Source: LM Wind Power - GE

Wind turbines

PHYS-E6572 Advanced Wind Power Technology L03

Timo Karlsson, Raul Prieto, based on material in Dipoli course by Petteri Antikainen and Andrea Vignaroli, Georg Böhmeke and other References

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Electricity from wind - Poul La Cour

- Danish physcist and inventor
- Built a wind turbine driving a DC dynamo in 1891
- Initially used electricity for electrolysis and stored the H2 gas.
- Used shutter sails to limit rotational speed, and fan wheels to control yaw
- Marketed by the Lykkegard company, by the end of WW1, ~120 wind turbines of this type powered DC grids in rural settlements.
- Turbines were 10 to 35kW, with rotor diameters up to 20m, and reported an efficiency ~22%

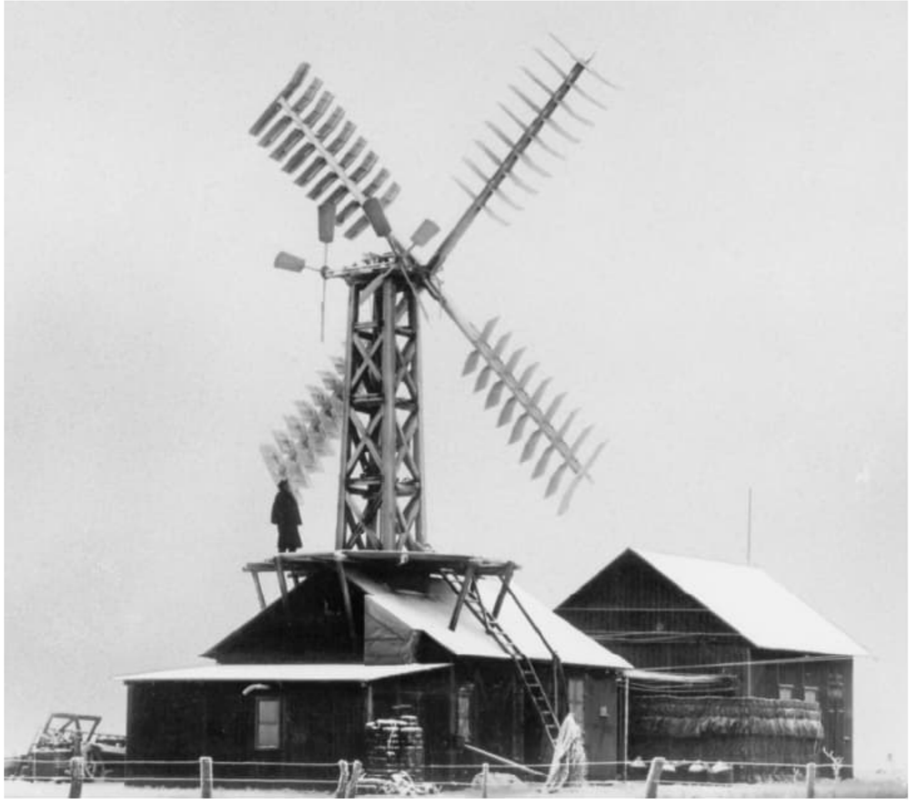


Fig. 2.1. Poul La Cour's first electricity producing wind turbine in 1891 in Askov, Denmark [1]

Erich Hau "Wind Turbines" Ed 3.

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Wind energy converter concepts

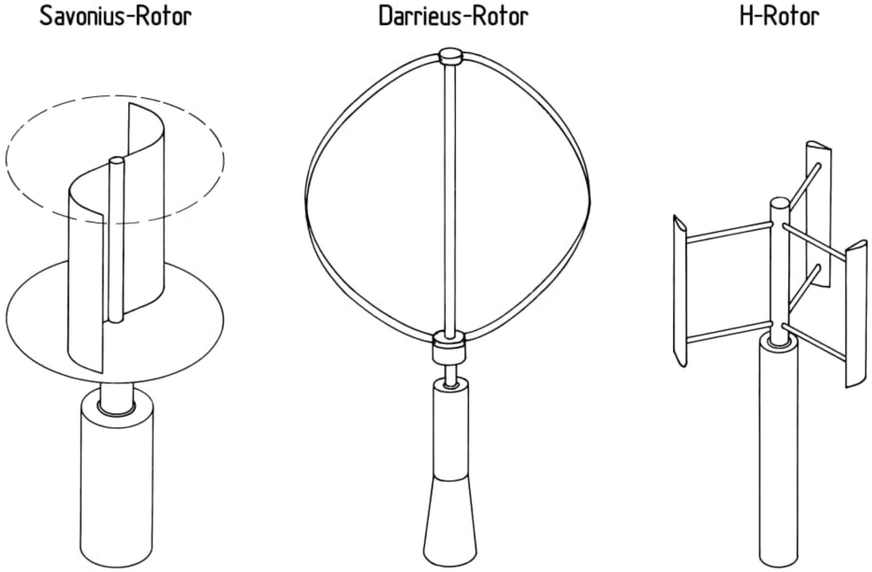


Fig. 3.1. Rotor concepts with a vertical axis of rotation

Source: Hau, E. (2013). Basic Concepts of Wind Energy Converters. In: Wind Turbines. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-27151-9_3

Source: https://windenergy.dtu.dk/english/news/2017/09/what-makes-a-wind-turbine-rotate

Wind energy converter concepts

- Almost all wind turbines today are three blade horizontal axis (propeller) type
  - Rotor speed and power output easy to control
  - Protection against overspeed in extreme wind speeds
  - Higher efficiency
  - Three-bladed rotor is always balanced, leading to more even loads


Photo © VTT, Mikko Tiihonen, 2016

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Betz momentum theory (I)

- The Energy of a mass of air **m** flowing with velocity **V** is

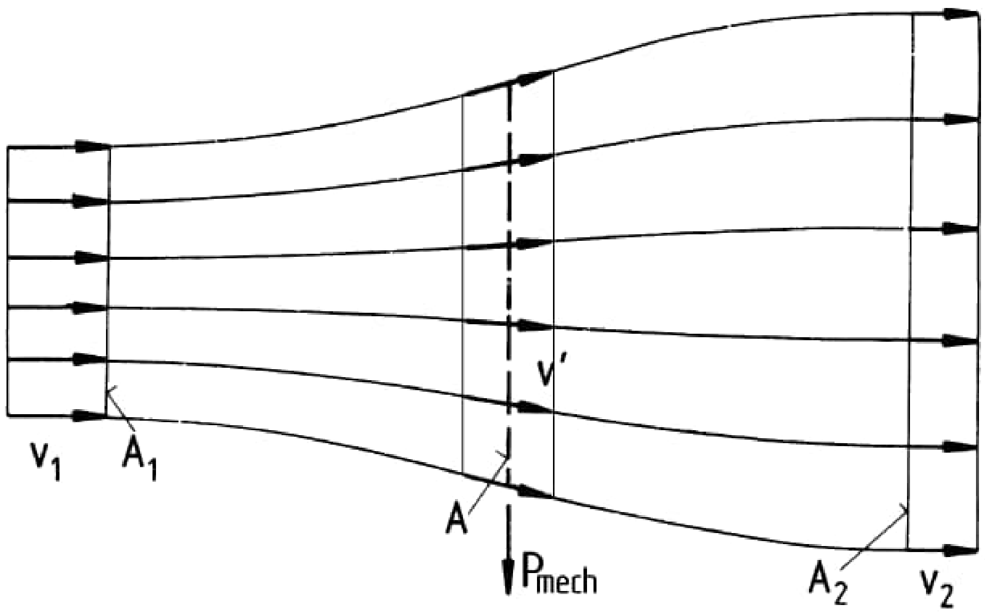
$$E = \frac{1}{2} m V^2$$

- The mass flow of air with density **rho** through an area **A** normal to the flow is

$$\dot{m} = \rho A V$$

- The amount of air kinetic energy flowing through a section perpendicular to the flow, with area A per unit time is

$$P = \frac{1}{2} \rho V^3 A$$



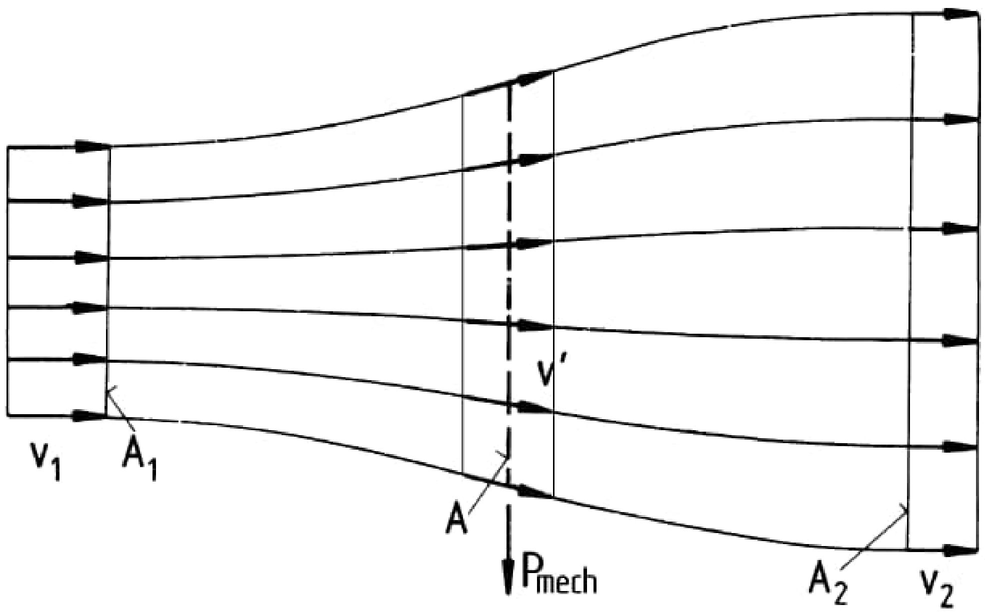
Erich Hau "Wind Turbines" Ed 3.

Betz momentum theory (II)

- In a streamtube formed by the flow passing through a wind turbine (section **A**)
- Control volume formed by the walls of the streamtube, and the boundaries **A1** upstream, and **A2** downstream
- Let's consider a extraction of mechanical power **P** at the section **A**
- The energy equation applied to the air flowing past the control volume

$$P = \frac{1}{2}\dot{m}(V_1^2 - V_2^2)$$

- It follows that P=0 for both cases
  - V2=V1 (the flow is not disturbed)
  - V2=0 (no flow at all)



Erich Hau "Wind Turbines" Ed 3.

Betz momentum theory (III)

- If the extracted power is zero in both cases V2=V1 and V2 = 0, so there must be a Value of V2/V1 for which the extracted power P is maximum
- Let's define the aerodynamic power coefficient **Cp**, namely the ratio of power extracted from the wind to the power contained in the air stream

$$Cp = \frac{P}{\frac{1}{2}\rho V_1^3 A}$$

- By combining the **energy** and **momentum** equations applied to the flow in the control volume it can be shown that

$$Cp = 4a(1-a)^{2}$$

- Where **a** is called **axial induction factor**, and relates to V1 and V2 as follows:

$$a = \frac{1-\frac{V_2}{V_1}}{2}$$

- The axial induction factor **a** represents the amount of velocity reduction of the flow in the section **A** compared to the velocity upstream. The axial induction factor is related to the flow velocity **v'** in the section A as follows:

$$v' = V_1(1-a)$$

Betz momentum theory (IV)

- The ideal optimum energy extraction would result in

$$V_2 = \frac{1}{3}V_1$$

- The maximum value of Cp is attained when a=1/3 and has a value Cp=16/27=0.593.

- This is known as the **Betz limit**, and represents the theoretical maximum aerodynamic power which can be extracted from the wind.

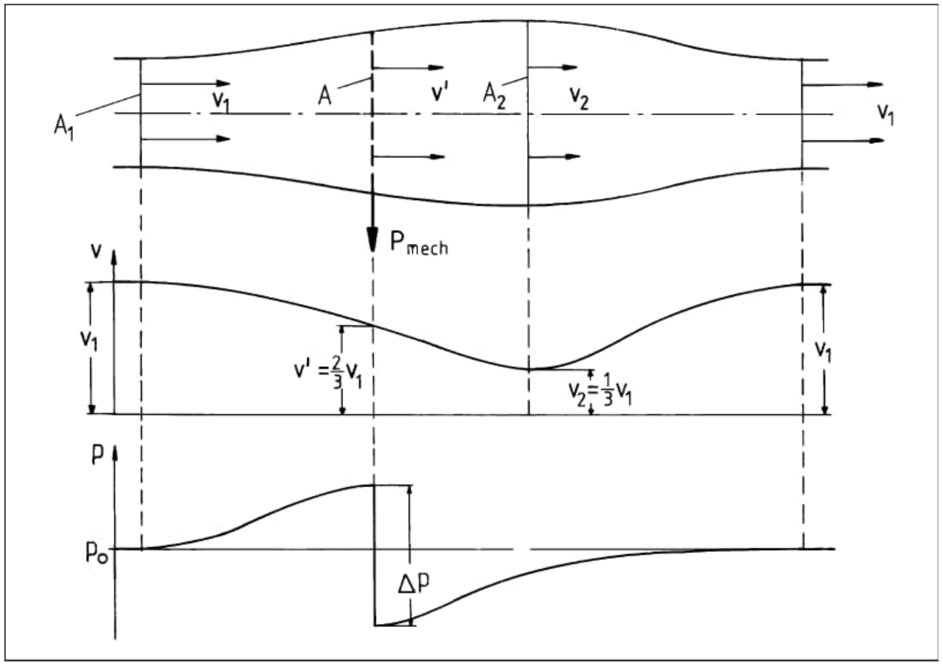


Fig. 4.3. Flow conditions of the stream through an ideal disk-shaped energy converter with the maximum possible extraction of mechanical power

Erich Hau "Wind Turbines" Ed 3.

Departure from ideal flow – aerodynamic losses

- Several factors contribute to reduce the aerodynamic power coefficient:

  - **Wake losses:** the wake spins in opposite direction to the rotation of the rotor, removing energy from the flow.

  - **Airfoil drag** due to the the friction between the blade and passing air, and flow separation.

  - **Blade tip losses**, due to the blade tip **vortices** generated at the tip of each blade which alter the flow field. Slender blades (small chords compared to the blade length) result in lower tip losses.

  - **Blade root losses**, due to separated flow near the blade root, generated by blunt blade geometry, root vortices and the interaction with the nacelle

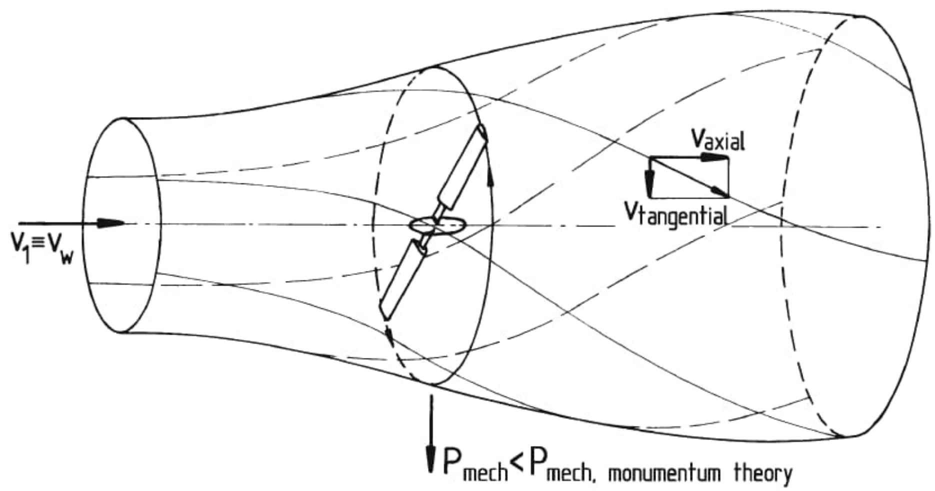


Fig. 5.2. Extended momentum theory, taking into consideration the rotating rotor wake

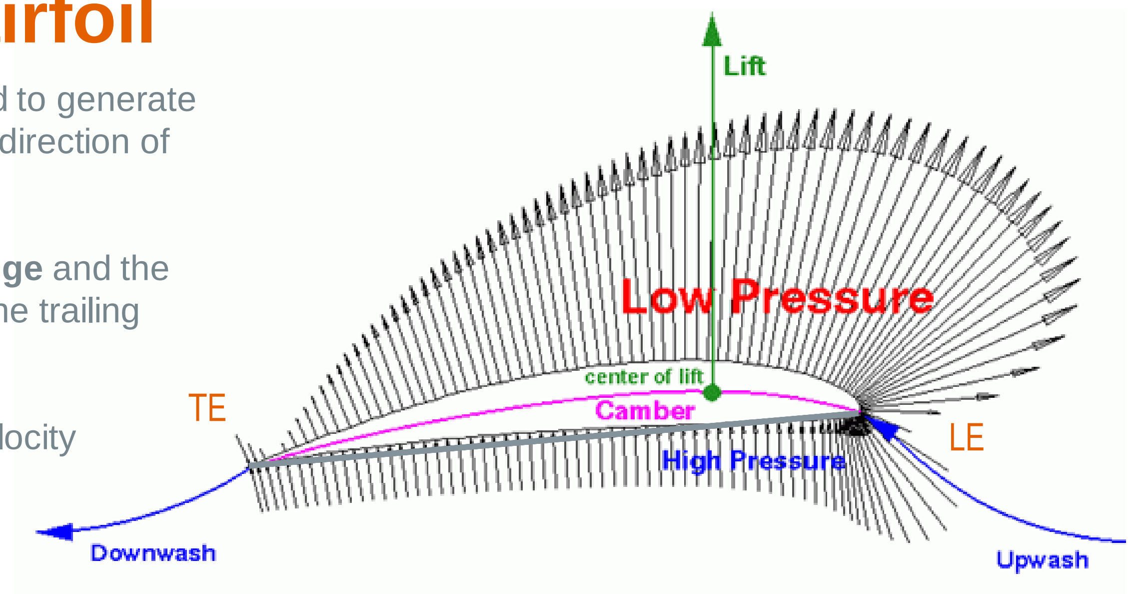
Erich Hau "Wind Turbines" Ed 3.

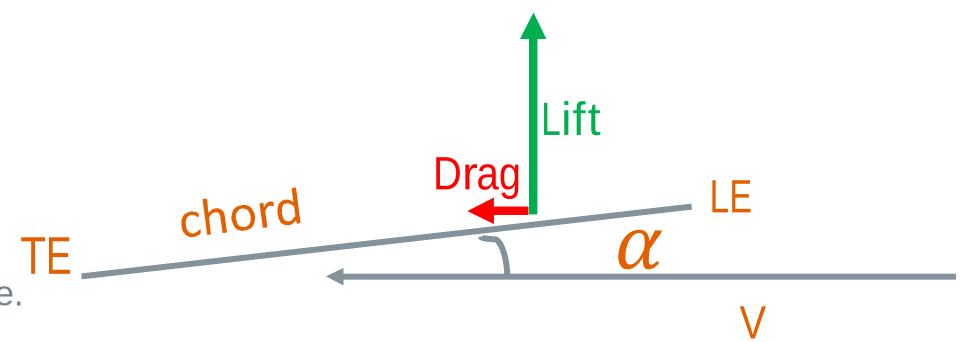
Aerodynamic losses

- Wakes of neighbouring turbines affect the operation of wind turbines in a larger array
- Reduced speed and incresed turbulence in wake decrese production and increse loads

Aerodynamics of an airfoil

- An airfoil is a 2D geometrical shape designed to generate a fluid dynamic force (**Lift**) perpendicular to the direction of the incoming flow.
- The **chord** is the line between the **trailing edge** and the **leading edge** (point of the airfoil farthest from the trailing edge).
- The angle between the chord and the flow velocity upstream **V** is called **angle of attack α**
- Lift and Drag are functions of α
- The combination of curvature (**camber**) and **angle of attack** , generates the lift due to the asymmetric distribution of air pressure in the airfoil surface.
- The **Drag**, is an undesirable fluid dynamic force in the direction of the upstream velocity. It is produced by the resultant of pressure forces in the airfoil and tangential forces due to friction between the fluid and the airfoil surface.





Wind turbine blade

- A blade is not just one airfoil, the shape of the blade changes along the way for optimal aerodynamic performance
- The blade will bend from the wind pressure, modern blades are also slightly pre-bent
- In order to maximize the produced torque the blade twists around it's axis
- Examples from:

- Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf

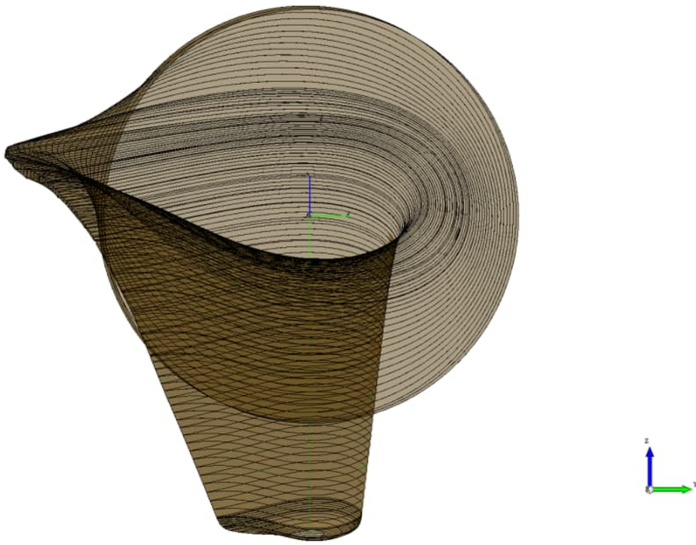


Figure 2-5. Lofted blade shape

Figure 2-1. View from the suction side (top) and trailing edge (bottom) of the offshore wind turbine blade

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Tip Speed Ratio – λ

- The **Tip Speed Ratio λ** represents the ratio between the blade tip speed and wind speed upstream. It is a key driver of the aerodynamic design.

$$\lambda = \frac{\Omega R}{V_w}$$

- Three-bladed Horizontal Axis Wind Turbines (**HAWT**) have **lower optimum λ** compared to two-bladed rotors, so they operate at lower tip speeds, being **quieter**. Its **high Cp**, has made them the choice for modern utility scale wind power plants.

- Two-bladed Horizontal Axis Wind Turbines are less sensitive to variations of **λ** .

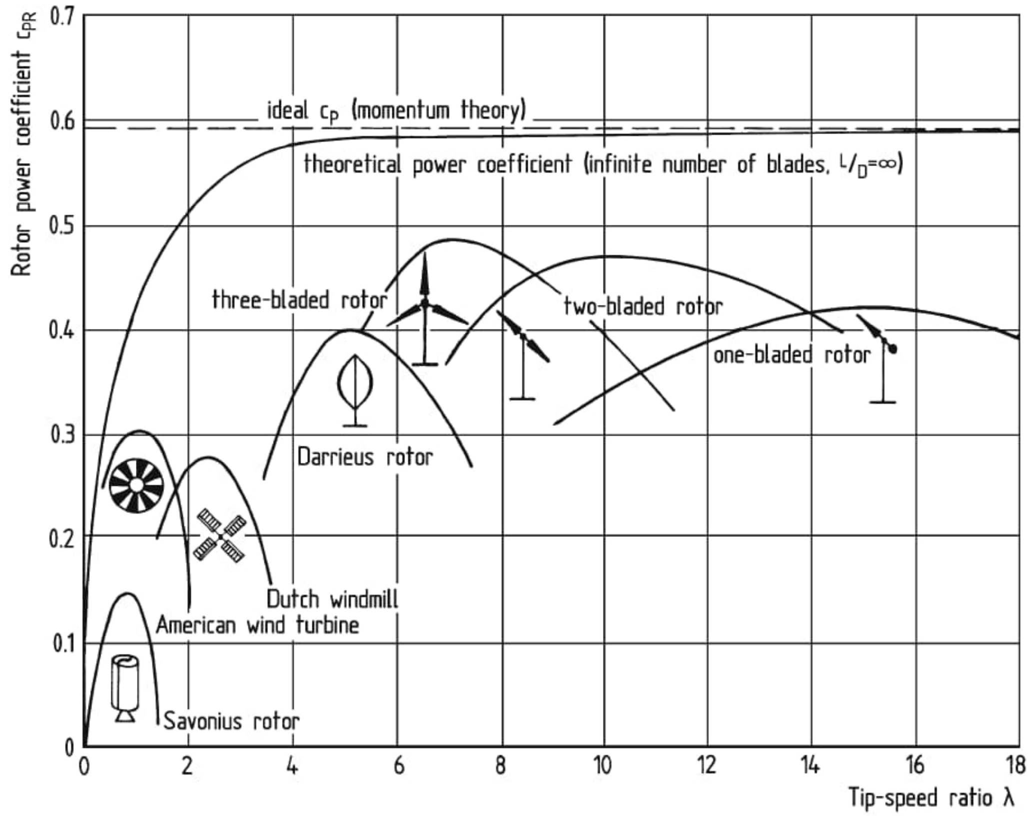


Fig. 5.15. Power coefficients of wind rotors of different designs [2]

Erich Hau "Wind Turbines" Ed 3.

Rotor solidity and number of blades

- The rotor solidity is the total blade area divided by the rotor disk area

- Solidity can be increased by adding identical blades to the rotor, or by increasing the chord lenght for existing blades

- Low solidity → high optimal tip speed ratio, and lower maximum cp with a broad maximum.

- High solidity → low optimal tip speed ratio, and higher maximum cp

- Increasing the number of blades while keeping the solidity constant increases the cp, because of the lower blade tip losses. This is due to the individual blades being more slender.

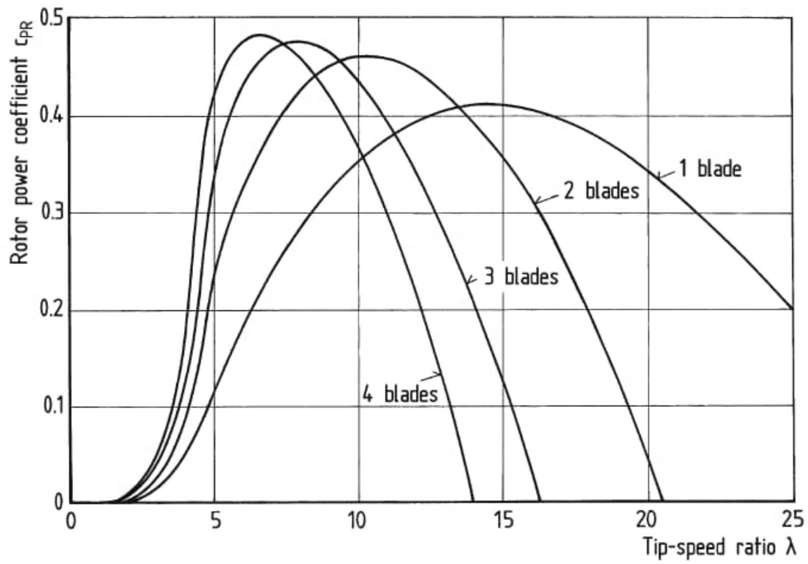


Fig. 5.45. Influence of the number of blades on the rotor power coefficient and the optimum tip-speed ratio

Erich Hau "Wind Turbines" Ed 3.

Relative wind velocity in a blade section (I)

- The diagram shows a blade section, with the velocities involved in the calculation of the aerodynamic force

- Note that the resultant air force, combination of lift and drag, has a positive component in the direction of rotation

- Increasing in the angle theta ϑ (**pitching towards feather**) reduces the angle of attack α -> reduces the tangential force -> reduces the aerodynamic power P

- Reducing the angle theta ϑ (**pitching towards stall**) increases the angle of attack α -> increases the tangential force -> increases the aerodynamic power P,

- but if α is increased too much the blade **stalls** increasing Drag and reducing the tangential force

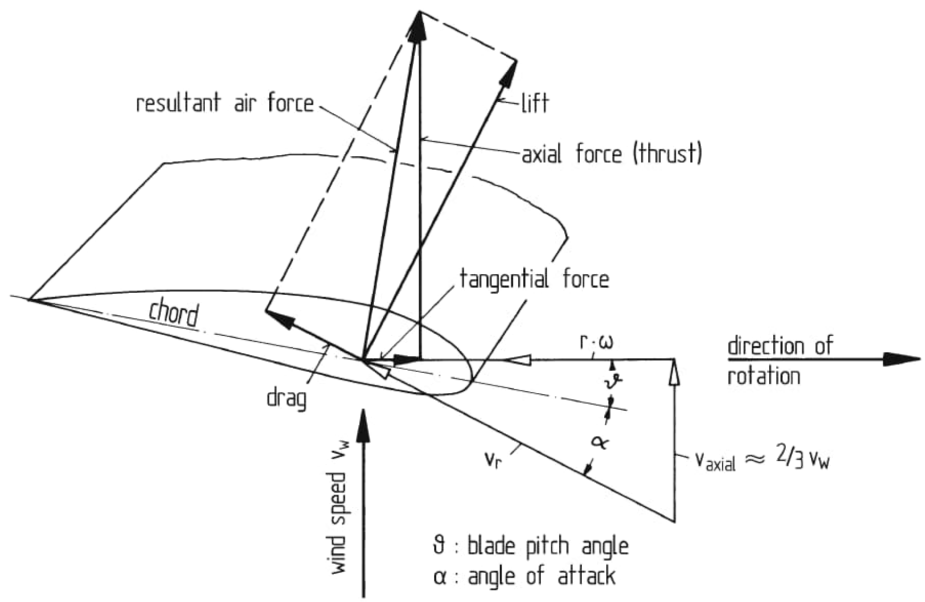
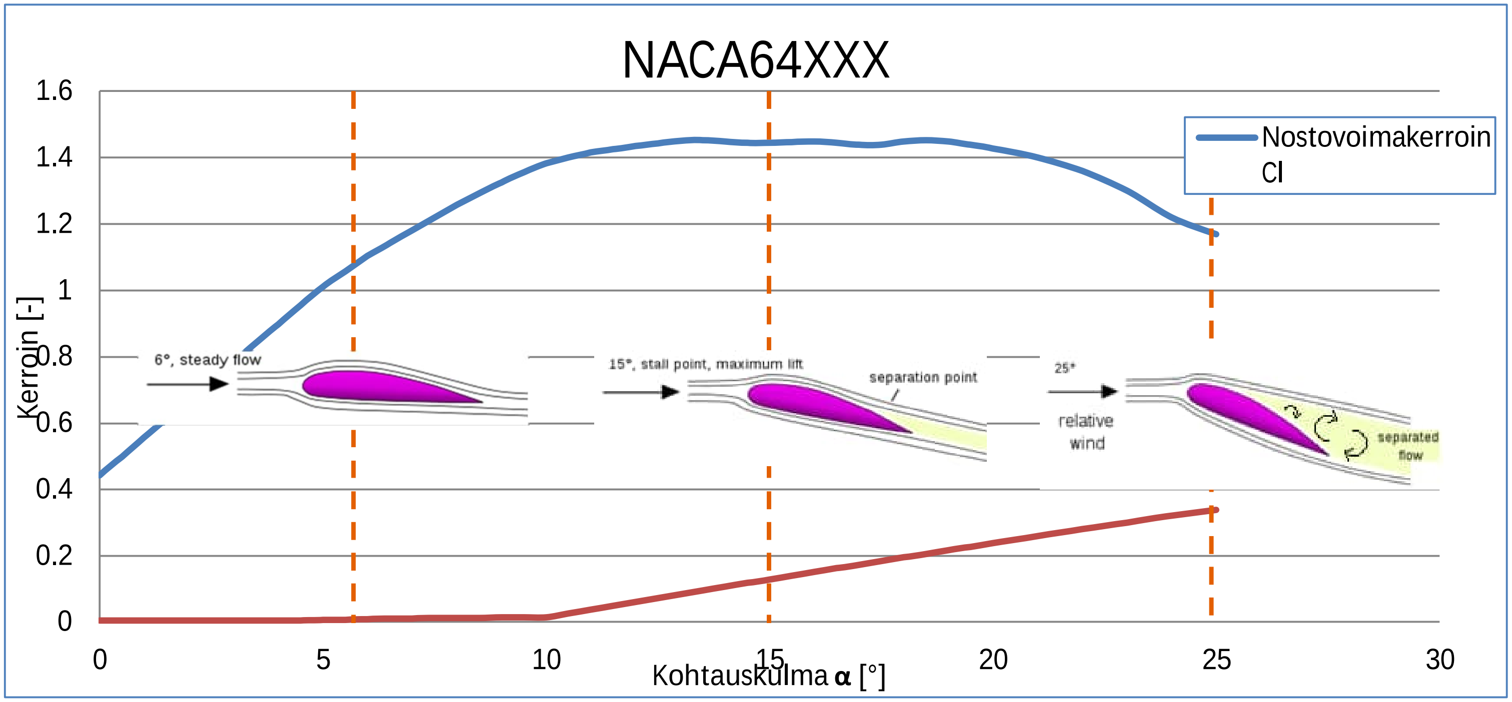


Fig. 5.4. Flow velocities and dynamic forces at the airfoil cross-section of a blade element

Erich Hau "Wind Turbines" Ed 3.

Stall of blade airfoils

- The lift coefficient (blue) and drag coefficient (red) are function of the angle of attack
- At angles of attack above 12-15deg , the flow starts to separate in the upper side (suction side).
- Drag increases largely and lift is constant or decreases.



Blade stall for power curtailment

- A fixed-speed & fixed pitch HAWT limits power at high speeds passively : For very high wind speeds, the angle of attack α increases beyond αstall, causing the flow to detach, and reducing aerodynamic power

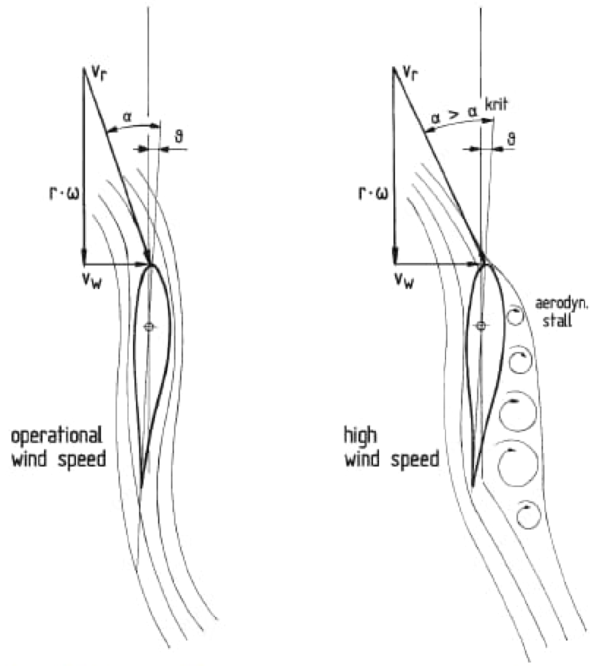


Fig. 5.24. Aerodynamic stall at a rotor blade with fixed blade pitch angle at increasing wind velocities and fixed rotor speed

Erich Hau "Wind Turbines" Ed 3.

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Offshore

Wind turbine performance (I)

$$\lambda = \frac{\Omega R}{V_w}$$

- The aerodynamic power coefficient Cp depends on the tip speed ratio λ and on the blade pitch angle theta ϑ

$$Cp = f(\vartheta, \lambda)$$

- Modern pitch-regulated horizontal axis wind turbines operate at the maximum Cp for wind speeds below rated power. At rated wind speed and above, pitch angle is increased (pitching towards feather) to keep the electric power equal to the rated generator capacity

- In the blade of the example (right), the optimal pitch angle (”fine pitch”) is -2deg , and the optimal tip speed ratio λopt $\simeq$ 8

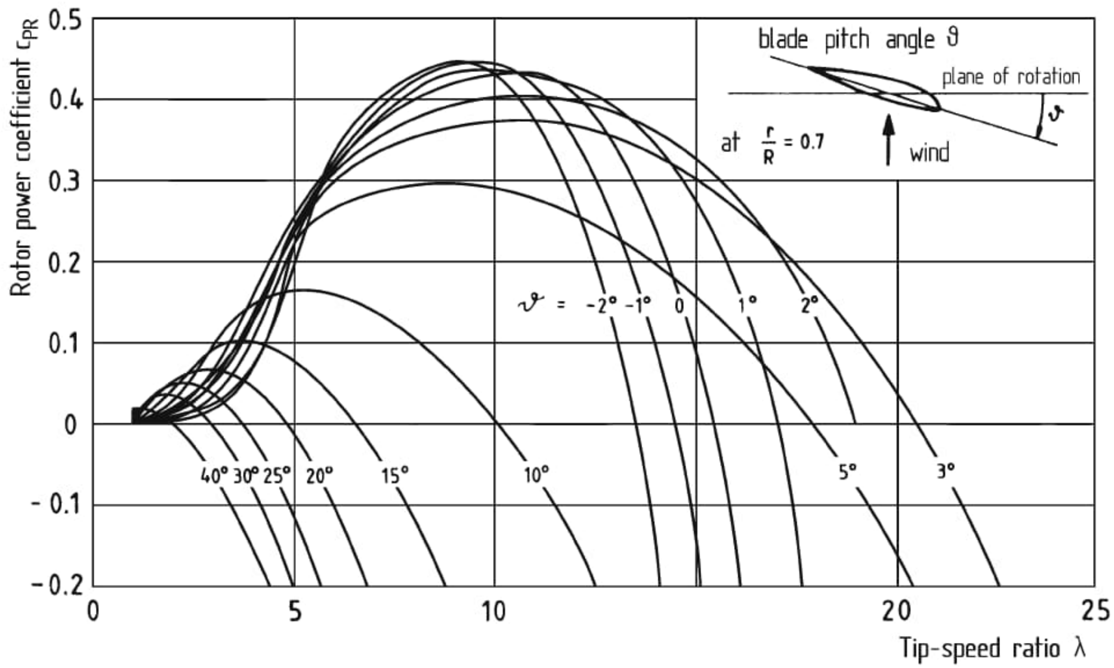


Fig. 5.13. Rotor power characteristics for the experimental WKA-60 wind turbine

Erich Hau ”Wind Turbines” Ed 3.

Wind turbine performance (II)

- Currently, utility scale wind turbines are HAWTs with **variable-speed** operation
- The **power curve** provides the wind turbine electric power as a function of wind speed
- It takes into account power losses as an **efficiency factor η** (mechanical, electrical, and ancillary consumption)

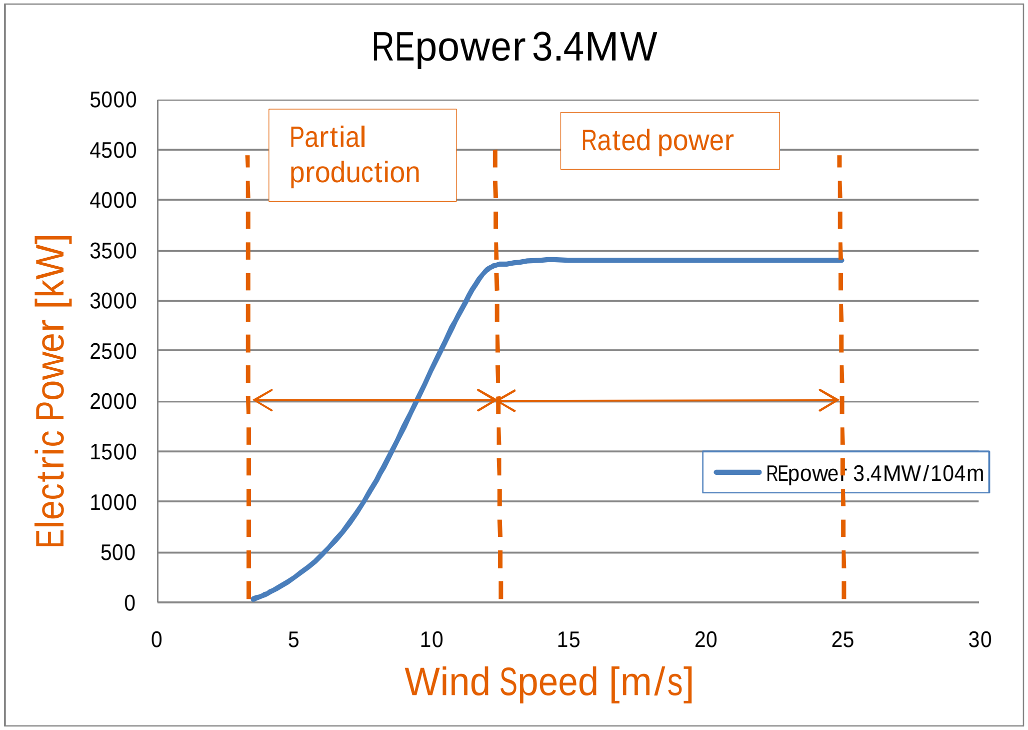
$$P_{elec} = P_{aero}.\eta$$

- There are two main regions in the power curve:
  - **Partial production** (P < Prated) : In this region the angular speed of the rotor is controlled through the **Generator Torque** in order to maintain the optimal tip speed ratio

$$P_{elec} = \eta.\frac{1}{2}.\rho.A.V^3.Cp(\lambda_{opt},\vartheta_{opt})$$

  - **Rated power** (P=Prated) : In this region the angular speed of the rotor is **constant**, and the pitch angle changes dependign on wind speed in order to maintain constant P=Prated

$$P_{elec} = P_{rated}$$



Wind Turbine Specific Rating (I)

Class IEC	I	II	III
Vref [m/s]	50	42,5	37,5
Vave [m/s]	10	8,5	7,5

- The **specific rating [kW/m2]** measures the **rated capacity** of the generator to the **swept area** of the rotor.

- For the same wind class, a lower specific rating means:
  - larger rotor, higher energy yield and design loads
  - The Cost of Energy (COE) will depend on the trade-off between energy yield and the cost of the wind turbine

- Higher **IEC class** (lower wind) favours lower machine ratings (chart in the right)

- Technological improvement allows increased rotor sizes for the same class, therefore reducing the specific rating

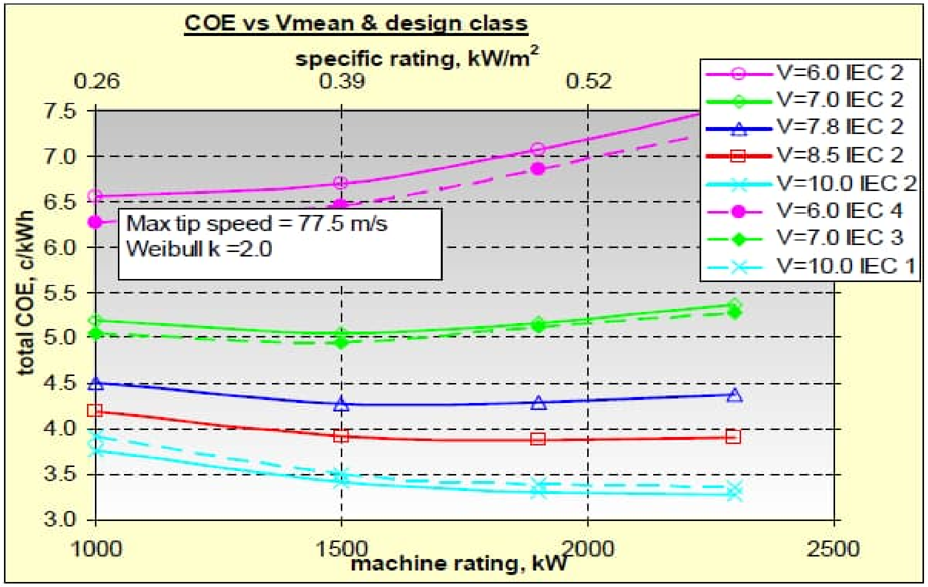


Figure 4-14. Effect on COE of mean wind speed and design class.

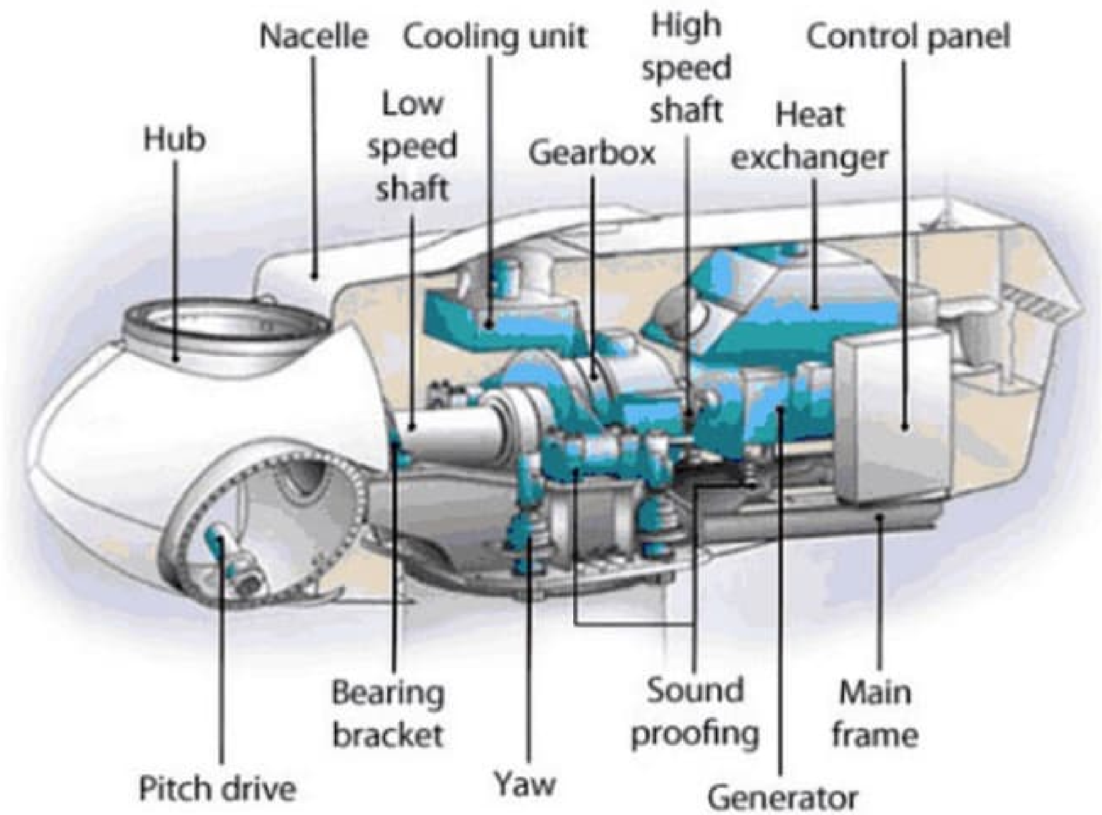
Source: WindPACT Turbine Rotor Design, Specific Rating Study, NREL, 2003

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Wind turbine systems

- A classical layout in a wind turbine nacelle is shown below



Source: https://www.e-education.psu.edu/earth104/node/923

List of of wind turbine systems
Rotor hub (cast, slip ring)
Pitch system
Rotor bearings
Blade pitch bearings
Blades
Nacelle
Main frame
Drive train - gearbox
Generator
Generator switching system
Converter
Compensator
Transformer
Control system (sensor array + industrial pc)
Supervisory Control & Protection / SCADA
Yaw system
Tower
Tower inner support structure
Foundation structure
Lubrication
Hydraulic
Cooling
Air conditioning /Air circulation
Electrical Auxiliary Power Supply
Earthing / Lightning Protection System
Obstacle Warning System
Fire extinguishing
Personnel Rescue System
Service lights
Lifting equipment (cranes, elevators)
IT Network & telephone
Process monitoring (fire alarm, video monitoring, environmental measurement)

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Drive train architectures

- **Wind is the prime mover** driving the generator, so input torque and speed will fluctuate substantially.
- There are five main architectures for the power transmission:
  - Fixed-speed SCIG, **”the Danish concept”**: Constant pitch rotor moving a fixed speed Squirrel Cage Induction Generator (SCIG), directly conected to the grid. A gearbox links the Low Speed Shaft (LSS) and the High Speed Shaft (HSS).
  - **High-speed geared DFIG**: Variable speed rotor with individual pitch drives a gearbox moving a Doubly-Fed Induction Generator (DFIG) controlled by a power converter.
  - **Low-speed Direct Drive**: Variable speed rotor with individual pitch directly moves a Generator - either Permanent Magnet Synchronous Generator (PMSG) or Electrically Excited Synchronous Generator (EESG). A Frequency Converter transforms generator frequency to grid frequency. No gearbox is required.
  - **Medium-speed geared ”the Multibrid concept”**: Variable individual pitch rotor connected to a gearbox which leads to a medium speed PMSG.

Variable-speed

The *”Danish concept”*

- The first widespread utility scale wind turbine had the following features:
  - 3 blades upwind of the tower
  - Fixed rotational speed
  - Fixed blade pitch, use of **passive stall** to limit the power at high winds
  - Gearbox
  - SCIG directly connected to the grid. Capacitor bank provides reactive power compensation

- Advantages:
  - **Simplicity and robustness** of generator
  - Simple control system (passive power limitation)
  - Damping of induction generator
  - **Low rotational speed** is benign regarding noise, and number of fatigue load cycles
  - Arguably more **pleasant to look at** than two-bladed turbines

- Disadvantages:
  - Low efficiency: it cannot maintain optimum λ at all wind speeds
  - Cannot maintain a constant rated power,
  - Obsolete due to evolving grid compliance requirements

Windmatic-Windmühle

Hersteller
Wind-Matic Aps.
Vester Lindvej 32
DK-7400 Herning

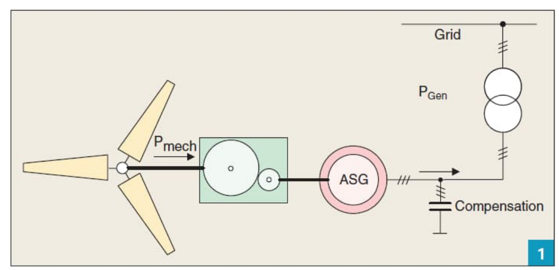
Konstruktionsprinzip
– Mittelschnelläufer, λ = 4,39;
– Dreiblattrotor;
– profilierte starre Flügel mit großer Blattiefe, hergestellt in Verbundbauweise aus nichtrostendem Stahl, GFK und Polyurethanschaum;
– Luvläufer mit 2 Seitenrädern;
– netzgeführte Anlage mit konstanter Drehzahl;
– Leistungsregelung durch Spoiler;
– Sicherung bei Sturm oder Netzabwurf durch automatische mechanische Bremse;
– Stahlgittermast.

Technische Daten

Masthöhe	12 m
Rotorkreisdurchmesser	10 m
Rotornenndrehzahl	67/min
Generator	Drehstrom-Asynchron, 1000/min
Getriebeübersetzung	1:14,83
Nennleistung	10 kW
Nennfrequenz	50 Hz
Nennspannung	220/380 V
Nennwindgeschwindigkeit	8 m/s

Source: Windmatic / Böhmeke ”*Wind Power Concepts” (2010)*

15



Fixed speed “Danish” concept.

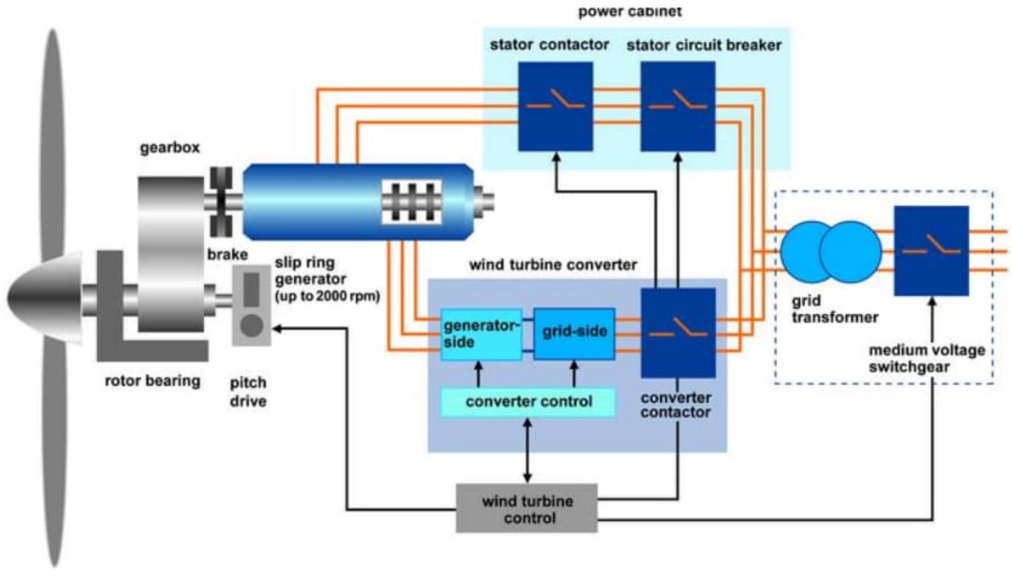
Source: S. Müller et al. ”Doubly-fed induction generator systems”
IEEE INDUSTRY APPLICATIONS MAGAZINE MAY|JUNE 2002”

The high-speed geared DFIG (I)

- Introduced in 1996 by Tacke Windtecknik (now GE) in 1.5MW machine. Vestas and others followed (year 2000)
- Now arguably the mainstream turbine onshore. It has the following features:

  - 3 blades upwind
  - gearbox
  - Variable individual pitch to mantain power constant above Vrated

  - DFIG machine:
    - **Variable generator speed** ~ +/-30% of synchronous speed [nmin, nmax]
    - Rotor connected to the grid via a **Power Converter**, and the Stator is directly conected to the grid
    - The power converter requires a capacity only 20%-35% of the generator rated capacity
    - Rotor over-current protection (passive crowbar)
    - Control of reactive power
    - Direct Torque Control to keep rotor at λopt, and Pitch Control

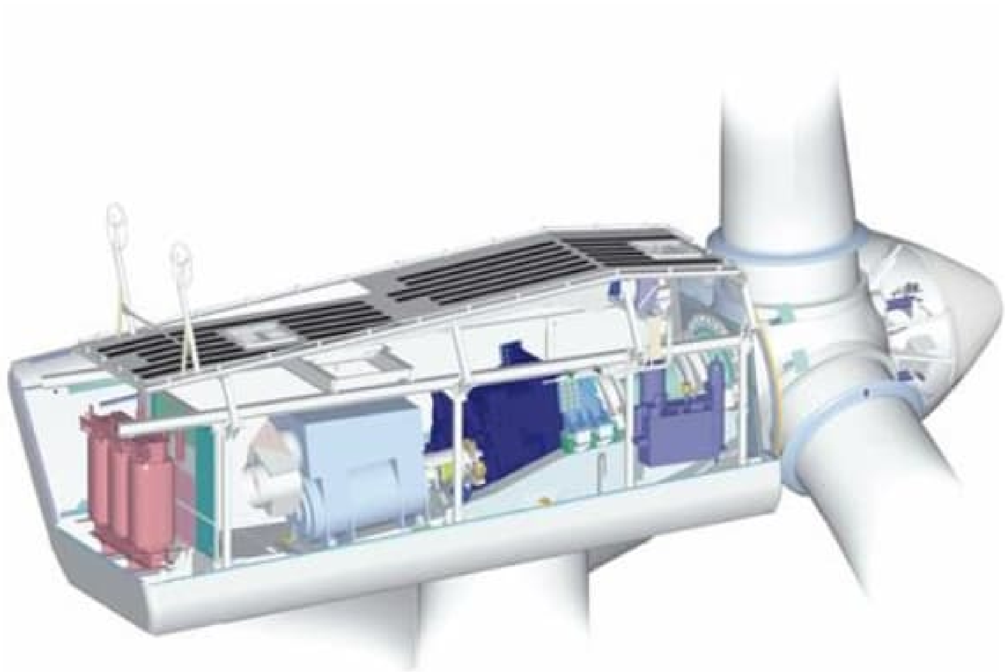


Source: ABB

The high-speed geared DFIG (II)

- Advantages:
  - High **efficiency**: Operates at **λopt**, and therefore at maximum Cp in the interval [nmin,nmax]
  - **Reduced loads** in the drive train: the rotor accelerates during gusts storing energy as mechanical inertia
  - Improved response to **grid requirements**, better power quality – less fluctuation
  - Reduced noise: can operate at reduced tip speed in low winds
  - Relatively inexpensive power converter

- Disadvantages:
  - Higher energy losses compared to synchronous generators (e.g. PMSG)
  - It ”only” operates optimally between [nmin,nmax] , therefore efficiency is low at very low wind speeds near cut-in
  - Still requires a gearbox



Revert to DFIG... A typical Vestas 2MW layout, with main shaft supported in two main bearings

Source: Vestas, Windpower Monthly (2013)

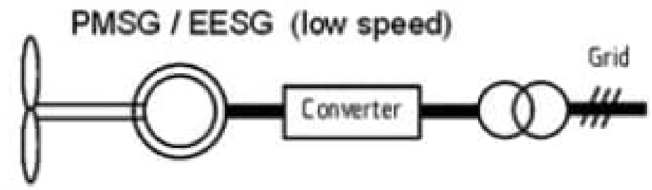
The Direct Drive (I)

- The Direct Drive (DD , ”gearless”) turbine was first introduced by Enercon in 1995, using a Electrically Excited Synchronous Generator (EESG). Most manufacturers use a Permanent Magnet Synchronous Generator (PMSG)

- It has the following features:
  - 3 blades upwind, variable individual pitch
  - Generator, followed by full capacity power converted

  - Advantages:
    - **Full range** of generator speed
    - **Higher mechanical and electrical efficiency**: no mechanical losses due to gearbox. Also in case of PMSG, the generator is more efficient than DFIG as it does not require energy for electric excitation
    - **Reliability**: does not need gearbox

  - Disadvantages:
    - Exposed to fluctuation in the price of **rare earths** (mostly Neodymium and Dysprosium).
    - **Large generator** due to lower rotational speed , and higher input torque
    - Generator exposed directly to rotor loads, requires clever design of load path
    - Expensive Full Scale Converter



Source: ”Technological evolution of onshore wind turbines – a market-based analysis”. J Serrano-González and R- Lacal-Arántegui Wind Energ. 2016; 19:2171–2187

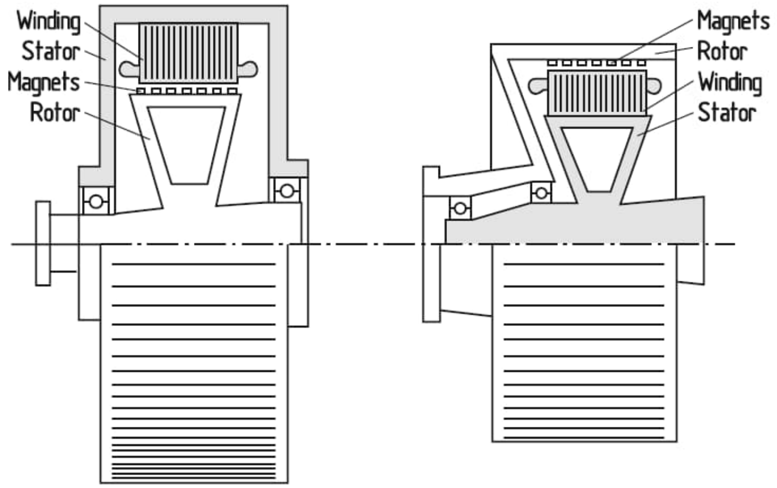
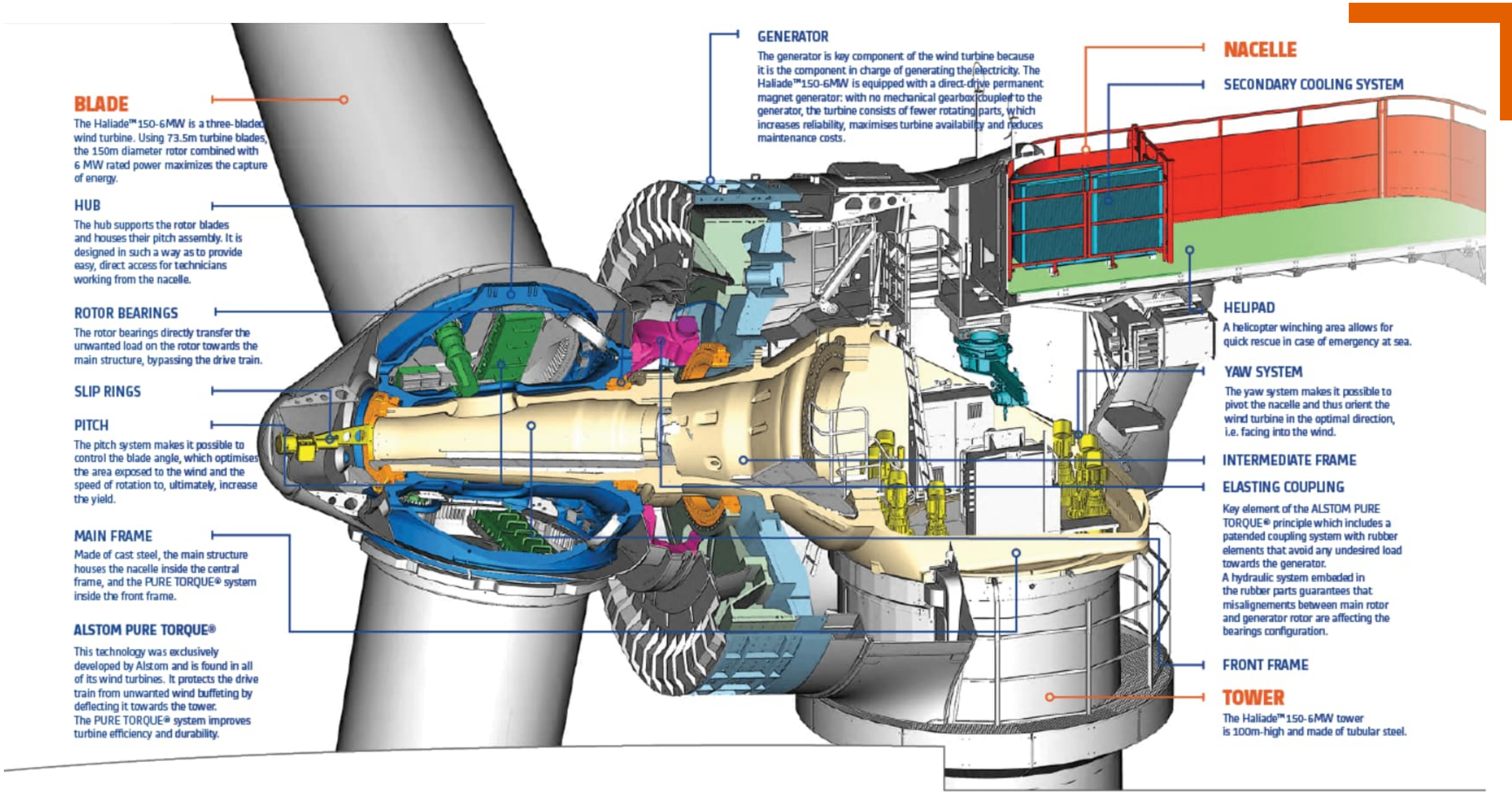


Fig. 10.14. Low-speed permanent magnet generators with “inner” and “outer” rotor design

Erich Hau ”Wind Turbines” Ed 3.



Built upon ALSTOM PURE TORQUE® proven technology for drive train reliability, Alstom has developed a new generation, 6 MW direct drive offshore wind turbine. Suitable for all offshore conditions -uncompromising on reliability-, the turbine will deliver a leading cost of offshore energy while supplying electric power for up to 5,000 households.

ALSTOM
Shaping the future

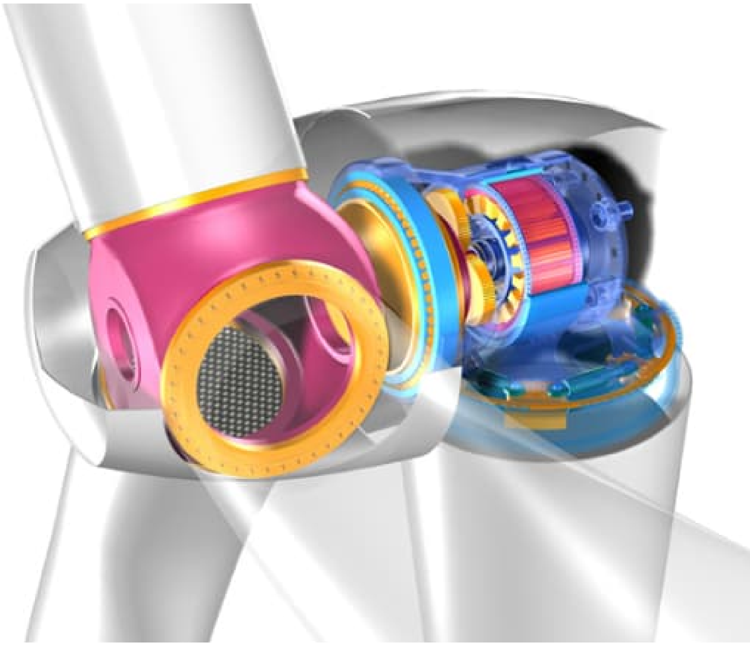
Source: Windpower Engineering - General Electric - Alstom

The *”Multibrid concept”* (I)

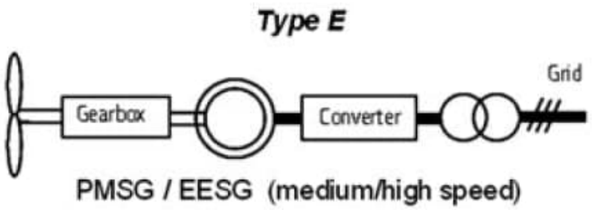
- The Multibrid (from ”multimegawatt and hybrid”) is a drive train solution which emerged as a response to early problems of DFIG and DD machines:
  - gearbox failure (leading to expensive field gearbox replacement) , and
  - the high cost of DD generators.
- It was patented in 1997 by German consultancy Aerodyn, and the first prototype was erected in 2004.

- It had the following features:

  - 3-blades upwind, variable individual pitch
  - Lightweight **single-stage gearbox** (gear ratio ~1:6)
  - **Medium-speed generator** (frequently PMSG)
  - **Gearbox housing, generator housing, and rotor bearing encapsulated into one cast mainframe**



Source: Future Power Oy



Source: ”Technological evolution of onshore wind turbines – a market-based analysis”. J Serrano-González and R- Lacal-Arántegui Wind Energ. 2016; 19:2171–2187

The *”Multibrid concept”* (II)

- Advantages:
  - Lower tower head mass compared to DFIG, and DD
  - Less amount of rare earths required compared with DD
  - Less corrosion due to encapsulated components
- Disadvantages:
  - Requires a gearbox
  - Expensive full scale converter
- The concept inclucenced later designs such as the recent Adwen 8MW 180 offshore turbine

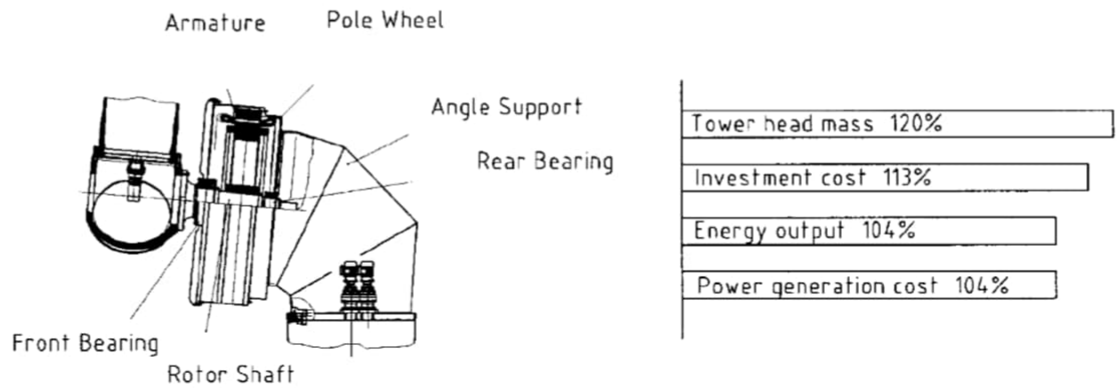


Figure 2. Direct drive generator

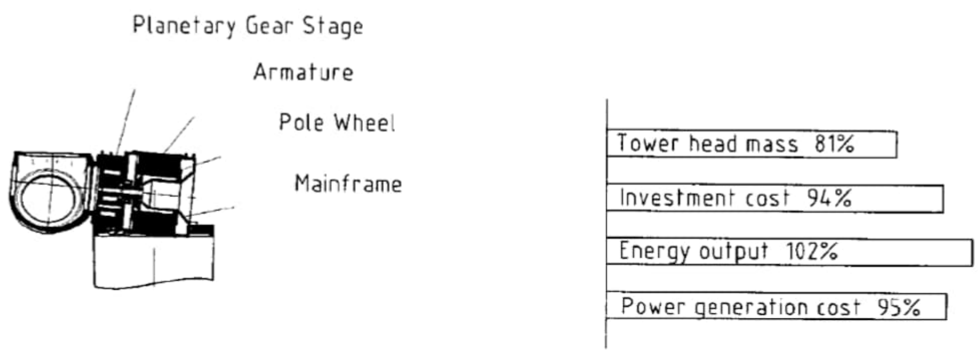


Figure 3. Multibrid installation

Source: S. Siegfriedsen, G. Böhmeke "Multibrid Technology - A Significant Step to Multi-megawatt Wind Turbines" Wind Energ., 1, 89-100 (1998)

The pitch system (I)

- The pitch system adjust the **blade pitch angle** by rotating the blades around their longitudinal axis. It has three missions:

  - **Power control:** To adjust the blade pitch angle to keep constant power above the rated wind speed
  - **Safety element:** as aerodynamic brake, pitching to approx +90deg (pitch to feather) to stop the rotor. This function requires a **energy reserve** in case of wind turbine power outage (either batteries or hydraulic accumulator)
  - **Load control:** Pitch control is also used, as part of the control system, to control the dynamic response of the turbine, reducing loads

- Early pitch drives (1980s) were mostly **collective pitch** (all blades pitch at the same time) with a hydraulic actuator and mechanical coupling. This arrangement results in high design loads in some failure cases.

- Nowadays the market seems to lean towards **electric pitch drives**, mainly because of perceived risk of fire due to leakage. Vestas continues to use hydraulic pitch.

	Hydraulic pitch	Electric pitch
Pros	* Simpler (fewer components)	* Compact design
	* Low maintenance	* Precise control
	* High reliability	* Clean
	* Fluid in the system damps structural vibrations	* Operation in all climatic conditions
	* No backlash	
	* No wear in pitching gears	
	* Operation up to -30C, Survival up to -40C	
Cons	* Leakage risk: during service and replacement, a high level of cleanliness must be obtained	* Backlash between gears
		* Wear in pitching gears, difficult to lubricate pitch gear due to small movements
		* Batteries: difficult to monitor, low power at low temperature and frequent replacement

23.9.2022 L03 topics

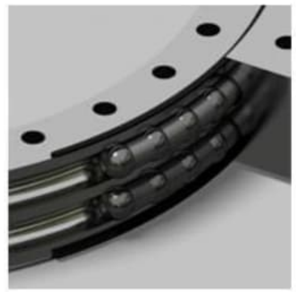
- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

The pitch system (II)

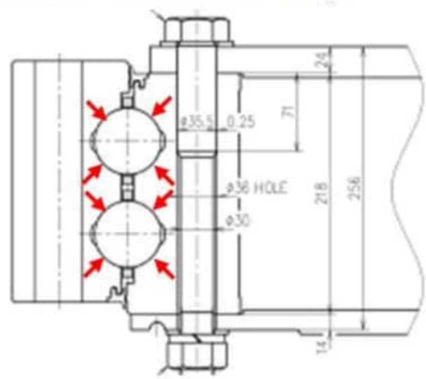
- The blades are connected to the rotor hub by the **rotor blade bearing** (pitch bearing):
- Typically double row, 8-point contact sealed ball bearings are used

Fig. 9.23. Hydraulic blade pitch system in the interior of the rotor hub (Rexroth)

Erich Hau "Wind Turbines" Ed 3.

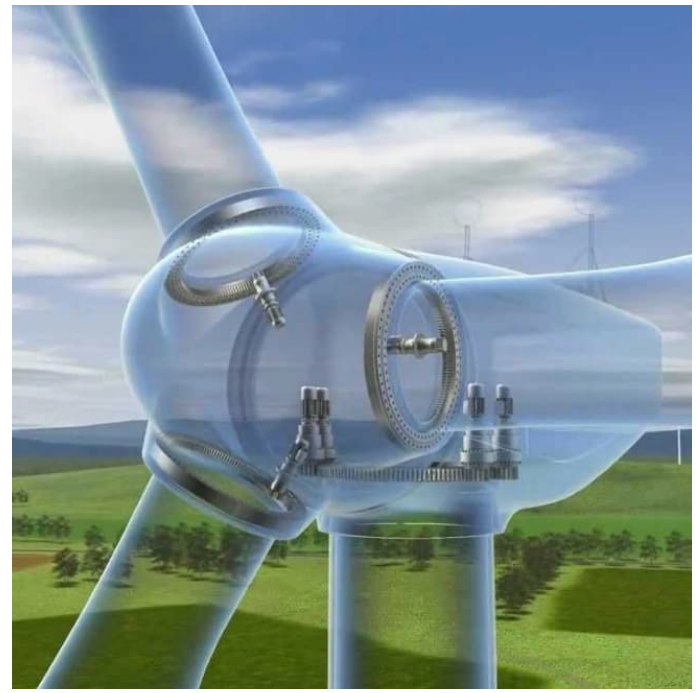


Typical 8 Point Contact Bearing



Bearing Cross Section

Source: WindPower Engineering / RBB Engineering



Electric pitch drives ("slewing gearbox", pitch bearings, and yaw drives
(Source: Liebherr)

23.9.2022 L03 topics

- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

The yaw system

- The yaw system orients the wind turbine nacelle against the wind linking the nacelle and the tower, and prevents any unwanted relative rotation. The system comprises the following elements:

- **Azimut bearing,** traditionally double row, 8-point contact sealed ball bearings are used, although friction bearings are also possible
- **Driving mechanism**, a layout similar to the pitch system, with a number of electric motors each moving a planetary gearbox, and a "slewing gearbox". Hydraulic drives are also possible
- **Yaw brakes** prevent the yaw drives from absorbing yaw loads during operation. They typically consist on calipers acting on a brake ring inside the tower
- **Yaw misalignment sensors**, traditionally the nacelle anemometers, but also other solutions (ROMO-wind pressure measurement, nacelle mounted forward looking LIDAR)
- **Cable twist sensor**, a rotary encoder to track nacelle rotation and prevent cable twisting

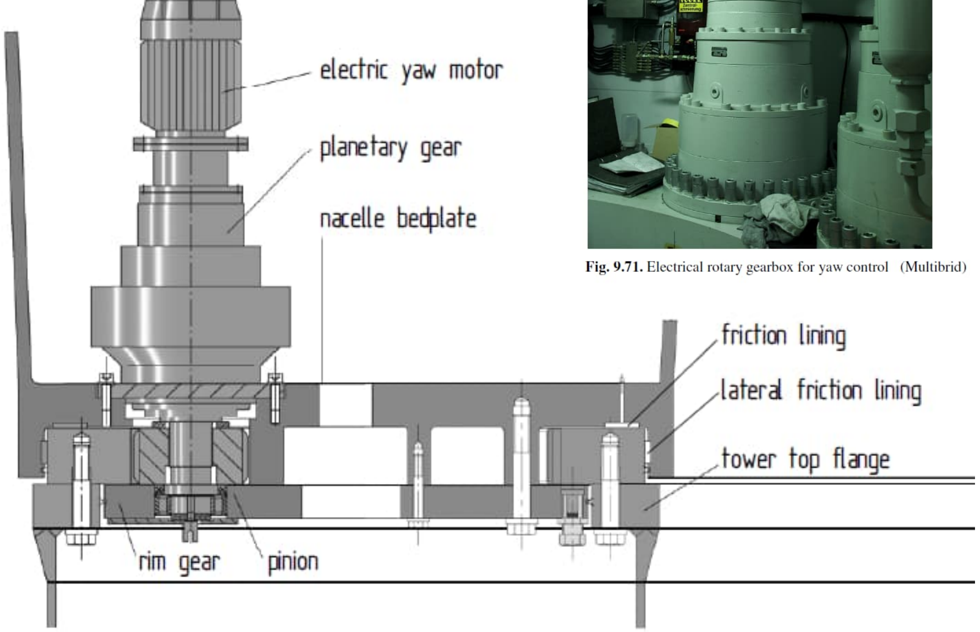


Fig. 9.71. Electrical rotary gearbox for yaw control (Multibrid)

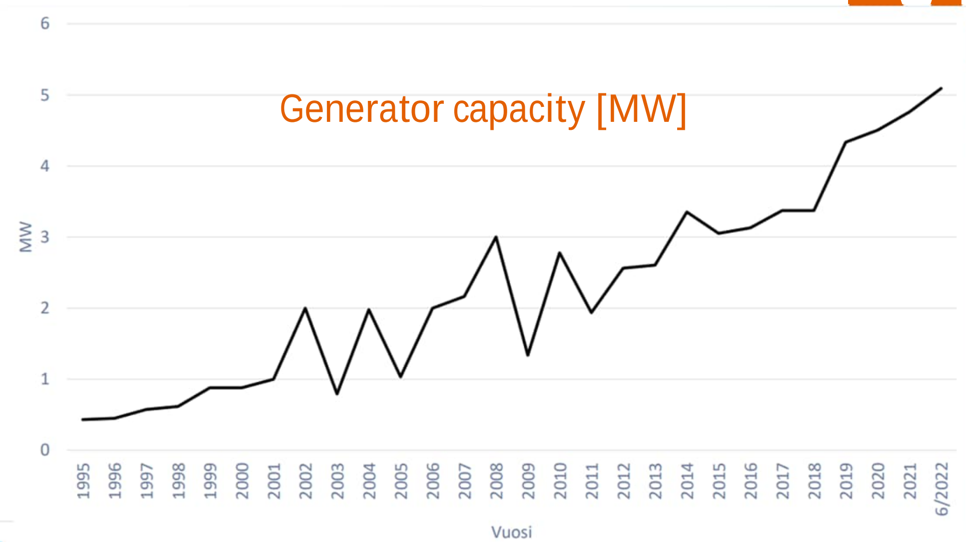
Erich Hau "Wind Turbines" Ed 3.

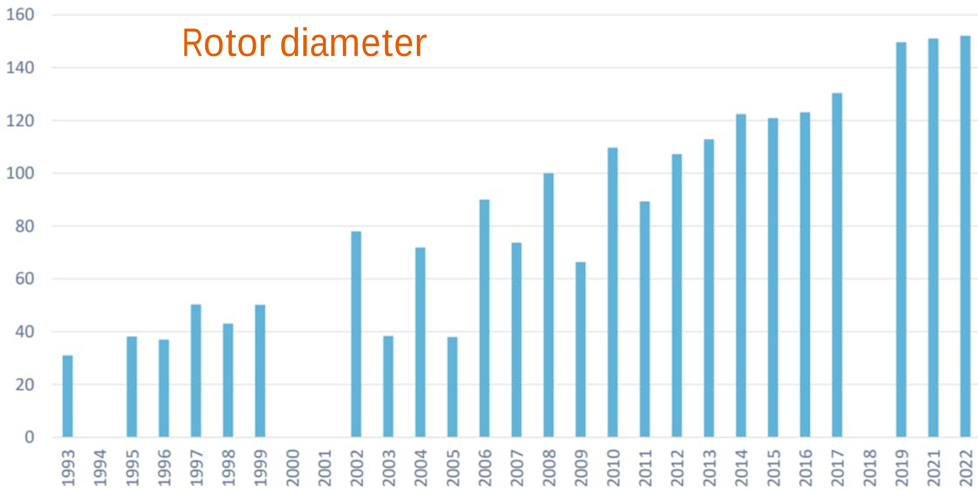
23.9.2022 L03 topics

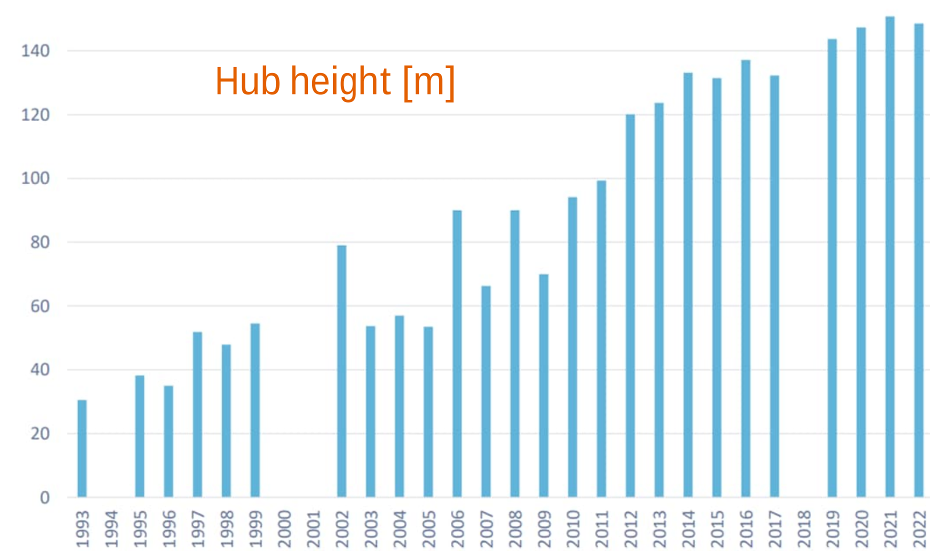
- Electricity from wind – Poul La Cour
- Wind energy converter concepts
- Wind turbine aerodynamics
- Key design drivers
- Wind turbine performance
- Wind turbine systems
- Drive train architectures
- Pitch system
- Yaw system
- Modern wind turbine

Modern wind turbine

- Statistics from Finland
- Collected by Suomen tuulivoimayhdistys







Modern wind turbine

- Increase rotor size has improved turbine efficiency
- Increase in tower height has improved yield
- New materials and new manufacturing processes
- Square-cube –law:
  - Power output ~ r^2
  - Weight / materials ~ r^3
- ➔there is a limit where increase in size will no longer be worth it

Manufacturing a blade for Vestas V236 wind turbine prototype
Blade length 115.5m.

https://www.vestas.com/en/products/offshore/V236-15MW/prototype

Future

- Blades have reached 100m
- Generator capacity 15 MW
- Offshore
- Increased interest in floating offshore

Hywind Tampen – Assembly of the world's largest floating wind farm - YouTube

Haliade-X offshore wind turbine - installation time lapse - YouTube

Photo courtesy of Cobra Group.
Source:
https://www.principlepower.com/news/kowl-worlds-largest-floating-windfarm-fully-operational

References

- *Erich Hau ”Wind Turbines” Ed 3*
- *Peter Jamieson, DNVGL, SUPERGEN Wind training seminar Sept 2010*
- *T. Burton et al. ”Wind Energy Handbook” Wiley & Sons. 2001*
- *Herbert J. Sutherland, et at A Retrospective of VAWT Technology. SANDIA REPORT SAND2012-0304 (2012)*
- *Böhmeke, ”Wind Power Concepts” (2010)*
- S. Müller et al. ”Doubly-fed induction generator systems” IEEE INDUSTRY APPLICATIONS MAGAZINE May-June 2002
- ”Technological evolution of onshore wind turbines – a market-based analysis”. J Serrano-González and R- Lacal-Arántegui Wind Energ. 2016; 19:2171–2187

Source: Vestas