Introduction to wind turbine technology training course

Session 1.5: architecture of wind turbines

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Wind energy conversion concepts

Rotors

Vertical axis wind turbine (VAWT or VAT)

horizontal axis wind turbine (HAWT or HAT) with ducted rotor

Conventional wind turbine

Non-rotors

Translating aerofoils

Airborne wind concepts

Electrodynamic converter

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Key variables

- HAWT or VAWT
- Design tip speed
- Number of blades
- Pitch or stall
- Upwind or Downwind
- Drive train layout and components

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VAWT Designs from the 1980’s

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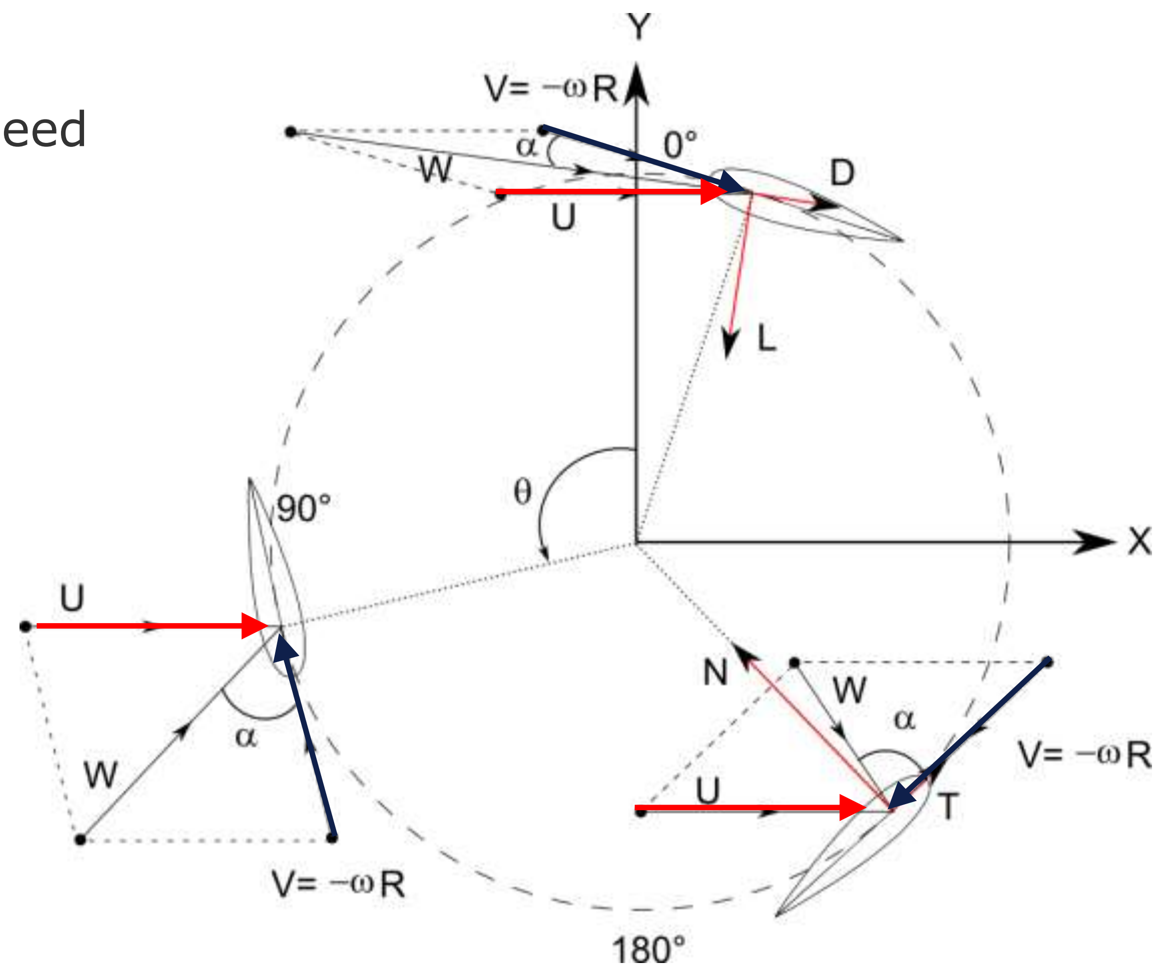
VAWT Aerodynamics – More Complicated!

Tangential speed

Wind speed



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VAWT Design Conclusions

- Market failure of VAWT design can be seen as a consequence of the energy-torque dilemma. In simple terms, VAWTs are less efficient and intrinsically slower running – therefore substantially less energy, higher torque, weight and cost.

- Niche markets exist for VAWTs at small scale

- VAWT revivalists argue that cyclic gravity loading of blades is avoided compared to HAWTs but cyclic loads due to the intrinsic torque cycle of VAWTs and many other dynamic loads are just as problematic

- The VAWT may yet have a future but probably needs conceptual development beyond the historic Darrieus and H type forms to be cost effective

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Design Tip Speed

Maximum tip speed:

- High maximum tip speed implies low drive torque and low gearbox or DD mass and costs
- Limits to the maximum tip speed:
  - Aero-acoustic noise emission typically limits the tip speed to 65 ms for constant speed stall machine and to 75 m/s for variable speed pitch machines in Europe.
  - Leading edge erosion limits the tip speed of offshore turbines to 85 m/s

Optimum tip speed ratio:

- High optimum tip speed ratio:
  - Reduces the solidity of the blade (solidity is often expressed as projected blade area divided by the swept area). Low solidity reduces the storm loads in idling and gust loading in operation
  - Increases the flexibility of the blade and makes the blade structural design less efficient.

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Design Tip Speed Trends

Tip speed ratio

Monopteros

Lambda=15,

tip speed=120 m/s

Modern 3 bladed

Lambda=7 to 8,

tip speed= 70 to 80 m/s

Old Dutch

Lambda=3 to 4,

tip speed= 30 to 40 m/s

Water pump

Lambda=2 to 3,

tip speed= 30 to 40 m/s

Maximum tip speed

Number of Blades – some of the issues

- A wind turbine has an optimum thrust loading for maximum power – adding blades to an optimised turbine reduces power!
- More blades with optimal rotor design is slightly more power – reduces tip loss
- Hence 3 bladed turbine about 2% more power than 2 bladed and about 8% more than one bladed but depends very much on design details and operational strategy
- Optimum rotor speed reduces with increasing blade number
- Easier to make stiff rotors with fewer blades
- However flexible blades relieve loads

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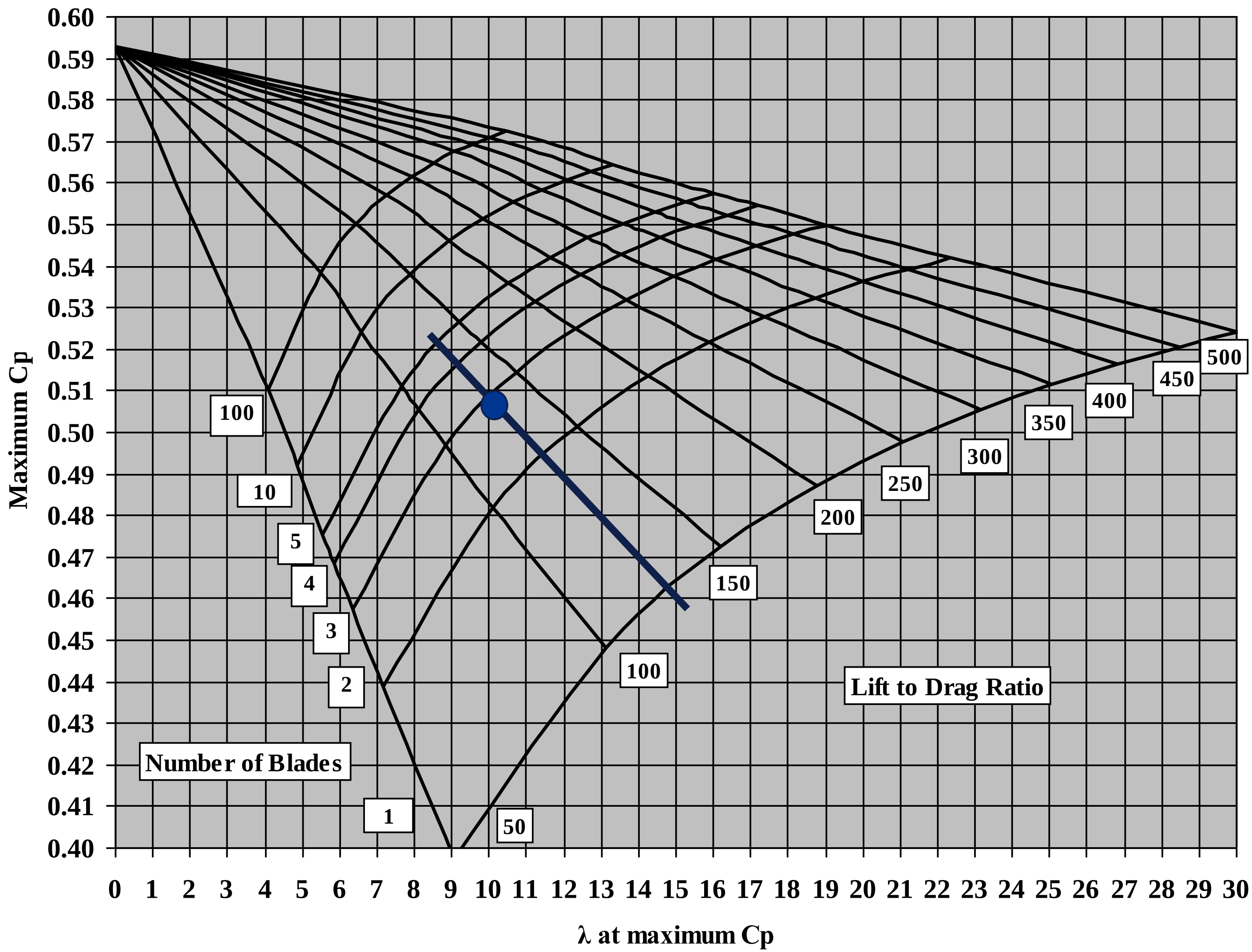
Rotor Power Coefficient



Number of Blades – Dynamic issues

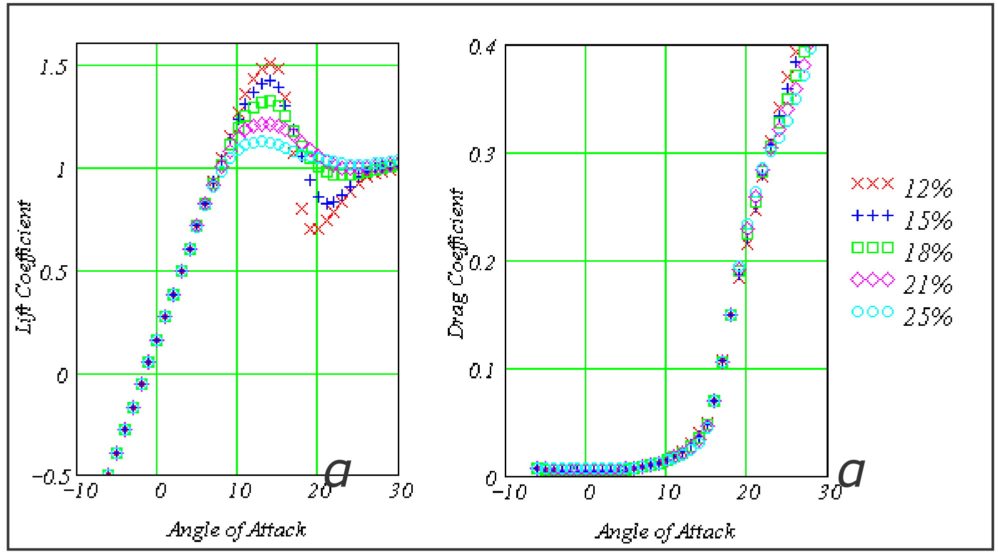
- 3 Blades provide good dynamic balance with respect to blade weight, rotation of the rotor about the tower axis – yawing and aerodynamic forces in wind shear conditions.
- 2 Blades are balanced in rotating mass but have variable inertia about the yaw axis and varying aerodynamic forces in wind shear conditions.
- 1 Blade is completely unbalanced and needs a counterweight!

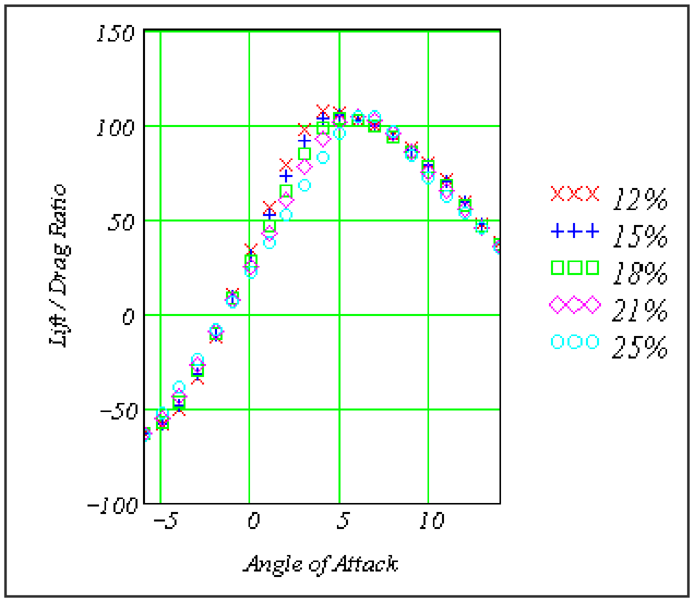
Loose analogy with vehicles and number of wheels - tricycle stable, bicycle OK but requires active balancing, one wheel only for circus tricks!

Number of Blades – Summary

- 2 bladed rotors are probably lighter but often not as 2/3 mass of a 3 bladed rotor
- Energy differences of a few percent are not to be dismissed – often they are more significant for overall cost of energy than quite substantial capital cost impacts on individual components
- Many issues relating to blade number are easily identified but any definitive conclusion about what is optimum requires comparison of complete wind turbine designs and is very complex
- The preference for 3 blades over 2 has been established in consideration of visual impact and there is no clear decision on purely technical and cost aspects
- Although traditional multi-bladed turbines are of low efficiency and mostly used for pumping applications, multi bladed turbines can be highly efficient aerodynamically. They may need a rim or other structural solutions.

Pitch or stall; angle of attack





$$C_l = \frac{Lift - per - unit - span}{\frac{1}{2} \cdot \rho \cdot U^2 \cdot c}$$

$$C_d = \frac{Drag - per - unit - span}{\frac{1}{2} \cdot \rho \cdot U^2 \cdot c}$$

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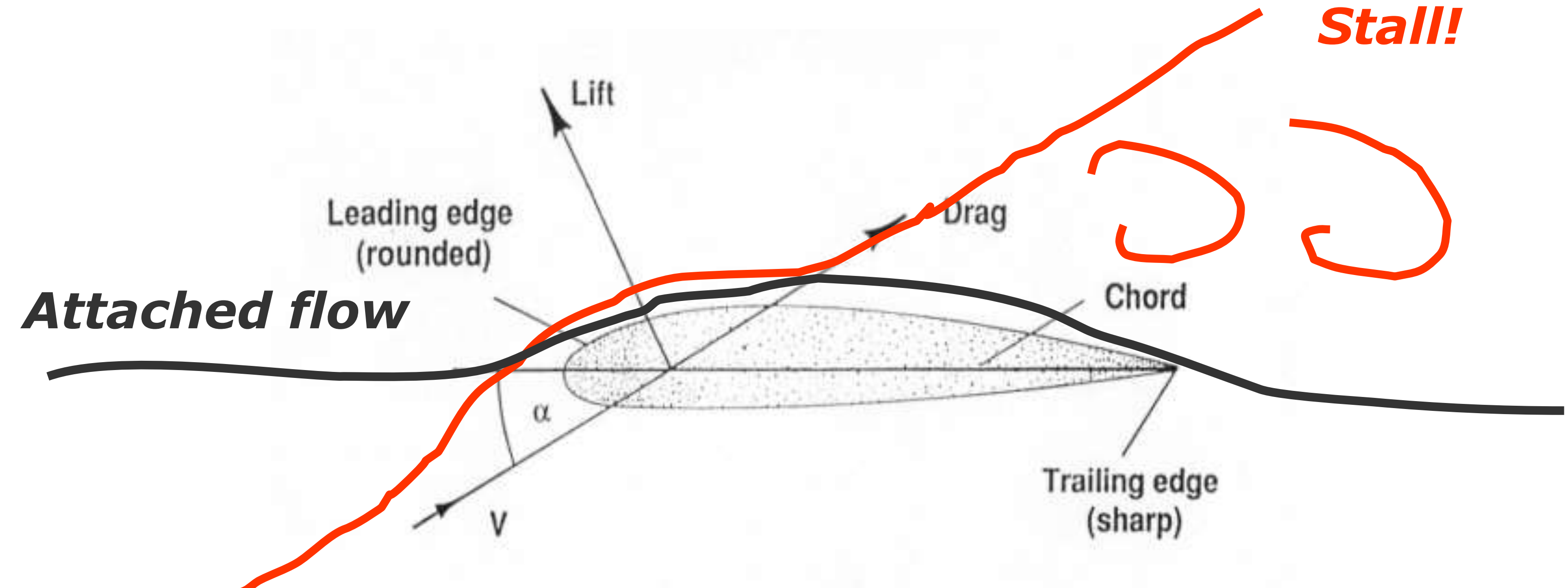
Stall Regulation – How does it Work?



Drag	- in direction of flow
Lift	- at right angles to flow
α	- angle of attack - angle between flow direction and chord line
Chord	- distance between extreme leading edge and trailing edge points

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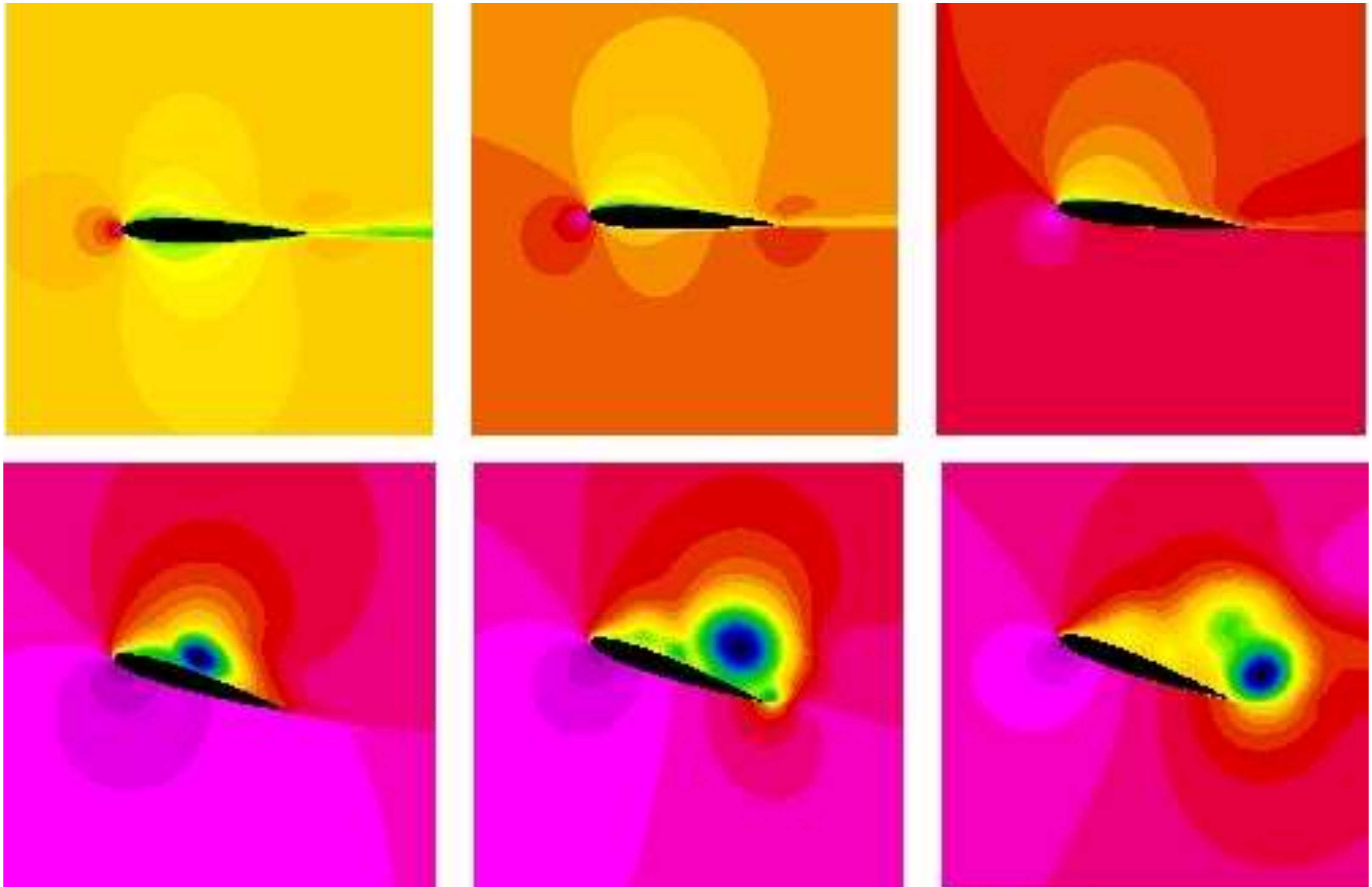
Stall Regulation –What is stall?



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Pitch or Stall - Overview

- In the 1980's to 1990's, total numbers of each type were similar although most pitching wind turbines were Vestas
- Control of fixed speed, variable pitch wind turbines was difficult in high wind speeds – often they shut down early (say 15 m/s rather than 25 m/s) or reduced output power in high winds. Others problems related with (passive) stall control are: stall induced vibrations, varying power performance and acoustic noise.
- This drove the development of innovative solutions – high slip generators provided a degree of variable speed (Vestas OptiSlip and Suzlon FlexiSlip still use this design solution)
- Fatigue for operation in stall compared to operation in attached flow arises differently but the overall impacts are similar
- Compliance with increasingly stringent network requirements (grid codes) has favoured variable speed pitch regulated wind turbines and stall regulation is declining as a design route.

Upwind or Downwind?

- In the downwind configuration the wind strikes the support structure (tower) before it encounters the blades
- The support structure always disturbs the flow and reduces the average wind speed over a sector. The effect is generally more severe in the downwind configuration where it may cause additional impulsive blade loading and low frequency sound
- This interference effect of the support structure is often referred to as "tower shadow"
- No point in a down wind configuration with a conventional wind turbine design that can operate satisfactorily upwind.
- Down wind is often supposed to offer more stable yaw and perhaps free yaw but yaw stability is very complex and free yaw is a marginal benefit
- Probably the most justifiable reason for a down wind configuration is to facilitate a light weight system with much reduced loading from having very flexible blades

Wind Turbine Architecture

- HAWT design only is considered
- Nacelle layout
- Pitch and yaw systems
- Support structures
- Drive train technology

Nacelle layout

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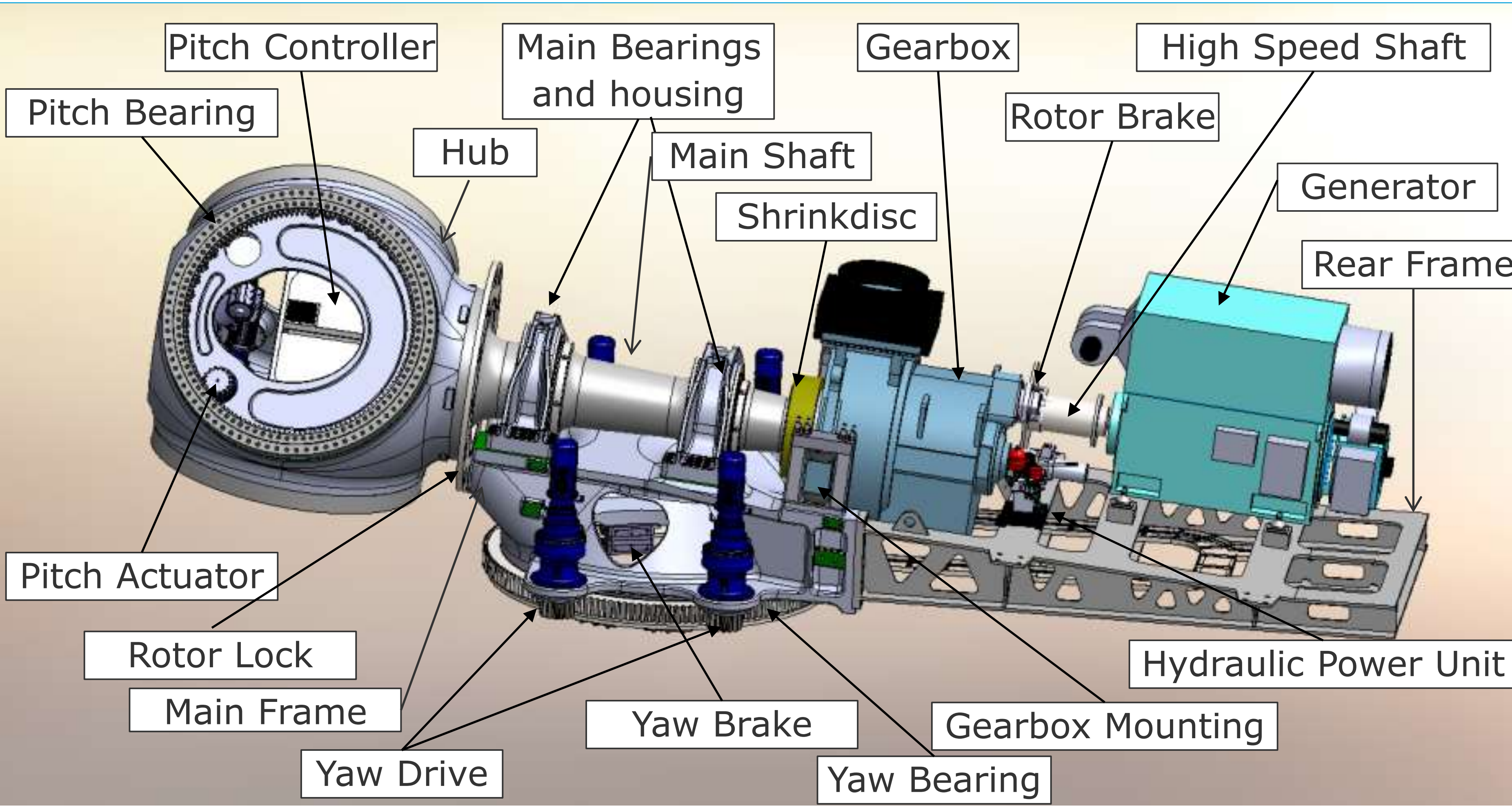
Wind Turbine Architecture
Overview of Main Nacelle Components



2.0MW Conventional modern geared Wind Turbine Nacelle Design

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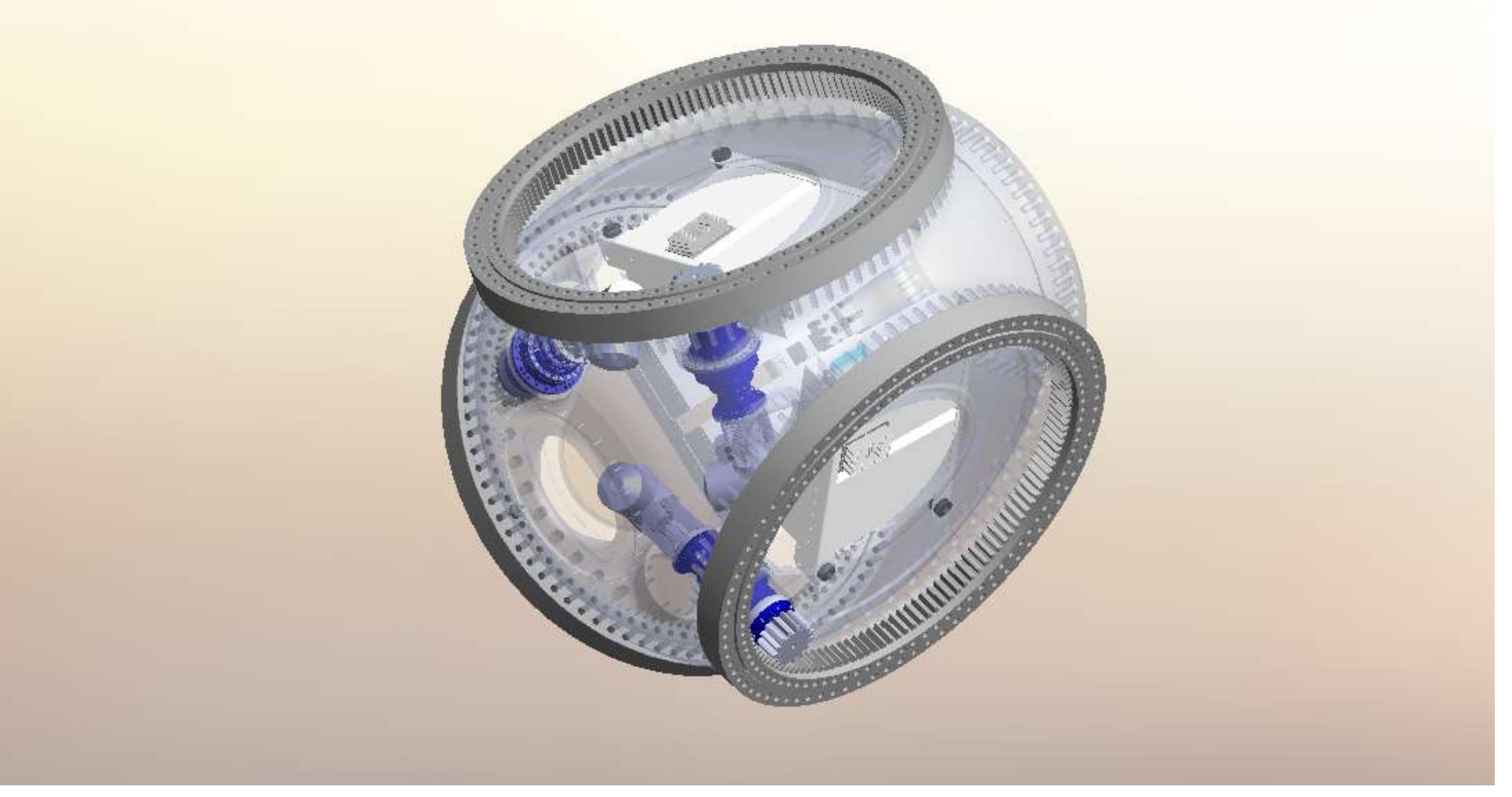
Pitch System



2.0MW Wind Turbine Pitch System

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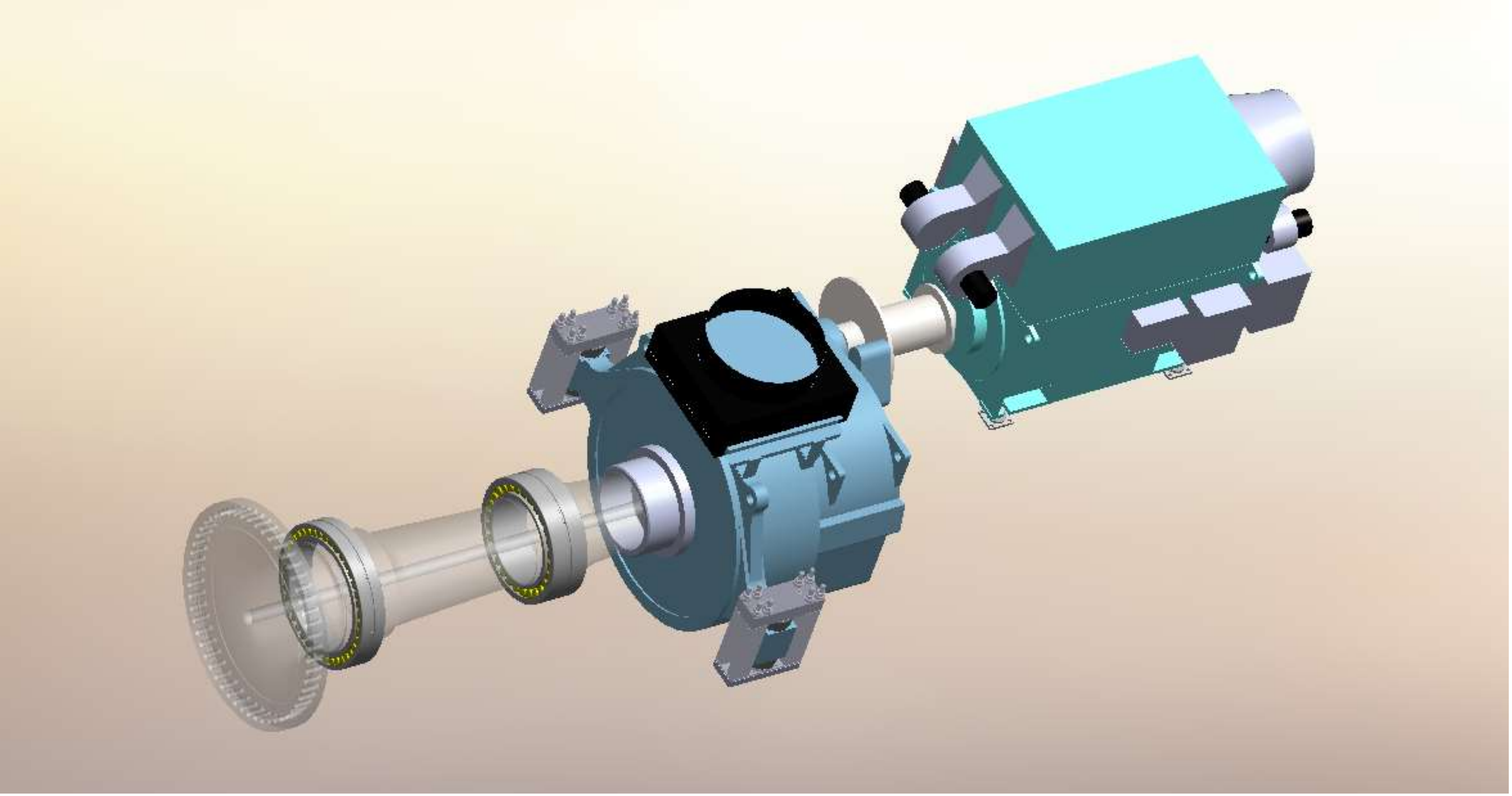
Drivetrain System



2.0MW Wind Turbine Drive Train

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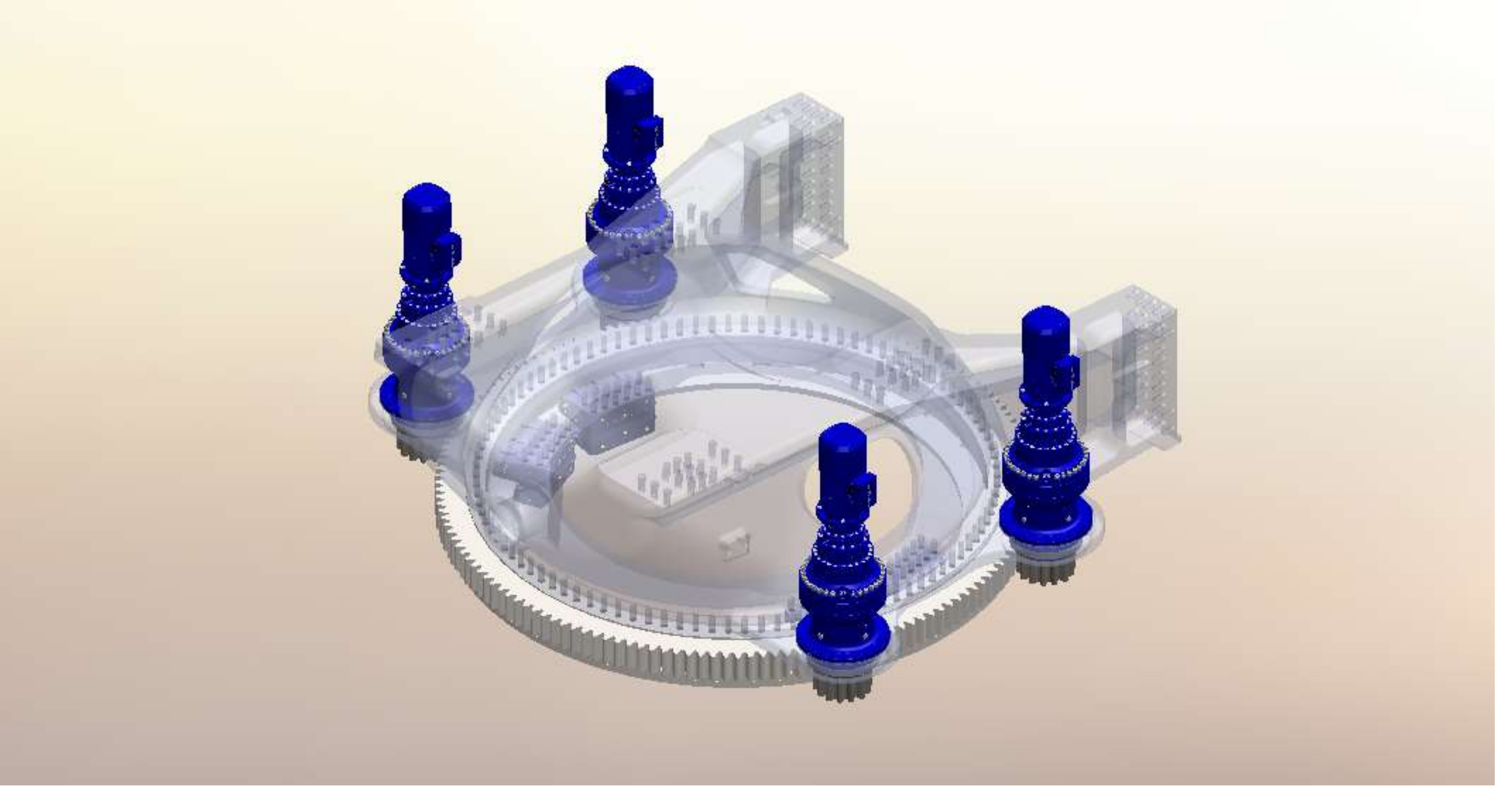
Yaw System



2.0MW Wind Turbine Yaw System

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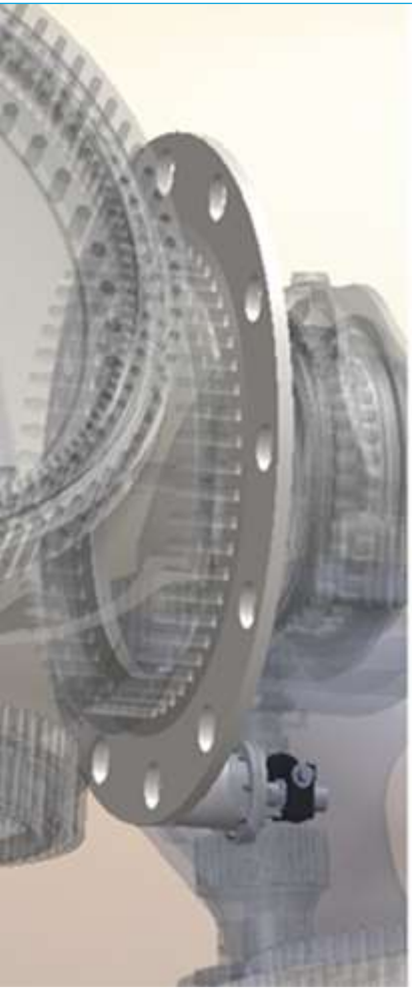
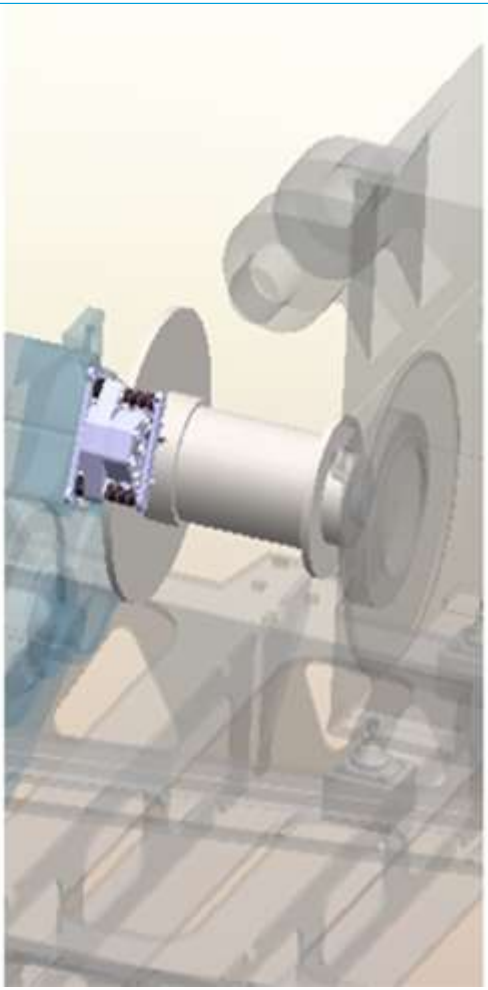
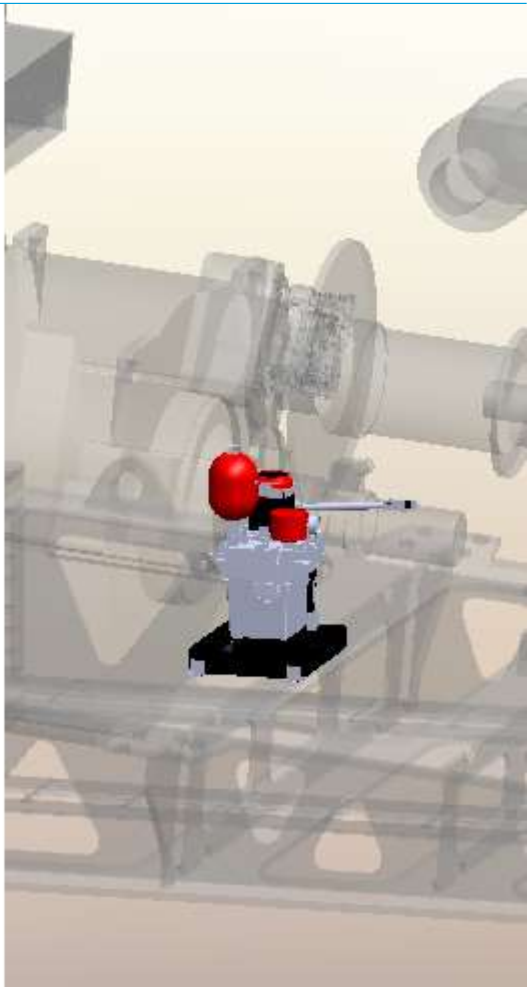
Other Mechanical Systems

2.0MW Wind Turbine Other Mechanical System

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Pitch System

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Pitch System
A brief overview of the contents

- The functions of the pitch system
- Pitch system layouts
- Typical pitch system components
- Loads on the pitch system components
- Known problems
- Effects of de-rating on the pitch system

Total failure of the pitch systems can lead to loss of turbine though rotor overspeed & then tower collapse due to thrust.

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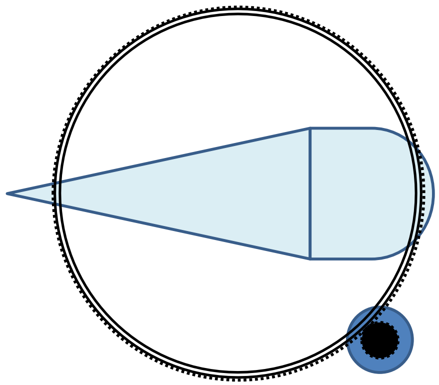
Pitch System
The functions of the pitch system

- To provide the torque demanded by the converter (control power)
- To control the rotor speed
- To maximise the energy captured from the wind
- Transfer blade loads into the rotor hub
- Independently pitching blades reduce the risk of a single fault disabling the whole pitch system
- Loads in the rest of the turbine are strongly affected by the behaviour of the pitch system

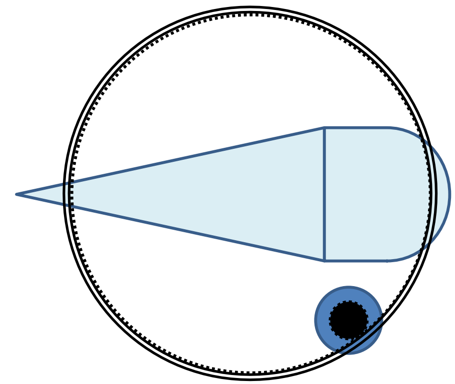
Pitch System
Pitch system layouts: Electrical pitch system

External ring gear



- Blade mounted onto largest diameter
- Easy access to pitch drives
- Larger pinion-ring gear ratio
- Better heat dissipation possible
- Less protected pitch drives
- Limited space for mounting the pitch drives

Internal ring gear



- Blade mounted onto smallest diameter
- Restricted access to pitch drives
- Lower pinion-ring gear ratio
- Heat build-up inside the hub
- Good protection of the pitch drives
- Sufficient space for mounting the pitch drives

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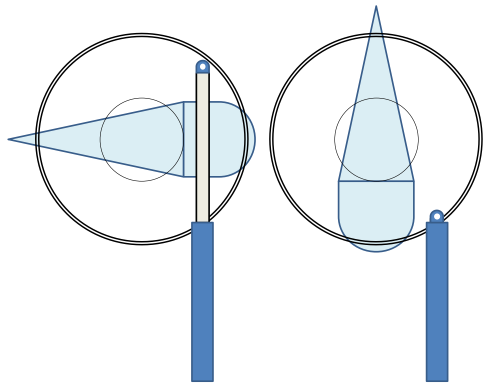
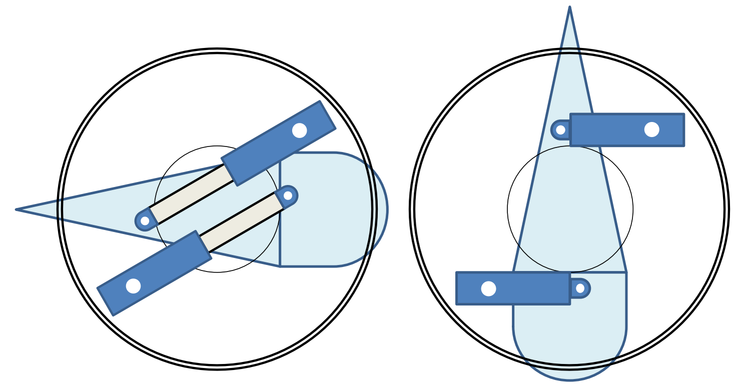
Pitch System
Pitch system layouts: Hydraulic pitch system

External hydraulic pitch actuator(s)



- Simple an cheap design
- “Easy” replacement of actuator
- Very high capacity possible
- Very long linear hydraulic actuator
- Hole through hub/hub extender required

Internal hydraulic pitch actuators



- Compact design
- No structural disrupting holes in hub
- Lower capacity
- More difficult to replace
- More expensive

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Pitch System
Typical pitch system components

Typical component in the pitch system are:

- Pitch Bearing
- Pitch Actuator (also acts as brake system)
  - Electric
  - Hydraulic
- Pitch Controller/Backup power
  - Control Cabinet / Hydraulic Pitch Power Pack
  - Backup Battery Cabinet / Hydraulic Pitch Accumulator
- Lubrication System
  - Bearing Lubrication
  - Gear Lubrication
  - Waste Grease Collecting Bottles
- Encoder/Limit Switches/Locking system

Pitch System
Typical pitch system components: Electric pitch system

- The electric pitch actuator system consists out of 5 main components:

1. Pitch Drive Pinion
2. Pitch Drive Gearbox
3. Pitch Drive Electric Motor
4. Pitch Control Cabinet
5. Pitch Battery Cabinet

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Pitch System
Typical pitch system components: Hydraulic pitch system

- The hydraulic pitch actuator system consists out of 4 main components:

1. Pitch Actuator
2. Pitch Accumulator
3. Hydraulic Pitch Power Pack
4. Control Panel

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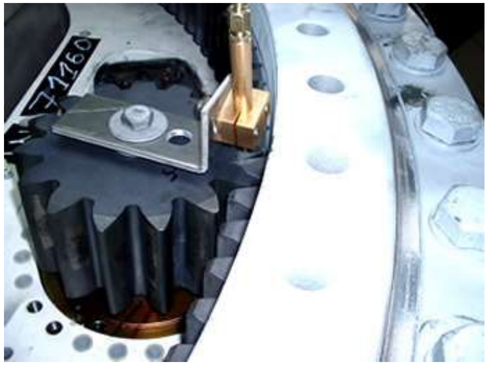
Pitch System
Typical pitch system components: Lubrication system

- The right lubricant and lubrication system is very important for the pitch system
  - The limited motion results in difficulties keeping a wear protective film inside the bearing and on the gears
  - Protection against corrosion
- The lubrication system consists out of:
  - Bearing lubrication system
  - Ring gear lubrication system
    - Spraying nozzles
    - Foam/grease wheel
    - Self lubricating pinion
  - Waste grease collecting bottles
  - The right lubricants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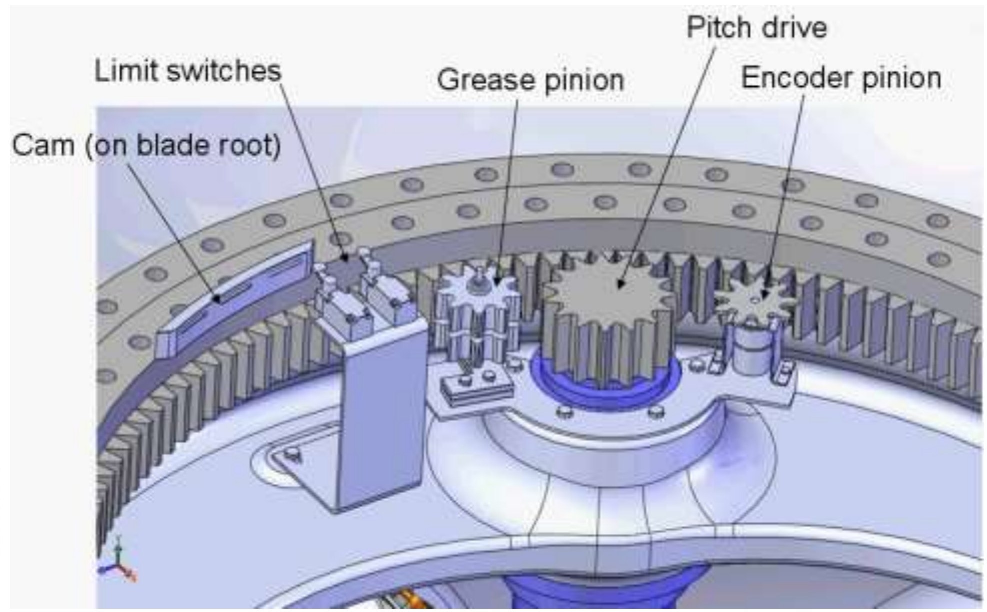
Pitch System
Typical pitch system components: Encoder/Limit switches/Lock

- To allow the safety and control systems to know the current pitch angle requires sensors and switches, these are often mounted at the edge of the pitch bearing. The required sensors typically are:
  - Encoder pinion for pitch angle
  - Limit switches

- A pitch lock for the blade



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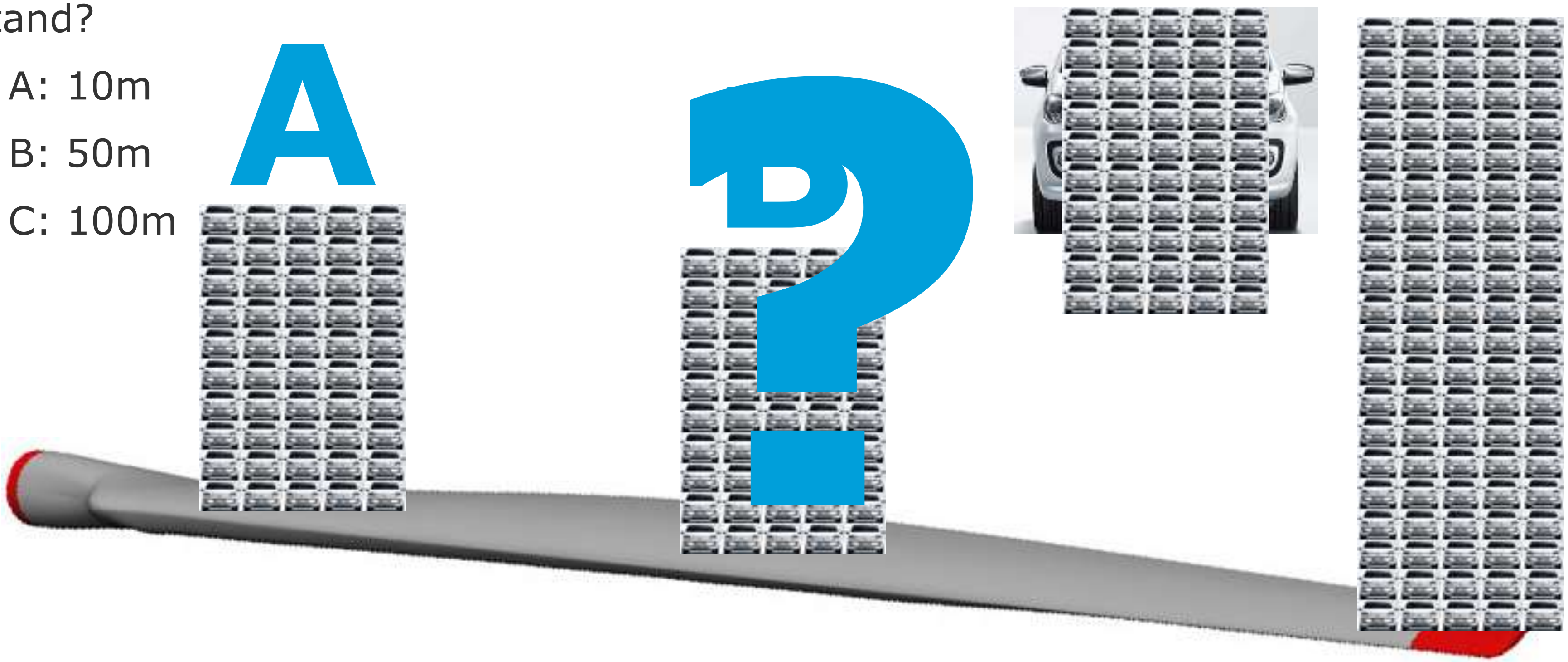
Pitch System
Sizing the pitch system: Quiz

- 10MW+ wind turbines might have 100m long blades 80,000kNm of bending moment at the bearing.
- A typical very compact car is approximately 800kg
- If we have 50 of these cars standing at the blade,at which distance would they stand?
  - A: 10m
  - B: 50m
  - C: 100m



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Yaw System

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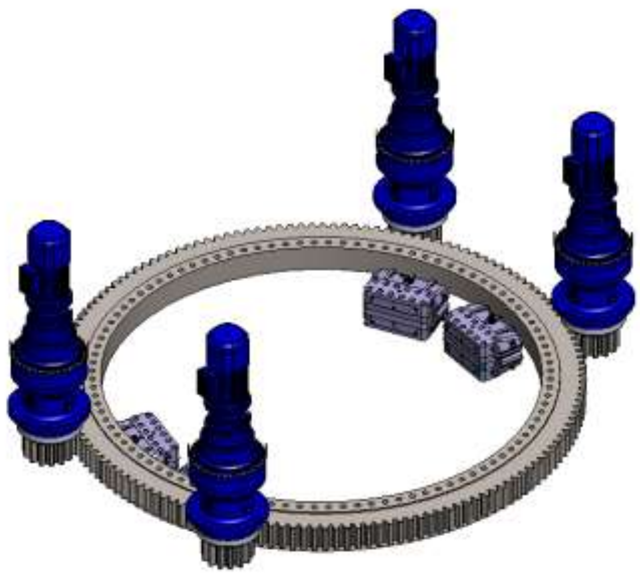
Yaw System
A brief overview of the contents

- The functions of the yaw system
- Yaw system layouts
- Typical yaw system components
- Loads on the yaw system components
- Known problems
- Effects of de-rating on the yaw system



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Yaw System
The functions of the yaw system

- To align the rotor with the wind direction
- To maximise the energy captured from the wind
- To keep misalignment with wind direction when idling
- To transfer nacelle loads into the tower
- Extreme loads during storm conditions in the rest of the turbine are strongly affected by the behaviour of the yaw system

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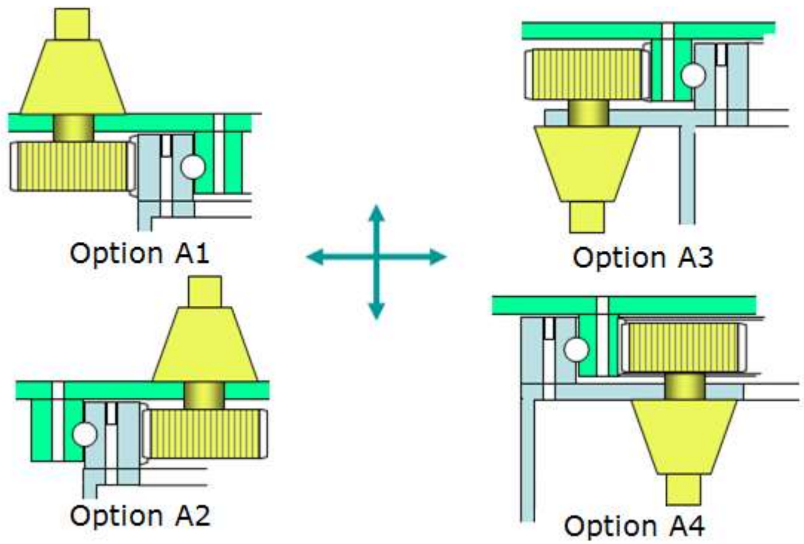
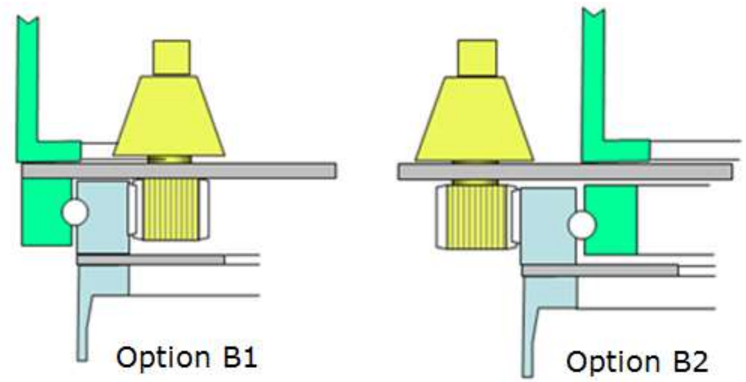
Yaw System
Yaw system layouts

Yaw bearing mounted between tower and mainframe



- A1-A2 yaw drive on mainframe
- A3-A4 yaw drive on tower
- A1-A3 external ring gear
- A2-A4 internal ring gear

Yaw bearing mounted between two tower sections (yaw tube)



- B1 internal ring gear
- B2 external ring gear

Yaw System
Typical yaw system components

Typical component in the pitch system are:

- Yaw Bearing
- Yaw Actuator
  - Electric
  - Hydraulic
- Yaw Brake System
  - Brake callipers
  - Yaw brake disc
- Lubrication System
  - Bearing Lubrication
  - Ring Gear Lubrication Pinion
  - Waste Grease Collecting Bottles
- Encoder/Locking system

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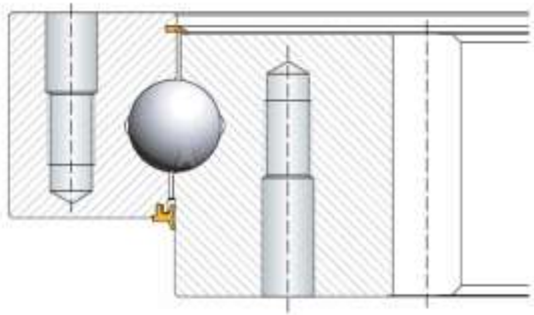
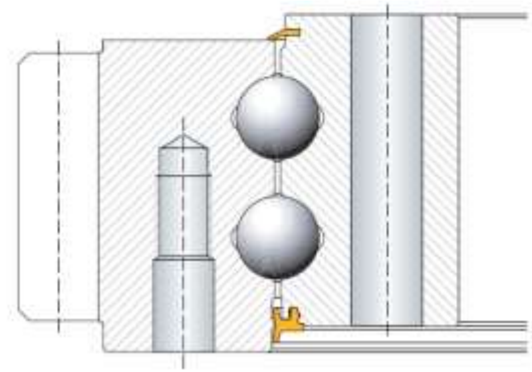
Yaw System
Typical yaw system components: Yaw bearing

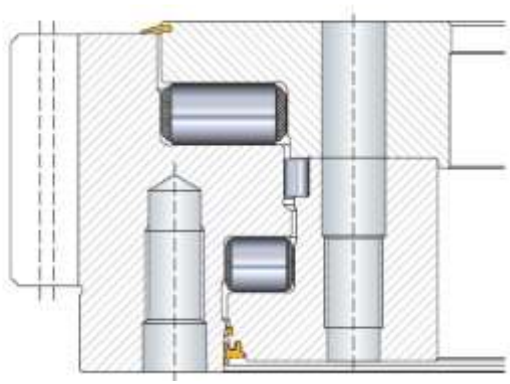
- 4-point contact ball bearing



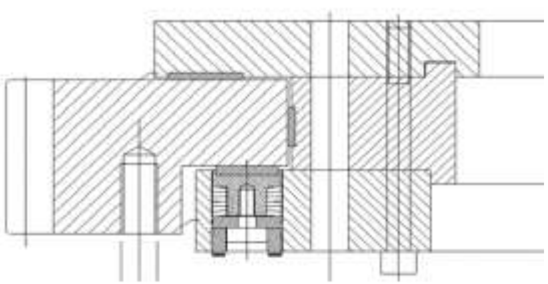
- 8-point contact ball bearing (large turbines)



- 3-row cylindrical roller bearing



- Plain bearing



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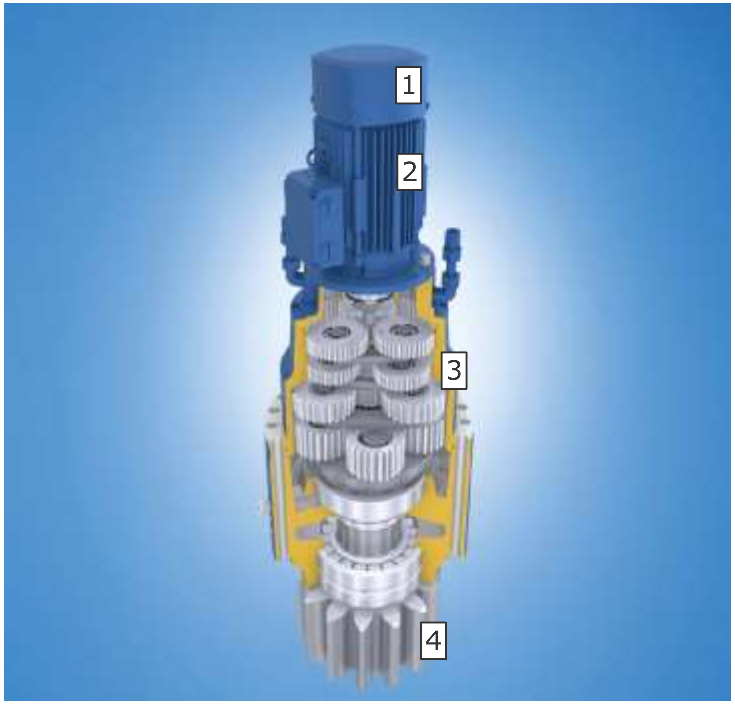
Yaw System
Typical yaw system components: Yaw Actuator

- The yaw actuator system consists out of 4 main components:

1. Yaw Drive Motor Brake
2. Yaw Drive Electric Motor
3. Yaw Drive Gearbox
4. Yaw Drive Pinion



- The electric motor can be replaced by a hydraulic motor to make it a hydraulic yaw actuator

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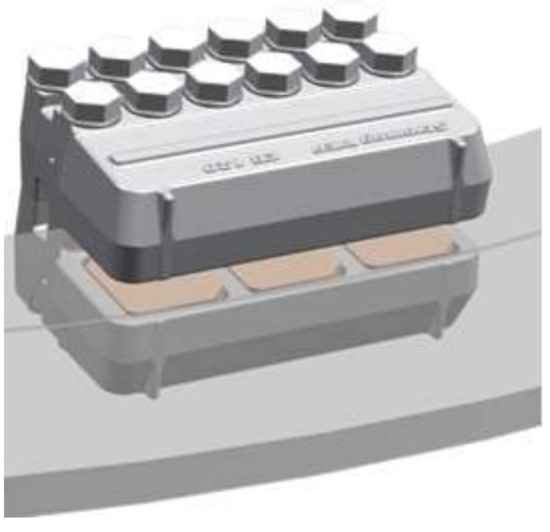
Yaw System
Typical yaw system components: Yaw Brake Calliper

- Currently 2 type of yaw brake callipers are in use:
  - Hydraulic yaw brake calliper, is by far most common and still is the traditional choice.
  - Electrical yaw brake calliper, is a relatively new development in the wind industry. Allows for a full electrical wind turbine design



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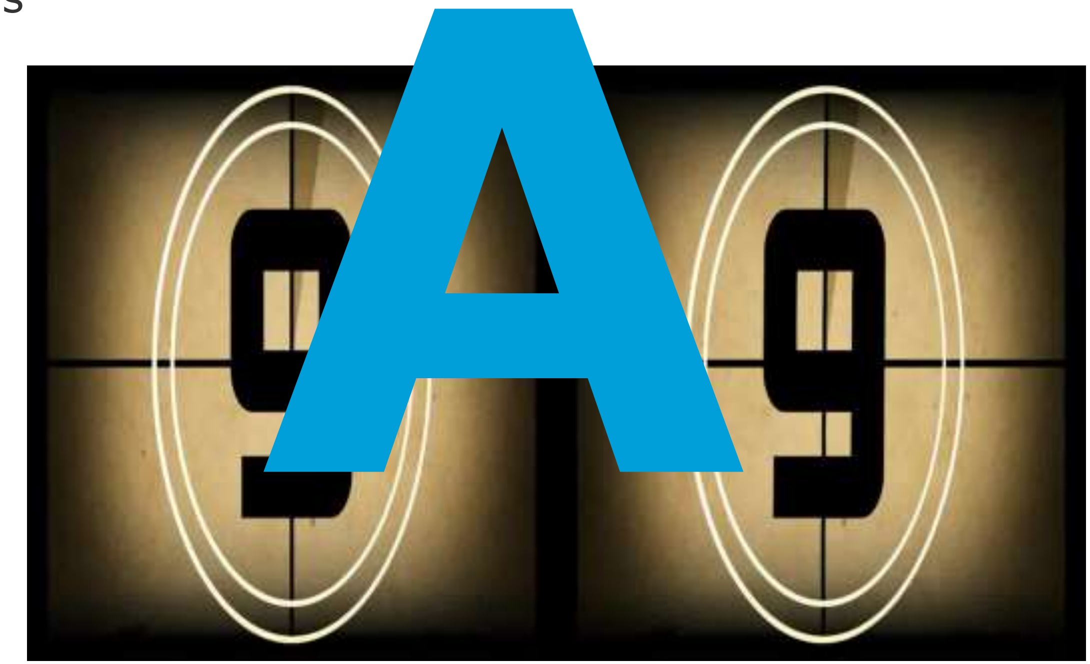
Yaw System
Loads on the yaw system components: Quiz

- A wind turbine has two systems which can be used as a yaw brake system, the yaw brake callipers and the motor brakes on the yaw actuators.
- How does the brake capacity from the yaw actuators or yaw drives compare against the yaw brake callipers in a typical yaw system ?
  - Callipers : Drives
  - A: 25 : 75
  - B: 50 : 50
  - C: 75 : 25
  - D: 10 : 90



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Support Structures

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Tower design

100% tubular towers are most common. But due to transportation limits and increasing size of turbines a trend towards alternative design can be observed.

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Tower design

Lattice tower:

Fuhrlander, Seeba tower

Lattice tower+:

GE Space Frame tower

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Tower design

Guyed tower:

Small wind turbine

Guyed tower:

Mervento 3.6MW

Braced tower:

V48 + Valmont system

Tower design

Multi sided tower:

Andresen tower for Siemens wind:

Multi sided tower:

Lagerwey Wind L100 on 135m hub height:

Tower design

Full concrete tower:

E.g. Enercon

Hybrid tower:

E.g. Advance tower systems

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Tower design

The general trend is that towers are becoming **taller** because:

- Large availability of the lower wind speed class sites (fewer good sites) where higher towers are required for turbine efficiency;
- Larger rotors requiring taller towers (this also links together wind low wind speed class);
- Wind turbine in forested areas with additional tree line height;

The following tower solutions are expected to play a more important part in the future European onshore market:

- Multi sided folded plate tower designs;
- Hybrid solutions (concrete base, steel top).

The remaining presentation will focus on the design and analysis of **steel tubular towers.**

Tower design

Main functions:

1. Transfers Forces and Moments from the nacelle structure to the foundation;
2. Bring the rotor to required height;
3. Provide access route from base to the nacelle.

Tower plate Cold climate material:

S355J2G3, or equivalent with charpy impact values of 27 Joules average at –40 deg C;

Flange material Cold climate material:
S355NL, with a weld neck of min. 35mm or equivalent with charpy impact values of 27 Joules average at –40 deg C

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Tower design: Transportation size and weight constraints

Constraint	Rough Limits
Maximum diameter (height under bridges)	4.3-4.6m
Maximum section length	25-35m
Maximum section mass	60-80t

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Tower design: Transportation size and weight constraints

Road transportation limits

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Tower design: Transportation size and weight constraints

Maximum mass and size limitation in manufacturing facility

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Tower design: Manufacturing process






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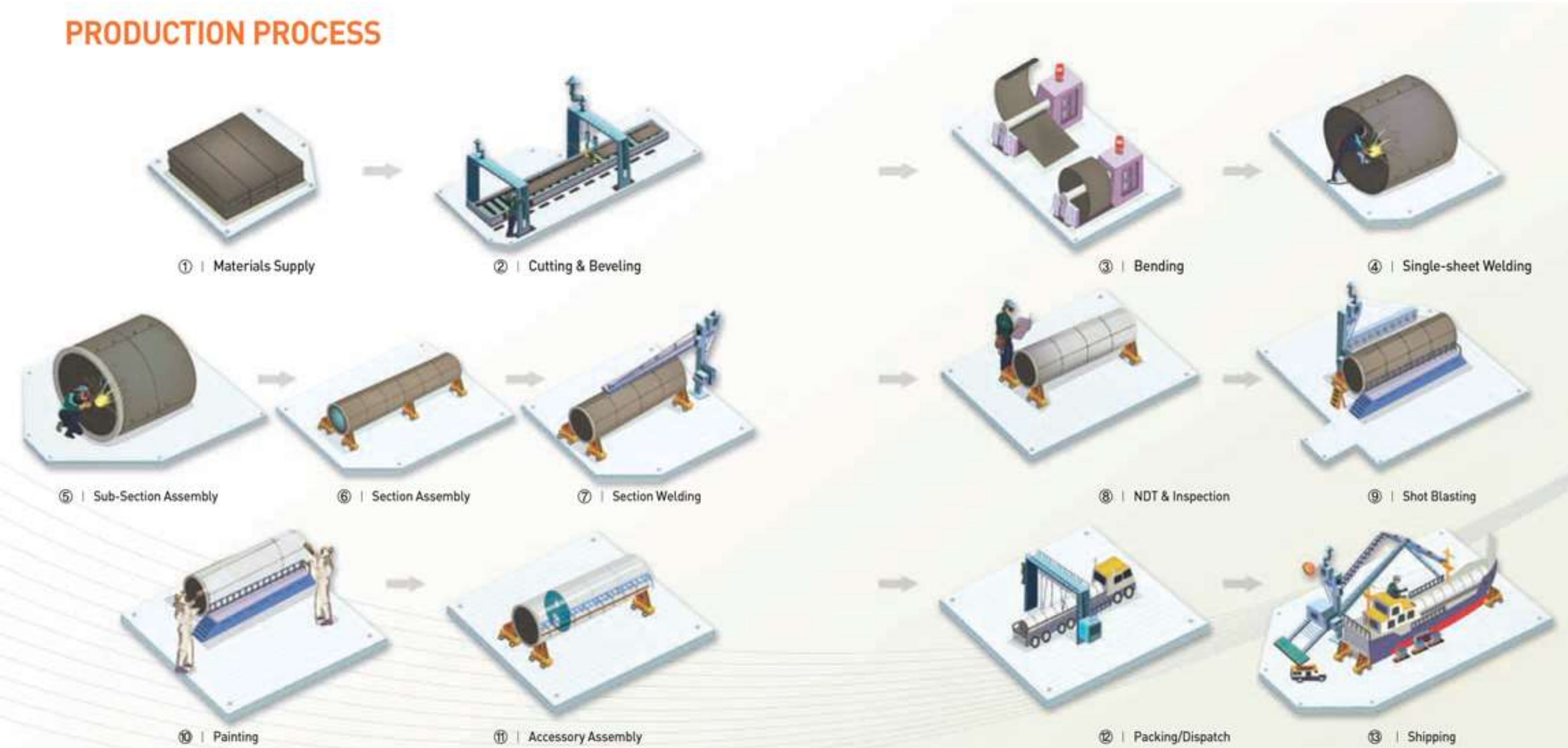
Tower design: Manufacturing process



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Tower design

Towers design are never standard and are made specifically designed for:

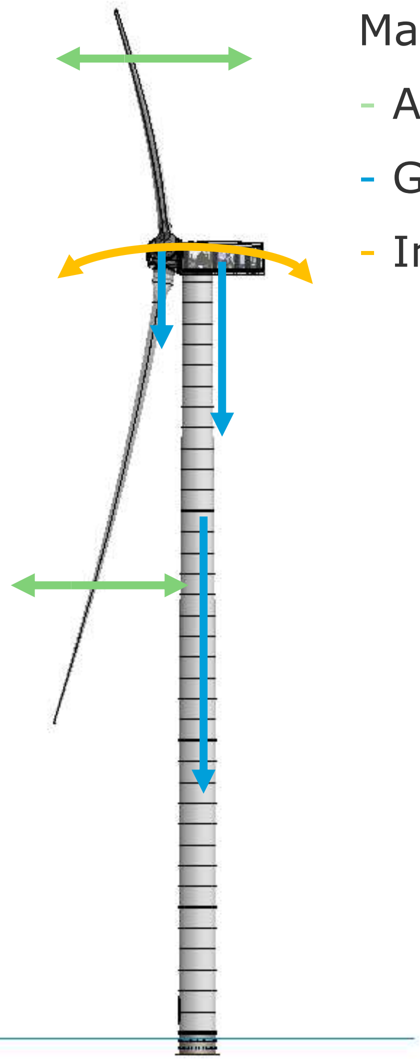
- Turbine design;
- Rotor design (blade);
- Wind class.

Tower loading is very depending on:

- Blade design (size, aerodynamic design, mass);
- Control design.

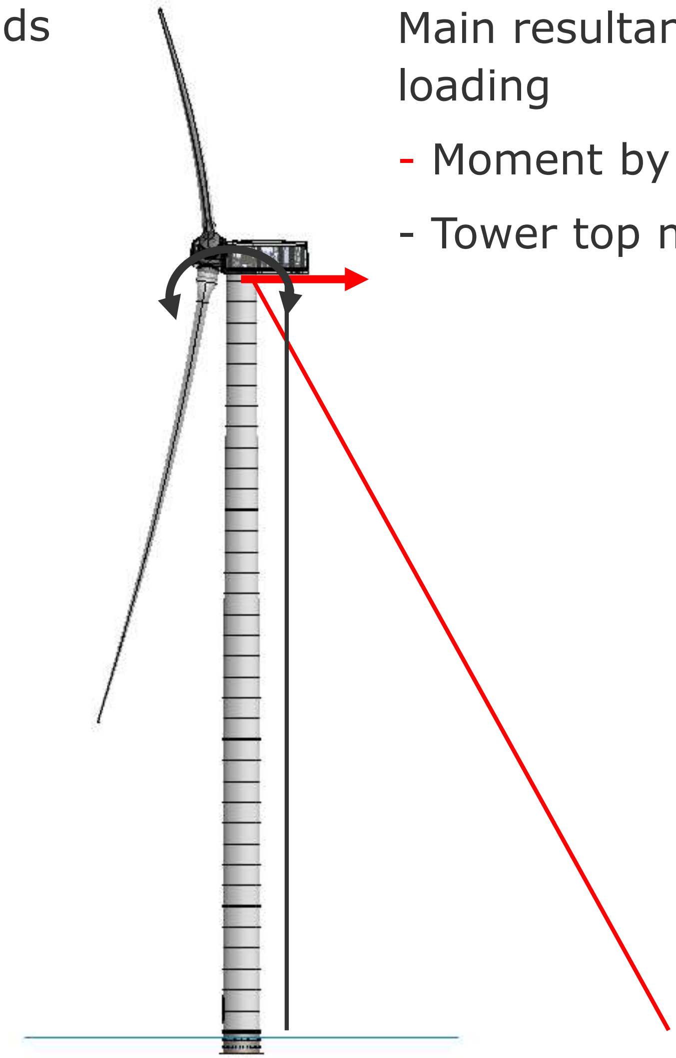
For large wind farms tower designs can also be site specific (rather than wind class design) to find the optimal balance for structural design and hub height.

Tower design
Main Tower loading



Main excitation loads

- Aerodynamic
- Gravitational
- Inertia forces



Main resultant tower loading

- Moment by Force*arm
- Tower top moment

Tower design
General tower design goals

Targets for good tower design:

1. To meet the required hub height (sometimes the hub height must be changed for frequency reasons);
2. To meet manufacturing and transportation limitations/requirements;
3. Structurally strong enough but at the same time mass optimised;
4. Good stiffness behaviour resulting in as little as possible 1P/3P excitation.

Drive Train Technology

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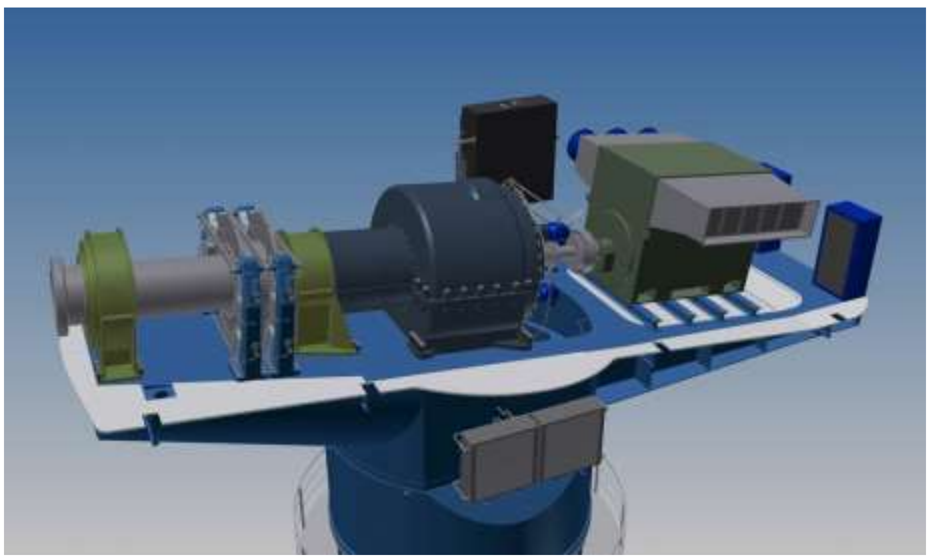
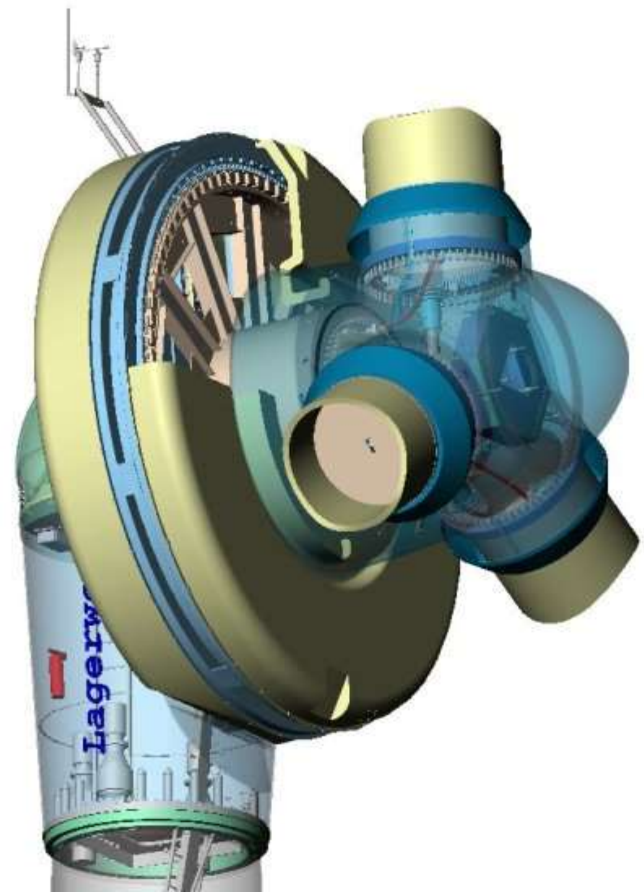
Drivetrain technology
A brief overview of the contents

- Drivetrain system layouts
- Typical drivetrain system components
- Loads on the drivetrain system components
- Known ~~problems~~ challenges





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Drivetrain System
Drivetrain system layouts: Main bearing layouts

- The 3 main bearing layouts currently in use are:
  1. Single main bearing
     - One bearing to react all rotor bending moments and forces
     - Compact design possible, but large diameter
     - Limited capacity
     - Bearing can be integrated into the gearbox
  2. Two main bearings spaced on a shaft (rotating or stationary)(4-point layout)
     - Both bearings share the rotor bending moments and forces
     - Longer design due to spacing between bearings
     - Very high capacity
  3. One bearing on a rotating shaft, gearbox support the other end of the shaft (3-point layout)
     - Bearing on shaft and bearing in gearbox share the rotor bending moments and forces

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Drivetrain System
Typical drivetrain system components

Typical mechanical components in the drivetrain system are:

- Main bearing(s)
- Gearbox (if geared)
- Gearbox mounting
  - Rubber
  - Hydraulic
- High Speed Shaft
- Generator
  - Direct drive
  - Separate
  - (Semi-) Integrated with gearbox

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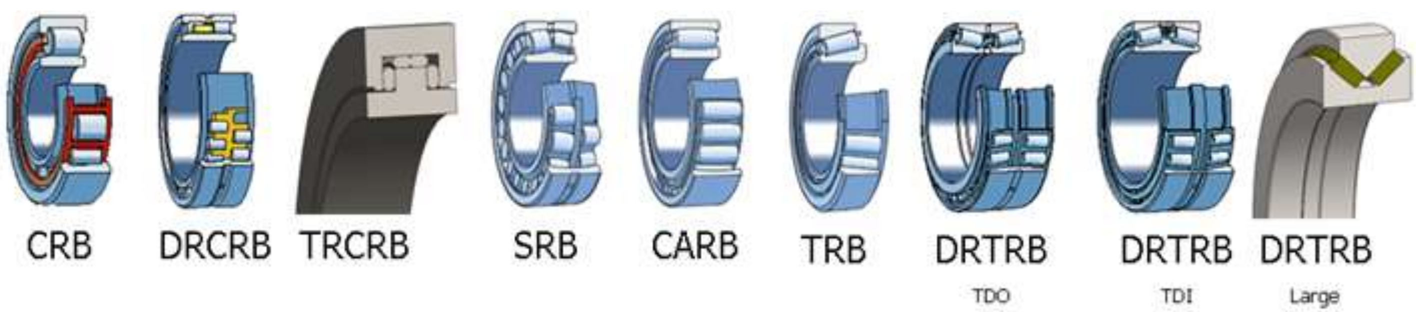
Drivetrain System
Typical drivetrain system components : Main bearing(s)

- The following abbreviations are used for the different bearing types:
  - CRB – Cylindrical Roller Bearing
    - DRCRB – Double Row Cylindrical Roller Bearing
    - TRCRB – Triple Row Cylindrical Roller Bearing (U configuration)
  - TRB – Tapered Roller Bearing
    - DRTRB – Double Row Tapered Roller Bearing
  - SRB – Spherical Roller Bearing
  - CARB – Compact Aligning Roller Bearings



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Drivetrain System
Typical drivetrain system components : Main bearing(s)

- The most common main bearing combinations are:
  - Single main bearing
    - DRTRB (SKF Nautilus)
    - 2x TRB mounted back to back
    - TRCRB (reliability issues)
  - Two main bearings
    - SRB and SRB (forged shafts)
    - SRB and CARB (forged shafts)
    - DRTRB and CRB (cast/forged shafts)
    - 2x TRB mounted widely spaced (cast shafts)
  - Bearing(s) fully or partially integrated in gearbox
    - Option 1: See single main bearing
    - Option 2: SRB on shaft (smaller turbines)

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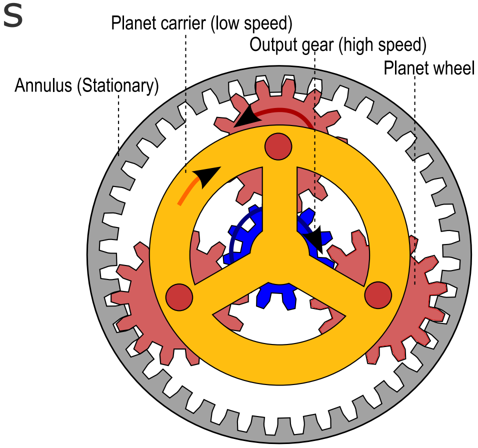
Drivetrain System
Typical drivetrain system components : Gearbox

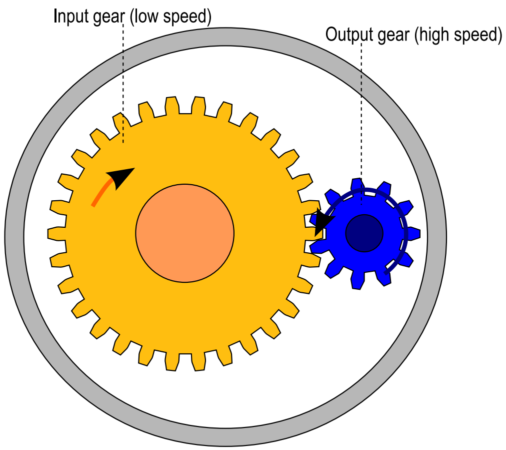
- Wind turbine gearboxes are used to:
  - Improve generator efficiency
  - Reduce generator size
  - Reduce generator mass
  - Reduce costs
- Unfortunately a gearbox has losses, adds a large and heavy gearbox and is costly requiring regular maintenance
- The CoE of direct drives vs. geared is nearly identical. Size and site will be driving the optimum
  - Good example is Siemens who are now offering both direct drive and geared

Drivetrain System
Typical drivetrain system components : Gearbox

- All wind turbine gearboxes are using one or more of the following types of stages:
  - Planetary
    - 3 or more planet gears revolving
    - Balancing forces
    - Larger tooth contact allowing more torque
    - Typically used in low speed stages
    - Torque splitting possible
  - Parallel
    - Stationary shafts
    - Side loading forces
    - Lower torque
    - Typically used in high speed stages
    - Multiple output shafts possible



Planetary Stage



Parallel Stage

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Drivetrain System
Typical drivetrain system components : Gearbox

- Common gearbox layouts are:
  - Single stage planetary
    - Ratio approximately 1:8 – 1:12
    - Compact gearbox design
    - Very low gearbox losses
    - Low speed generator

  - 2 Stage: Planetary – Planetary
    - Ratio approximately 1:25-1:45
    - Low gearbox losses
    - Medium speed generator
    - Integrated gearbox generator design
    - Trend using this gearbox with PMG generator

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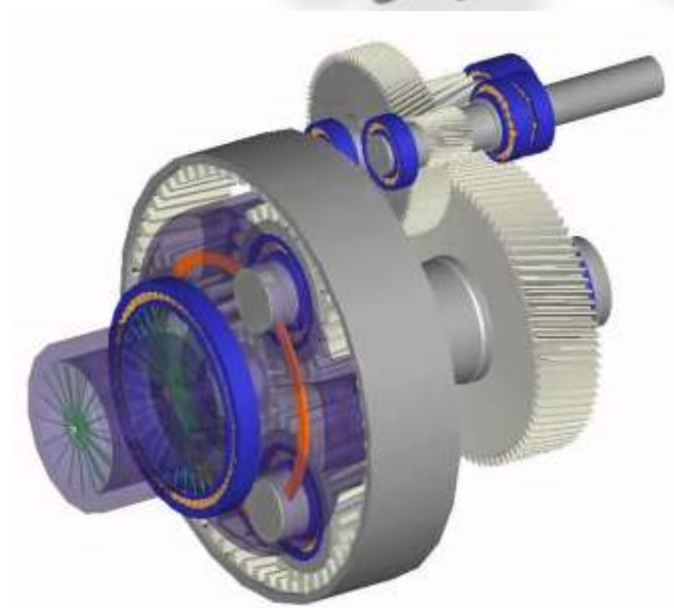
Drivetrain System
Typical drivetrain system components : Gearbox

- Common gearbox layouts are:
  - 3 Stage: Planetary – Planetary - Parallel
    - Ratio approximately 1:80 – 1:130
    - Medium gearbox losses
    - High speed generator
    - Common design combined with DFIG

  - 3 Stage: Planetary – Parallel- Parallel
    - Ratio approximately 1:80 – 1:130
    - Medium gearbox losses
    - High speed generator
    - Lower torque capacity than previous



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Drivetrain System
Typical drivetrain system components : Gearbox

- Larger turbines have an increasing torque capacity, which require more tooth surface area. There are several solution to achieve this:
  - Increase tooth surface
    - The width is limited due to deformations
    - The tooth module is limited due to gearbox diameter
  - Increase number of gears
    - Using conventional planetary designs is "limited" to 3
    - 3+ planets results in overdetermined system
    - Some cheats:
      - Add 4th planet and calculate strains in system
      - Cutting wider planets in 2 and runs on single pin

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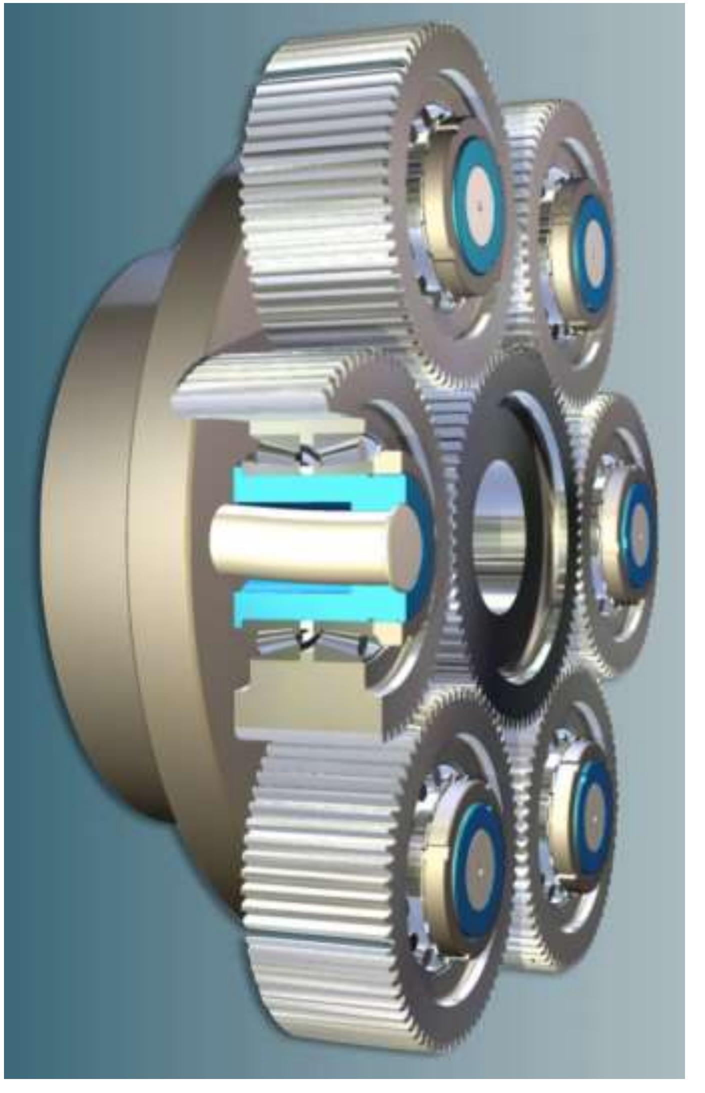
Drivetrain System
Typical drivetrain system components : Gearbox

- Other options to increase the number of gears:
  - Use flexible planet mountings (flex pin)
    - Planets “settle” under loads
    - 5-9 planets possible
    - Ratio comparable to traditional planetary gear
    - Compact design
    - Medium/High losses
    - Cost effective



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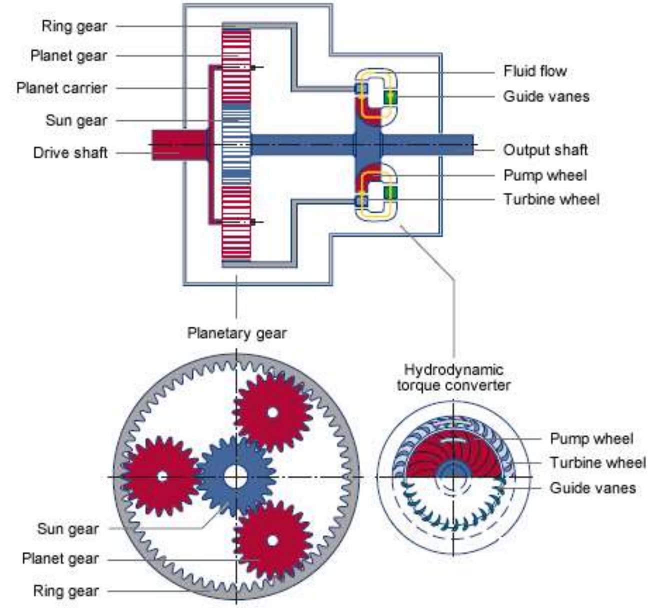
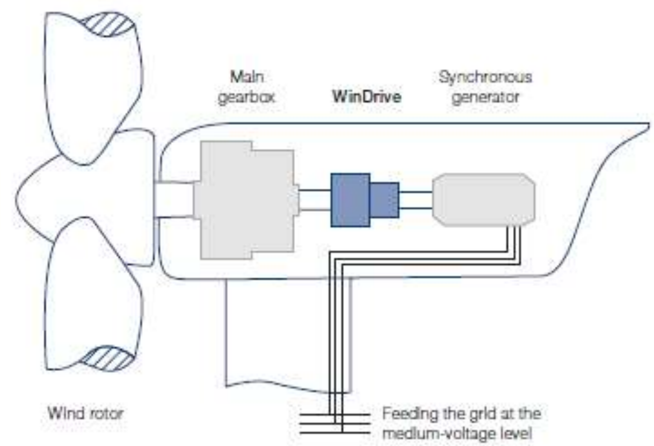
Drivetrain System
Typical drivetrain system components : Gearbox

- Continuously Variable Transmission
  – The use of a CVT has the following advantages
    – No power converters required
    – Run generator at higher RPM at low wind speed
  – But there are disadvantages too
    – Expensive system
    – Large/heavy additional component
    – Mechanical losses
  – Examples of CVT systems are
    – Voith WinDrive
    – Wikov SPG
    – Other options are under development





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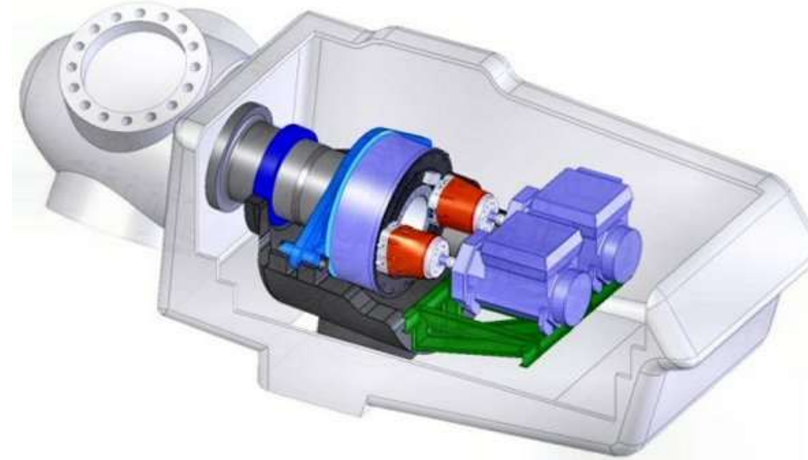
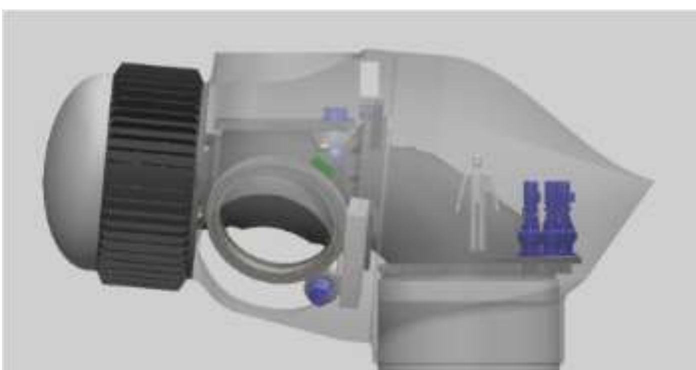
Drivetrain System
Typical drivetrain system components : Gearbox

- Other transmission systems are:
  - Hydraulic
    - Removes need for power converter
    - Generators running at optimum rpm
    - Mechanical losses?
  - Magnomatics Pseudo Direct Drive
    - Magnetic gearbox and generator in one
    - Very high efficiency at full and partial load





Drivetrain System
Typical drivetrain system components : Gearbox Mounting

- The gearbox needs to react the rotor torque and in some cases all rotor loads into the mainframe structure. This needs to be done through a flexible connection.
- Common solutions are elastomer and elastomer-hydraulic mounts to:
  - Reduce stresses
  - Reduce noise
  - Reduce effects of overdetermined system (4-point mounting)

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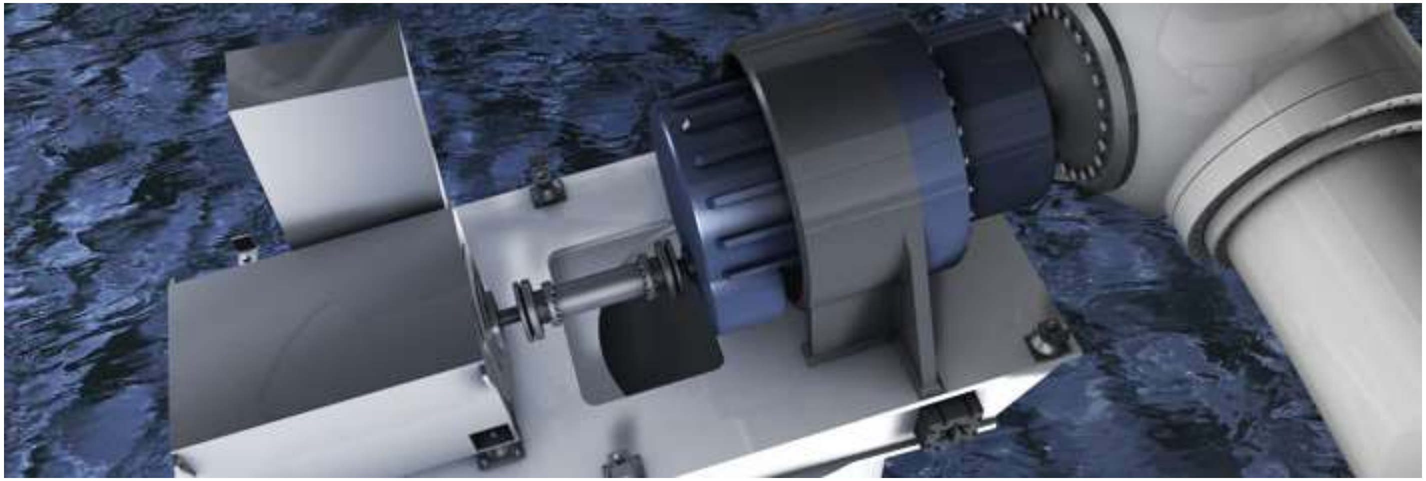
Drivetrain System
Typical drivetrain system components : Gearbox Mounting



- For a gearbox with integrated main bearing it is most common to use a ring of rubber bushings

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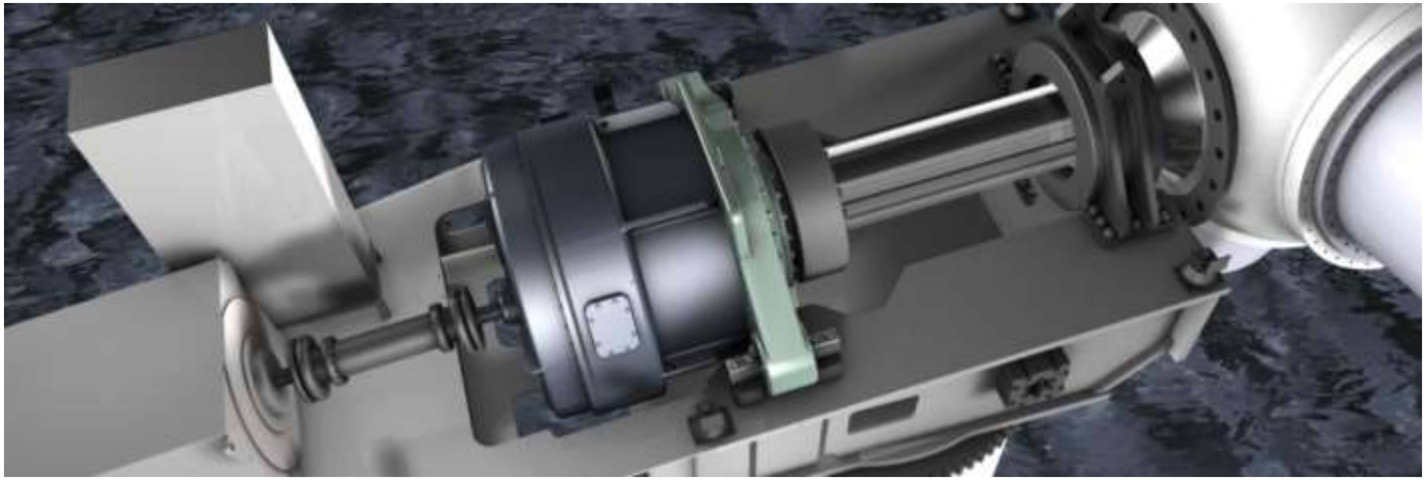
Drivetrain System
Typical drivetrain system components : Gearbox Mounting



- For a gearbox which acts as the second main bearing (3-point) it is most common to use pins and rubber bushings at the gearbox torque arm

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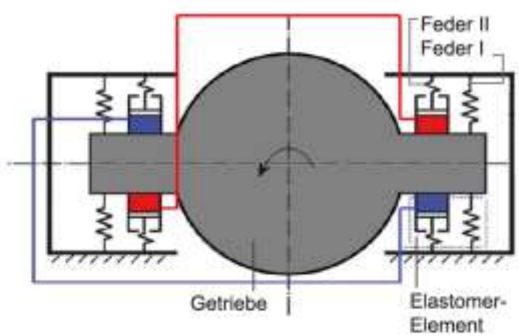
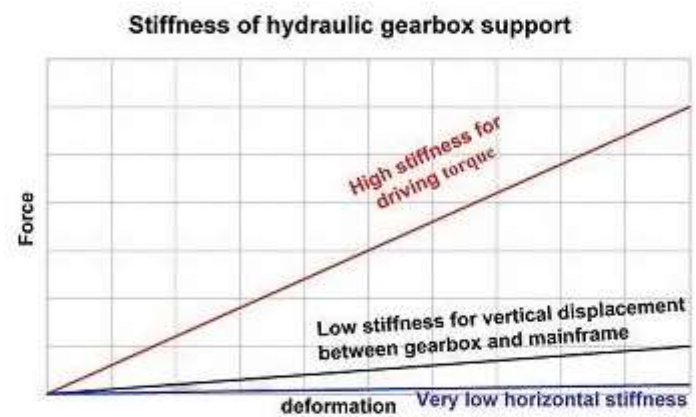
Drivetrain System
Typical drivetrain system components : Gearbox Mounting

- If a gearbox is mounted on a main shaft using 2 main bearing (4-point) you have an overdetermined system. One option which partially solves this is by using relatively soft rubber elements. This is difficult because the torque needs to be reacted too.

Drivetrain System
Typical drivetrain system components : Gearbox Mounting

- The other (better) option is by using hydraulic torque supports





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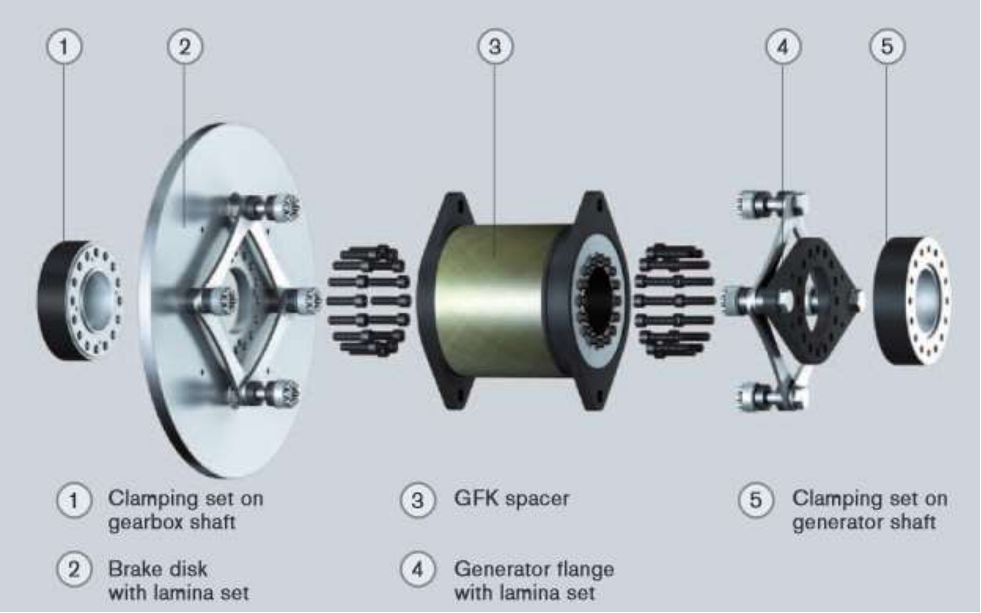
Drivetrain System
Typical drivetrain system components : High Speed Shaft

- The High Speed Shaft typically has multiple functions, they are:
  - Transfer torque from gearbox to generator
  - Reduce misalignment issues due to deformation under loads
  - Limit torque during generator short circuit (slipping clutch)
  - Allow gearbox removal without removing the generator
  - Electrically isolate the generator
  - Contain the rotor brake disc



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Drivetrain System
Typical drivetrain system components : Generator

- The generator is part of the drive train, but also part of the electrical systems the electrical properties will be covered in the electrical systems section.

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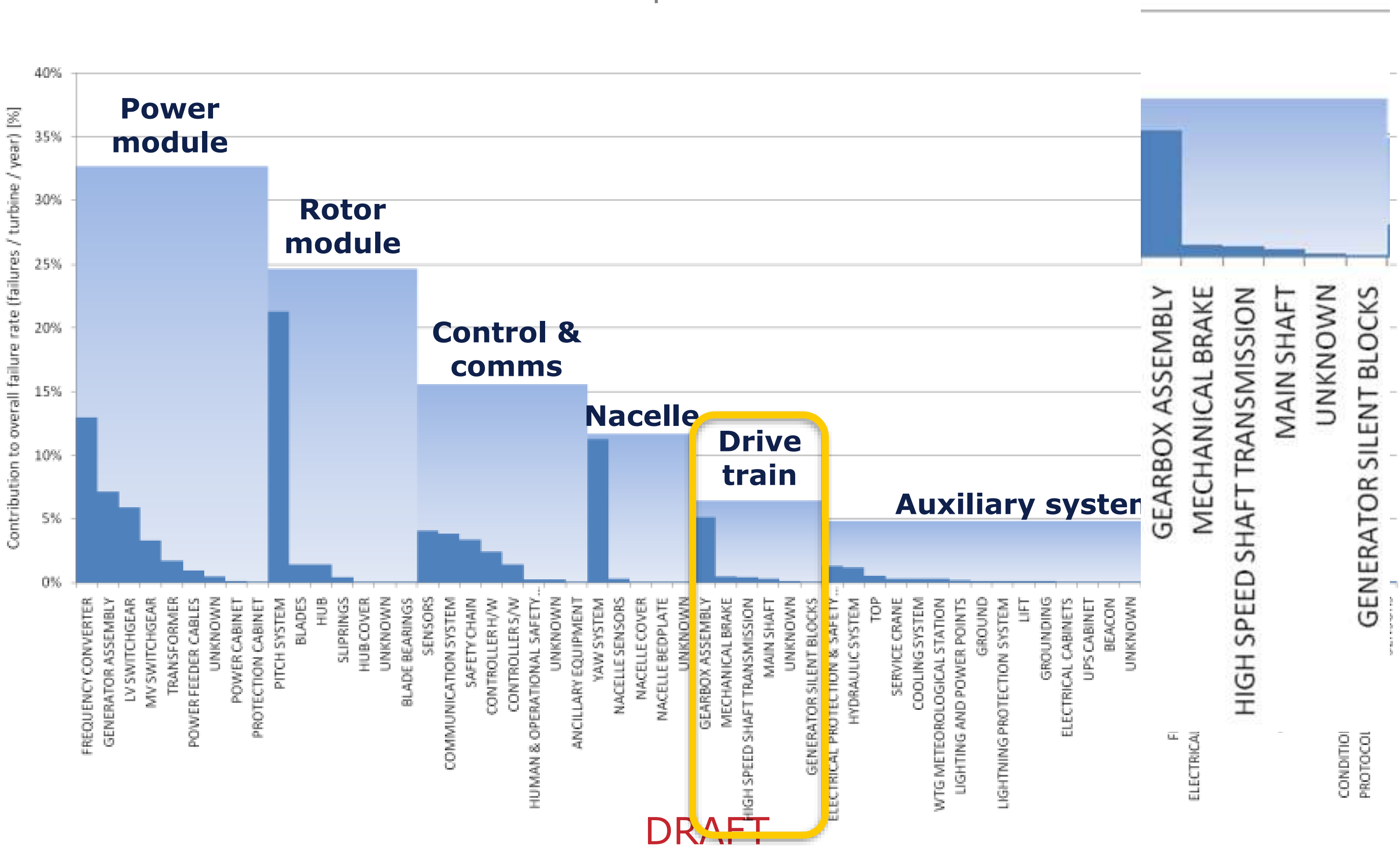
Drivetrain System
Known problems: Failure Rate

Percentage contribution to overall failure rate
Data source: onshore turbines from multiple manufacturers



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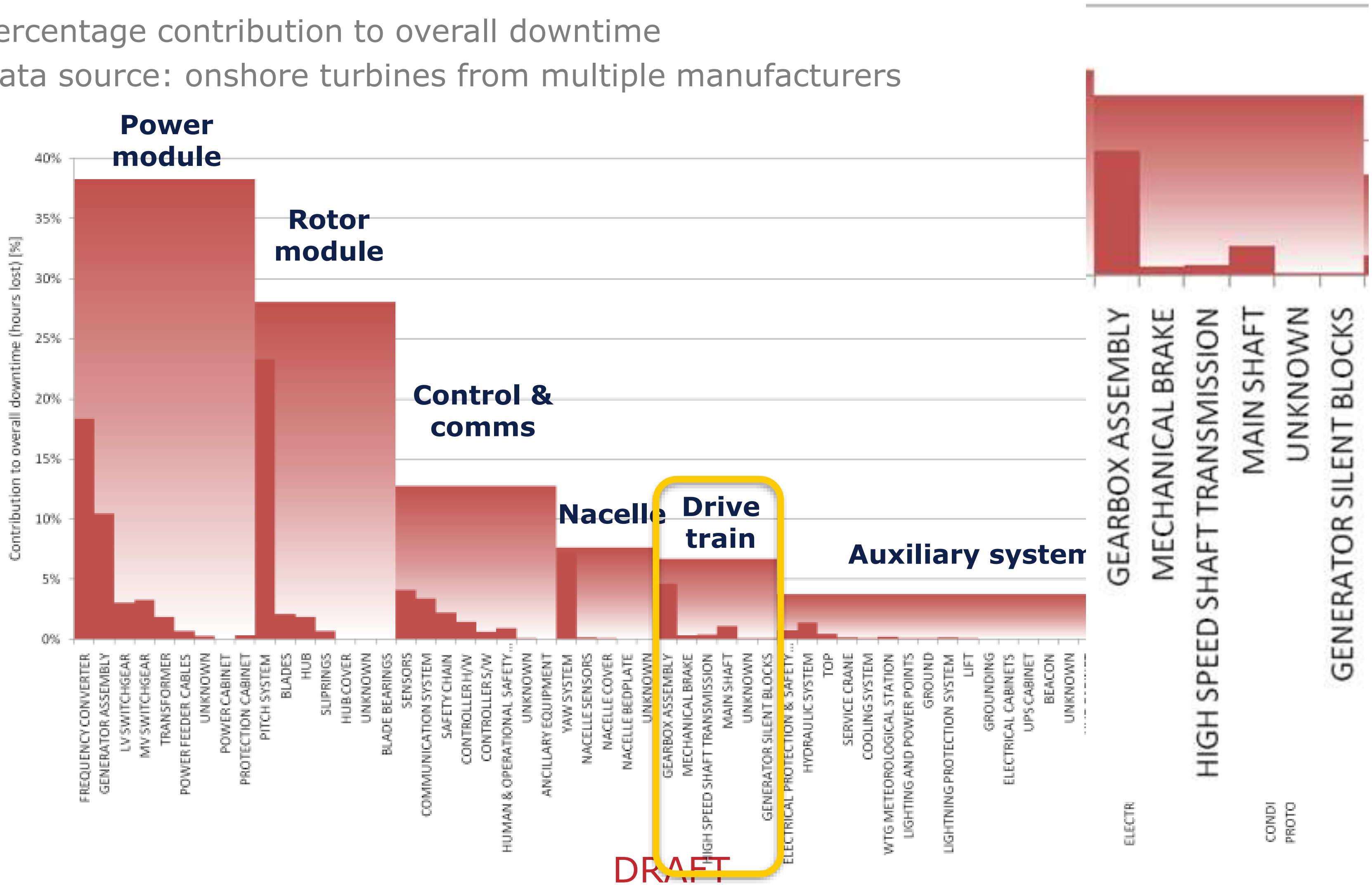
Drivetrain System
Known problems: Downtime

Percentage contribution to overall downtime

Data source: onshore turbines from multiple manufacturers



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Drivetrain System
Known problems: Main Bearing(s)

- Statistically main bearing failures are rare but are costly and time consuming
- It involves a lot of work
  - Removing blades
  - Removing hub
  - Disconnecting gearbox
  - Removing mainshaft including main bearing(s)
  - Removing main bearing(s) from the mainshaft
- Often the whole mainshaft and gearbox is replaced in a single lift




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Drivetrain System
Known problems: Main Bearing(s)

- Common causes of failure are:
  - Different loads
  - Unexpected bearing behaviour (skidding, slipping of rolling elements)
  - Material failures often hardening issues
  - Tolerance errors (machining faults)
  - Sealing failures (water or dust entering bearing)
  - Incorrect bearing support (wrong mainshaft/bearing housing design)
    - Local pressure spots
    - Higher than expected deformation
  - Lubrication failures

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Drivetrain System
Known problems: Gearbox & Gearbox Mounting

- Unfortunately gearbox failures are more common, but typically the failures are minor and can be repaired relatively easy.
- Common failure are:
  - Sensor failure
  - High-speed bearing failures
  - Lubrication system failures
  - Planet bearing failures
  - Gear failure (hardening)
  - Planet carrier bearing failures
  - Cooling system failures
  - Shaft failures
- Failures in the gearbox mounting are few and typically have to do with the aging of the rubber elements

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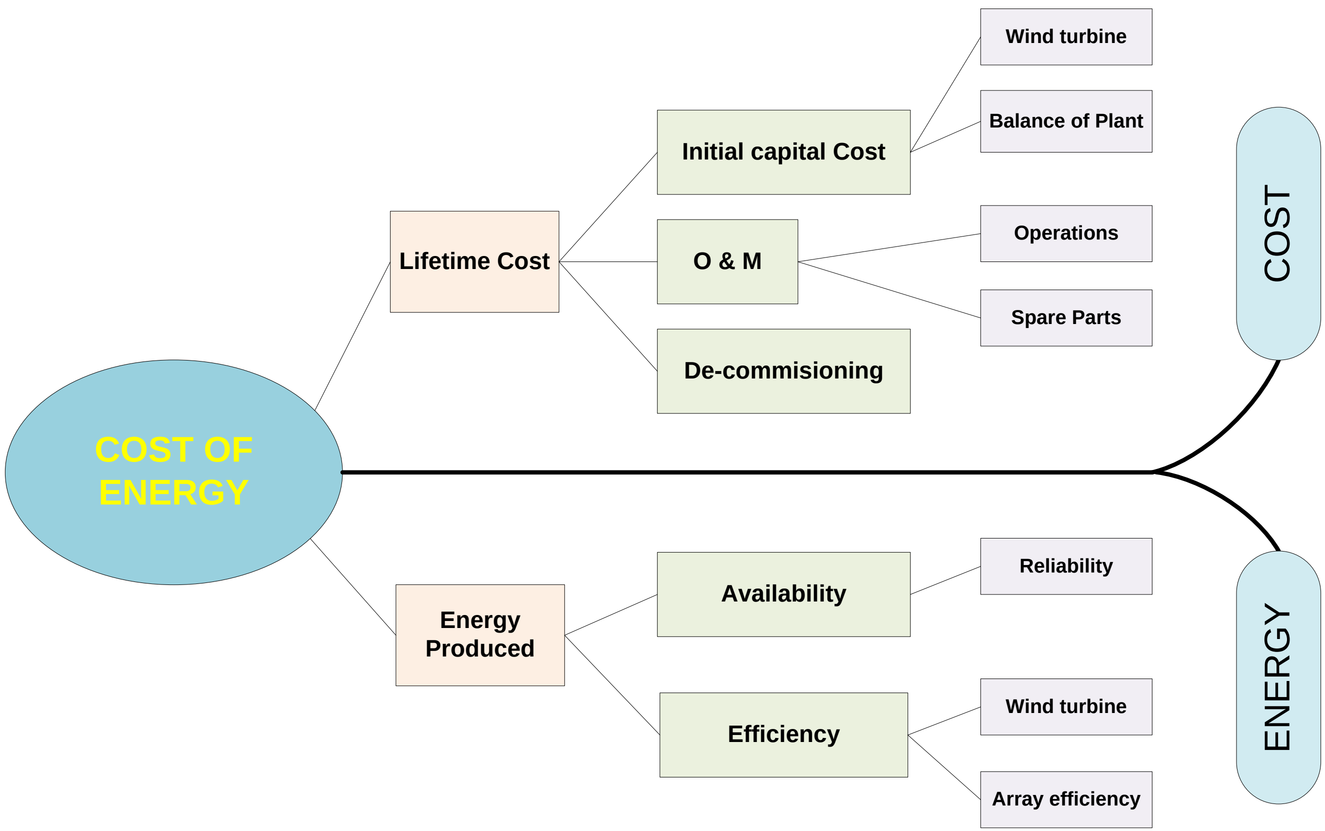
Drivetrain System
Known problems: High Speed Shaft & Generator

- High Speed Shafts typically have few failures because most potential defective parts are replaced during preventive maintenance
- If the HSS is subjected to a lot of misalignment, stresses on the lamina could result in fractures.
- Disintegration of the whole HSS due to broken lamina, when this happens at high speed the damage can be very serious and could result in a turbine loss
- Slipping clutch failure due to too much slip

- The electrical generator failures will be covered in the electrical systems section of this training.
- Due to the very high number of revolutions during the lifetime bearings and slip rings require preventive maintenance
- Lubrication system failures

Cost of Energy



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Cost of Energy – ENERGY!

- **The prime value - purpose of the wind turbine system**
- Depends on;
  - power performance – rotor design and drive train efficiency
  - availability
  - reliability

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Energy – The Power Curve

- pitch and stall regulated design and similarity rules
- rating of wind turbines
- impact of wind turbulence on power performance

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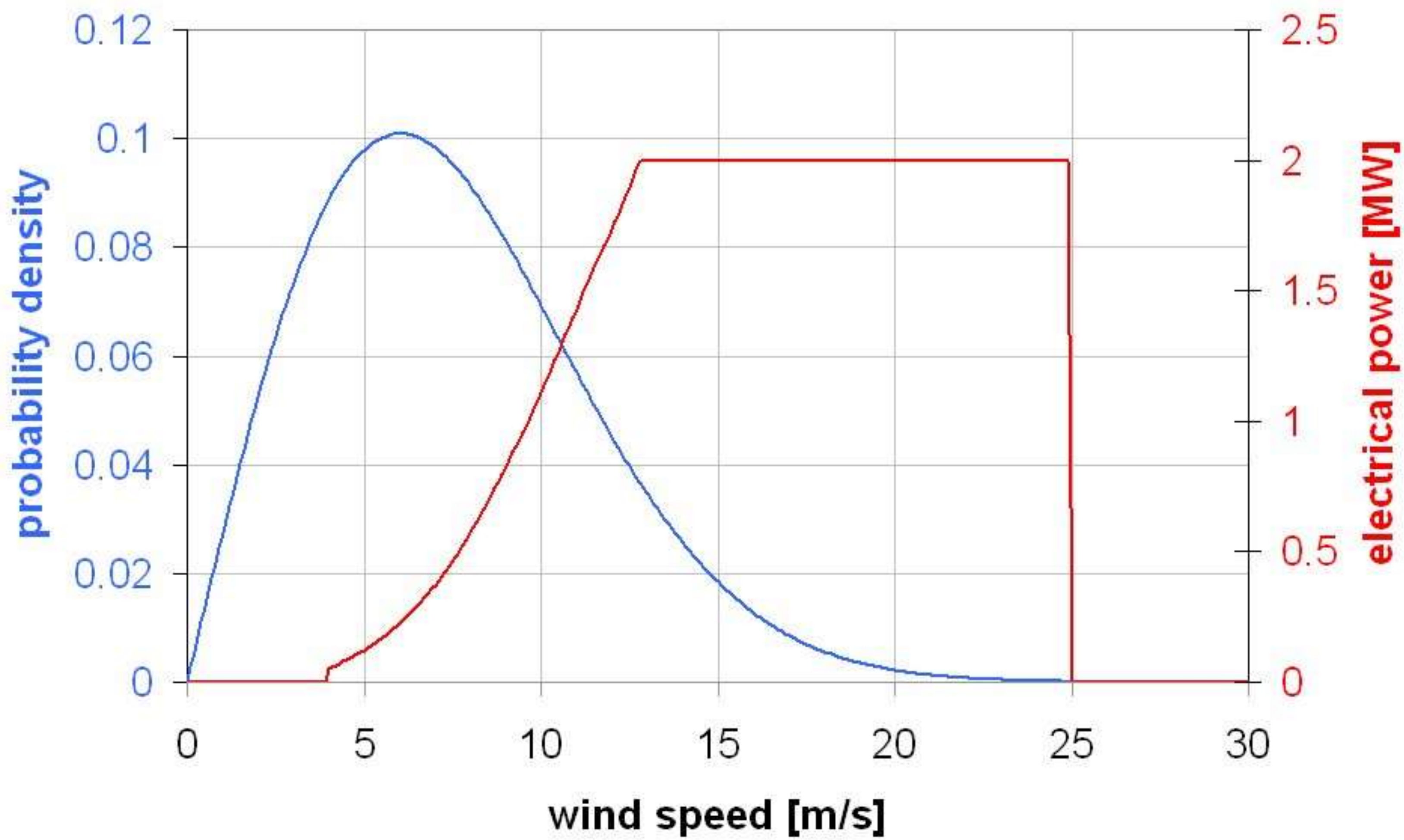
Wind distribution and power curve



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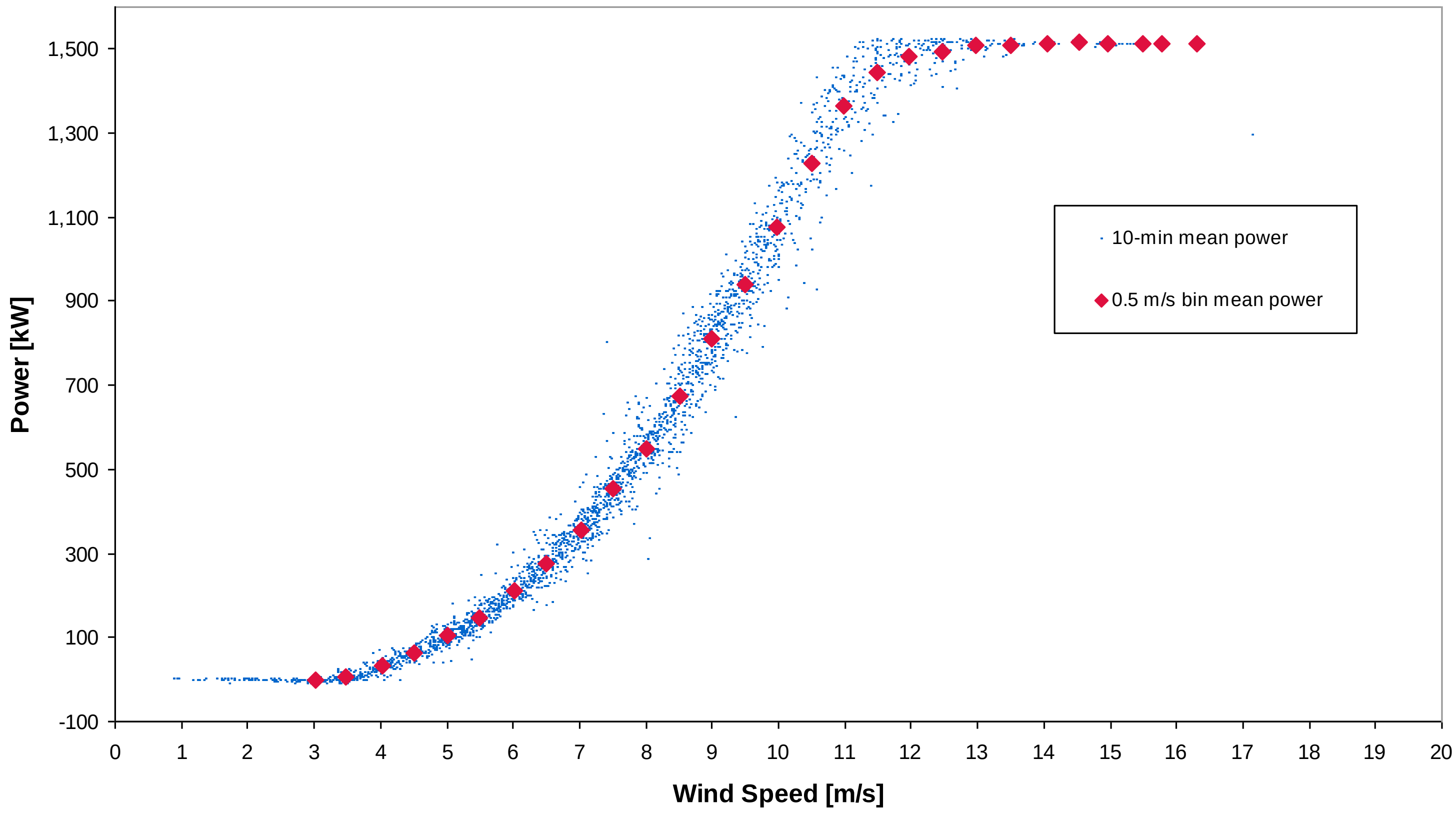
Power Curve – wind speed to power

- Power curve measured on GEWE 1.5 MW turbine
- Shows measurement scatter but consistent pattern



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Relative Cost COE Model Offshore

Wind turbines	0.30
Balance of plant	0.30
O&M	0.33
De-commissioning	0.07

- numbers can vary considerably
- turbines are a much smaller proportion of total lifetime costs – for sure!
- aim is to put importance of different cost elements into a broad perspective

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Cost of Energy – Reliability

- Time to establish databases of failure statistics
- Categorisation of failures and availability of data
- Systemisation, analysis – DOWEC, Supergen, Reliawind projects
- Simplicity a treacherous criterion?
  - Stall v pitch
  - No of gear stages

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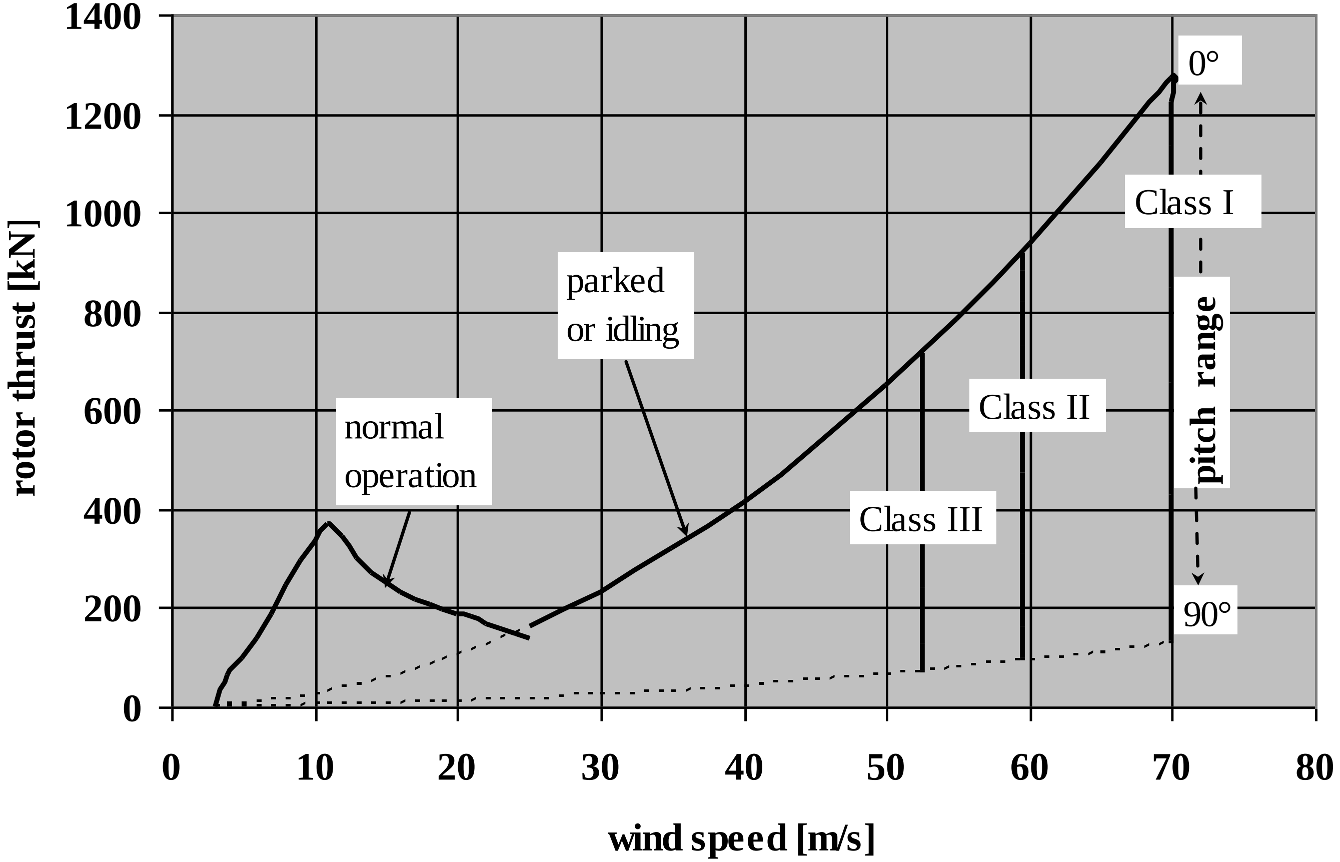
Cost of Energy – Impact of Loads

Load Regimes – 3 MW wind turbine



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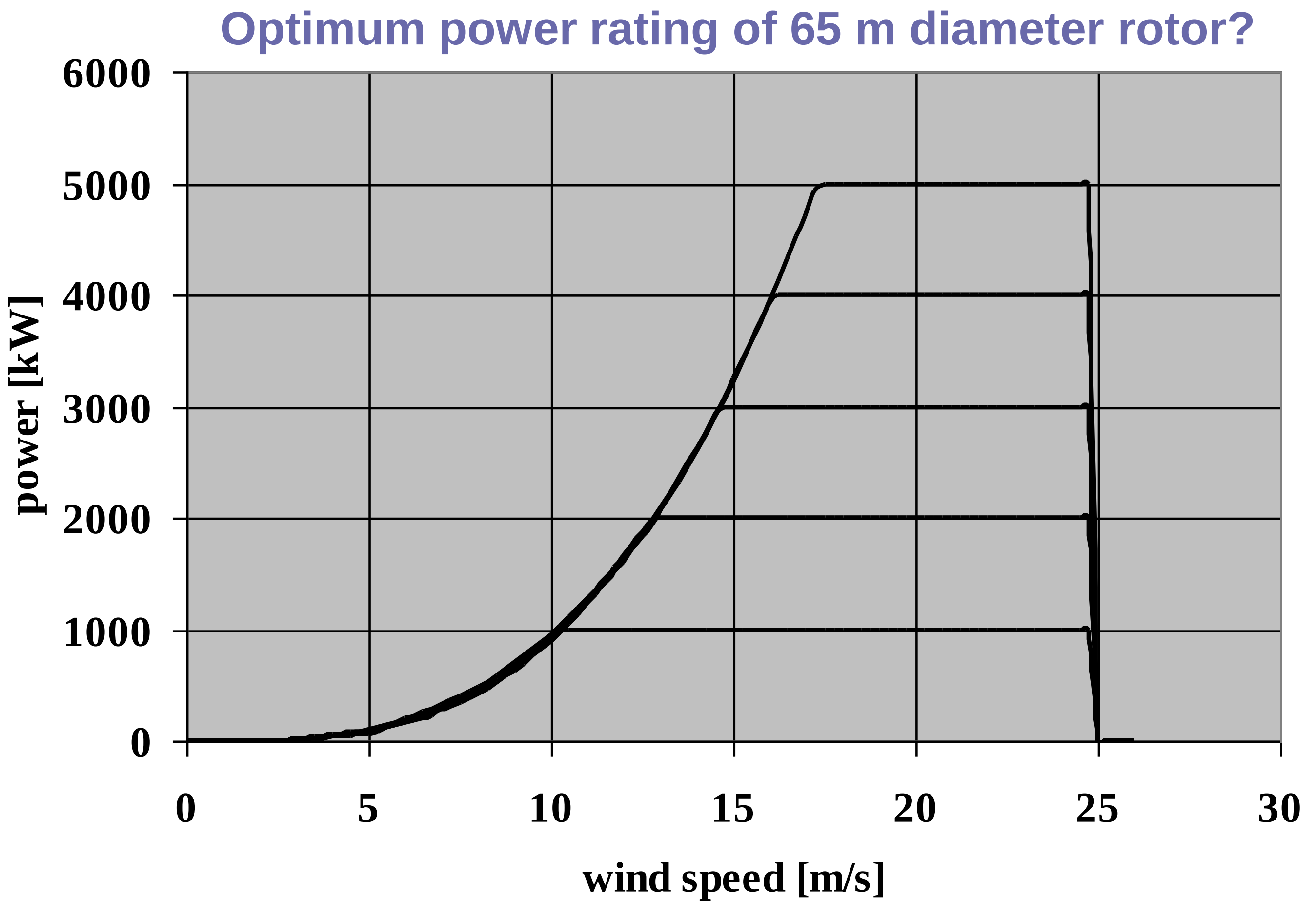
COE Evaluation Example



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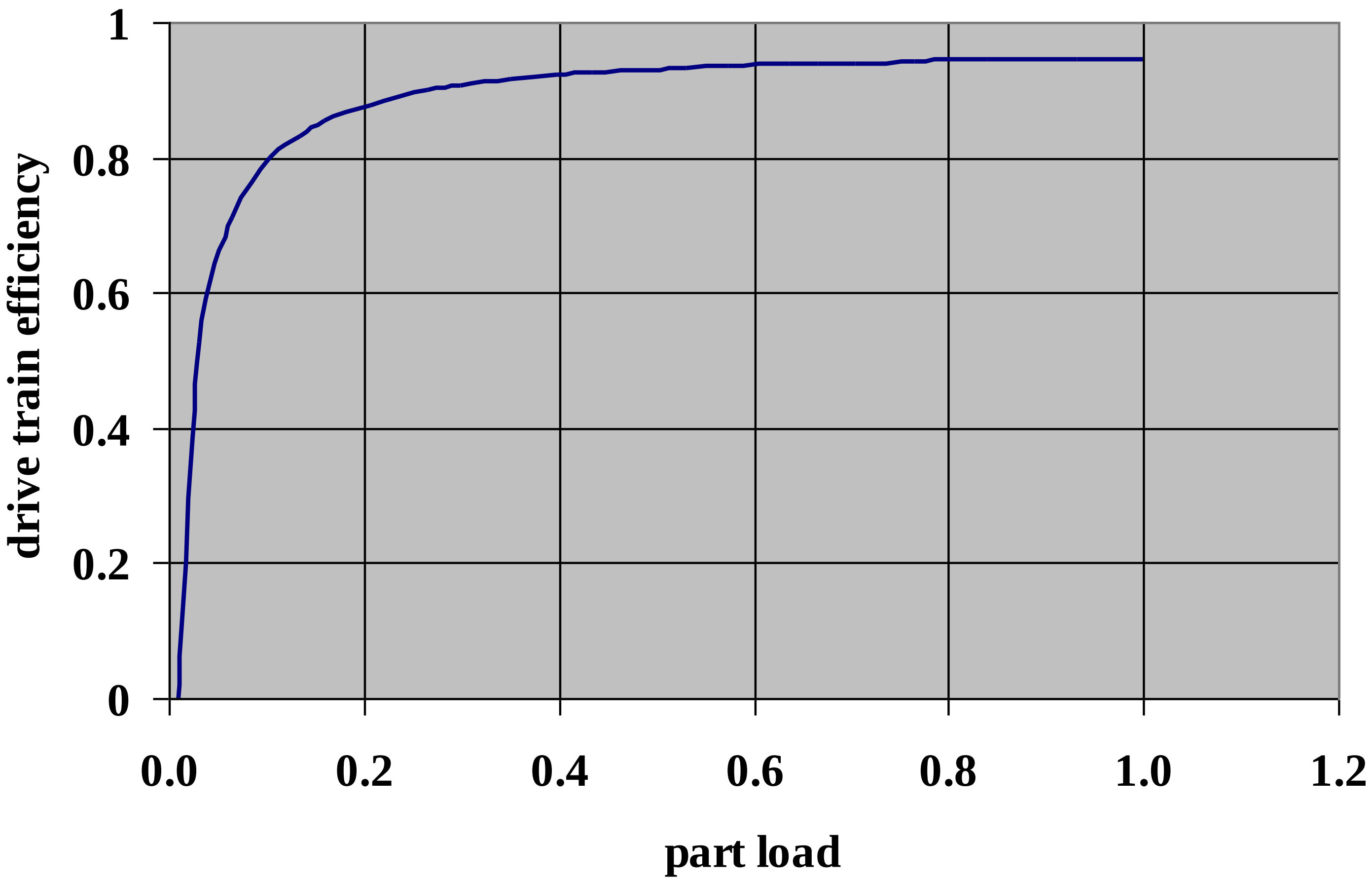
Drive train efficiency - DFIG



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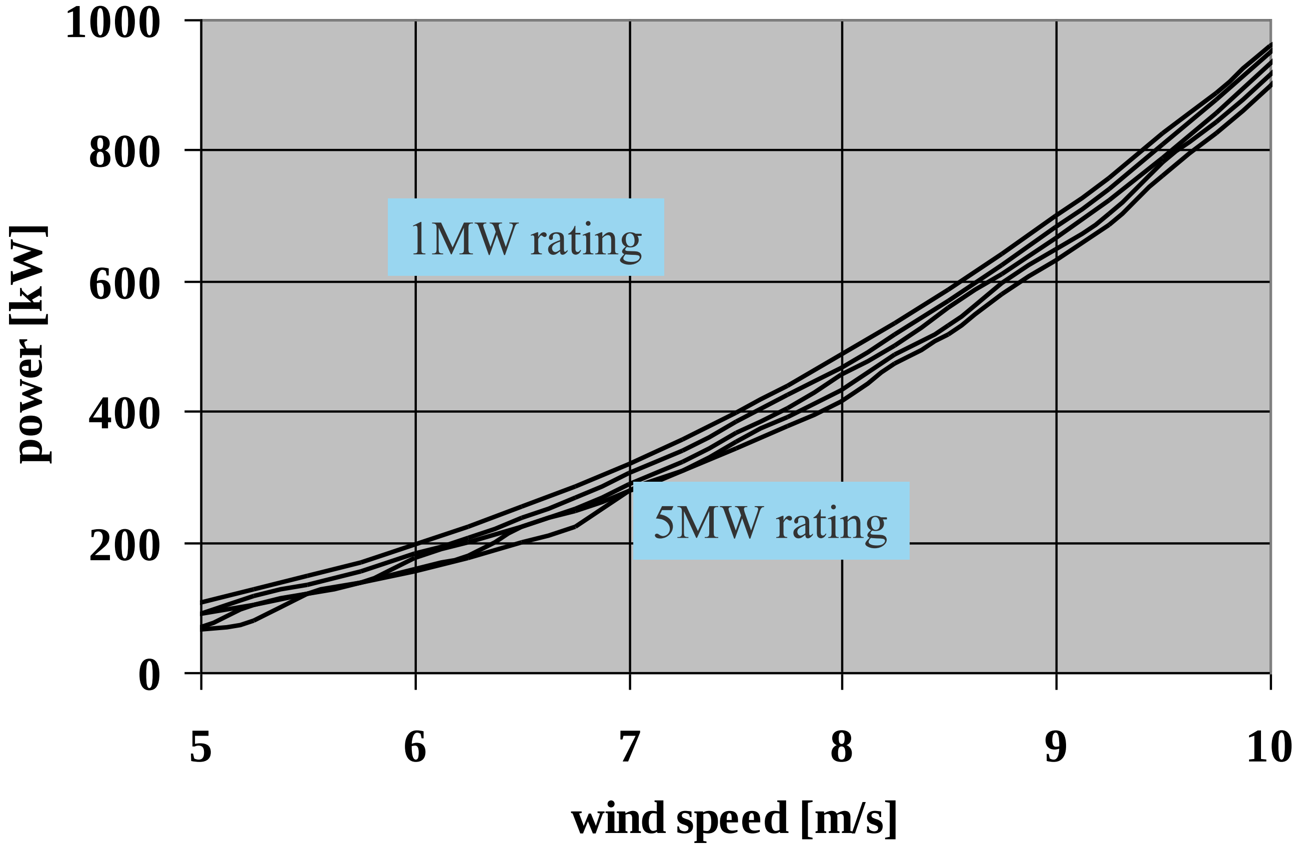
Power Curves Snapshot



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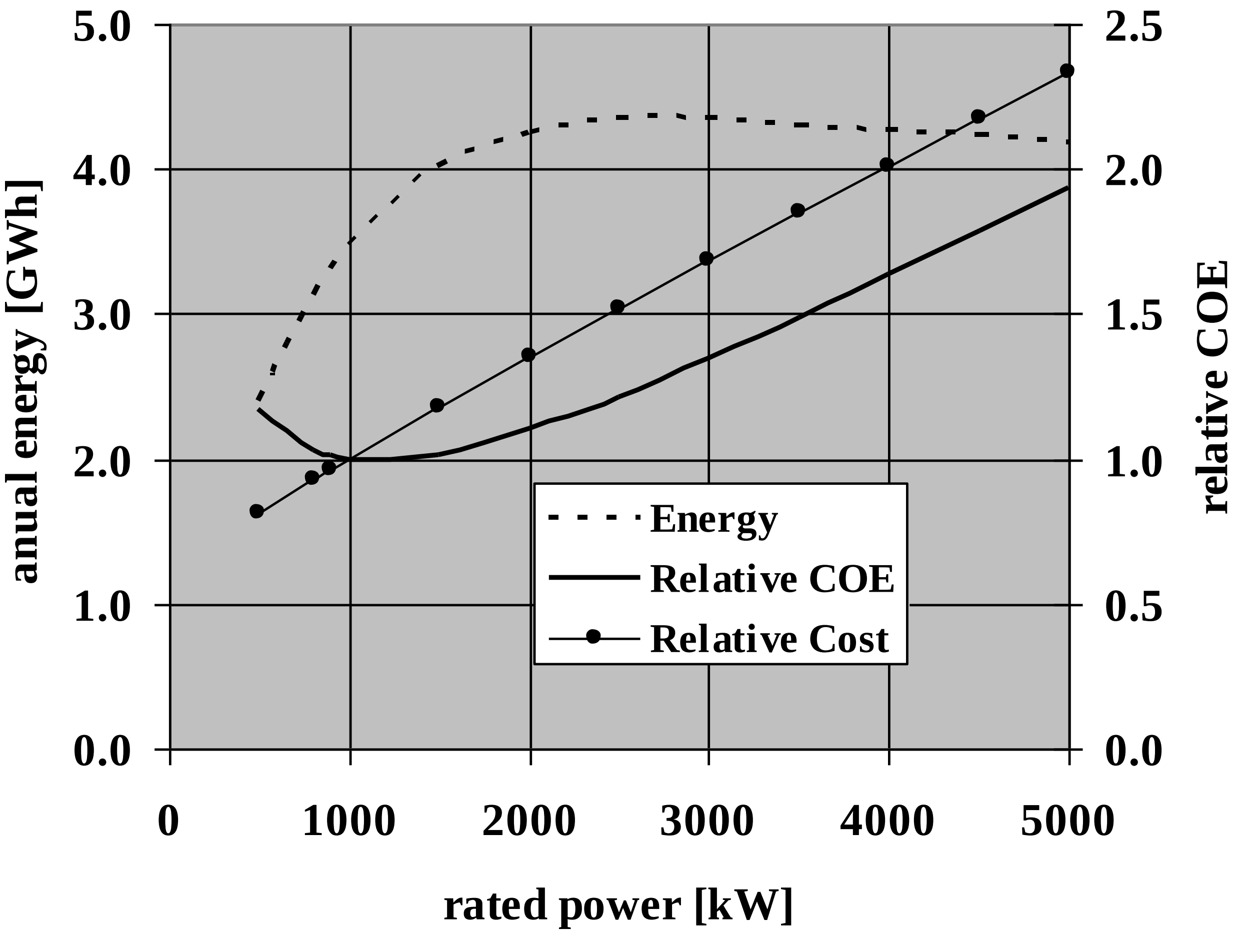
Minimisation of COE



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Conclusions

- COE widely accepted as the most relevant metric
- Not the only one: recent EU policy suggests that maximising installed capacity = resource utilisation may be given priority in some circumstances
- Cost models of varying levels of sophistication can be based on COE
- Emphasis here is on having a broad perspective to give immediate feedback on relative importance of lifetime cost components

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Introduction to wind turbine technology training course

Session 1.5: architecture of wind turbines

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