Mechanical systems in wind engineering

Module 2.2

Module Presentation
Lecture 0

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Objectives

The purpose of this module is to provide the basic knowledge of mechanical systems in wind engineering for Master Students, covering the aspects of aerodynamics, mechanical design, and control of wind turbine systems.

ECTS: 3.5

EQF level: 7

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Learning Outcomes

The main objective of the course is to learn how to apply fundamental principles of fluid mechanics, materials and mechanical systems to design reliable wind turbine components. After the course, the students are expected to be able to :

O1. Understand aerodynamic and mechanical loading acting on wind turbines, mechanical design requirements of main components of a wind turbine, and have knowledge of governing industry standards on the mechanical design of wind turbines.

O2. Design the wind turbine main components using basic principles, design wind turbine main components using modelling and simulation, and assess and verify the design of wind turbine components.

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Learning Outcomes

The main objective of the course is to learn how to apply fundamental principles of fluid mechanics, materials and mechanical systems to design reliable wind turbine components. After the course, the students are expected to be able to :

O3. Use the necessary computer-aided tools for the appropriate modelling of wind turbines, appreciate the development of design needs and innovation in the international market, and understand the code-compliant mechanical design.

O4. Prototype their designs using computational modelling and simulation tools, and present, discuss and argue mechanical design aspects of wind turbines.

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Technical Contents

1. **Introduction to PBL and rotor blade theory**
2. **Aerodynamic design of HAWT blade and loads calculation using BEM theory**
3. **Optimal blade design, effect of number of blades**
4. **Wind turbine types and performance curves**
5. **Estimation of energy capture and turbine control**
6. **Sources of loading and design load assumptions**
7. **Design standards and certification guidelines**
8. **Blade structural design and materials**
9. **Component loading and design**
10. **Brakes, yawing/pitching mechanism and generator**
11. **Power control**
12. **O&M general**
13. **Condition monitoring**

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Recommended literature

Books:

[M. L. O. Hansen, Aerodynamics of Wind Turbines, 2nd Ed, Earthscan]

[Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, 3rd Ed, Springer]

Web links:

- **https://www.re-explorer.org/launch.html**
- **Solar and Wind energy resource assessment (SWERA): https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)**
- **https://globalwindatlas.info/**
- **MIT Wind: http://web.mit.edu/windenergy/**

Software:

- **COMSOL Multiphysics**
- **Ansys**
- **Solid Works / Inventor**
- **RETScreen http://www.nrcan.gc.ca/energy/software-tools/7465**

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Mechanical systems in wind engineering

Module 2.2

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Introduction to the Problem-base Learning (PBL) and Rotor Blade Theory

Lecture 1.1

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Objective

The purpose of this module is to learn how to apply fundamental principles of fluid mechanics, materials and mechanical systems to design reliable wind turbine components. The focus will be on the fundamentals of horizontal-axis wind turbines (HAWT), including energy conversion; wind turbine aerodynamics; performance; materials and design of wind turbine components. Another area of focus will be the compliance to codes and standards in today's design.

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Learning outcomes

O1. To have the basic knowledge of problem-based learning

O2. To know the basics of rotor blade theory

O3. To have the knowledge of rotor aerodynamics

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Technical Contents

- Problem-based learning – what is PBL?
- Wind energy
- Basic aerodynamics
- Wind energy concentrators

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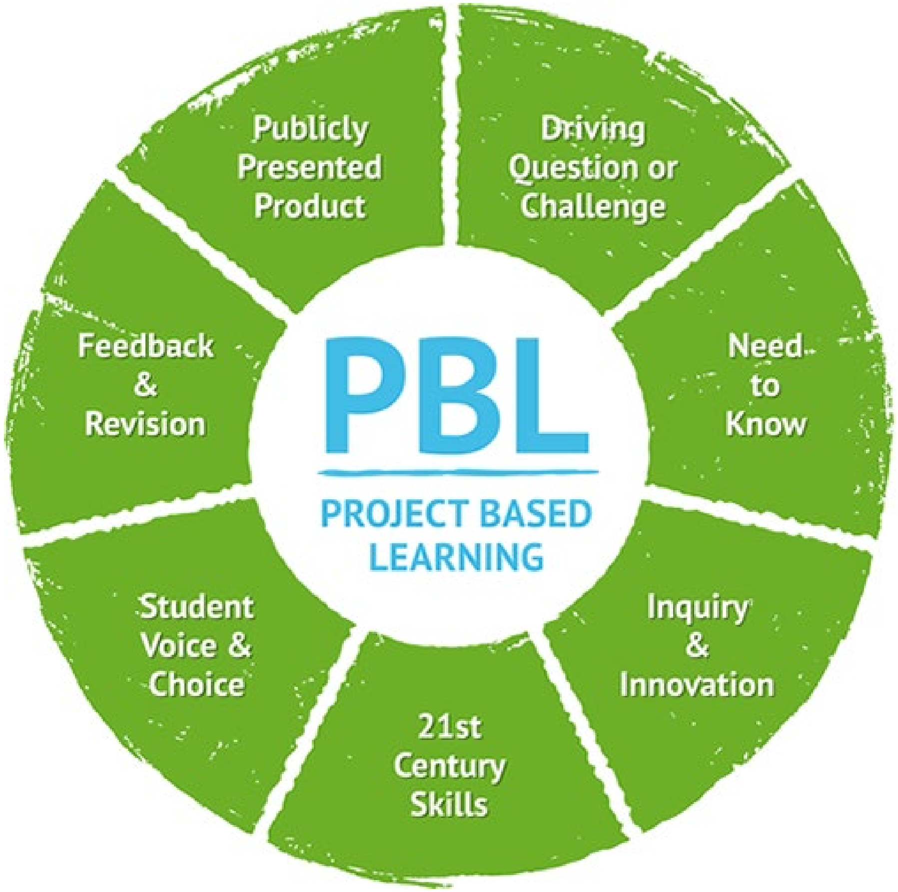
Problem-based Learning (PBL)

- Student-centered teaching approach that integrates knowing and doing
- Students learn core curriculum and also implement this knowledge to solve real world problems



Source: [1]

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Core Principles of the Pedagogical Model - 1

Problem orientation

A problem or a wonder appropriate to the study program serve as the basis for the learning process. A problem can be more or less theoretical and practical orientated but it needs to be authentic. "Authentic" means that it offers an opportunity to put theoretical knowledge into a practice that is relevant to the specific discipline.

Project organization

The project is a goal oriented process limited in time, usually a semester. The project stands as both the means through which the students address the problem and the primary means by which students achieve the articulated educational objectives.

Courses supporting the project

In order to secure that the students are presented to a wide range of theories and methods that might be used in the projects, the students participate in mandatory and optional courses. The courses include a high level of student activity and are organised as a mix of lectures, workshops, laboratory work, seminars, and exercises.

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Core Principles of the Pedagogical Model - 2

Team-based approach

A majority of students' problem/project work is conducted in groups of three or more students. The students manages the project and they support each other in achieving the goals. The collaboration includes knowledge sharing, group decision making, subject based discussions, and feedback to each other.

Exemplarity

Exemplarity means that the learning outcome is transferable to other situations which the students might meet in their professional life.

Responsibility for own learning

Students have a high degree of freedom to choose the projects. The ability to assess the quality of own work and knowledge is a central theme for PBL. Each group gets assigned a supervisor who facilitates the group. However, it is the group who has the sole responsibility for the collaboration, planning of the project, and it results, including their own learning.

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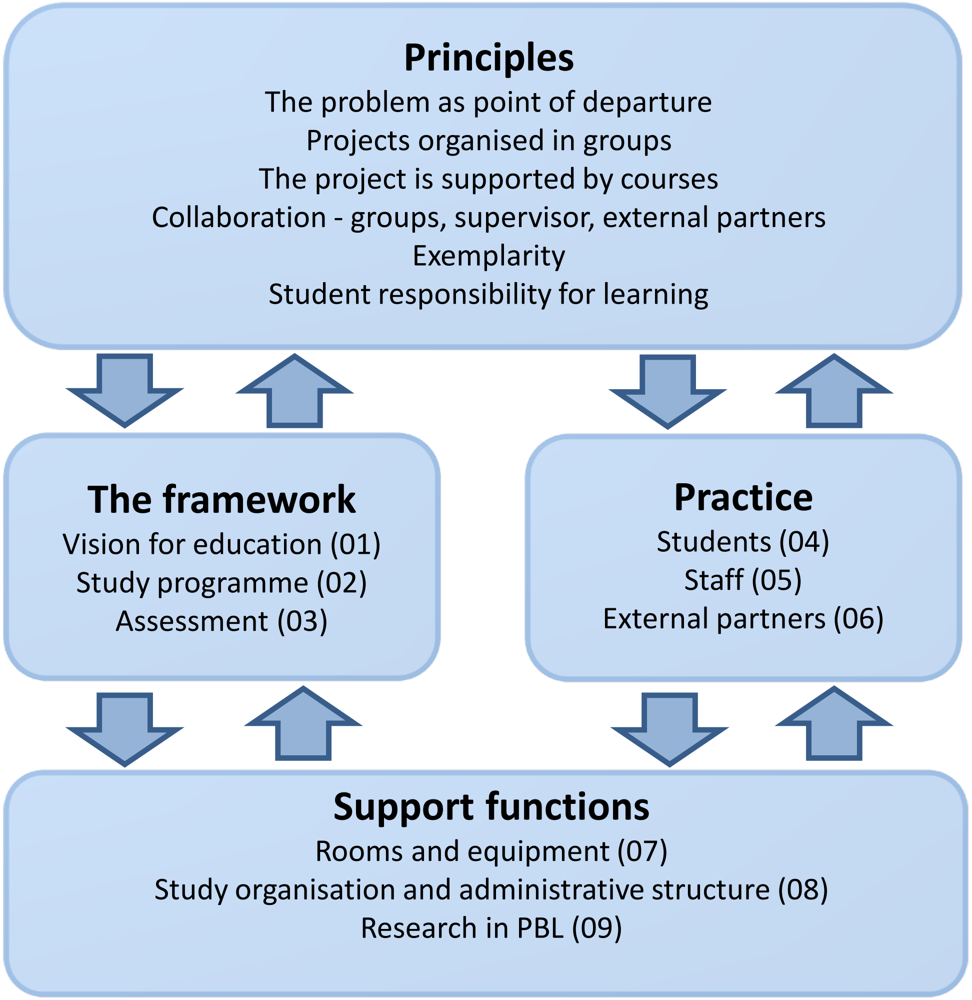
Core Principles – A graphic illustration

Generally:

Projects and working with problems create a frame, which imposes intentionality and meaning on all study activities



Principles

The problem as point of departure
Projects organised in groups
The project is supported by courses
Collaboration - groups, supervisor, external partners
Exemplarity
Student responsibility for learning

The framework

Vision for education (01)
Study programme (02)
Assessment (03)

Practice

Students (04)
Staff (05)
External partners (06)

Support functions

Rooms and equipment (07)
Study organisation and administrative structure (08)
Research in PBL (09)

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Special PBL at Aalborg University

- Flexible learning environment (from own group rooms to wide spaces)
- The type of problems
- The length of the project period
- The attention towards the learning process
- The attention towards acquiring process skills
- Group based assessment (links to video on YouTube in the notes below)
- Strong group commitment

Source: [2]

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Tight Connection of Courses and Projects

- Every semester is set within a ‘thematic framework’
- Although the thematic frameworks are broad, they support defining the focus of the students’ projects
- Courses are developed and taught with reference to the theme of the semester or specific external requirements for the study programme
- A major part of the theoretical knowledge used in the projects is introduced to the students through the courses.

Source: [2]

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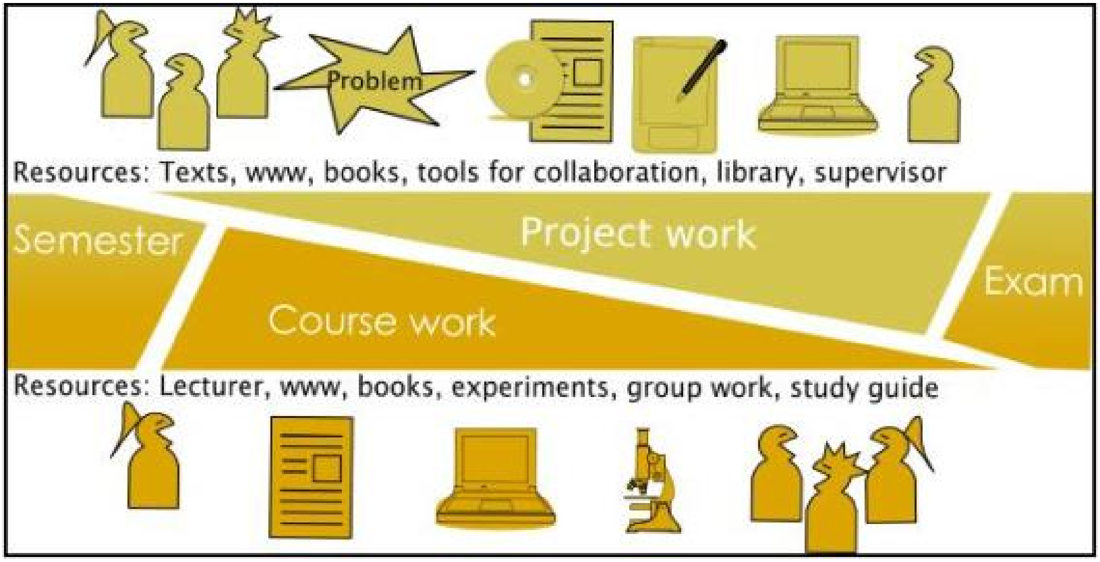
Time Allocation in PBL

50% Project work: a major assignment within a given subject-related framework determined for each semester (thematic framework)

50% Mandatory courses relating to the overall academic profile of the curriculum. Evaluated through individual written or oral examinations



Source: [3]

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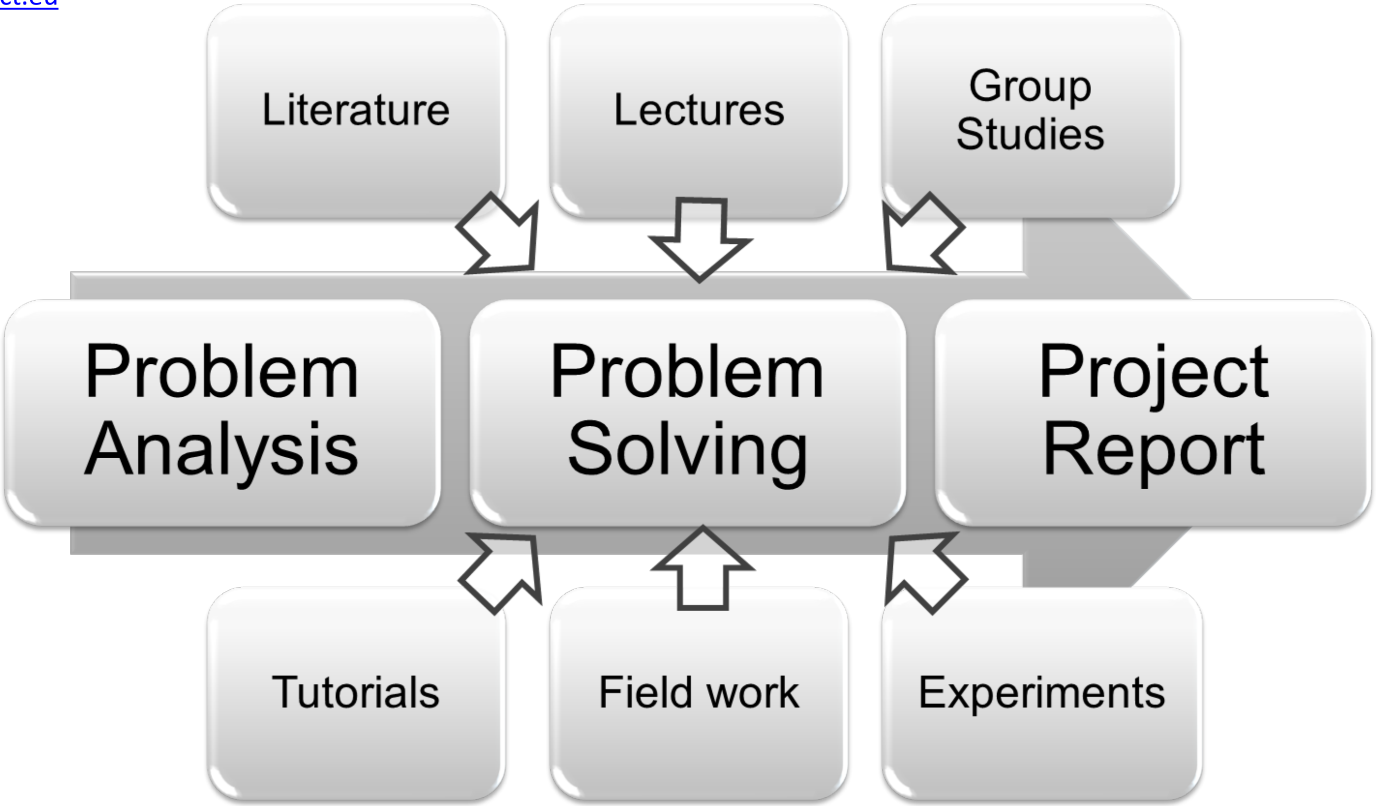
PBL – the Process



Literature

Lectures

Group Studies

Problem Analysis

Problem Solving

Project Report

Tutorials

Field work

Experiments

Source: [3]

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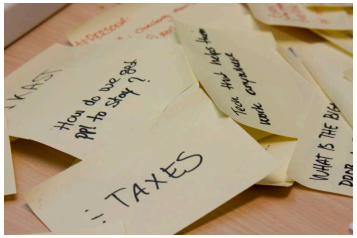
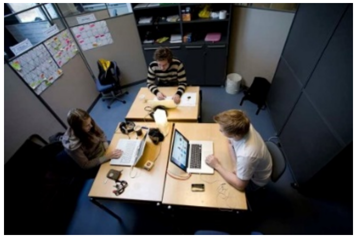
Typical Components of Project Work

- Supervisors present the thematic framework of the semester
- Students brainstorm on ideas for projects and form groups
- Students produce an early problem formulation
- The students will have to:
  - Find a problem and case, identify methods on how to investigate the problem (purely theoretical, through interviews, video-observation and analysis, questionnaires, ethnographic observation etc.)
  - Discuss their methods, and why they investigate their problem in a particular manner
  - Identify theories or theoretical concepts that will help them understand their problem
  - (Often) conduct empirical investigations, that are analysed
- All this is done in collaboration with the supervisor, who helps the students to identify relevant methods, theories etc.





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Q&A

Any Questions so far?

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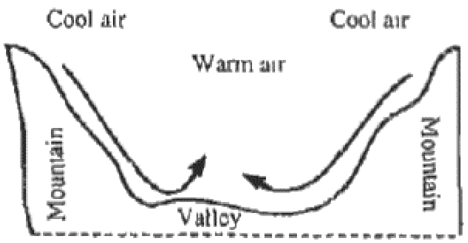
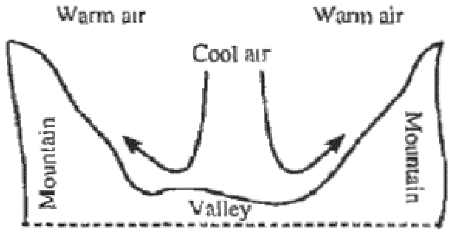
Wind Energy

Indirect form of solar energy induced by the uneven heating and cooling of the earth's crust by the sun combined with the rotation of the earth

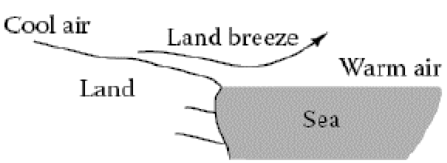


Night

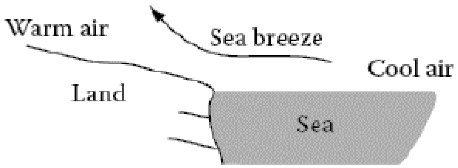


Day

Night



Day



Source: [4]

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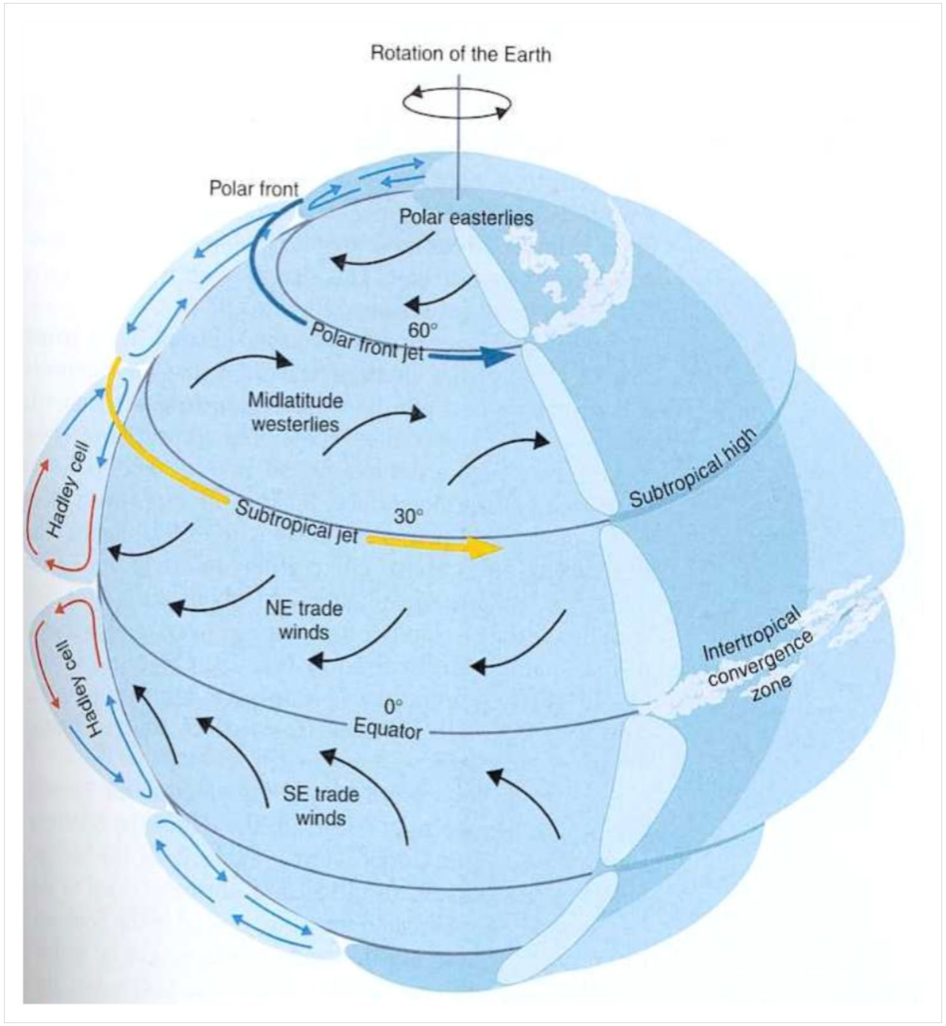

Source: [5]

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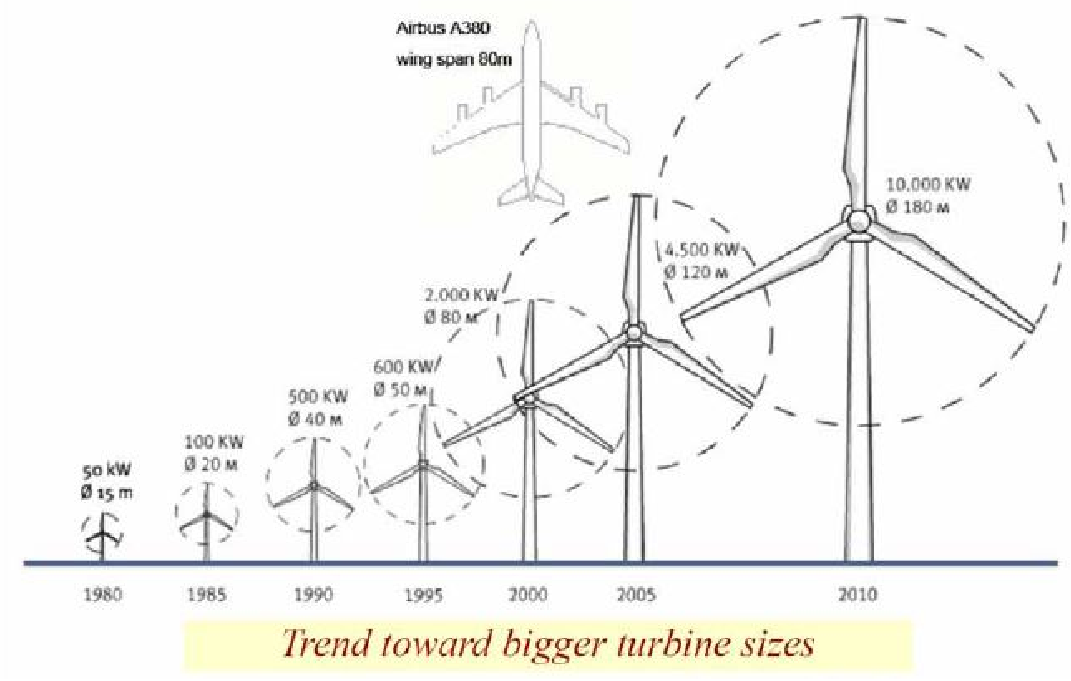
Examples

Source: [3]

Rotor Diameter Growth



Largest wind turbine in the world:
12 MW wind turbine Haliade-X from General Electric

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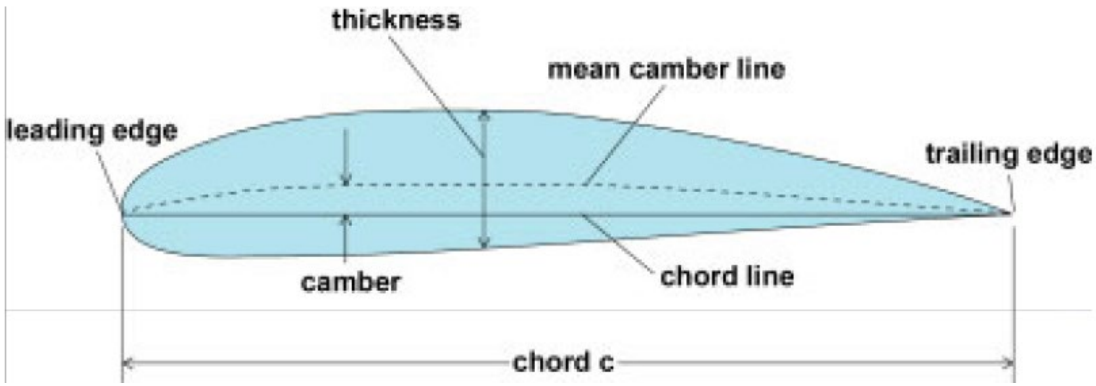
Airfoil Nomenclature

Wind turbines use the same aerodynamic concepts as an aircraft



Source: [5]

The rotor’s aerodynamic function is characterized by the fact of whether the power is captured from the aerodynamic drag or lift of the air stream

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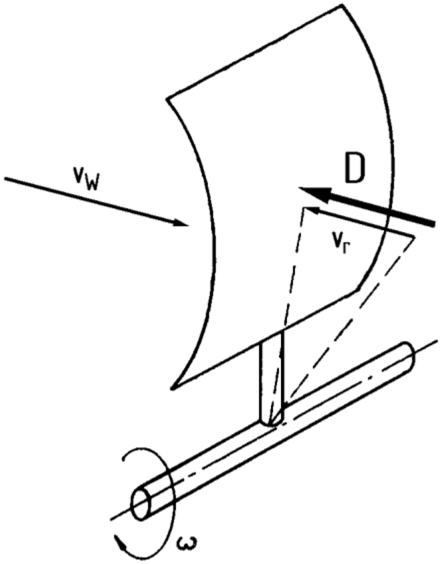
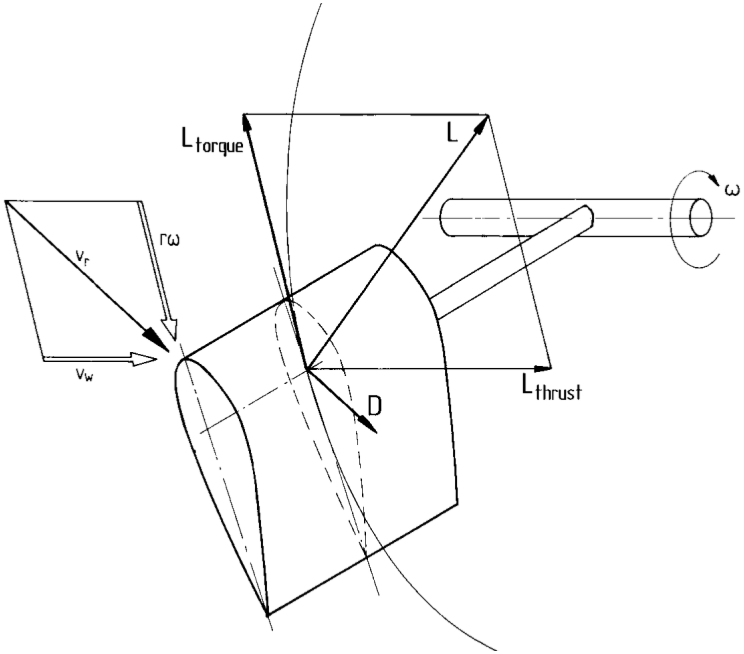
Wind Energy Converters

Drag Devices	Lift Devices
	

Source: [5]

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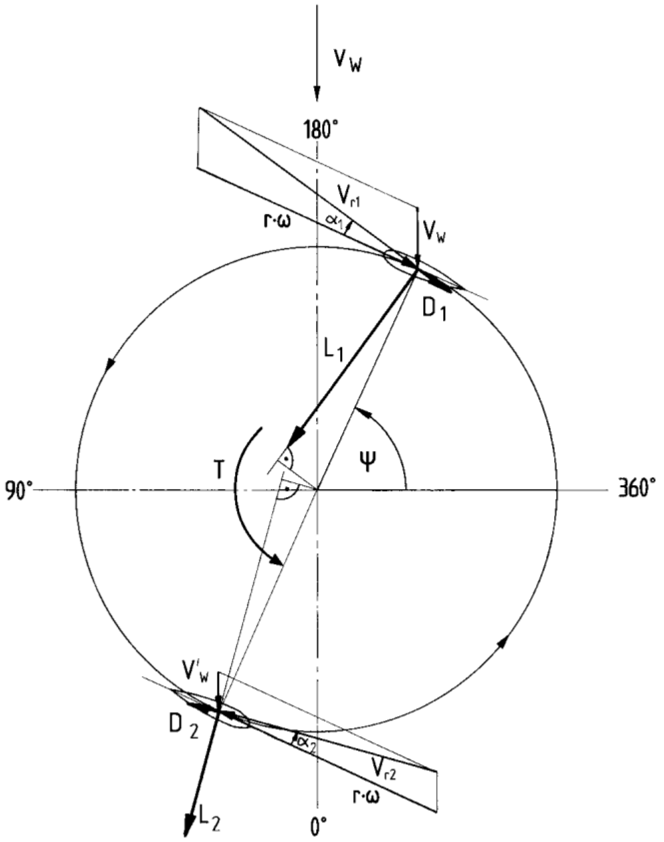
Aerodynamics of VAWT

- The angle of attack of the blades vary constantly during rotation
- One blade moves on the downwind side of the other blade in the range of 180 to 360 degrees of the rotational angle; the wind speed is already reduced at this area due to energy extracted by the upwind blades
- Hence, less power is generated downwind
- In one revolution, alternation of torque is balanced with 3 rotor blades so we get an increasing and decreasing torque which is positive.



Source: [5]

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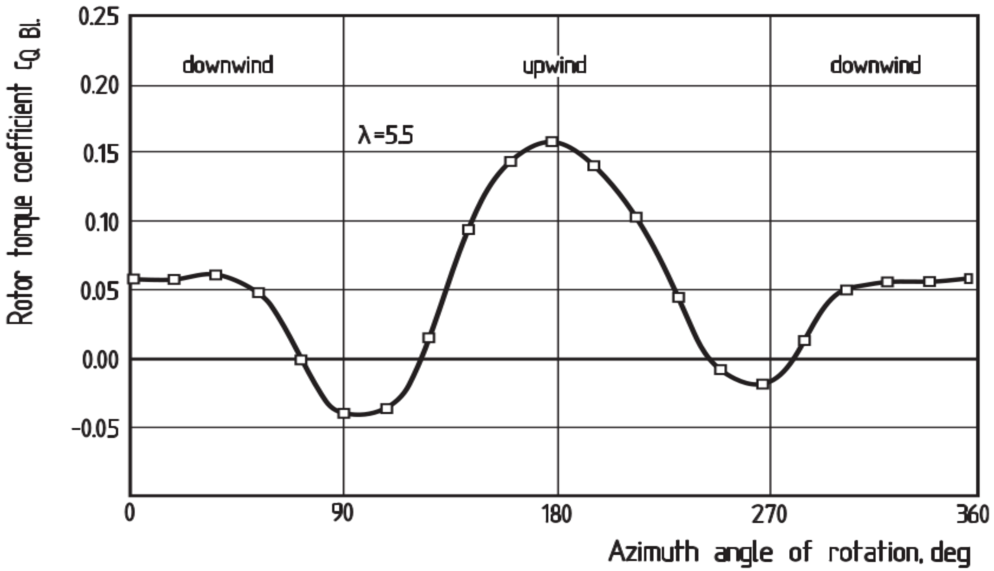
Torque Variation of a Single Rotor Blade

- In one revolution, a blade generates a mean positive torque
- However, some short sections produce negative torque as well



Source: [4]

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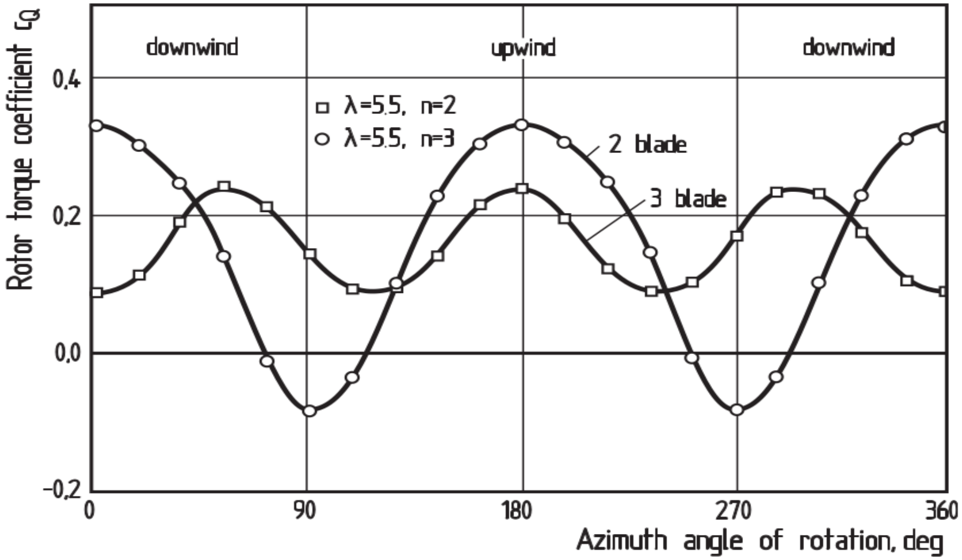
Torque Variation of a VAWT

- In one revolution, alternation of torque can be balanced with 3 rotor blades.

➔ We get an increasing and decreasing torque which is positive.



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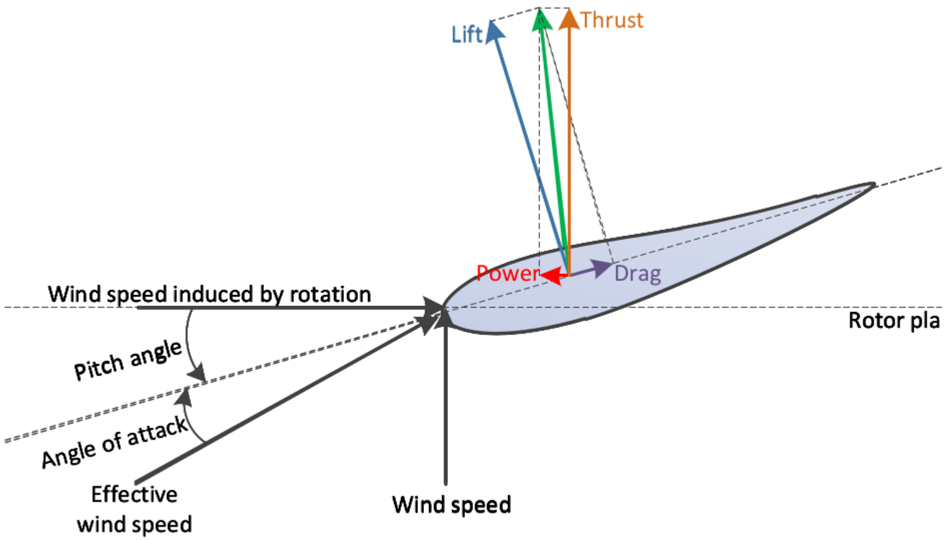
Basic Aerodynamics (HAWT)



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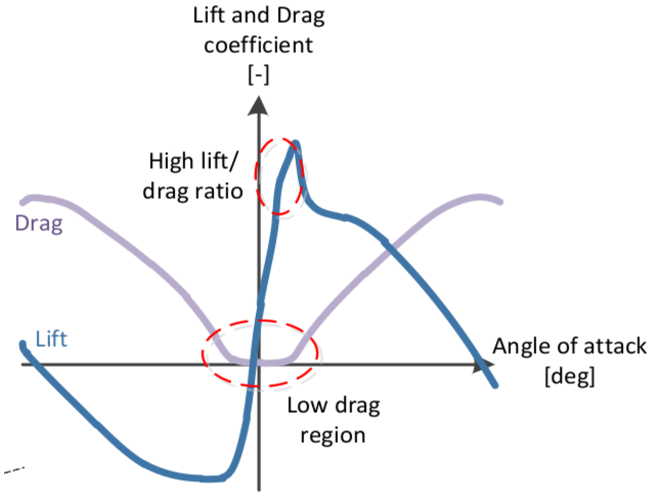

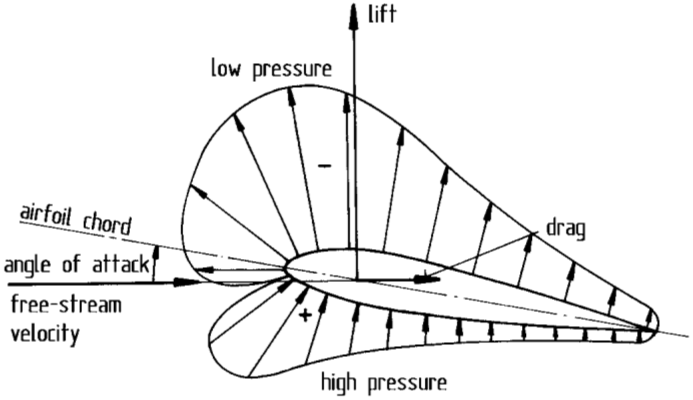

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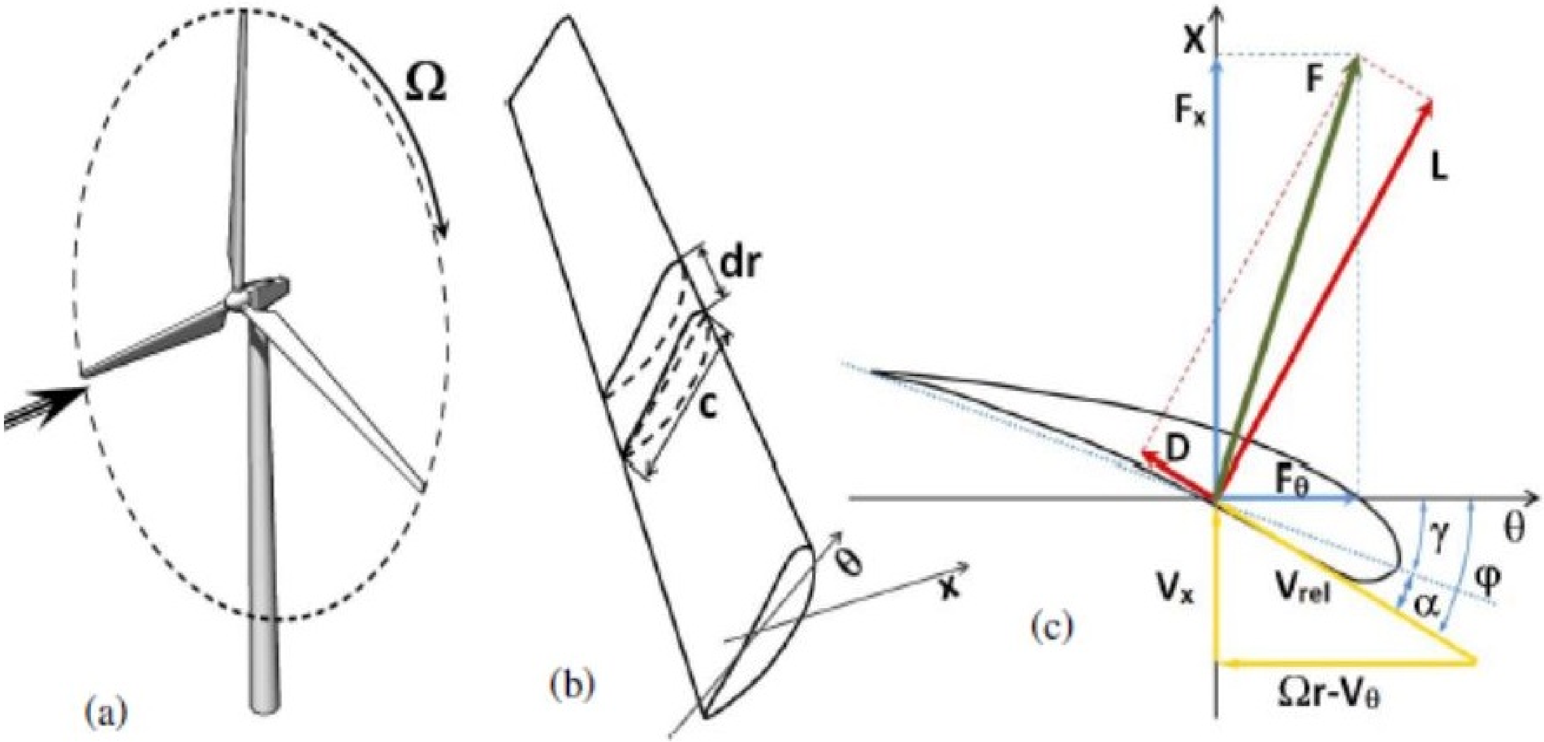
Aerodynamic Forces and Geometry (HAWT)



Source: [5]

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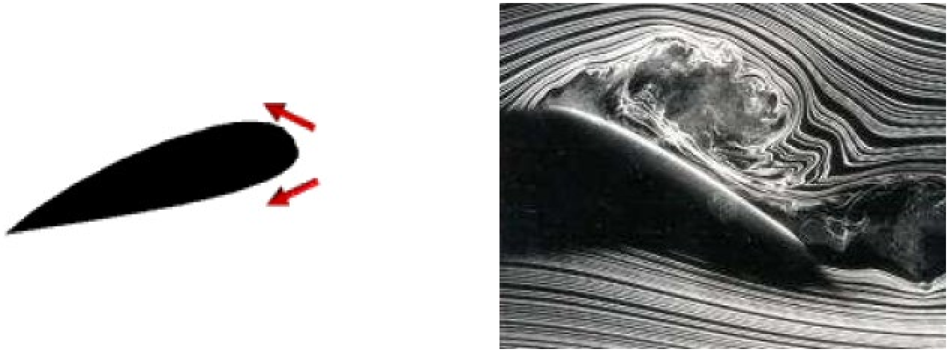
Airfoil in Stall

- Stall occurs as a result of the separation of the flow from the airfoil surface
- Stall results in the decrease of the lift coefficient with the increase of the angle of attack
- This behavior is complex due to blade rotation



Source: [4]

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Tip Speed Ratio

The tip speed ratio is a ratio between the rotational speed of the blade tip and the speed of the free wind stream.

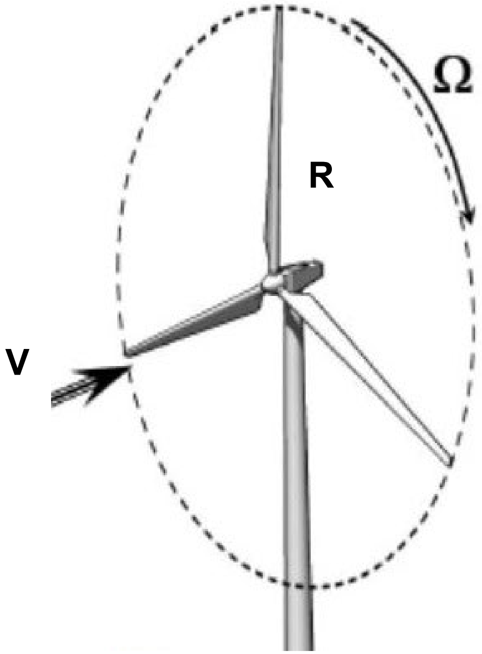
$$\lambda = \frac{\Omega R}{V}$$

where,

Ω: rotational speed in rad/sec.

R: Rotor radius

V: free wind stream velocity



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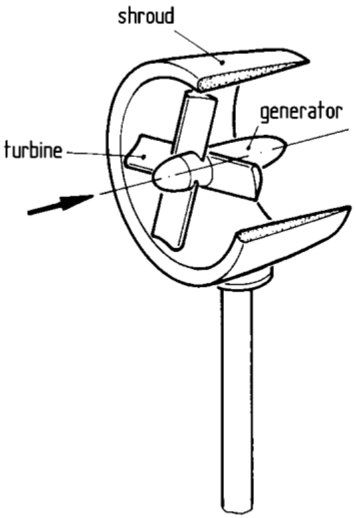
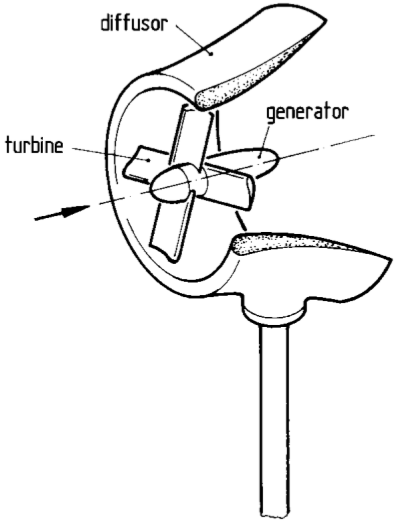
Wind Energy Concentrators

Basically, the idea is to increase power yield in relation with rotor-swept area.

Examples:



Shrouded wind turbine



Wind turbine with diffusor

Source: [5]

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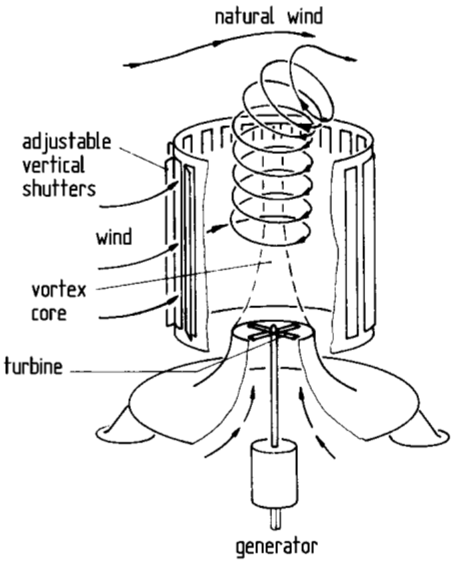
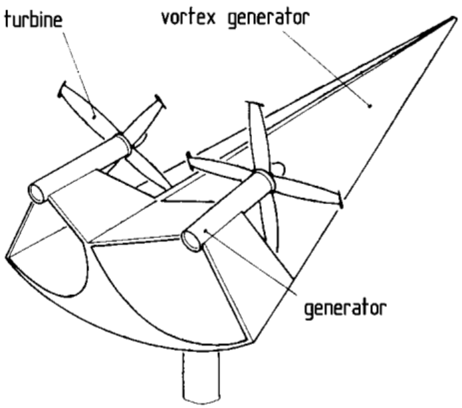
Wind Energy Concentrators

Examples:



Tornado tower



Delta wing vortex concentrator

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Summary of provided knowledge

Module 2.1

- Problem based learning concept and implementation
- Wind energy basics
  - Resources
  - Components
  - Aerodynamics

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References

[1] “Why Project Based Learning Isn't Just for Students.” Zulama, https://www.carnegielearning.com/solutions/applied-sciences/computer-science/

[2] “Aalborg University.” Aalborg University - Knowledge for the World, 21 Nov. 2014, https://www.en.aau.dk/about-aau/aalborg-model-problem-based-learning/

[3] Ryberg, Thomas. “ICT Supporting PBL - Phases in Project Work.” E-learning Lab - AAU (Aalborg University), E-Learning Lab - AAU (Aalborg University)

[4] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

[5] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

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Aerodynamic Design of HAWT Blade and Loads Calculation using BEM Theory

Lecture 1.2

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Learning outcomes

O1. Aerodynamic knowledge about the HAWT

O2. Load calculations when designing HAWT systems

O3. Blade element momentum theory

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Technical Contents

- How does a wind turbine work
- Theories that led to BEM model
- Review of basic fluid dynamics
- Actuator disk theory

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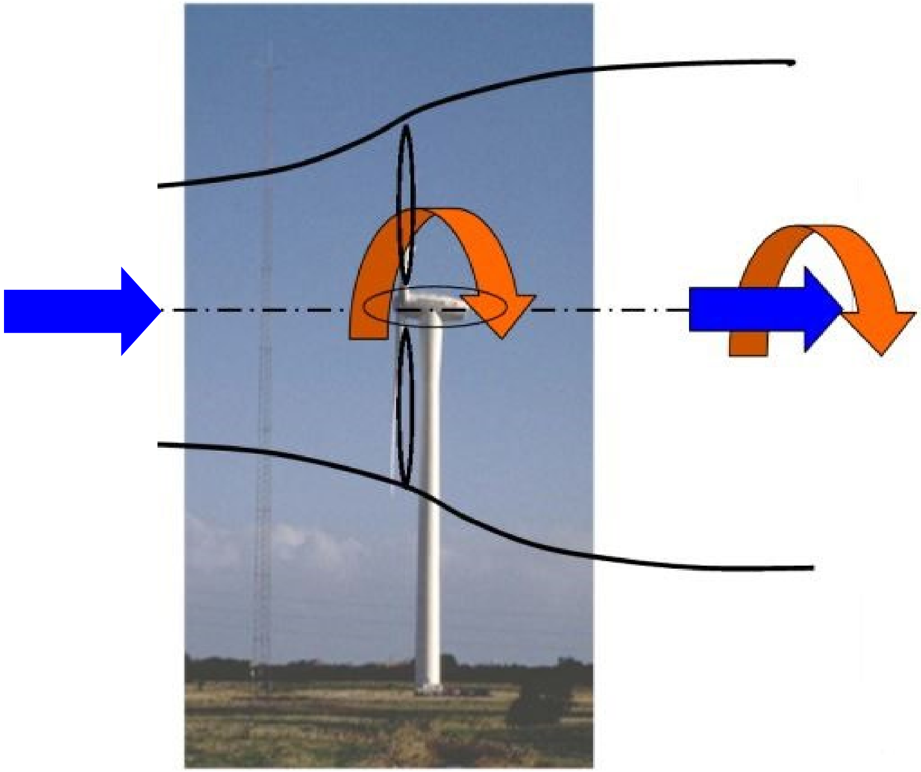
How Does a Turbine Work?

- The wind hits the rotor plane
- The combination of wind speed and blade rotation results in a pressure distribution on the rotor blades
- The pressure distribution causes a turning moment (torque)
- The turning moment rotates the shaft
- The shaft is coupled to a generator that produces electrical power



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Formulating the BEM Model


Actuator disk theory

General momentum theory

Blade Element theory

BEM Model

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Conservation Equations

- All the conservation equations are usually expressed with quantities that move with the body (or material volume talking about fluids), following the so-called ***Lagrangian*** approach.
- Using the ***Eulerian*** approach which is based on the description of the flow motions passing through a fixed control volume.
  - This implies that, unless the flow velocity is zero within the control volume, the conservation equations must be modified to account for the different fluid parcels involved

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Mass Conservation

- Under normal circumstances, mass cannot be destroyed or created
- If we consider a material fluid volume, *V*(t) with mass *m*=$\int_{V(t)} \rho dV$, where ρ is the fluid density

$$\frac{dm}{dt} = 0 \rightarrow \frac{d}{dt} \int_{V(t)} \rho dV = 0$$

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Conservation of Angular Momentum

- The rate of change of the moment of momentum is equal to the external angular moment applied to the body

$$\frac{d(\vec{r}\times\vec{Q})}{dt} = \overrightarrow{M^{(e)}} \rightarrow \frac{d}{dt}\int_{V(t)} \vec{r} \times (\rho\vec{U})dV = \overrightarrow{M^{(e)}}$$

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Conservation of Energy

- The ***rate of change of the energy*** of a given volume is equal to the sum of the ***rate of work done by the system*** plus the ***rate of heat supplied from the volume to the universe***

$$\frac{dE}{dt} = -\dot{W} - \dot{Q} \;\rightarrow\; \frac{d}{dt}\int_{V(t)} \rho(e + \frac{|U|^2}{2})dV = -\dot{W} - \dot{Q}$$

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Notes

- In all previous equations, the material volume of fluid is deformable and depends on time, *t*, since they are expressed in ***Lagrangian formulation.***
- Therefore, the time derivative cannot be transferred inside the integral without accounting for the deformation of *V*(t)
- This can be done by means of the following formula:

$$\frac{d}{dt}\int_{V(t)} \emptyset dV = \int_V \frac{\partial \emptyset}{\partial t} dV + \int_S \emptyset (U.n) dS$$

where *S* is the bounding surface of the generic volume *V* now fixed in time and the vector *n* is the local normal to the surface *S*.

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Conservation Laws in Eulerian Formulation-1

- Mass Conservation:

$$\frac{d}{dt}\int_{V(t)} \rho dV = \underbrace{\int_V \frac{\partial \rho}{\partial t} dV}_{\text{Rate of change of mass in C.V.}} + \underbrace{\int_S \rho(\vec{u}.\vec{n})dS}_{\text{Net rate of mass flow}} = 0$$

Assuming the steady incompressible flow:

$$\int_S \rho(\vec{u}.\vec{n})dS = \underbrace{\int_{S_1} \rho(\vec{u}.\vec{n})dS}_{\text{Mass flow in}} + \underbrace{\int_{S_2} \rho(\vec{u}.\vec{n})dS}_{\text{Mass flow out}} + \underbrace{\int_{S_e} \rho(\vec{u}.\vec{n})dS}_{\text{Mass flow through the stream tube surface}} = 0$$

which reduces to:

$$\boxed{-\dot{m}_1 + \dot{m}_2 = 0}$$

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Conservation Laws in Eulerian Formulation-2

- Momentum Conservation:

$$\frac{d}{dt}\int_{V(t)} \rho\vec{U}dV = \int_V \frac{\partial\rho\vec{U}}{\partial t}dV + \int_S (\rho\vec{U})(\vec{U}.\vec{n})dS = \overrightarrow{F^{(e)}}$$

Assuming the steady incompressible flow:

$$\overrightarrow{F^{(e)}} = \int_{S_1}(\rho\vec{U})(\vec{U}.\vec{n})dS + \int_{S_2}(\rho\vec{U})(\vec{U}.\vec{n})dS$$

$$F_{x_{ie}} = -\rho {U_1}^2 S_1 + \rho {U_2}^2 S_2$$

which leads to:

$$\boxed{\boldsymbol{F_{x_{ie}} = \dot{m}(U_2 - U_1)}}$$

i.e. velocity variation must be caused by a force

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What Kind of Force?

- Volume Forces like gravitational force which is neglected because there is no significant difference in altitude

- Surface forces like:
  - Viscous Forces: $\boldsymbol{F_{viscous}} = \boldsymbol{\mu \frac{dU}{dy}}$

    If the velocity gradient $\boldsymbol{\frac{dU}{dy}}$, isn't so big like in solid bodies then it should be neglected compared to pressure forces
  - Pressure Forces: $F_{pressure}$ which will be our main focus

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Conservation Laws in Eulerian Formulation-3

- Energy Conservation:

$$\int_V \frac{\partial}{\partial t}\rho(e+\frac{U^2}{2})dV + \int_S \rho(e+\frac{U^2}{2})(\vec{U}.\vec{n})dS = -\dot{W} - \dot{Q}$$

$$-\rho(e_1+\frac{{U_1}^2}{2})U_1S_1 + \rho\left(e_2+\frac{{U_2}^2}{2}\right)U_2S_2 = -\dot{W} - \dot{Q}$$

$$-\dot{W} - \dot{Q} = \dot{m}(e_2 - e_1 + \frac{{U_2}^2}{2} - \frac{{U_1}^2}{2})$$

which reduces to:

$$\boxed{-\dot{\boldsymbol{W}} = \dot{\boldsymbol{m}}(\frac{{\boldsymbol{U}_2}^2}{2} - \frac{{\boldsymbol{U}_1}^2}{2})}$$

i.e. the variation of kinetic energy along the stream tube is equal to the rate of work done by the system

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Bernoulli's Theorem

- For an incompressible inviscid steady flow, with conservative volume forces, the expression

$$\frac{P}{\rho}+\frac{U^2}{2}+gz=const.$$

is constant along any given streamline

- If the vertical height variations are small, i.e., as usually is for wind turbines blades where

$$g\Delta z \ll U^2$$

the gravitational term can be neglected and Bernoulli's theorem simplifies to a simple balance between pressure potential energy and kinetic energy.

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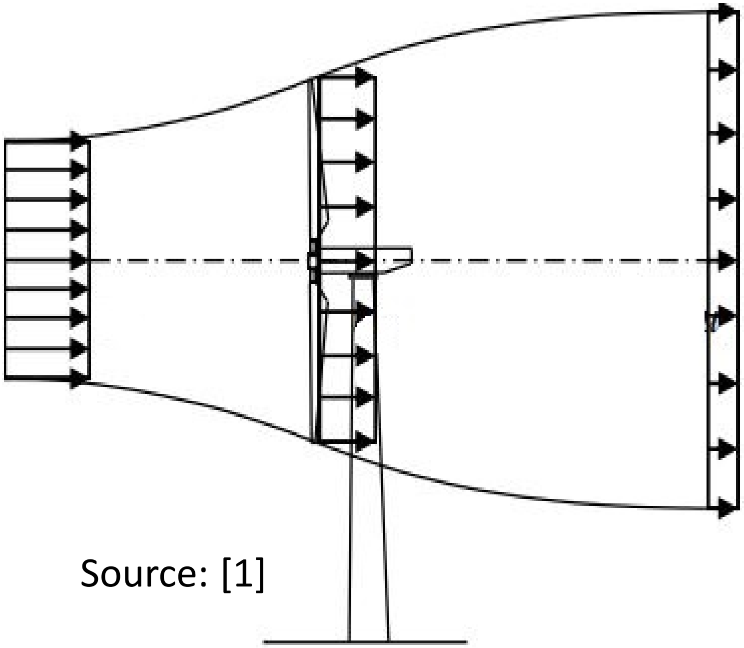
The Actuator Disk Theory

- A simple model may be used to determine the power from an ideal turbine rotor, the thrust of the wind on the ideal rotor and the effect of the rotor operation on the local wind field.
- The analysis assumes a control volume, in which the boundaries are the surface of a stream tube and two cross-sections of the stream tube.



Source: [1]

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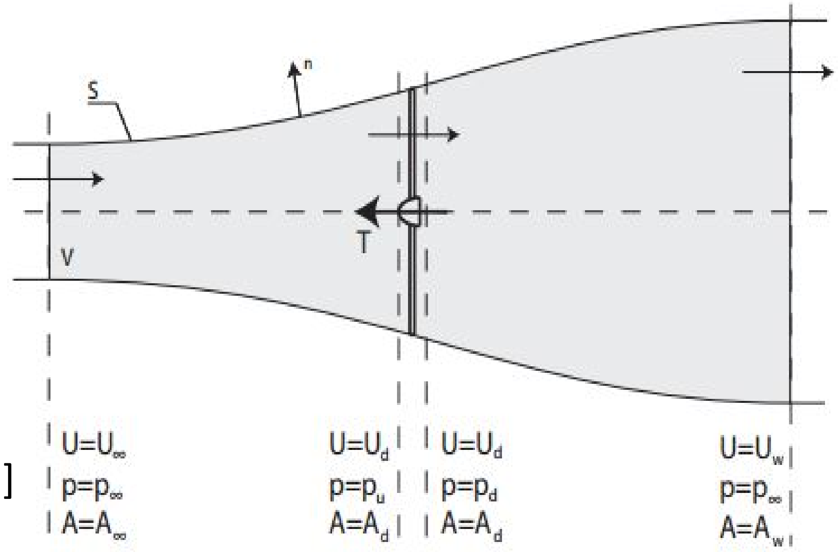
The Actuator Disk Theory

- Assumptions:
  - Homogeneous, incompressible, steady wind
  - No frictional drag
  - Infinite number of blades
  - Uniform thrust over the disk or rotor area
  - Non-rotating wake
  - The static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure



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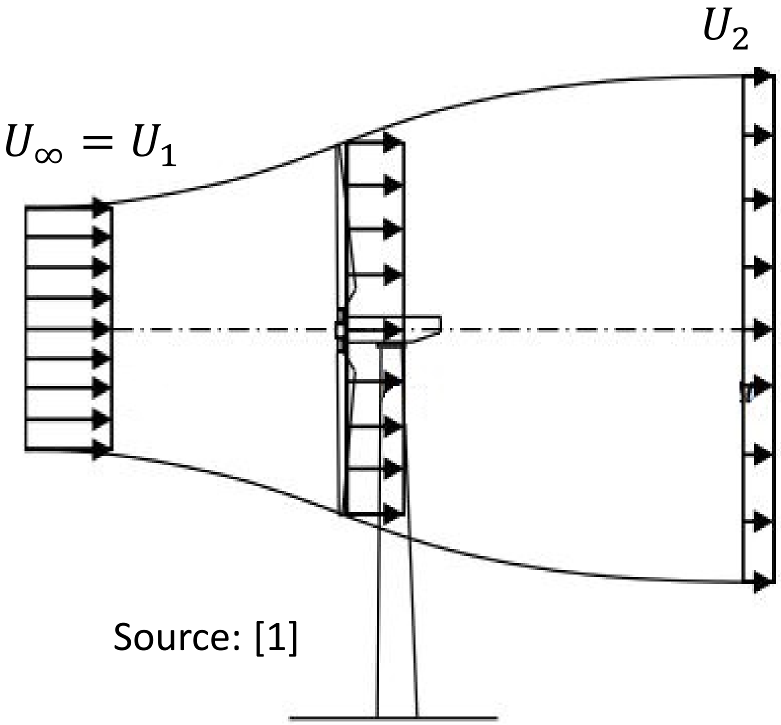
The Actuator Disk Theory

- As mentioned, a wind turbine is a machine that converts kinetic energy of an incoming flow field into mechanical energy transmitted subsequently to a shaft.
- This implies that an incoming flow with free-stream velocity U_∞ will be slowed down of some amount related to the quantity of kinetic energy extracted from it according to

$$-\dot{W} = \dot{m}\left(\frac{U_2{}^2}{2} - \frac{U_1{}^2}{2}\right)$$

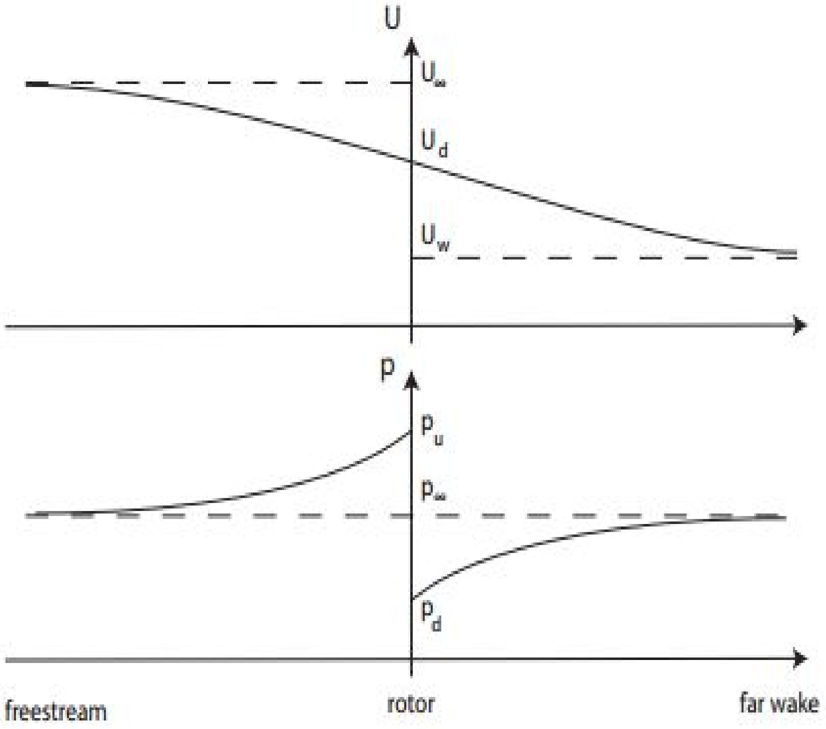


Source: [1]

The Actuator Disk Theory

- By means of Bernoulli's theorem it is possible to recognize that, since the velocity is decreasing along the turbine axis, the pressure must increase accordingly with a jump across the rotor due to the energy extracted by the turbine.

$$\frac{P}{\rho}+\frac{U^2}{2}=const.$$



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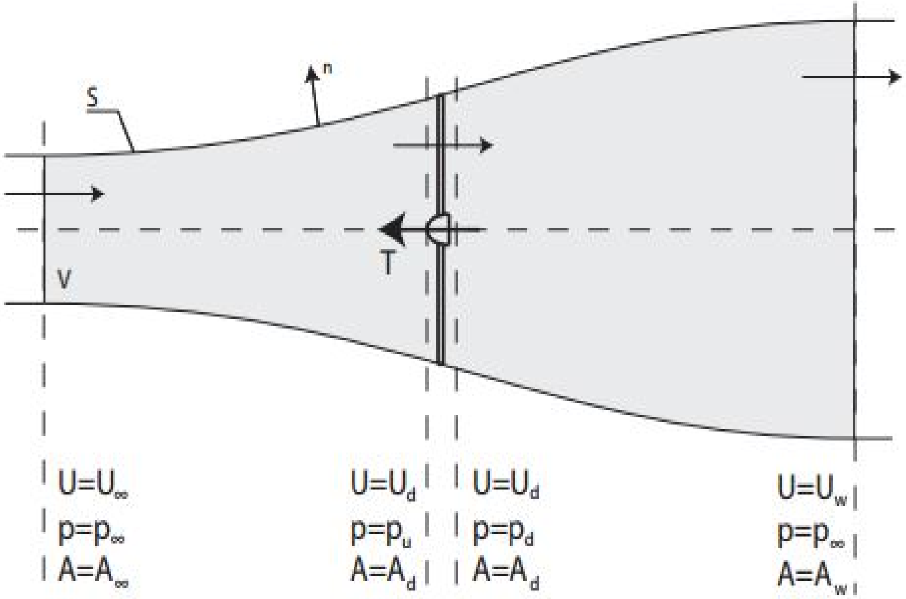
The Actuator Disk Theory

- Intuitively p_u > p_d, from both energy conservation arguments and the physical intuition that the air must push the rotor downstream. Therefore, the force T applied to the rotor can be expressed as

$$T = A_d(p_u - p_d)$$



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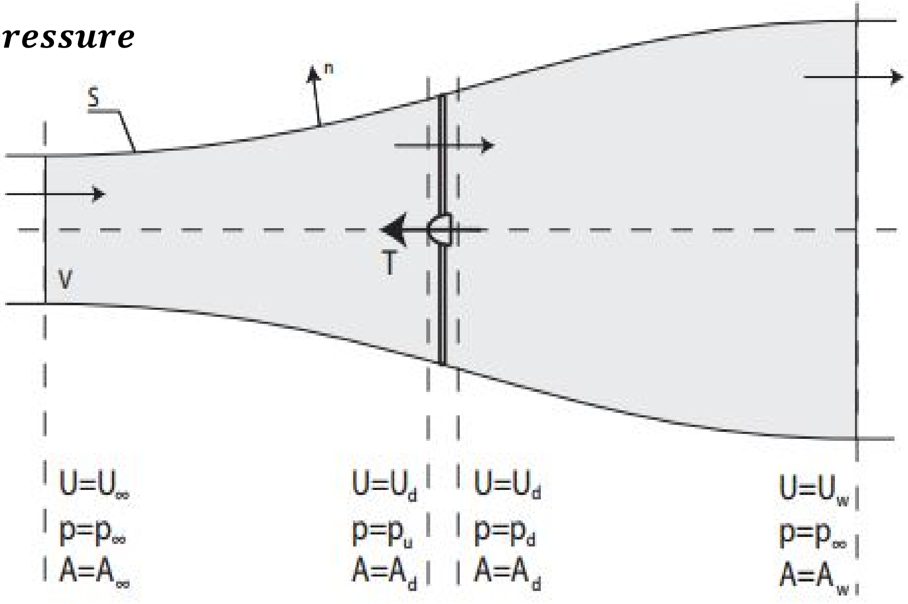
The Actuator Disk Theory

- The first equation to be used is the mass conservation equation

$$\dot{m} = \rho U_\infty A_\infty = \rho U_d A_d = \rho U_w A_w$$

- The axial-momentum conservation equation is

$$\begin{aligned} &\dot{m}(U_w - U_\infty) \\ &= -T + F_{volume} + F_{viscous} + F_{pressure} \end{aligned}$$

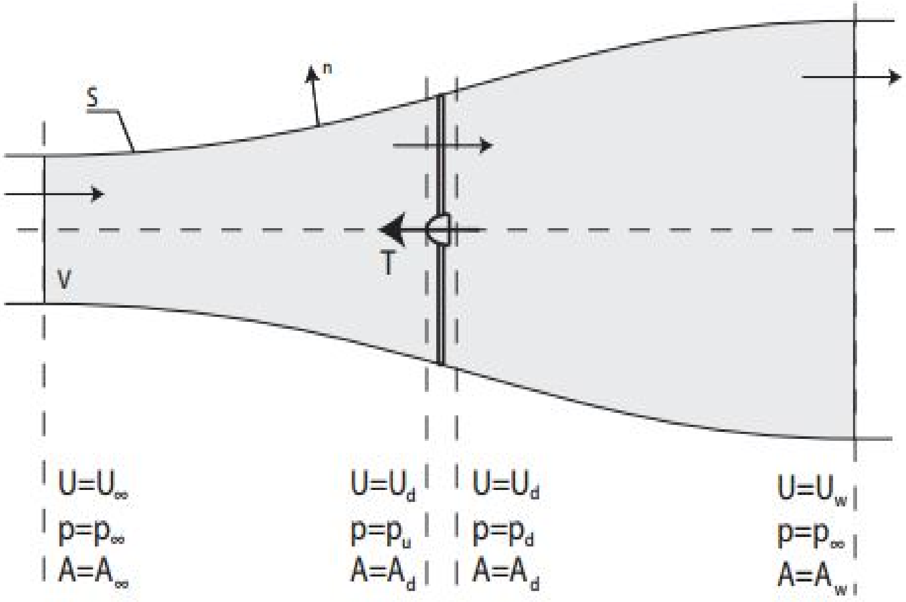


Source: [2]

The Actuator Disk Theory

- The pressure forces on the external surface are important but they are assumed to be very small and negligible in most studies.

$$F_{Press.} = \int_S p n_x dS = 0$$



Source: [2]

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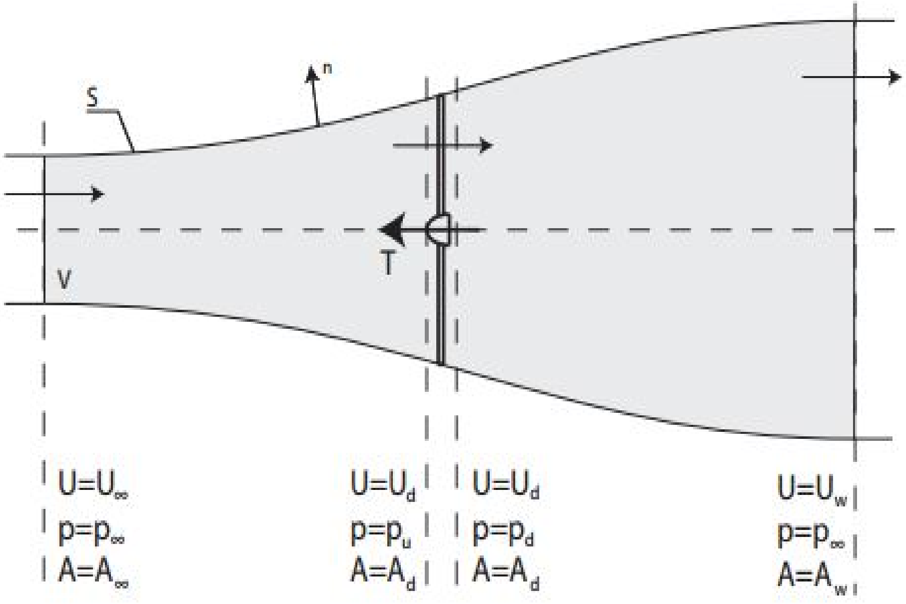
The Actuator Disk Theory

- The third equation we need is provided by Bernoulli's theorem
  - The application of the theorem upstream the rotor leads to:

$$\frac{p_u}{\rho}+\frac{{U_d}^2}{2}=\frac{p_\infty}{\rho}+\frac{{U_\infty}^2}{2}$$

  - While downstream becomes

$$\frac{p_d}{\rho}+\frac{{U_d}^2}{2}=\frac{p_\infty}{\rho}+\frac{{U_w}^2}{2}$$



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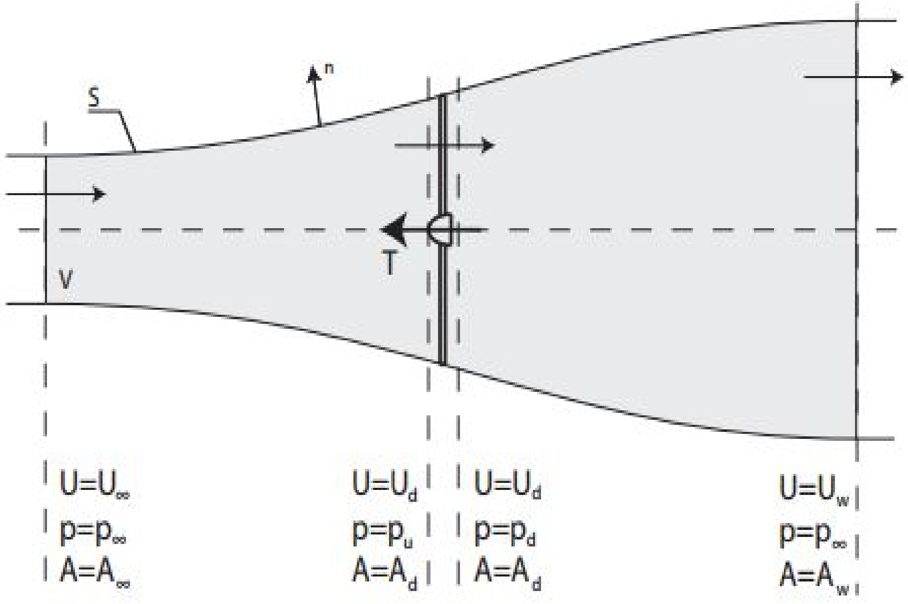
The Actuator Disk Theory

- The difference between the 2 equations leads to an expression of the pressure difference across the rotor

$$p_u - p_d = \frac{\rho}{2}({U_\infty}^2 - {U_w}^2)$$

Related to the variation of K.E within the C.V.



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The Actuator Disk Theory

- Since $T = A_d(p_u - p_d)$, it is possible to combine the equations obtaining:

$$T = \frac{\rho A_d}{2}\left({U_\infty}^2 - {U_w}^2\right) = \rho U_d A_d (U_\infty - U_w)$$

Then,

$$\boxed{U_d = \frac{U_\infty + U_w}{2}}$$

which states that the velocity at the rotor is the arithmetic mean between the free-stream velocity and the far-wake velocity.

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The Actuator Disk Theory

- It is useful at this point to introduce the definition of ***axial induction factor a*** as:

$$U_d = U_\infty(1 - a)$$

- From this definition, the far-wake velocity can be expressed as

$$U_w = U_\infty(1 - 2a)$$

- The higher the axial induction factor, the higher the blockage of the rotor and the consequent slow down of the wake velocity.
- However, for a > 0.5, the present theory leads to a negative wake velocity which is not physically possible, and this implies that the theory is not valid for **$a \geq 0.5$**

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The Actuator Disk Theory

- Combining the equations:

$\mathrm{T} = \rho U_d A_d (U_\infty - U_w)$ and $U_w = U_\infty (1 - 2a)$

We obtain,

$$\boxed{\mathrm{T} = 2\rho {U_\infty}^2 A_d \mathrm{a}(1 - a)}$$

- The power: rate of work of the thrust force:

$$\boxed{P_w = T U_d = 2\rho A_d {U_\infty}^3 a(1 - a)^2}$$

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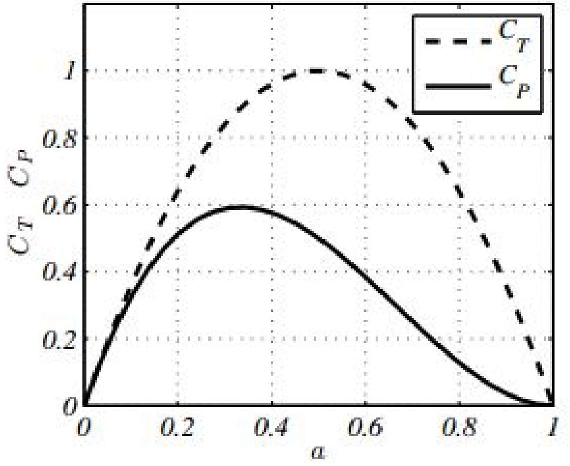
The Betz Limit

- Thrust Coefficient:

$$C_T = \frac{T}{\frac{1}{2}\rho {U_\infty}^2 A_d} = \frac{2\rho {U_\infty}^2 A_d \mathrm{a}(1-a)}{\frac{1}{2}\rho {U_\infty}^2 A_d} = 4a(1-a)$$

- Power Coefficient:

$$C_p = \frac{P_w}{\frac{1}{2}\rho {U_\infty}^3 A_d} = \frac{2\rho A_d {U_\infty}^3 a(1-a)^2}{\frac{1}{2}\rho {U_\infty}^3 A_d} = 4a(1-a)^2$$



Source: [1]

To get the max. $C_p \rightarrow \frac{dC_p}{da} = 0 \rightarrow a = 1$ (not suitable for WT) & $\boxed{a = \frac{1}{3}}$

Therefore, $\boxed{C_{p_{max.}} = \frac{16}{27} \cong 0.593}$ → known as the Betz Limit

i.e., the power we can extract $P_w < \frac{1}{2}\rho {U_\infty}^3 A_d . \frac{16}{27}$

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Summary of the provided knowledge

- Principle of wind turbine systems
- Theory of the BEM model
- Fluid dynamics basics
- Actuator disk theory

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References

[1] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

[2] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

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Q&A

Questions?

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Optimal Blade Design,
Effect of Number of Blades

Lecture 1.3

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Learning outcomes

O1. Aerodynamic knowledge about the HAWT

O2. Load calculations when designing HAWT systems

O3. Blade element momentum theory

O4. Blade design and analysis

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Technical Contents

- General momentum theory
- Blade element theory
- Blade element momentum model
- Prandtl’s correction factor
- Advantages and disadvantages of using BEM model
- Other corrections

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General Momentum Theory

- Let’s consider an annular section of the rotor disc, located at a radial position *r* and with thickness *dr*
- Let’s consider the stream tube originated from this annular section as our control volume where the conservation equations are applied.

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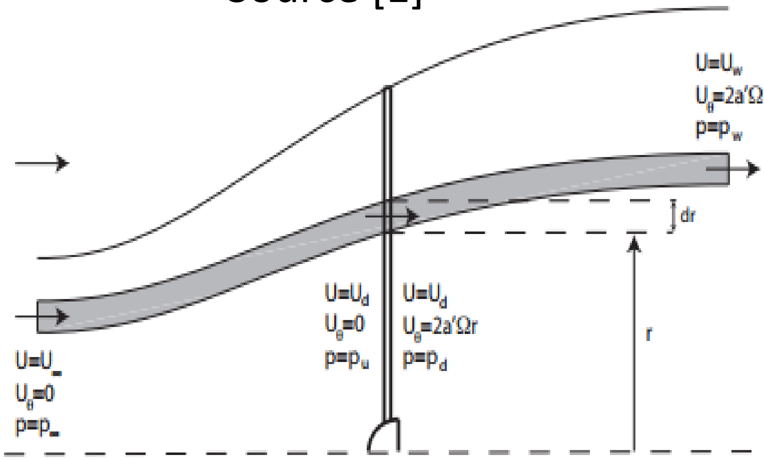

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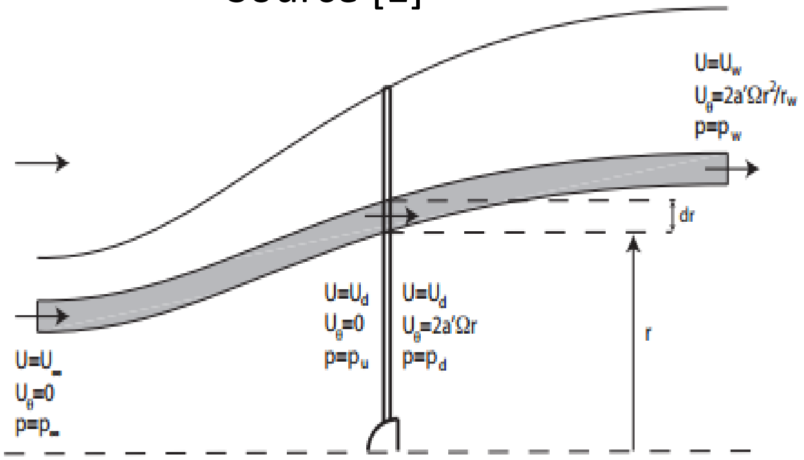
General Momentum Theory, cont'd

- Since dr is supposed to be small, the velocity vector **U** = (U; U_r; U_θ) can be considered uniform in the radial direction within the infinitesimal area **dS = 2πrdr**
- The hypotheses of steady incompressible flow and of rotor with infinite number of blades are here used too
- Under this last assumption, the azimuthal variation of the physical quantities is zero and the flow can be treated as axisymmetric


Source [1]

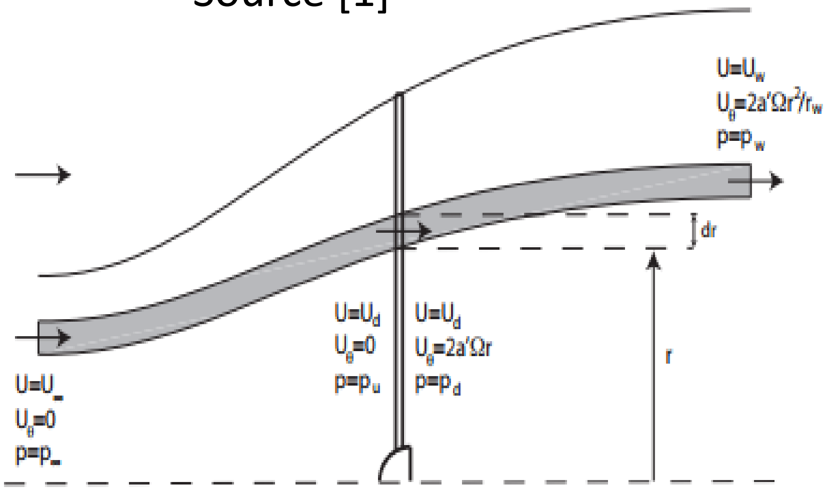
General Momentum Theory, cont’d

- Mass Flow Conservation:

  $d\dot{m} = 2\pi r \rho U dr = const.$
- Momentum Conservation: (axial direction)

  $d\dot{m}(U_\infty - U_w) = dT + dF_{pressure}$

  where the viscous and gravitational forces are neglected already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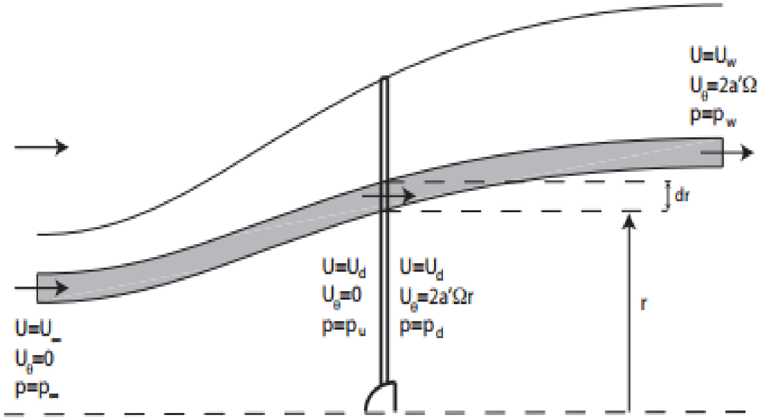
General Momentum Theory, cont’d

- The pressure contribution

  $F_{Press.} = \int_S p n_x dS = 0$

  is non-zero because the wake pressure $p_w \neq p_\infty$ due to wake rotation, leading to an imbalance between these two regions
- Glauert (1935) accounted for the different pressures between free-stream and wake region, but it is often neglected in many references (even Glauert proposed this simplification)



Source [1]

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General Momentum Theory, cont’d

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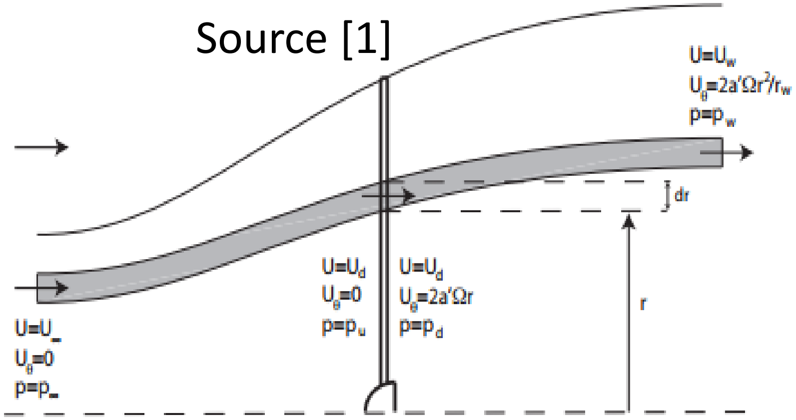
- Let’s consider separately the upstream streamtube half, terminating somewhere upstream of the rotor disc.
- The angular of momentum conservation equation:

$$\boldsymbol{d\dot{m}\left(r_{\infty}U_{\theta,\infty}-r_{up}U_{\theta,up}\right)=d\dot{m}\left(-r_{up}U_{\theta,up}\right)=dM_x=0}$$



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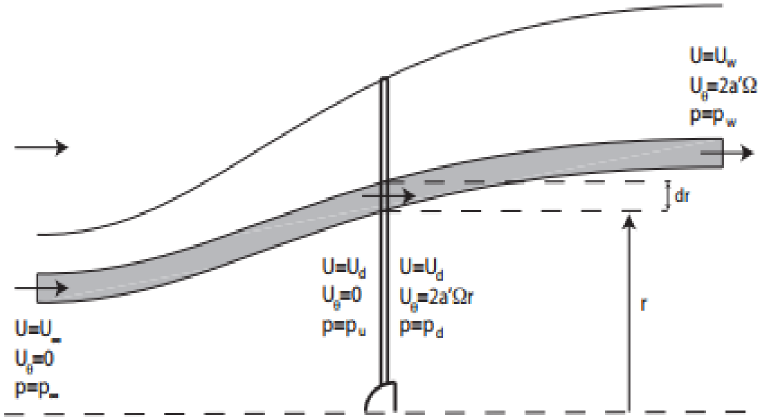
General Momentum Theory, cont'd

- Since the free-stream is not rotating, all the upstream flow is not rotating as well and $\boldsymbol{U_{\theta,up}}$= 0, despite the presence of the rotor.
- The same argument, applied downstream of the rotor disc, leads to the equation:

$$r_w U_{\theta,w} = r_{down} U_{\theta,down}$$



Source [1]

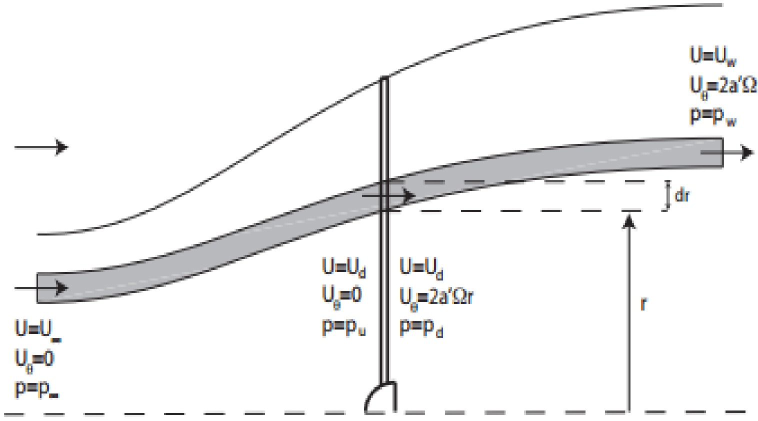
General Momentum Theory, cont’d

- Conventionally, the azimuthal velocity U_θ at the rotor disc is scaled with the rotor angular velocity Ω so that

  $U_\theta = 2a'\Omega r$,

  where a' is called tangential induction factor and plays a similar role of the axial induction factor a.

  The factor 2 in the a' definition is associated to the idea that exactly at the disc the rotational velocity should be $U_{\theta,d} = a'\Omega r$, similarly to the relationship between free-stream and wake velocity, allowing a mild transition between the non-rotating state upstream and the rotating state downstream.



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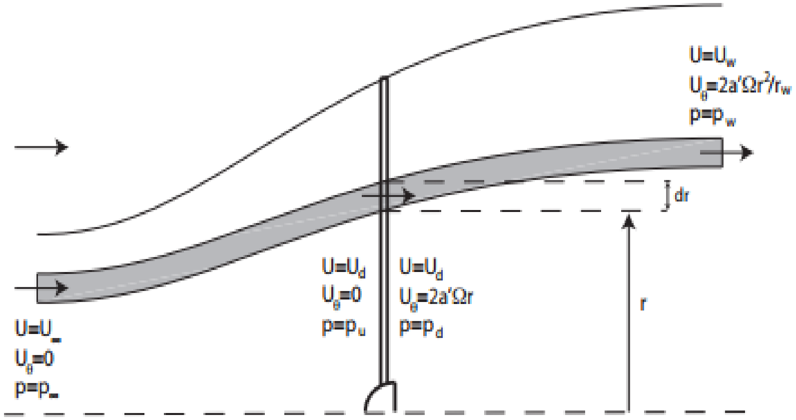
General Momentum Theory, cont'd

- The application of Bernoulli's equation upstream of the rotor disc leads to:

$$\frac{p_u}{\rho}+\frac{{U_d}^2}{2}=\frac{p_\infty}{\rho}+\frac{{U_\infty}^2}{2}$$

while downstream becomes

$$\frac{p_d}{\rho}+\frac{({U_d}^2+{U_{\theta,d}}^2)}{2}=\frac{p_w}{\rho}+\frac{({U_w}^2+{U_{\theta,w}}^2)}{2}$$



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General Momentum Theory, cont'd

- The difference between these two equations gives:

$$p_u - p_d = p_\infty - p_w + \frac{\rho}{2}\left({U_\infty}^2 - {U_w}^2\right) + \frac{\rho}{2}({U_{\theta,d}}^2 - {U_{\theta,w}}^2)$$

- For simplification, we apply $p_w \approx p_\infty$ and neglect the variation ${U_{\theta,d}}^2 - {U_{\theta,w}}^2$, to obtain the equation

$$\boxed{\boldsymbol{p_u - p_d \approx \frac{\rho}{2}\left({U_\infty}^2 - {U_w}^2\right)}}$$

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General Momentum Theory, cont'd

- A relationship between $a\ and\ a'$ can be derived by considering the Bernoulli's equation expressed in a reference frame rotating with angular speed Ω, so that the empty spaces between the blades are filled by streamlines.

$$\frac{p_u}{\rho}+\frac{(\Omega r)^2}{2}+\frac{{U_d}^2}{2}=\frac{p_d}{\rho}+\frac{(\Omega r+U_{\theta,d})^2}{2}+\frac{{U_d}^2}{2}$$

Namely

$$p_u-p_d=\rho U_{\theta,d}\frac{2\Omega r+U_{\theta,d}}{2}=2\rho\Omega^2r^2a'(1+a')$$

On the other hand

$$p_u-p_d\approx\frac{\rho}{2}\left({U_\infty}^2-{U_w}^2\right)\approx 2\rho {U_\infty}^2 a(1-a)$$

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General Momentum Theory, cont'd

- Combining the 2 equations, we obtain

$$a(1-a) = (\frac{\Omega r}{U_\infty})^2 a'(1+a') = \lambda^2 \mu^2 a'(1+a')$$

where, $\lambda = \Omega R / U_\infty$ is the tip-speed ratio and $\mu = \frac{r}{R}$ is the local radial position scaled with the rotor radius, R.

- As a quick estimation, the a'^2 term can be neglected and the equation can be simplified to

$$a' \approx \frac{a(1-a)}{\lambda^2 \mu^2}$$

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General Momentum Theory, cont'd

- It is useful now to express the contribution of the annular element to the force and power extracted by the turbine
- The axial force contribution is derived from equation

$$dT = d\dot{m}(U_\infty - U_w) = 4\pi\rho r {U_\infty}^2 a(1-a)dr$$

- The power extracted by the turbine is dP = ΩdM_x, where

$$\mathrm{d}M_x = d\dot{m}r_w U_{\theta,w} = d\dot{m}rU_{\theta,d}$$

Leading to,

$$\boldsymbol{dP = 4\pi\rho r^3\Omega^2 U_\infty a'(1-a)dr}$$

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General Momentum Theory, cont’d

- Thrust and power coefficients become,

$$\boldsymbol{dC_T = \frac{2dT}{\rho {U_\infty}^2 A_d} = 8\mu a(1-a)d\mu}$$

And

$$\boldsymbol{dC_P = \frac{2dP}{\rho {U_\infty}^3 A_d} = 8\mu^3\lambda^2 a'(1-a)d\mu}$$

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Glauert’s Optimum

- Max. power generation is associated to the maximization of the product $a'(1-a)$ for given operating conditions, with the constraint

$$a(1-a) = \lambda^2\mu^2 a'(1+a')$$

- This results in the following relation for an optimum rotor

$$(1-a)\frac{da'}{da} - a' = 0$$

- Differentiate with respect to a gives,

$$1-2a = \lambda^2\mu^2(1+2a')\frac{da'}{da}$$

- Combining equations, gives: $\boldsymbol{a'} = \frac{\mathbf{1-3}\boldsymbol{a}}{\mathbf{4}\boldsymbol{a}\mathbf{-1}}$

Glauert’s Optimum, cont’d

- Substituting, we obtain,

$$\boldsymbol{16a^3 - 24a^2 + a(9 - 3\lambda^2\mu^2) - 1 + \lambda^2\mu^2 = 0}$$

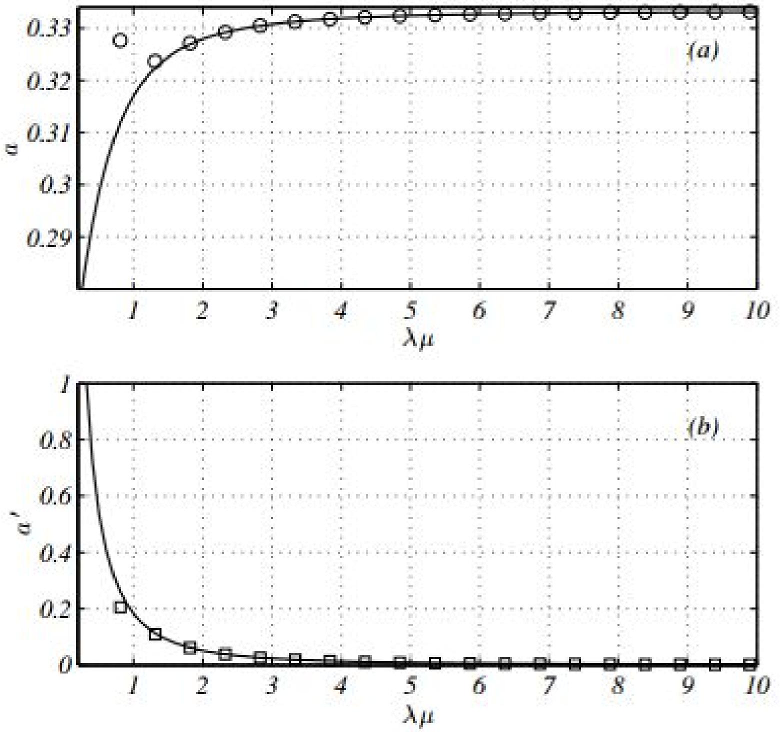
the exact solution of this equation can be obtained as a function of $\boldsymbol{\lambda\mu}$

Alternatively, the following approximated expansion:

$$\boldsymbol{a} \approx \frac{\mathbf{1}}{\mathbf{3}} - \frac{\mathbf{2}}{\mathbf{81}\boldsymbol{\lambda^2\mu^2}} + \frac{\mathbf{10}}{\mathbf{729}\boldsymbol{\lambda^4\mu^4}} \quad (\lambda\mu \gg 1)$$

A similar expansion can be obtained for a'

$$\boldsymbol{a'} \approx \frac{\mathbf{2}}{\mathbf{9}\boldsymbol{\lambda^2\mu^2}} - \frac{\mathbf{14}}{\mathbf{243}\boldsymbol{\lambda^4\mu^4}} \quad (\lambda\mu \gg 1)$$



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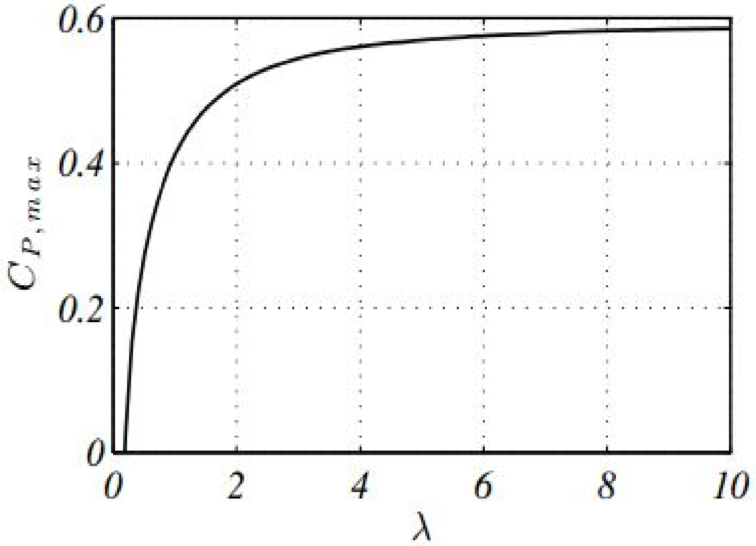
Glauert’s Optimum, cont’d

- Given the optimal distribution of $a \; and \; a'$ for the operating conditions $\lambda\mu$
- The integration of equation provides the maximum C_P attainable for a given λ

$$\boldsymbol{dC_P = 8\mu^3\lambda^2 a'(1-a)d\mu}$$



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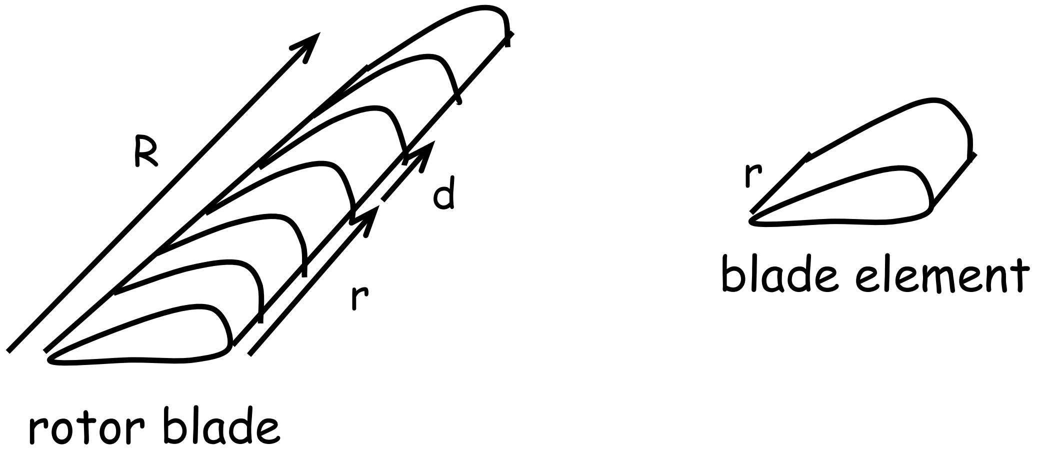
Blade Element Theory

Blade geometry is considered in this part and we may use this to calculate the induction factors that relates the thrust and rotor torque.



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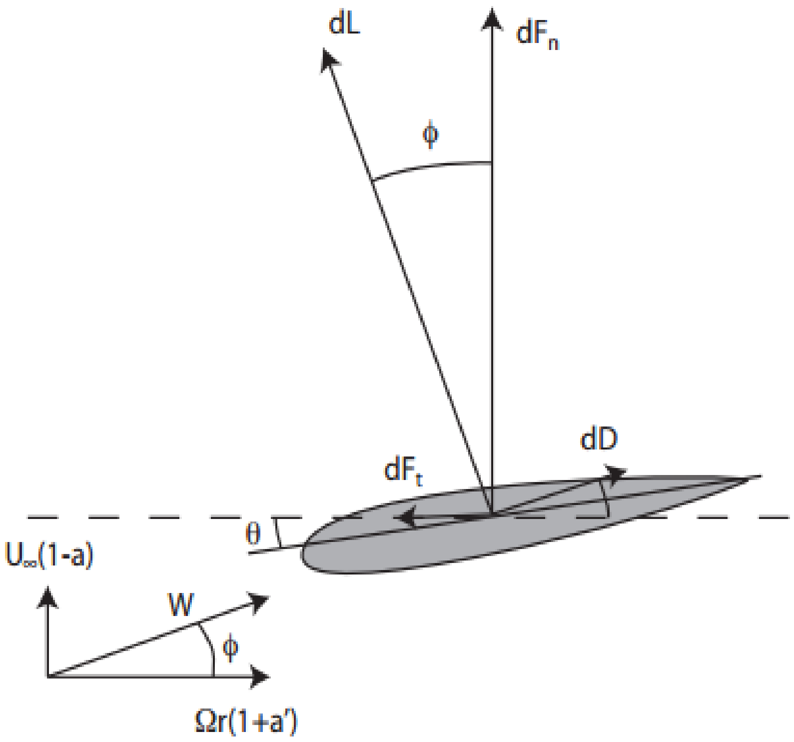
Blade Element Theory

- The Relative in-plane velocity vector (the radial velocity is neglected in this analysis)

$$W{=}U_\infty[1-a,0,\lambda\mu(1+a')]$$

$$|W|=\sqrt{{U_\infty}^2(1-a)^2{+}\Omega^2r^2(1+a')^2}$$

$$\tan\emptyset=\frac{1-a}{\lambda\mu(1+a')}$$



Source [2]

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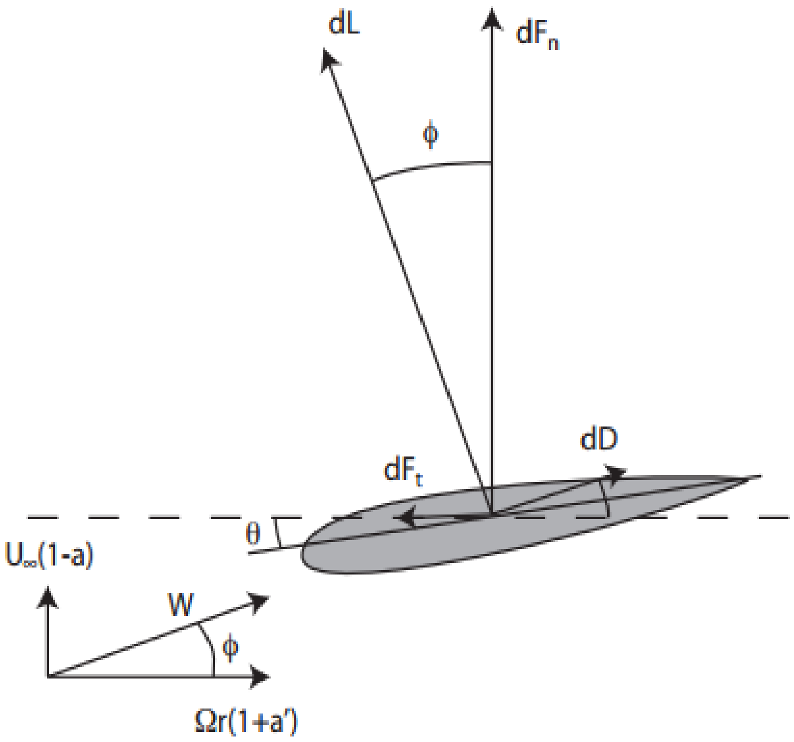
Blade Element Theory

- The infinitesimal blade section (of spanwise thickness dr) generates a lift, dL and drag force, dD, directed normal and parallel to W, respectively as:

$$dL = \frac{1}{2}\rho W^2 c C_l dr$$

and

$$dD = \frac{1}{2}\rho W^2 c C_d dr$$



Source [2]

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Blade Element Theory

$$dF_t = dL \sin \emptyset - dD \cos \emptyset$$

$$= \frac{1}{2}\rho W^2 c(C_l \sin \emptyset - C_d \cos \emptyset)dr$$

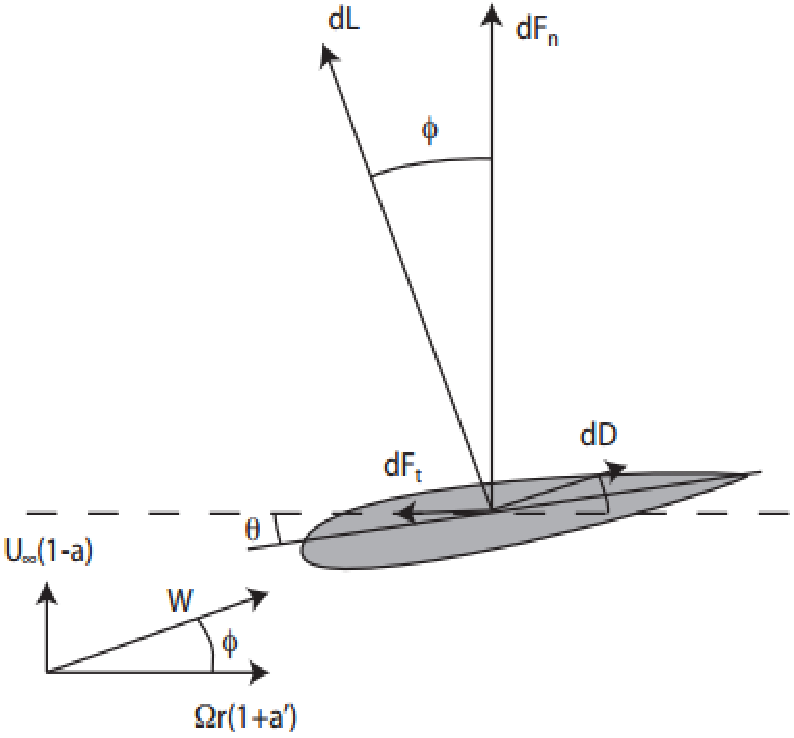
$$\therefore \boldsymbol{dF_t = \frac{1}{2}\rho W^2 c C_t dr}$$

and

$$dF_n = dL \cos \emptyset - dD \sin \emptyset$$

$$= \frac{1}{2}\rho W^2 c(C_l \cos \emptyset - C_d \sin \emptyset)dr$$

$$\therefore \boldsymbol{dF_n = \frac{1}{2}\rho W^2 c C_n dr}$$



Source [2]

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Blade Element Theory

- At this point it is known that the axial force applied on the given radial annulus by the N_b blades is

$$\boldsymbol{dT = dF_n = \frac{N_b c}{2} \rho W^2 C_n dr}$$

That must balance the equation derived within the general momentum theory

$$\boldsymbol{\frac{2dT}{\rho {U_\infty}^2 A_d} = 8\mu a(1-a)d\mu}$$

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Blade Element Momentum Theory

- After some algebra, the final expression becomes

$$\boxed{\boldsymbol{\sigma_r \left(\frac{W}{U_\infty}\right)^2 C_n = 4a(1-a)}}$$

where $\sigma_r = \frac{N_b c}{2\pi r}$ is called solidity and represents the ratio between the sum of all the blades sections chord and the circumference length where they lie.

- The higher the solidity, the higher the blockage imparted by the blade sections on the incoming flow.

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Blade Element Momentum Theory

- The tangential force contributes in the creation of torque

$$dQ = rdF_t$$

and power

$$dP = \Omega rdF_t$$

Therefore, the power contribution from the blade sections is

$$\boldsymbol{dP = \Omega rdF_t = \Omega r\frac{N_b c}{2}\rho W^2 C_t dr}$$

That must balance the equation derived in the general momentum theory, leading to the second fundamental equation of the BEM method

$$\boxed{\boldsymbol{\sigma_r(\frac{W}{U_\infty})^2 C_t = 4\lambda\mu a'(1-a)}}$$

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Blade Element Momentum Theory

- Since W/$U_\infty = (1 - a)/\sin\emptyset$
  the fundamental BEM equations can be combined to get the direct relations:

$$\boxed{\boldsymbol{a} = \left(\frac{4sin^2\emptyset}{\sigma_r C_n} + \mathbf{1}\right)^{-1}}$$ and $$\boxed{\boldsymbol{a'} = \left(\frac{4\sin\emptyset\cos\emptyset}{\sigma_r C_t} - \mathbf{1}\right)^{-1}}$$

Tip Loss Correction Factor

- The ***infinite number of blades is an approximation*** that was introduced to have a steady axisymmetric flow both upstream and downstream the rotor.

- Modern rotors have instead ***two or three blades***, so that this approximation is quite crude.

- ***Prandtl*** derived a correction to the general momentum theory to account for the finite number or blades, generally referred as ***tip-loss correction***

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Tip Loss Correction Factor

- This Correction is defined as

$$F(r) = \frac{1}{2\pi a_b}\int_0^{2\pi} a(r,\theta)\, d\theta$$

where $a(r,\theta) = 1 - \frac{U(r,\theta)}{U_\infty}$ is the local axial induction factor at a radial position r and angle θ from the first wind turbine blade (located at θ=0) and $a_b = a(r,0)$ is the a value of the blade

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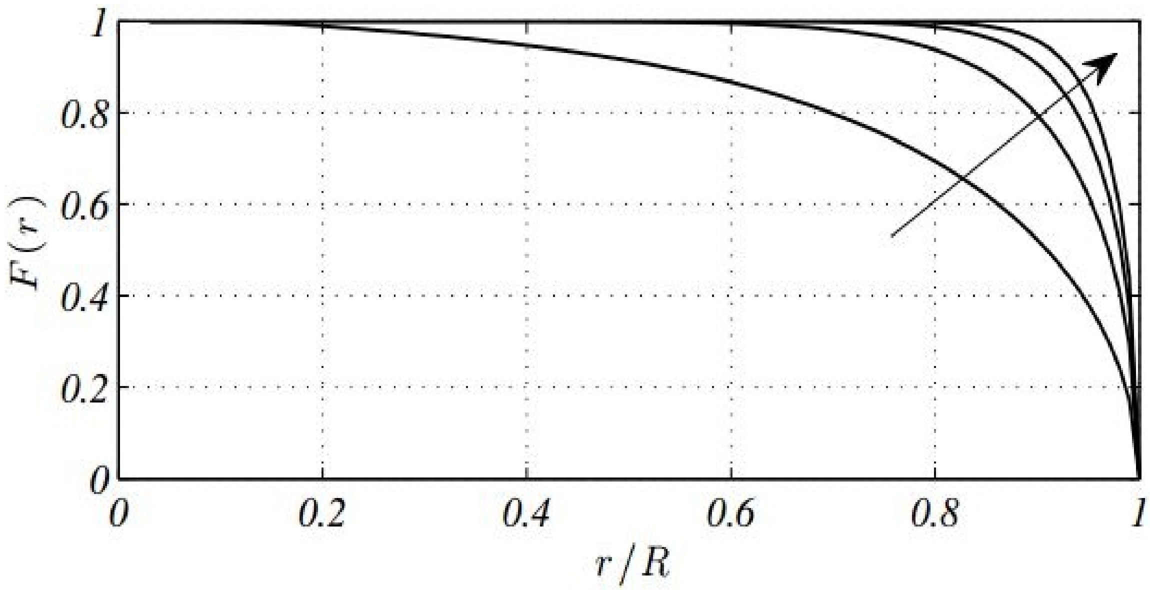
Tip Loss Correction Factor



Prandtl tip-loss correction for the Glauert optimal blade with $\lambda = 5$ and $N_b = 1, 3, 5, 7$.

Source [2]

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Tip Loss Correction Factor

- The inclusion of the tip-loss correction in equations derived before leads (in the Glauert formulation) to a straightforward formula to determine the induction coefficients as

$$\boxed{\boldsymbol{a} = (\frac{4Fsin^2\emptyset}{\sigma_r C_n} + 1)^{-1}}$$

and

$$\boxed{\boldsymbol{a}' = (\frac{4\ \mathrm{F}\ \sin\emptyset\ \cos\emptyset}{\sigma_r C_t} - 1)^{-1}}$$

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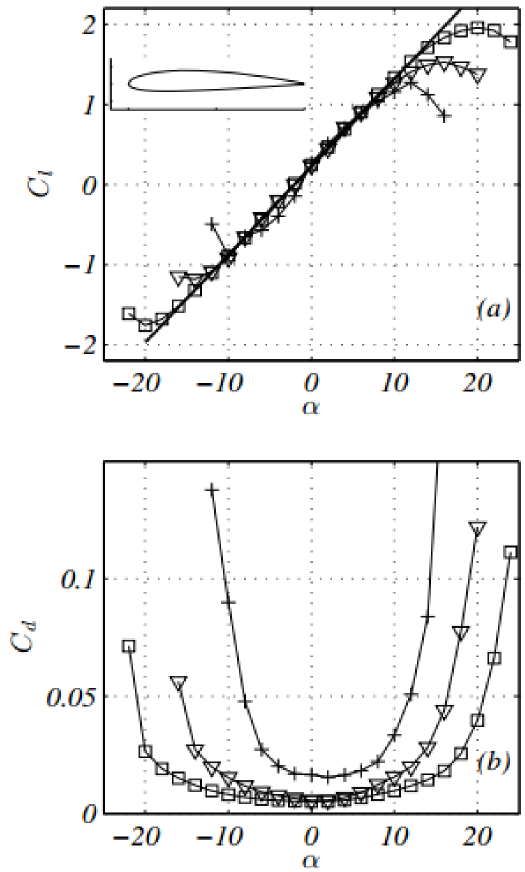
How you design an Optimum Rotor

- Given a certain airfoil and operating conditions
- You can measure the lift and drag coefficients or use numerical simulations like CFD.
- Choose an optimum angle of attack at maximum $\frac{C_l}{C_d}$
- Then, use BEM to get the optimum twist and chord distributions along the blade.



Source [2]

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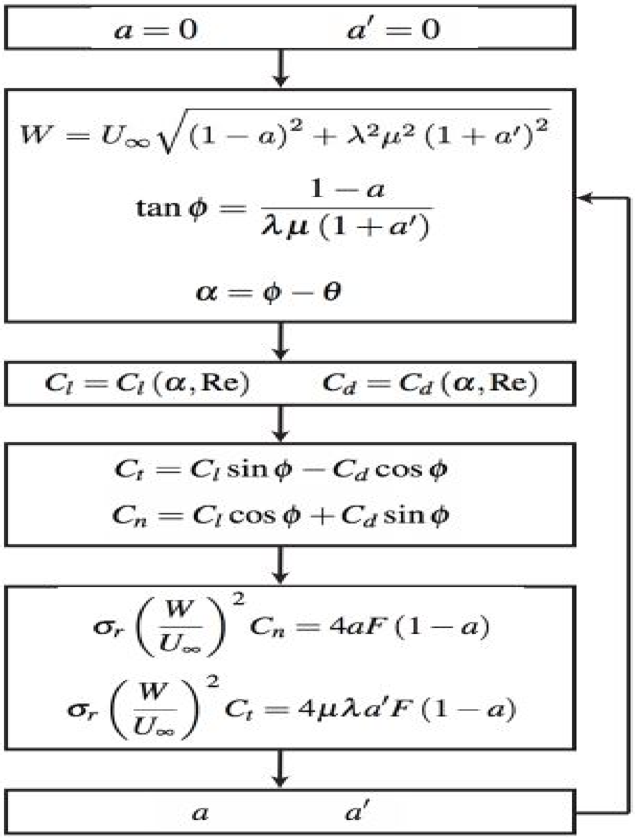
BEM Block Diagram



$$a = 0 \qquad a' = 0$$

$$W = U_\infty \sqrt{(1-a)^2 + \lambda^2 \mu^2 (1+a')^2}$$

$$\tan\phi = \frac{1-a}{\lambda\mu(1+a')}$$

$$\alpha = \phi - \theta$$

$$C_l = C_l(\alpha, \mathrm{Re}) \qquad C_d = C_d(\alpha, \mathrm{Re})$$

$$C_t = C_l \sin\phi - C_d \cos\phi$$

$$C_n = C_l \cos\phi + C_d \sin\phi$$

$$\sigma_r \left(\frac{W}{U_\infty}\right)^2 C_n = 4aF(1-a)$$

$$\sigma_r \left(\frac{W}{U_\infty}\right)^2 C_t = 4\mu\lambda a'F(1-a)$$

$$a \qquad a'$$

Source [2]

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Advantages and Disadvantages of BEM Model

- Advantages:
    - Easy to implement and use on a computer
    - Contains most of the physics representing rotary aerodynamics
    - Proven to be accurate for the most common flow conditions and rotor configurations

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Advantages and Disadvantages of BEM Model

- Disadvantages:
  - Relies on empirical input to a large extent, that is not always available
  - If we look at more realistic operating situations, wind turbines are subjected to atmospheric turbulence, wind shear from the ground effect, wind directions that change both in time and in space, and effects from the wake of neighboring wind turbines. As a consequence, the forces vary in time and space and a dynamical description is an intrinsic part of the aerodynamic analysis
  - When the wind changes direction, misalignment with the rotational axis occurs, resulting in yaw error. This causes periodic variations in the angle of attack and invalidates the assumption of axisymmetric inflow conditions

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Other Corrections

Heavily loaded rotors:

$$C_T = \frac{dT}{{}^1/_2 \rho U_\infty^2 2\pi r dr} = 4aF(1-a) \ \textbf{for a} \ < {}^1/_3$$

Yaw correction:

$$w_i = w_{io}\left(1 + \frac{r}{R} tan\left(\frac{\chi}{2}\right) cos(\theta_{blade} - \theta_o)\right)$$

$$C_T = 4aF\left(1 - \frac{a}{4}(5-3a)\right) \ \textbf{for a} > {}^1/_3$$

Dynamic wake:

$$Rf\left(\frac{r}{R}\right)\frac{du_i}{dt} + 4u_i(U_o - u_i) = \frac{\Delta T}{2\pi r \Delta r}$$

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Group Project

- Form groups (max 4 members)
- Implement what has been learned and develop BEM code to test airfoils and design optimal blade geometry
- Presentations of the project
  - 20 minutes each
  - Presentation skills (50%)
  - Technical contents (50%)

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Summary of the provided knowledge

- General momentum theory
- Basics of blade element theory
- More details of the BEM model
- Pros and cons of using BEM model

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References

[1] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

[2] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

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Wind Turbine Types and Performance Curves (Power, torque and thrust) – 1

Lecture 2.1

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Learning outcomes

O1. Further study on the wind turbine types

O2. Know how to assess the wind turbine system performance

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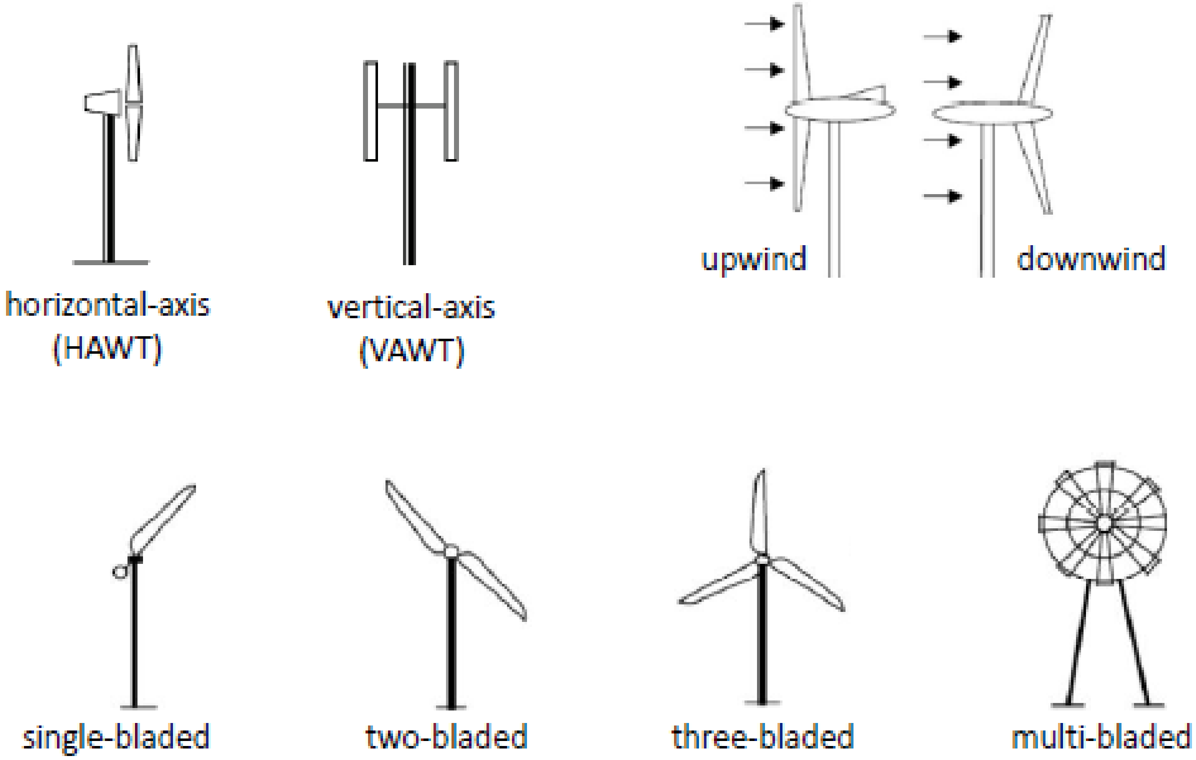
Wind Turbines Classification



Source [1]

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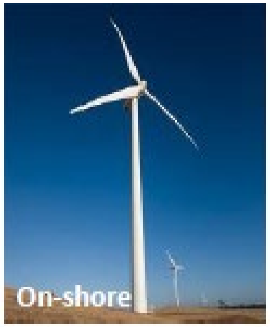
Wind Turbine Types

Horizontal Axis (HAWT)



Vertical Axis (VAWT)

Source [1]

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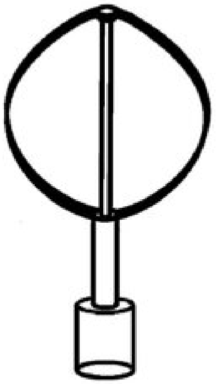
Lift vs. Drag-based VAWTs

Lift based design (Darrieus type)	Drag based Design (Savonius type)
- Low solidity airfoil blades	- High solidity cup shapes are pushed by the wind
- More efficient than drag based turbines	- Can barely capture 15% of incoming wind energy
	

Source [2]

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Pros and Cons of VAWTs

Advantages	Disadvantages
Omnidirectional: accepts wind from any direction	Centrifugal force cause significant stresses on blades
Components can be mounted at ground level	Poor self-start capability
Easier installation and maintenance since the rotor is close to the ground	Must be supported at the top of the rotor
	Require rotor removal to replace bearings
	Rotors are near the ground generally where wind is poorer
	Overall poor performance
	Unsuccessful commercially due to high costs and low efficiency

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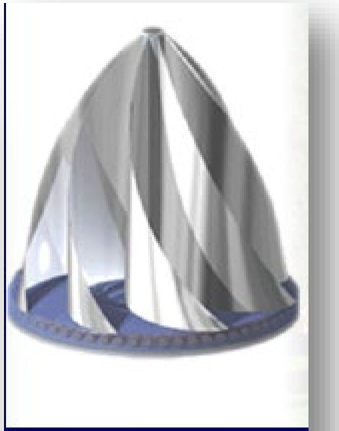
VAWT's Future

Every few years a new company comes along with a promising revolutionary idea in wind turbine design that is low cost and outperforms existing designs in the market. They can also be installed on a roof or in a city where wind is poor.


Wind Wandler


Mag-Wind

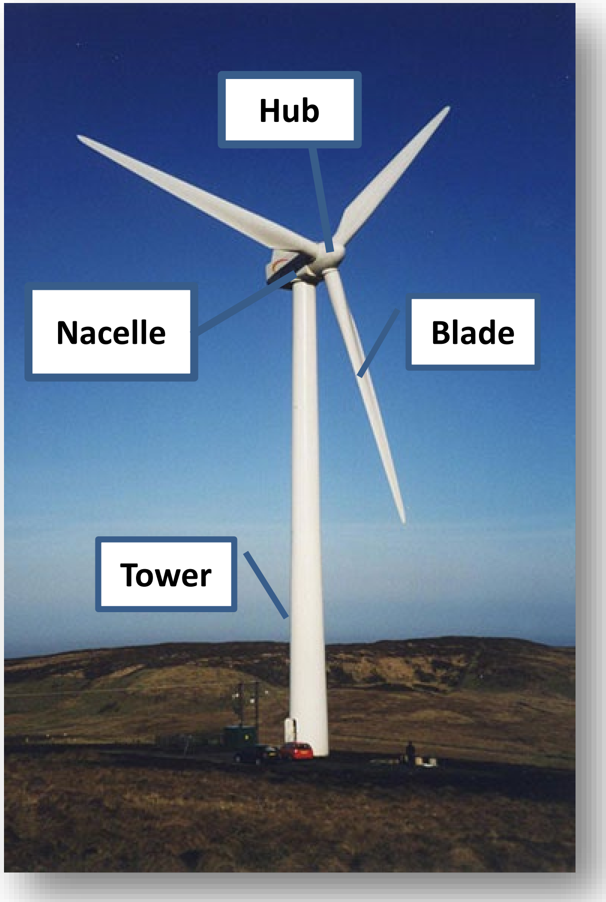

WindStor


WindTree

Source [1]

Horizontal Axis Wind Turbines (HAWT)

- HAWT beats VAWT in every aspect:
    - Energy production
    - Less land requirement than VAWT
    - Weight and cost specially for large-scale power generation



Source [1]

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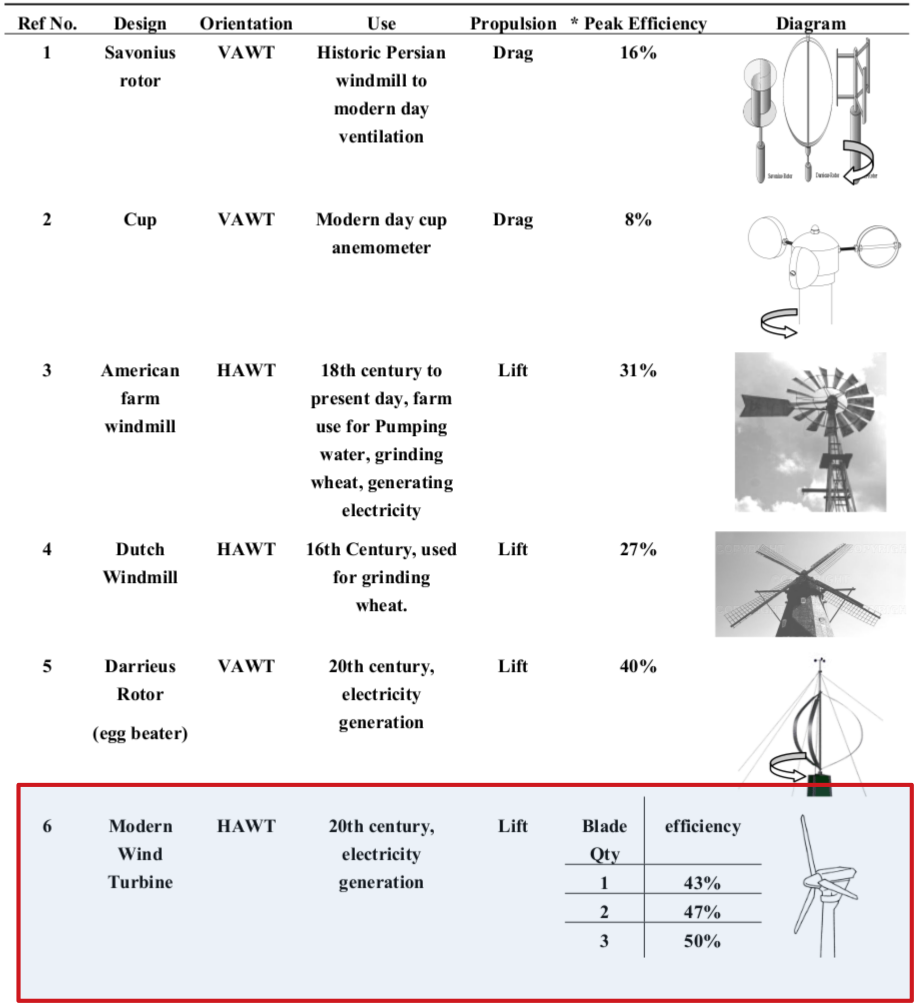
Benchmarking

Comparison between the types of historical and modern wind turbines



Ref No.	Design	Orientation	Use	Propulsion	* Peak Efficiency	Diagram
1	Savonius rotor	VAWT	Historic Persian windmill to modern day ventilation	Drag	16%	
2	Cup	VAWT	Modern day cup anemometer	Drag	8%	
3	American farm windmill	HAWT	18th century to present day, farm use for Pumping water, grinding wheat, generating electricity	Lift	31%	
4	Dutch Windmill	HAWT	16th Century, used for grinding wheat.	Lift	27%	
5	Darrieus Rotor (egg beater)	VAWT	20th century, electricity generation	Lift	40%	
6	Modern Wind Turbine	HAWT	20th century, electricity generation	Lift	Blade Qty – efficiency 1 – 43% 2 – 47% 3 – 50%	

Source [1]

One-Blade Turbines

- Rotor must move at higher speed to capture the same energy
  - Gearbox ratio is reduced
  - A counterbalance weight must be added which negates the lighter weight benefits
  - Higher speed means more noise, visual and wildlife impacts
- Blades are easier to install (on ground)
- Capture less energy than 2 blade design
- Ultimately no cost savings is provided

Source [1]

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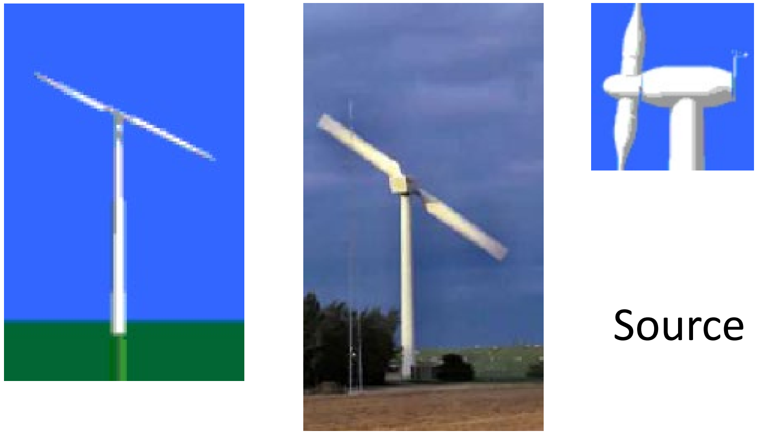
Two-Blade Turbines

- Advantages and disadvantages are similar to one blade
- Need teetering hub and/or shock absorbers because of gyroscopic imbalance
- Capture less energy than three blade designs



Source [1]

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Three-Blade Turbines

- Balance of gyroscopic forces
- Slower rotation
- Increases gearbox and transmission costs
- Less noise, fewer bird strikes

Source [1]

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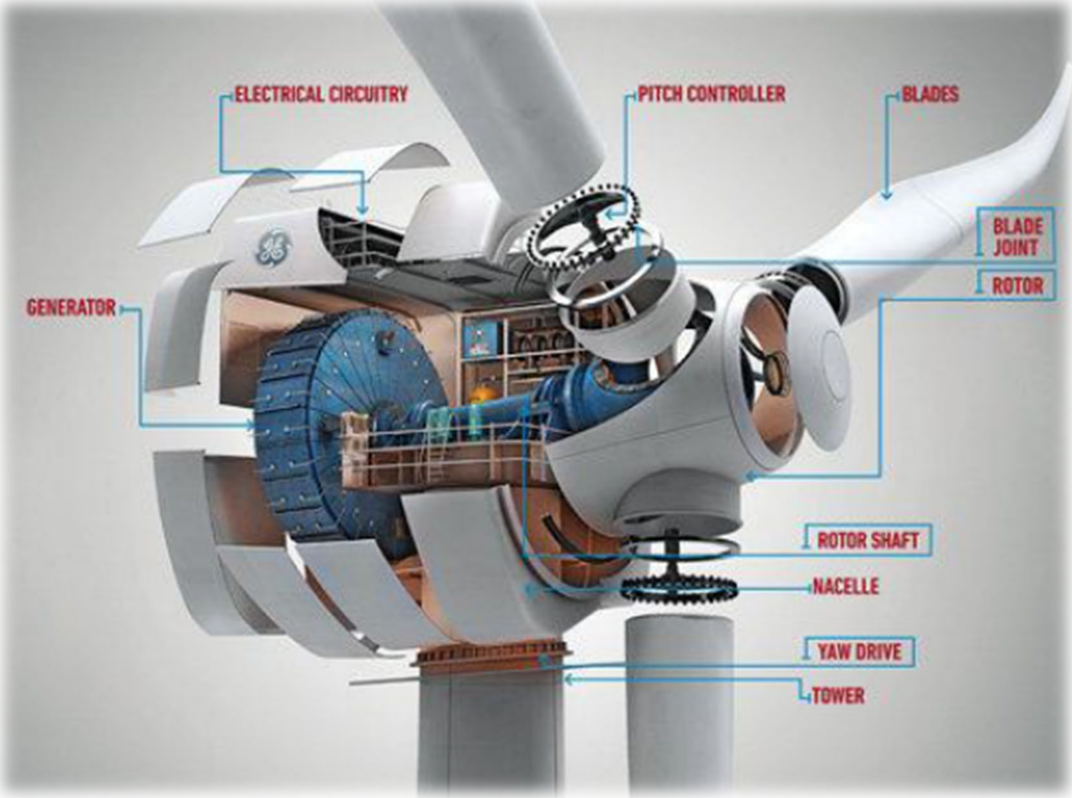
Commercial Products



Source [1]

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Summary of the provided knowledge

- Types of wind turbines
  - VAWT
  - HAWT
- Number of blades of wind turbines

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References

[1] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

[2] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

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Wind Turbine Types and Performance Curves (Power, torque and thrust) – 2

Lecture 2.1

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Learning outcomes

O1. Further study on the wind turbine types

O2. Know how to assess the wind turbine system performance

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Wind Turbine Performance Curves

- Performance of a wind turbine is characterized by the variation against wind speed of three main indicators:
  1. Power → determines amount of energy captured
  2. Torque → determines the size of the gearbox which must be matched with the generator driven by the rotor
  3. Thrust → influences the structural design of the tower

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Wind Turbine Performance Curves

- Performance is usually expressed by means of non-dimensional, characteristic performance curves from which actual performance can be computed.
- Based on the assumption that the aerodynamic performance of the blades doesn't deteriorate

  →

  The non-dimensional aerodynamic performance will depend on the tip speed ratio and if appropriate, the pitch setting of the blades.

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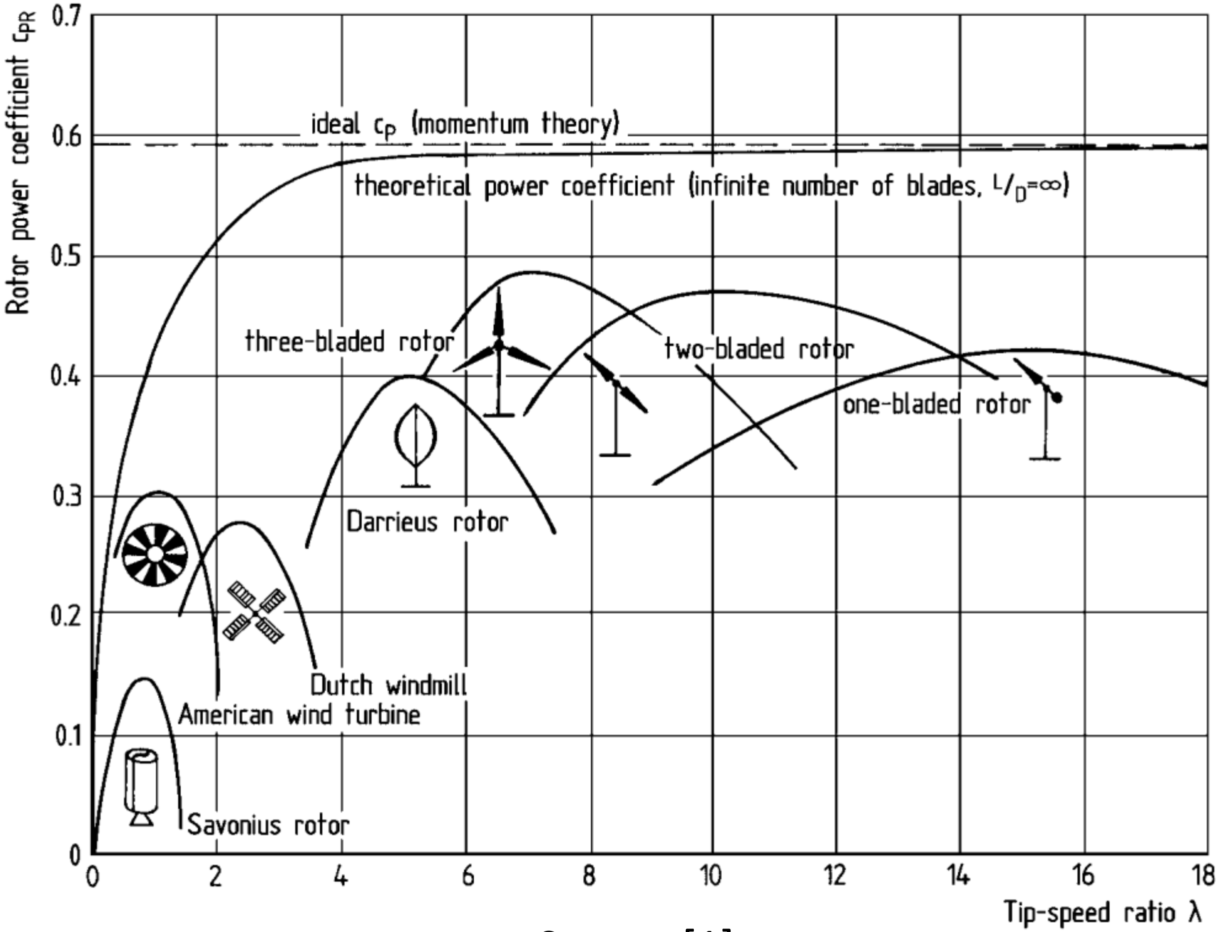
Power Coefficient Curves



Source [1]

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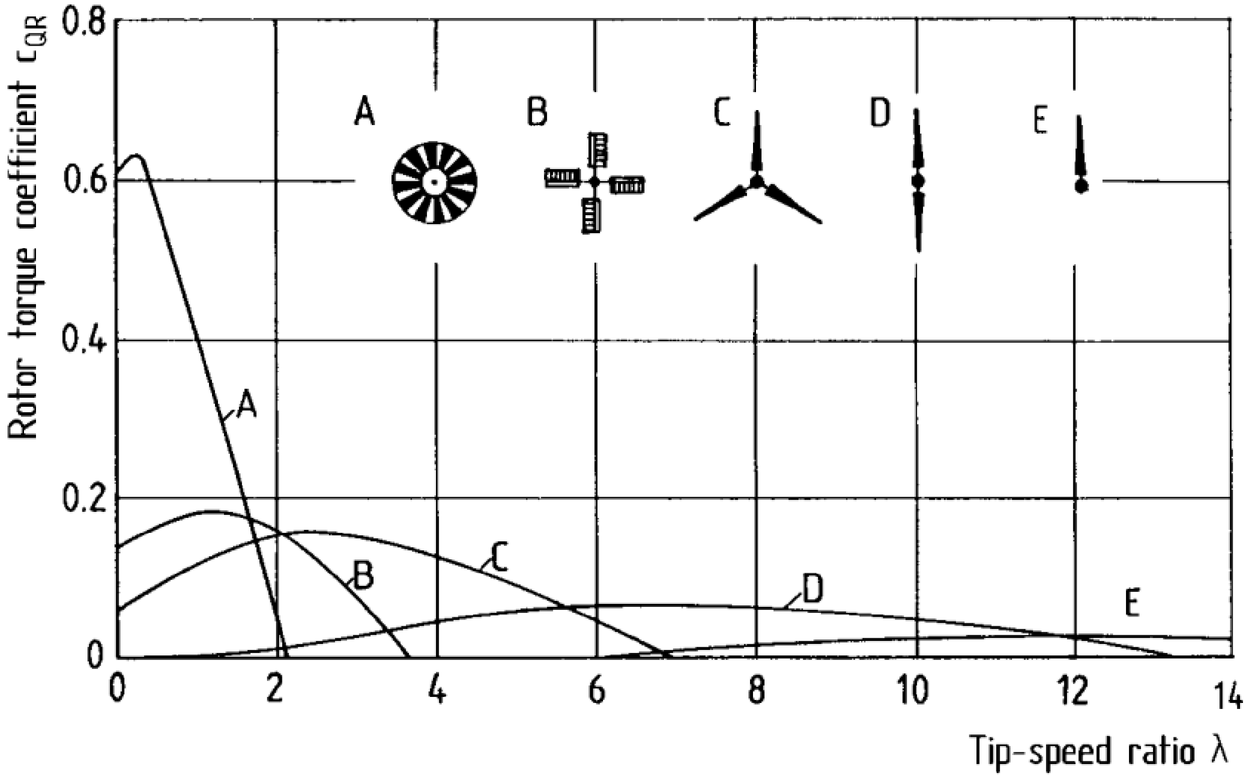
Torque Coefficient Curves



Source [1]

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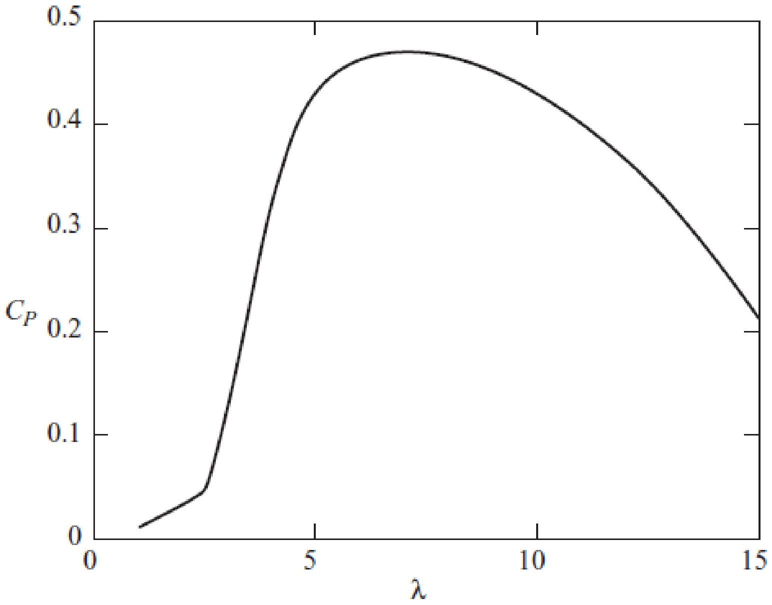
Typical Curve

- Typical modern three-blade turbine C_p – λ Curve

  Max value of C_p is only 0.47 achieved at tip speed ratio of 7, which is much less than the Betz limit
  - Drag and tip losses are the cause of this discrepancy
  - Stall also reduces C_p at low values of tip speed ratio



Source [2]

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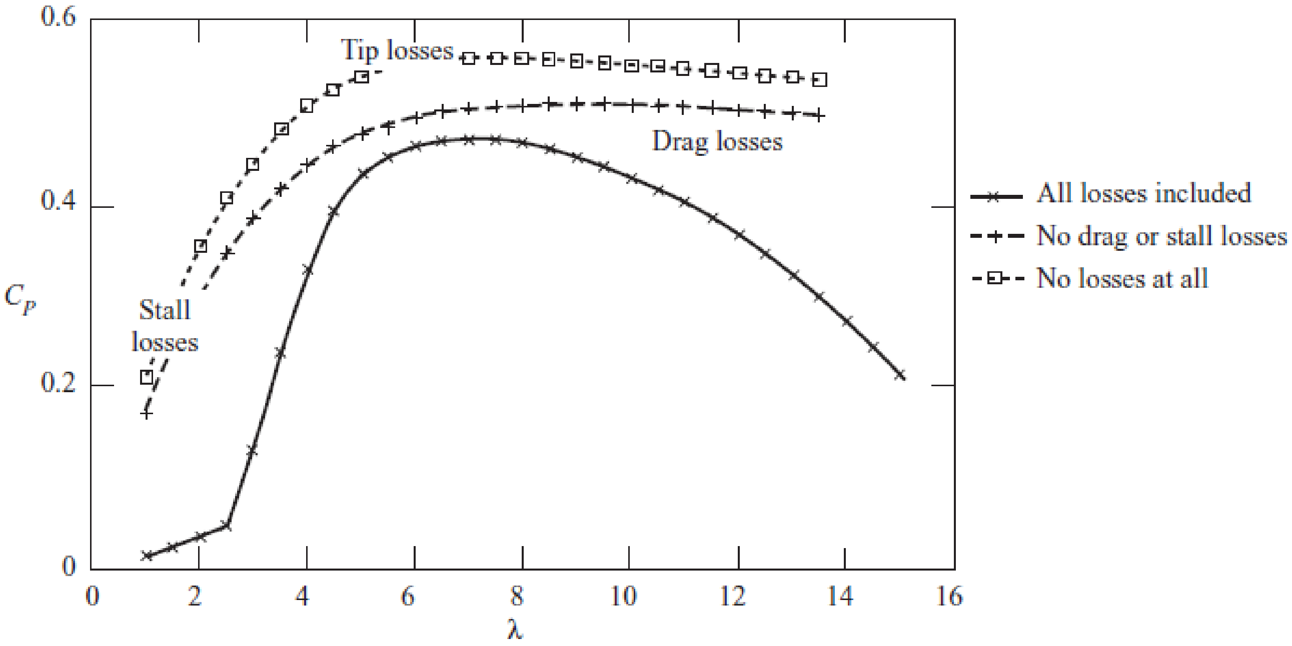
Typical Curve

- Typical modern three-blade turbine C_p – λ Curve
  Even if there's no losses included, Betz limit is still not reached



Source [1]

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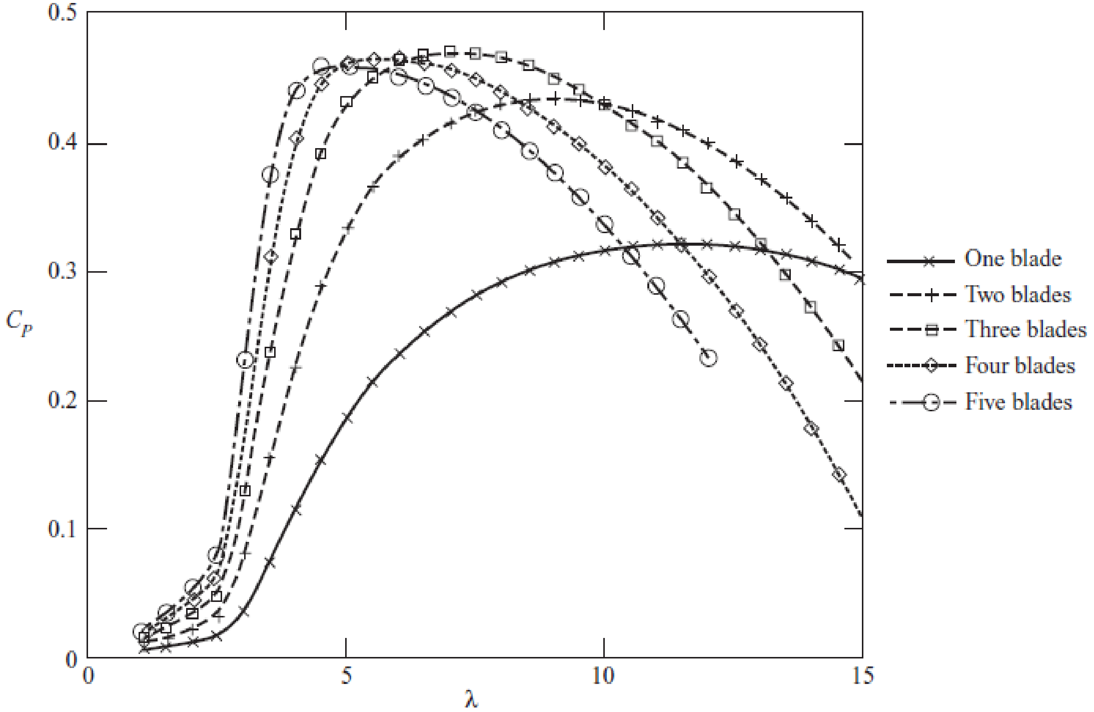
Typical Curve

- Effect of solidity on the C_p – λ Curve

  Solidity is defined as the total blade area divided by the swept area



Source [1]

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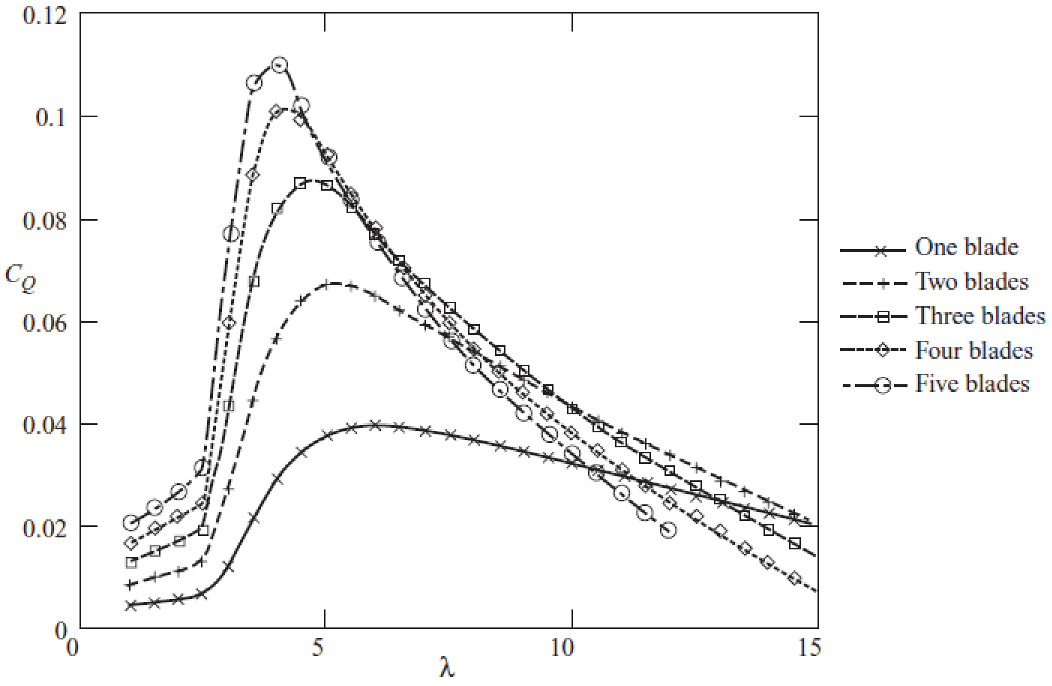
Typical Curve

- Effect of solidity on the $C_Q - \lambda$ Curve
  - Torque coefficient is derived from power coefficient by dividing by the tip speed ratio
  - It doesn't give additional information about the performance
  - It is only used for assessment purposes when the rotor is connected to a gearbox and a generator

Source [1]



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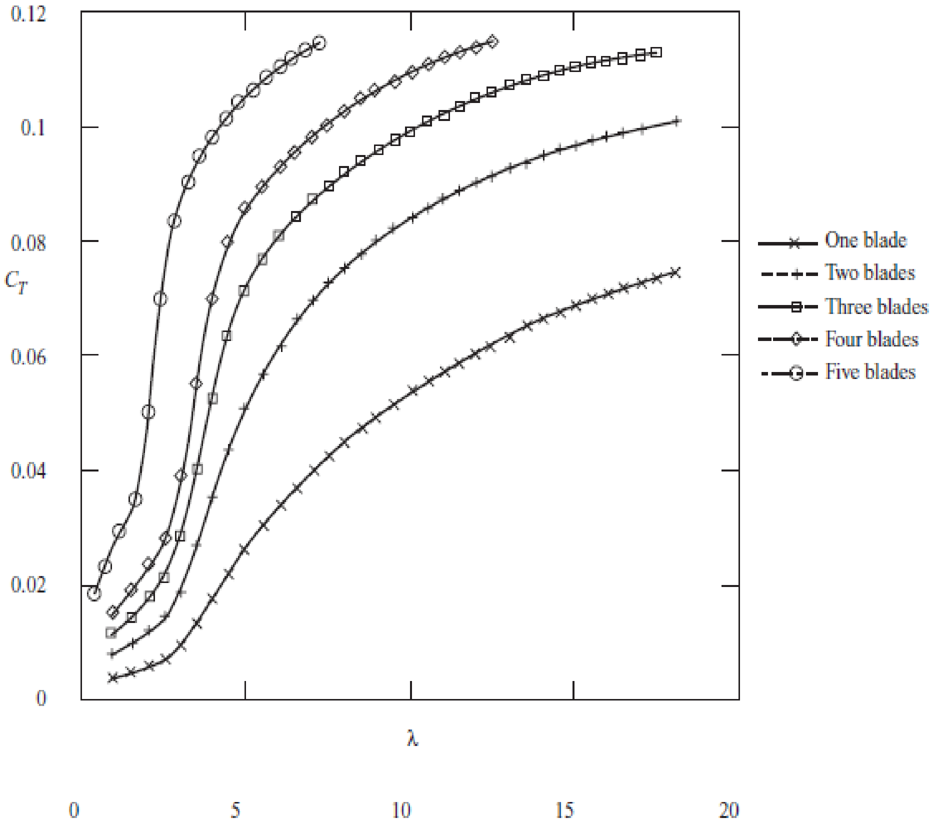
Typical Curve

- Effect of solidity on the $C_T - \lambda$ Curve
  - The thrust force on the rotor is directly applied on the tower so it influences the tower structural design significantly
  - Thrust on the rotor increases with the increase in solidity



Source [1]

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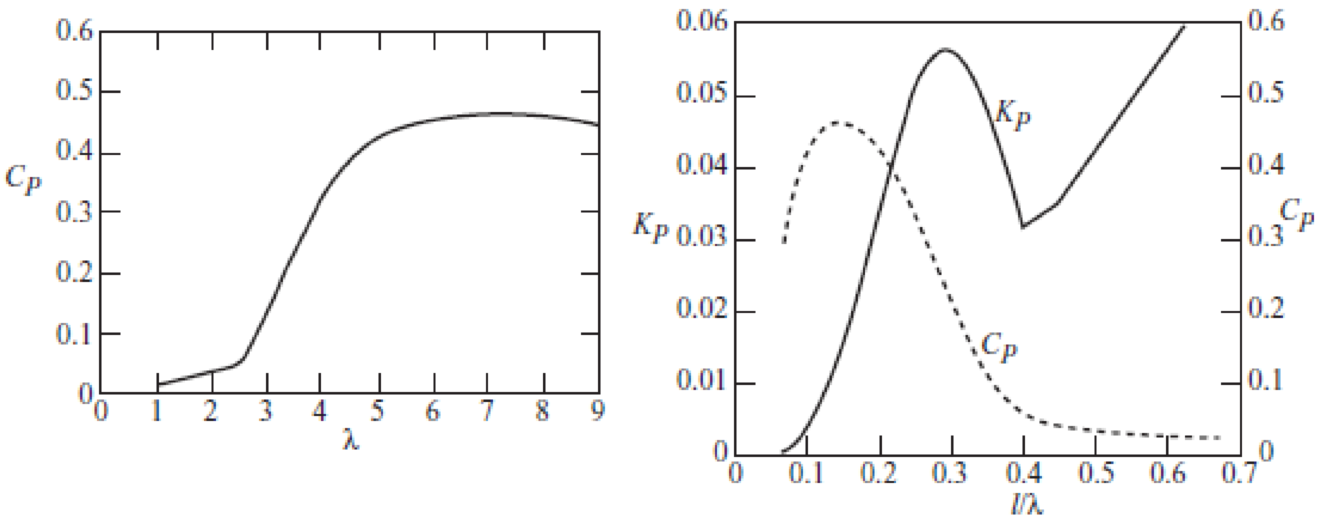
Constant Rotational Speed Operation

$$K_P = \frac{\text{Power}}{\frac{1}{2}\rho(\Omega R)^3 A_d} = \frac{C_P}{\lambda^3}$$



Non-dimensional Performance Curves for Constant Speed Operation (Source [1])

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Stall Regulation

- Main Advantage:
  1) it provides the simplest means of controlling max. power generated to suit the different sizes of generators
- Disadvantages:
  1) Power vs wind speed curve is fixed by the aerodynamic c/cs of the blades (stall behavior).
  2) Post stall power output varies unsteadily.
  3) The stalled blade exhibits low vibration damping giving rise to large vibration displacement amplitudes and thus, higher bending moments and stresses accompanying them causing fatigue damage.
  4) When parked in high turbulent winds, a rotor with fixed pitch blades may be subjected to large aerodynamic loads that can't be avoided by feathering the blade.

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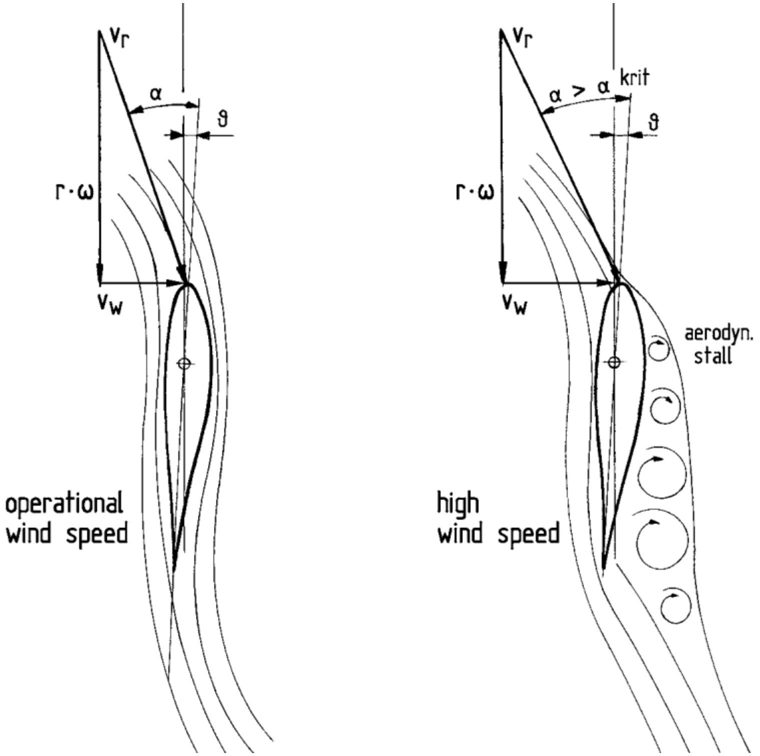
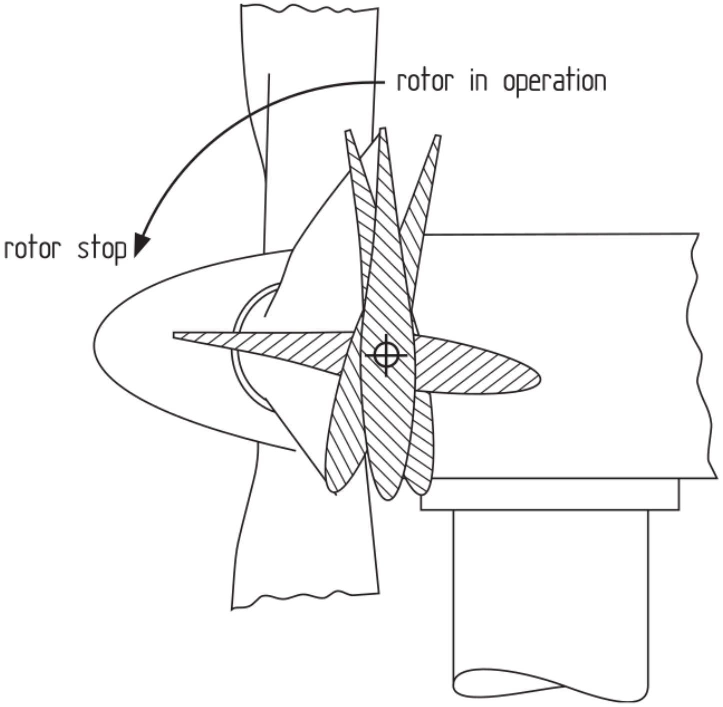
Stall Regulation – Passive & Active



Source [1]



Active stall control with a number of blade pitch angles in operation and in standstill

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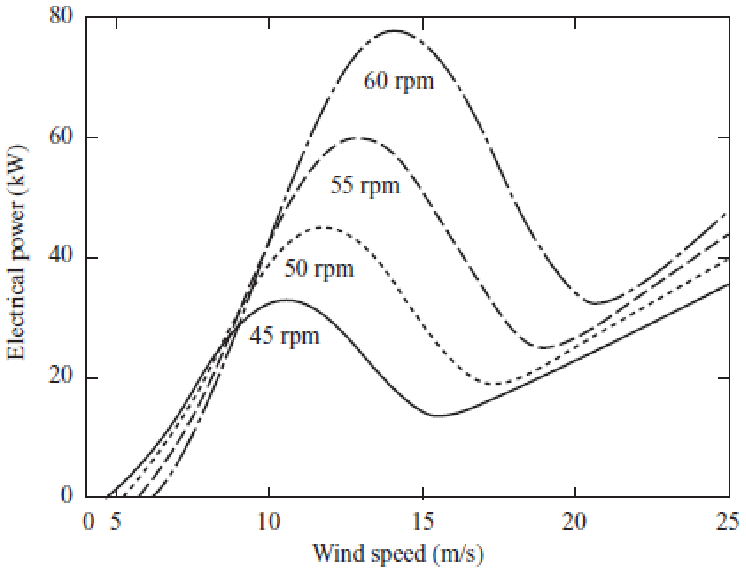
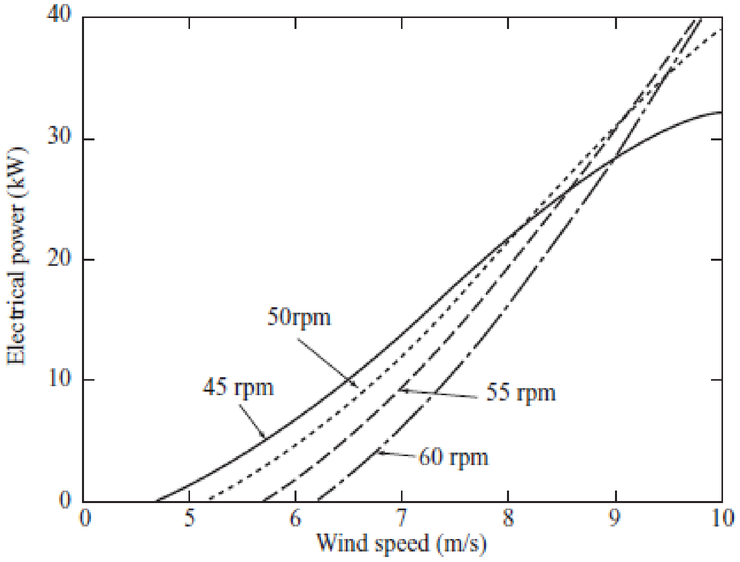
Effect of Rotational Speed Change



Effect on Extracted Power of Rotational Speed



Effect on Extracted Power of Rotational Speed at Low Wind Speeds

Source [1]

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Effect of Blade Pitch Change

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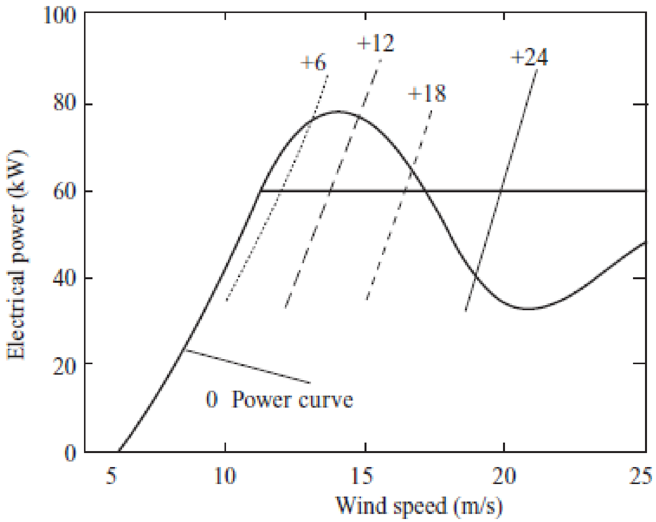
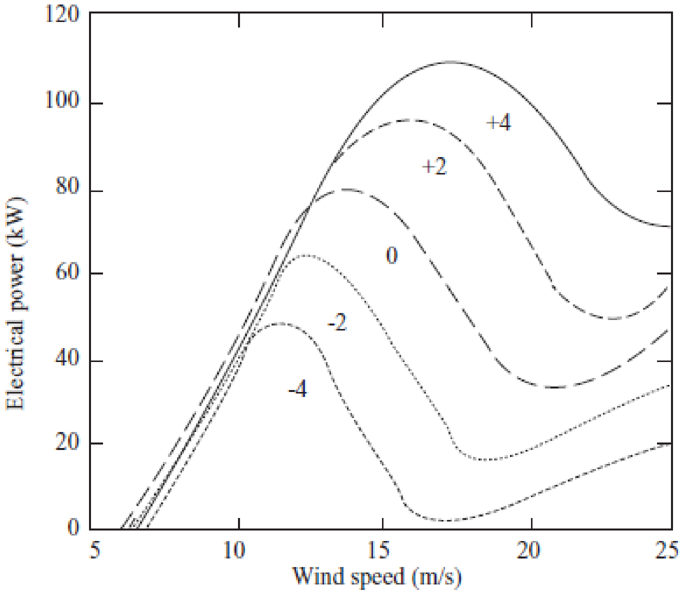


Pitching to Feather Power Regulation Requires Large Changes of Pitch Angle



Effect on Extracted Power of Blade Pitch Set Angle

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Pitch Regulation

- Power regulation is achieved either by pitching to stall or feather to reduce the lift force on the blades by reducing the angle of attack.
- Fixed pitch/stall regulation shortcomings can be overcome by providing active pitch angle control
- Main benefits:
    1) Power output is very sensitive to pitch angle change making it possible to regulate power output.
    2) Adopting large positive pitch angle generates a large starting torque as the rotor starts rotating.
    3) 90 degrees positive pitch angle (feathered blade) is usually used when shutting down to minimize the idling speed at which the parking brake is applied.
    4) Using continuous pitch control, the power output can be kept constant from rated wind speed up to cut-out speed

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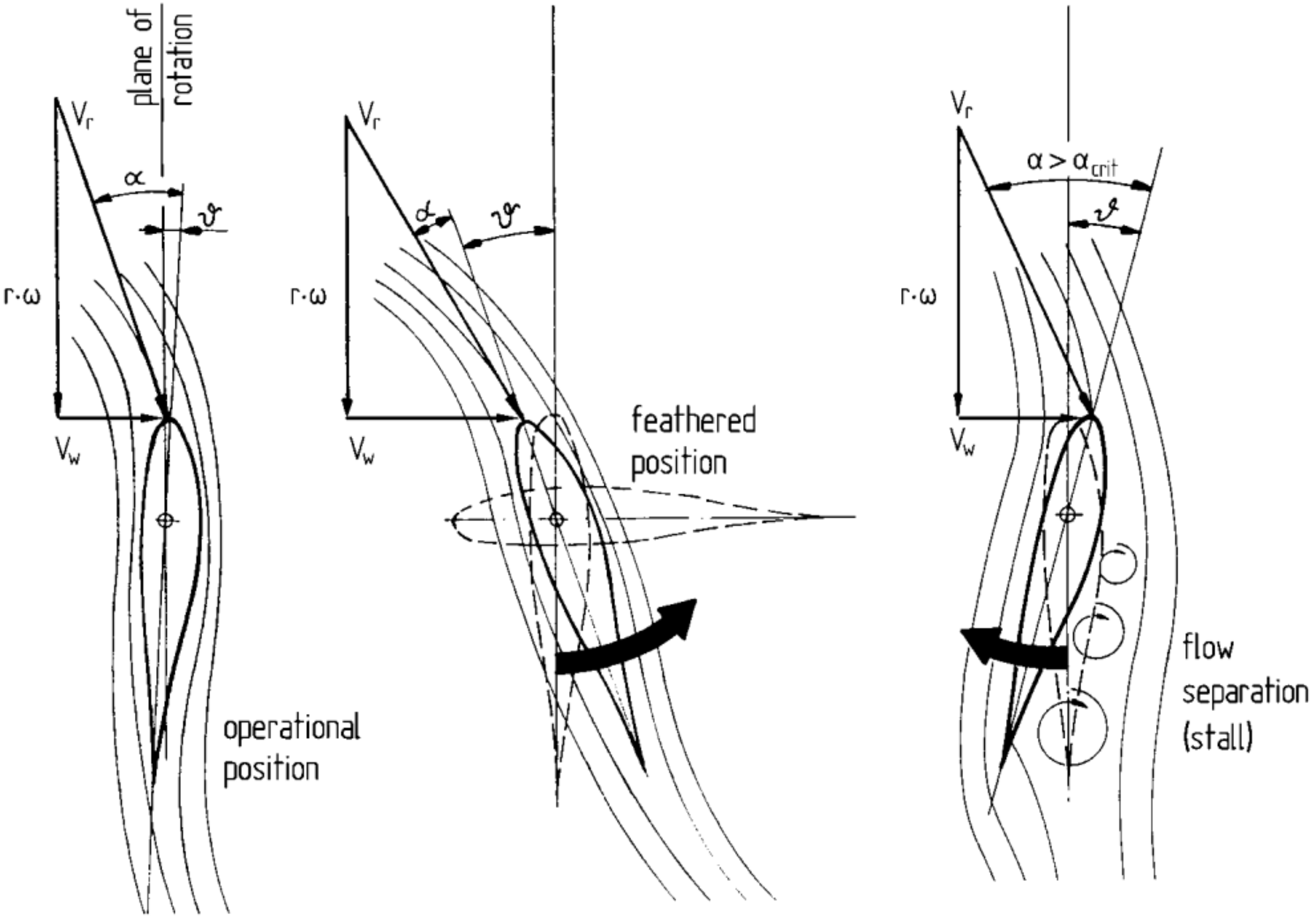
Pitch Regulation



Source [1]

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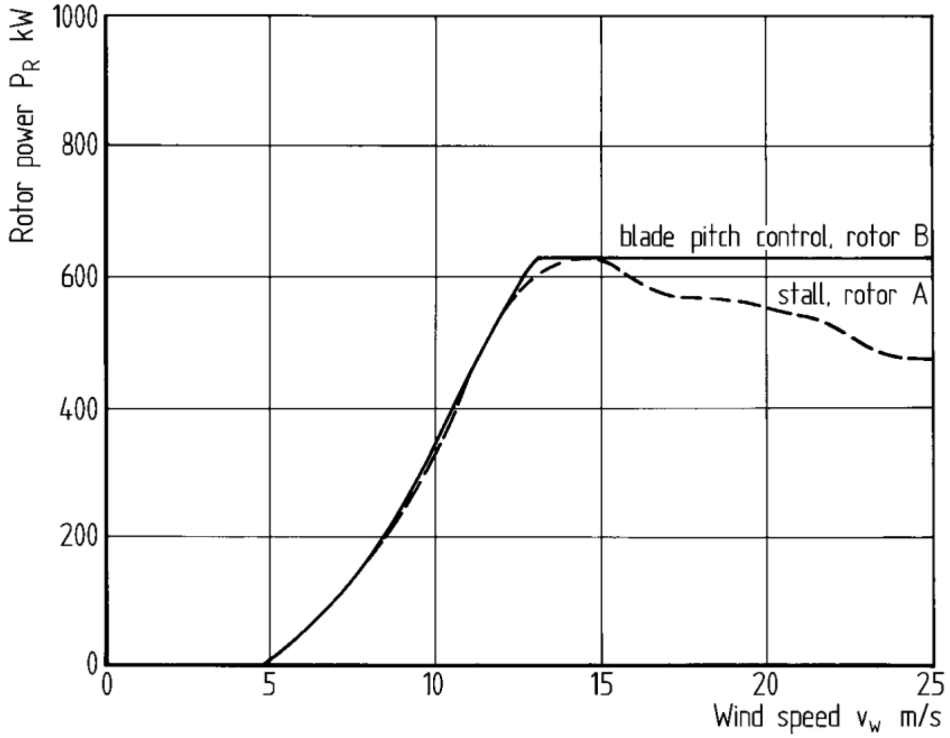
Pitch Regulation vs. Stall Regulation



Source [1]

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Comparison of Measured with Theoretical Performance Curves

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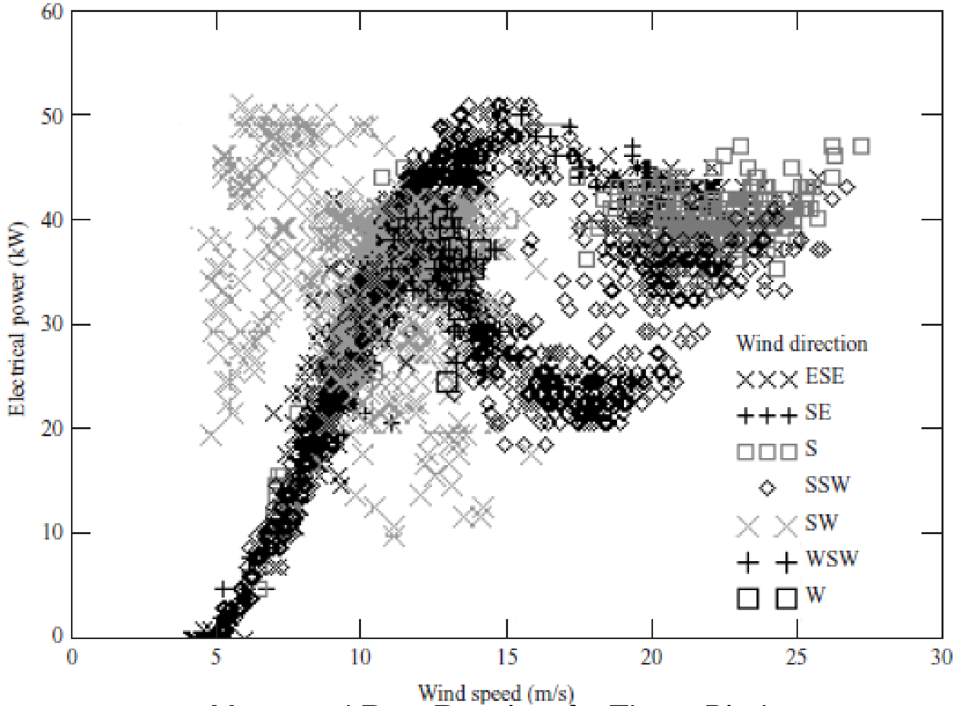
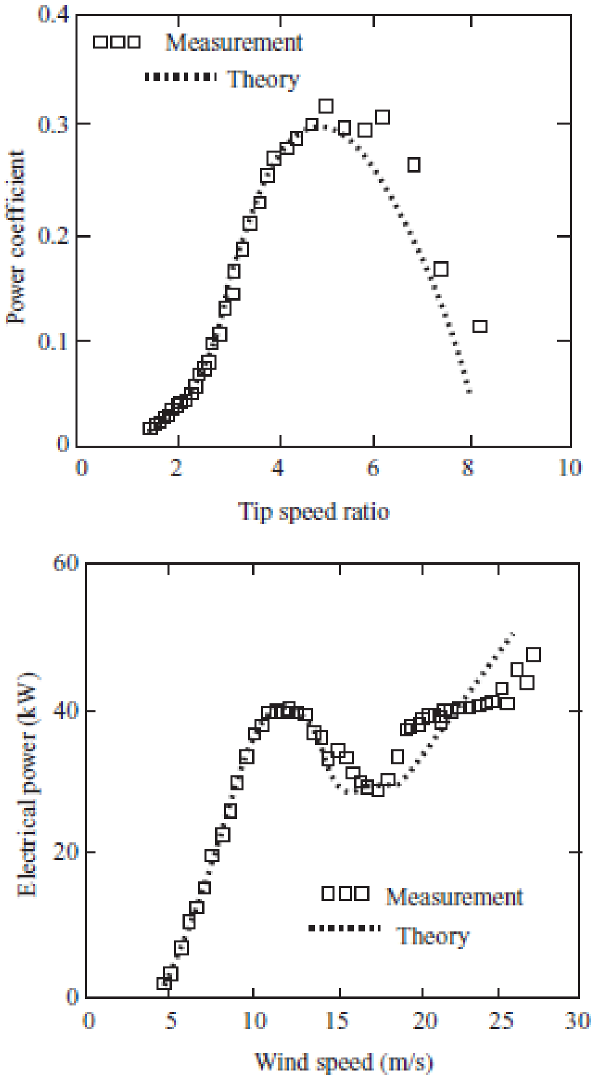


Measured Raw Results of a Three-Blade Wind Turbine

Source [1]



Comparison of Measured and Theoretical Performance Curves

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Variable Speed Operation

❑ The efficiency of the turbine can be increased significantly if:

- The speed of the rotor is being adjusted continuously to keep the tip speed ratio constant at the level achieving max Cp
- Active pitch control is necessary to achieve this constant tip speed ratio but only in adjusting rotational speed
- The pitch angle should always return to optimum setting for highest efficiency
- Pitch control regulation is also needed in conditions above rated wind speed when the rotational speed is kept constant.

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Summary of the provided knowledge

- Wind turbine performance curves (power, torque, thrust)
- Effect of various parameters on the performance curves
    - Rotational speed change
    - Blade pitch change
    - Solidity

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References

[1] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

[2] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

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Estimation of Energy Capture

Lecture 2.2

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Learning outcomes

O1. Know how to estimation wind energy production

O2. Methods to be used for wind energy capture estimation

O3. Modelling of the system

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Technical Contents

1. Wind Resource estimation methods
2. Why method is considered important
3. Meteorology
4. Topography
5. Meteorological Models

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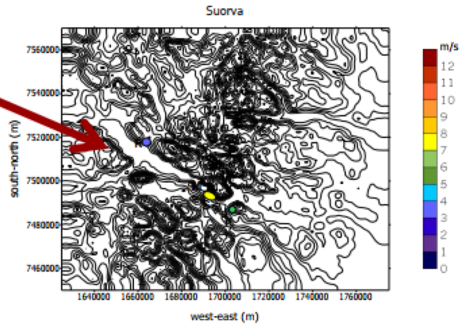
How to Estimate

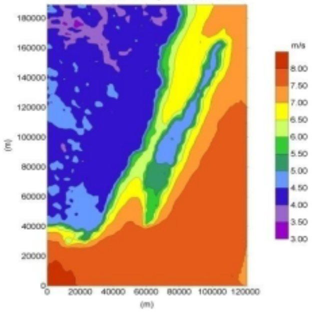
Two methods:

1) <u>Measurements</u>
   Challenge:
   Long-time corrections
2) <u>Modelling</u>
   Challenge:
   To what extent it can be trusted

Wind measurements –
Poor geographical coverage.
Climatologically representative?



Modelling –
Good geographical coverage
but
different models may give different results.



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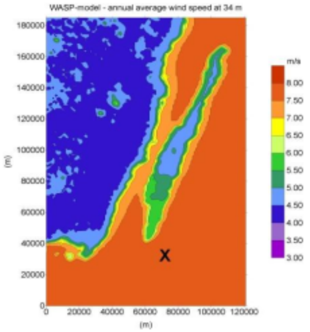

Source [1]

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Why Method Choice is Important?

- If the **wind speed** is **overestimated** by **10%**, the **energy** will be **overestimated** by **33%.** Since,

$$E = ku^3$$

$$\frac{E_2}{E_1} = \frac{ku_2{}^3}{ku_1{}^3} = \frac{(1.1u)^3}{u^3} = 1.1^3 = 1.33$$

- Therefore, the accuracy of measurements/ model selected is of high importance!

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Estimation of Wind Energy Capture

The amount of energy captured by a wind turbine depends on:

- → Wind speed distribution at the turbine site location
- → Wind direction distribution
- → Wind Shear
- → Turbulence

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Wind

- Wind is defined as:

  “Stream of air that moves relative to surface of the earth”

- Newton’s first law states that a body remains at rest as long as it is not affected by any external forces.
- Therefore, to create wind, air has to be affected by forces

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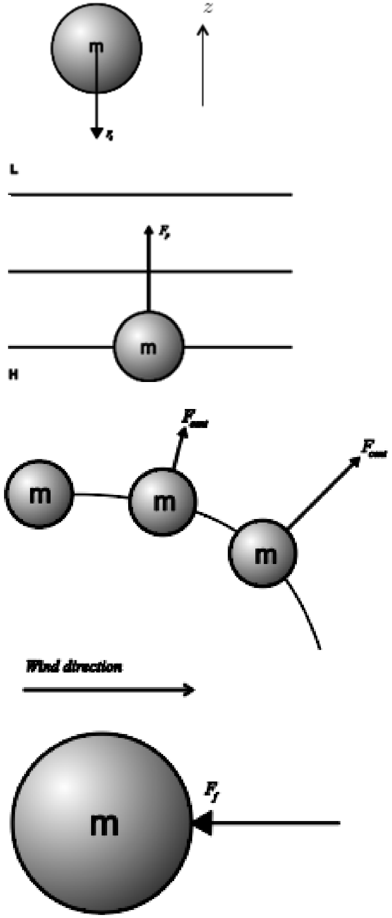
Forces

- Gravitational force: $F_g = mg$
- Pressure gradient force: : $F_p = -\frac{1}{\rho}\frac{\partial p}{\partial n}$
- Coriolis force: $F_c = \pm fu, f = 2\omega \sin(\varphi)$
- Centrifugal force: $F_{cent.} = m\frac{u^2}{r}$
- Friction force: $F_f = -ku, k = f(z_0), z_0 = ze^{-\frac{ku}{u_*}}$



Source [1]

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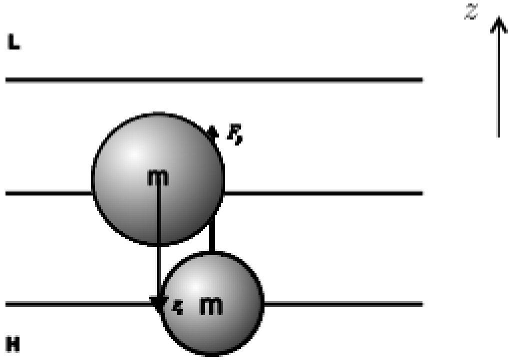
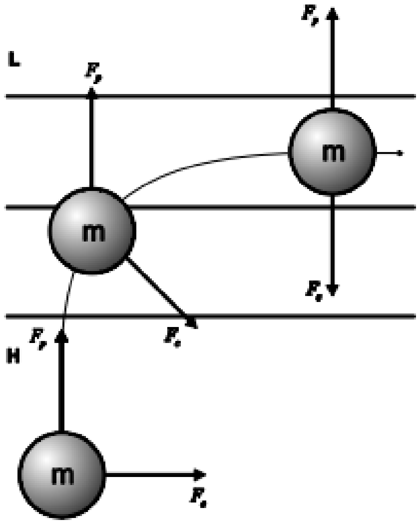
Physical Models

- Hydrostatic balance
  In the vertical (z) direction
  Only F_g and F_p are involved



- Geostrophic balance (High altitudes)
  In the horizontal plane
  Only F_p and F_c are involved



Source [1]

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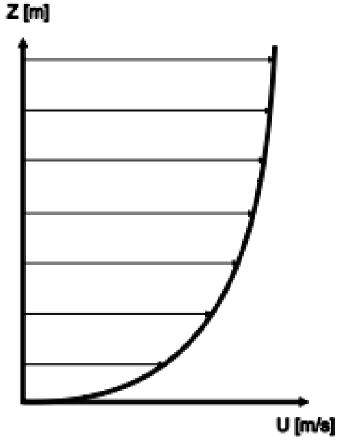
Physical Models

- Gradient balance (High altitudes)
  - In the horizontal plane
  - F_p, F_c and F_{cent} are involved
  - Centrifugal force is included since air rarely travels in straight lines

- Guldberg-Mohn's balance (low altitudes)

  Includes the friction force F_f

  Logarithmic wind profile or the power law profile



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Atmospheric Stability

- Atmospheric stability
  - Stable conditions
  - Unstable conditions
  - Neutral conditions

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Turbulence

- Defined as fast fluctuations in wind speed and direction
- Decreases horizontal wind speed
- Increase fatigue loading on turbines
- Measured in level of turbulence intensity (%)

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Topography: The Terrain

- The terrain is defined by the topography which includes all variations in the terrain which are usually fixed in time:
  1) Roughness: defined by roughness class or roughness length
  2) Orography

Roughness class	Roughness length [m]	Type of landscape
0	≤ 0.0002	Open water
1	0.003	Open landscape
2	0.10	Partly open landscapes
3	0.40	Smaller cities
4	1.60	Large cities or dense forests

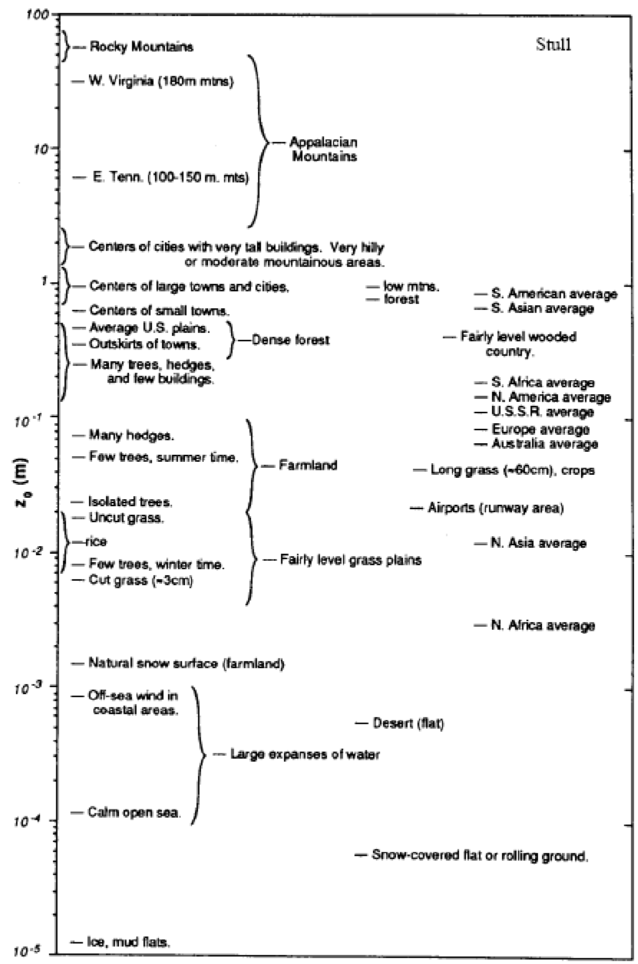

Fig. 9.6 Aerodynamic roughness lengths for typical terrain types. (After Garratt 1977, Smedman-Högström & Högström 1978, Kondo & Yamazawa 1986, Thompson 1978, Napo 1977, and Hicks 1975).

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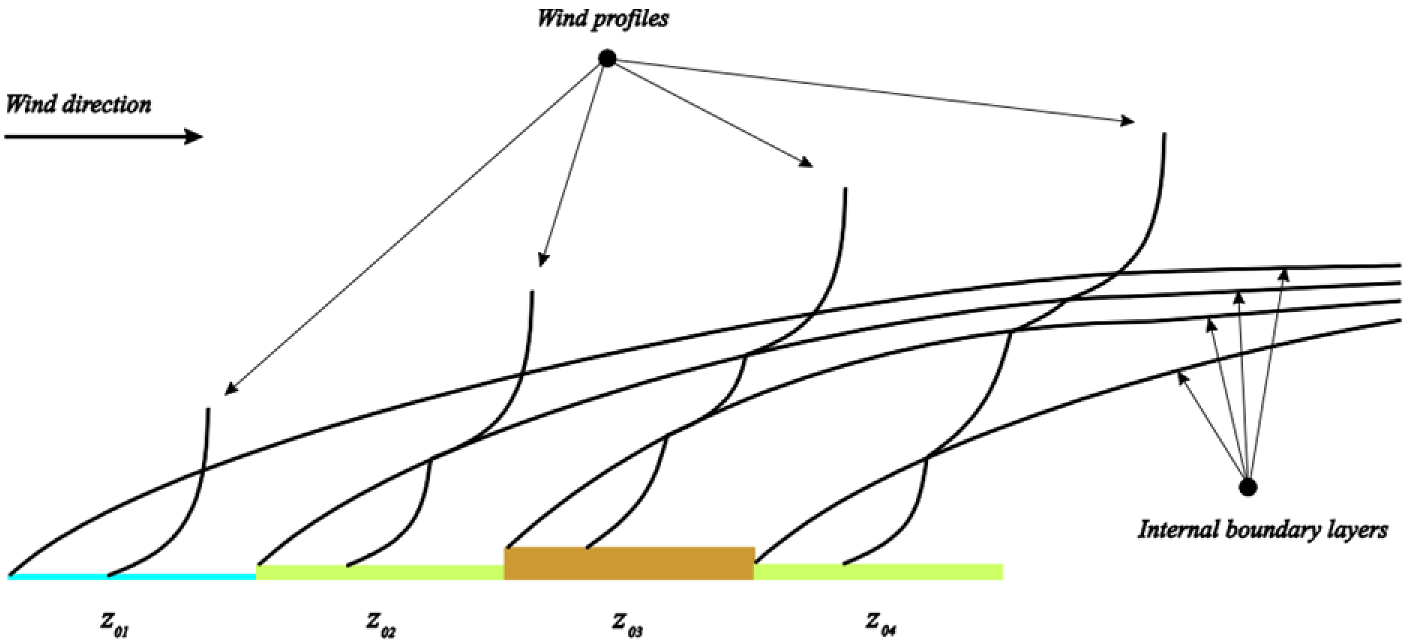
Topography: Roughness

- Internal boundary layer changes due to roughness changes



Source [1]

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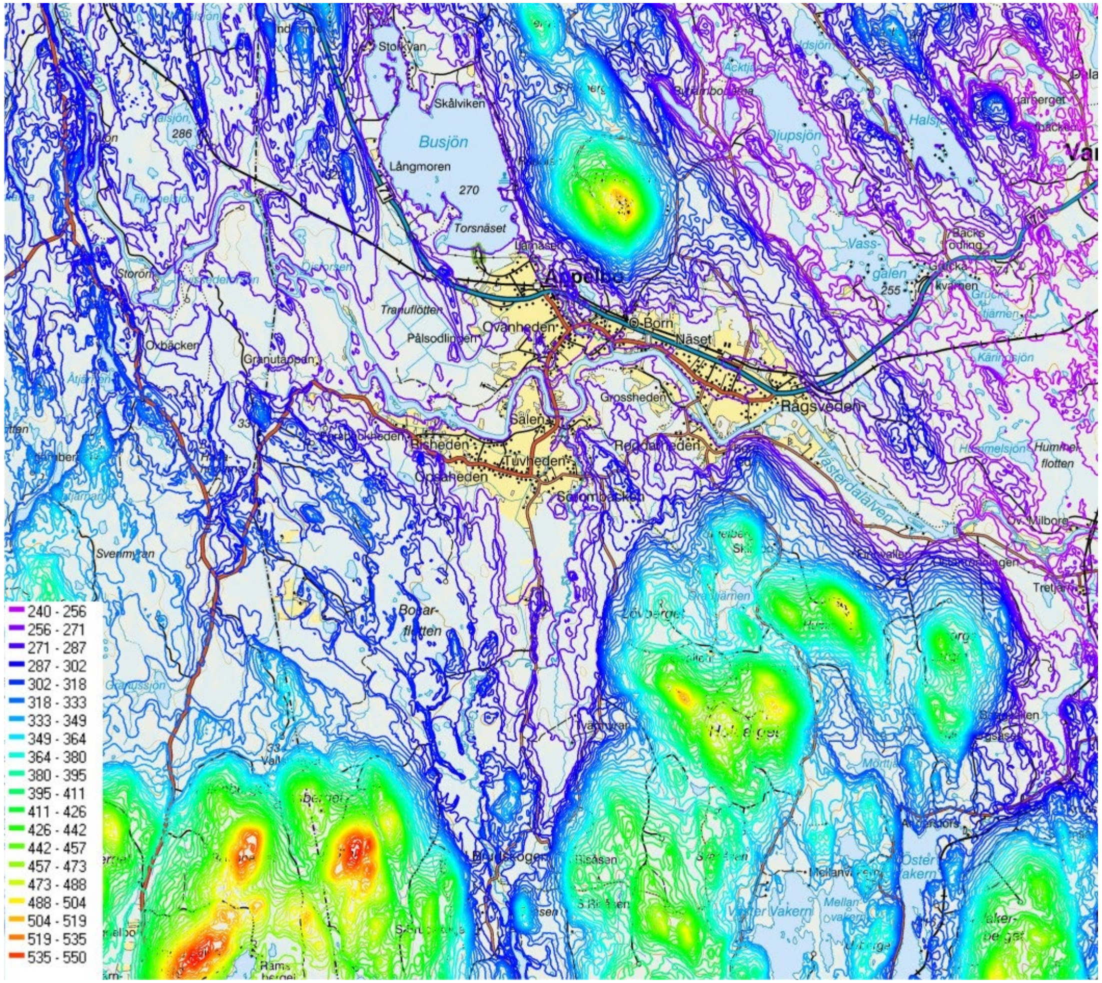
Topography: Orography

- Variations in height are often described by height contours



Source [1]

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Wind Speed Distribution

The most commonly used is the Weibull's distribution

$$f(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{(k-1)} . e^{-\left(\frac{u}{A}\right)^{k}}$$

where

u : Wind Speed (m/s)
f(u) : Weibull Distribution
A : Scale parameter
k : Shape factor (if k = 2 → it is referred to as Rayleigh's distribution)

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Wind Shear

Most commonly, the exponential profile is used

$$\frac{U(z_2)}{U(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha}$$

where

U: Wind Speed (m/s)

z_1 and z_2 : two heights (m)

α: climatologically estimated exponent depending on roughness and thermal stability

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Meteorological Models

1) Prognostic models (Numerical or CFD models)

   Global circulation models → resolution of 100 km

   High resolution limited area models → resolution of 10-50 km

   Mesoscale models → good resolution of boundary layer and a horizontal resolution of 0.1-10 km

   Large Eddy simulation models → resolves larger scales of turbulence

   Direct simulation models → resolves turbulence down to scales of the order cm

2) Analytical models, e.g. WASP

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Principals of Analytical Models

- The boundary layer consists of :
  1) Surface layer (constant flux layer)
  2) Transition layer (Ekman layer) where the wind direction change with height

- Different relations are used for these 2 layers

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Surface Layer (Monin-Obukhov Similarity Theory)

- Stationary and horizontally homogeneous conditions are assumed
- It is based on a dimensionless wind gradient: $\Phi_m = \frac{kz}{u_*}.\frac{\partial U}{\partial z} = f(\frac{z}{L})$

where, L is the Obukhov length: $L = \frac{-T{u_*}^3}{kg\overline{w'T'}}$

u_* : friction velocity, T: Temperature,

g: gravitational acceleration,

k: von Karman constant = 0.4,

$\overline{w'T'}$: heat flux, $\boldsymbol{z}$: height, $\boldsymbol{\frac{z}{L}}$: stability measure

- For neutral stability Φ_m=1 and we get the logarithmic wind profile:

$$U = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right)$$

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Transition layer – Ekman layer

- Stationary and horizontally homogeneous conditions gives the equations of motion:

$$\begin{cases} 0 = -f\left(v_g - v\right) - \frac{\partial(\overline{u'w'})}{\partial z} \\ 0 = f\left(u_g - u\right) - \frac{\partial(\overline{v'w'})}{\partial z} \end{cases}$$

where

f : Coriolis parameter

u_g and v_g : Geostrophic wind components

$\overline{u'w'}$ and $\overline{v'w'}$: Turbulent momentum transports

u and *v* : wind components

- First order closure K-theory with constant K_m gives:

$$\overline{u'w'} = - K_m \frac{\partial u}{\partial z}; \qquad \overline{v'w'} = - K_m \frac{\partial v}{\partial z}$$

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Transition layer – Ekman layer

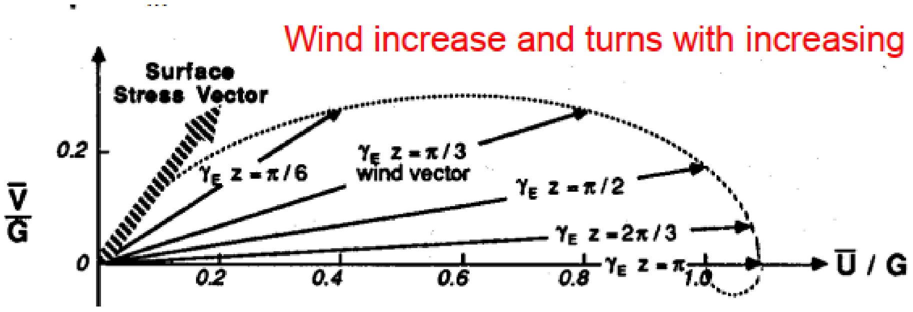
With x-axis along the geostrophic wind u_g = G and v_g=0,

So we get
$$\begin{cases} fv = -K_m \dfrac{\partial^2 u}{\partial z^2} \\ f(u-G) = K_m \dfrac{\partial^2 v}{\partial z^2} \end{cases}$$

Boundary layer conditions: u=v=0 at z=0, u→G as z→∞, v→0 as z→ ∞

Thus, it is assumed that winds become geostrophic away from the surface

The solution will be:
$$\begin{cases} u = G(1 - e^{-\gamma z}\cos(\gamma z)) \\ v = G(e^{-\gamma z}\sin(\gamma z)) \end{cases}$$
where $\gamma = \sqrt{\dfrac{f}{2K_m}}$



Wind increase and turns with increasing height

Source [1]

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Principals of a Mesoscale Model

- The following time dependent relations are included:
  1. Momentum equation (Navier-Stokes equation) to determine the wind field
  2. Thermodynamic equation (energy equation) to determine the temperature field
  3. Humidity equation
  4. Turbulent kinetic energy equation to determine atmospheric turbulence

This system of equations is solved numerically

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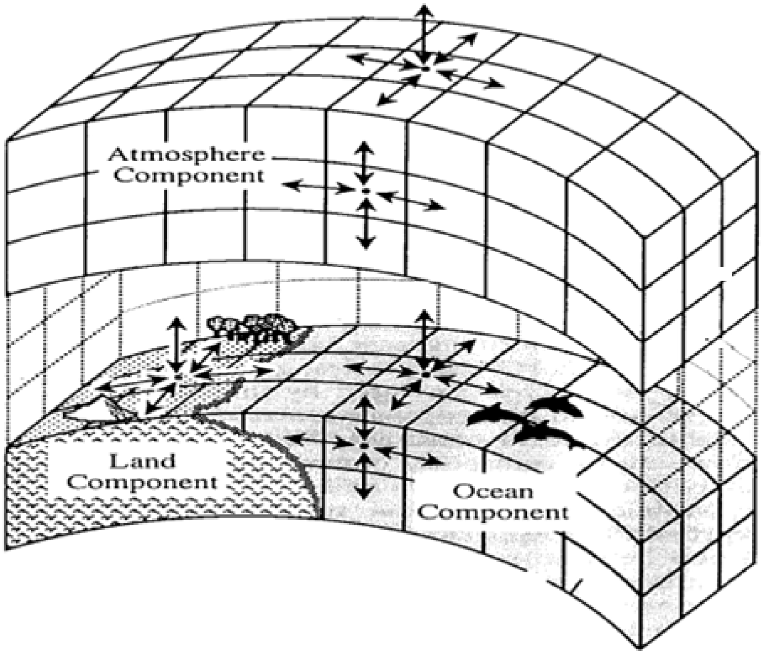
Principals of a Mesoscale Model

Equations solved for grip points (volumes)



Source [1]

Schematic representation of a computer general circulation model, coupling the Earth's surface and atmosphere to the ocean. The arrows represent the fluxes that must be calculated at each step. The dimensions and number of layers vary depending upon the model and computer used.

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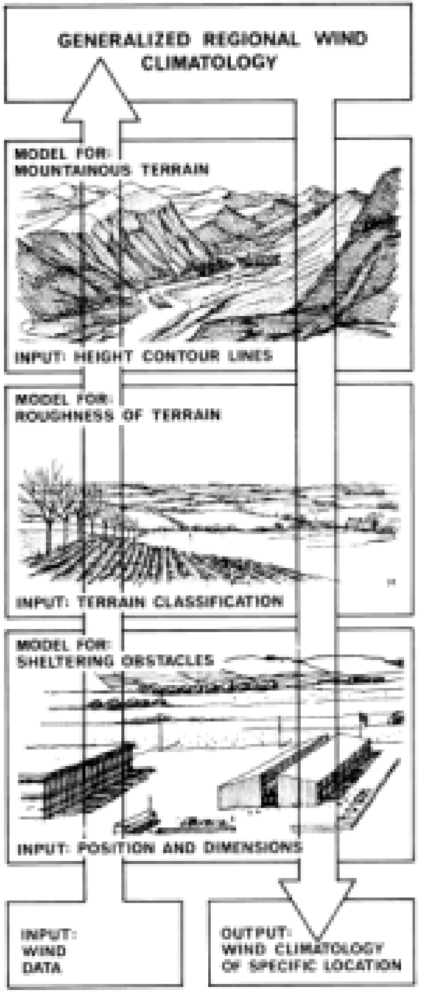
More Models

- Measurements are required
- Non-complex terrain
- At one sector of the roughness rose, the model takes into account: the power law, uniform roughness (equivalent roughness), one obstacle, very simple slope model
- It can’t include meteorological effects, e.g.: atmospheric stability, turbulence
- Time efficient and doesn’t require much experience.



Source [1]

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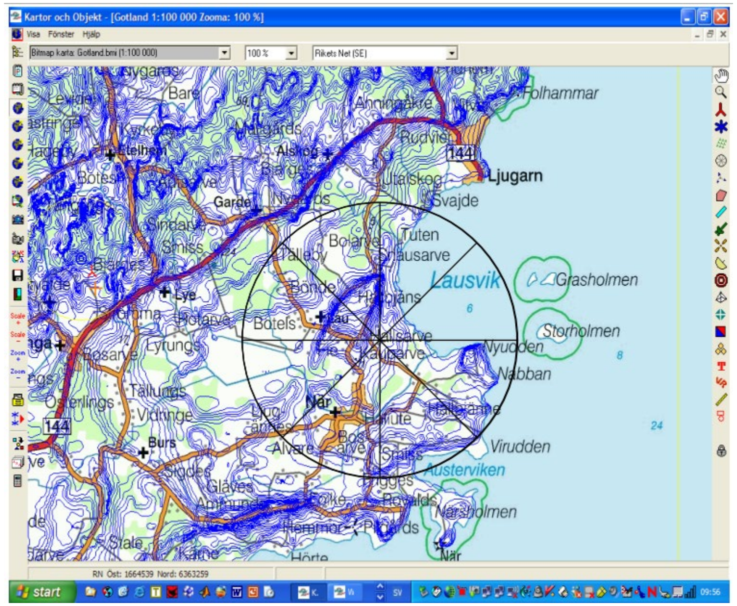
More Models

WASP (Wind Atlas analysis and Application Program)

- At one sector of the roughness rose, the model takes into account: geostrophic balance, logarithmic wind profile, a specific but uniform stability, roughness variations, height variations
- It can't include turbulence (non-linear effects)
- Time efficient and doesn't require much experience when using it with WindPRO



Source [www.wasp.dk], accessed June 2019

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More Models

HAWC2-DWM

- Aeroelastic simulations combined with the DWM (Dynamic Wake Meandering model) concept
- Inflow turbulence generated with the Mann Model
- Generate statistics about power production and wake induced fatigue

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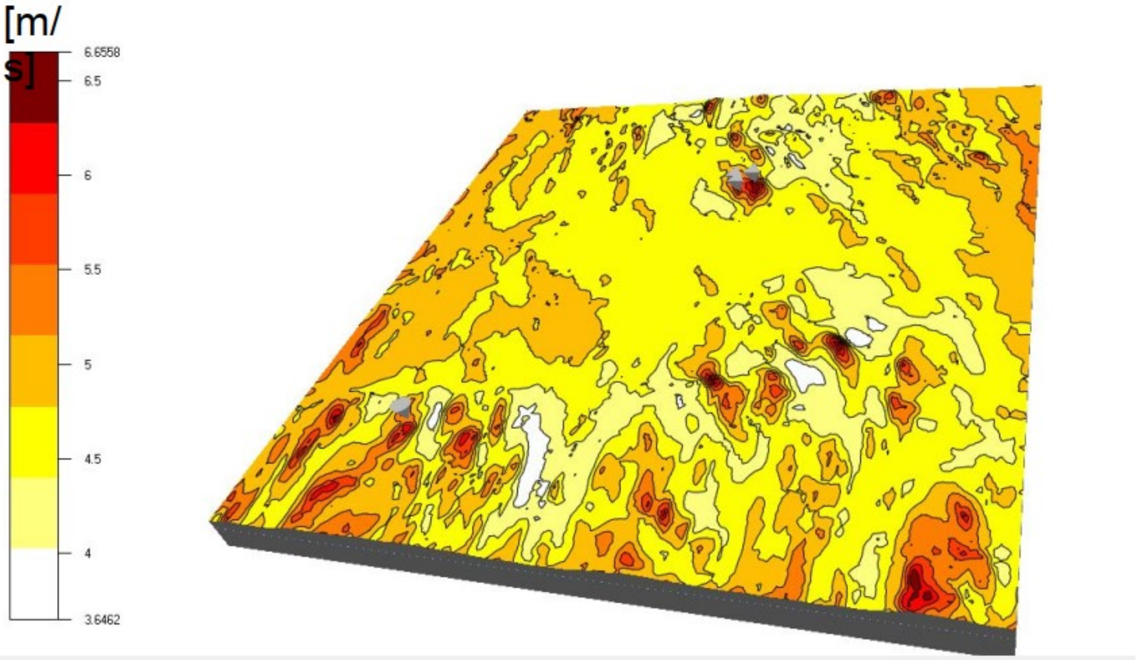
More Models

RANS (WindSim)



Source [www.windsim.com], accessed June 2019

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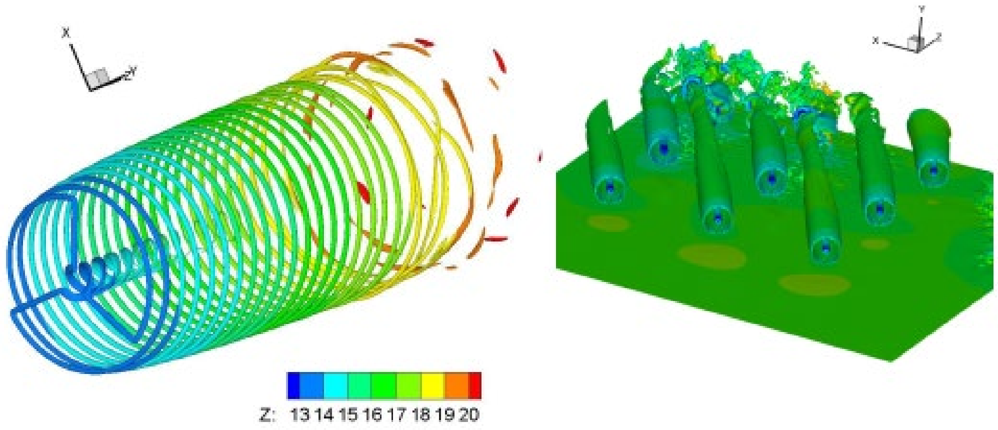
More Models

DNS/LES (EllipSys3D)



Source [www.windsim.com], accessed June 2019

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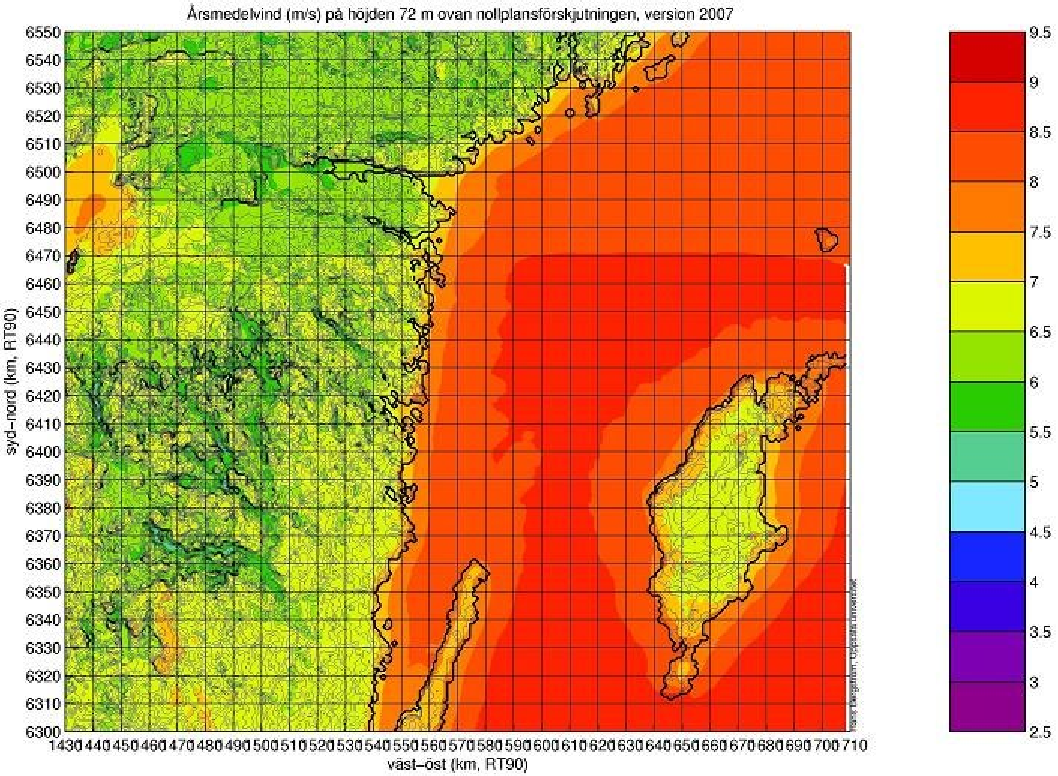
More Models

MIUU



Source [www.windsim.com], accessed June 2019

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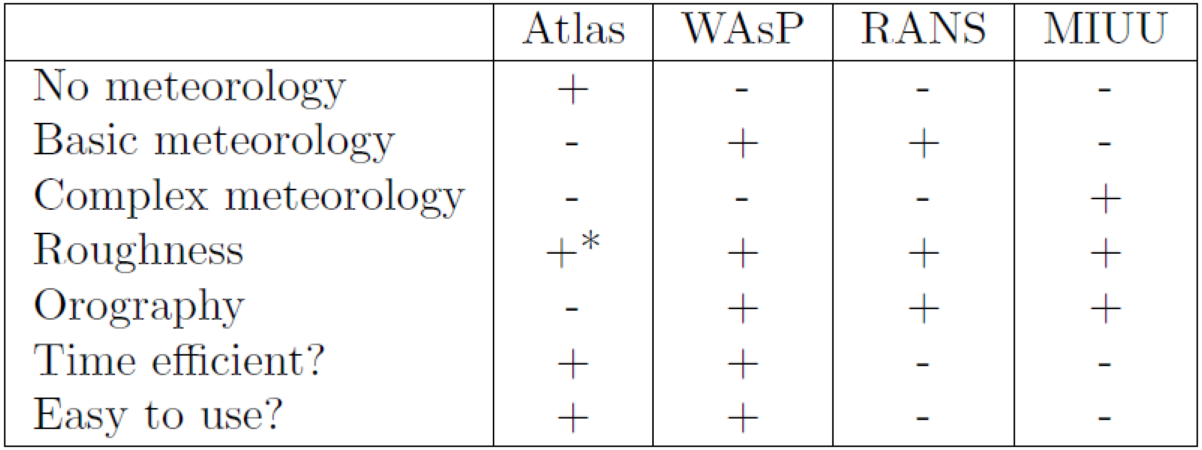
Model Comparison



	Atlas	WAsP	RANS	MIUU
No meteorology	+	-	-	-
Basic meteorology	-	+	+	-
Complex meteorology	-	-	-	+
Roughness	+*	+	+	+
Orography	-	+	+	+
Time efficient?	+	+	-	-
Easy to use?	+	+	-	-

* Simplified

Source [1]

Summary of the provided knowledge

- Wind resource estimation
- Wind energy capture estimation
- Various models for energy capture estimation
- Comparison of models
  - Choose model wisely
  - Be aware of each model limitations
  - Be critical to results given by each model

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References

[1] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

[2] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

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Design and Manufacture of HAWT

Lecture 3.1

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Learning outcomes

O1. Know the concerns when designing the structure

O2. Know the wind turbine loads and characteristics

O3. Have the knowledge on how to assume the loading

O4. How to design the structure

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Technical Content

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Introduction

- Due to wind nature, Wind turbines are subjected to highly variable loads.
- Varying loads are hard to deal with than static loads as the material gets fatigued.
- The air which is the working medium, has a low density and hence, the surface required for energy capture must be large.
- If the rotor dimensions increased, the dimensions of other components also increase.

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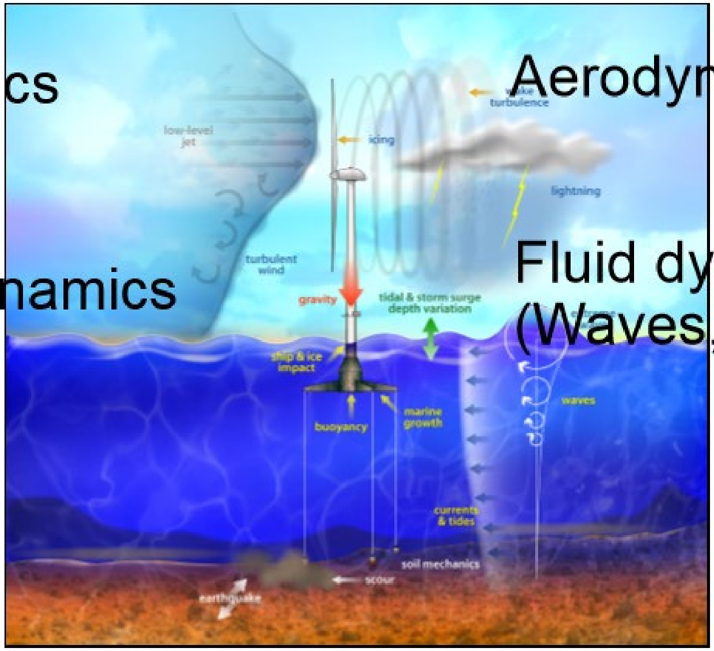
Problem Complexity



Meteorology

Aeroelastics

Aerodynamics

Power dynamics

Fluid dynamics
(Waves, streams)

Structual dynamics

Source [1]

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Structure Design Considerations

Design of turbine components must consider:

1. The components must be designed for extreme loads
2. Fatigue life of the components must be guaranteed for the service life of the turbine
3. Components must be stiff enough to avoid critical deflections and have a controlled vibration behavior.

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Loads on a Wind Turbine

These include:

- Steady loads: Aerodynamic, inertial and gravitational loads
- Unsteady loads: cyclic and non-cyclic loads

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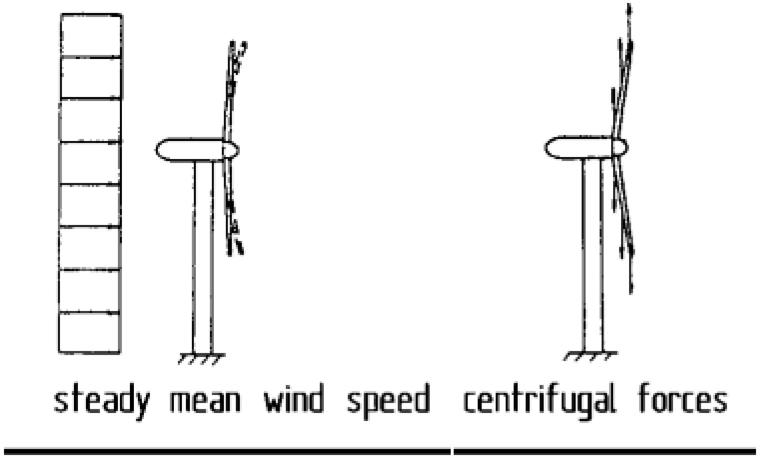
Loads on a Wind Turbine

I. Steady loads:

- Aerodynamic loads with a uniform and steady wind speed
- Centrifugal forces generate time dependent, steady state loads as the rotor is operating at constant speed



Source [2]

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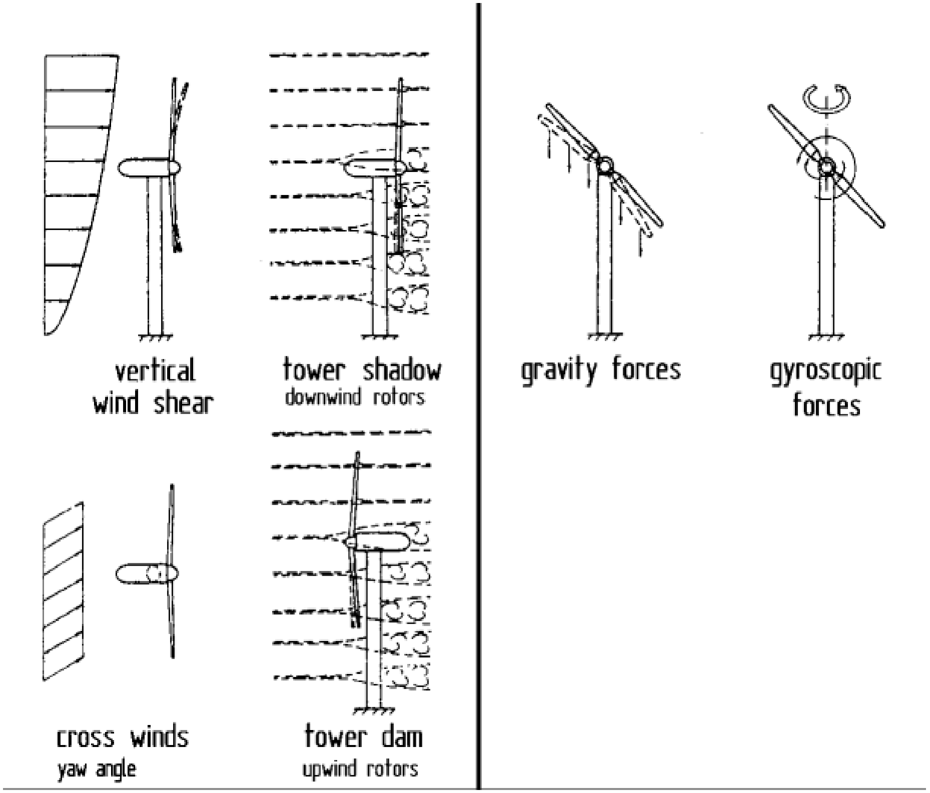
Loads on a Wind Turbine

II. Unsteady loads:

A) Cyclic loads are due to:

- Uneven airflow due to increase of wind speed with height and cross-flow interference due to flow around the tower
- Inertia forces due to dead weight of the blades
- Gyroscopic forces due to yawing the rotor



Source [2]

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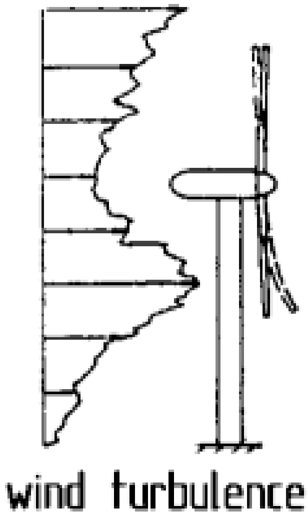
Loads on a Wind Turbine

II. Unsteady loads:

B) Non- cyclic loads:

- Wind turbulence and gusts cause non-periodic and stochastic loads



Source [2]

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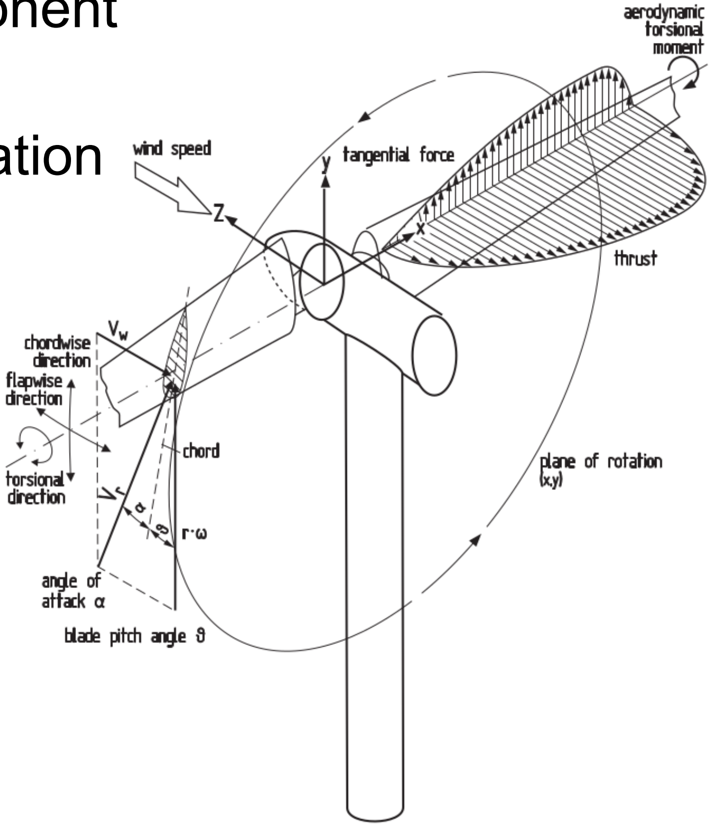
Coordinates and Loads on the Rotor

- In a rotating co-ordinate system, forces and moments acting on the rotor blades are resolved into:
  a. Chordwise/Edgewise component
  b. Flap-wise component
- With respect to rotor plane of rotation
  a. Tangential component
  b. Thrust component



Source [1]

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I. Uniform and Steady-state Air flow

- For practical purposes, a uniform steady wind is assumed to calculate the mean load level occurring over a long time period.
- Steady-state aerodynamic forces are determined by the varying effective wind speed from root to tip.

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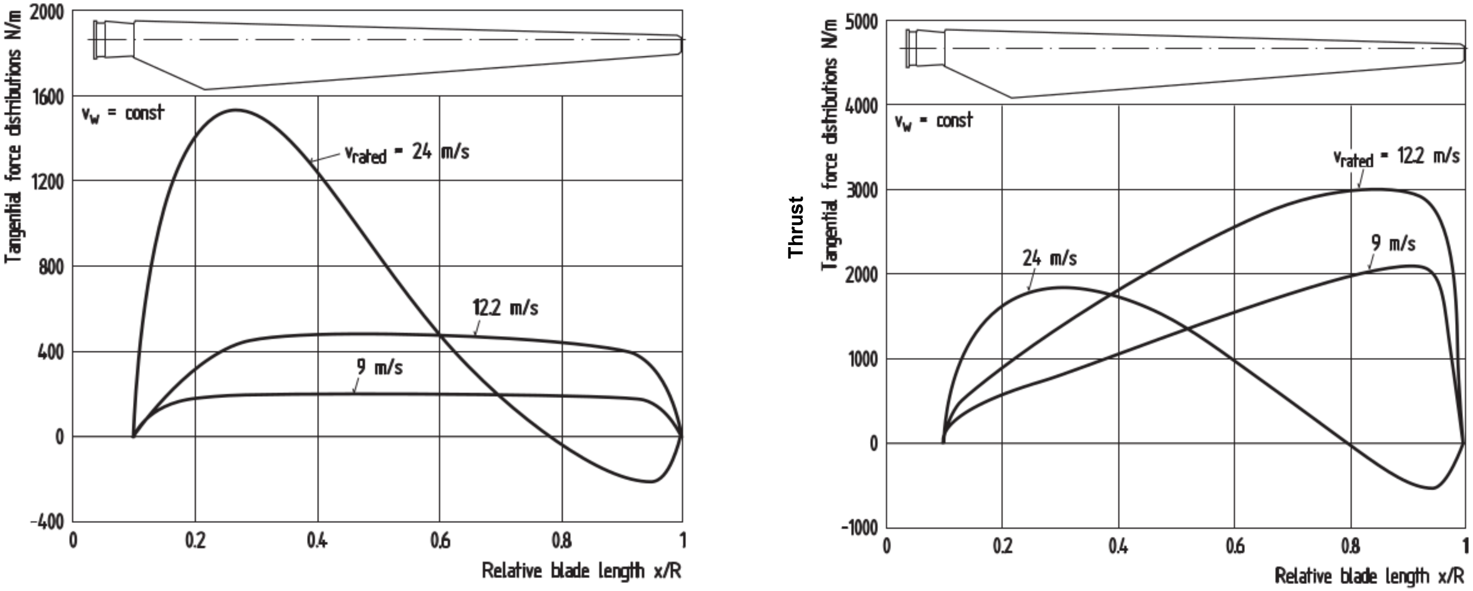
I. Uniform and Steady-state Air flow

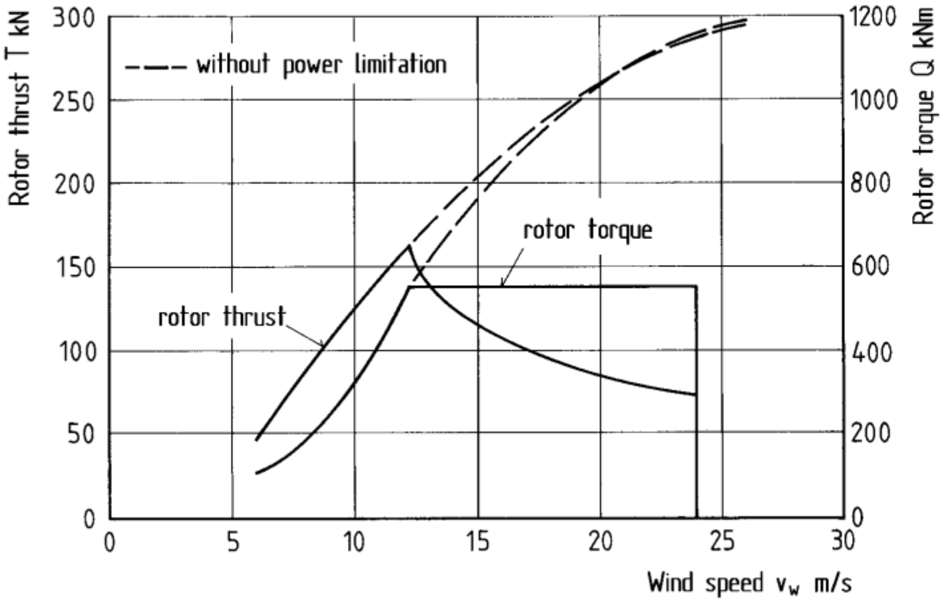
- Bending moments in Chordwise direction are a result of tangential forces while thrust loading is responsible for flap-wise bending moments.



Source [1]

I. Uniform and Steady-state Air flow

- Rotor blade twist cause changes to this distribution from start-up to shut-down speeds
- Twist is only optimized for rated wind speed and thus aerodynamic loads correspond approximately to the theoretical optimum for this wind speed only



Source [1]

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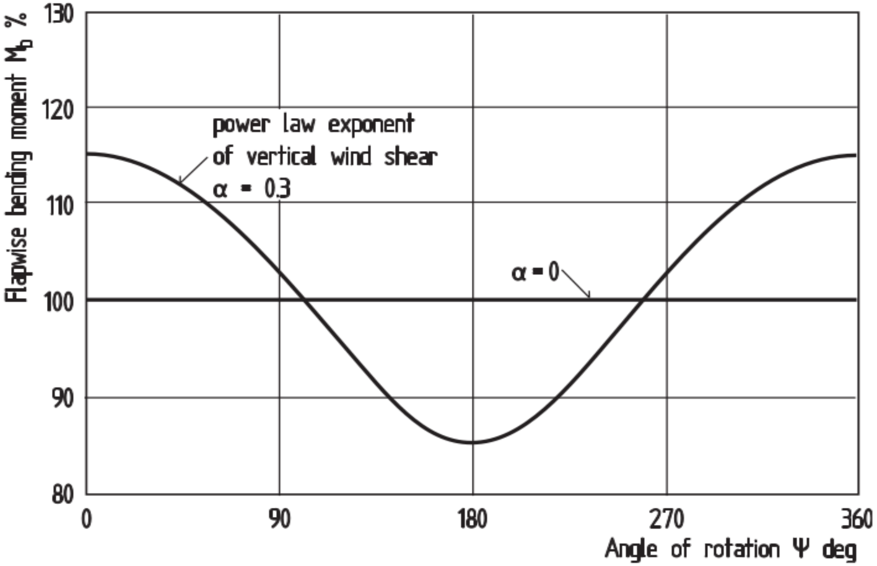
II. Vertical Wind shear and Cross winds

- Wind speed increase with height from the ground.
- Each revolution, the rotor blades are subjected to higher wind speeds in the upper rotational sector and thus, higher loads that the sector closer to ground.



Source [1]

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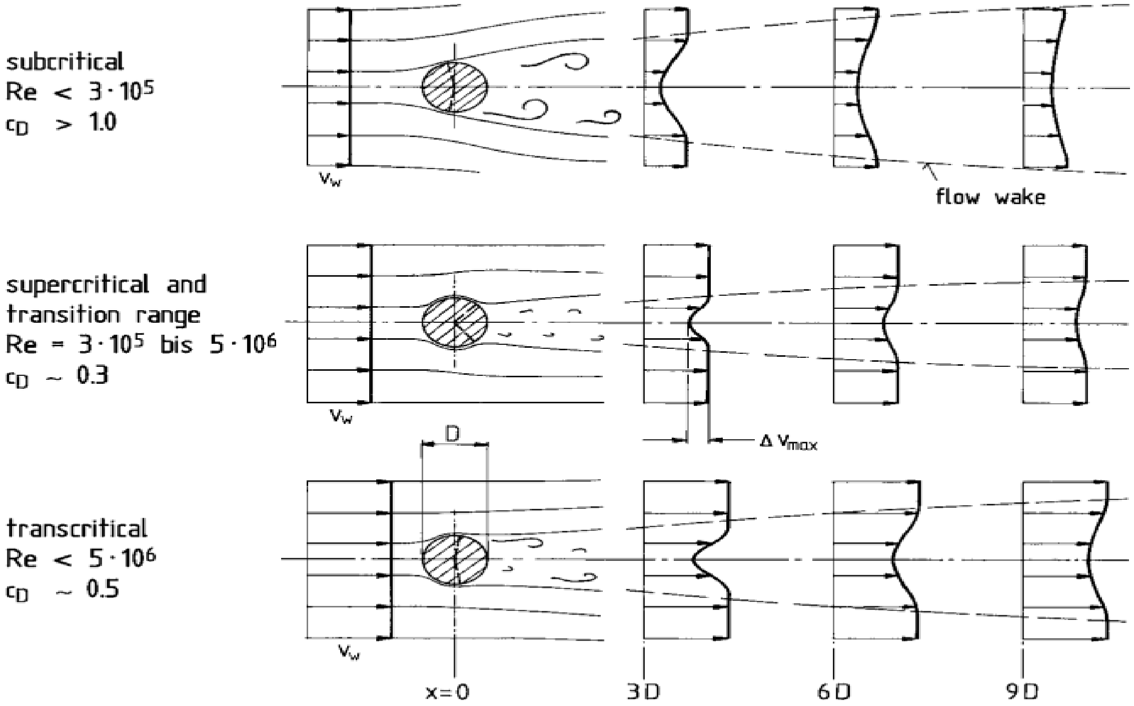
II. Tower Interference



Source [1]

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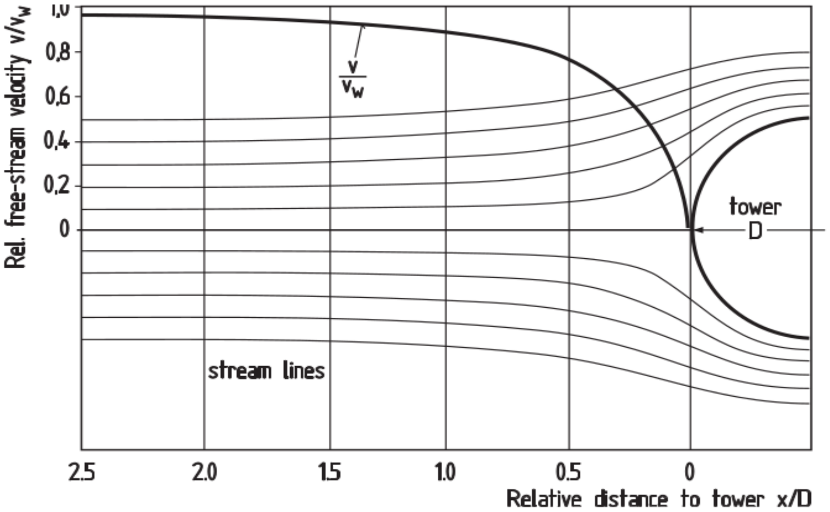
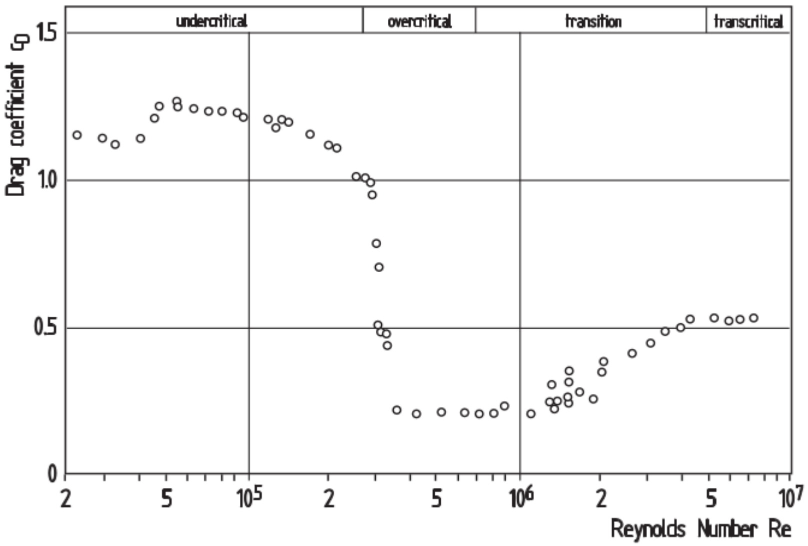
Sources of Loading

II. Tower Interference

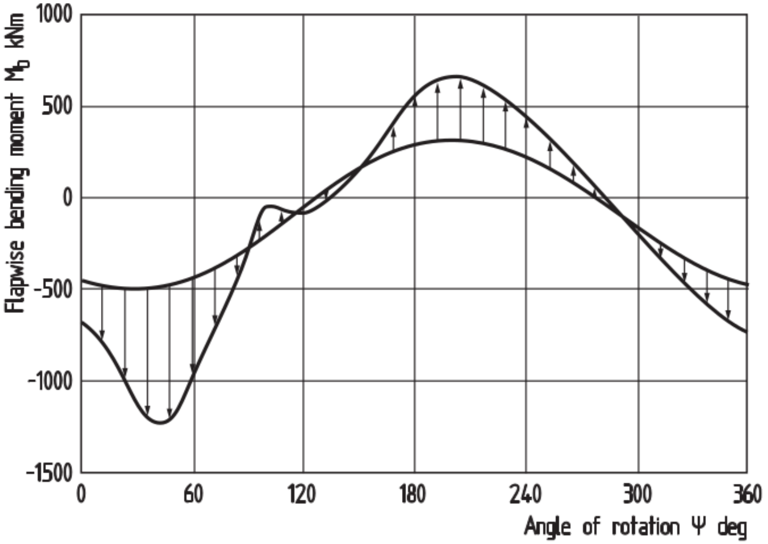


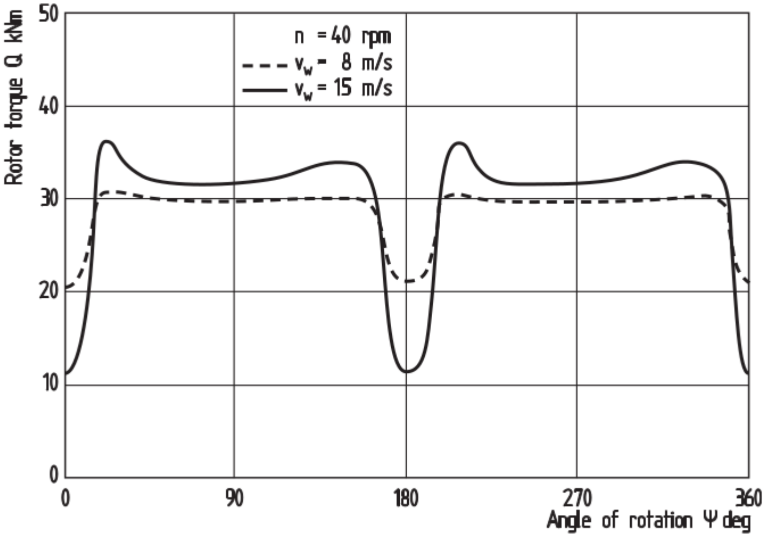


Source [1]

Sources of Loading

II. Tower Interference





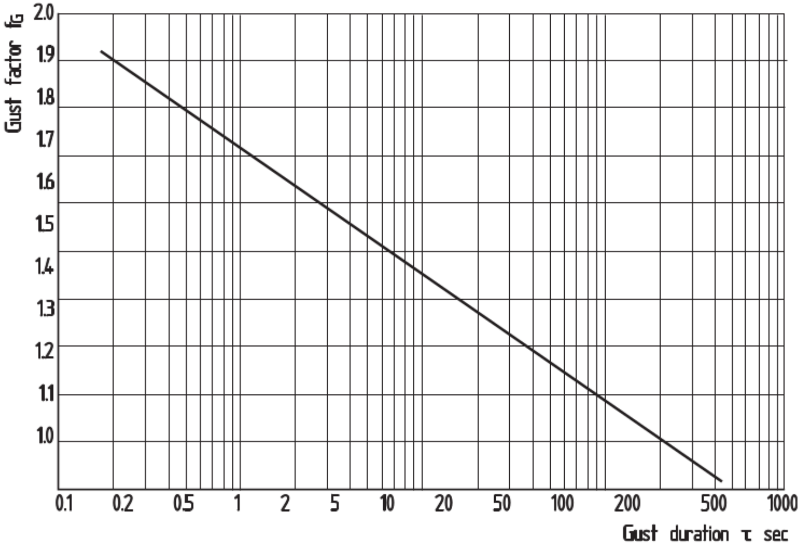
Source [1]

II. Wind Turbulence and Gusts

- Non-cyclic fluctuating loads are determined by short-term fluctuations of the wind speed.
- Wind turbulence contributes considerably to material fatigue of the turbine components, the blade in particular.
- In load calculations, the wind consists of a mean wind speed which varies on a time-scale of an hour or more, with turbulent fluctuations superimposed.
- Turbulence spectral models are usually utilized in load calculations on the rotor assuming 1D fluctuation in the longitudinal direction. (In reality, there are lateral components too)

II. Wind Turbulence and Gusts

- Gust is an increase of wind speed averaged over a period of time with a reference to the mean speed of the wind.
- Classification of gusts are established with the aid of “Gust factor”
- Sudden drop in wind speed from the average wind speed is usually referred to as “Negative gust”.



Source [1]

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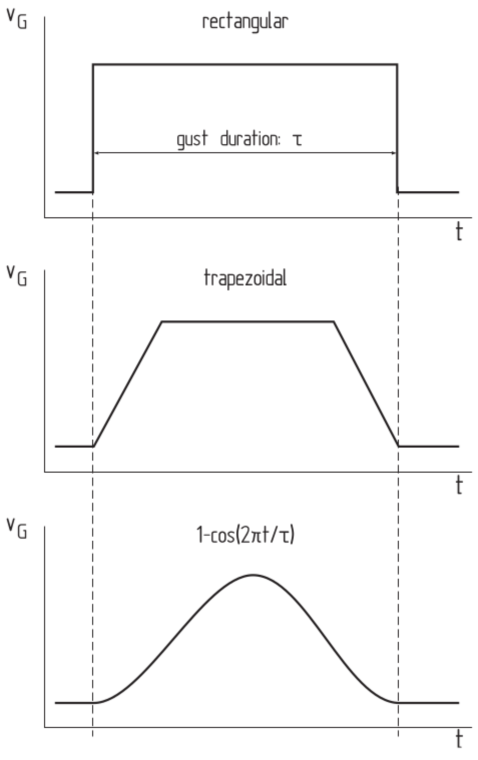
II. Wind Turbulence and Gusts

- Spectral model of turbulence is of a statistical nature, however, a deterministic approach can also be used.
- The idea is to define discrete idealized gust shapes; increasing and decreasing wind speed over time.



Source [1]

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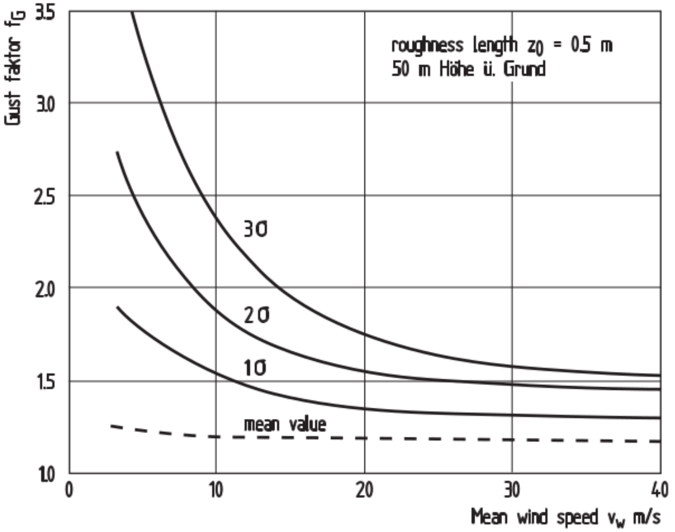
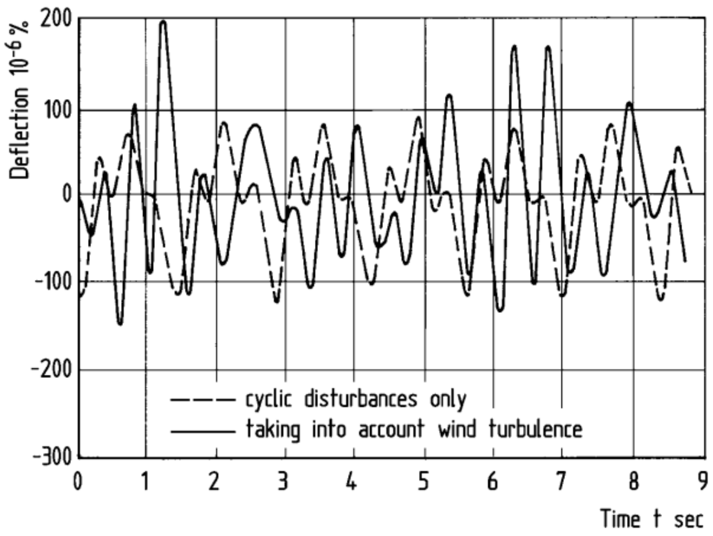
II. Wind Turbulence and Gusts





Source [1]

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Design Load Assumptions

- Knowing the reasons for loads, the task is to recognize the conditions a wind turbine may be subjected to these loads.
- These conditions are recorded in the form of what is called “Design Load Cases”
- The loads calculated in these defined Load Cases are referred to as “Design Load Assumptions” which may deviate from real loads.
- However, these Design Load Assumptions must always be higher than the expected operating loads to ensure the turbine is safe.

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Design Load Assumptions

- Attempts for systematic definition of Design load assumptions and load cases started back in the seventies and further developed through the years.
- Today the standards and rules issued by International Electrotechnical Commision (IEC) are generally accepted worldwide as a common basis.
- **IEC 61400** defines a standard set of Design load cases families
  - Each family has a number of families with several seeds
- Evaluation is divided into ***Ultimate/Extreme*** and ***Fatigue loading***

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IEC-61400 Wind Classes

	IEC I	IEC II	IEC III	IEC IV
Average wind speed	10 m/s	8.5 m/s	7.5 m/s	6.5 m/s
50-year extreme gust	70 m/s	59.5 m/s	52.5 m/s	42 m/s
Turbulence Class A	0.18			
Turbulence Class A	0.16			
Turbulence Class A	0.12			
Wind Shear Exponent	0.2			

Source [3]

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Load Cases: DLC1

Design Situation	DLC	Wind Conditions	Description
Power Production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	Normal Production
	1.2	NTM $V_{in} < V_{hub} < V_{out}$	Normal Production with ice on blades
	1.3	ETM $V_{in} < V_{hub} < V_{out}$	Normal Production with higher turbulence
	1.4	ECD $V_{hub} = V_r + [-2,0,2]m/s$	Gust and wind direction change
	1.5	EWS $V_{in} < V_{hub} < V_{out}$	Normal Production with extreme wind shear

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

NTM: Normal turbulence model

ETM: Extreme turbulence model

ECD: Extreme coherent gust with direction change

EWS: Extreme wind shear

Source [3]

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Load Cases: DLC2

Design Situation	DLC	Wind Conditions	Description
Power Production + fault occurrence	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault or electrical network fault
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Protection system or internal electrical fault
	2.3	EOG $V_{hub} = V_r \pm 2\ m/s$ $V_{hub} = V_{out}$	External or internal electrical fault including loss of grid
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control, protection or electrical system faults including loss of grid

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

NTM: Normal turbulence model

EOG: Extreme operating gust

Source [3]

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Load Cases: DLC3

Design Situation	DLC	Wind Conditions	Description
Start up	3.1	NTM $V_{in} < V_{hub} < V_{out}$	Start up in normal production
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2, V_{out}$	Start up with gust
	3.3	ECD $V_{hub} = V_{in}, V_r \pm 2, V_{out}$	Start up with gust and direction change

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

NTM: Normal turbulence model

EOG: Extreme operating gust

ECD: Extreme coherent gust with direction change

Source [3]

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Load Cases: DLC4

Design Situation	DLC	Wind Conditions	Description
Normal shut down	4.1	NTM $V_{in} < V_{hub} < V_{out}$	Shut down in normal production
	4.2	EOG $V_{hub} = V_{in}, V_r \pm 2, V_{out}$	Shut down with gust

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

NTM: Normal turbulence model

EOG: Extreme operating gust

Source [3]

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Load Cases: DLC5

Design Situation	DLC	Wind Conditions	Description
Emergency shut down	5.1	NTM $V_{in} < V_{hub} < V_{out}$	Emergency shut down in normal production

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

NTM: Normal turbulence model

Source [3]

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Load Cases: DLC6

Design Situation	DLC	Wind Conditions	Description
Parked (idling)	6.1	NTM 50-year recurrence period	
	6.2	EWM 50-year recurrence period	Loss of grid
	6.3	EWM 1-year recurrence period	Extreme yaw misalignment
	6.4	NTM $V_{hub} = 0.7\,V_{ref}$	Fatigue loading

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

V_{ref}: 1-year extreme mean wind speed

NTM: Normal turbulence model

EWM: Extreme wind speed model

Source [3]

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Load Cases: DLC7

Design Situation	DLC	Wind Conditions	Description
Parked + fault conditions	7.1	EWM 1-year recurrence period	Emergency brakes applied

V_{in}: Cut-in wind speed

V_{out}: Cut-out wind speed

V_{hub}: Wind speed at hub height

V_r: Rated wind speed for the turbine

EWM: Extreme wind speed model

Source [3]

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Load Cases

- Number of simulated seeds is in the range of 4000-5000
- Simulations results are usually combined to a summary format for making comparison possible

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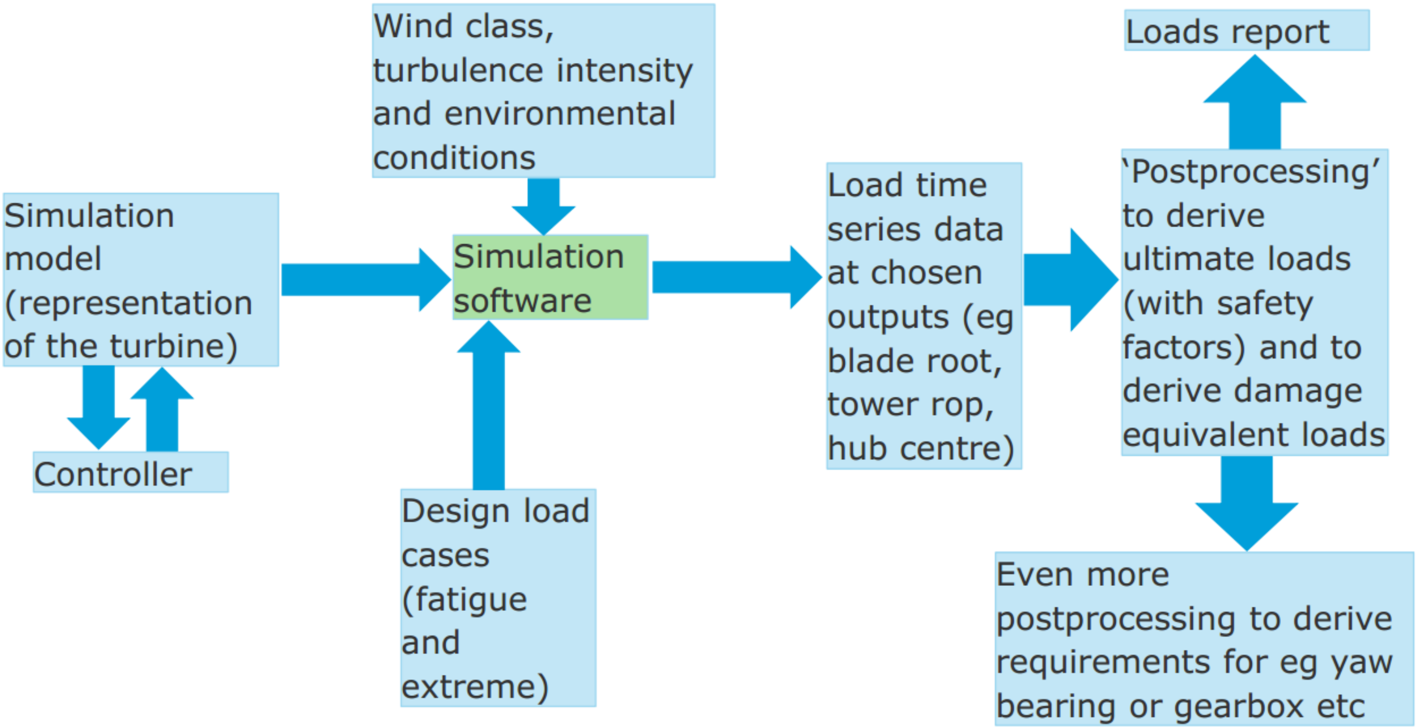
Loads Calculation and Postprocessing



Wind class, turbulence intensity and environmental conditions

Simulation model (representation of the turbine)

Controller

Simulation software

Design load cases (fatigue and extreme)

Load time series data at chosen outputs (eg blade root, tower rop, hub centre)

'Postprocessing' to derive ultimate loads (with safety factors) and to derive damage equivalent loads

Loads report

Even more postprocessing to derive requirements for eg yaw bearing or gearbox etc

Source [1]

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Group Project 1

- Form groups (max 4 members)
- Development of 3D CAE model and static finite element analysis of the blade's structure
- Presentations of the project
  - 20 minutes each
  - Presentation skills (50%)
  - Technical contents (50%)

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Group Project 2

- Form groups (max 4 members)
- Hands-on blade manufacturing
- Presentations of the project
  - 20 minutes each
  - Presentation skills (50%)
  - Technical contents (50%)

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Summary of the provided knowledge

- Discussed on the structural design considerations
- Provided loads on a wind turbine
- Sources of loading are detailed
- Design load assumptions for various load cases

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References

[1] Erich Hau, Wind Turbines: Fundamentals, Technologies, Application, Economics, Springer

[2] M. L. O. Hansen, Aerodynamics of Wind Turbines, Earthscan

[3] IEC 61400 Standard, www.iso.org (2019)

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Q&A

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Thank You for Your Attention!

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Contact: info@weset-project.eu *weset.erasmusplus@uva.es*

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Component loading and design: Nacelle

Lecture 4.1

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Learning Outcomes

The main objective of the lesson is understanding of mechanical design requirements of Nacelle main components of a wind turbine, making the students able to:

O1. Understand the different components of the Nacelle and how they work.

O2. Familiarize the different designs and alternative of each component.

O3. Be able to design or select proper components for wind turbine Nacelle.

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Technical Contents

1. *Nacelle components.*
2. *Hub types and Design.*
3. *Main shaft: role, types and design.*
4. *Gearbox functions, types and design/selection.*

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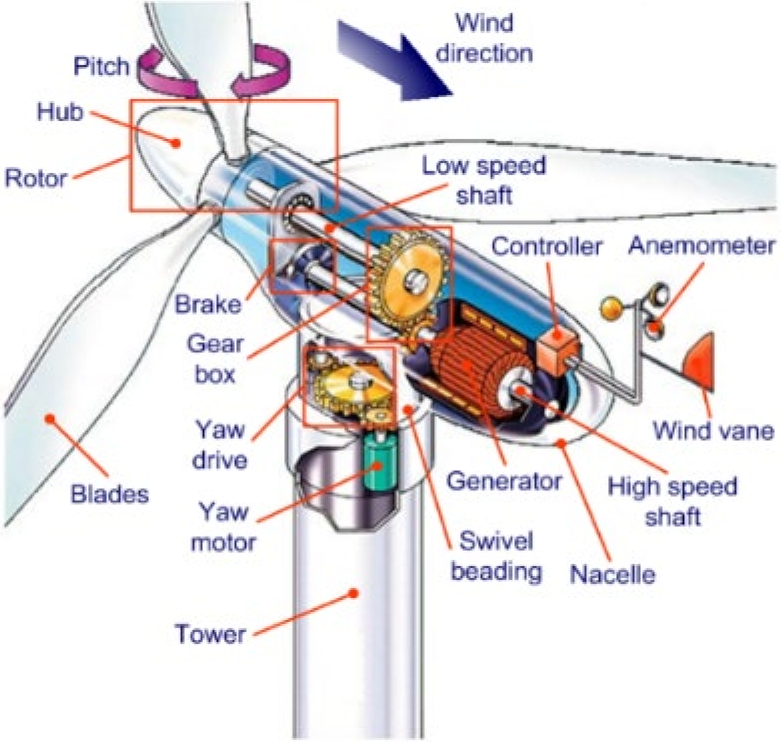
Nacelle Components

The Nacelle mainly contains (Sources [1] and [2]:

- The main shaft (low speed shaft)
- The gearbox and high speed shaft.
- The generator.
- Some controller parts.

It also contains part of the yawing mechanism. The Nacelle supports the rotor with all its components



Source: [3]

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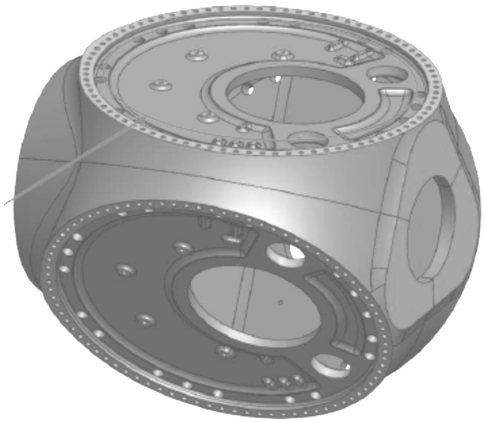
Rotor Hub

- Supports the wind turbine blades and transfer the rotation from the blades to the main shaft
- Contains the pitching mechanism responsible for pitching the blades to control the wind turbine rotation according to the wind condition and the required output
- Earthing connections responsible for lightning protection passes from the blades through the hub



Source: [3]

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Rotor Hub

- Has several designs and it varies according to the size, the included components and environmental conditions
- Being the heaviest and most complex component of the wind turbine, it is mainly produced through casting in special foundries

Source: [3]

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Rotor Hub

- The rotor hub takes several further manufacturing steps from casting to final product.

Source: [3]

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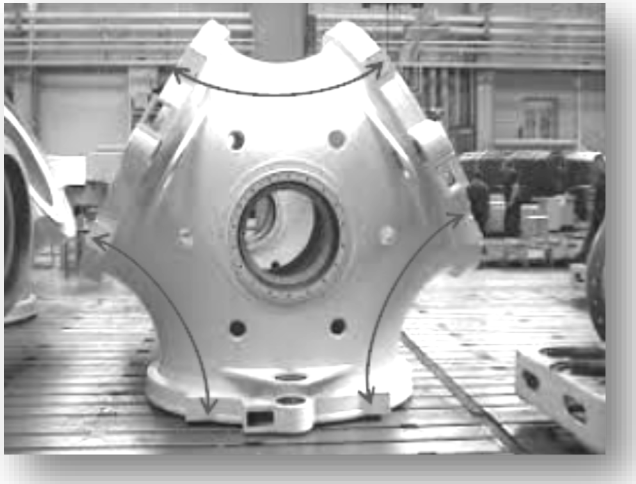
Rotor Hub

- Its designs can vary in shape from Star (upper design) to ball (lower design).
- Pitching mechanism included inside the hub may be gear and pinion actuated or hydraulically actuated, each with relevant connections and mechanisms.



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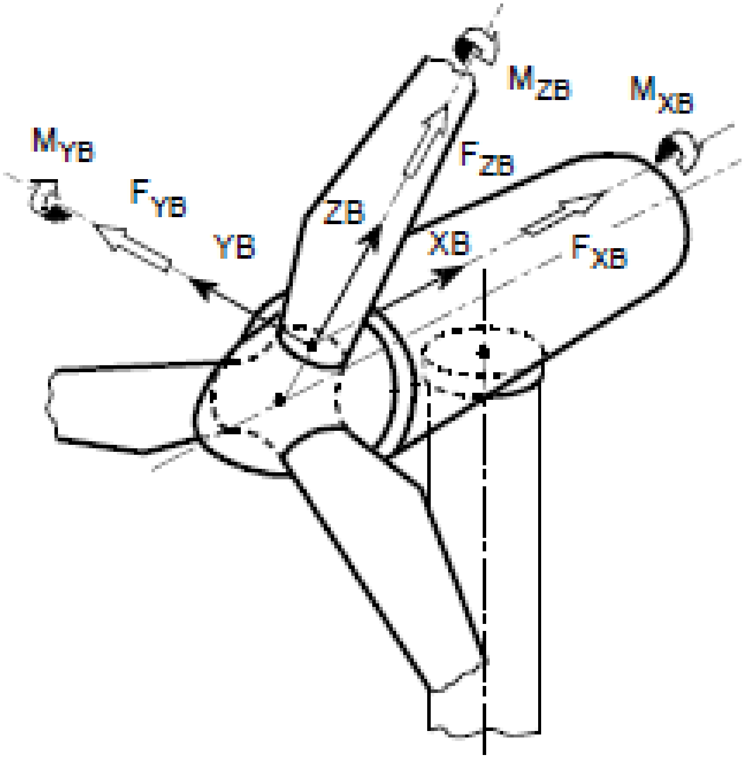
Source: [3]

Rotor Hub

Loading on hub

- Aerodynamic
- Gravitational
- Inertia



XB	in direction of the rotor axis
ZB	radially
YB	so that XB, YB, ZB rotate clockwise

Source: [3]

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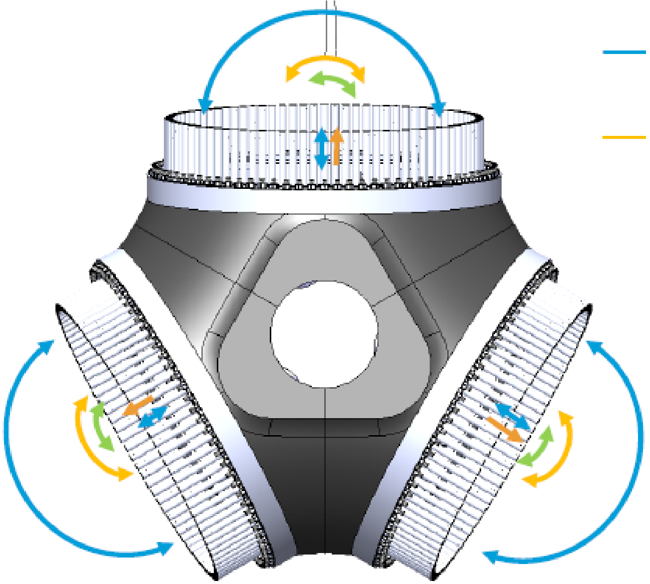
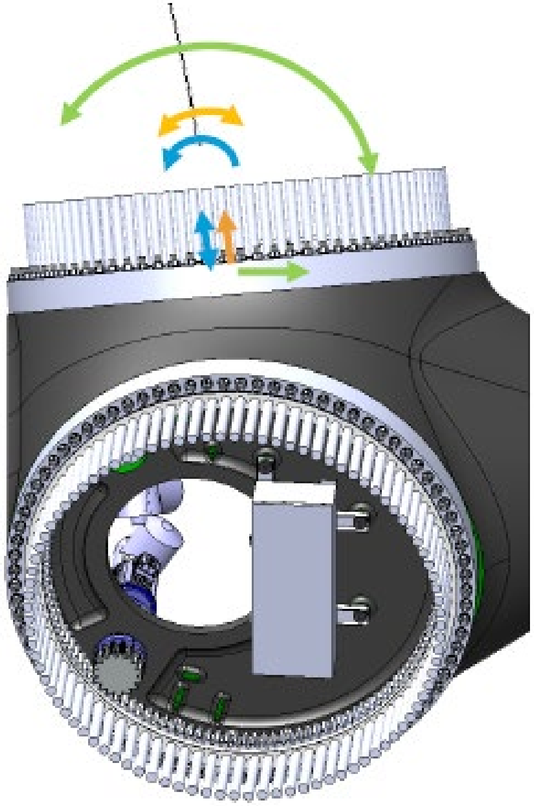
Rotor Hub

Loading on hub

---- Aerodynamic
---- Gravitational
---- Inertia





Source: [3]

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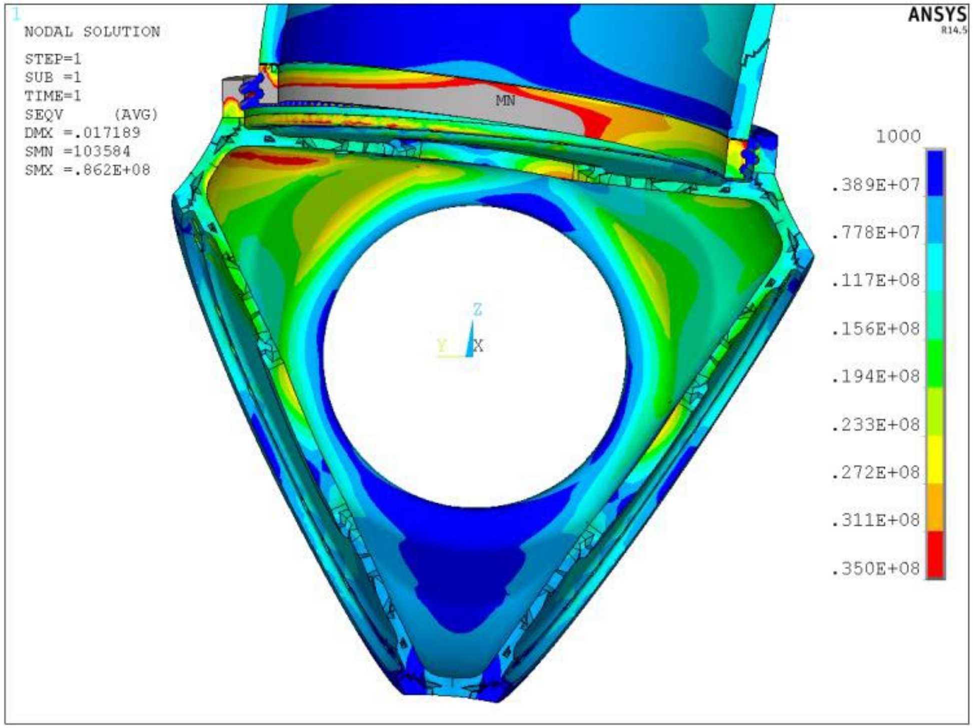
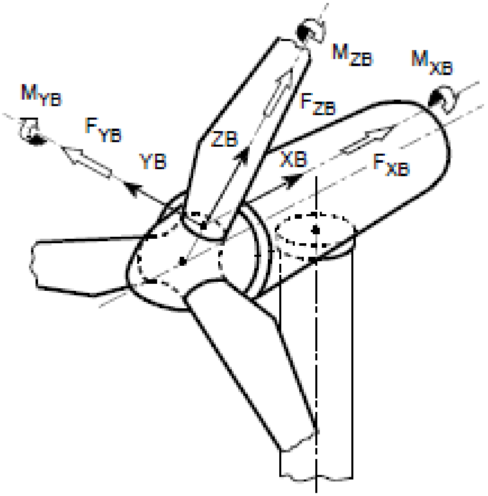
Rotor Hub

Sample results: Mx (unit load)



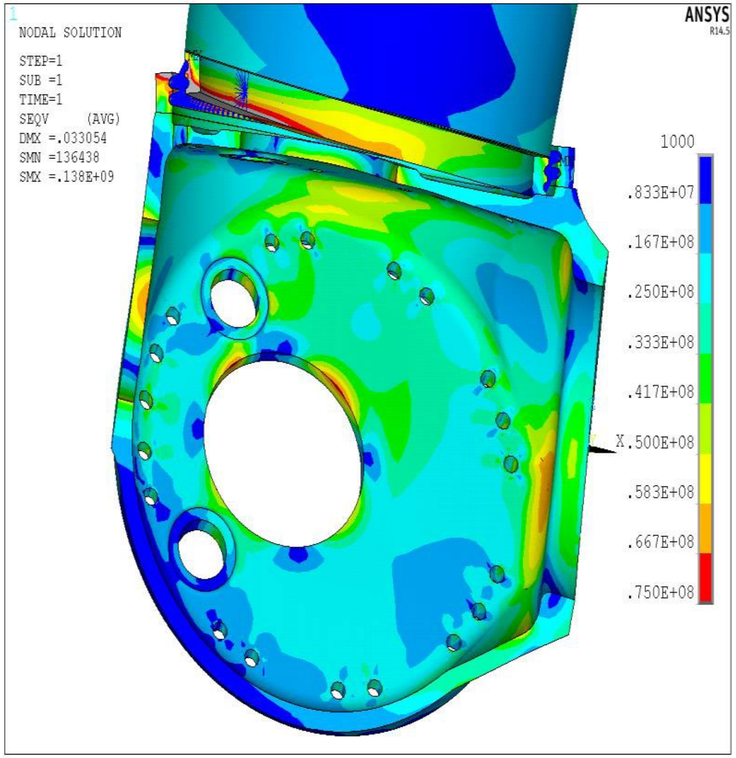


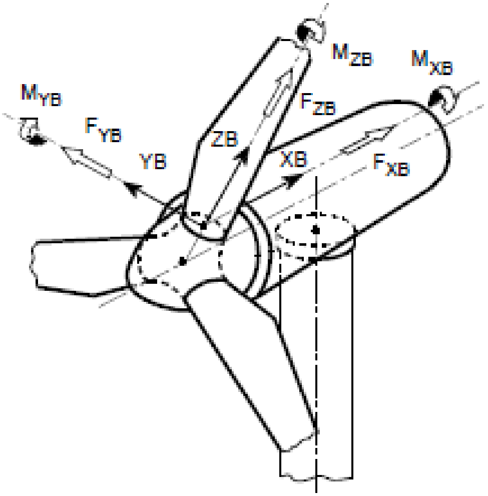
XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

Source: [3]

Rotor Hub

Sample results: My (unit load)





XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

Source: [3]

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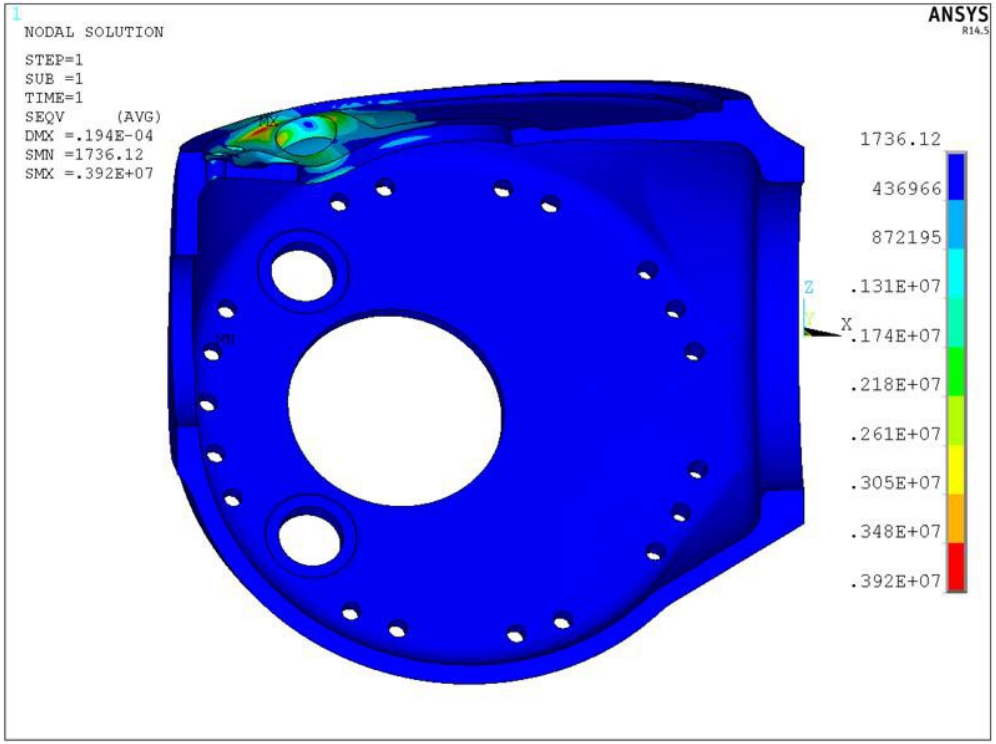
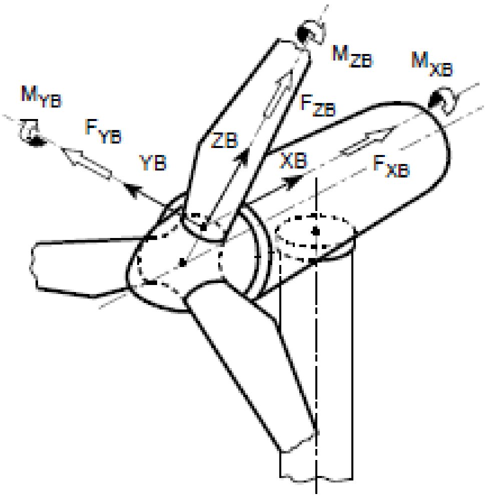
Rotor Hub

Sample results: Mz (unit load)





XB	in direction of the rotor axis
ZB	radially
YB	so that XB, YB, ZB rotate clockwise

Source: [3]

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Main Shaft

- is the low-speed shaft connecting the hub to the generator through the gearbox.
- is subjected to various types of static and fatigue loading. They should be all taken into consideration while designing the main shaft.
- supports the following components:
-     - Hub.
-     - Gearbox.
- the loading from these components should be taken into consideration as applied loads on the shaft.

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Main Shaft

Main shaft Designs:
- Forged main shaft (solid and hollow)
- Casted main shaft (hollow)

Source: [3]

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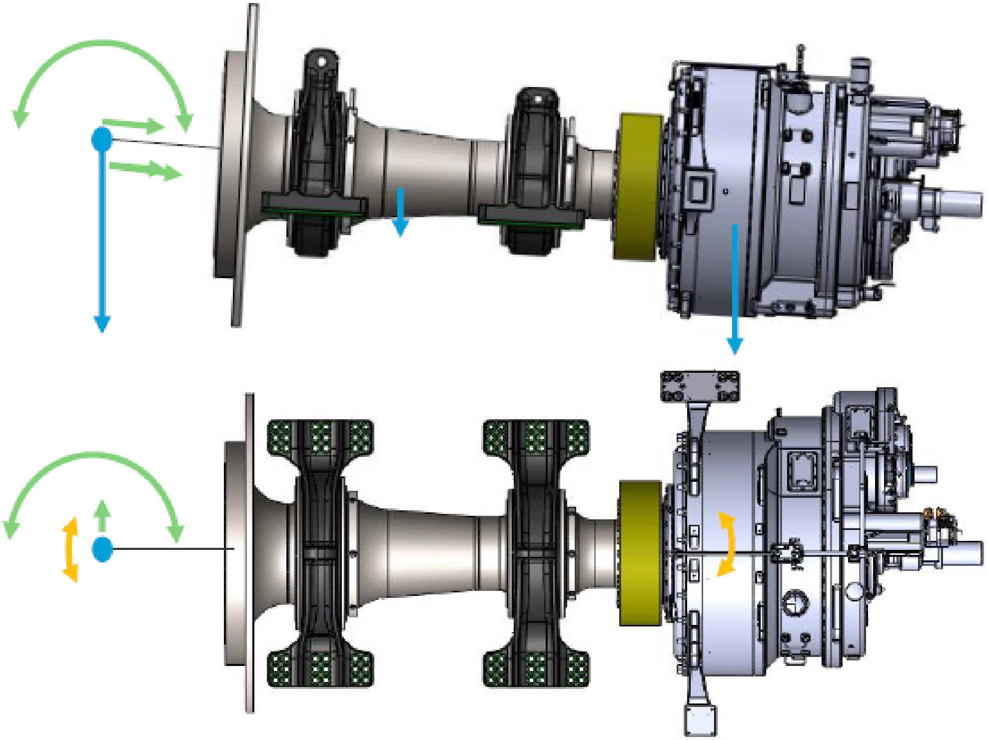
Main Shaft

- Example of loading types on main shaft

---- Aerodynamic

---- Gravitational

---- Inertia



Source: [3]

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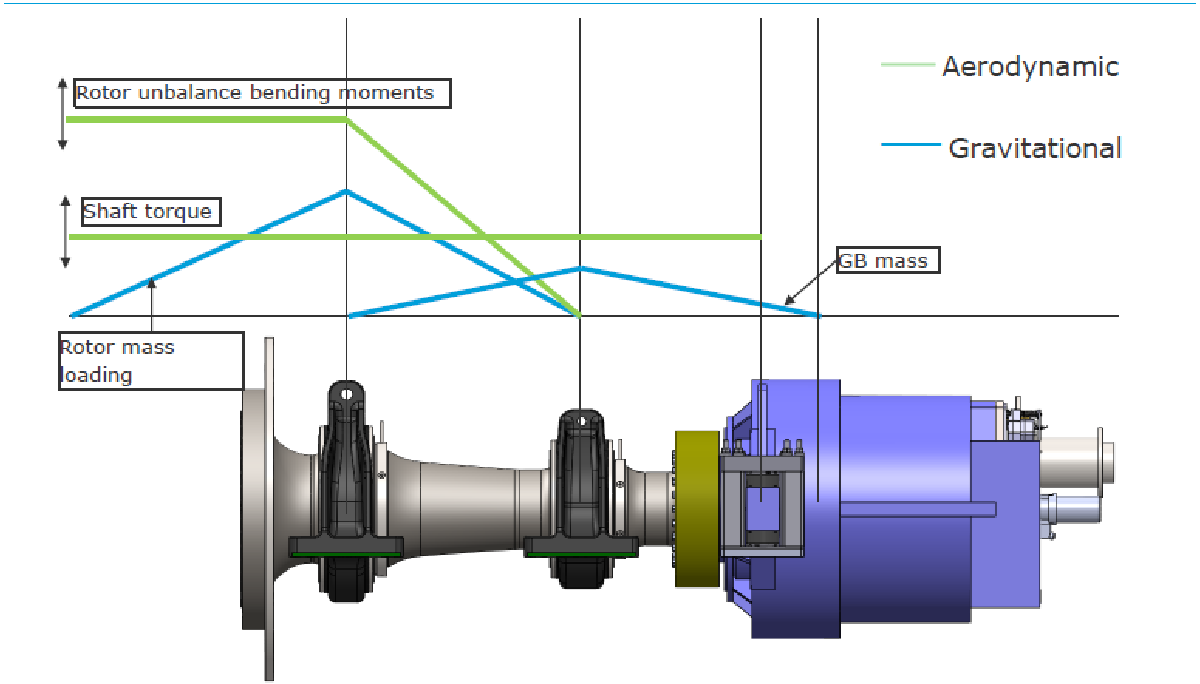
Main Shaft

Example of loading distribution along the main shaft



Source: [3]

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Main Shaft

- The main shaft analysis should be conducted carefully and including all factors in order to have a reliable, accurate design.

- The main source of failure in main shaft is fatigue failure, therefore stress concentration geometries should be eliminated as much possible to avoid crack initiation and propagation from such zones.

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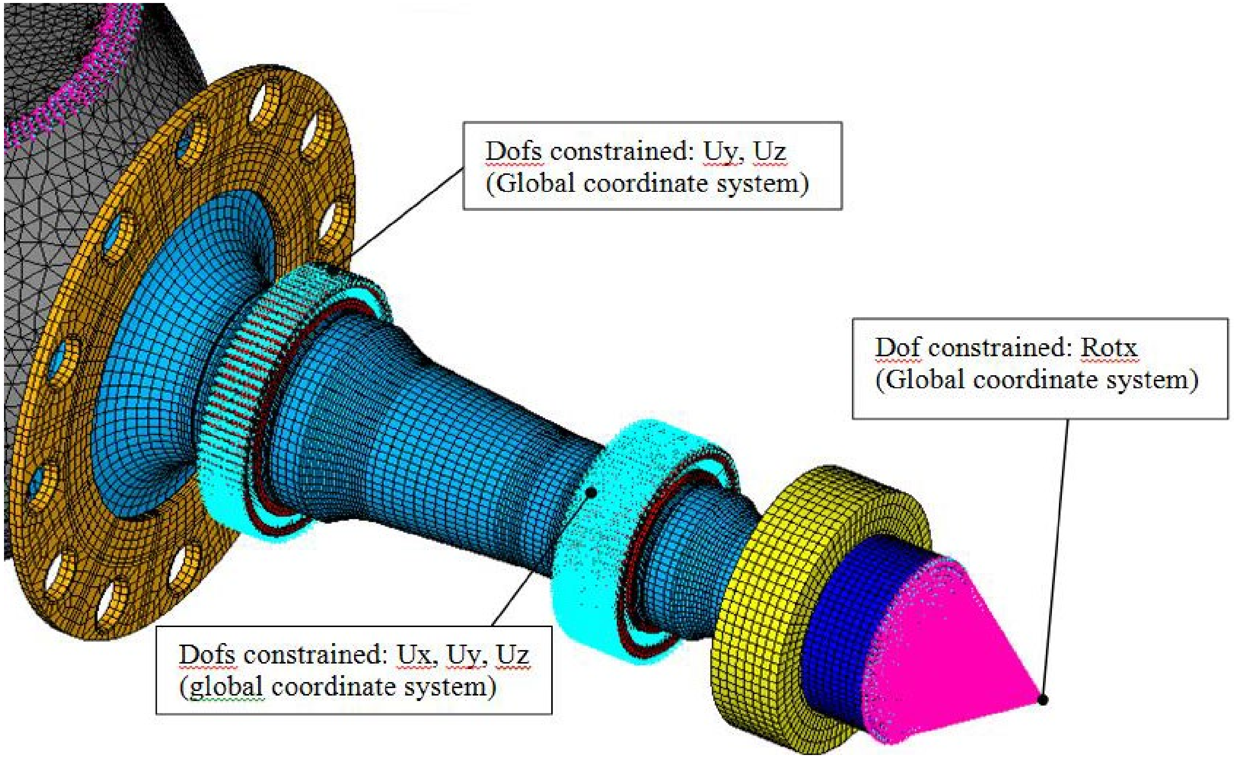
Main Shaft

Example of FE analysis of main shaft



Dofs constrained: Uy, Uz
(Global coordinate system)

Dof constrained: Rotx
(Global coordinate system)

Dofs constrained: Ux, Uy, Uz
(global coordinate system)

Source: [3]

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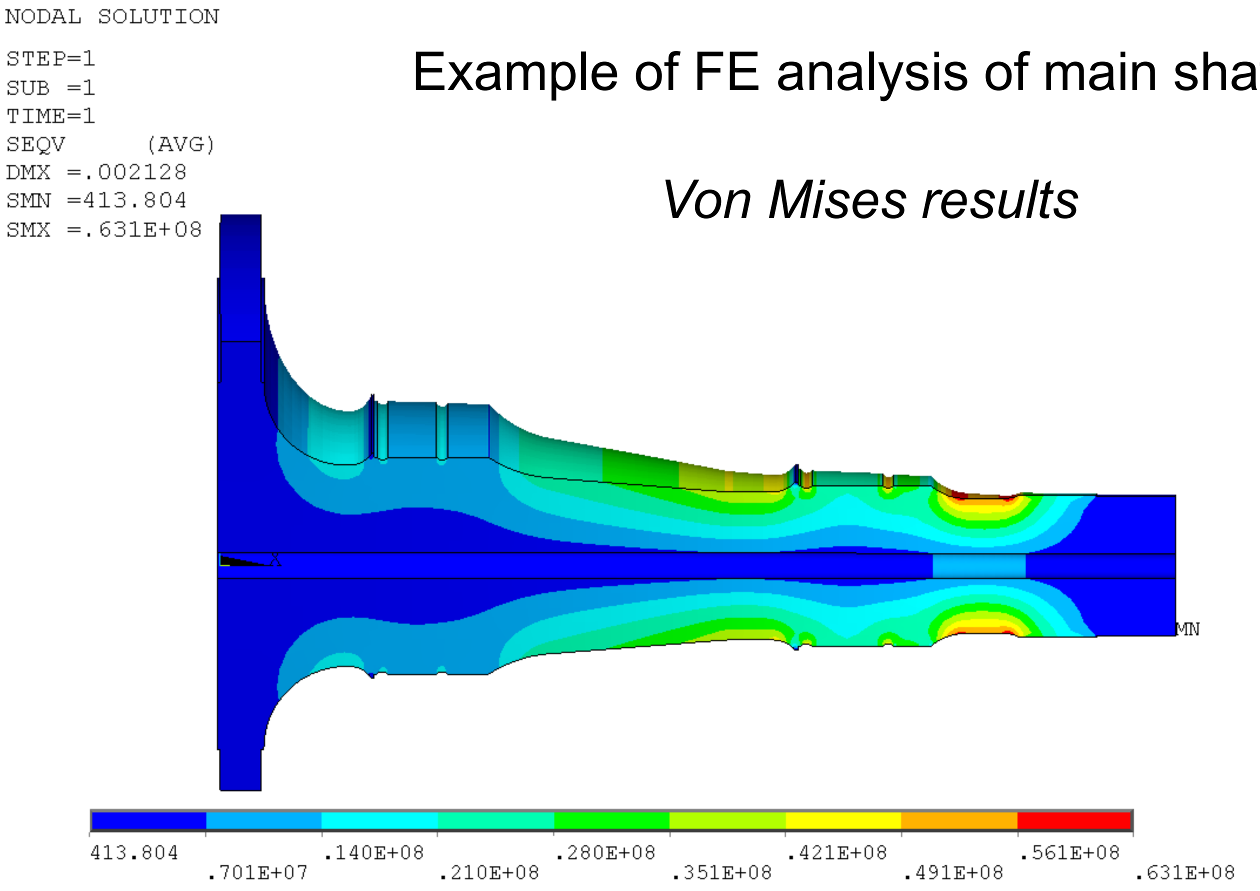
Main Shaft

Example of FE analysis of main shaft

Von Mises results



Source: [3]

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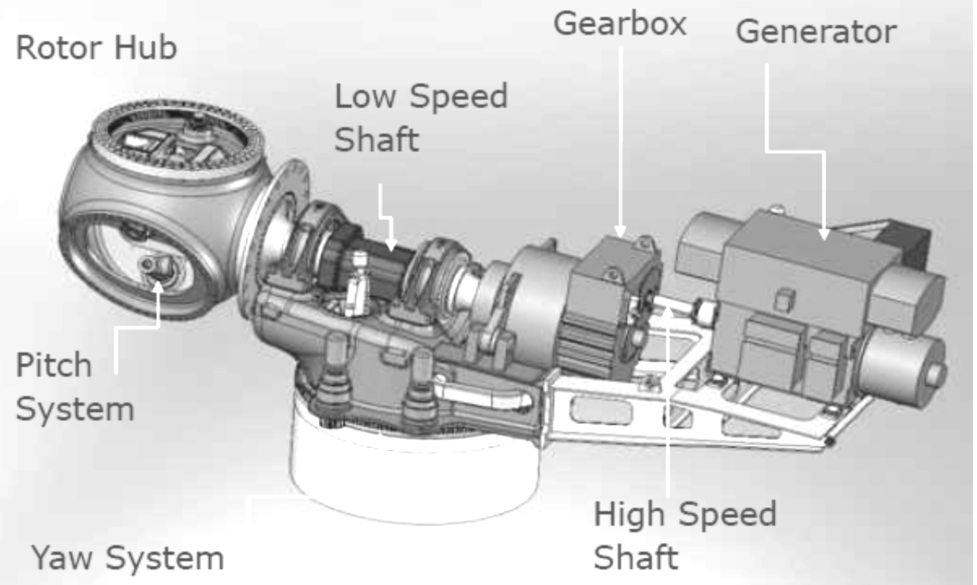
Gears and Gearbox

- Gears are elements used in transferring torque from one shaft to another while controlling the torque (or speed) ratio.
- There are several applications for gears in wind turbines:
  - Drive train gearbox (most prominent application)
  - Yaw drives
  - Pitch linkages



Source: [3]

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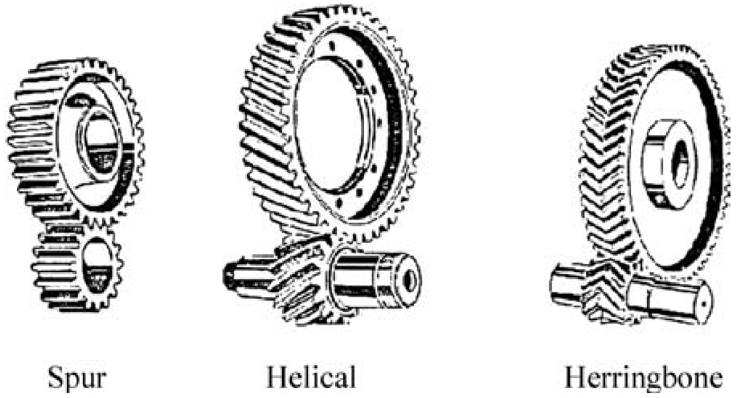
Gears and Gearbox

- Common types of gears:
  - Spur gears.
  - Helical gears.
  - Worm gears.
  - Internal gears.
- Spur gears have teeth whose axes are parallel to the rotational axis of the gear.
- Helical gears teeth are inclined at an angle relative to the gear’s rotational axis.
- Worm gears have helical teeth, and transfer of torque between shafts at right angles to each other.
- An internal gear has teeth on the inside of an annulus.



Source: [3]

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Gears and Gearbox

- Gears may be made from a wide variety of materials, but the most common material in wind turbine gears is steel.
- High strength and surface hardness in steel gear teeth is often obtained by carburizing or other forms of heat treating.
- Gears may be grouped together in gear trains.

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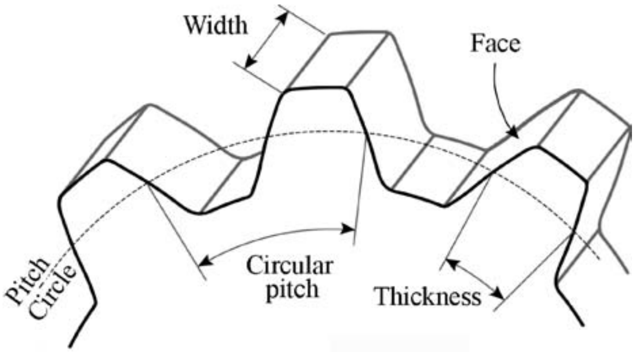
Gears and Gearbox

- Gears have special geometry and nomenclature.
- The pitch circle is the circumference of a virtual circle at which both gears are rolling tangent to each other without sliding motion at the point of contact. The diameter of the pitch circle is known as the pitch diameter, *d.*
- The face of the tooth is the location that meets the corresponding face of the mating gear tooth. The width of the face, *b*, is the dimension parallel to the gear's axis of rotation.
- The circular pitch, *p*, of the gear is the distance from one face on one tooth to the face on the same side of the next tooth around the pitch circle.

$$p = \frac{\pi d}{N}$$

where *N* is the number of teeth.



Source: [3]

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Gears and Gearbox

- Speed Relations
  Two meshing gears, with pitch diameters d1 and d2, and rotational speed n1 and n2 respectively, have the following speed ratio:

$$\frac{n_1}{n_2} = \frac{d_2}{d_1} = \frac{T_2}{T_1} \; .$$

where *T1* and *T2* are the torque values at teach gear.

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Gears and Gearbox

- The bending stress on a gear tooth of width b and height h can be calculated by application of the bending equation for a cantilevered beam:

$$\sigma_b = \frac{6M}{bh^2}$$

- The moment, M, is based on a load Fb applied at a distance L to the weakest point on the tooth. The result is:

$$\sigma_b = \frac{F_b}{y\,p\,b}$$

where y is the Lewis factor $y = h^2/6pL$

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Gears and Gearbox

- Gearbox are essential in Nacelle to connect the main shaft to the generator.
- Generator speed is often 1800 rpm in 60 Hz grids or 1500 rpm in 50 Hz grids.
- Assuming a wind turbine rotor have a rotational speed of 60 rpm then the speed-up ratio for the gearbox should be 30 : 1 to operate a 1800 rpm generator.
- Seperate partially integrated or fully integrated gearbox is therefore required in most of wind turbine designs.

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Gears and Gearbox

- Gearbox types used in Nacelle are either parallel-shaft gearboxes or planetary gearboxes.

- Parallel-shaft gearboxes:

- gears are carried on parallel shafts.
- have mainly two shafts: low-speed and a high-speed.
- have a limit to the size ratio of the two gears that can be used in a single-stage parallel-shaft gearbox, thus gearboxes with large speed-up ratios use multiple shafts and gears.

- Planetary gearboxes:

- input and output shafts are coaxial.
- have multiple pairs of gear teeth meshing all the time, thus loads on each gear are reduced.
- are relatively light and compact.

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Gears and Gearbox

- Gearbox design and selection should take into account the following considerations:
  - Parallel-shaft or planetary gearbox
  - Separate gearbox or integrated gearbox
  - Speed-up ratio and number of stages
  - Weight and cost of the gearbox
  - Loads applied on the gearbox
  - Lubrication and effects of intermittent operation
  - Reliability

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Summary of the provided knowledge

- Introduced components of nacelle in wind turbines
- Design considerations of the components of nacelles
  - Rotor hub
  - Main shaft
  - Gears and gearbox

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References

[1] Wind Turbines: Fundamentals, Technologies, Application, Economics/ Erich Hau, 3rd Ed, Springer (2006).

[2] Wind energy explained : theory, design, and application / James Manwell, Jon McGowan, Anthony Rogers, 2nd Ed. (2009).

[3] Training materials notes for WESET training in Denmark, February 2019.

[4] www.ewea.org European Wind Energy Association

[5] www.wwindea.org World Wind Energy Association

[6] www.awea.org American Wind Energy Association

[7] www.nrea.gov.eg/test/en/Home New and Renewable Energy Authority

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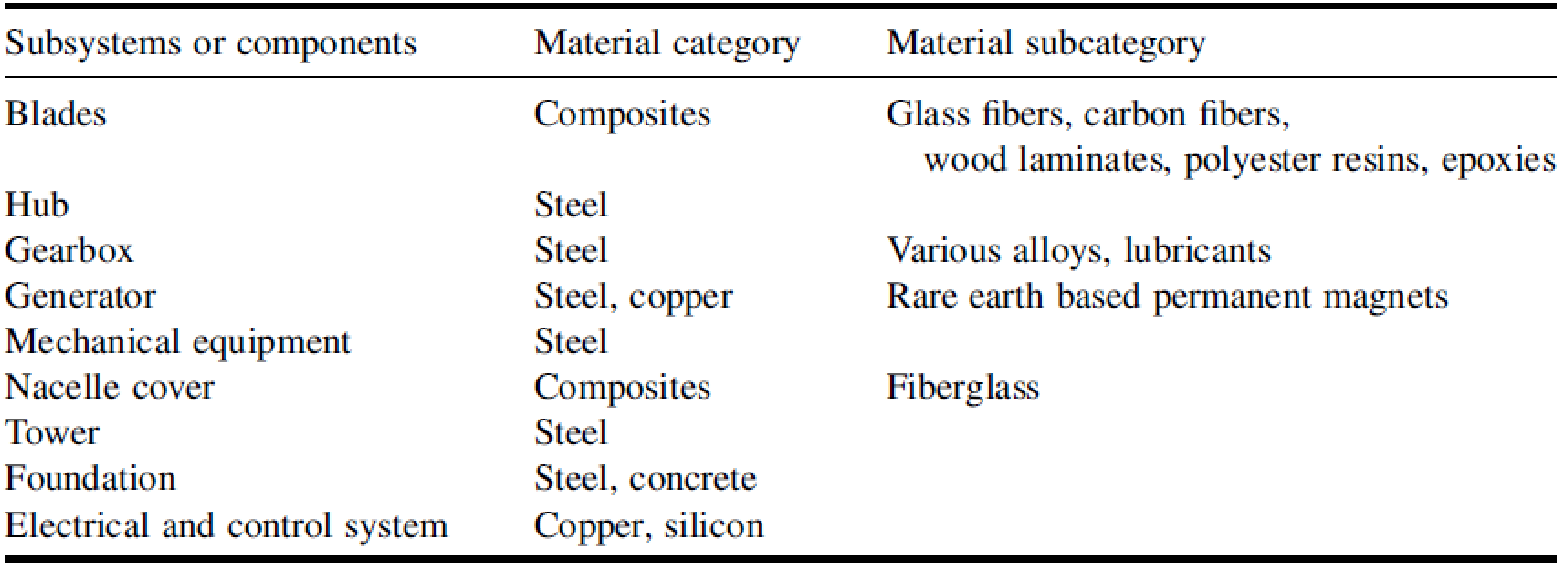
Appendix – Material for Wind Turbine



Subsystems or components	Material category	Material subcategory
Blades	Composites	Glass fibers, carbon fibers, wood laminates, polyester resins, epoxies
Hub	Steel	
Gearbox	Steel	Various alloys, lubricants
Generator	Steel, copper	Rare earth based permanent magnets
Mechanical equipment	Steel	
Nacelle cover	Composites	Fiberglass
Tower	Steel	
Foundation	Steel, concrete	
Electrical and control system	Copper, silicon	

Source: [2 and 3]

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Q&A

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Component loading and design: Tower

Lecture 4.1

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Learning outcomes

The main objective of the lesson is understanding the mechanical design of wind turbine towers, making the students able to:

O1. Understand the different structures of wind turbine towers and basement and how they work

O2. Become familiar with the different designs of each structure

O3. Be able to design or select proper structure for wind turbine tower

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Technical Contents

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Tower Definition

- Wind turbine tower is the lower and tallest part in the wind turbine.

  It has the following main functions (Sources 1, and 2):

  - Rotor and nacelle fixation and positioning on the designed height
  - Support of loads from the rotor and nacelle to the foundation
  - Electrical power and control cable connections path from/to the plant
  - Human access from base to the nacelle

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Tower Types

Structure:

Truss tower:

- Simple
- With space frame

Steel tower:

- Tubular
- Multi-sided

Concrete tower:

- Full concrete
- Hybrid

Source: [3]

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Tower Types

Wind turbine towers length are trending to taller designs to meet the following requirements:

- Lower wind speed class sites are more spread around the world which requires higher towers for better turbine efficiency
- Larger rotors requiring taller towers
- Forest sites require taller tower for tree line height

Consequently, challenges for tower design are higher and the hybrid (concrete + steel) or multisided steel towers are the most suitable design for such requirements.

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Tower Foundations

- On-shore towers:
  - Gravity Spread foundation with steel insert
  - Gravity Spread foundation with anchor studs
  - Gravity Spread foundation with piles underneath

Source [3]

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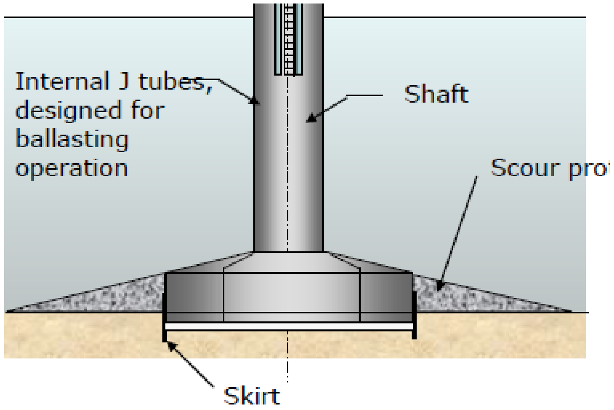
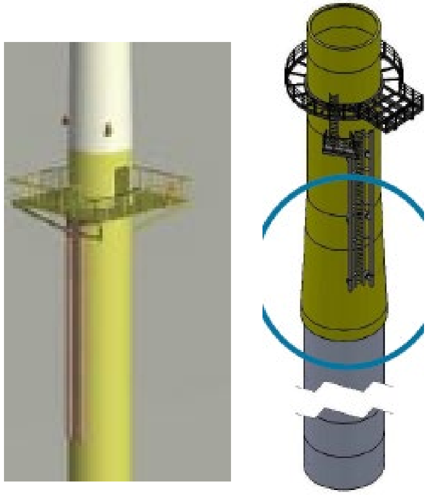
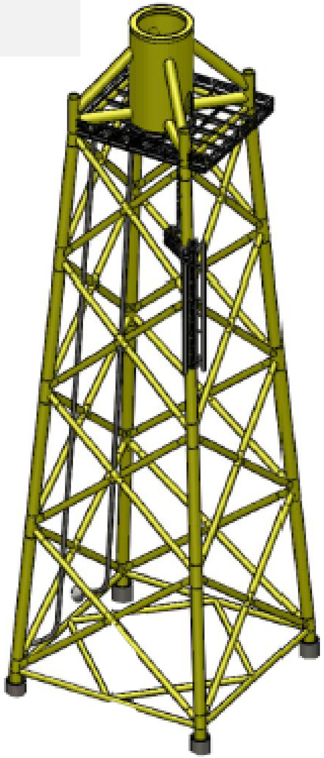
Tower Foundations

- Off-shore towers:
  - Monopile structures (MP)
  - Gravity base structures (GBS)
  - Jacket structures







Source [3]

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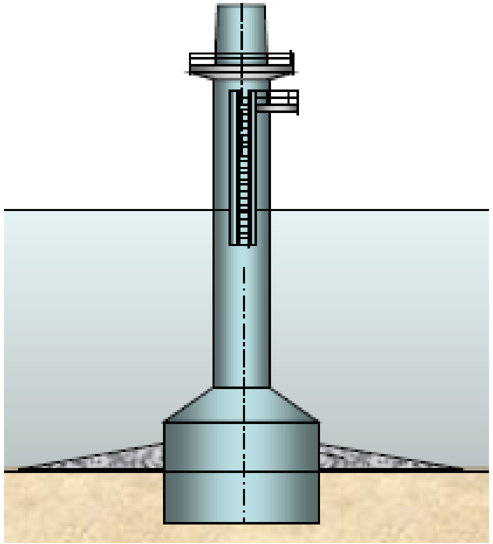
Tower Foundations

- Off-shore towers (cont’d):
  - Suction bucket
  - Floating foundations
  - Pile cap foundations



Source [3]

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Tower Foundations

- Factors affecting selection of foundation type:
  - Water depth
  - Soil and bed conditions
  - Environmental loading
  - Construction methodology
  - Availability/capacity of installation vessels
  - Cost

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Tower Design Calculations and Stress Analysis

- According to codes, the following checks should be done:
  - Tower shell segments: yield check – buckling – fracture toughness - lamellar tearing
  - Tower welds: fatigue damage
  - Top flange weld: yield check – fatigue damage
  - Door frame weld: yield check – fatigue damage
  - Flange connection: ultimate strength
  - Bolts: fatigue damage
  - Tower (general): Vortex induced vibrations

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Tower Design Calculations and Stress Analysis

- Main design parameters:
  - Maximum loads and fatigue loads
  - Hub Height
  - Maximum section length and mass
  - Tower top diameter fixed by Yaw bearing
  - Foundation type / stiffness and tower base diameter
  - Transport limits base T-flange diameter - maximum can diameter
  - Rotor passing Frequency (1P and multiples)

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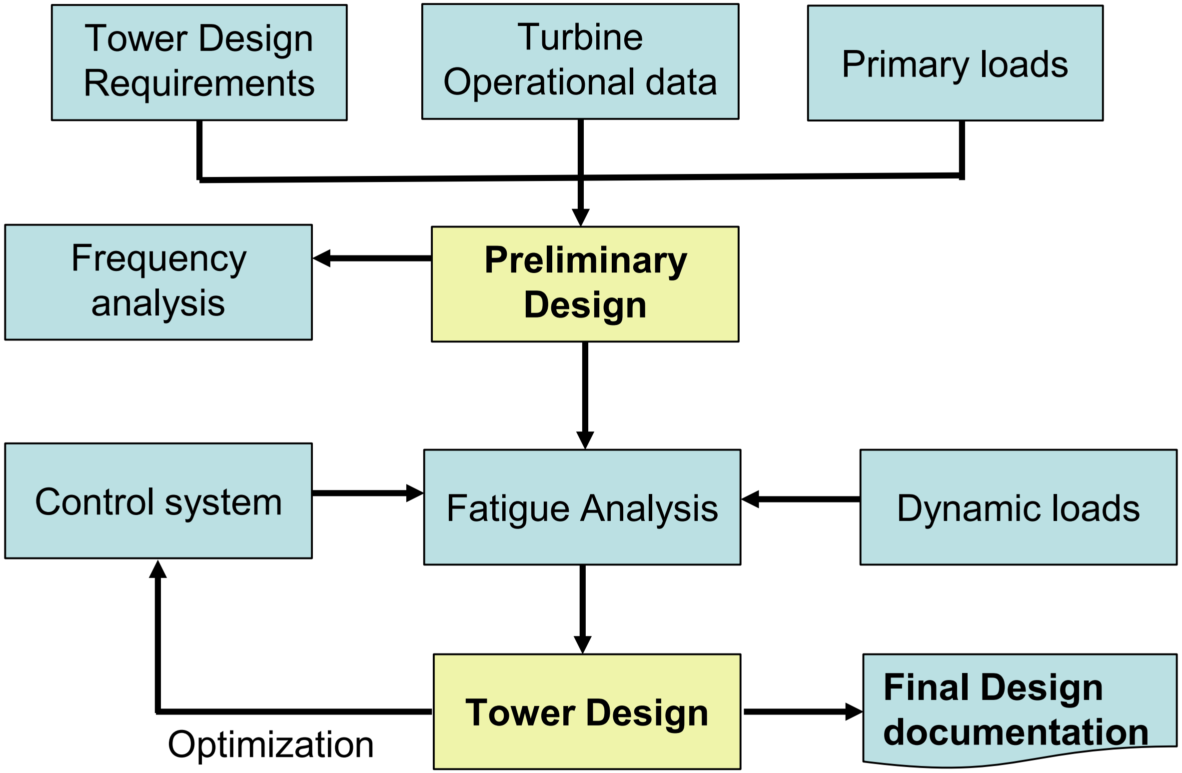
Tower Design Process



Source [3]

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Tower Design Calculations
Main Moments Loadings

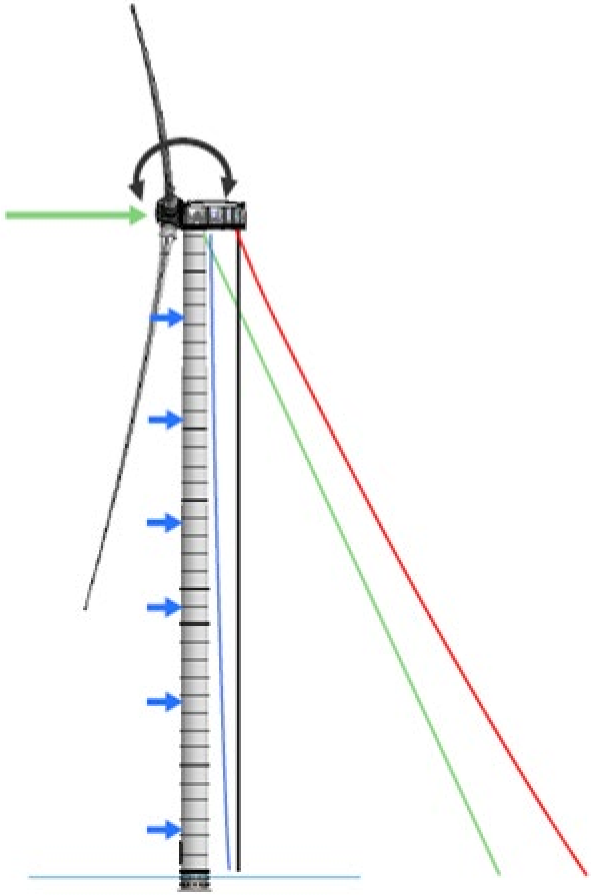
Main Moments loading on tower

----- *Moment from tower top*

----- *Moment from Thrust force*

----- *Wind loading on tower*

----- *Summation of moments*



Source [3]

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Tower Design Calculations and Stress Analysis

- While performing tower shell segment fatigue analysis, the following features should be checked against fatigue failure:
  - Tower circumferential butt welds
  - Internal bracket attachment welds
  - Locations of stress concentration

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Tower Design Calculations and Stress Analysis

Tower shell segment fatigue analysis

Two types of fatigue analysis are performed:

1. Nominal stress method

   For all weld locations for which Nominal stress can be calculated using standard membrane stress theory formulas; Examples: Can to can weld, Can to Flange, Internal attachments like brackets, studs.

2. Geometric (hotspot) stress method

   For all weld locations for which stress level needs to be determined with the aid of Finite Element Analysis. Examples: Tower door and Tower top Flange.

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Tower Design Calculations and Stress Analysis

Nominal stress method

The “nominal stress” can be defined as the stress in the parent material or in a weld adjacent to a potential crack location calculated in accordance with elastic theory excluding all stress concentration effects.

There are 2 techniques proposed to apply the nominal stress method

- Damage Equivalent Loads (DEL)
- Load Time History series (LTH)

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Tower Design Calculations and Stress Analysis

- Damage Equivalent Loads (DEL)

$$DEL = \left(\frac{\sum n_i S_i^m}{n_{ref}}\right)^{\frac{1}{m}}$$

Where:

n_{ref} is the reference number of cycles,

m is the S-N slope $m = 4$ is used for steel material

N_{ref} = Txf is the reference number of cycles which is commonly set at 1e7

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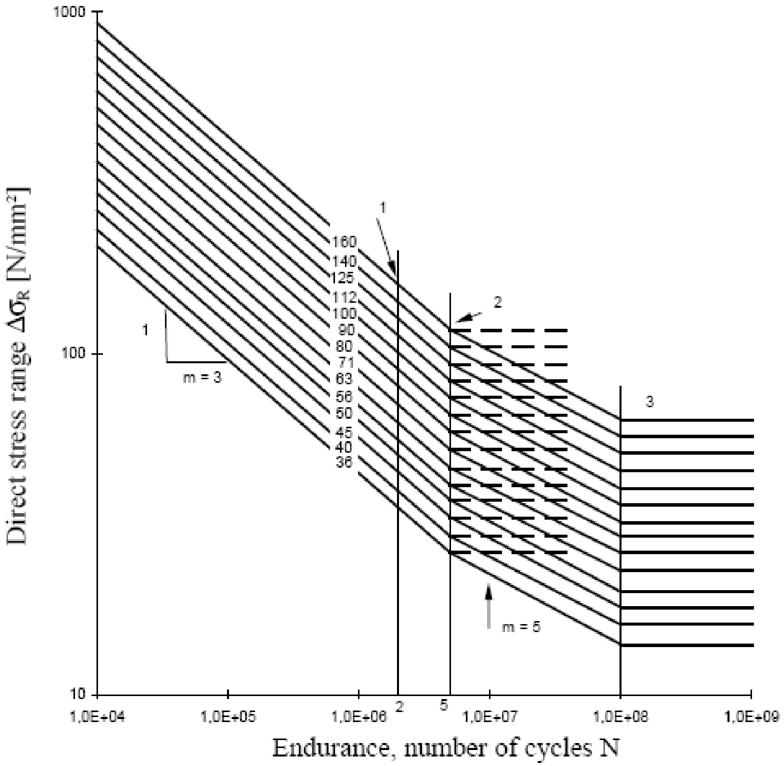
Tower Design Calculations and Stress Analysis

- SN curves from Eurocode EN1993-1-9 by the Detail



1 Detail category $\Delta\sigma_C$

2 Constant amplitude fatigue limit $\Delta\sigma_D$

3 Cut-off limit $\Delta\sigma_L$

Source [3]

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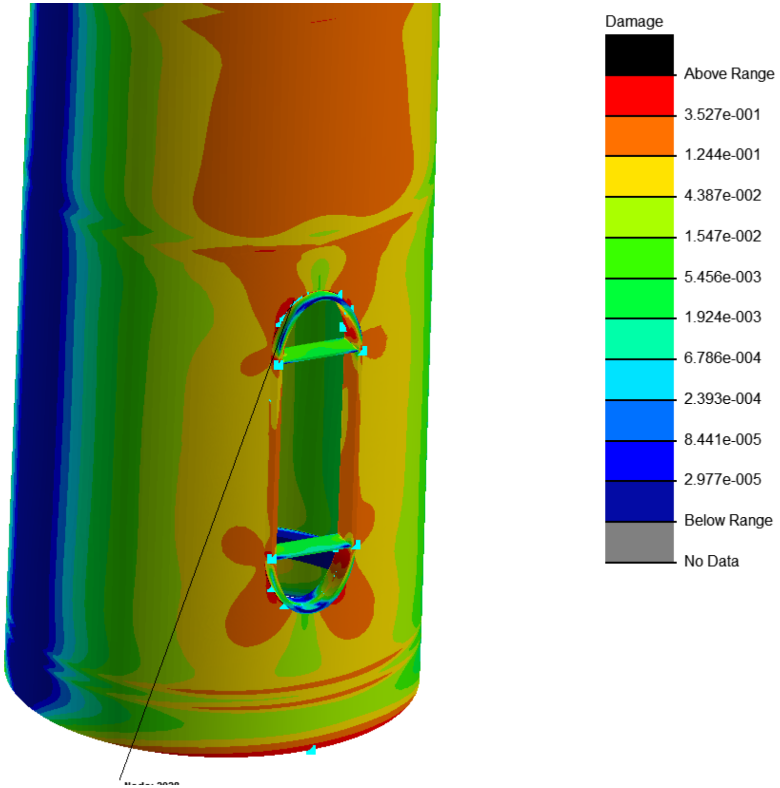
Tower Design Calculations and Stress Analysis

Geometric (hotspot) stress method

Used for all zones at which stress level needs to be determined with the aid of Finite Element Analysis (FEA).



Source [3]

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Tower Design Calculations
Top Flange Analysis

In top flange analysis, the following aspects need to be considered:

- Non-linear yaw bearing behavior;
- Pre-loaded bolted connections (opening possible);
- Mainframe stiffness (distribution over bearing);
- Tower and local part other stiffness's.

The most suitable technique for accurate strength analysis for the flange is FEA.

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Tower Design Calculations
Top Flange Analysis

While doing FEA for tower top flange, the following geometrical features should be carefully considered: Main frame - Bearing layout - Yaw bearing - Tower top – Bolts and preload.

Geometrical simplification should be done (when possible) to reduce unnecessary computational resources:

- Remove unnecessary bosses, holes, welded attachments and similar features, if they do not directly affect stress concentrations in the tower top.
- Coarse mesh for mainframe as only required for stiffness with higher refinement of mesh around tower top flange neck and weld
- Analysis of bolted connection and tower top welds can be done in the same model.

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Tower Design Calculations
Fracture Toughness

Brittle fracture presents a sudden failure mechanism and is therefore not permitted (i.e. ductile plastic failure is required because this provides additional post yield strength)

Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present.

For towers, Fracture toughness of a material is dependent on following:

- Material grade
- Temperature during operation
- Material plate thickness

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Tower Design Calculations
Natural Frequencies

According to simplified calculations, considering the tower as simple cantilever, the resonance (natural) frequency *f* can be calculated as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M}} = \frac{1}{2\pi}\sqrt{\frac{3EI}{ML^3}} = \frac{1}{2\pi}\sqrt{\frac{3E\,\frac{\pi}{64}(Do^4 - Di^4)}{MH^3}}$$

where ***M*** is the total mass, ***H*** is the tower height, *Do* and *Di* are the outer and inner diameters at the tower base respectively.

It should be noted that the above calculations give approximate values as it has some assumptions during derivation.

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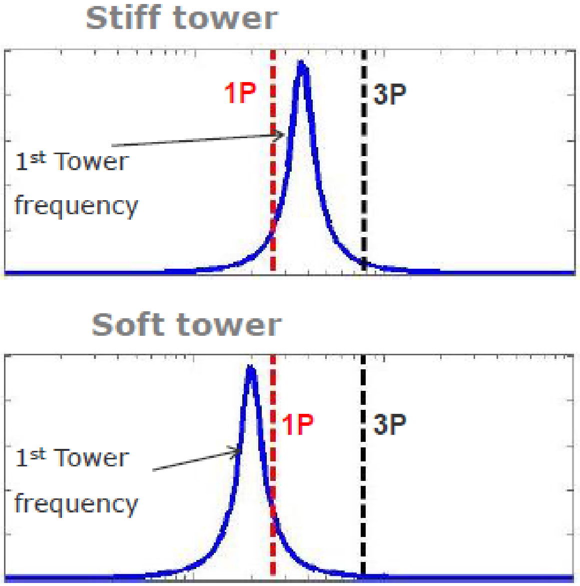
Tower Design Calculations Natural Frequencies

It can be concluded that the natural frequency is affected by the following parameters:

- Tower Height → main factor
- Tower base diameter
- The Total mass

It can be concluded also that stiffer towers have higher natural frequencies. Therefore, less stiff towers can reduce both the natural frequency and the cost

→ favorable in industry



Significant cost reduction (less steel) but suitable control design needed to avoid resonance

Source [3]

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Tower Design Calculations
Natural Frequencies

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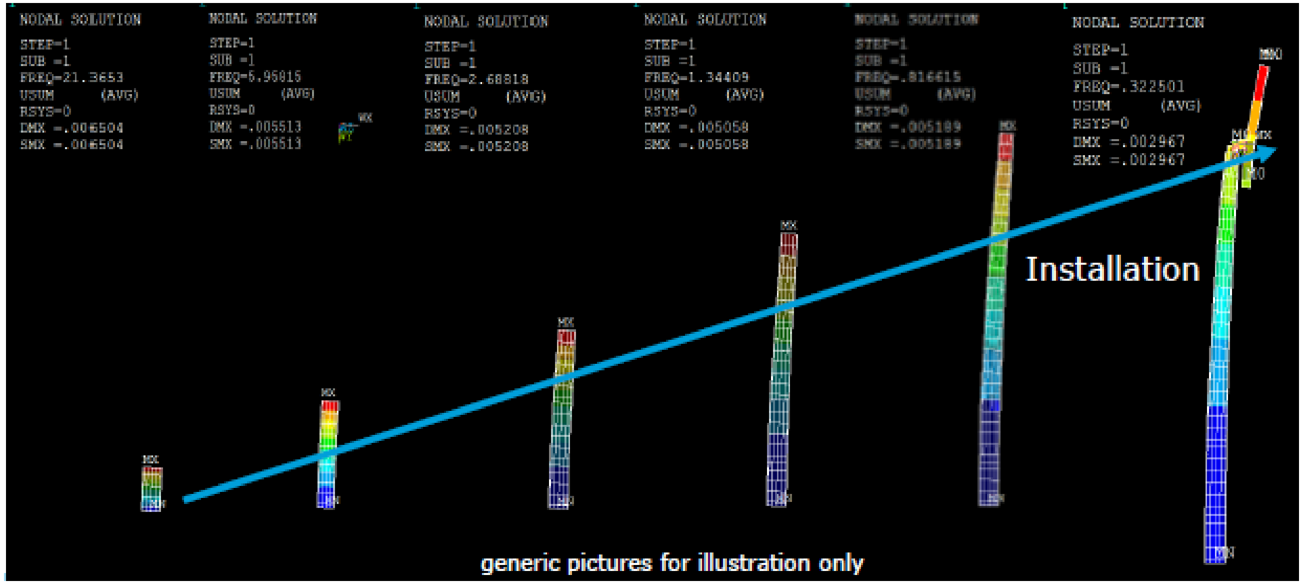
Vortex induced transvers vibration analysis should be checked for each assembly stage. Critical results should be considered for implementation of VIV mitigation methods to reduce the effect of such vibrations.



```
NODAL SOLUTION

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SMX =.006504
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```

generic pictures for illustration only

Source [3]

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Summary of the provided knowledge

- Detailed the structures of wind turbine towers and basement
- Operational principles of the towers
- Design methods of each structure of towers
- Stress analysis

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References

[1] Wind Turbines: Fundamentals, Technologies, Application, Economics/ Erich Hau, 3rd Ed, Springer (2006).

[2] Wind energy explained : theory, design, and application / James Manwell, Jon McGowan, Anthony Rogers, 2nd Ed. (2009).

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[4] www.ewea.org European Wind Energy Association

[5] www.wwindea.org World Wind Energy Association

[6] www.awea.org American Wind Energy Association

[7] www.nrea.gov.eg/test/en/Home New and Renewable Energy Authority

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Brakes, Yawing/Pitching Mechanism and Generator

Lecture 4.2

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Learning outcomes

The main objective of the lesson is to acquire the necessary knowledge on HAWT components design, making the students able to :

O1. Understand the principles regarding HAWT components design

O2. Be familiar with different HAWT components such as brakes, yawing/pitching mechanism and generator

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Technical Contents

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Control Systems in Wind Turbines

- The purpose of the control system of a wind turbine is to manage the safe, automatic operation of the turbine

- This reduces operating costs, provides consistent dynamic response and improved product quality, and helps to ensure safety

- This operation is usually designed to maximize annual energy capture from the wind while minimizing turbine loads

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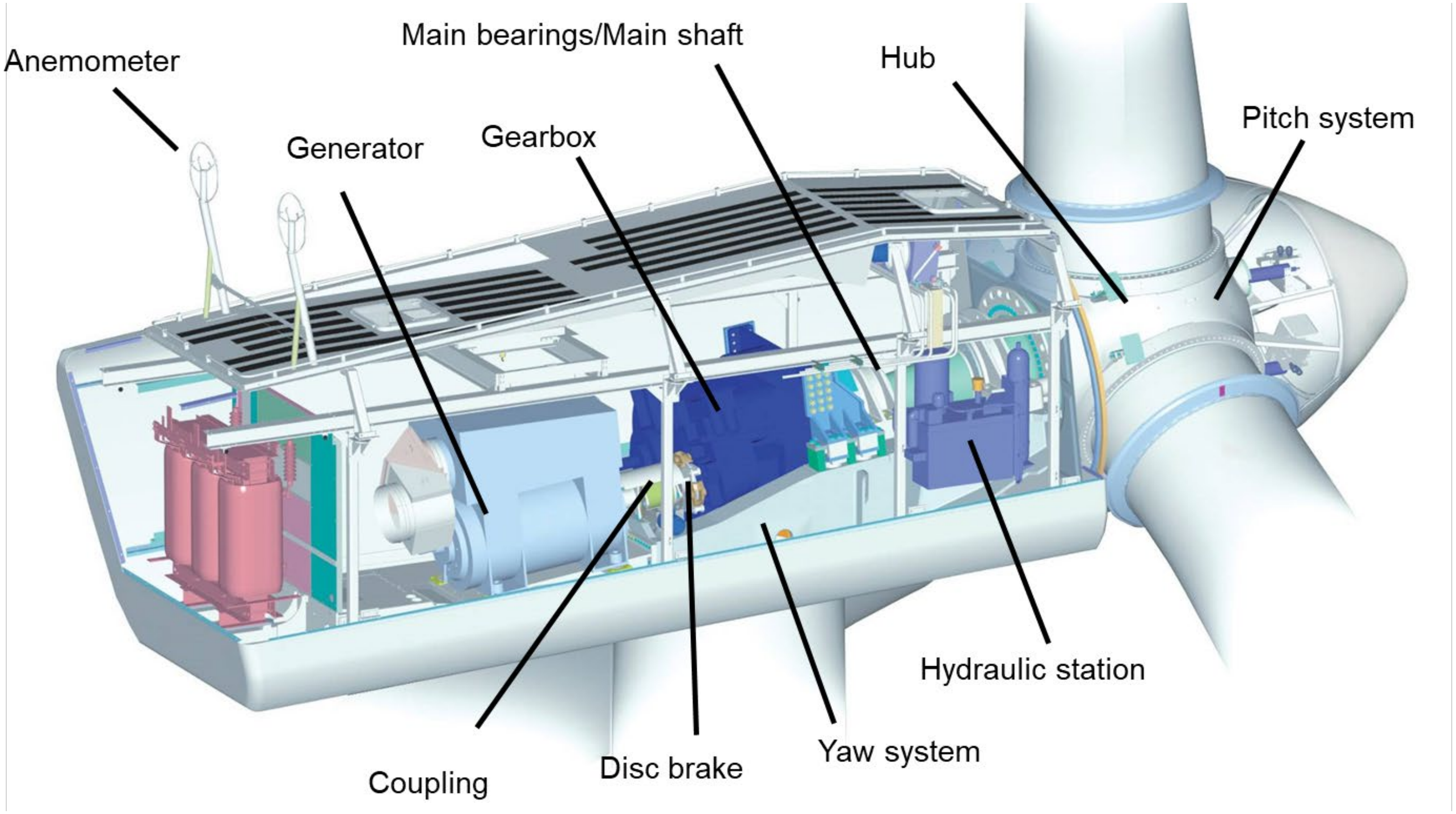
Main Components in the Nacelle



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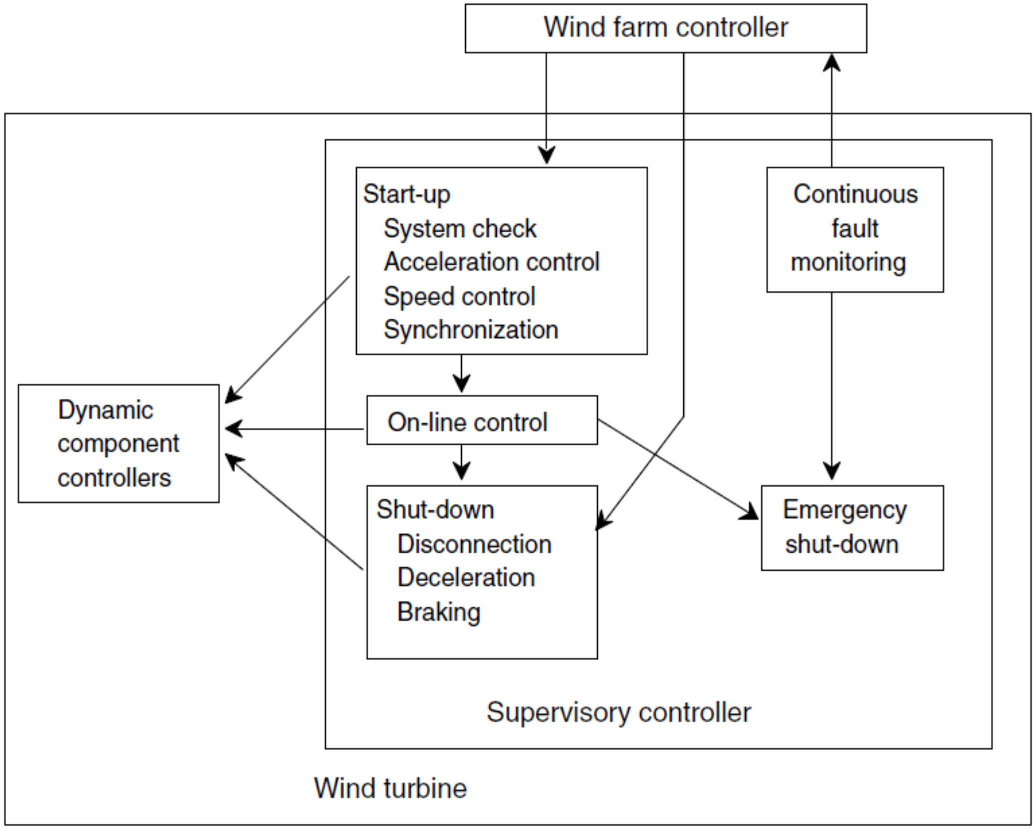
Source: [1,2]

Control System Architecture

- "Supervisory control" is on high level for turbine operating status
- "Dynamic control" is on low level (e.g. torque, pitch, power, etc)



Source: [1]

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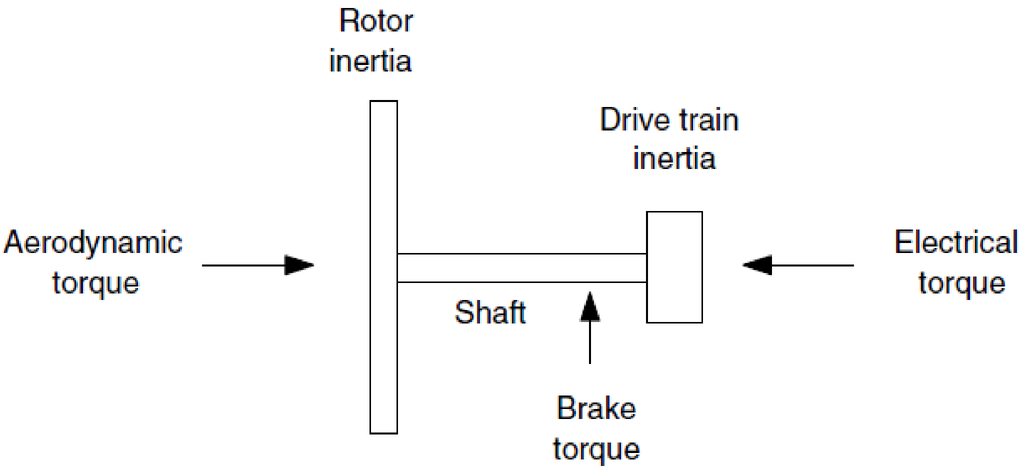
Basic Turbine Model

- A simplified horizontal axis wind turbine model is useful for understanding the integration of control systems into a modern wind turbine. A typical wind turbine can be modeled as a drive shaft with a large rotor inertia at one end and the drive train (including the generator) inertia at the other end. An aerodynamic torque acts on the rotor and an electrical torque acts on the generator. Somewhere on the shaft is a brake.
- The aerodynamic torque is the net torque from the wind, consisting of contributions related to the rotor tip speed ratio, blade geometry, wind speed, yaw error, and any added rotor drag.



Source: [1]

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Basic Turbine Model

- In a turbine designed to operate at nearly constant speed, the generator torque is a function of the fluctuating aerodynamic torque and drive train and generator dynamics. That is:

  Constant speed generator torque = f (aerodynamic torque; system dynamics)

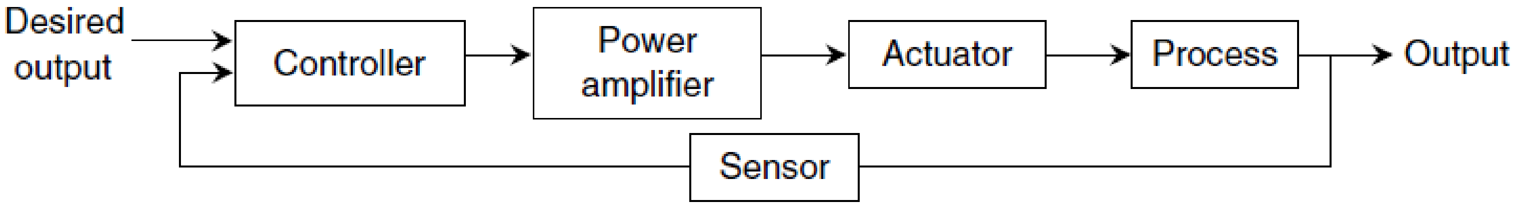
- The drive train and generator dynamics are determined by the design of the various components and are not controllable. Thus, the only method for controlling generator torque in a constant-speed wind turbine is by affecting the aerodynamic torque.

- In a variable-speed, pitch-regulated turbine, the generator torque can be varied independently of the aerodynamic torque and other system variables. That is:

  Variable-speed generator torque = f (generator torque control system)

Control System Components

- Control of mechanical and electrical processes requires five main functional components:
    1. A process that has a point or points that allow the process to be changed or influenced.
    2. Sensors or indicators to communicate the state of the process to the control system.
    3. A controller, consisting of hardware or software logic, to determine what control actions should be taken. Controllers may consist of computers, electrical circuits, or mechanical systems.
    4. Power amplifiers to provide power for the control action. Typically, power amplifiers are controlled by a low-power input that is used to control power from an external high-power source.
    5. Actuators or components for intervening in the process to change the operation of the system.



Source: [1]

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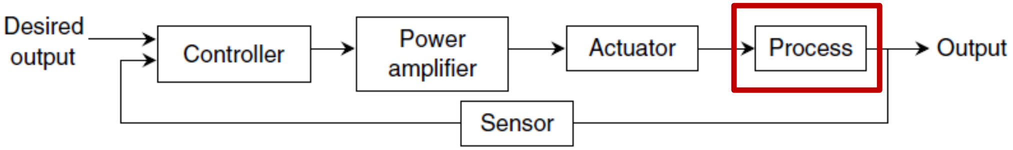
Controllable Processes in Wind Turbines

- Controllable wind turbine processes include, but are not limited to:
  - The development of aerodynamic torque.
  - The development of generator torque.
- The conversion of electrical current and fluid flow into motion. Yaw drives and pitch mechanisms often use the control of electrical current or the flow of hydraulic fluid to control valves and the direction and speed of mechanical motion.
- The conversion of electrical power from one form into another. Using power electronic converters, the voltage and power factor of the power from the turbine can be determined separately from that of the power from the generator.
- Overall conversion of wind energy into electrical power. The successful conversion of the kinetic energy in the wind into useful electrical energy requires the monitoring and sequencing of a number of subprocesses. These larger aspects of turbine operation are also subject to control system actions. These might include connecting the generator to the grid, turning on compressors and pumps, or opening valves.



Source: [1]

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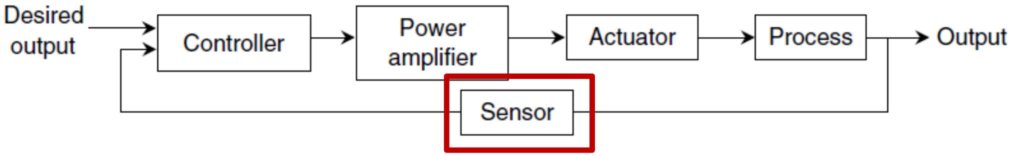
Wind Turbine Sensors

- On a large modern wind turbine, many sensors are used to communicate important aspects of turbine operation to the control system. These measured variables might include:
  - speeds (generator speed, rotor speed, wind speed, yaw rate, direction of rotation);
  - temperatures (gearbox oil, hydraulic oil, gearbox bearing, generator bearing, generator winding, ambient air, electronic temperatures);
  - position (blade pitch, teeter angle, aileron position, blade azimuth, yaw position, yaw error, tilt angle, wind direction);
  - electrical characteristics (grid power, current, power factor, voltage, grid frequency, ground faults, converter operation);
  - fluid flow parameters (hydraulic or pneumatic pressures, hydraulic oil level, hydraulic oil flow);
  - motion, stresses, and strain (tower top acceleration, tower strain, shaft torque, gearbox vibration, blade root bending moment);
  - environmental conditions (turbine or sensor icing, humidity, lightning).



Source: [1]

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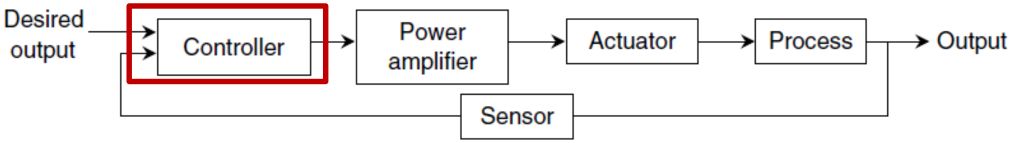
Wind Turbine Controllers

- Controllers provide the connection between the measurement of an aspect of turbine operation and actions to affect that turbine operation. Typical controllers in a wind turbine include:
  - Mechanical mechanisms. Mechanical mechanisms, including tail rotors, linkages, springs, fly ball governors, etc., can be used to control blade pitch, yaw position, and rotor speed.
  - Electrical circuits. Electrical circuits may provide a direct link from the output of a sensor to the desired control action. For example, sensor signals can be used to energize coils in relays or switches. Electrical circuits can also be designed to include a dynamic response to input signals from sensors in order to shape the total system dynamic operation.
  - Computers. Computers are often used for controllers. Computers can be configured to handle digital and analog inputs and outputs, and can be programmed to perform complicated logic and to provide dynamic responses to inputs. The ease with which control code, and thus control operation, can be changed by reprogramming the computer is a major advantage of computer control systems.



Source: [1]

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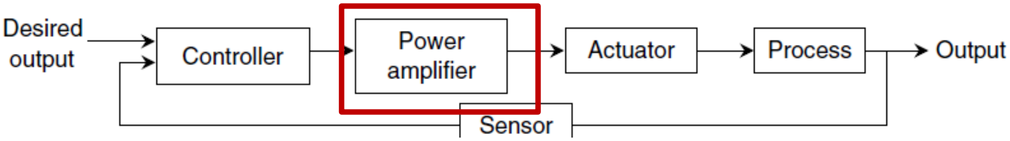
Power Amplifiers in Wind Turbines

When the control signal from the controller is not powerful enough to power the actuator, then an amplifier is needed between the controller and the actuator. Typical power amplifiers in a wind turbine include:

- Switches: a variety of switches can be controlled with a small amount of current or a small force, but which act as amplifiers in that they can switch high currents or high forces. These include relays, contactors, power electronic switches such as transistors and silicon-controlled rectifiers (SCRs), and hydraulic valves
- Electrical amplifiers: directly amplify a control voltage or current to a level that can drive an actuator are often used as power amplifiers in a control system
- Hydraulic pumps: provide high-pressure fluid that can be controlled with valves that require very little power



Source: [1]

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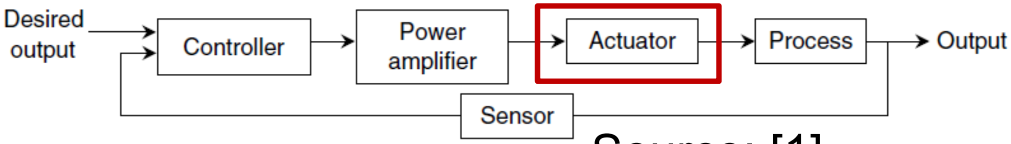
Wind Turbine Actuators

- Actuators in a wind turbine may include:
  - Electromechanical devices: include DC motors, stepper motors, AC motors with solid state controllers, linear actuators, magnets and solid state switching components
  - Hydraulic pistons: often used in positioning systems that need high power and speed
  - Resistance heaters and fans: used to control temperature
- Actuator systems may include gears, linkages, and other machine elements that modify the actuating force or direction.



Source: [1]

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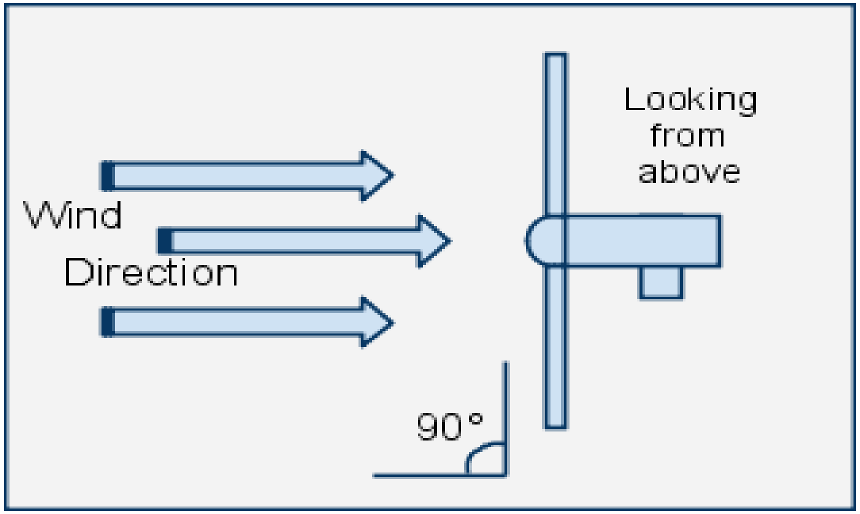
Yawing

What is it? Why is this mechanism needed?

- Wind constantly changes direction
- Conventional wind turbines are not omni-direction, so as wind changes, so must the direction the rotor faces to keep it in the wind
- Having the rotor at right-angles to the wind direction maximizes the energy captured by the rotor and therefore the energy output of the WTG
- Turning the rotor into the wind is called yawing
- A WTG is said to have yaw error if rotor is not perpendicular to the wind direction



Source: [1]

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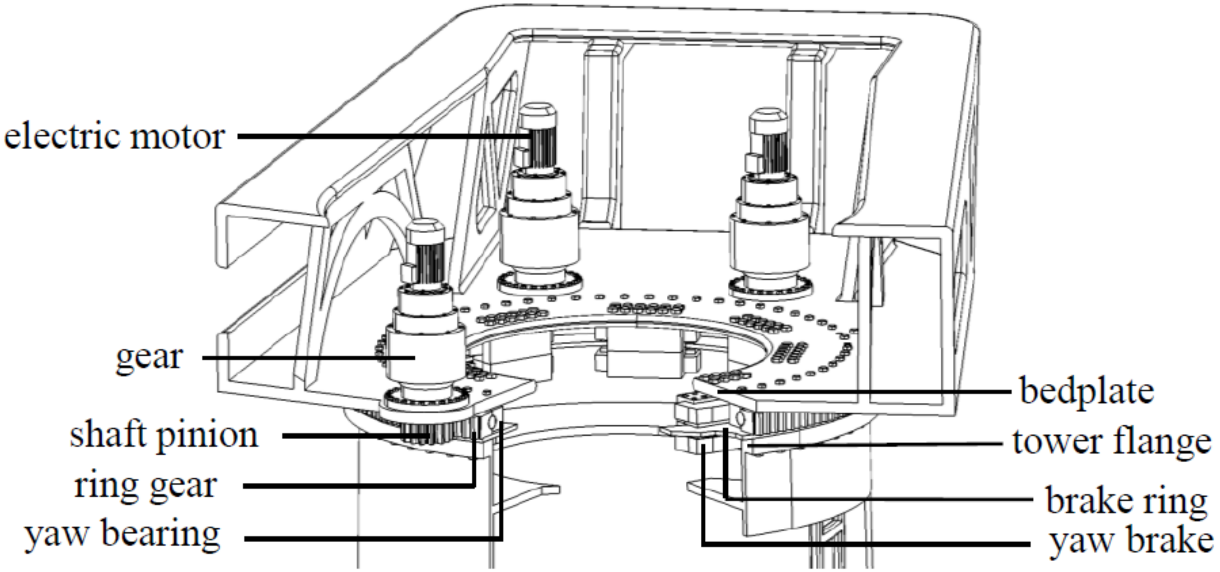
Example of a Yaw System

- This is an example of a yaw arrangement comprising multiple yaw drives, yaw brakes and a yaw bearing. The shown yaw drive consist of an electric motor, a reduction gear and a shaft pinion engaged with a ring gear on the yaw bearing. The yaw brakes apply a braking torque on the brake disc which is mounted between the tower flange and the yaw bearing.



Source: [1,2]

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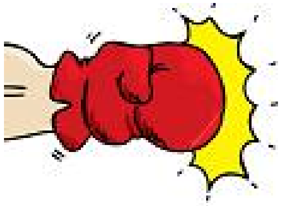
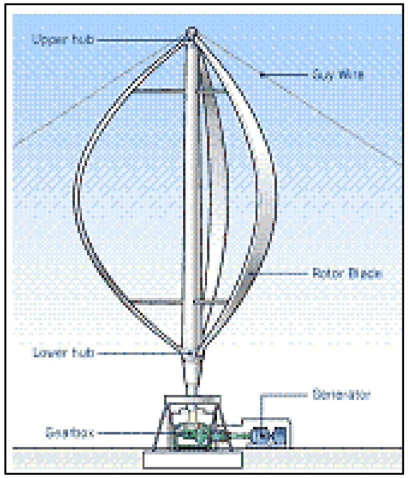
Yawing

Vertical Axis Wind Turbines (VAWTs)



vs

Horizontal Axis Wind Turbines (HAWTs)



- Omni-directional
- Always facing the wind
- No yaw mechanism

- Need to yaw as wind changes direction

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Source: [1]

HAWT yawing technique categories

or

- electronic or hydraulic motors move the nacelle to yaw the rotor into the wind

- wind used to rotate the nacelle and rotor into the wind

Perhaps sitting in the middle...

- wind used to power a mechanical yaw system

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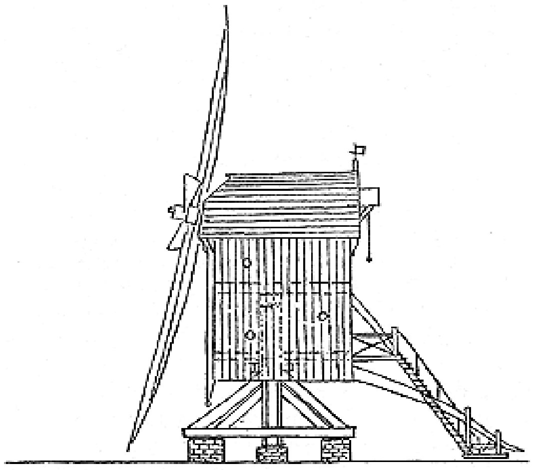
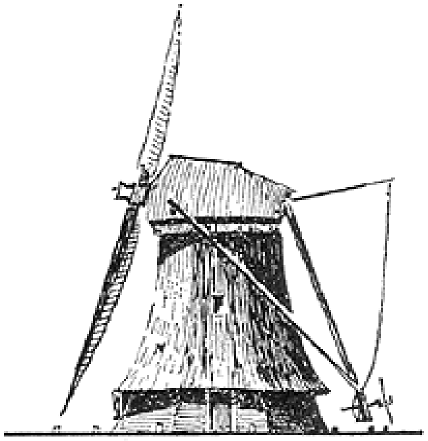
Yawing

- Pre 1745 Dutch windmills used "Miller yaw"... yaw powered by a miller who monitored the wind all day and turned the mill around to face the wind with a tail pole, crank or capstan wheel. This was a laborious task.



Post mill



Tower mill

Source: [1]

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Yawing

- Much to the embarrassment of millwrights everywhere, it took a blacksmith to invent the Fantail (or rosette) in 1745.

Source: [1]

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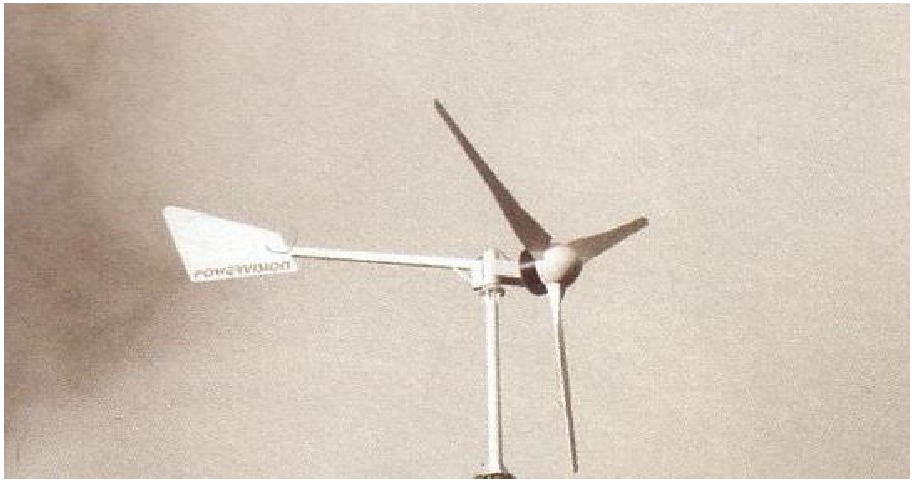
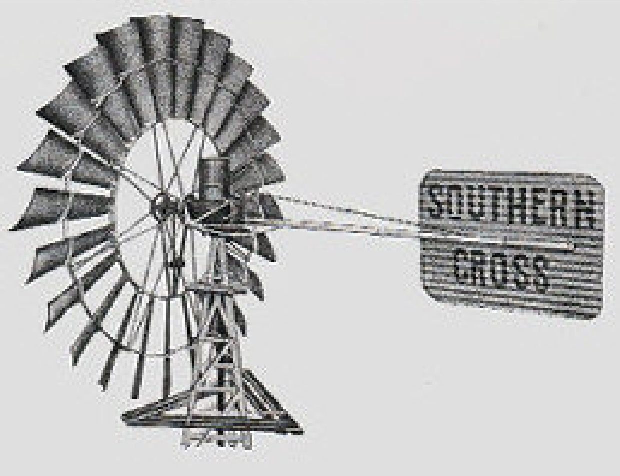
Yawing

- WTGs (and wind pumps) up to 10 m diameter may be yawed into the wind in a passive way using Tail Vanes.
- They are deceptively simple, often requiring engineering to get them just right.





Source: [1]

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Yawing Summary

- WTGs need to be yawed into the wind as it changes direction to capture the most energy
- VAWTs are omni-directional so no yaw mechanism required
- HAWT yaw mechanisms
    - Miller driven capstan wheels as seen on 18th C. Dutch windmills
    - Fantails on Dutch windmills and a small number of other windmills
    - Tail vanes on household sized WTGs (up to 10m diam), wind pumps
    - Coning on downwind turbines
    - Yaw drives on medium to large sized WTGs
        - controller polls wind vane many times a second
        - yaw brakes and permanent friction brakes to protect gears
        - cable twist counter and pull switch
- Yaw damper sometimes used to reduce the rate of yaw in turbulent winds (turbulent or gusty winds can make a turbine yaw unwieldy which cuts performance)

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Furling

What is it? Why is a mechanism needed?

- Furling is turning the rotor out of the wind
- Decreasing frontal area of the rotor intercepting the wind
- It is needed for
  - over-speed protection (turbine operating outside its safe range)
  - maintenance shut down
  - protecting WTG components in strong winds
  - reducing the cost of tower and rotor (robustness costs $)
  - reducing wear and tear, only operating in winds feasible to capture
  - managing power output as wind speed increases

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Furling

Low rotor speed and robust construction

- small wind turbines <= 1 m diam.
- yacht and marine WTGs, designed to survive harsh environments with very strong construction
- no furling mechanism except a hole in tail vane for manual furl with a pole hook used when maintaining or when not in use.

Marlec Rutland (above)
Ampair (left)

Source: [1,2]

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Furling

Halladay Rosette / umbrella mill (water pump)

- when unfurled it looks like a typical water pump windmill
- in high winds, automatically opens segmented rotor into a hollow cylinder letting wind pass through
- each segment consisted of several blades mounted on a shaft allowing segment to swing into/out of wind
- flip action balanced by adjustable counterweights

Source: [1]

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Furling

Horizontal Furling

- hinge between tail vane and rotor allowed rotor to furl towards the tail, thus decreasing frontal area capturing wind
- rotor disk takes shape of a narrower and narrower ellipse as it reduces the area exposed to wind
- offsetting the axis of rotor slightly from axis of yaw allows self-furl in high winds, or (adjustable) spring tension or counterweights are used to set furl speed. Some use gravity (weight of tail) rather than springs to return.
- many small, household sized WTGs use this technique

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Source: [1]

Furling

Vertical Furling

- tip the rotor out of the wind like a helicopter, and as wind subsides rock back towards horizontal
- springs or counterweights to control furl speed
- gusty winds can cause it to rock back and forth jarring blades and main shaft so dampening is required (rubber pad, shock absorber)
- alternatively, rotor + nacelle + tail vane all tip up, however can cause rapid yawing around the tower

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Source: [1]

Furling

Variable geometry H-rotor (VAWT)

- to avoid overspeed, reefing mechanism incorporated in the machine's design, thus allowing the blades to be feathered in high winds ("variable geometry")
- straight blades of the H-rotor are hinged so that they tilt towards the horizontal at higher speeds, reducing swept area

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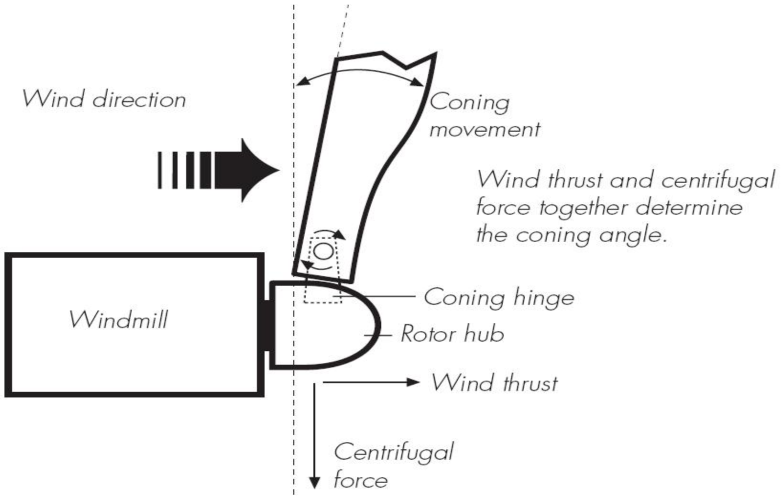
Source: [1,2]

Furling

Coning

- allowing blades to increasingly cone downwind of tower
- also involves changing blade pitch
- Musgrove's variable-geometry H-rotor (vertical axis) has blades hinged to crossarm, tensioned with springs. In high winds, blades approach horizontal, thus reducing swept area.
- sometimes under certain tip speed ratios it may cause the turbine to run upwind



Polypropylene blades with flexible hinge on a downwind turbine.

Source: [1,2]

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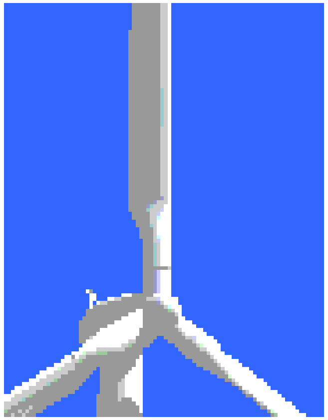
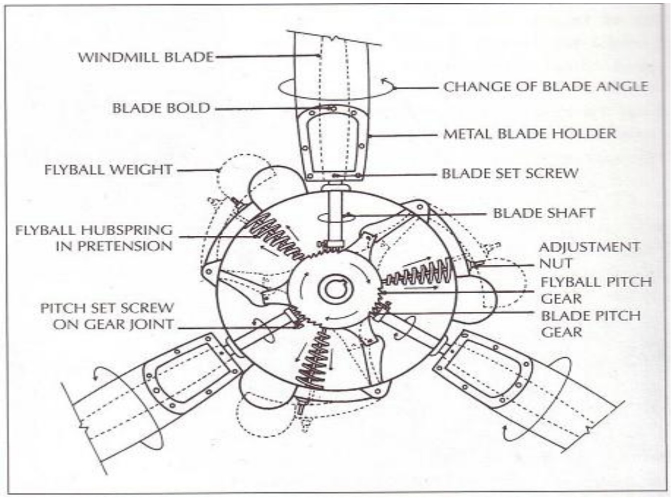
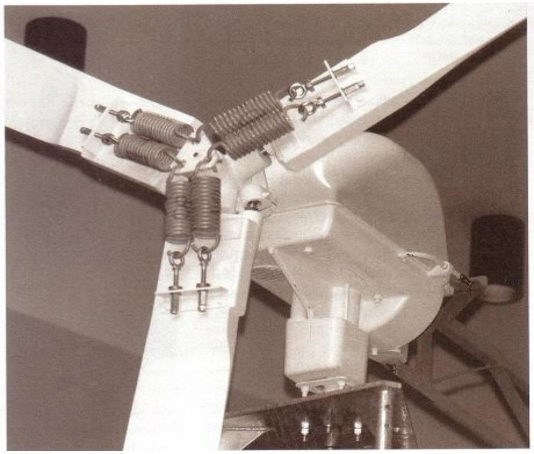
Furling

Blade pitch (also used for power regulation)

- controlling the amount of lift the blade produces influences rotor speed
- by feathering (turning towards parallel to wind direction, 90° pitch)
- 1930s flyball/Watt governor for passive pitching, weights would feather all three blades at high wind speeds
- blade-actuated governor uses weight of blades as they slide out along blade shaft away from the hub, to simultaneously feather blades, with springs
- modern wind turbines with pitch control use hydraulics







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Source: [1,2]

Furling

Aerodynamic Stall

- passive stall - blade aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind. Passive stall avoids moving parts in rotor but it is requires complex aerodynamic design
- active stall (1 MW and up) - very much like pitch controlled WTGs except as it reaches cutout speed, machine pitches blades in opposite direction to pitch control (feather) - rather it makes the blades go into deeper stall to waste excess energy. Operated using hydraulics or electric stepper motors.

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Furling Summary

- Furling is taking rotor out of wind for overspeed protection or to stop rotor during servicing
- Low rotor speed and rugged construction used on yachts
- Horizontal furling (tail vane) and vertical furling (helicopter)
- Halladay's Umbrella mill opened into a hollow cylinder
- Coning used for downwind HAWTs and Musgrove's VAWT
- Blade design for static stall at cut-out speed
- Variable blade pitch (and stall) usually requires active components and complicated control to manage lift and drag as WTG reaches cut-out speed
- Mechanical brakes used in combination with aerodynamic (pitch or stall) mechanisms on high or low speed shaft in nacelle

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Pitch Mechanism

- The pitch mechanism in large wind turbines enables the rotation of the blades on their longitudinal axis. It can change the angle of attack of the blades with respect to the wind, by which the aerodynamic characteristics of the blade can be adjusted.
- This provides a degree of control over the captured power to improve conversion efficiency or to protect the turbine.
- When the wind speed is at or below its rated value, the angle of attack of the blades is kept at an optimal value, at which the turbine can capture the maximum power available from the wind.

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Pitch Mechanism

- When the wind speed exceeds the rated value, the pitch mechanism is activated to regulate and limit the output power, thus keeping the power output within the designed capability.
- For this purpose, a pitch range of around 20 to 25 degrees is usually sufficient.
- When the wind speed increases further and reaches the limit of the turbine, the blades are completely pitched out of the wind (fully pitched or feathering), and no power will be captured by the blades. The wind turbine is then shut down and protected.

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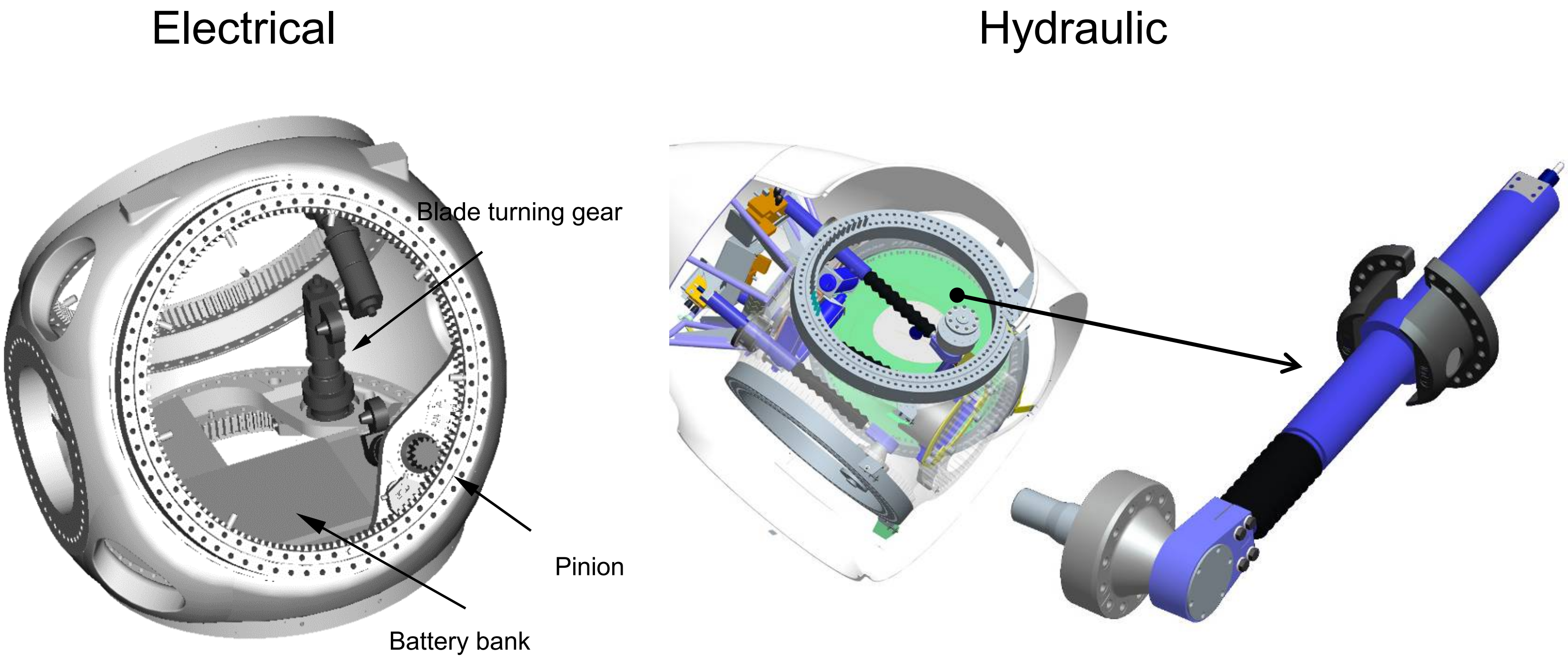
Pitch Mechanism

- The pitch mechanism can be either hydraulic or electric. Electric pitch actuators are more common nowadays since they are simpler and require less maintenance.
- Traditionally, all blades on the rotor hub are pitched simultaneously by one pitch mechanism. Modern wind turbines are often designed to pitch each blade individually, allowing an independent control of the blades and offering more flexibility.
- The pitch system is usually placed in the rotor hub together with a backup energy storage system for safety purposes (an accumulator for the hydraulic type or a battery for the electric type).

Pitch Mechanism



Source: [1,2]

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Gearbox

- The rotor of a large three-blade wind turbine usually operates in a speed range from 6-20 rpm. This is much slower than a standard 4- or 6-pole wind generator with a rated speed of 1500 or 1000 rpm for a 50 Hz stator frequency and 1800 or 1200 rpm for a 60 Hz stator frequency. Therefore, a gearbox is necessary to adapt the low speed of the turbine rotor to the high speed of the generator.
- The gearbox conversion ratio *(r_{gb}), also known as the gear ratio, is designed to* match the high-speed generator with the low-speed turbine blades. For a given rated speed of the generator and turbine, the gearbox ratio can be determined by

$$r_{gb} = \frac{n_m}{n_M} = \frac{(1-s)\cdot 60 \cdot f_s}{P \cdot n_M}$$

- Where r_{gb} is Gearbox conversion ratio, n_m is Generator rated speeds and n_M is Turbine rated speeds, P is Number of pole pairs of the generator, s is the rated slip, and f_s is Rated stator frequency.

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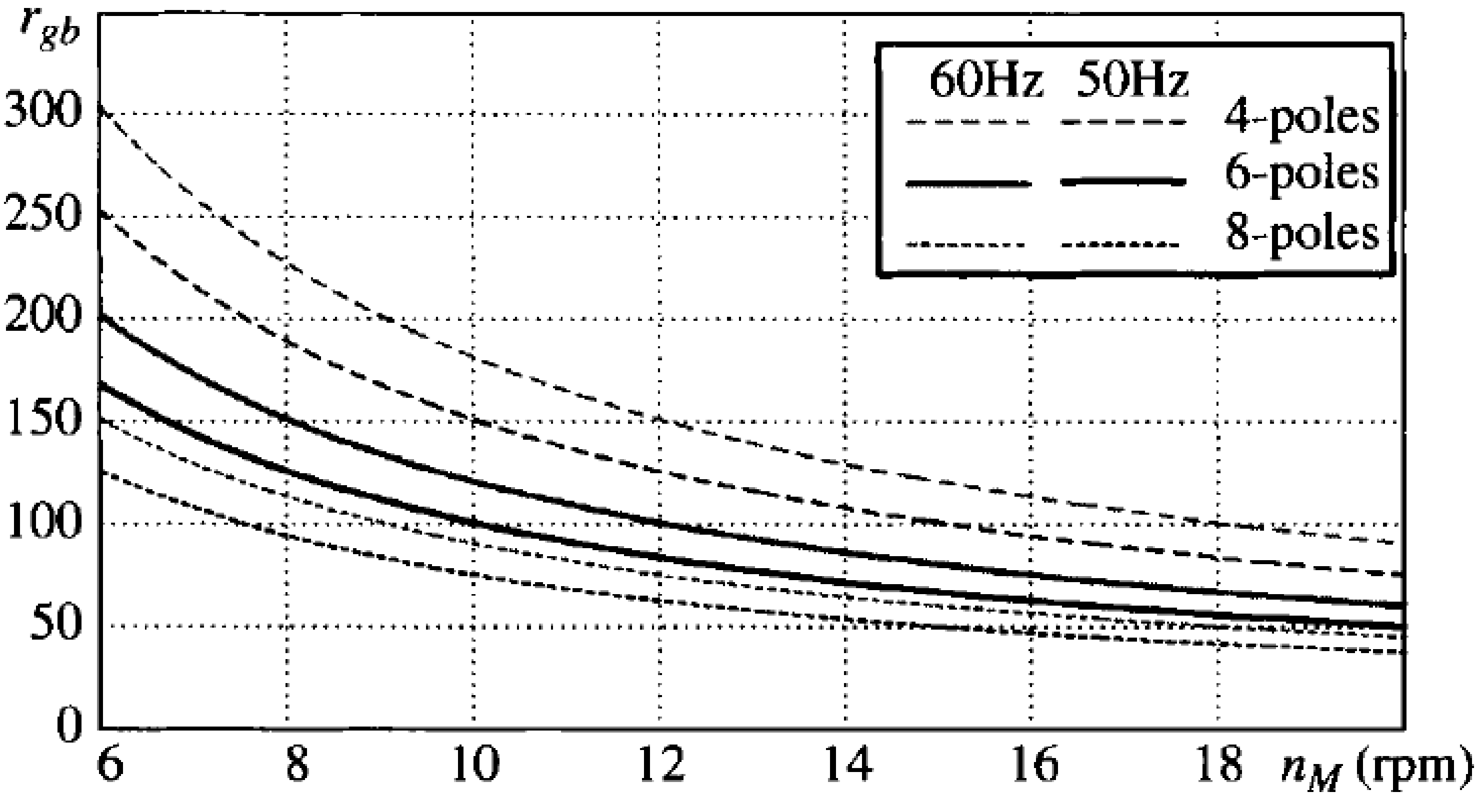
Gear Ratio vs. the Rated Turbine Speed (s = 0.01)



Source: [1]

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Gearbox

- The wind turbine gearboxes normally have multiple stages to achieve the high conversion ratio needed to couple the turbine rotor and generator. For example, with a rated turbine rotor speed of 15 rpm and a 4-pole, 50 Hz induction generator, a gear ratio of 100 is needed, as shown in the next figure which is difficult to achieve by one gear stage.
- The gearbox usually generates a high level of audible noise. The noise mainly arises from the meshing of individual teeth. The efficiency of the gearbox normally varies between 95% and 98%.
- The gearbox is a major contributor to the cost of the wind turbine in terms of initial investment and maintenance.

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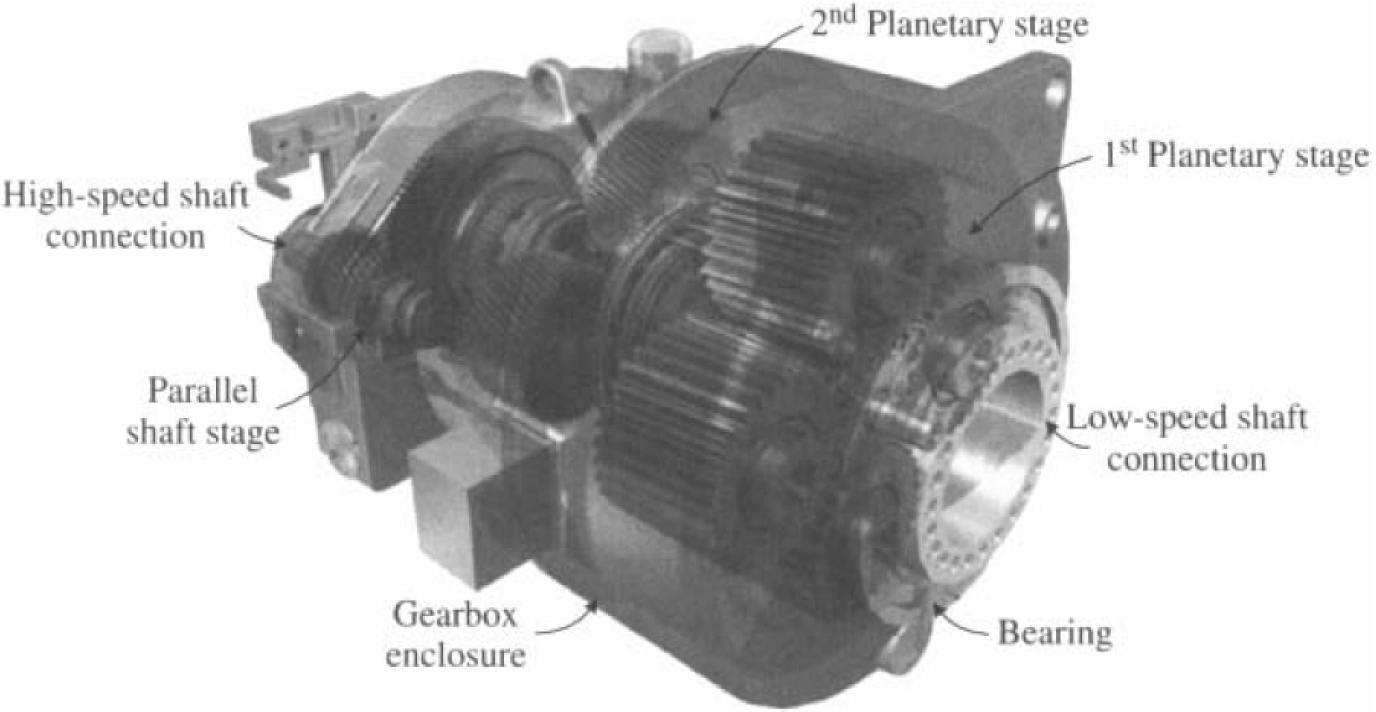
Two-Stage Gearbox of A Large Wind Turbine



Source: [1]

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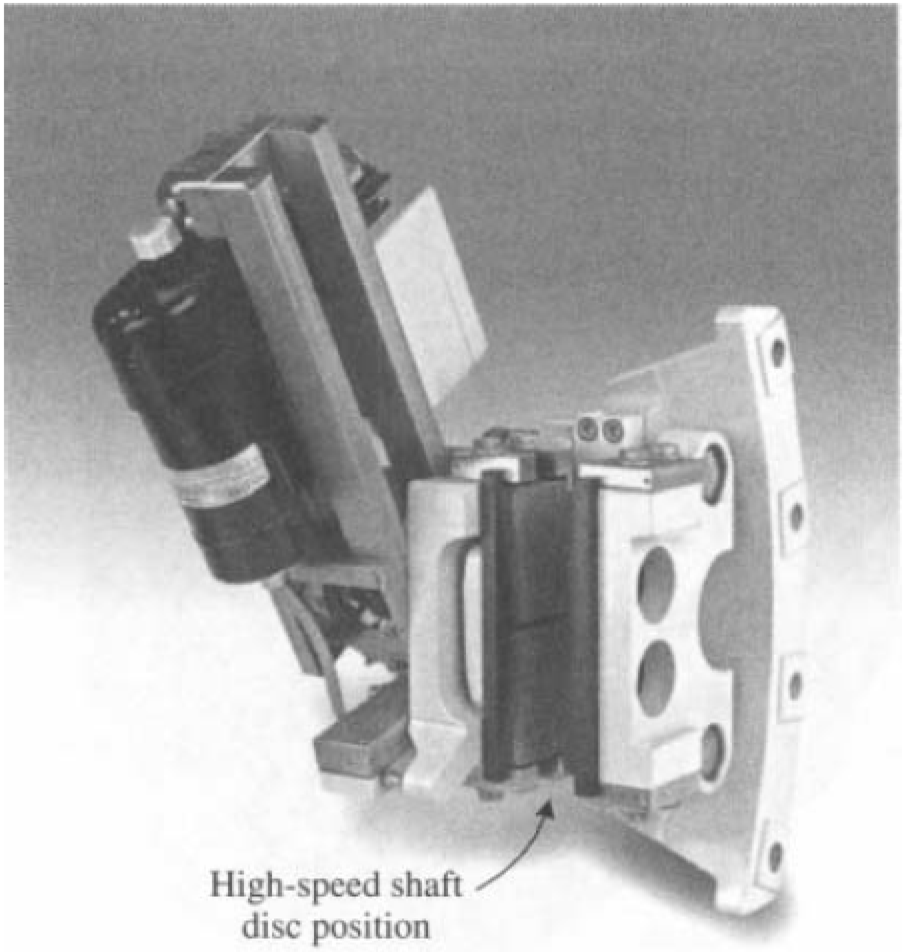
Rotor Mechanical Brake



Source: [1,2]

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Rotor Mechanical Brake

- A mechanical brake is normally placed on the high-speed shaft between the gearbox and the generator, but there are some turbines in which the brake is mounted on the low-speed shaft between the turbine and gearbox.
- The main advantage of placing the brake on the high-speed shaft is that it handles much lower braking torque.
- The brake is normally used to aid the aerodynamic power control (stall or pitch) to stop the turbine during high speed winds or to lock the turbine into a parking mode during maintenance.

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Rotor Mechanical Brake

- Hydraulic and electromechanical disc brakes are often used.
- To minimize the wear and tear on the brake and reduce the stress on drive train during the braking process, most large wind turbines use the aerodynamic power control to reduce the turbine speed to a certain level or zero, and then the mechanical brake to stop or lock the wind turbine. However, the mechanical brake should be able to bring the turbine rotor to a complete stop at any wind speeds, as required by some standards such as IEC61400-1.

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Wind Turbine Generator

- The conversion of rotational mechanical energy to electric energy is performed by the generator.
- Different generator types have been used in wind energy systems over the years. These include the squirrel cage induction generator (SCIG), doubly fed induction generator (DFIG), and synchronous generator (SG) (wound rotor and permanent magnet) with power ratings from a few kilowatts to several megawatts. The SCIG is simple and rugged in construction. It is relatively inexpensive and requires minimum maintenance.

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Wind Turbine Generator

- Traditional direct grid-connected wind energy systems are still available in today's market. All these turbines use SCIGs and operate at a fixed speed. Two-speed SCIGs are also commercially available, in which a tapped stator winding can be adapted to change the pole pairs to allow two-speed operation.
- The SCIGs are also employed in variable-speed wind energy systems. To date, the largest SCIG wind energy systems are around 3.5 MW in offshore wind farms.
- The DFIG is the current workhorse of the wind energy industry. The stator of the generator is connected to the grid directly, while the rotor is interfaced with the grid through a power converter system with reduced power capacity.

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Wind Turbine Generator

- The DFIG typically operates about 30% above and below synchronous speed, sufficient for most wind speed conditions.
- It also enables generator-side active power control and grid-side reactive power control.
- The reduced-capacity converter is less expensive and requires less space, which makes the DFIG WECS popular in today's market.
- The synchronous generator is very well suited for direct-drive wind turbines.

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Wind Turbine Generator

- Wound rotor synchronous generators (WRSGs) and permanent magnet synchronous generators (PMSGs) are used in wind energy systems with a maximum power rating up to 7.5 MW.
- Permanent magnet generators have higher efficiency and power density as compared to wound rotor generators. Recent trends indicate a move toward direct drive turbines with PMSG. Although most SG-based turbines are direct driven, some manufacturers have developed SG turbines with gearbox drive trains.

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Wind Turbine Generator

- Wind turbine components:
  - wind turbine runs at low speed (0.5 Hz)
  - mechanical drive train includes a gear box
    - converts low speed of turbine to high speed of generator
- Mechanical speed regulation:
  - blade pitch angle control
    - each blade rotated about longitudinal axis
    - variable speed
  - stall control
    - no pitch actuators required
    - fixed speed
- Types of generators
  - induction generator
  - synchronous generator
  - doubly fed induction generator
- WTG ratings range from 25 kW to 3 MW

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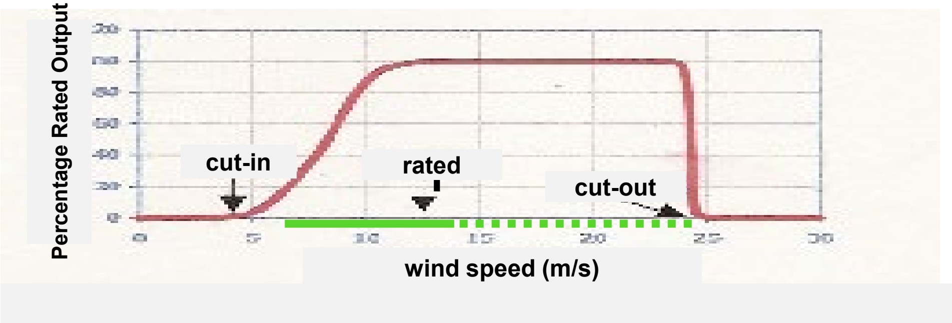
Typical Wind Turbine Generator "Power Curve"

- Fig below shows typical output versus wind speed characteristics of wind turbines:



Source: [1,2]

- The cut-in, rated and cut-out speeds shown are typical for utility-scale WTGs
- Generally, WTGs are designed to work at maximum aerodynamic efficiency between cut-in and rated wind speed
- For wind speeds higher than rated and lower than cut-out:
  - blade pitching or blade stalling is used to maintain loading within the equipment's rating
- WTGs shut down for wind speeds higher than cut-out speed to avoid excessive mechanical stress

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Types of Wind Turbine Generator Technologies

Presently four major types of WTG Technologies used:

1. Squirrel Cage Induction Generators driven by fixed-speed, stall-regulated wind turbines
2. Induction Generators with variable external rotor resistance driven by a variable-speed, pitch regulated wind turbines
3. Doubly-Fed Induction Generators driven by variable-speed, pitch regulated wind turbines
4. Synchronous or Induction Generators with full converter interface (back-to-back frequency converter), driven by variable-speed, pitch regulated wind turbines

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Doubly-Fed Induction Generator (DFIG)

- Wound rotor induction generator with slip rings
- Rotor is fed from a three-phase variable frequency source, thus allowing variable speed operation
  - reduction of mechanical stress; higher overall efficiency, reduced acoustical noise
- The variable frequency supply to rotor is attained through the use of two voltage-source converters linked via a capacitor

Note: A more appropriate designation for this type of generator is: Doubly Fed Asynchronous Generator

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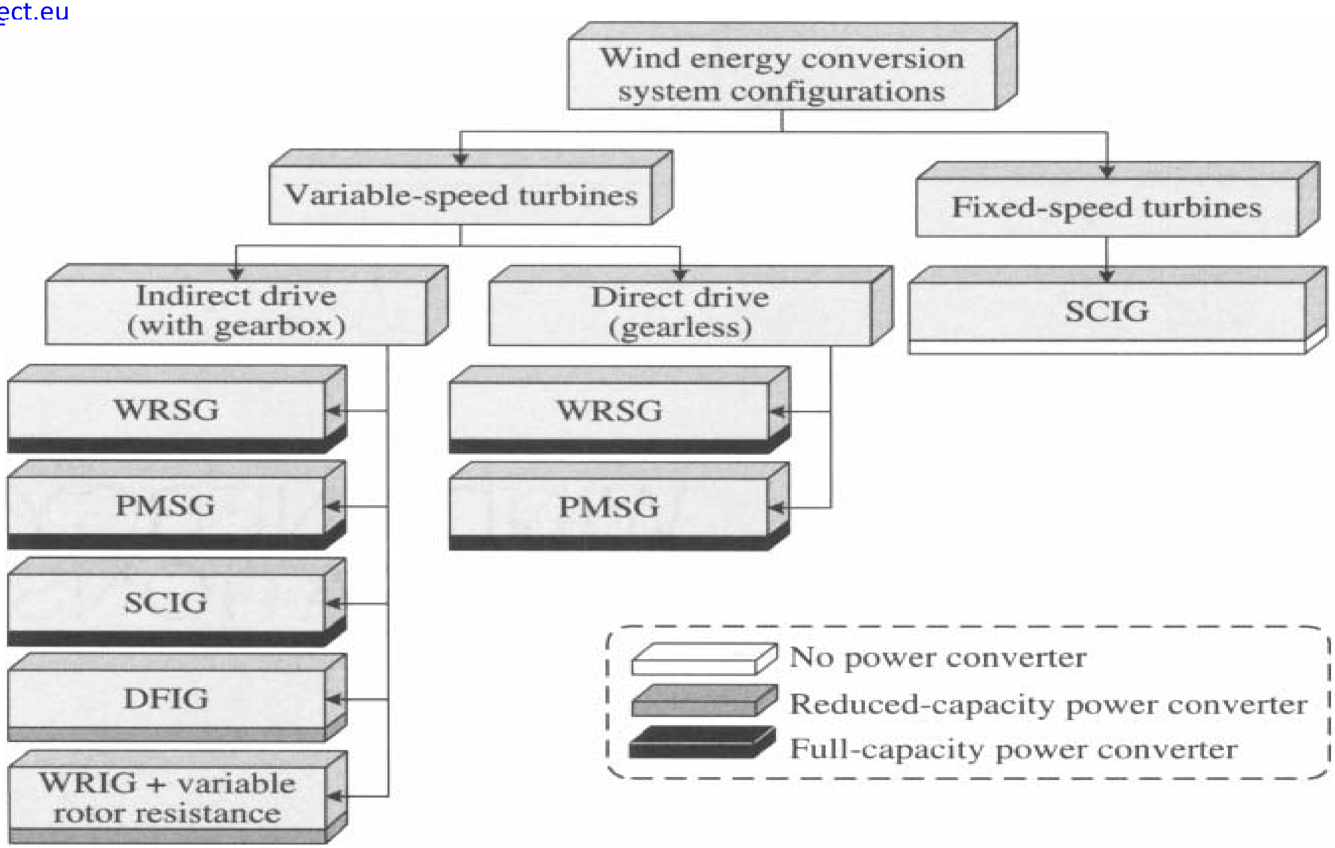
Wind Energy System Classifications



Wind energy conversion system configurations

Variable-speed turbines

- Indirect drive (with gearbox)
  - WRSG
  - PMSG
  - SCIG
  - DFIG
  - WRIG + variable rotor resistance
- Direct drive (gearless)
  - WRSG
  - PMSG

Fixed-speed turbines

- SCIG

▭ No power converter

▨ Reduced-capacity power converter

■ Full-capacity power converter

Source: [1]

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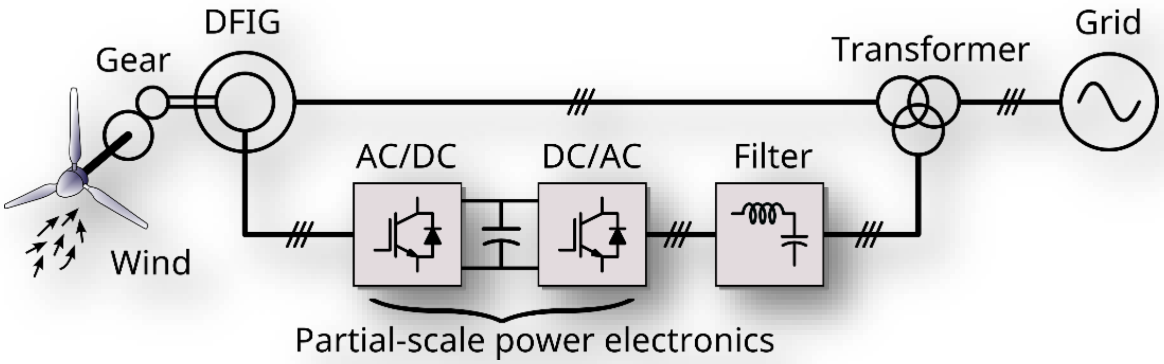
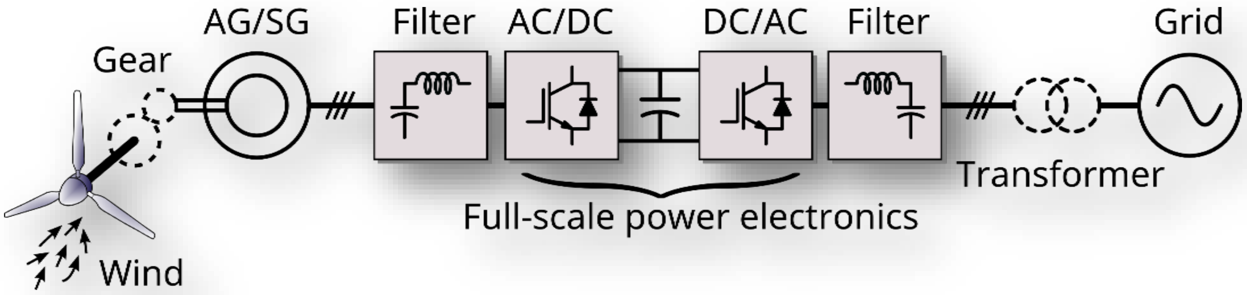
Wind Turbine Concepts

- DFIG



- PMSG



Source: [1,2]

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Top 5 Wind Turbine Manufacturers & Technologies

Manufacturer	Concept	Rotor Diameter	Power Range
Vestas (Denmark)	DFIG PMSG	80 m 100 m	2.0 MW 3.3-8.0 MW
Siemens Gamesa (Spain)	SCIG PMSG DFIG	120 m 128 – 154 m 90 m	3.6 MW 4.5 – 6.0 MW 2.0 MW
GE (USA)	DFIG PMSG	104 m 100 – 113 m	3.0 MW 2.5 – 4.1 MW
Goldwind (China)	PMSG	70 – 110 m	1.5 – 3.0 MW
Enercon (Germany)	WRSG	82 – 126 m	2.0 – 7.5 MW

Source: [1,2]

DFIG: Doubly-Fed Induction Generator

PMSG: Permanent Magnet Synchronous Generator

SCIG: Squirrel-Cage Induction Generator

WRSG: Wound Rotor Synchronous Generator

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Top 10 Biggest Turbines

Manufacturer	Power Rating (MW)	Rotor Diameter (m)	Drivetrain	IEC Class
MHI Vestas	9.5	164	Medium-speed geared	S
Siemens Gamesa	8	167	Direct drive	S (IB)
Goldwind	6.7	154	PM direct drive	I
Senvion	6.15	152	High-speed geared	S
GE	6	150	Direct drive	IB
Ming Yang	6	140	Medium-speed geared	IIB
Doosan	5.5	140	High-speed geared	I
Hitachi	5.2	126-136	Medium-speed geared	S
Haizhuang	5	151	High-speed geared	IIB
Adwen	5	135	Low-speed geared	IA

Source: [3]

Wind Power, Ten of the Biggest Turbines, 3 Sept. 2018,
https://www.windpowermonthly.com/10-biggest-turbines

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Control of Rotor-Side Converter

- The converters handle ac quantities:
  - rotor-side converter carries slip frequency current
  - stator-side converter carries grid frequency current
- Hence, they are controlled using vector-control techniques:
  - based on the concept of a rotating reference frame and projecting currents on such a reference
  - such projections referred to as d- and q-axis components
- With a suitable choice of reference frame, AC quantities appear as DC quantities in the steady state

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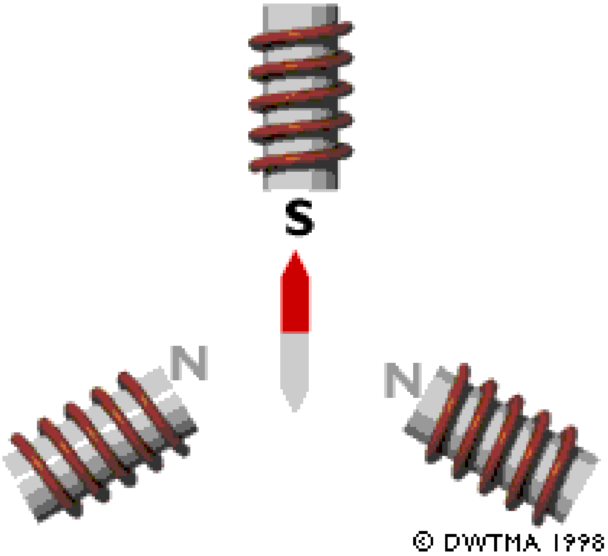
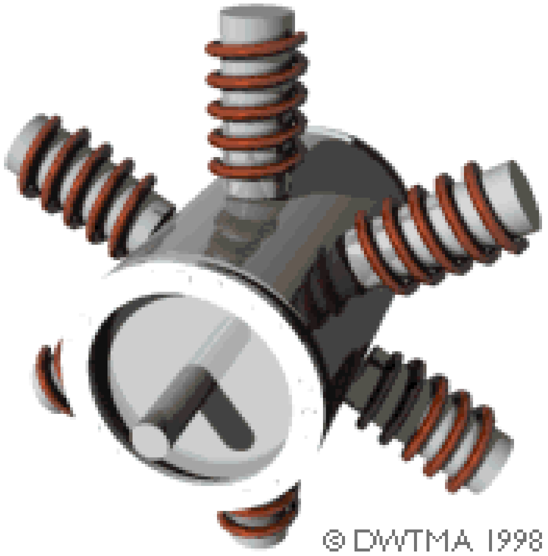
Types of Generators

Synchronous



Asynchronous



Source: [1,2]

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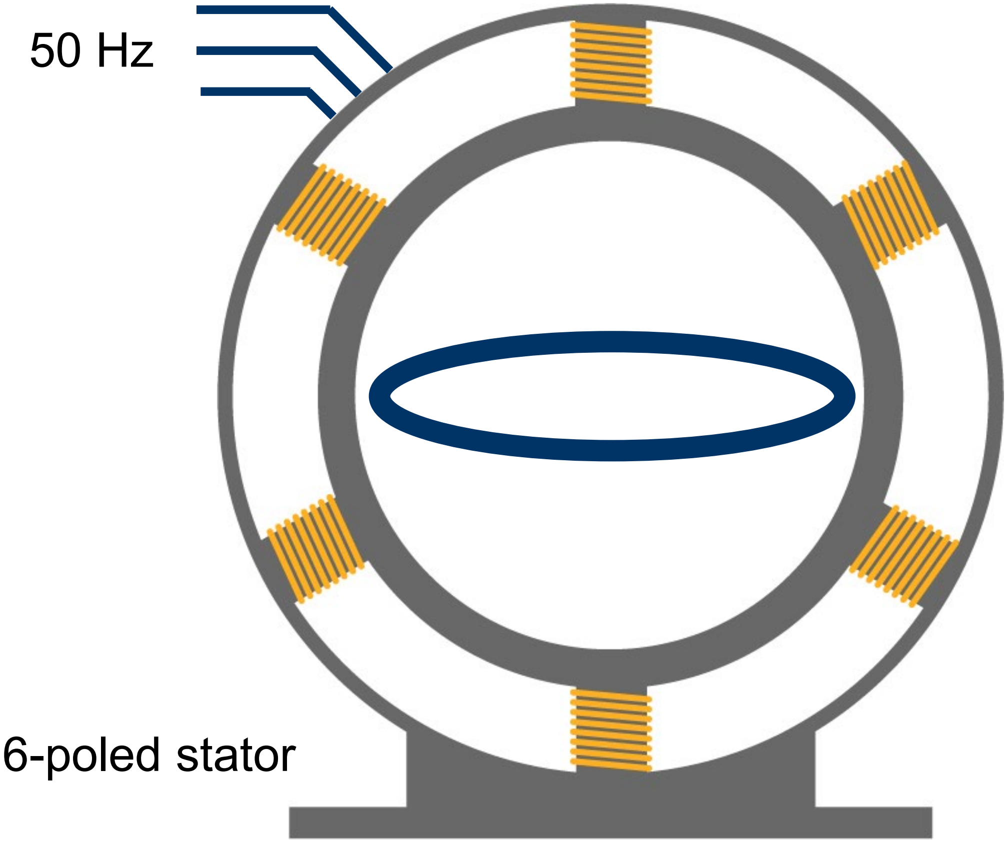
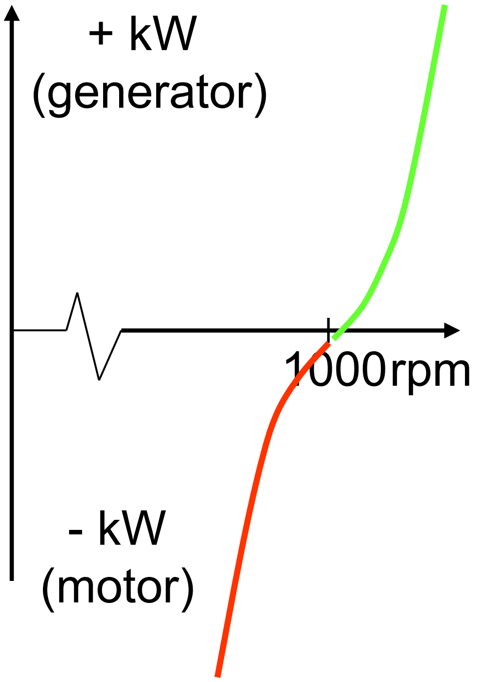
Types of Generator
Fixed Speed Asynchronous Generator





Rotational Speed

$$\text{rpm} = \frac{60 \text{ x frequency}}{\text{number of pole pairs}}$$

Source: [1,2]

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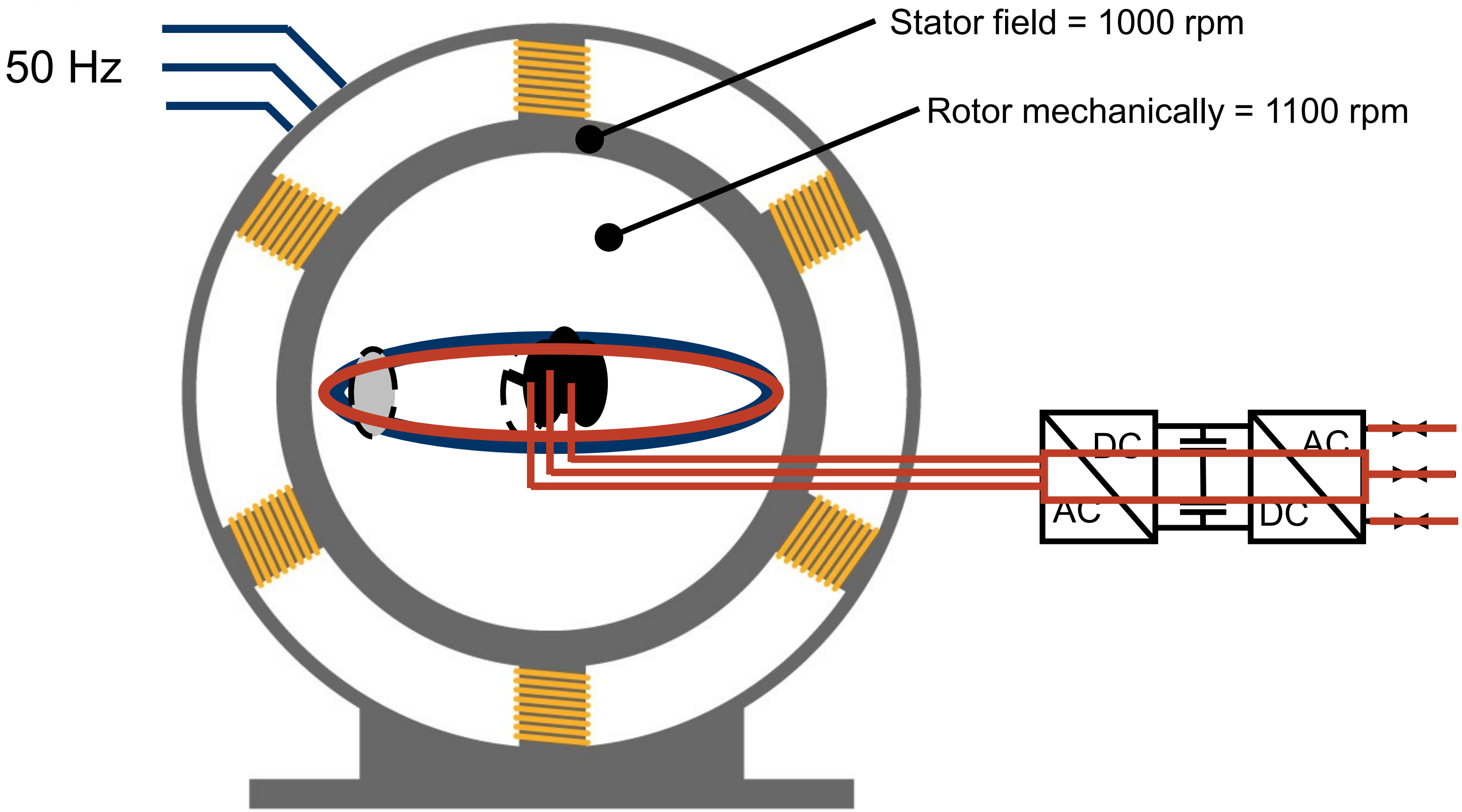
Types of Generator
Variable Speed Asynchronous Generator



Source: [1,2]

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Summary of the provided knowledge

- Detailed discussions on the wind turbines
  - Yawing mechanisms
  - Furling mechanisms
  - Pitch mechanisms
  - Gearbox
  - Rotor mechanical brake
- Wind turbine generator types
  - State-of-the-art technologies
    - DFIG
    - PMSG

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References

[1] Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained: theory, design and application. John Wiley & Sons, 2010.

[2] Hau, Erich. Wind turbines: fundamentals, technologies, application, economics. Springer Science & Business Media, 2013.

[3] Wind Power, Ten of the Biggest Turbines, 3 Sept. 2018, https://www.windpowermonthly.com/10-biggest-turbines

[4] https://www.re-explorer.org/launch.html

[5] Solar and Wind energy resource assessment (SWERA): https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)

[6] https://globalwindatlas.info/

[7] MIT Wind: http://web.mit.edu/windenergy/

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Module 2.2 Mechanical Systems in Wind Engineering

Power Control

Lecture 4.3

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Learning outcomes

O1. To know the power control in wind turbine systems

O2. Be familiar with the power regulation objectives

O3. Have the knowledge of power regulation methods

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Technical Contents

1. *Power regulation purpose*
2. *Methods of power regulation*
3. *Discussion of some power control schemes*

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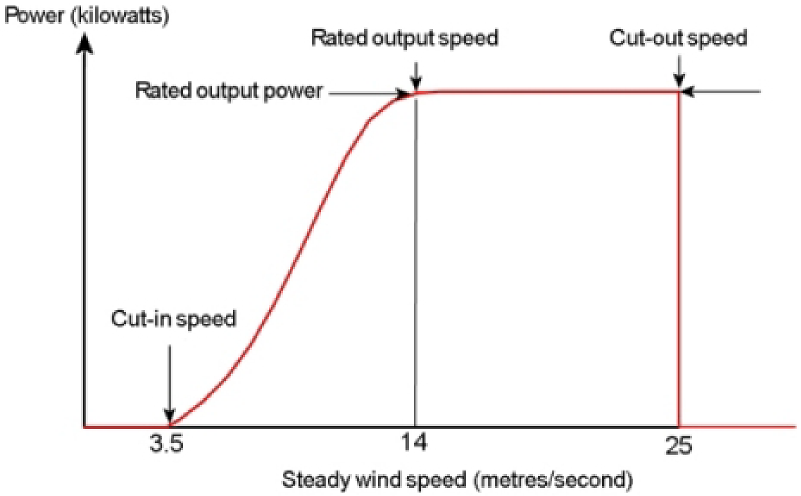
Wind Turbine Control

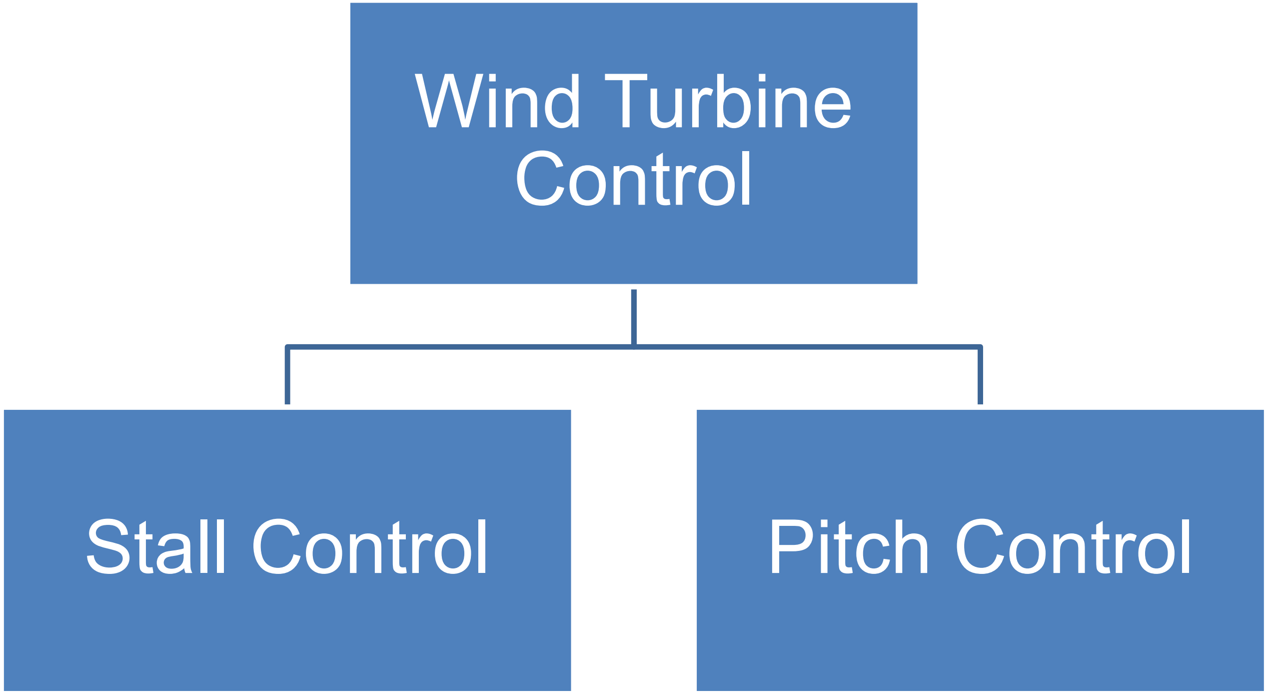
- Wind turbines are designed to produce electrical energy as cheaply as possible at a certain wind speed range
- In case of stronger winds it is necessary to waste part of the excess energy of the wind to avoid damaging the wind turbine
- All wind turbines are therefore designed with some sort of power control
- There are two different ways of doing this safely on modern wind turbines pitch and stall



Typical wind turbine power output with steady wind speed.

Source: [1]

Control Classification



Wind Turbine Control

Stall Control

Pitch Control

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Stall-Controlled Wind Turbines

- Blades are locked in place and do not adjust during operation.
- Blades are shaped to increasingly "stall" the blade's angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds.
- Stall-regulated turbines are often considered **more reliable** because they do not have the same level of mechanical and operational complexity as pitch-regulated turbines.

Source: [2]

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Pitch Control

- **Pitch control** maintain the optimum blade angle to achieve certain rotor speeds or power output.

- Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds.

Source: [2]

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An Example of the Pitch System

INSIDE THE MOOG PITCH CONTROL SOLUTION

PITCH SYSTEM 3

Space-saving solution ensures safe and reliable performance

Ⓐ Pitch Interface Module

Ⓑ Pitch Axis Box
(Pitch Servo Drive 3/Pitch Capacitor Module)

Ⓒ Pitch Motor

SLIP RING SOLUTIONS

Highly reliable power/data transmission

Ⓓ Slip Ring

Source: [3]

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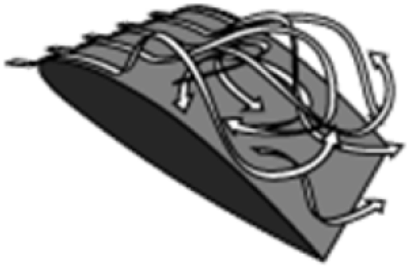
Pitch Control Methods

- **Stalling** the wind turbine, by increasing the angle of attack, which causes the flat side of the blade to face further into the wind.



- **Feathering** the wind turbine, by decreasing the angle of attack, causing the edge of the blade to face the oncoming wind.

Source: [2]

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Yaw Control

- Moving the axis out of the direction of the wind decreases angle of attack and cross-section.
- Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power.
- Yaw control can be achieved passively (for small wind turbines) with a fin attached to the nacelle on the opposite side of the rotor.

Source: [4]

Source: [2]

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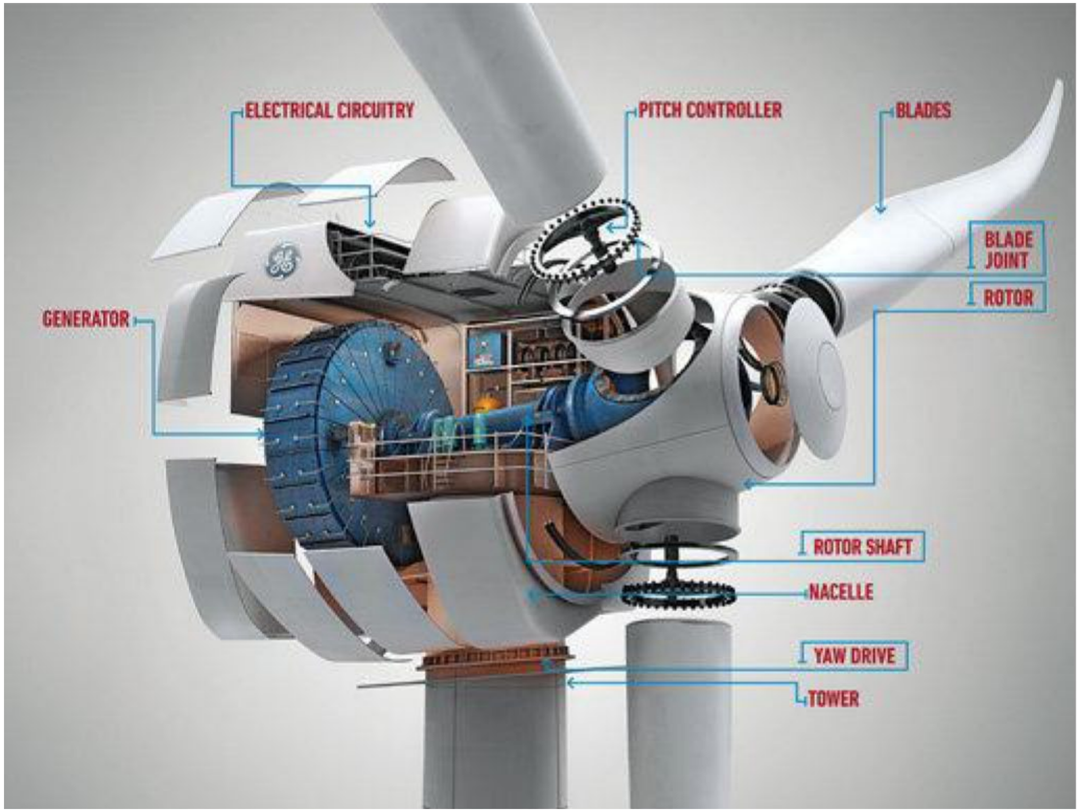
View of A Wind Turbine Showing Yaw and Pitch Drives



Source: [2]

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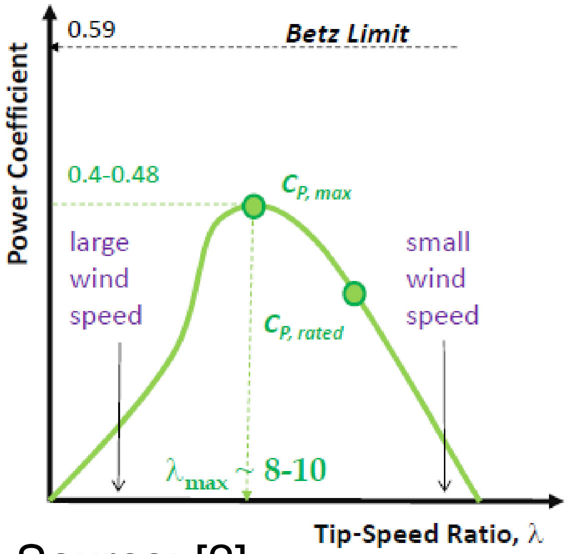
Control Considerations

- Most wind turbines operate at fixed rotational speeds.
- This simplifies the system operation when using synchronous generators connected to the utility grid.
- On the other hand, it prevents the turbine from operation at a speed which will excite mechanical resonance causing severe mechanical damage.
- However, fixed speed operation means that the maximum coefficient of performance is available only at one particular wind speed, with a lower coefficient for all other wind speeds which reduces the output power.
- If the wind turbine runs at constant rotational speed, the tip speed ratio will be large for low wind speeds and small for high wind speeds



Source: [2]

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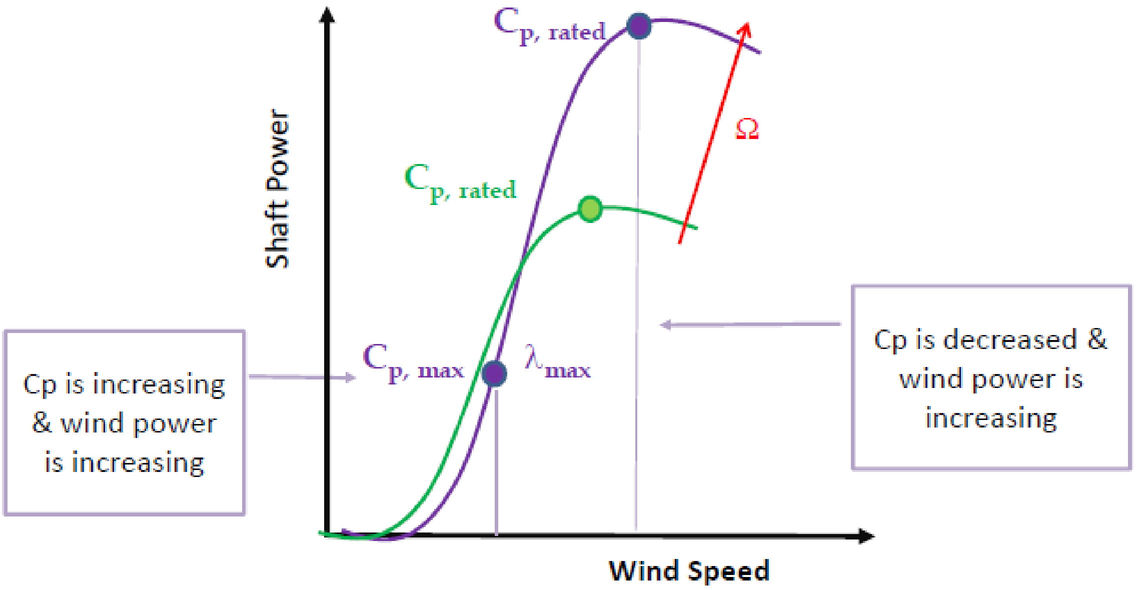
Control Considerations

- Some turbines operate at variable speed. That is if the turbine speed could be adjusted in relation to the wind speed, a higher average coefficient of performance and a higher average power output could be realized. Power electronics (inverters) is used for frequency decoupling.



Source: [2]

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Summary of the provided knowledge

- Discussed the purpose for power regulation in wind systems
- Detailed the power control methods
- Presented certain control schemes

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References

[1] Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained: theory, design and application. John Wiley & Sons, 2010.

[2] Hau, Erich. Wind turbines: fundamentals, technologies, application, economics. Springer Science & Business Media, 2013.

[3] https://www.machinedesign.com

[4] https://www.explainthatstuff.com

[5] https://www.re-explorer.org/launch.html

[6] Solar and Wind energy resource assessment (SWERA): https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)

[7] https://globalwindatlas.info/

[8] MIT Wind: http://web.mit.edu/windenergy/

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Group Project 1

- Form groups (max 4 members)

- Aeroelastic simulation of the designed HAWT

- Presentations of the project
  - 20 minutes each
  - Presentation skills (50%)
  - Technical contents (50%)

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Group Project 2

- Form groups (max 4 members)
- Manufacturing of wind turbine components, assembly and performance testing based on the presentations
- Presentations of the project
  - 20 minutes each
  - Presentation skills (50%)
  - Technical contents (50%)

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Power Control

Lecture 4.3

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Learning outcomes

The purpose of this lesson is to

O1. introduce the main aspects of the aerodynamic power control of HAWT including active, passive and pitch control for Master Students in Engineering

O2. focus on up-to-date technologies that are particularly relevant for South Mediterranean countries.

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Technical Contents

Aerodynamic Power Control:

1. *Passive Stall*
2. *Active Stall*
3. *Pitch Control*

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Aerodynamic Power Control: Passive Stall, Active Stall, and Pitch Control

- The aerodynamics of wind turbines are very similar to that of airplanes. The blade rotates in the wind because the air flowing along the surface that is not facing the wind moves faster than that on the surface against the wind. This creates a lift force to pull the blade to rotate.
- The angle of attack of the blade plays a critical role in determining the amount of force and torque generated by the turbine. Therefore, it is an effective means to control the amount of captured power.
- There are three aerodynamic methods to control the capture of power for large wind turbines: passive stall, active stall, and pitch control.

Passive-Stall Control

- blade is fixed onto the rotor hub at an optimal (rated) angle of attack
- When the wind speed is below or at the rated value, the turbine blades with the rated angle of attack can capture the maximum possible power from the wind
- With the wind speed exceeding the rated value, the strong wind can cause turbulence on the surface of the blade not facing the wind. As a result, the lifting force will be reduced and eventually disappear with the increase of the wind speed, slowing down the turbine rotational speed
- This phenomenon is called stall. The stall phenomenon is undesirable for airplanes, but it provides an effective means to limit the power capture to prevent turbine damage.

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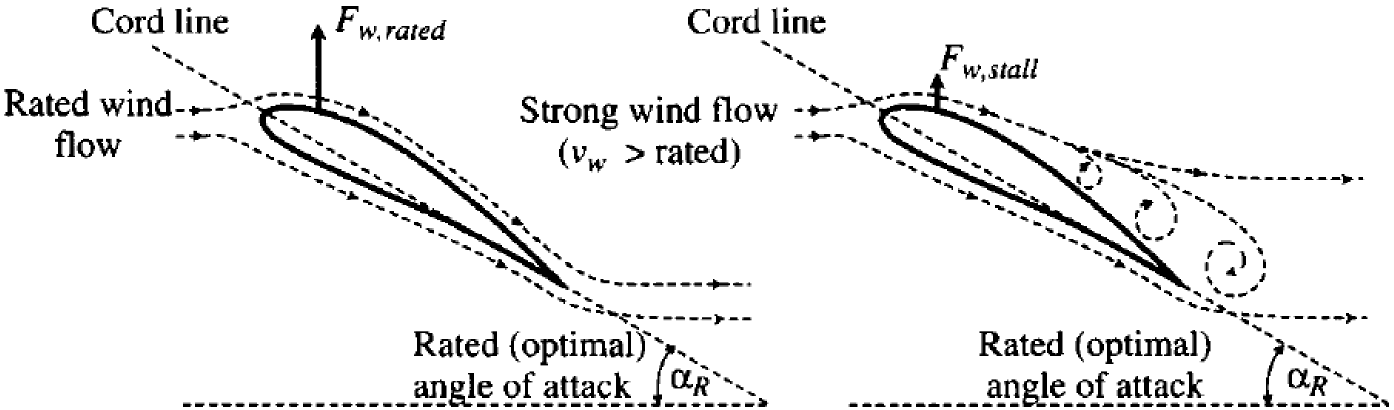
Passive-Stall Control

- Operating principle of the passive-stall control:

  - At higher than rated wind, stall lifting force Fw-stall is lower than the rated force Fw-rated



(a) At rated wind speed (b) Above rated wind speed

Source: [1]

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Passive-Stall Control

- The blade profile is aerodynamically designed to ensure that stall occurs only when the wind speed exceeds the rated value.
- To ensure that the blade stall occurs gradually rather than abruptly, the blades for large wind turbines are usually twisted along the longitudinal axis by a couple of degrees.
- The passive-stall-controlled wind turbines do not need complex pitch mechanisms, but the blades require a complex aerodynamic design. The passive stall may not be able to keep the captured power P_M at a constant value. It may exceed the rated power at some wind speeds, which is not a desirable feature.

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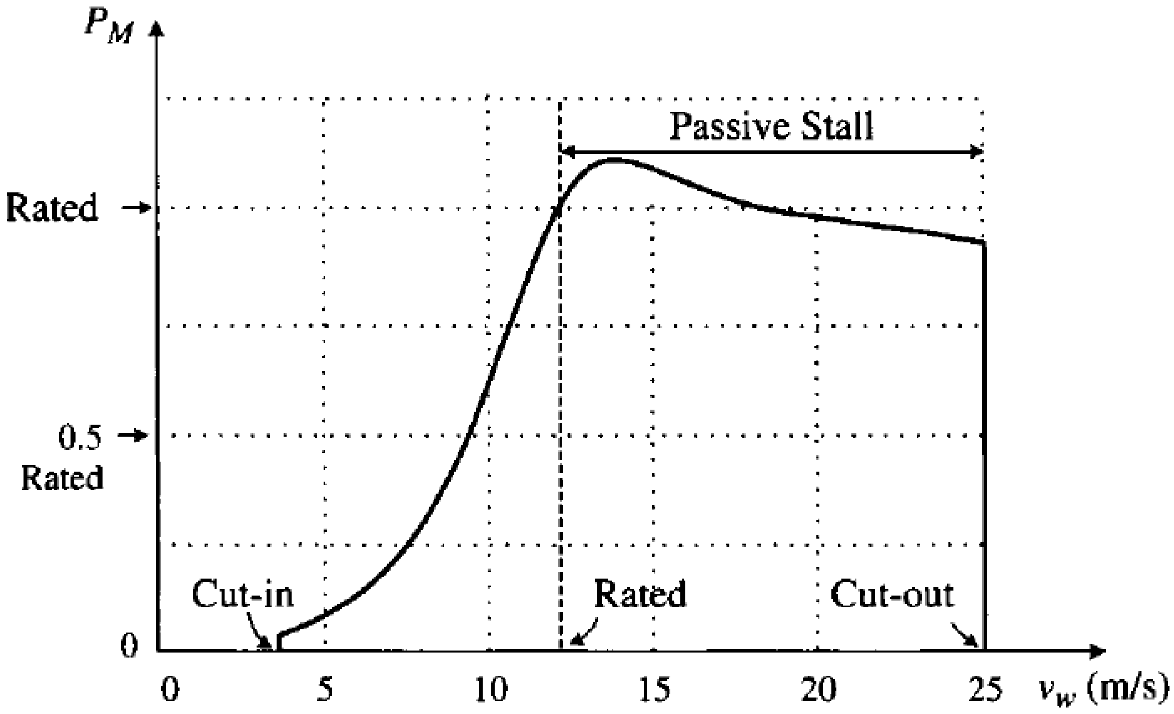
Passive-Stall Control



Source: [1]

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Active-Stall Control

- In active-stall turbines, the stall phenomenon can be induced not only by higher wind speeds, but also by increasing the angle of attack of the blade. Thus, active-stall wind turbines have adjustable blades with a pitch control mechanism. When the wind speed exceeds the rated value, the blades are controlled to turn more into the wind, leading to the reduction of captured power. The captured power can, therefore, be maintained at the rated value by adjusting the blade angle of attack.

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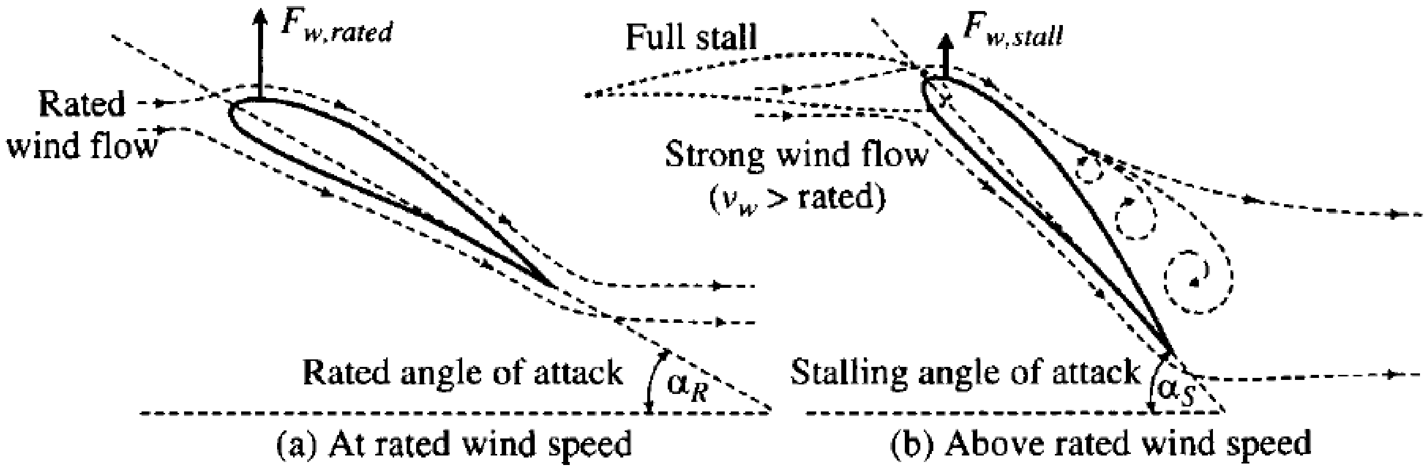
Active-Stall Control

- When the blade is turned completely into the wind, as shown in the dashed blade, the blade loses all interaction with the wind and causes the rotor to stop. This operating condition can be used above the cut-out wind speed to stop the turbine and protect it from damage.



Source: [1]

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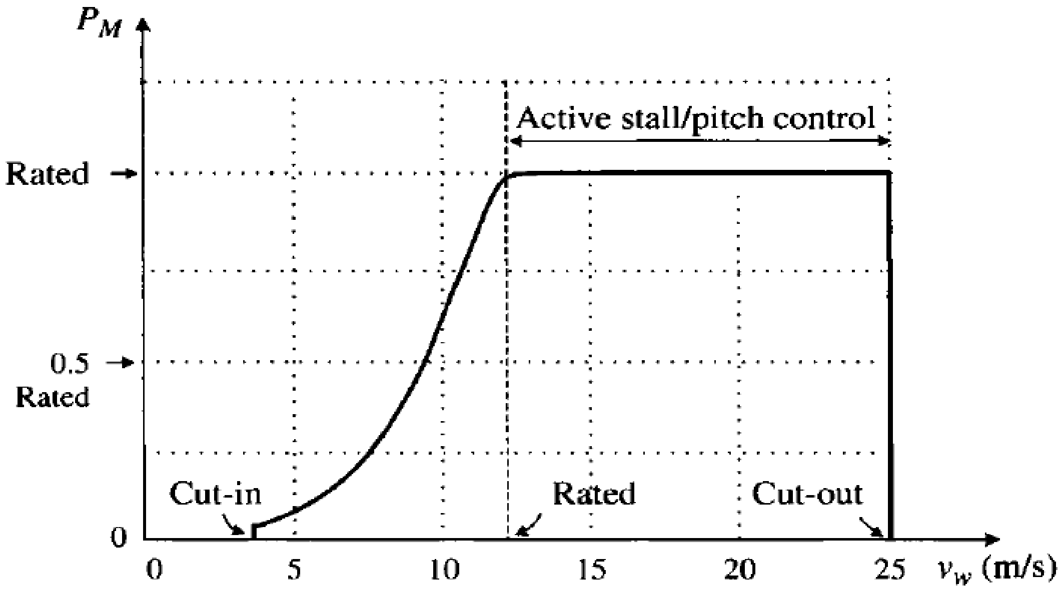
Active-Stall Control

- * With active-stall control, it is possible to maintain the rated power above the rated wind speed
- * Active-stall controlled large megawatt wind turbines are commercially available



Source: [1]

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Pitch Control

- Pitch-controlled wind turbines have adjustable blades on the rotor hub
- When the wind speed exceeds the rated value, the pitch controller will reduce the angle of attack, turning the blades (pitching) gradually out of the wind
- The pressure difference in front and on the back of the blade is reduced, leading to a reduction in the lifting force on the blade
- When the wind is below or at the rated speed, the blade angle of attack is kept at its rated (optimal) value α_R
- With higher than the rated wind, the angle of attack of the blade is reduced, causing a reduction in lift force, $F_{w\text{-}pitch}$

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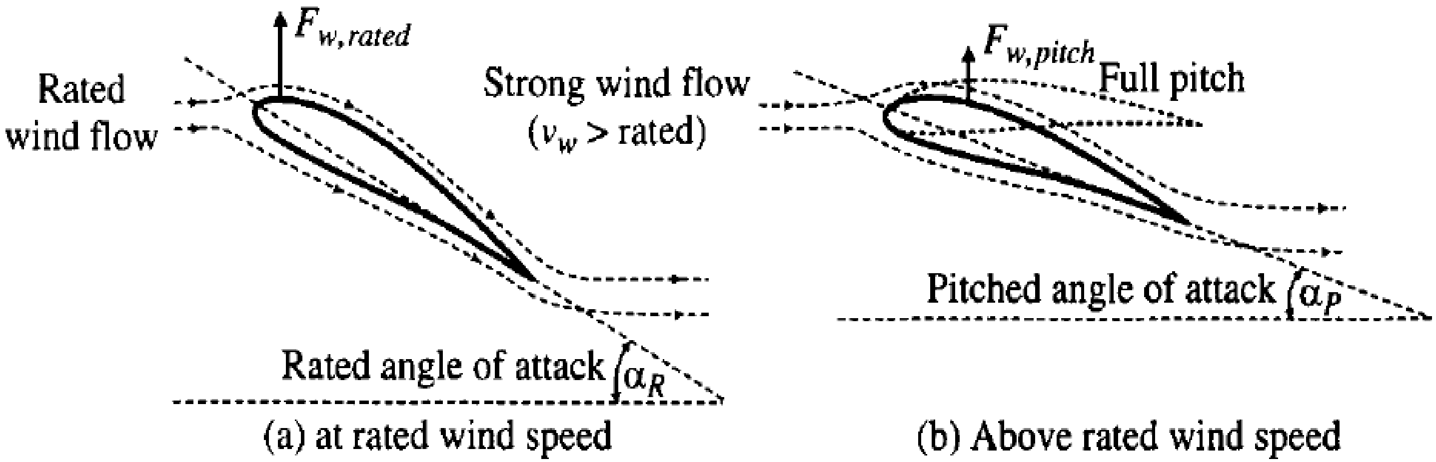
Pitch Control

- When the blade is fully pitched, the blade angle of attack is aligned with the wind, as shown by the dashed blade in the figure, and no lift force will be produced.
- The turbine will stop rotating and then be locked by the mechanical brake for protection.



Source: [1]

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Comparison
Active-Stall Control and Pitch Control

- Both pitch and active-stall controls are based on rotating actions on the blade

- Pitch control turns the blade out of the wind, leading to a reduction in lift force

- Active-stall control turns the blades into the wind, causing turbulences that reduce the lift force.

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Maximum Power Point Tracking (MPPT)

- The control of a variable-speed wind turbine below the rated wind speed is achieved by controlling the generator. The main goal is to maximize the wind power capture at different wind speeds, which can achieved by adjusting the turbine speed in such a way that the optimal tip speed ratio $\lambda_{T,\,opt}$ is maintained.

- For a given wind speed, each power curve has a maximum power point (MPP) at which the optimal tip speed ratio $\lambda_{T,\,opt}$ is achieved. To obtain the maximum available power from the wind at different wind speeds, the turbine speed must be adjusted to ensure its operation at all the MPPs.

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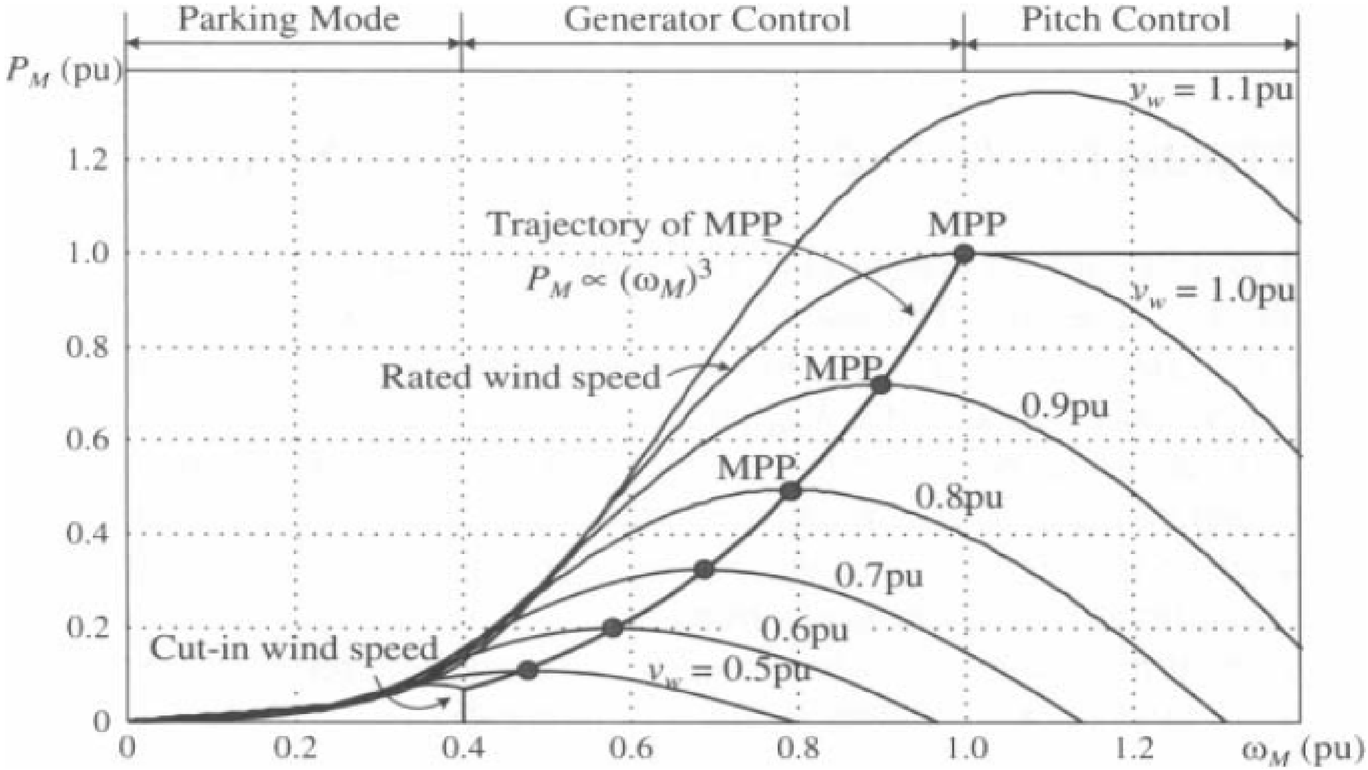
Maximum Power Point Tracking (MPPT)



Source: [2]

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Maximum Power Point Tracking (MPPT)

- The trajectory of MPPs represents a power curve, which is described by

$$P_M \propto \omega_M^3$$

- The mechanical power captured by the turbine can also be expressed in terms of the torque:

$$P_M = T_M \omega_M$$

where T_M is the turbine mechanical torque. Then, we have

$$T_M \propto \omega_M^2$$

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Maximum Power Point Tracking (MPPT)

- According to wind turbine power curve, the operation of the wind turbine can be divided into three modes: parking mode, generator-control mode, and pitch-control mode:
    - Parking mode. When the wind speed is below cut-in speed, the turbine system generates less power than its internal consumption and, therefore, the turbine is kept in parking mode. The blades are completely pitched out of the wind, and the mechanical brake is on.
    - Generator-control mode. When the wind speed is between the cut-in and rated speed, the blades are pitched into the wind with its optimal angle of attack. The turbine operates with variable rotational speeds in order to track the MPP at different wind speeds. This is achieved by the proper control of the generator.

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Maximum Power Point Tracking (MPPT)

- Pitch-control mode. For higher than rated wind speeds but below the cut-out limit, the captured power is kept constant by the pitch mechanism to protect the turbine from damage while the system generates and delivers the rated power to the grid. The blades are pitched out of the wind gradually with the wind speed, and the generator speed is controlled accordingly.

- When the wind speed reaches or exceeds the cut-out speed, the blades are pitched completely out of the wind. No power is captured, and turbine speed is reduced to zero. The turbine will be locked into the parking mode to prevent damage from the strong wind.

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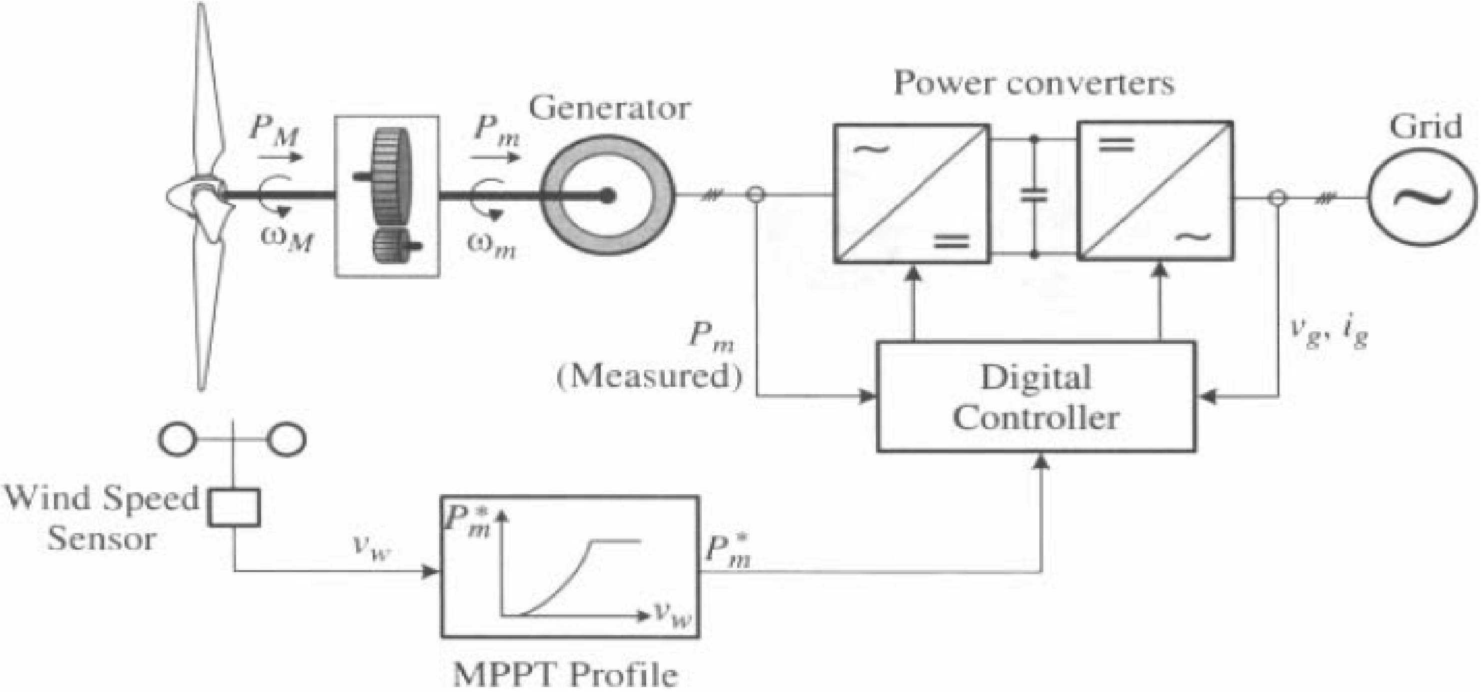
MPPT with Turbine Power Profile



Source: [2]

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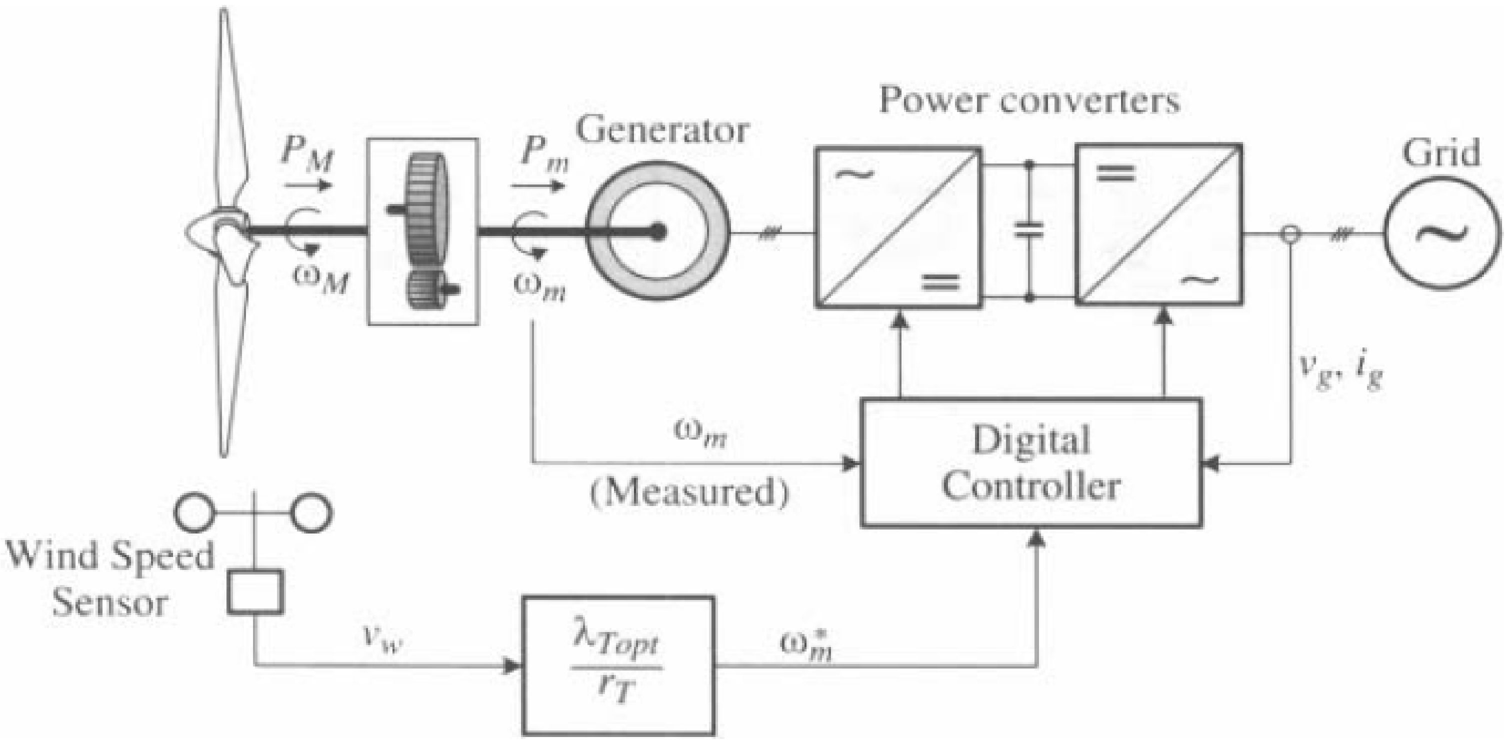
MPPT with Optimal Tip Speed Ratio



Source: [2]

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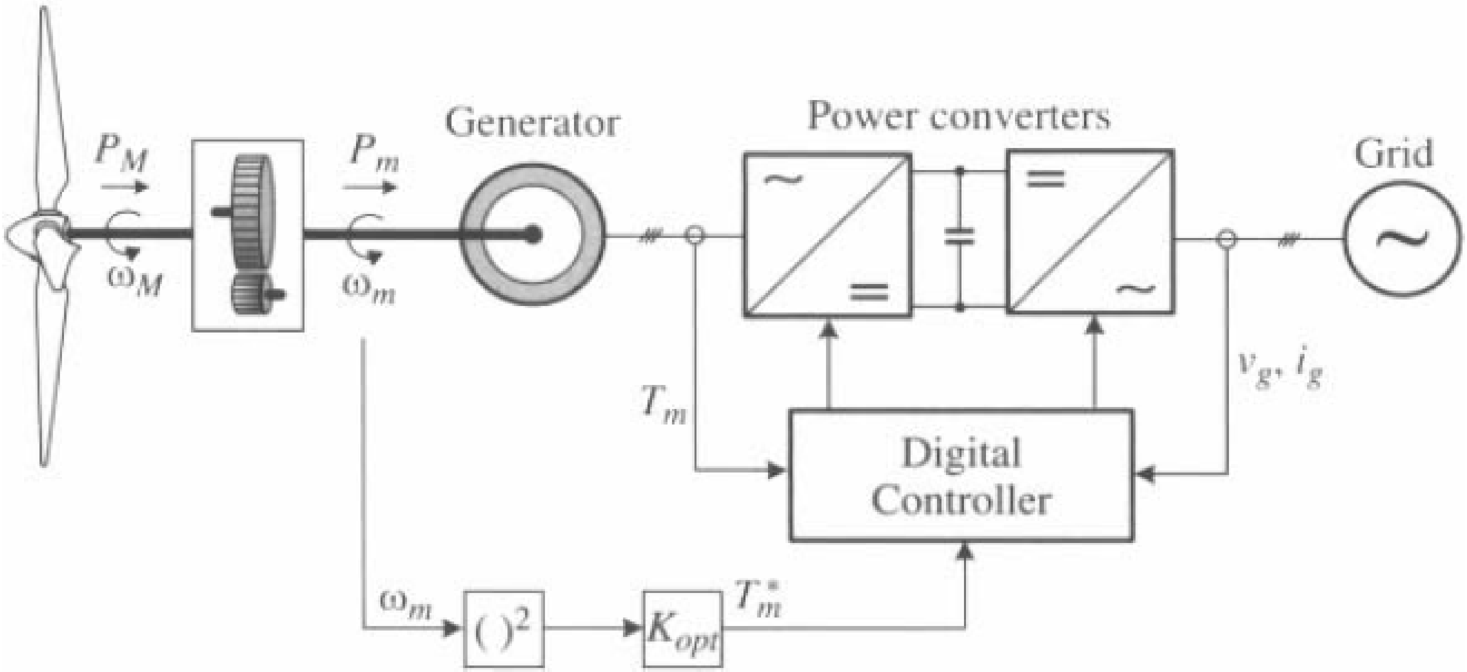
MPPT with Optimal Torque Control



Source: [2]

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Summary of the provided knowledge

- Aerodynamics control in wind turbine systems
  - Passive-Stall Control
  - Active-Stall Control
  - Pitch Control

- Maximum power point tracking (MPPT)
  - Turbine Power Profile
  - Optimal Tip Speed Ratio
  - Optimal Torque Control

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References

[1] Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained: theory, design and application. John Wiley & Sons, 2010.

[2] Hau, Erich. Wind turbines: fundamentals, technologies, application, economics. Springer Science & Business Media, 2013.

[3] https://www.re-explorer.org/launch.html

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[5] https://globalwindatlas.info/

[6] MIT Wind: http://web.mit.edu/windenergy/

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O&M in Wind Energy

Lecture 5.1

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Learning outcomes

O1. Understand the importance of O&M

O2. Cost in O&M

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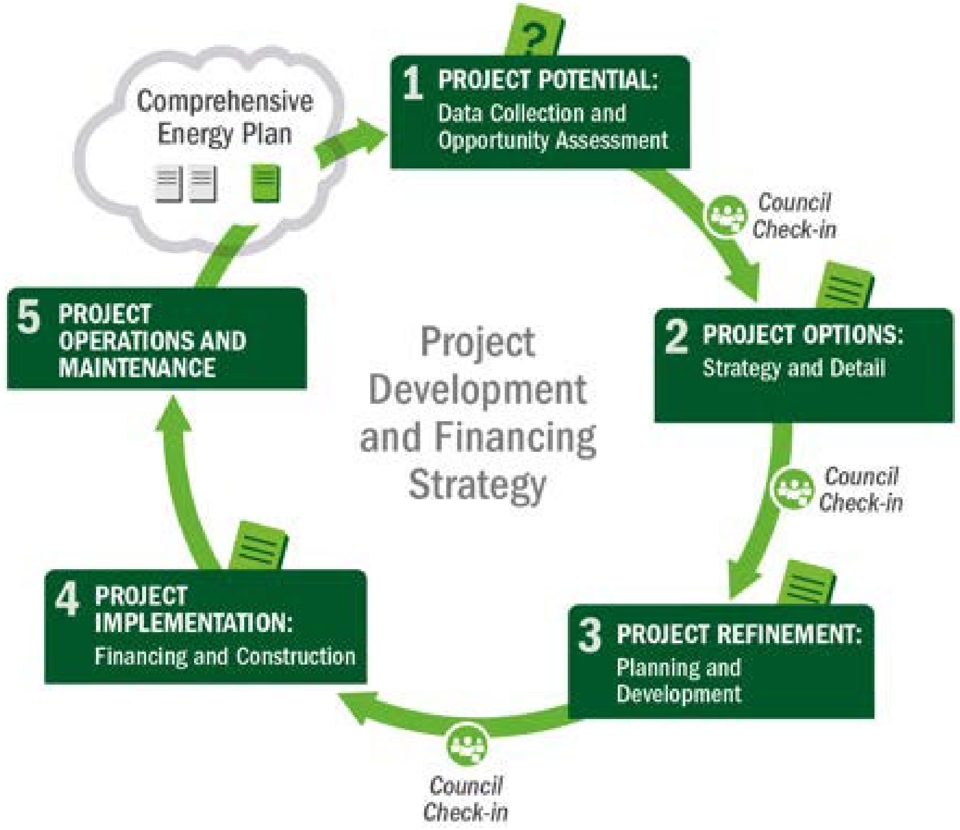
Where does O&M Fit in Wind Projects?



Source: [1]

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Motivations for Improving O&M

- Increase efficiency and energy delivery (kWh/kW)
- Decrease downtime (hours/year)
- Ensure safety and reduce risk
- Extend system lifetime
- Often required in financing and warranty

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What’s Included under O&M?

Preventive maintenance

- Scheduled and planned
- Expenditure is budgeted

Corrective maintenance

- Unplanned or condition-based
- Costs tend to increase over time
- Must be timely and effective
- Have sufficient funds available to cover
- cost of major component repair or replacement

Monitoring

- Metering for revenue
- Alarms
- Diagnostics
- Condition Monitoring

Administration

- Billing; accounting
- Hiring subcontractors
- Enforcement of warranties
- Management of budget and reserves

insurance

- General Liability
- Property
- Business Income (loss of profit)
- Equipment Protection (from breakdown)

Site maintenance

- Eg:
  - ○ Mowing around the tower base
  - ○ Snow removal from turbine driveway

Source: [2]

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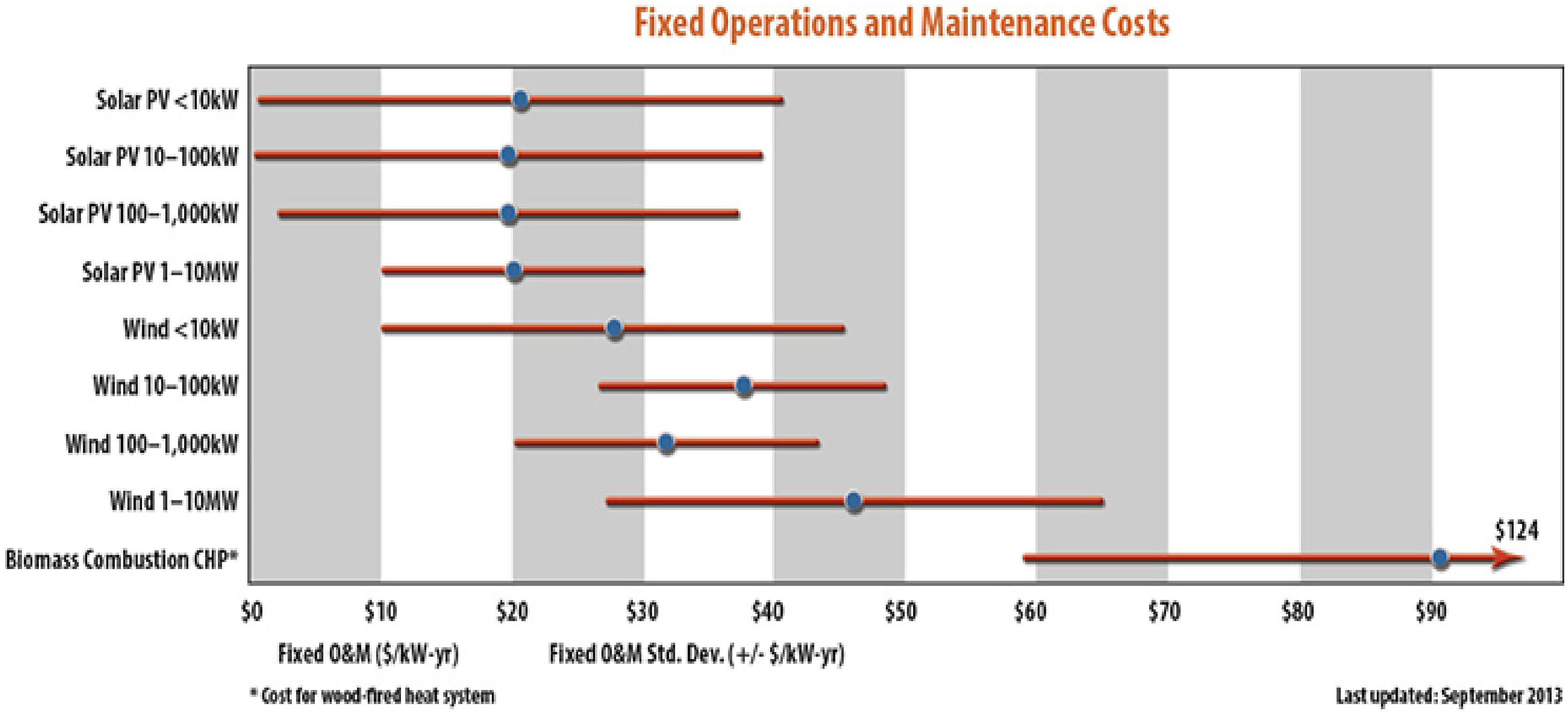
O&M Costs for Renewable Energy Technologies



Source: [3]

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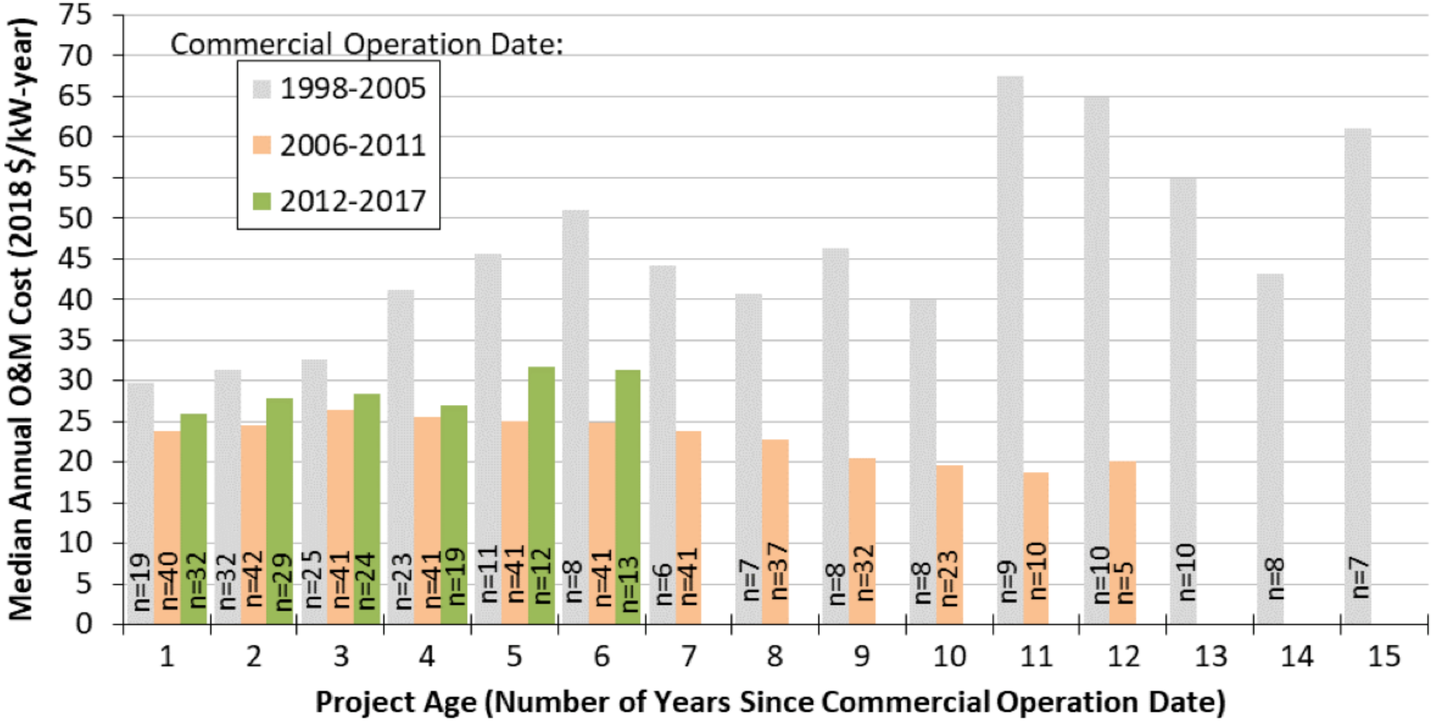
O&M Costs for Renewable Energy Technologies



Source: Berkeley Lab; medians shown only for groups of two or more projects, and only projects >5 MW are included

Source: [4]

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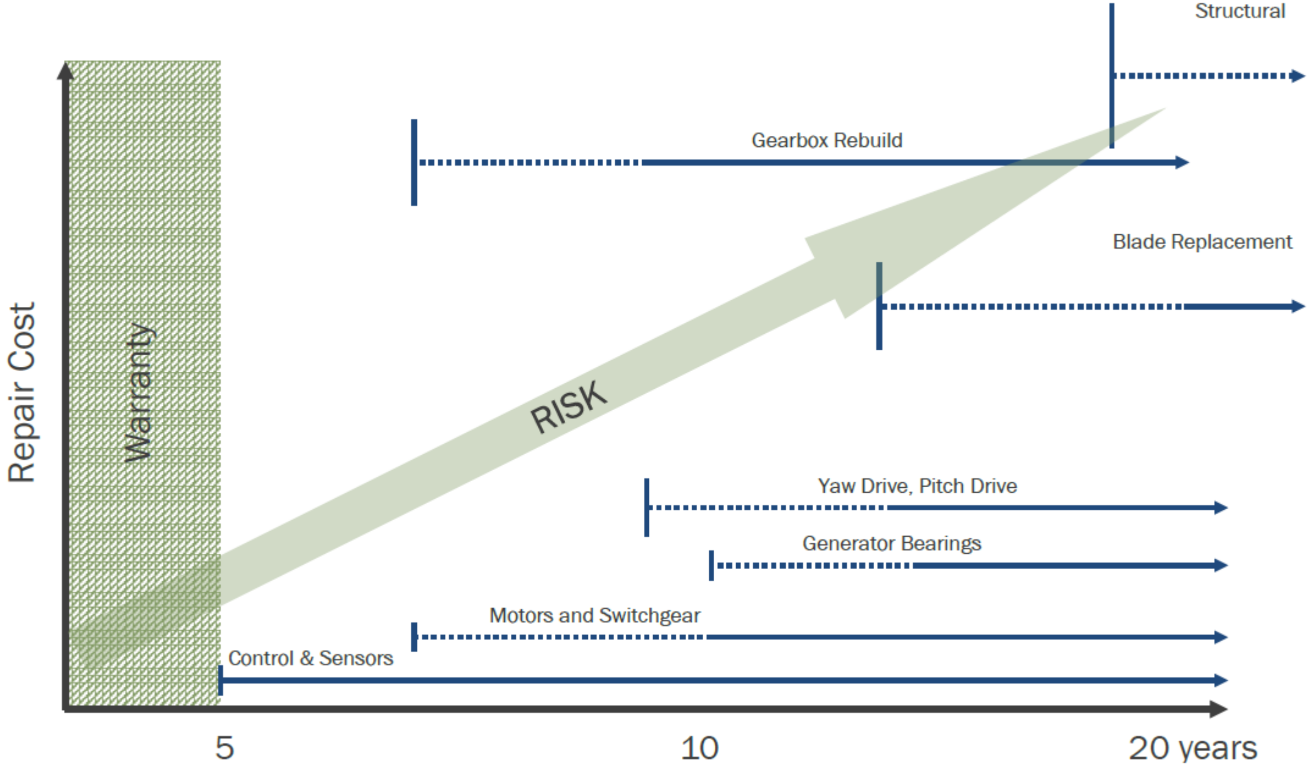
Major Components at Risk

- Equipment breaks—usually after the warranty expires



Source: [5]

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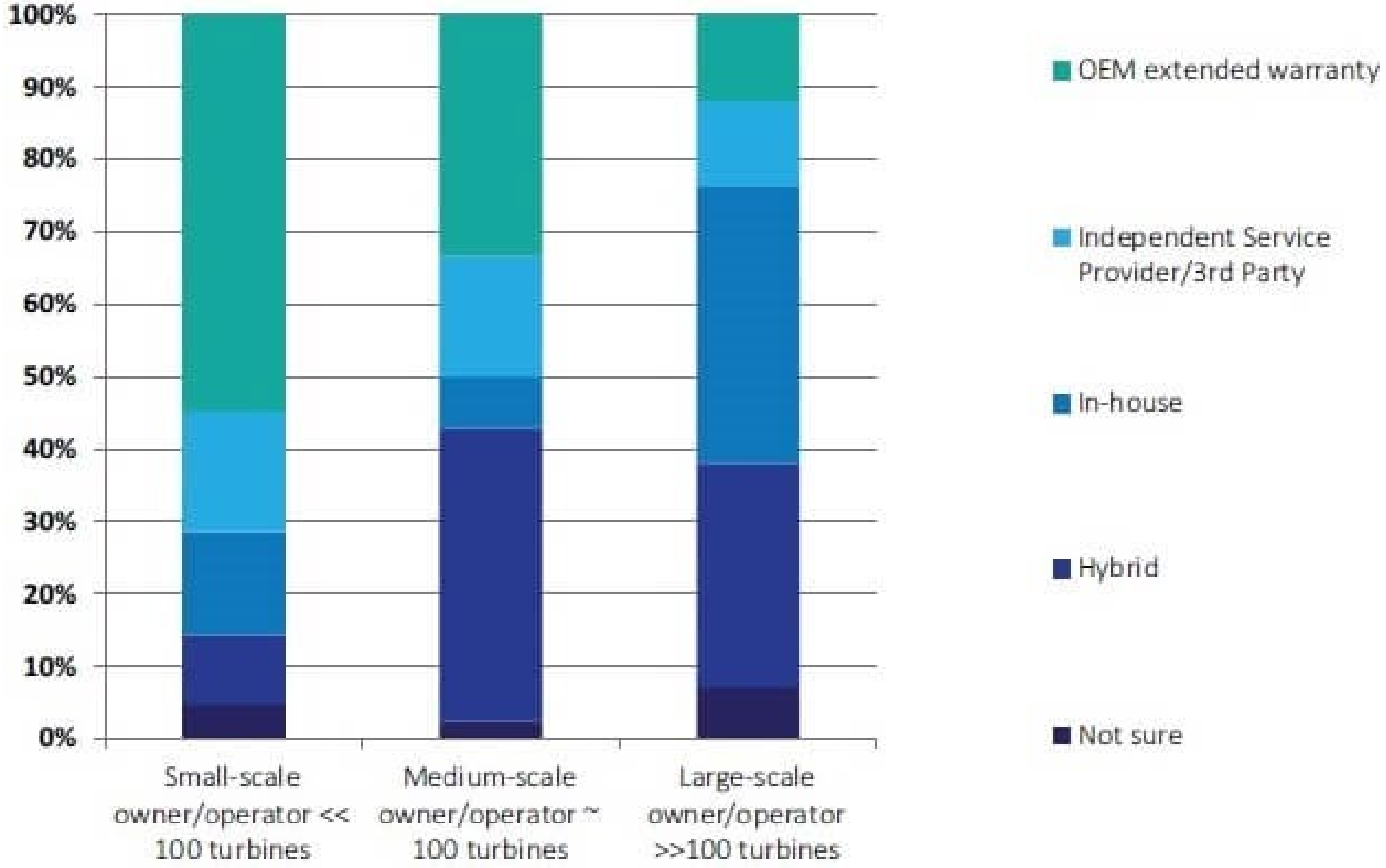
O&M Options and Lifecycle



Source: [6]

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Approaches to Reduce Cost of Energy

$$COE = \frac{C_{Cap} + C_{O\&M}}{E_{Annual}}$$

C_{Cap} – Capital cost

$C_{O\&M}$ – Operation and main. cost

E_{Annual} – Annual energy production

Approaches	*Important and related factors*	*Potential*
Lower C_{Cap}	Production / Policy	+
Lower $C_{O\&M}$	Reliability / Design / Labor	++
Higher E_{annual}	Reliability / Capacity / Efficiency / Location	+++

Reliability is an efficient way to reduce COE – lower $C_{O\&M}$ & higher E_{Annual}

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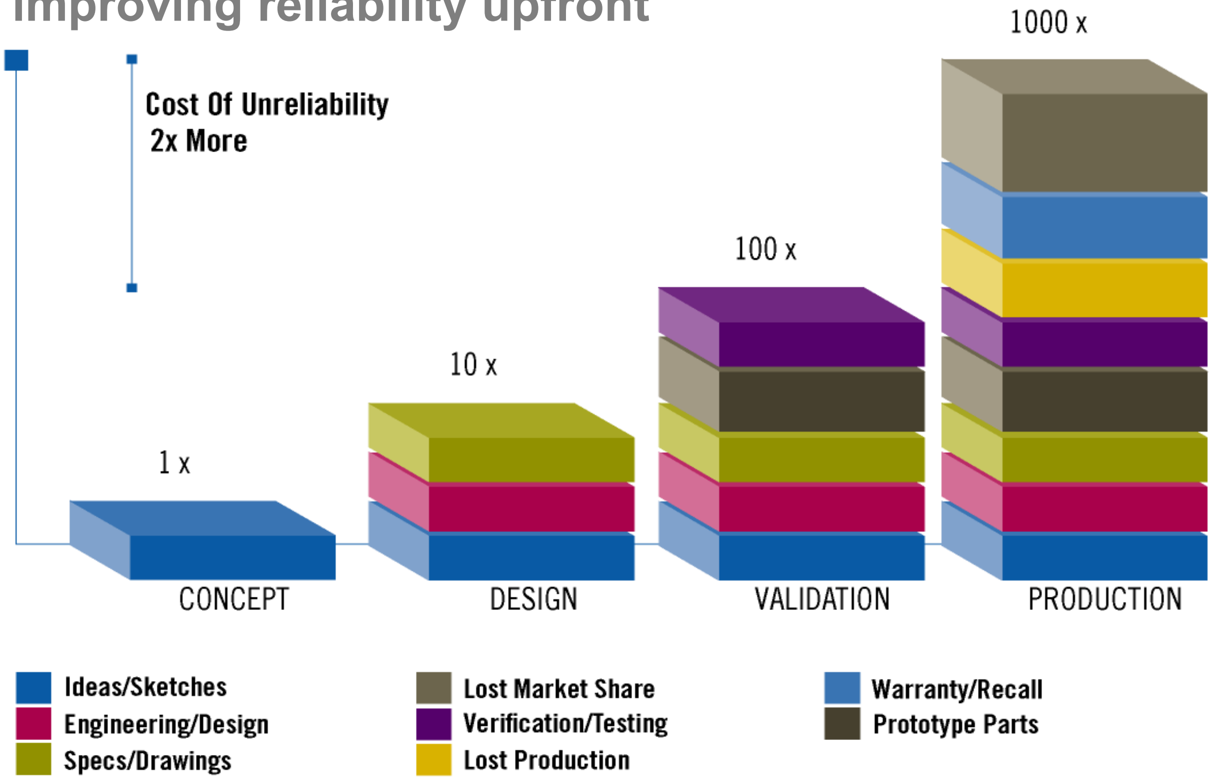
Cost of Unreliability

Reduce costs by improving reliability upfront



Source: DfR Solutions, Designing reliability in electronics, CORPE Workshop, 2012.

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Typical Lifetime Target

Applications	Typical design target of Lifetime
Aircraft	24 years (100,000 hours flight operation)
Automotive	15 years (10,000 operating hours, 300,000 km)
Industry motor drives	5-20 years (40,000 hours in at full load)
Railway	20-30 years (10 hours operation per day)
Wind turbines	20 years (18-24 hours operation per day)
Photovoltaic plants	20-30 years (12 hours per day)

Different O&M program

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Discussion

- O&M phase provides many opportunities to earn, save, or lose, a lot of money
- O&M considerations should be an important consideration in turbine selection (turbine quality, cost & availability of maintenance services).
- Ensure funds are available from the project beginning to cover cost of major repairs (R&R fund).
- Unit O&M costs likely to be higher for small (< 10 MW) projects
- Generally, the annual O&M costs increase over the life of the turbine, especially in later years of 20- to 25-year useful life

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O&M Examples

Source: [7]

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O&M Examples

Source: [8]

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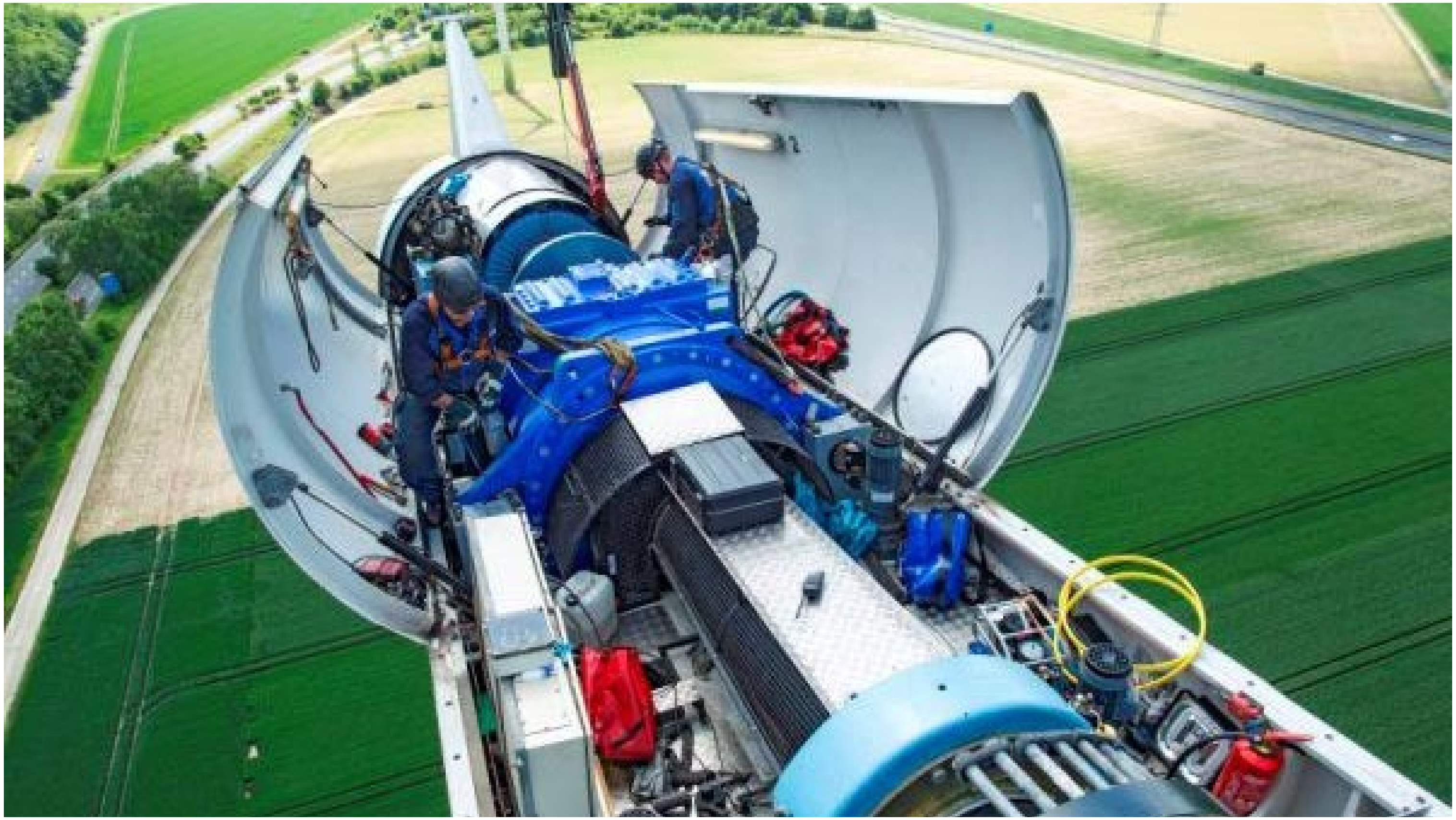
O&M Examples



Source: [9]

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Summary of the provided knowledge

- Discussed the objective of O&M
- O&M will increase the costs
- High reliability is a way to lower O&M cost

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Condition Monitoring

Lecture 5.2

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Learning outcomes

O1. Understand the reason for monitoring

O2. Know the benefits from condition monitoring

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Technical Contents

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What is Condition Monitoring?

- is the process of monitoring a parameter of condition in machinery (vibration, temperature etc.) in order to identify a significant change which is indicative of a developing fault.

- is a major component of predictive maintenance.

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Benefits of Condition Monitoring

- Early deterioration detection to avoid catastrophic failure
-
- Accurate damage evaluation to enable cost-effective maintenance practices (proactive instead of reactive)
- Increase turbine availability and reduce operation and maintenance (O&M) costs
- Root cause analysis to recommend improvements in component design or equipment operation and control strategies

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Applications of CM in Wind Turbines

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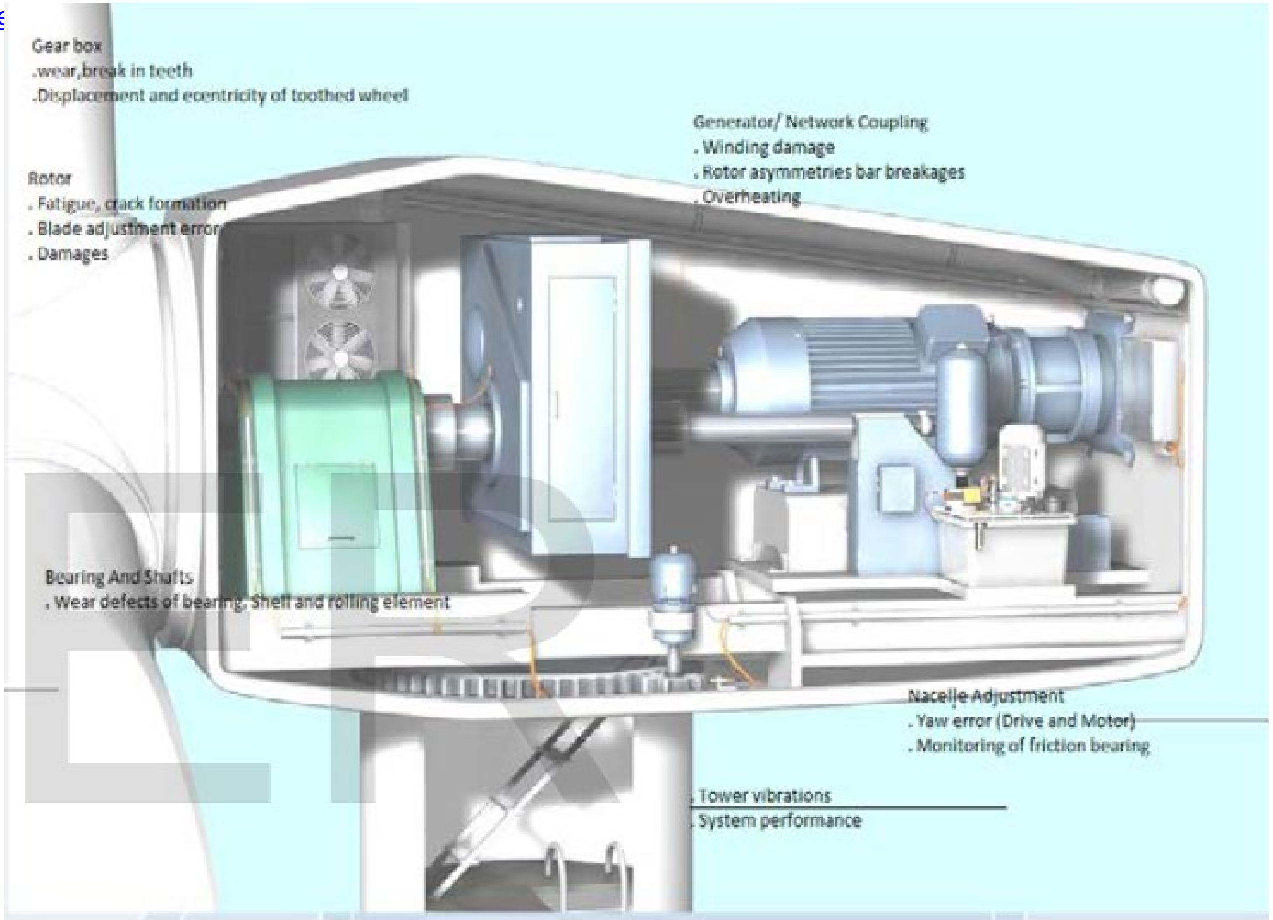

Source: [1]

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Reliability and Downtime of Turbine Subassemblies

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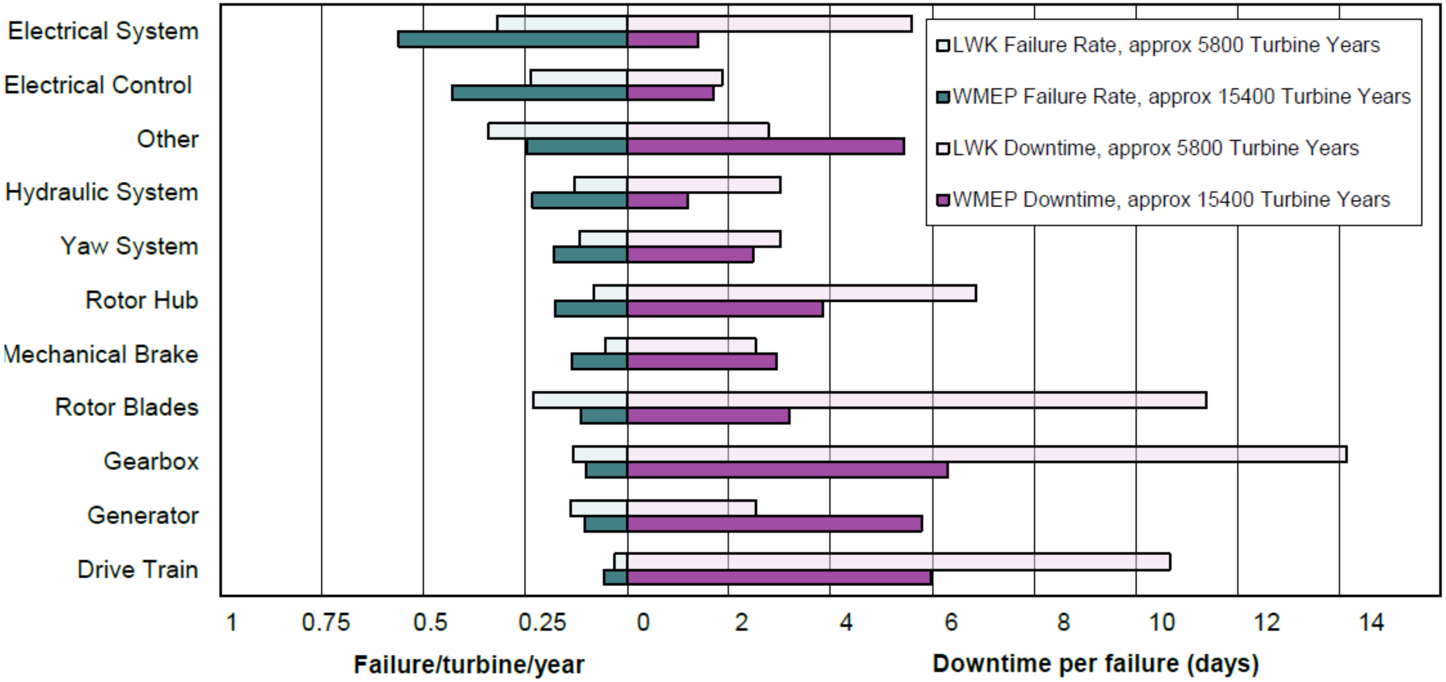
- WMEP: the Wissenschaftliches Mess- und Evaluierungsprogramm (WMEP) database was accomplished from 1989 to 2006 and contains failure statistics from 1,500 wind turbines.
- LWK: failure statistics published by Landwirtschaftskammer Schleswig-Holstein (LWK) from 1993 to 2006. It contains failure data from more than 650 wind turbines.



Source: [2,3]

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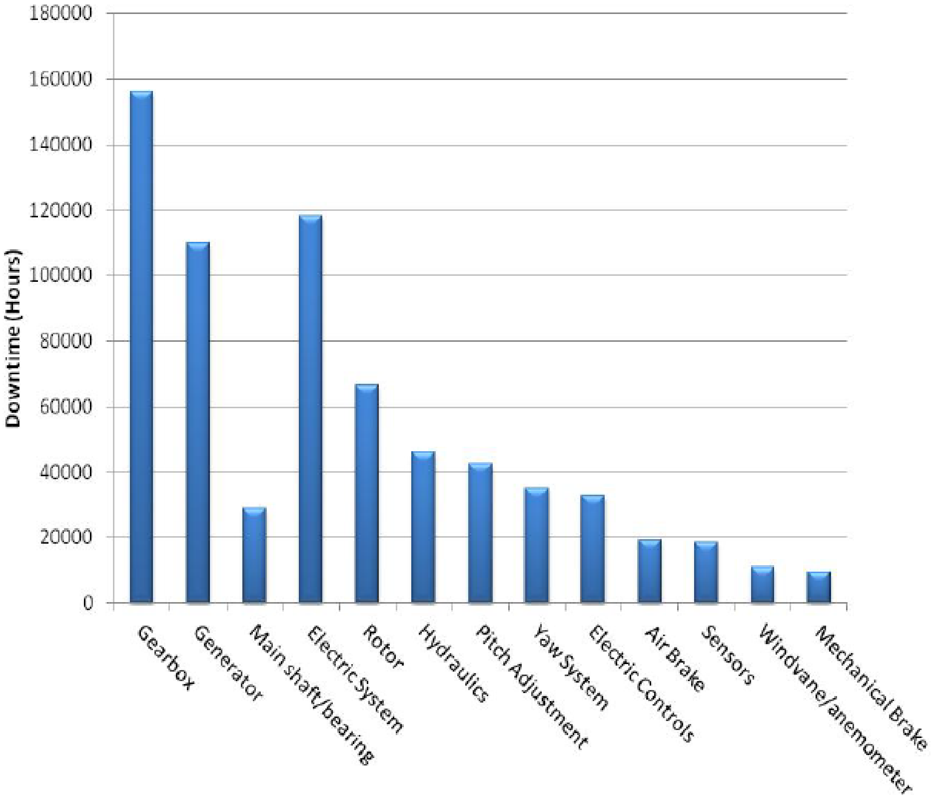
Downtime Caused by Subsystems

- Based on the data reported to Wind Stats for the first quarter of 2010, the data represents about 27,000 turbines, ranging from 500 kW to 5 MW.
- Top three:
  1. Gearbox
  2. Generator
  3. Electric Systems

Data source:
Wind Stats Newsletter
Vol. 16, Issue 1 to Vol. 22 Issue 4
Covering 2003 to 2009



Source: [4]

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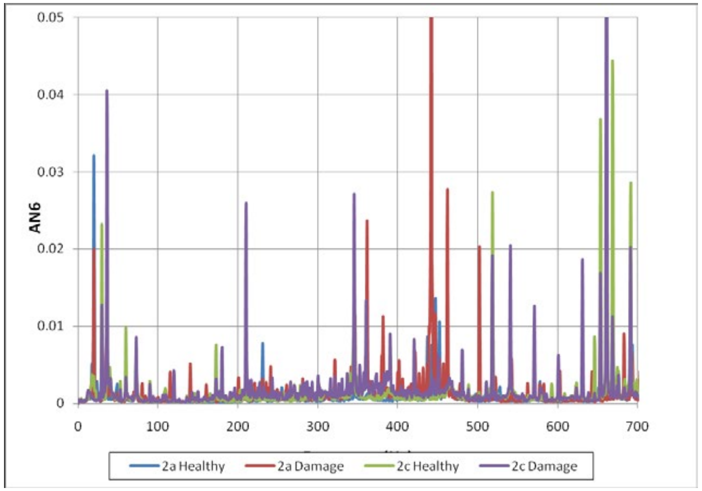
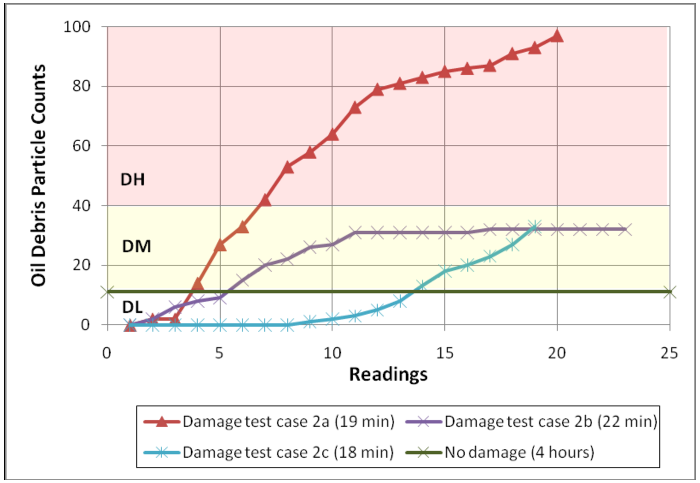
Typical Drivetrain CM Practices

- Techniques:
    - Supervisory control and data acquisition (SCADA) data
    - Acoustic emission (e.g., stress wave) analysis
    - Vibration analysis
    - Oil or grease analysis(oil debris analysis)
    - Electric signature
- Real-time continuous or offline periodic
- One or a combination of several



Sample vibration spectra



Sample oil debris counts

Source: [5]

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SCADA Data

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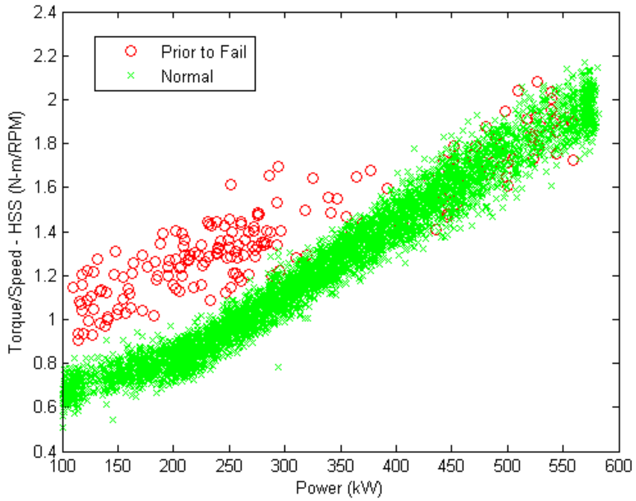
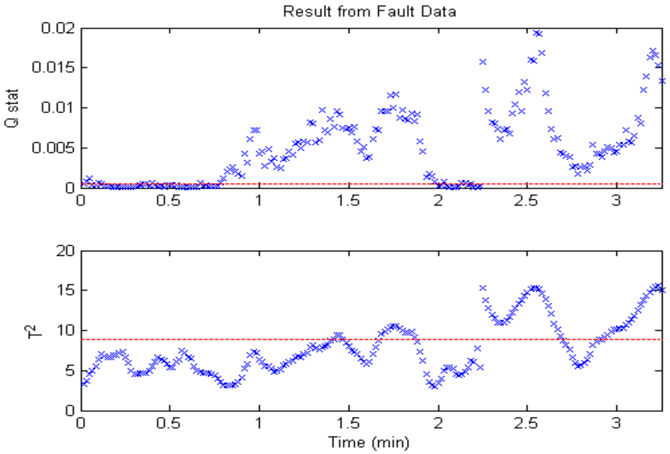
- Readily available and no need of investment on dedicated CM systems
- Beneficial for identifying outliers by looking at key performance parameters, e.g., power
- Temperature channels may be used for CM of main bearings, generator bearings, and gearbox high-speed stage bearings, and so on
- Not straightforward in pinpointing exact damaged subsystems/components



Torque to high-speed shaft speed ratio vs. power



Q-Stat and T^2 values for baseline and fault cases

Source: [6]

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Stress Wave Analysis

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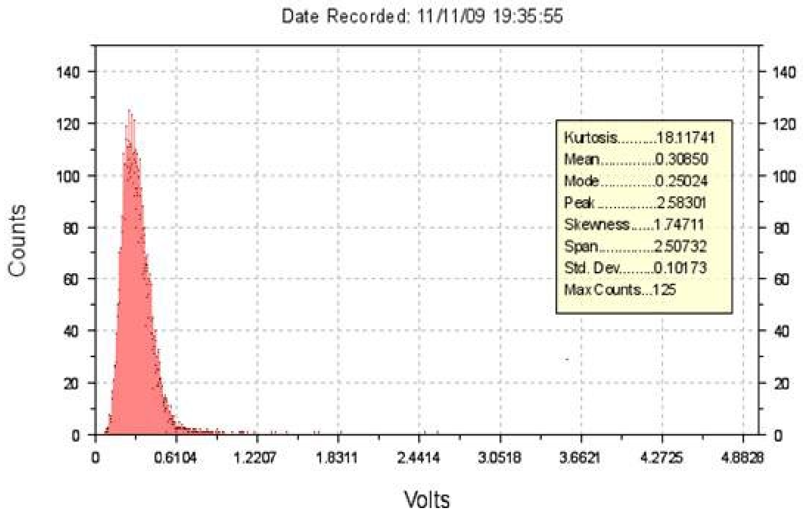
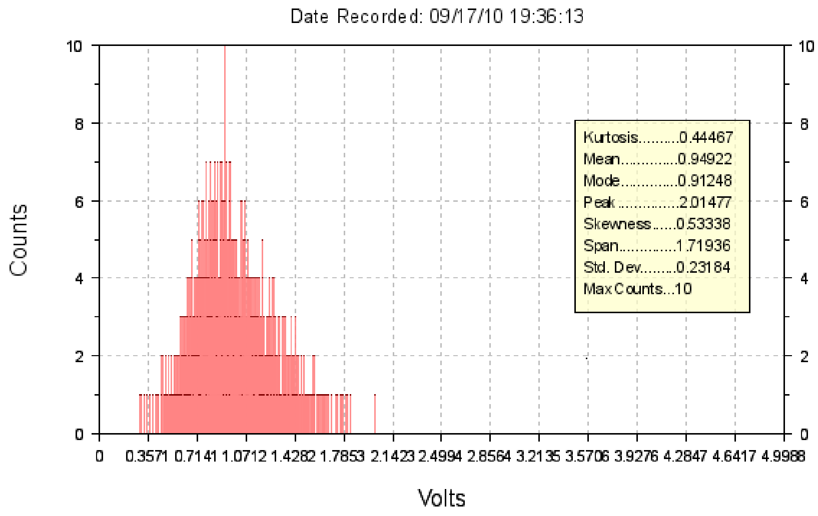
- Dynamometer test of a reference gearbox of the same design indicates healthy gearbox behavior



- Dynamometer retest of the damaged gearbox indicated abnormal gearbox behavior: distorted distribution and relatively higher amplitudes



Source: [7]

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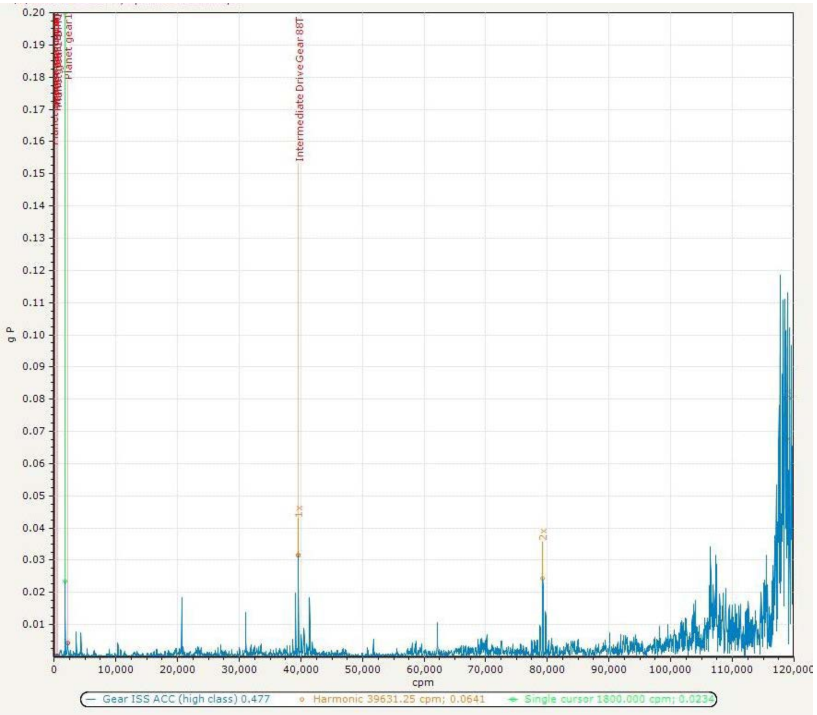
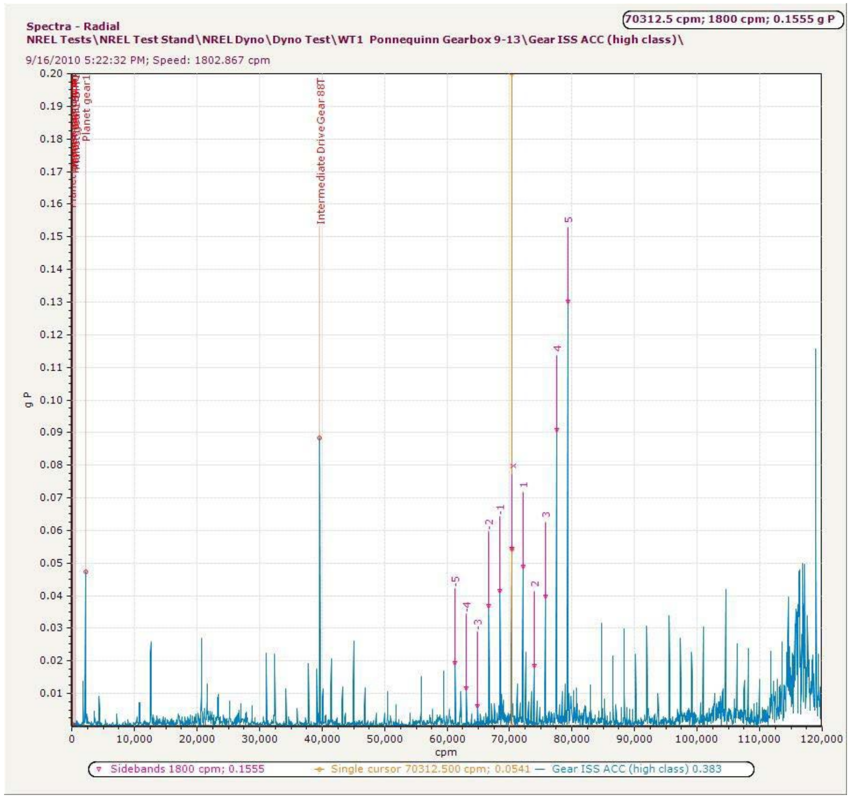
Vibration Analysis



Dynamometer test of the same reference gearbox (left) indicated healthy gearbox behavior



Dynamometer retest of the damaged gearbox (right) indicated abnormal behavior with more side band frequencies and elevated gear meshing frequency amplitudes

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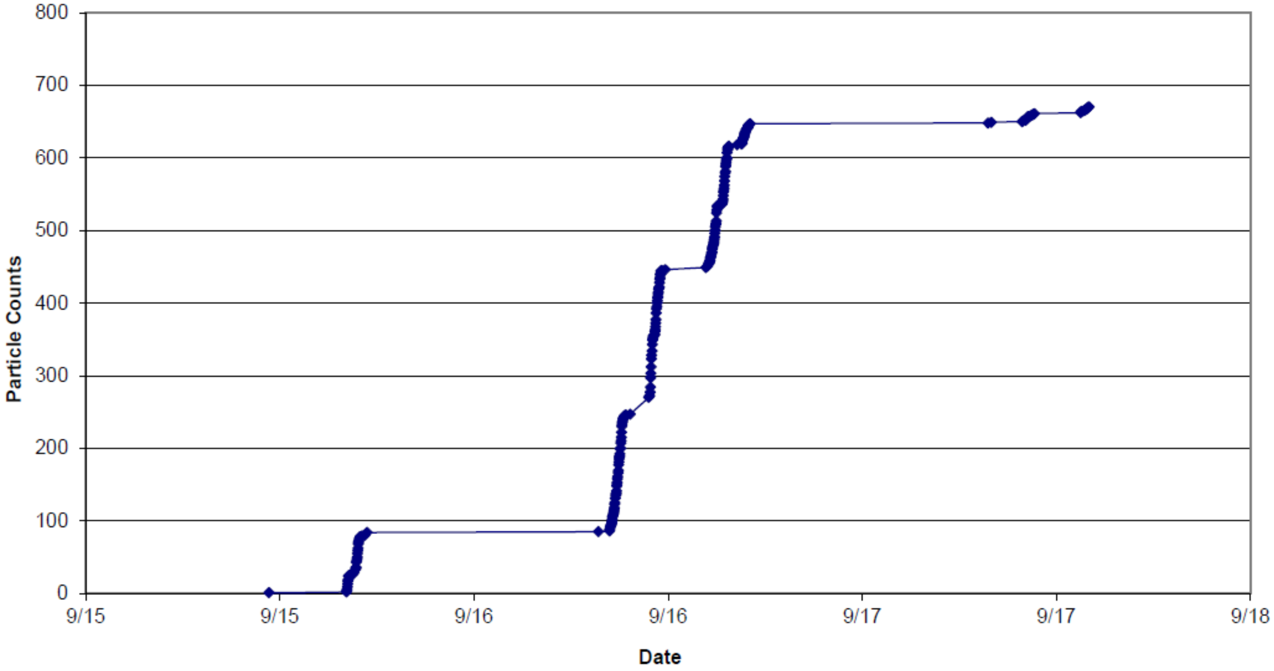
Source: [8]

Oil Debris Monitoring

- Particle generation rates:
  - Damaged test gearbox: 70 particles/hour on 9/16
  - Healthy reference gearbox: 11 particles over a period of 4 hours



Source: [8]

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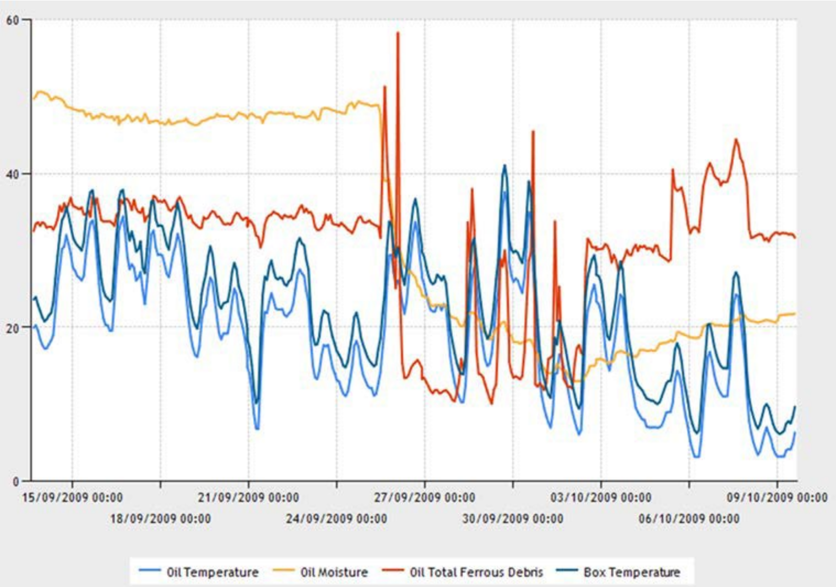
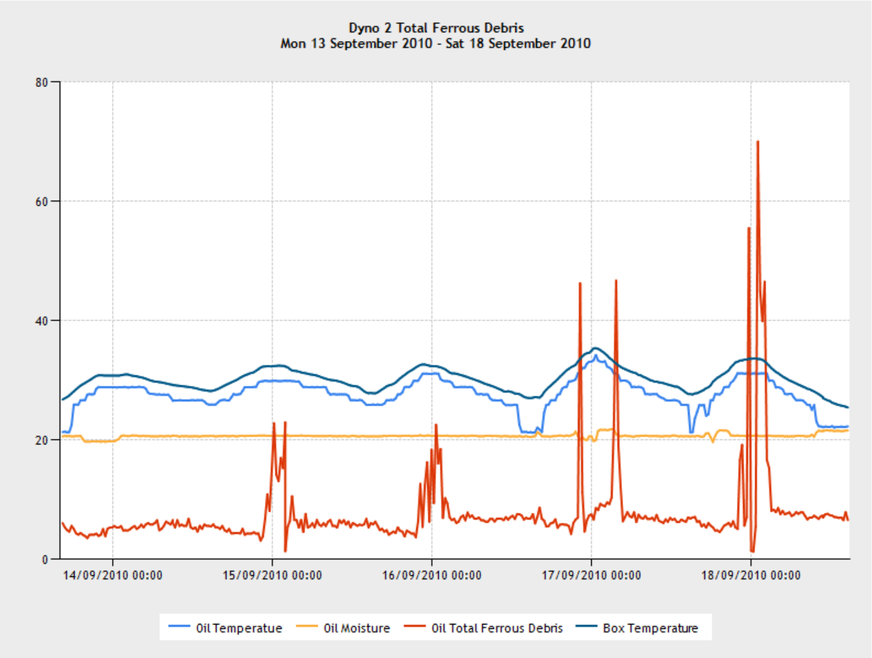
Oil Condition Monitoring





Field test of the test gearbox (left): • Wild dynamics • Possible damage

Dynamometer retest (right): • Well-controlled test conditions • Possible damage

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Source: [9]

Oil Sample Analysis

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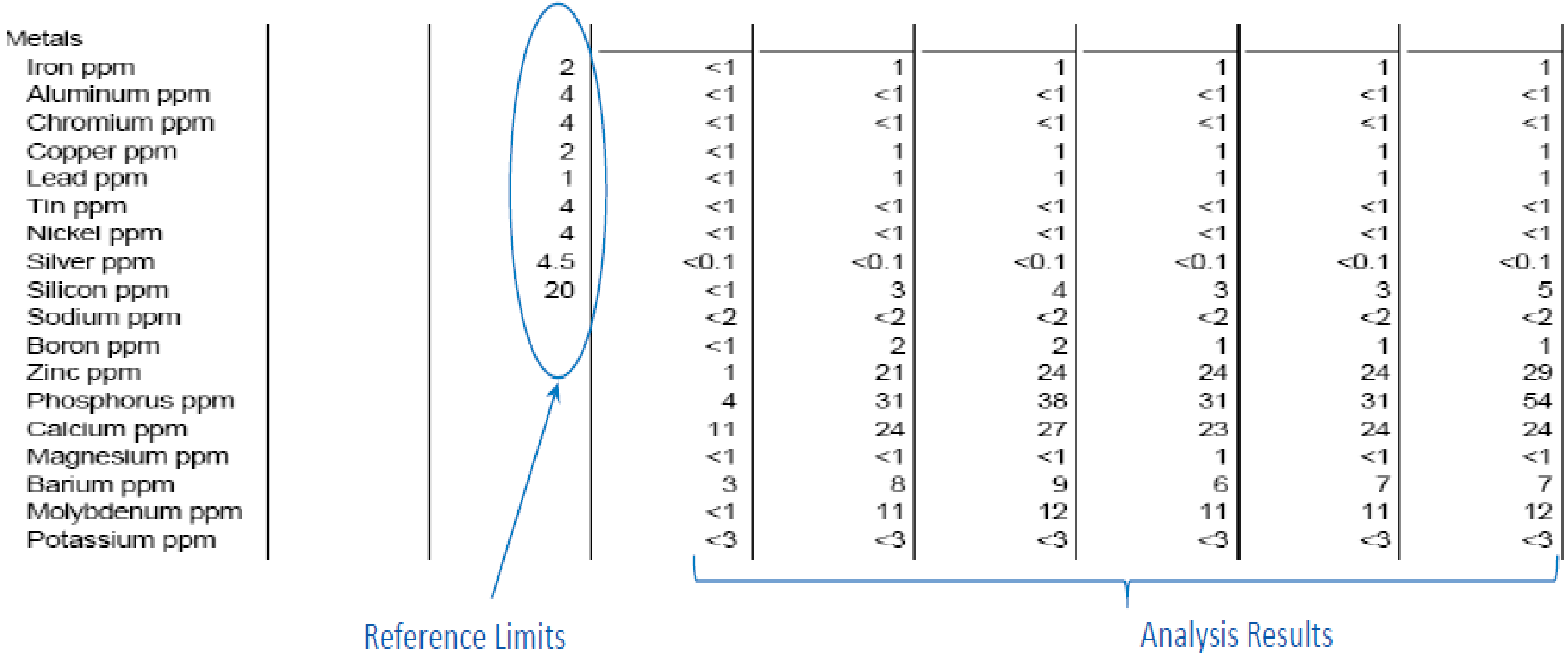

Metals								
Iron ppm		2	<1	1	1	1	1	1
Aluminum ppm		4	<1	<1	<1	<1	<1	<1
Chromium ppm		4	<1	<1	<1	<1	<1	<1
Copper ppm		2	<1	1	1	1	1	1
Lead ppm		1	<1	1	1	1	1	1
Tin ppm		4	<1	<1	<1	<1	<1	<1
Nickel ppm		4	<1	<1	<1	<1	<1	<1
Silver ppm		4.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Silicon ppm		20	<1	3	4	3	3	5
Sodium ppm			<2	<2	<2	<2	<2	<2
Boron ppm			<1	2	2	1	1	1
Zinc ppm			1	21	24	24	24	29
Phosphorus ppm			4	31	38	31	31	54
Calcium ppm			11	24	27	23	24	24
Magnesium ppm			<1	<1	<1	1	<1	<1
Barium ppm			3	8	9	6	7	7
Molybdenum ppm			<1	11	12	11	11	12
Potassium ppm			<3	<3	<3	<3	<3	<3

Reference Limits

Analysis Results

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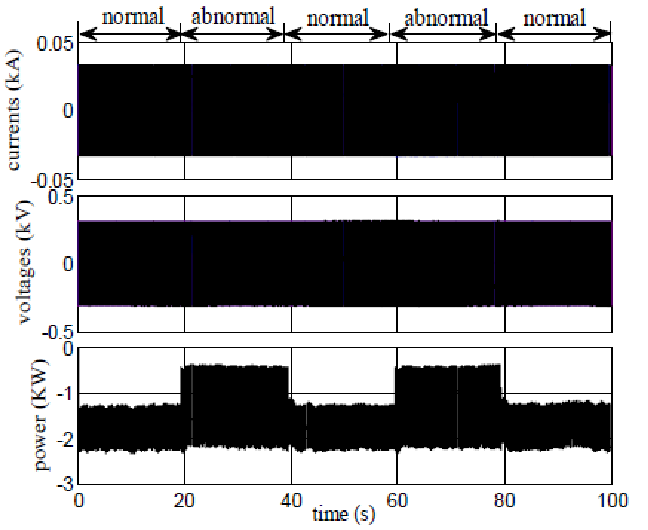
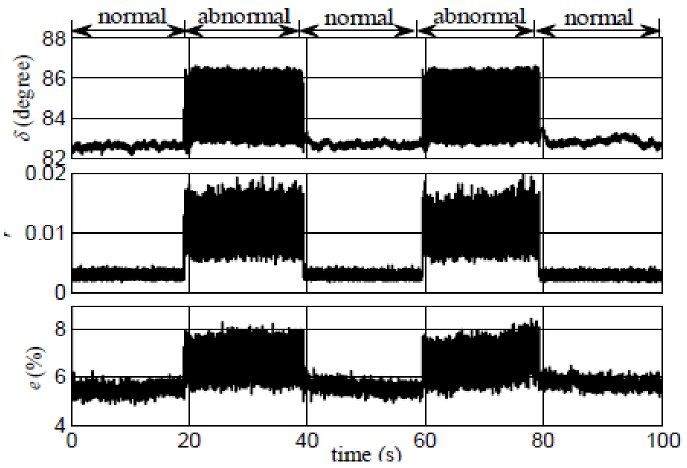
Source: [10]

Electric Signature Analysis

- Capable of detecting both mechanical and electrical faults seen in generators
- Power signals appeared more effective than either currents or voltages
- Not considered to be a suitable alternative to vibration monitoring in geared wind turbines
- May have potential for direct-drive wind turbine drivetrain CM, as generators will replace gearboxes to become the critical component



Electric signals collected from a 30-kW generator test rig with simulated winding asymmetry fault



Faults indicated by three different CM criteria

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Source: [10]

Summary
Condition Monitoring

- SCADA data are beneficial for identifying abnormal turbines by tracking key performance parameters, but are limited when carrying out a full condition monitoring of wind turbine subsystems/components.

- Temperature channels may be used for the CM of main bearings, generator bearings, or gearbox high-speed stage bearings and so on.

- Stress wave analysis (amplitude histogram) appears effective for detecting gearbox abnormal health conditions, but the sensors may be prone to environmental noises.

- Spectrum analysis of the vibration signal (or stress waves) can, to a certain extent, pinpoint the location of damaged gearbox components, but may have challenges with low speed components, such as gearbox planet stage bearings or main bearings.

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Summary
Condition Monitoring

- Oil debris monitoring, specifically particle counts, is effective for monitoring gearbox component damage, but not effective for pinpointing damage locations
- Damaged gearbox releases particles at increased rates
- Oil condition monitoring, specifically moisture, total ferrous debris, and oil quality:
  - Oil total ferrous debris appears indicative for gearbox component damage
  - More data is required to understand oil moisture and quality

- When obtaining particle counts through oil sample analysis, attention should be given to identifying particle types

- Periodic oil sample analysis may help pinpoint failed component and root cause analysis

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Summary
Condition Monitoring

- Electric current analysis appears effective for generator mechanical and electric fault detections:
  - Only verified on laboratory test rigs or small-scale wind turbines thus far
  - Some validations on utility-scale wind turbines are needed before the technique can have a bigger impact
  - Direct-drive wind turbines may present a good opportunity for electric signature analysis
- Given the diverse and complex failure modes seen in wind turbine drivetrains, an integration approach is recommended, starting with an initial digest of SCADA data and then fusing several dedicated techniques by considering their advantages and disadvantages.

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Challenges in Condition Monitoring

- Limited machine accessibility: makes retrofitting of CM systems or taking oil/grease samples difficult

- Cost-effective and universal measurement strategy: sensor readings are affected by mounting locations and various drivetrain and gearbox configurations

- Diagnostics: variable-speed and load conditions and very low rotor speeds challenge traditional diagnostic techniques developed for other applications

- Data interpretation for both SCADA and dedicated CM systems: requires expert assistance for data analysis and maintenance recommendations

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Challenges in Condition Monitoring

- Oil sample analysis: sample variations, different lubricant may require different sets of tests or procedures

- Additional complexity for offshore: foundation, undersea transmission lines, saltwater and wave influences on turbine, and weather forecast

- The limitations of existing industry standards in the application to wind industry

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Summary of the provided knowledge

- Discussed the importance of CM
- Presented various CM practices
- Discussed the challenges in CM

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[15] https://globalwindatlas.info/

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Presentation of the Designed Project

Lecture 6.1

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Learning outcomes

O1. Summarize the learning in the course

O2. Practice presentation skills

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Guidelines

- Students (max 4) should be in groups
- Present what has been learned from the course
- Maximum 20 mins + 5 mins Q&A
- Title is not limited

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References

[1] Manwell, James F., Jon G. McGowan, and Anthony L. Rogers. Wind energy explained: theory, design and application. John Wiley & Sons, 2010.

[2] Hau, Erich. Wind turbines: fundamentals, technologies, application, economics. Springer Science & Business Media, 2013.

[3] https://www.re-explorer.org/launch.html

[4] Solar and Wind energy resource assessment (SWERA): https://openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA)

[5] https://globalwindatlas.info/

[6] MIT Wind: http://web.mit.edu/windenergy/

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www.weset-project.eu

Thank You for Your Attention!

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