the wheels from the yaw motors, and the yaw brakes inside
- ✓ Most upwind machines brake the yaw mechanism whenever it is not used
- ✓ The yaw mechanism is activated by the electronic controller checking several times per second the position of the wind vane on the turbine whenever the turbine is running.

Yaw Error

- ✓ The wind turbine is said to have a yaw error, if the rotor is not perpendicular to the wind
- ✓ A yaw error implies that a lower share of the energy in the wind is captured by the rotor. The share drops as the cosine of the yaw error
- ✓ In the absence of adverse effects, the yaw control would be an excellent way of controlling the power output to the wind turbine rotor

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Yaw Error

- ✓ That part of the rotor which is closest to the source direction of the wind is subject to a larger force (bending torque) than the rest of the rotor
- ✓ This implies that the rotor has a tendency to yaw against the wind automatically, regardless of whether it is an upwind or a downwind turbine
- ✓ This also implies that the blades are bending back and forth in a flapwise direction for each turn of the rotor
- ✓ Wind turbines running with a yaw error are therefore subject to larger fatigue loads than wind turbines that are yawed in a perpendicular direction against the wind

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Wind Turbine Towers

- ✓ The tower of the wind turbine carries the nacelle and the rotor
- ✓ Towers of large wind turbines may be either:
  - tubular steel towers,
  - lattice towers,
  - concrete towers,
  - guyed tubular towers (used for small wind turbines)

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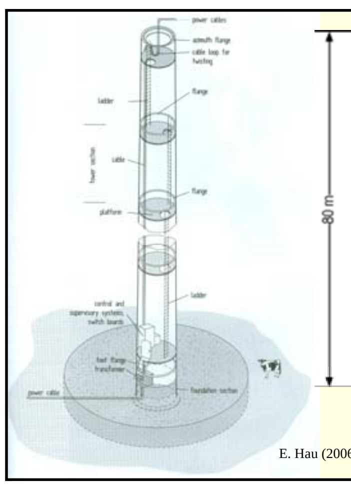
Tubular Tower



E. Hau (2006)

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Tubular Tower

http://www.middelgrunden.dk/MG_UK/project_info/turbine.htm

Tubular Steel Towers

Photograph © NEG-Micon A/S 1998

- ✓ Used for most large wind turbines
- ✓ Manufactured in sections of 20-30 meters with flanges at either end, and bolted together on the site
- ✓ The towers are conical, i.e., the diameter increases towards the base to increase their strength and to save material

Photograph © Nordex A/S 1998

Lattice Towers

- ✓ Lattice towers are manufactured from welded steel profiles

Advantage

- ✓ A lattice tower requires only about half the material of a freely standing tubular tower with a similar stiffness

Disadvantage

- ✓ Visual appearance (almost disappeared from large turbines due to esthetic reasons)

Guyed Pole Towers

Photograph Soren Krohn © 1999 DWIA

- ✓ Small wind turbines are built with narrow pole towers supported by guy wires

Advantage

- ✓ Weight and cost

Disadvantages

- ✓ Difficult access around the towers which make them less suitable in farm areas
- ✓ More prone to vandalism, thus compromising overall safety

Foundations

http://www.world-wind-energy.info/

Hybrid Tower Solutions

Photograph © Bonus Energy A/S 1998

- ✓ Some towers combine the previous concepts
- ✓ Example: Three-legged Bonus 95 kW tower – a hybrid between a lattice tower and a guyed tower

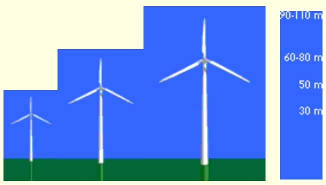
Cost Considerations

- ✓The price of a tower for a wind turbine is generally around 20% of the total price of the turbine
- ✓ For a tower around 50 meter high the additional cost of another 10 meters of tower is, e.g., $20,000 which is significant
- ✓ Lattice towers are the lowest cost

Aerodynamic Considerations

- ✓ Generally, it is an advantage to have tall towers in areas with high terrain roughness
- ✓ The wind speed increases with the height
- ✓ Lattice towers and guyed pole towers produce less wind shade than a tabular tower

Low vs Tall Towers



- ✓A larger turbine produces more energy than a small one, however for each of the three turbines 225 kW, 600 kW, and 1,500 kW with rotor diameters of 27, 43, and 60 meters, the tower heights differ

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Power Output Increases with the Swept Rotor Area

- ✓ The exact rotor diameter is determined based on the wind farm wind conditions
- ✓ A larger generator requires strong winds
- ✓ At low wind speed area the annual energy output is maximal for small generator for a given rotor size
- ✓ Example, for a 600 kW machine rotor diameters may vary from 39 to 48 m (128 to 157 ft)
- ✓ Larger output from a relatively smaller generator in a low wind area is produced due to the turbine running more hours in a year

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Reasons for Choosing Large Turbines

- ✓ Larger turbines are usually deliver electricity at a lower cost than smaller machines
- ✓ The turbine infrastructure plus a number of components are somewhat independent of the size of the machine
- ✓ Largest turbines are particularly well suited for offshore wind power as the foundation does not increase proportionally in the size of the turbine, and maintenance cost is largely independent of the size of the turbine
- ✓ Single turbine installed is usually large

Selection criteria
(e.g., cost, reliability, maintenance)
vs
Stakeholder/Location
(utility, private owner, offshore)

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Reasons for Choosing Smaller Turbines

- ✓ The local electric grid may be too weak to handle the electricity output from a large machine, e.g., remote area with low population density
- ✓ There is less fluctuation in the electricity output from a wind park consisting of many smaller machines (cancelling out of random fluctuations)
- ✓ The cost of using large cranes, and building roads can make smaller turbines more economic in some areas
- ✓ Aesthetical landscape considerations may sometimes dictate the use of smaller turbines

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Performance Enhancement Dilemma

Larger rotor

- ✓ Higher rotor cost for longer blades
- ✓ Rotor power grows with its diameter squared

Taller tower

Higher cost of taller towers

Greater output

The cost benefits are governed by the wind power law

$P = 0.5 \times \rho \times A \times v^3$

Solution: Building “smarter” rotors using lighter components

Turbine Safety

The components of a wind turbine are designed to perform usually for 20 years, i.e., 120,000 operating hours.
An ordinary automobile engine, usually operates only some 5,000 hours.

Industrial wind turbines are equipped with a number of safety devices to ensure safe operations, including:

- ✓ Sensors
- ✓ Testing wind turbine rotor blades
  - Overspeed protection
  - Aerodynamic braking system: Tip brakes
  - Mechanical braking system

Turbine Safety

Sensors

- ✓ Vibration sensor is a simple and widely safety device in many wind turbines (first installed in the Gedser turbine)
- ✓ It simply consists of a ball resting on a ring. If the turbine shakes, the ball falls off the ring and switches off the turbine
- ✓ Sensors installed in the nacelle, e.g., measuring oil temperature in the gearbox and the temperature of the generator

Turbine Safety

Rotor blades

- ✓ Safety regulations for wind turbines vary among countries. For example, Denmark requires that all new rotor blades are tested both:
  - Statically, i.e., applying weights to bend the blade, and
  - Dynamically, i.e., testing the blade's ability to withstand fatigue from repeated bending (e.g., more than five million times)

Turbine Safety

Overspeed protection of turbine rotor blades

- ✓ Overspeed protection by turbine stopping automatically in case of malfunction of a critical component, e.g., generator overheating or being disconnected from the electrical grid it will stop braking the rotation of the rotor, and the rotor will start accelerating rapidly
- ✓ An overspeed protection system is needed

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Turbine Safety

Aerodynamic braking system: Tip brakes

- ✓ Aerodynamic braking system is the primary braking system for most modern turbines
- ✓ It essentially turns the rotor blades about 90 degrees along their longitudinal axis (for a of a pitch/active controlled or in turning the rotor blade tips 90 degrees (for a a stall controlled turbine)
- ✓ These systems are usually spring operated (to allow functioning if the electrical power fails) and they are automatically activated if the hydraulic system in the turbine loses pressure

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Turbine Safety

Aerodynamic braking system: Tip brakes

- ✓ The electric/hydraulic system in the turbine is used turn the blades or blade tips back in place once the dangerous situation is over
- ✓ Experience has shown that aerodynamic braking systems are very safe
- ✓ The turbine stops the turbine in a matter of a couple of rotations
- ✓ The turbine breaks gently way of braking without a major stress, tear and wear on the tower and the machinery
- ✓ The aerodynamic braking system is commonly used for stopping modern turbines

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Turbine Safety

Mechanical braking system

© 1998 www.WINDPOWER.org

- ✓ The mechanical brake is used as a backup system for the aerodynamic braking system, and as a parking brake, once the stall controlled turbine is stopped
- ✓ Pitch controlled turbines rarely need to activate the mechanical brake (except for the maintenance), as the rotor cannot move very much once the rotor blades are pitched 90 degrees

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Turbine Occupational Safety

- ✓ The primary danger in working with wind turbines is the height above ground during installation work and when doing maintenance work
- ✓ Some turbines are required to have fall protection devices, e.g., the person climbing the turbine has to wear a parachutist-like set of straps
- ✓ The straps are connected with a steel wire to an anchoring system that follows the person while climbing or descending the turbine
- ✓ The wire system has to include a shock absorber, so that persons are reasonably safe in case of a fall

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Occupational Safety Considerations

- ✓ Turbine design and tower type selection impact occupational safety
- ✓ In fact, wind turbines should be designed for safety

Service crew working on a 32 m rotor blade on a 1.5 MW wind turbine
Photograph Christian Kjaer © 2000 DWIA

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Turbine Occupational Safety

Towers

- ✓ Modern wind turbines normally use conical tubular towers
- ✓ Safety, access, and comfort are the primary advantages of a conical tower over a lattice tower
- ✓ The disadvantage is a higher cost

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Turbine Occupational Safety

- ✓ Many turbine manufacturers place access ladders at a certain distance from the wall
- ✓ This enables service personnel to climb the tower while being able to rest the shoulders against the inside wall of the tower

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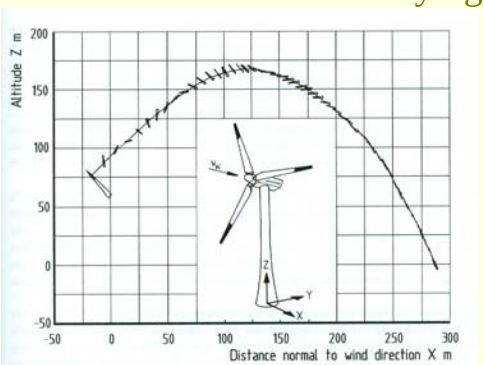
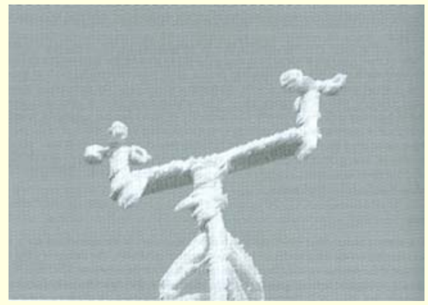
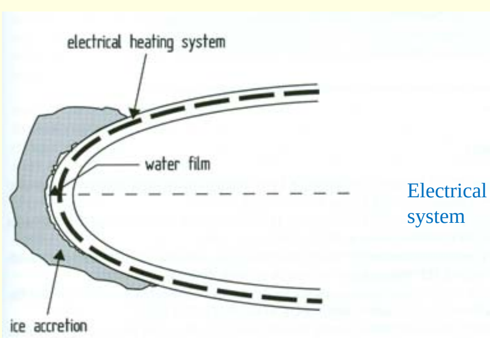
Flying Blade



Icing on the Anemometer

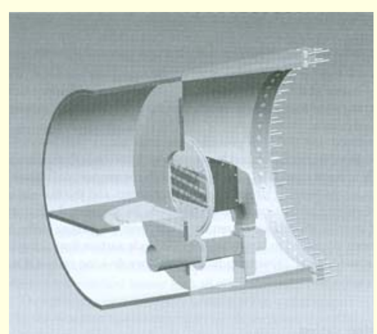


Blade De-icing System



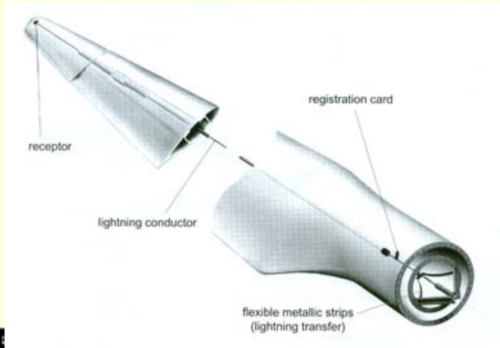
Electrical system

Blade De-icing System



Hot air

Lightning Protection



Hau (2006), p. 250

Lightning Protection

Example: DeWind blades
✓ Copper mesh covering the blade surface

Acknowledgement

The material included in the presentation comes largely from the Danish Wind Industry Association

Small Turbines

Manufacturer	Models (Rated Capacity)
Abundant Renewable Energy www.abundantre.com	AWP 3.6 (1 kW)
Bergey Windpower Co. www.bergey.com	BWC XL.1 (1 kW), BWC EXCEL (10 kW)
Distributed Energy Systems (previously known as Northern Power Systems) www.distributed-energy.com	NPS 100 (100 kW)
Energy Maintenance Service www.energyms.com	E15 (35 kW or 65 kW)
Entegrity Wind Systems www.entegritywind.com	EW15 (50 kW)
Lorax Energy www.lorax-energy.com	FL 25 (25 kW), FL 30 (30 kW), FL 100 (100 kW)
Solar Wind Works www.solarwindworks.com	Proven WT600 (600 W), WT2500, (2.5 kW) WT6000 (6kW), WT15000 (15kW)
Southwest Windpower Co. www.windenergy.com	AIRX (400 W), Whisper 100 (900 W), Whisper 200 (1 kW), Whisper 500 (3 kW)
Wind Turbine Industries Corp. www.windturbine.net	23-10 Jacobs (10 kW), 31-20 Jacobs (20 kW)

http://www.awea.org/faq/smsyslst.html