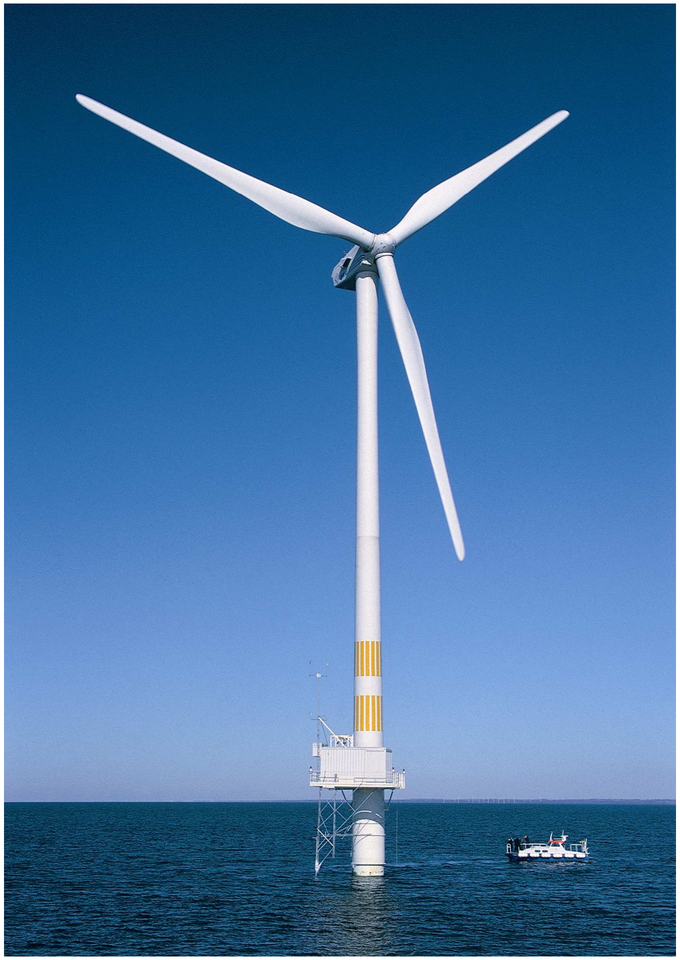
Introduction to wind energy

Relevant to offshore wind farm design



Offshore Wind Farm Design

Michiel Zaaijer

2007-2008

Overview

- Rotor aerodynamics
- Power and load control
- Energy production
- Turbine technology
- Multi-MW turbines turbines

Rotor aerodynamics

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Determining power and loads

0. The approach

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Blade element – momentum method

1. Momentum balance

Macroscopic perspective

Loads from conservation laws

$\equiv$

2. Blade elements

Local perspective

Loads from lift and drag

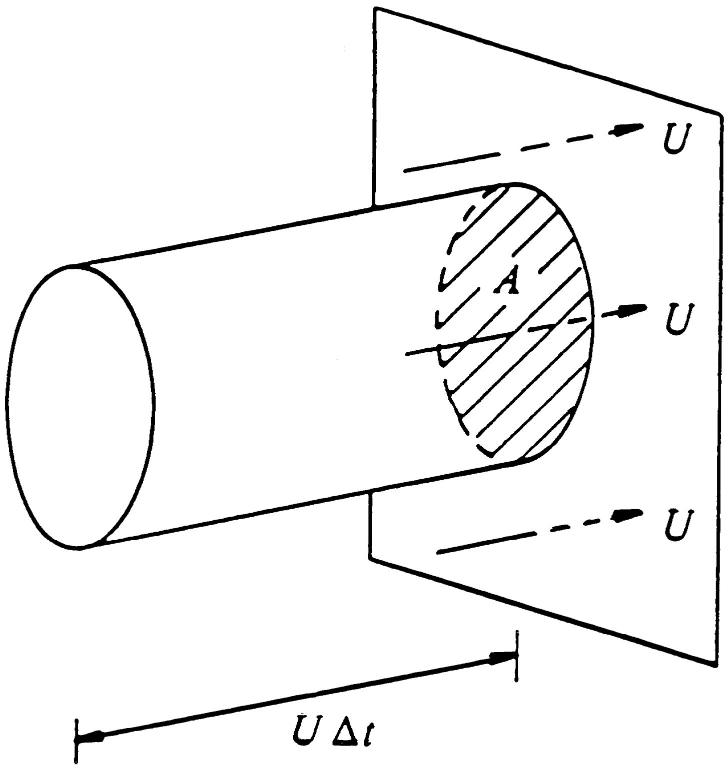
Determining power and loads

1. Momentum balance

Mass, momentum and energy flows

Mass per second through A:

Mass flow $\dot{m} = \rho\, U\, A$

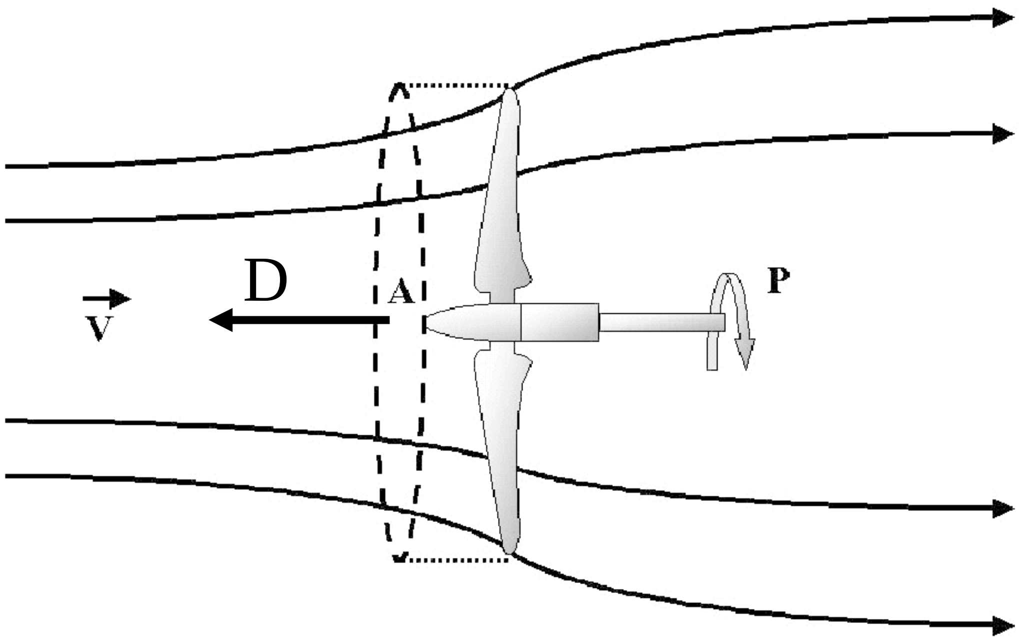


Substitute:

Momentum flow $\dot{m}\, U = \rho\, U^2\, A$

Energy flow $\frac{1}{2}\, \dot{m}\, U^2 = \frac{1}{2}\, \rho\, U^3\, A$

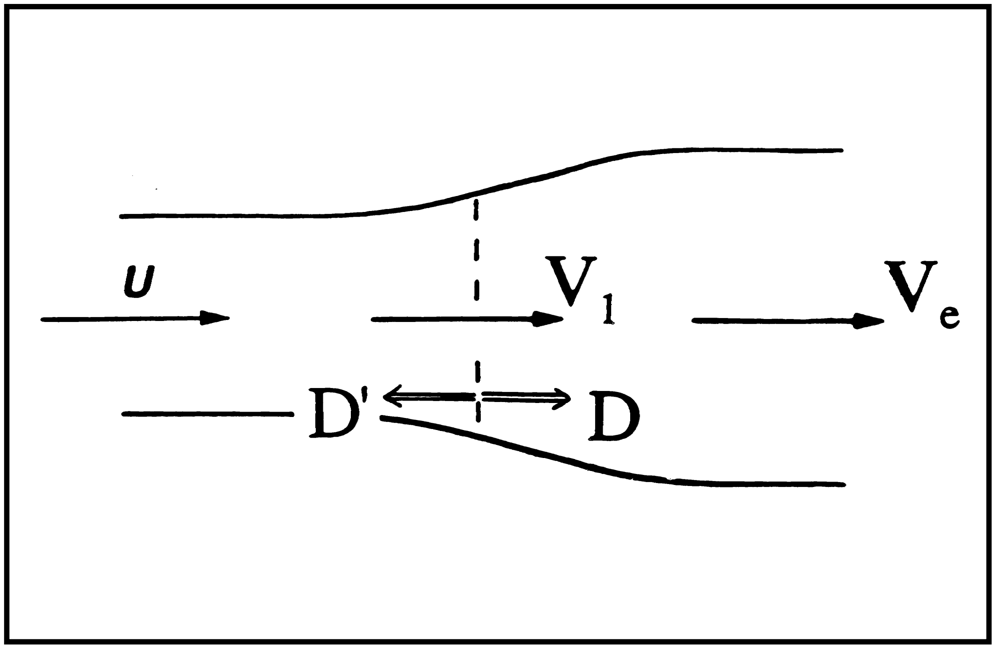
Actuator disc – represents rotor



At actuator disc:

Axial rotor force (thrust) D
Power extraction P

Conservation laws



Thrust ≡ change in momentum

$$D = m\,(U - V_e)$$

Power extracted at rotor disc

$$D\,V_1 = m\,V_1\,(U - V_e)$$

Kinetic energy loss in flow

$$\tfrac{1}{2}\,m\,(U^2 - V_e^2) =$$
$$\tfrac{1}{2}\,m\,(U - V_e)\,(U + V_e)$$

Power ≡ Energy loss

$$V_1 = \tfrac{1}{2}\,(U + V_e)$$

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Dimensionless induction factor

Define induction factor (dimensionless)

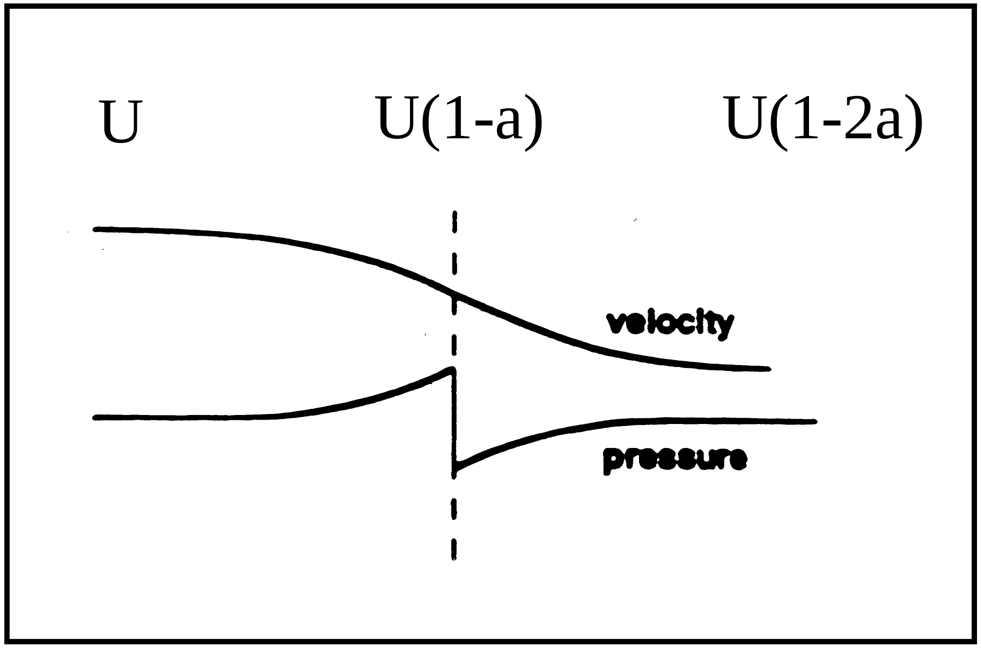
$a = (U - V_1)/U$

Rearrange

$V_1 = U\,(1-a)$

Substitute on previous page

$V_e = U\,(1-2a)$



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Substitution with induction factor

Mass flow

$m = \rho V_1 A \qquad = \rho U (1-a) A$

Thrust

$D = m (U-V_e) \qquad = \frac{1}{2} \rho U^2 A\, 4a(1-a)$

Power

$$P = \frac{1}{2} m (U^2-V_e^2)$$
$$= \frac{1}{2} m (U-V_e)(U+V_e) = \frac{1}{2} \rho U^3 A\, 4a(1-a)^2$$

Dimensionless thrust and power

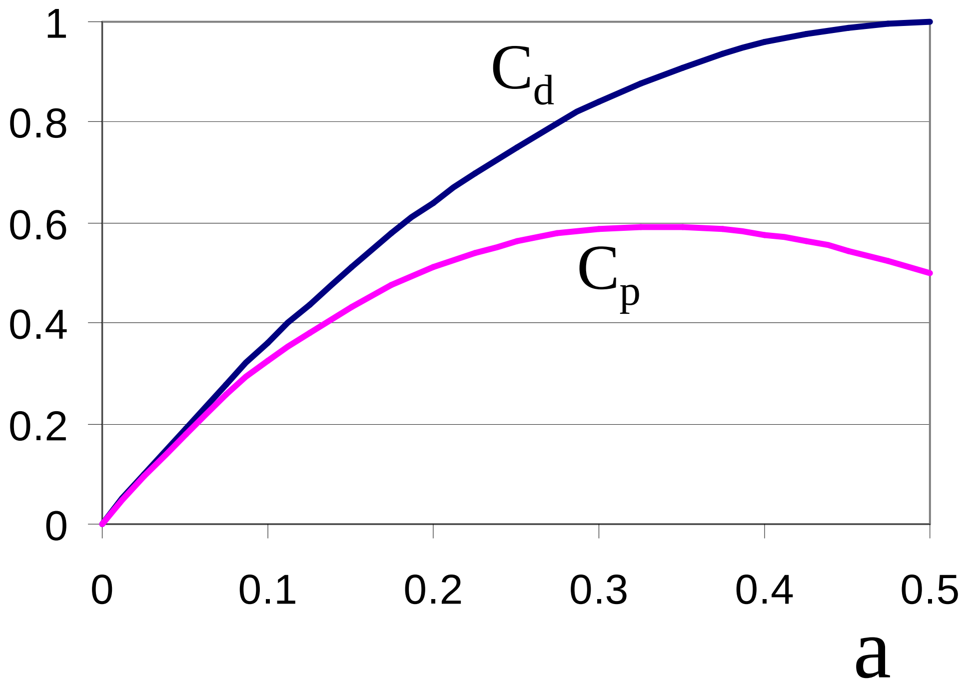
Define

$$D = \frac{1}{2} \rho U^2 A \, 4a(1-a) = \frac{1}{2} \rho C_d U^2 A$$
$$P = \frac{1}{2} \rho U^3 A \, 4a(1-a)^2 = \frac{1}{2} \rho C_p U^3 A$$

Dimensionless coefficients become

$$C_d = 4 a (1-a)$$
$$C_p = 4 a (1-a)^2$$

Intermezzo: Optimum power



The Betz optimum:
C_p is maximum when

$$\frac{dC_p}{da} = 0$$

Result

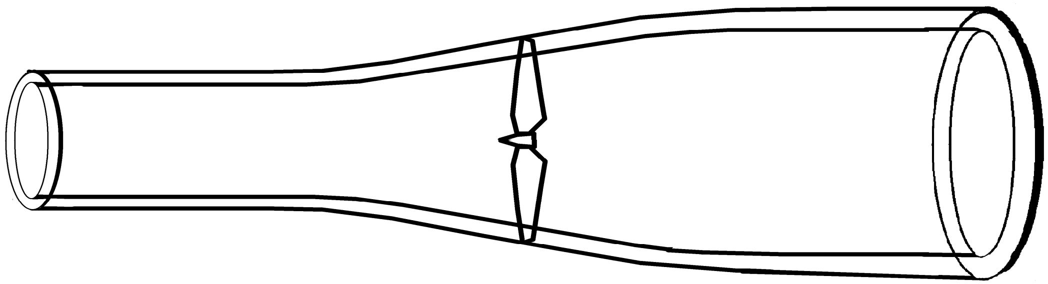
$a = 1/3$

$C_{P,max} = 16/27 \approx 0.59$

$C_d = 8/9$

Annular approach

Divide stream tube in concentric annuli, parallel to flow



Assumptions

1. Annuli don't interact
   - Induction factor 'a' independent of other annuli
   - No flow from one annulus to another)
2. No tangential change within one annulus
   - Induction factor 'a' constant over annulus

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Mass, thrust and power per annulus

Mass flow

$m \quad = \rho V_1 A \qquad = \rho U (1-a) A$

$dm \quad =$ mass per annulus $\quad = \rho U (1-a) 2\pi r\, dr$

Thrust

$D \quad = m (U-V_e) \qquad = ½ \rho U^2 4a(1-a) A$

$dD \quad =$ thrust per annulus $\quad = ½ \rho U^2 4a(1-a) 2\pi r\, dr$

Power

$P \quad = ½ m (U^2-V_e^2) \qquad = ½ \rho U^3 4a(1-a)^2 A$

$dP \quad =$ power per annulus $\quad = ½ \rho U^3 4a(1-a)^2 2\pi r\, dr$

Determining power and loads

2. Blade elements of a rotor

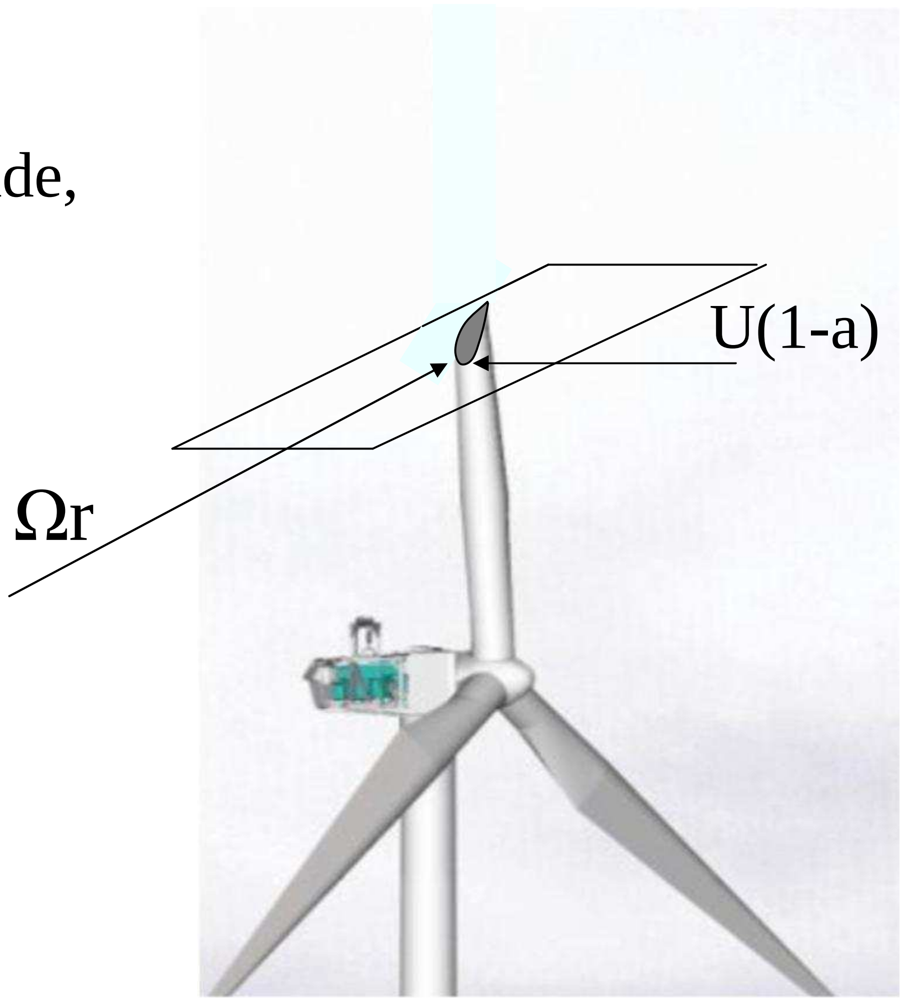
Cross-section of blade

Consider cross-section of blade,

perpendicular to blade axis,

with velocity vectors

U(1-a) and Ωr



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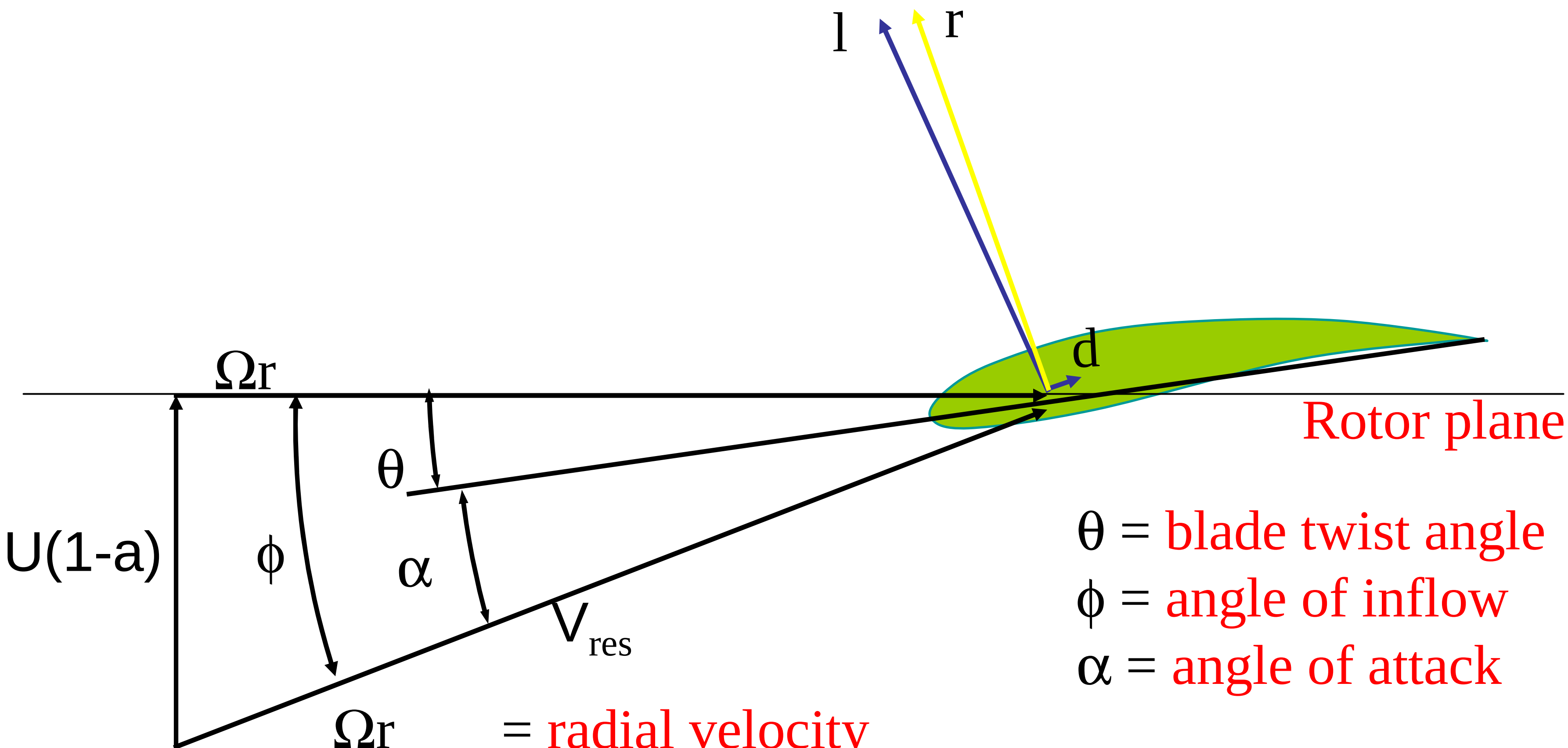
Aerofoil forces and velocities



θ = blade twist angle
ϕ = angle of inflow
α = angle of attack

Ωr = radial velocity
$U(1-a)$ = local wind speed
V_{res} = resultant speed

l = lift $\perp V_{res}$
d = drag // V_{res}

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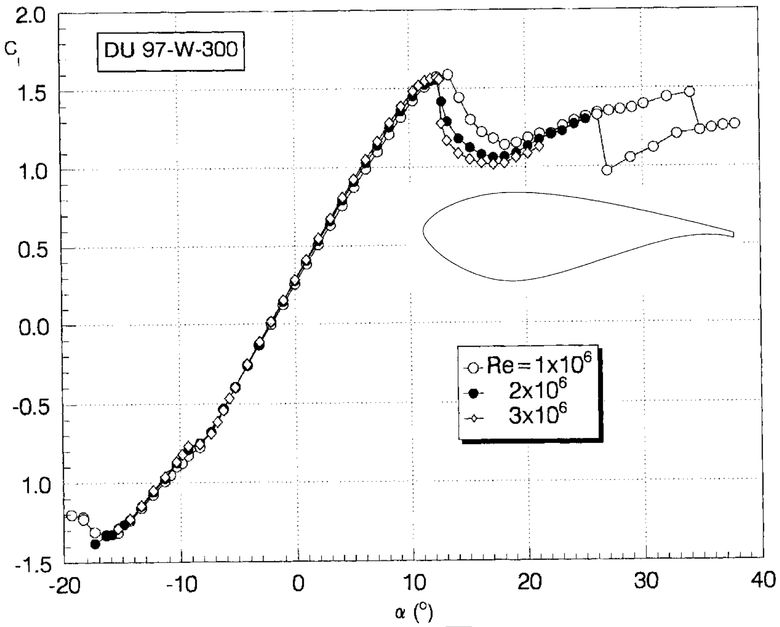
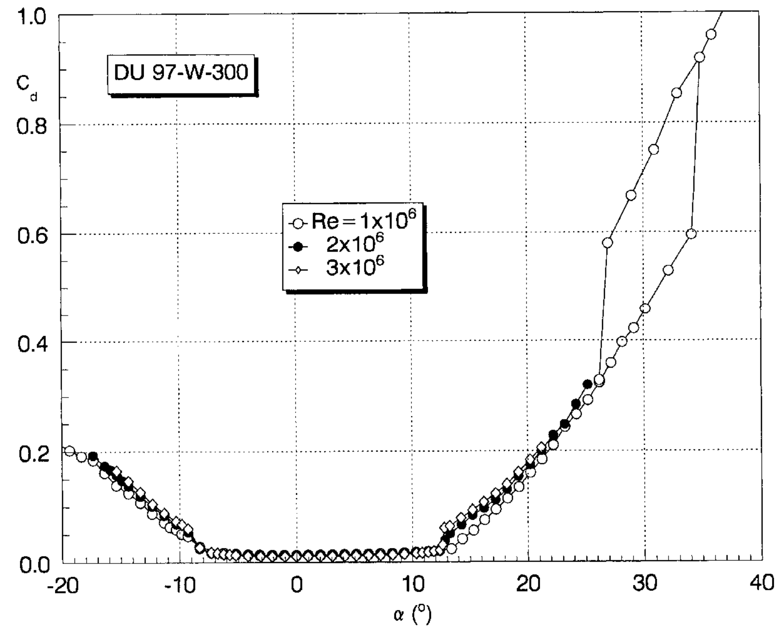
Lift and drag (2-dimensional flow)





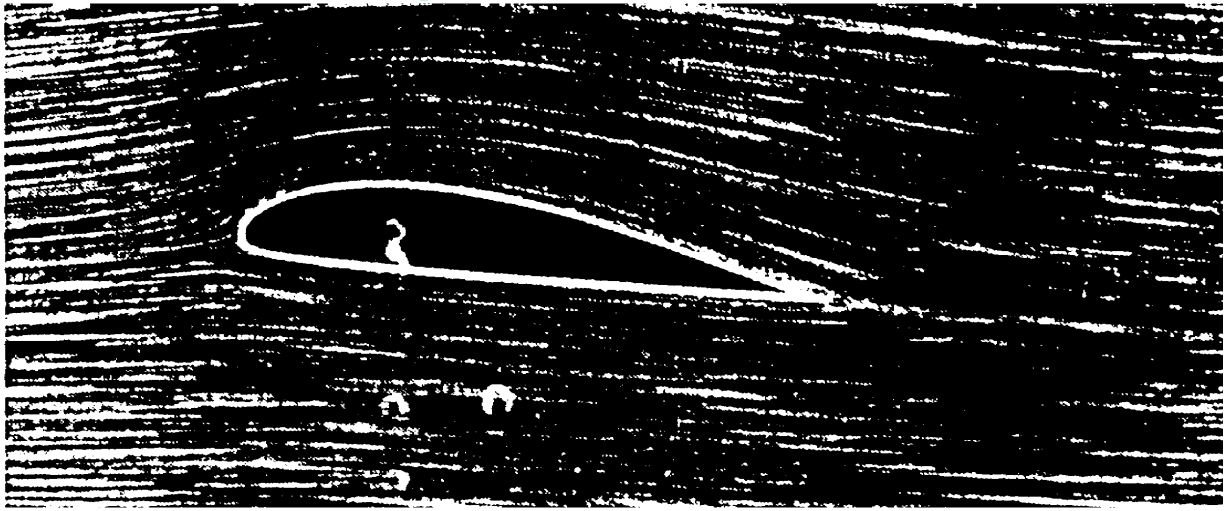
$$l = C_l \cdot \frac{1}{2} \rho U^2 c$$

Lift coefficient

$$d = C_d \cdot \frac{1}{2} \rho U^2 c$$

Drag coefficient

Flow regimes



after Prandtl and Wieselsberger

Attached flow

Separated flow (stalled)

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Thrust and power

Contribution to thrust dD per blade element dr

$dD = N\,(\,l\cos(\phi) + d\sin(\phi)\,)\,dr$ N = Number of blades

$dD = N\,(\,C_l\,\tfrac{1}{2}\,\rho\,V_{res}^2\cos(\phi) + C_d\,\tfrac{1}{2}\,\rho\,V_{res}^2\sin(\phi)\,)\,c\,dr$

$dD = N\,(\,C_l\,\tfrac{1}{2}\,\rho\,(\Omega r)^2 + C_d\,\tfrac{1}{2}\,\rho\,(U(1-a))^2\,)\,c\,dr$

Contribution to power dP per blade element dr

$dP = N\,(\,l\sin(\phi) - d\cos(\phi)\,)\,\Omega r\,dr$

$dP = N\,(\,C_l\,\tfrac{1}{2}\,\rho\,(U(1-a))^2 - C_d\,\tfrac{1}{2}\,\rho\,(\Omega r)^2\,)\,c\,\Omega r\,dr$

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Determining power and loads

3. Blade element – momentum method: BEM

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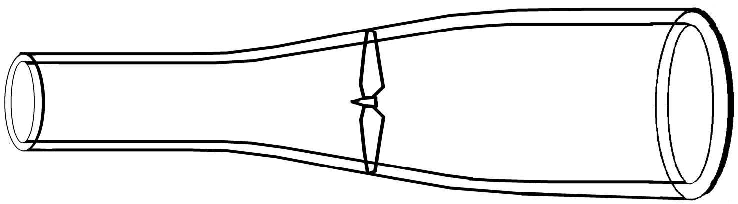
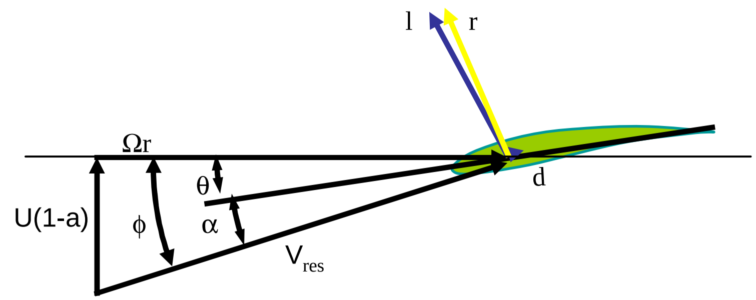
Combining two theories



Momentum balance

$$dD = \tfrac{1}{2}\,\rho\,U^2\,4a(1-a)\,2\pi r\,dr$$



Blade elements

$$dD = N\left(C_l\,\tfrac{1}{2}\,\rho\,(\Omega r)^2 + C_d\,\tfrac{1}{2}\,\rho\,(U(1-a))^2\right) c\,dr$$

When we assume $dD_{\text{momentum balance}} = dD_{\text{blade elements}}$

→ Two equations – two unknowns: dD and a

Solving induction factor with BEM

For each annulus:

Choose an initial value for ‘a’.

Use this to calculate angle of attack and from this C_l and C_d

Calculate axial aerodynamic force on blade element: dD

From dD follows a new value for ‘a’ with momentum theory

Continue until ‘a’ reaches a constant value.

Solving loads and power with BEM

Once ‘a’ is known for all annuli, integrate blade elements

Thrust on rotor

$$D = \int_0^R N \left(C_l \tfrac{1}{2} \rho (\Omega r)^2 + C_d \tfrac{1}{2} \rho (U(1-a))^2 \right) c \, dr$$

Power on main shaft

$$P = \int_0^R N \left(C_l \tfrac{1}{2} \rho (U(1-a))^2 - C_d \tfrac{1}{2} \rho (\Omega r)^2 \right) c \, \Omega r \, dr$$

Additions to BEM

- Tip losses / infinite number of blades
- Wake rotation (tangential forces and velocities)

Included in all state-of-the-art calculation tools

Characterising rotor aerodynamics

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The C_p - λ curve

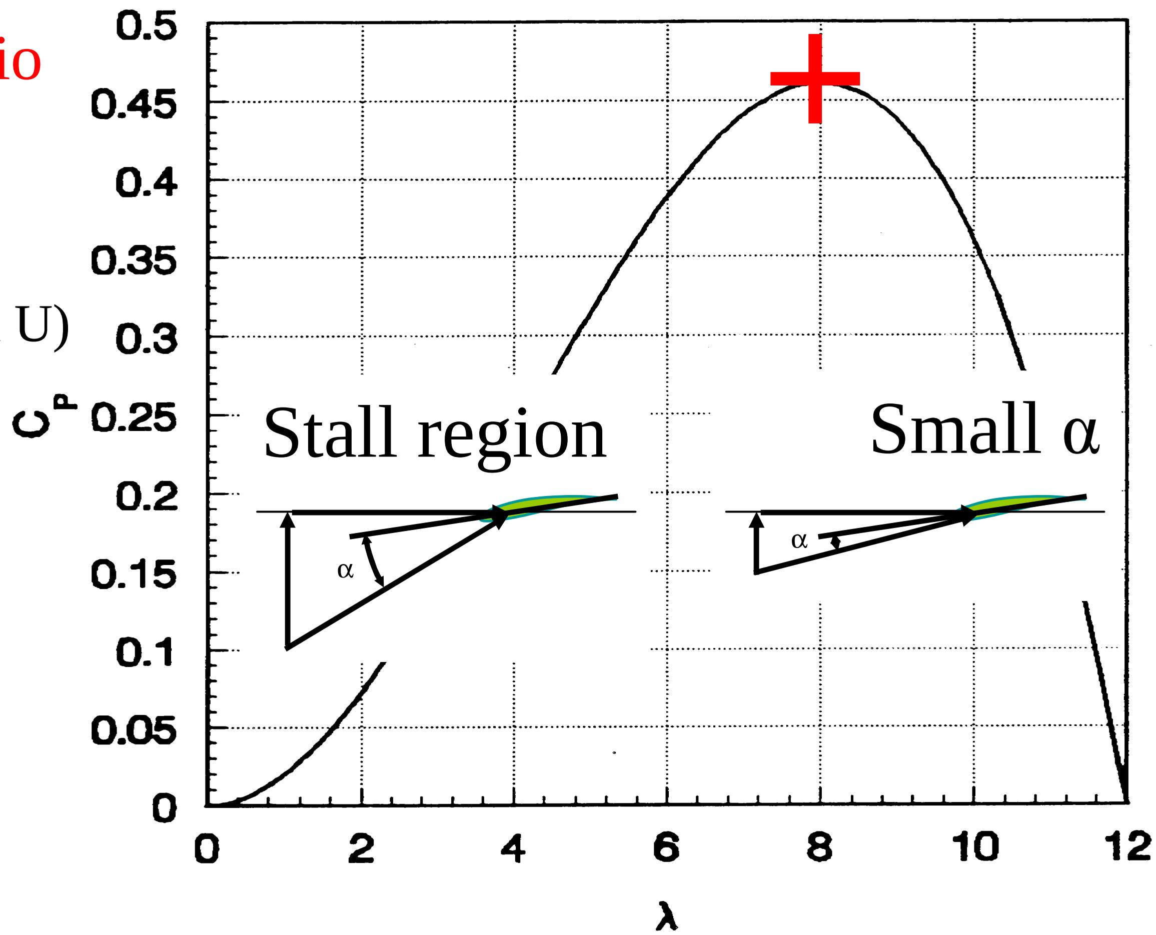
Define tip speed ratio

$$\lambda = \Omega R / U$$

(Low λ = low Ω or high U)

Example

$\lambda_{design} = 8$
$C_{p,max} = 0.46$



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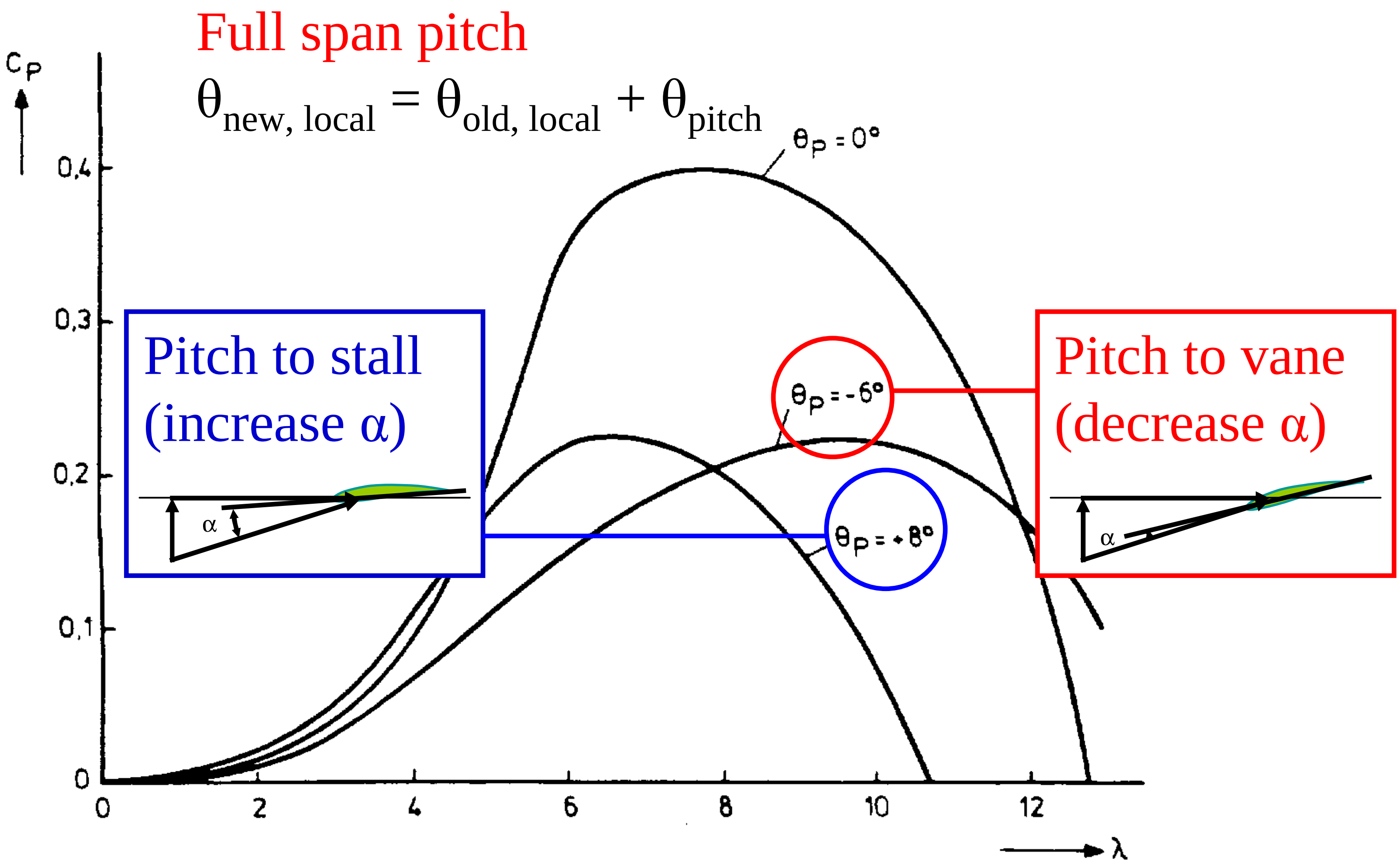
Cp-λ curves for different pitch



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Wind turbine control

Aerodynamic aspects

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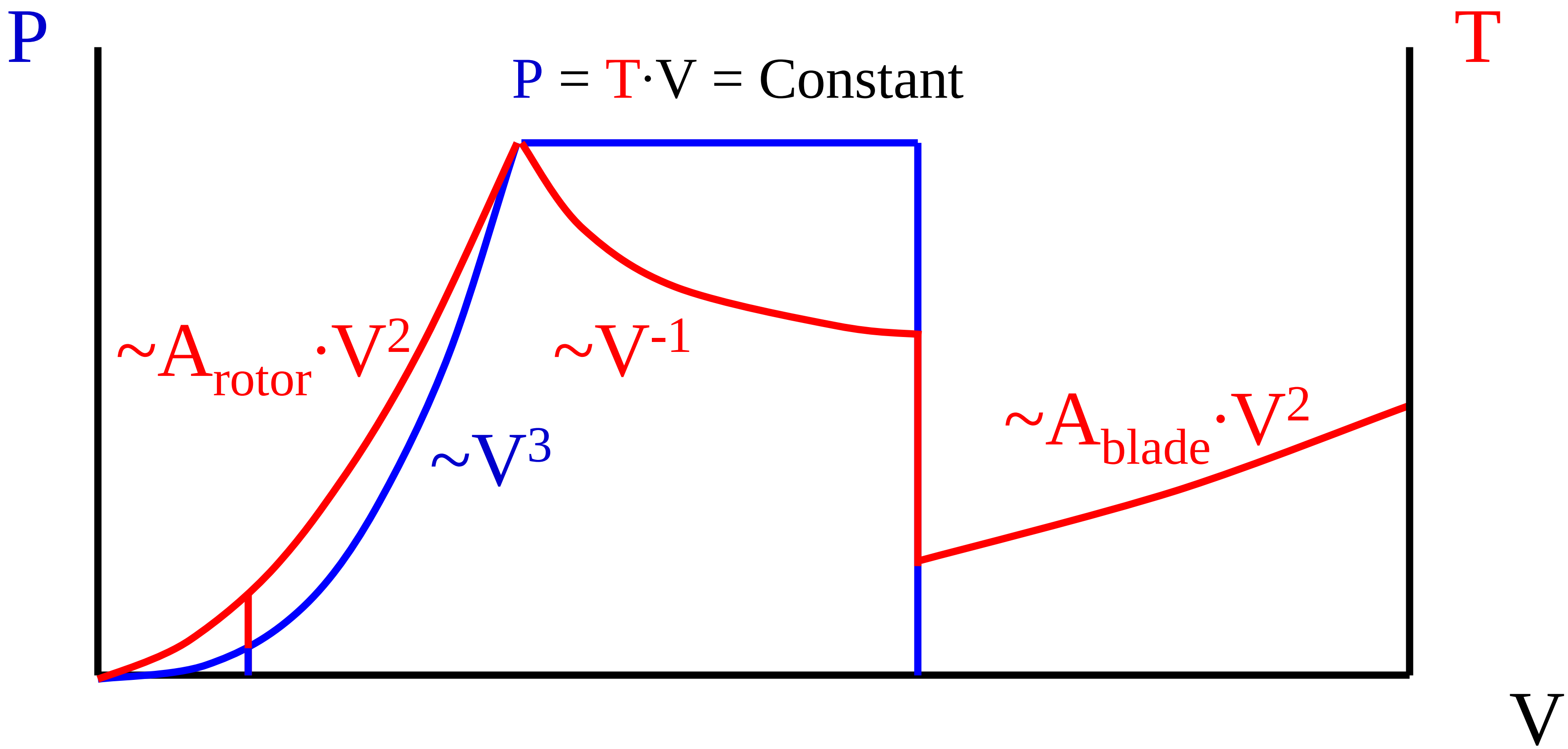
Power and thrust curves

"Ideal" Power and thrust curves



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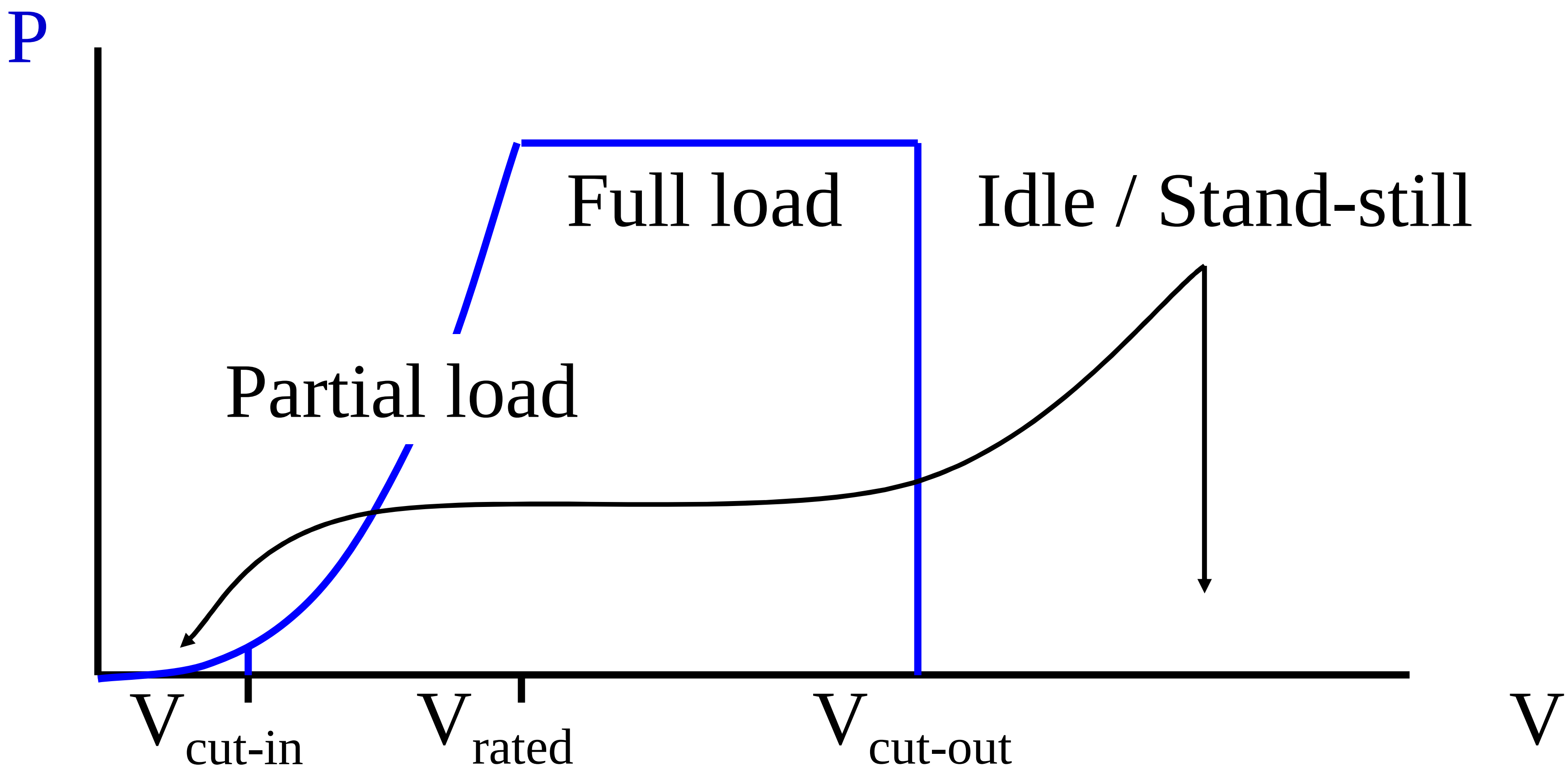
Terminology for regions of operation



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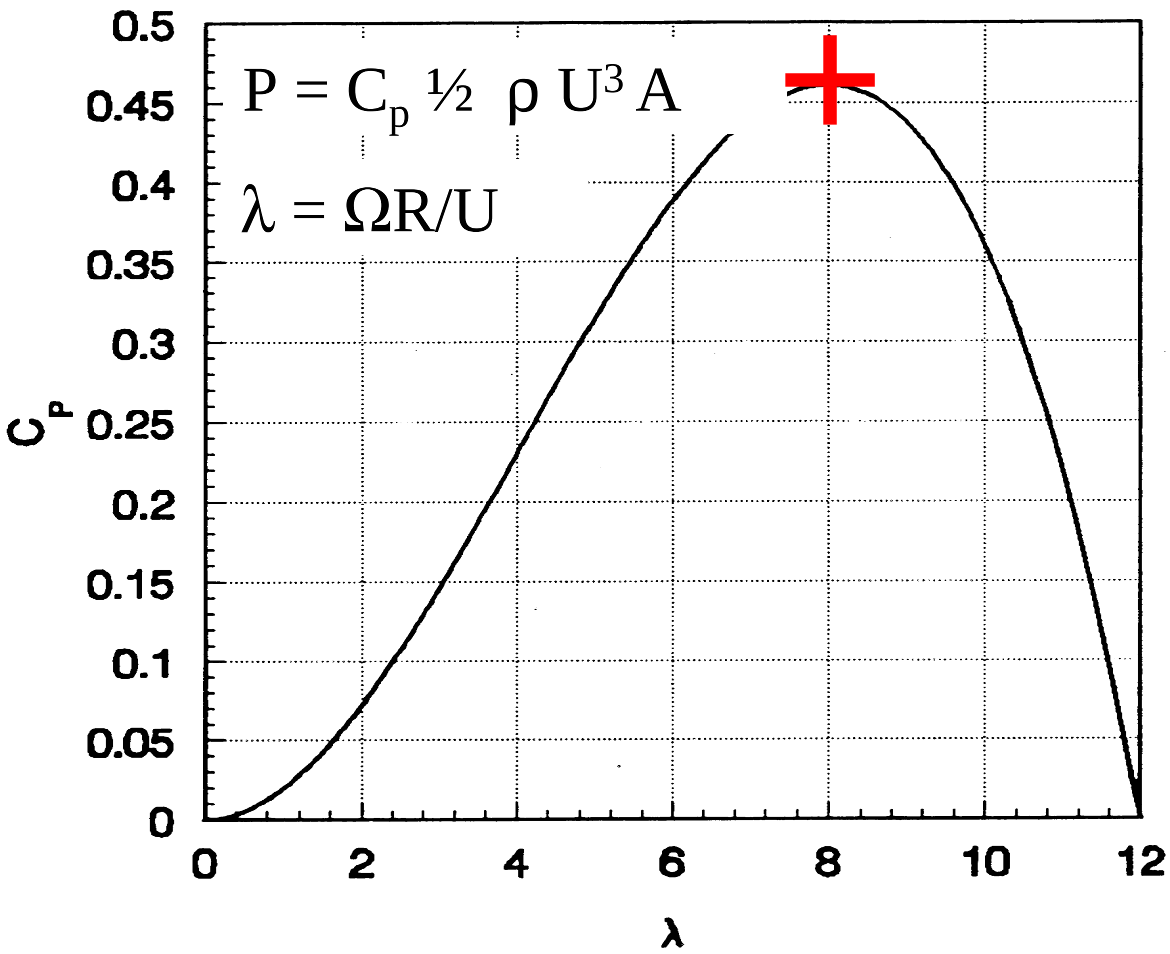
Partial load – power control

Ideal power control – variable speed



$P \sim U^3$

$\rightarrow C_p(\lambda) = C_{p,max}$

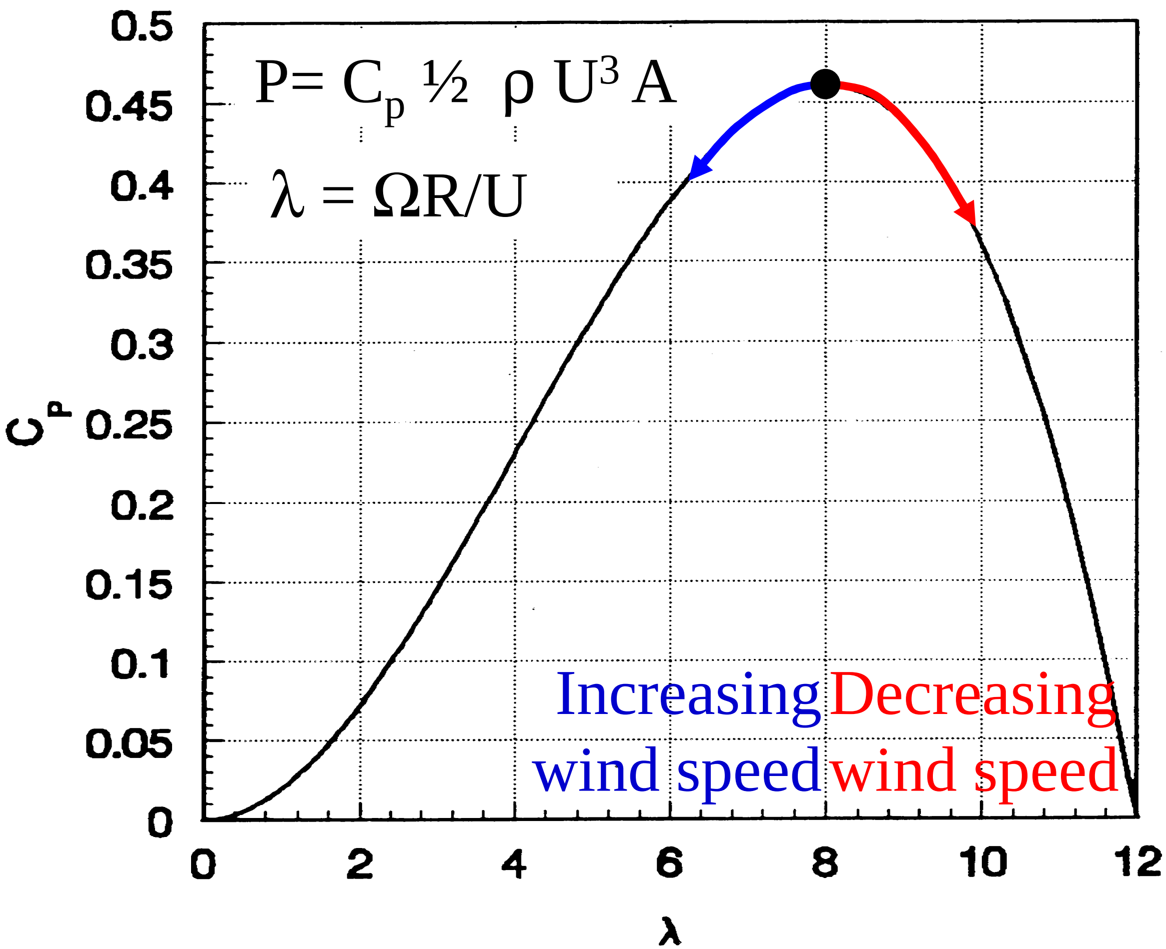
$\rightarrow \lambda = \lambda_{design}$

$\rightarrow \Omega \sim U$

Variable speed!
(Fixed pitch)

$\lambda_{design} = 8$
$C_{p,max} = 0.46$

Constant speed power control



$P \leq P_{variable\ speed}$

$C_{p,max}$ only at one wind speed

$\lambda_{design} = 8$

$C_{p,max} = 0.46$

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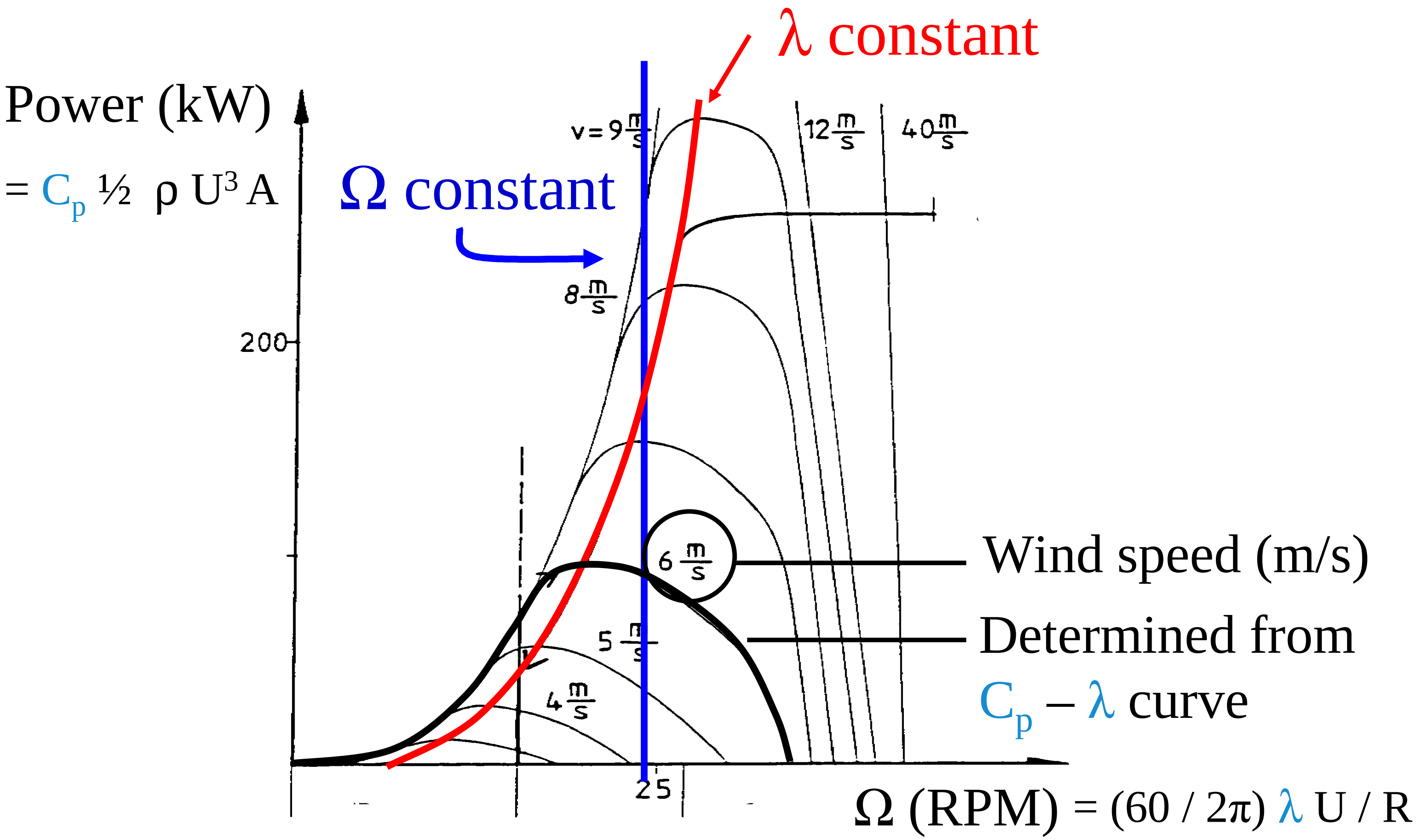
Power, RPM, wind speed



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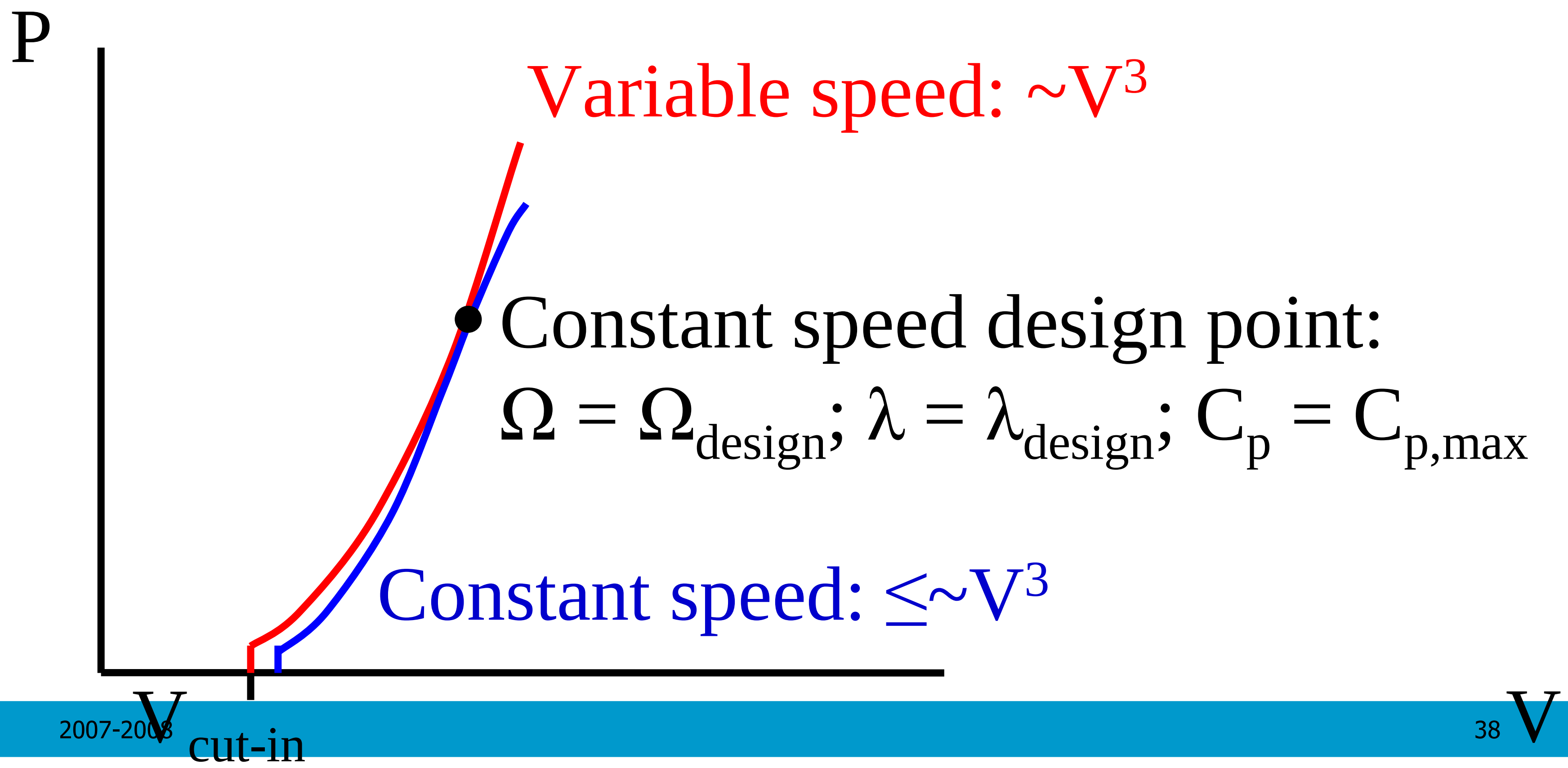
Power difference (partial load)



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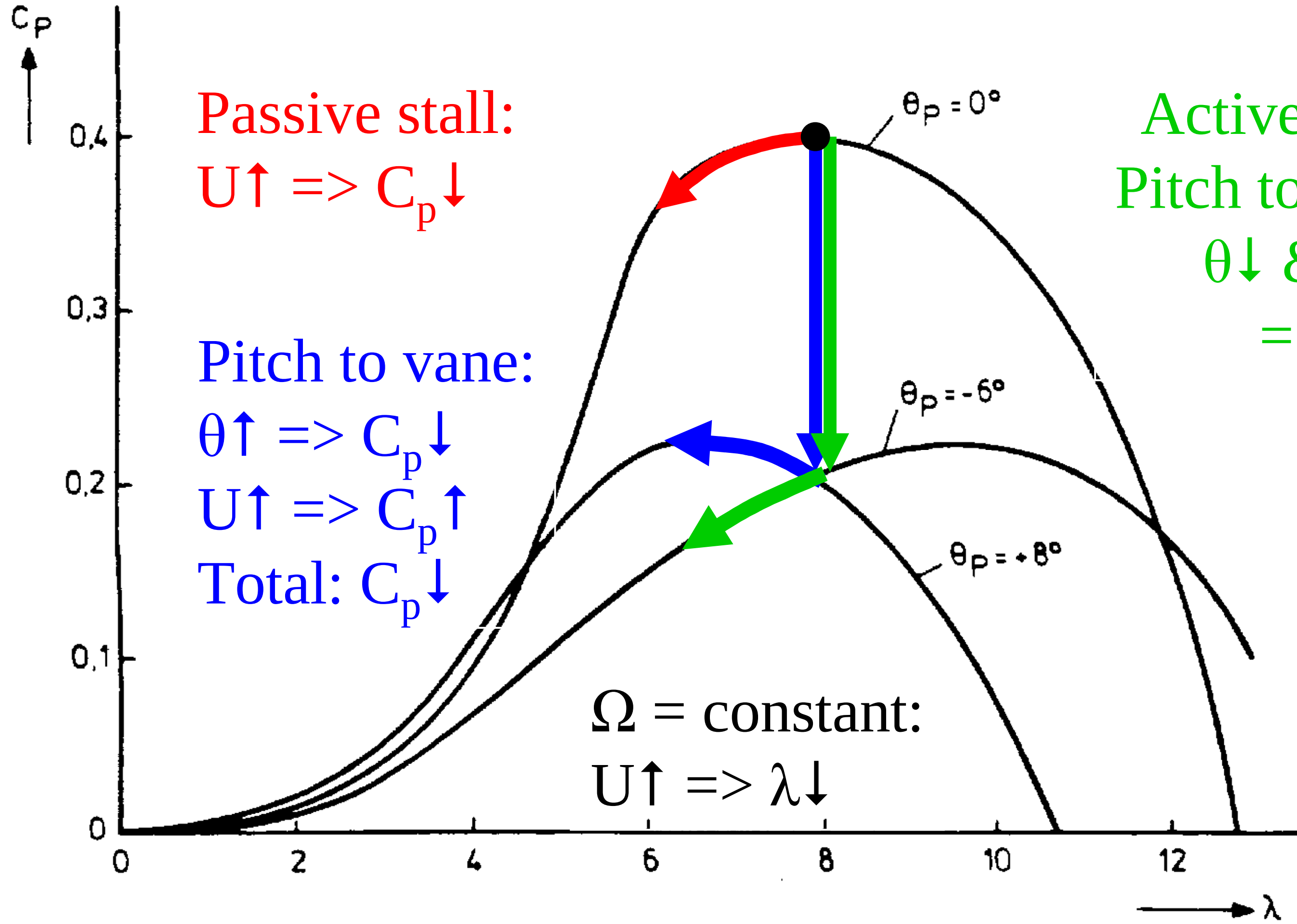
Full load – power control

Control options (constant speed)



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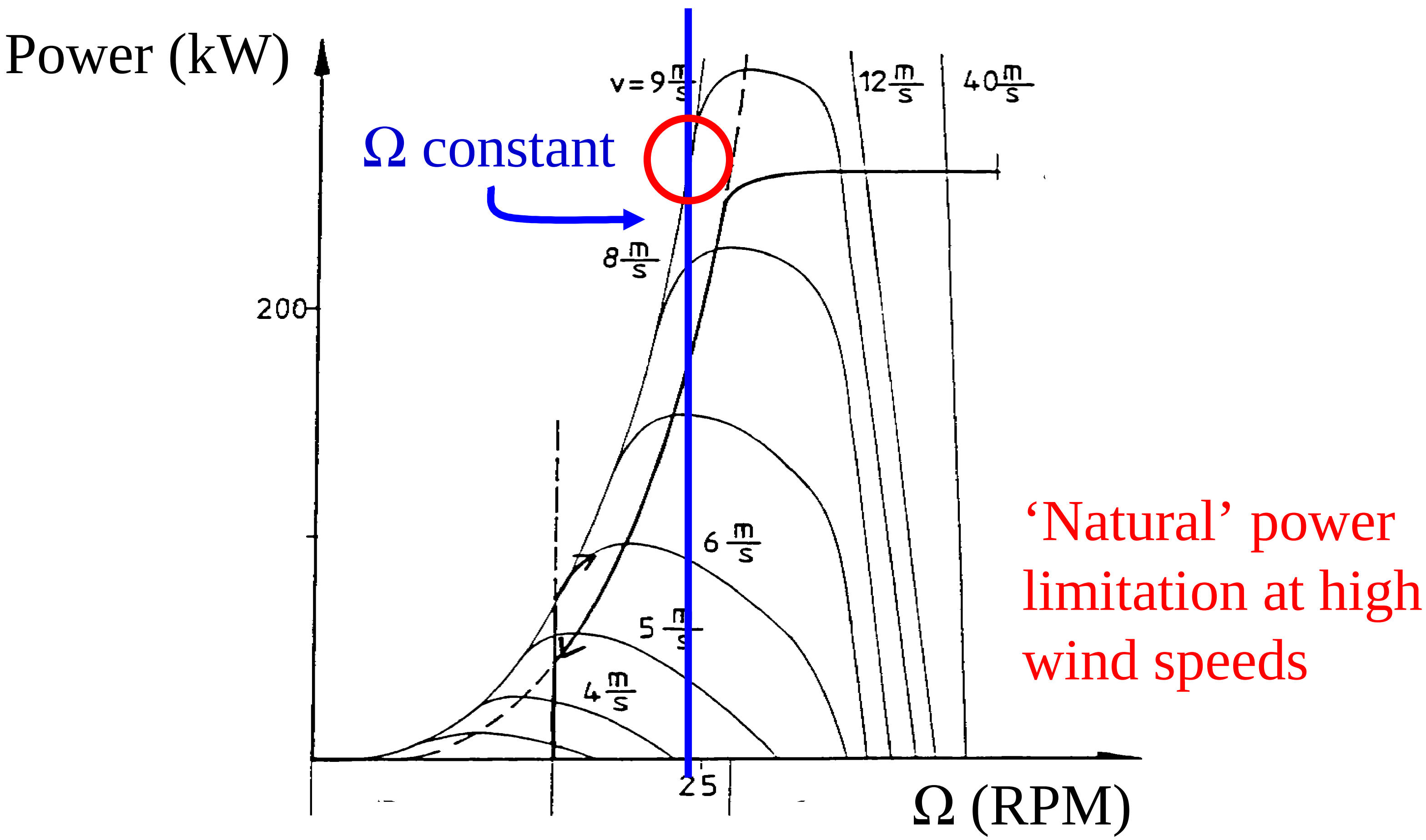
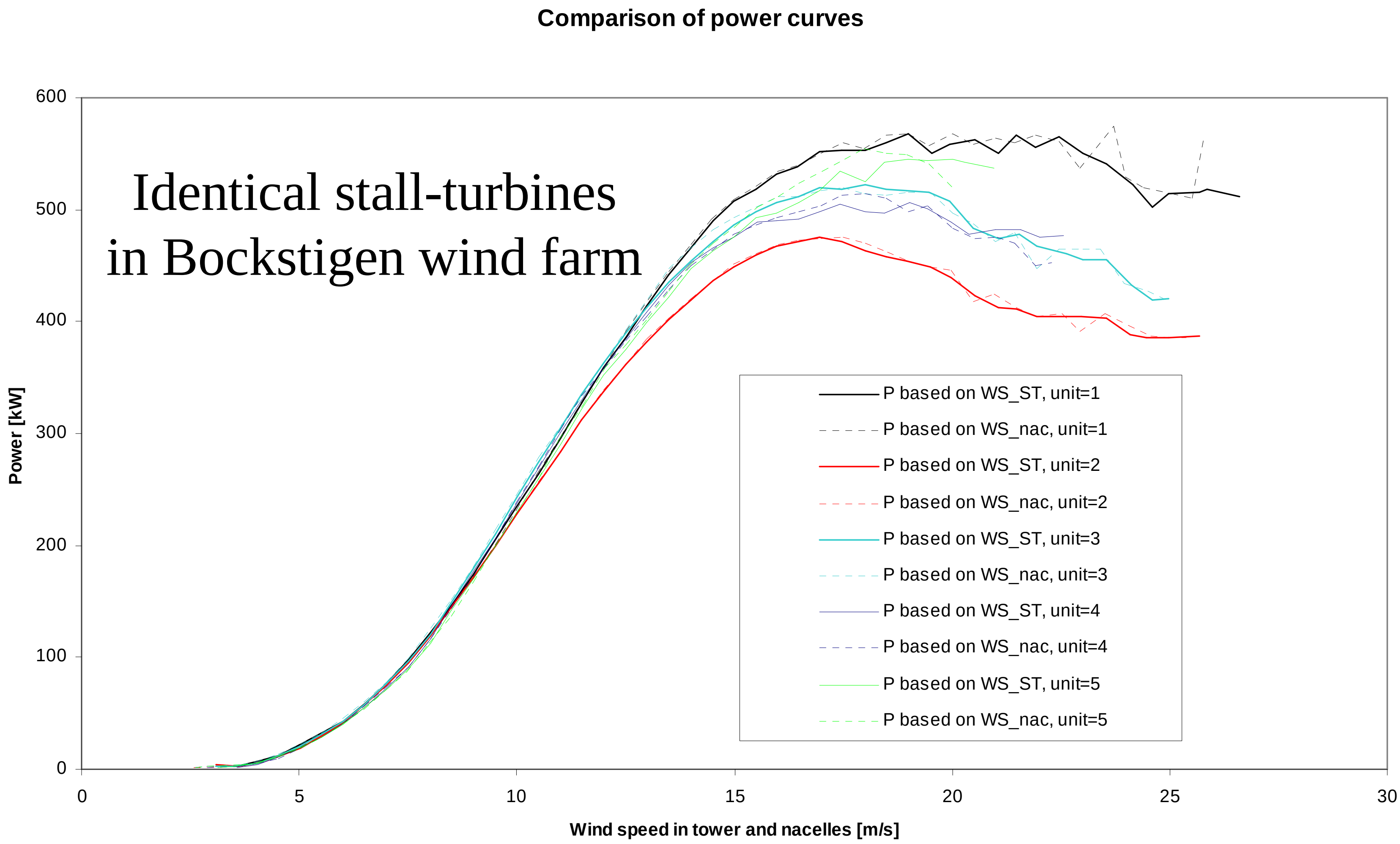
Passive stall control



Passive stall power curves



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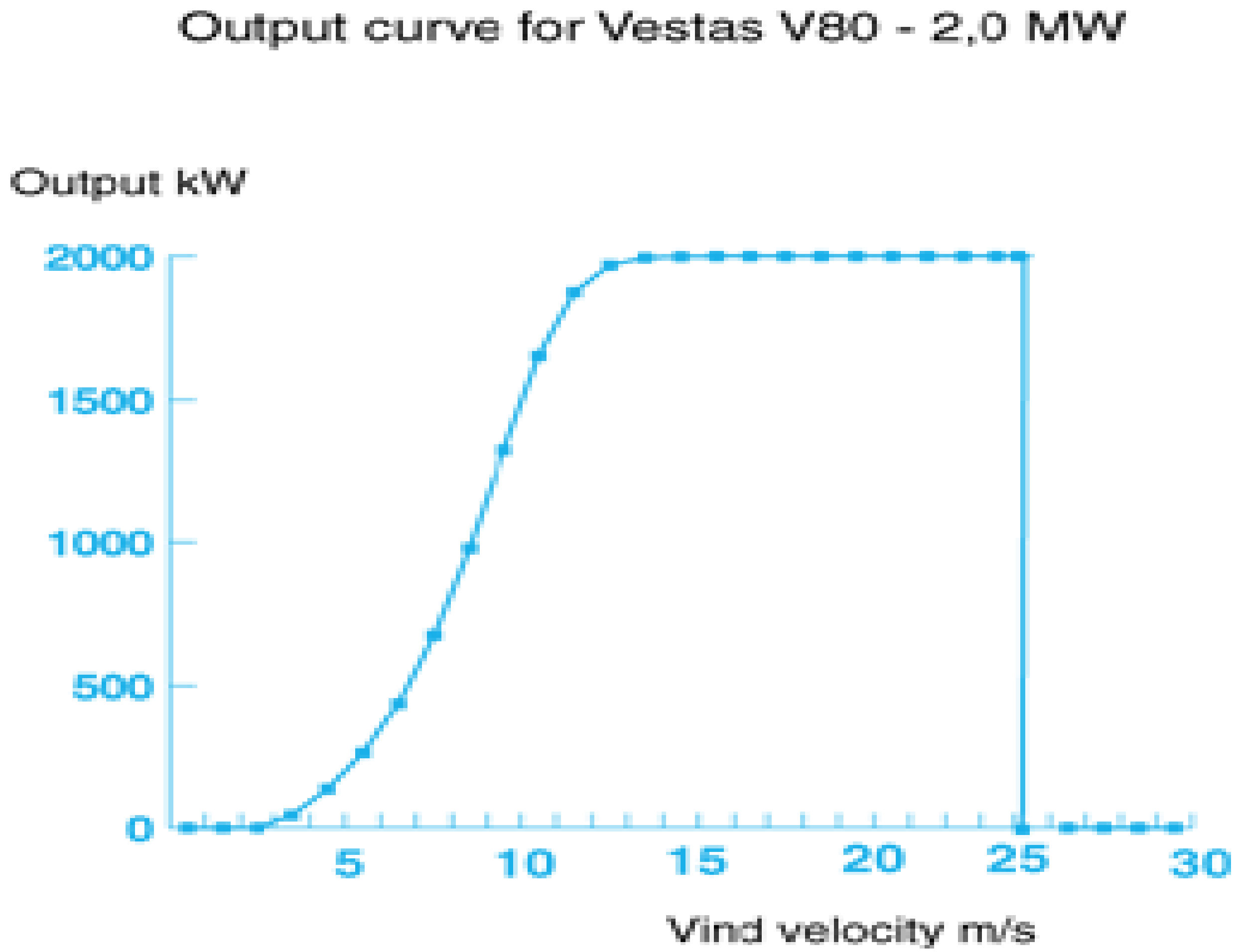
Pitch to vane power curve



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Full load - Loads

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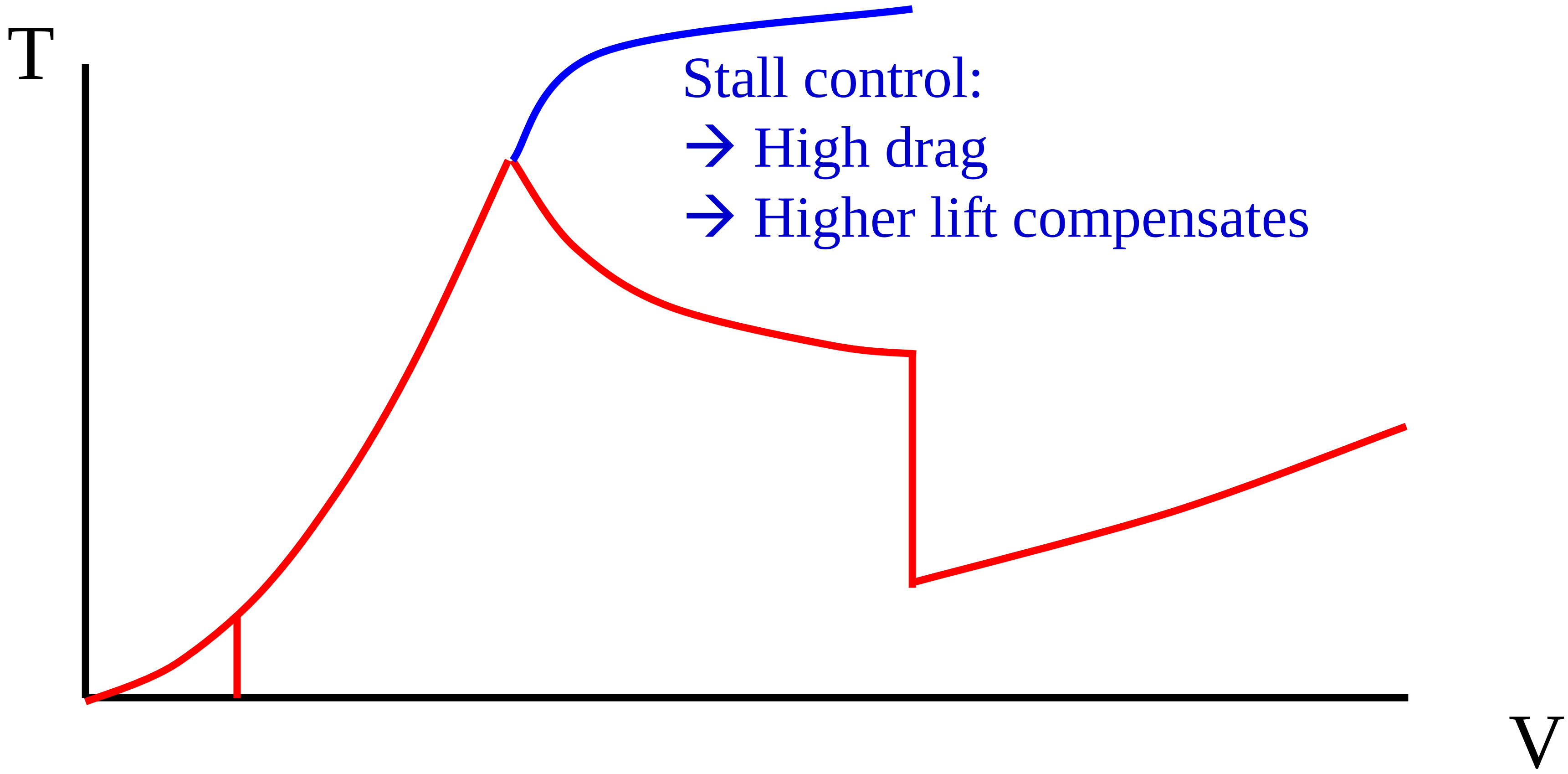
Non-ideal thrust of stall control



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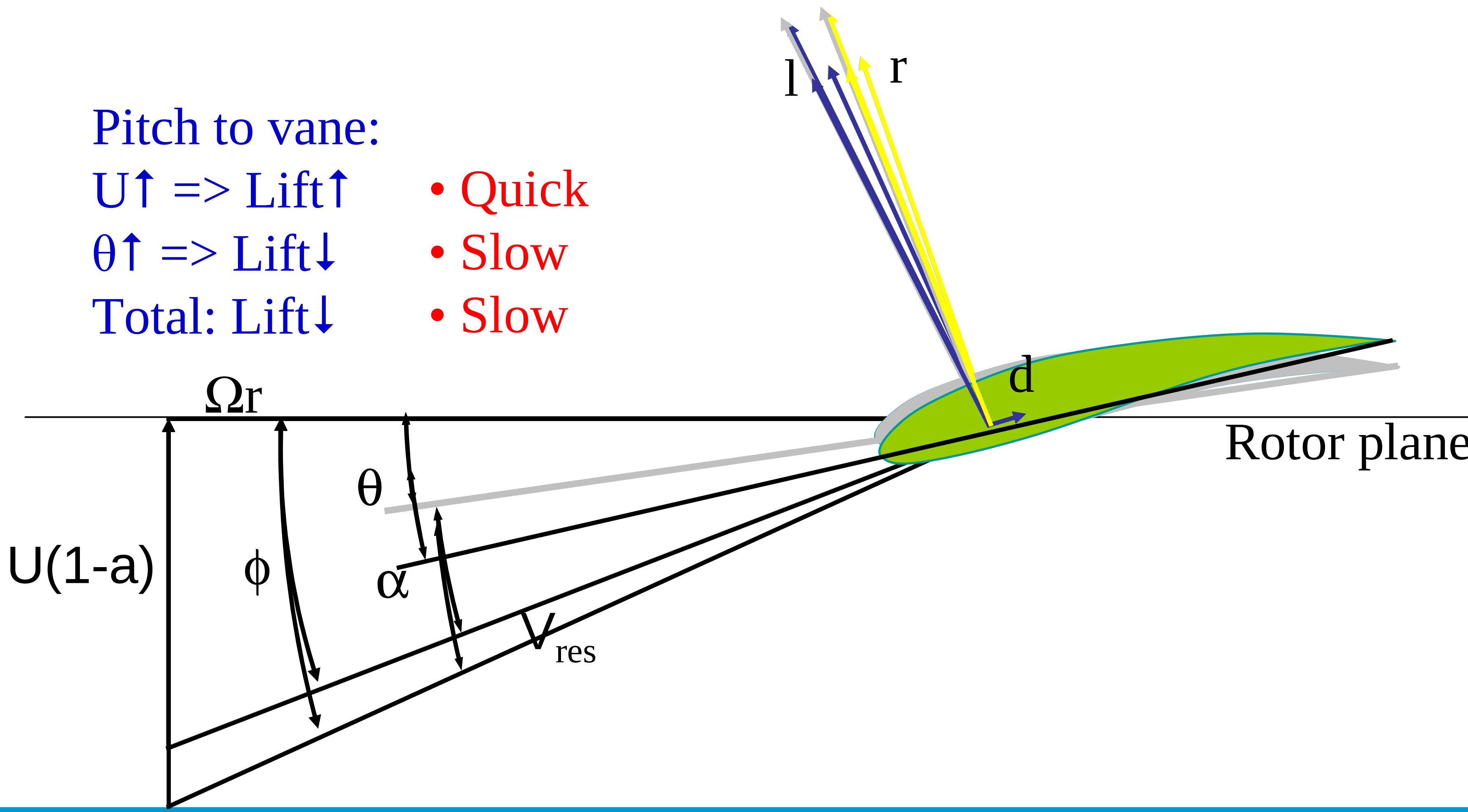
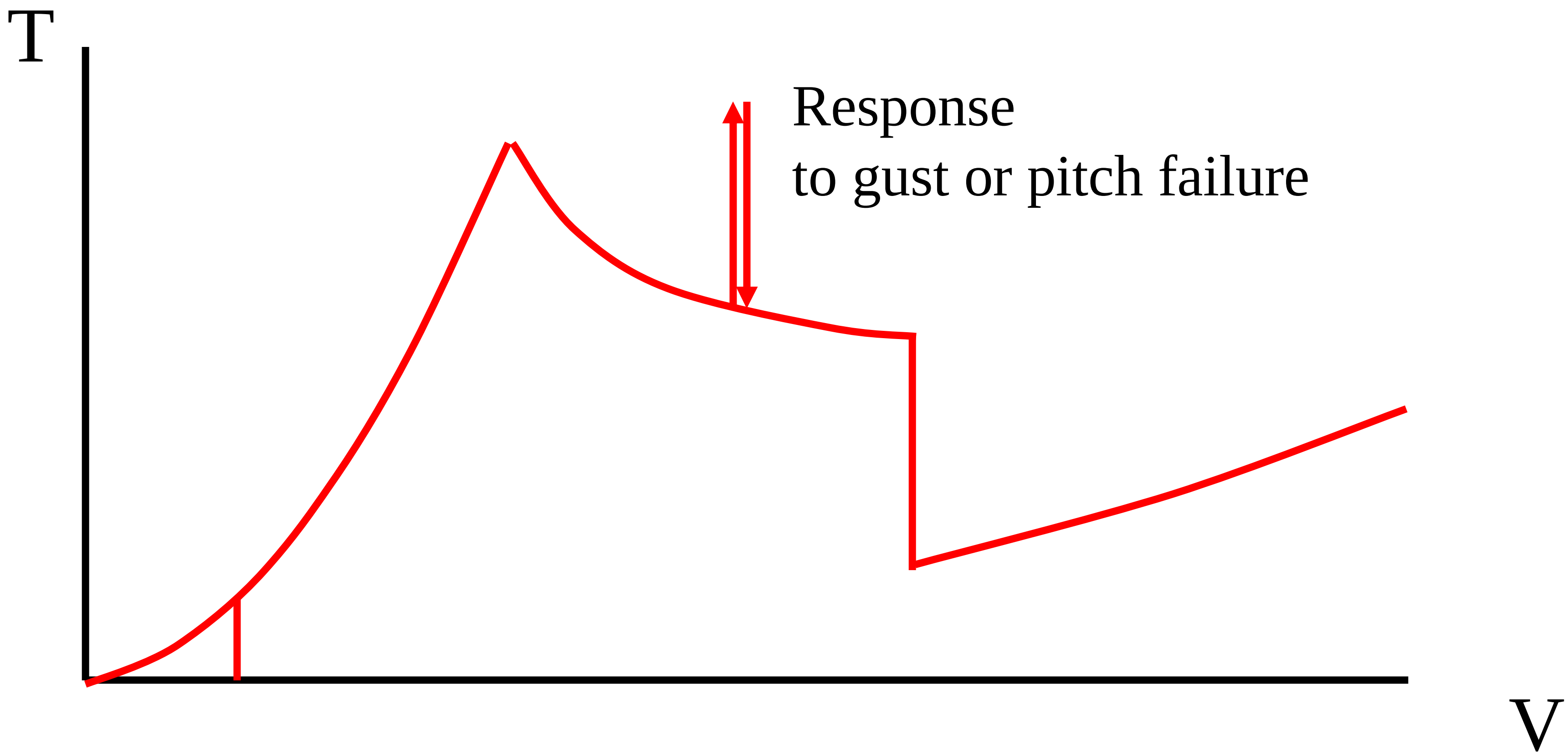
Dynamic loads of pitch control

Pitch to vane:

U↑ => Lift↑	• Quick
θ↑ => Lift↓	• Slow
Total: Lift↓	• Slow



Dynamics thrust of pitch control



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Load alleviation: gust response

Use rotor as a flywheel
→ Increase speed to absorb energy
→ Decrease speed to release energy
→ Reduce torque variations & peaks
→ Reduce power variations

→ Axial loads are NOT reduced!

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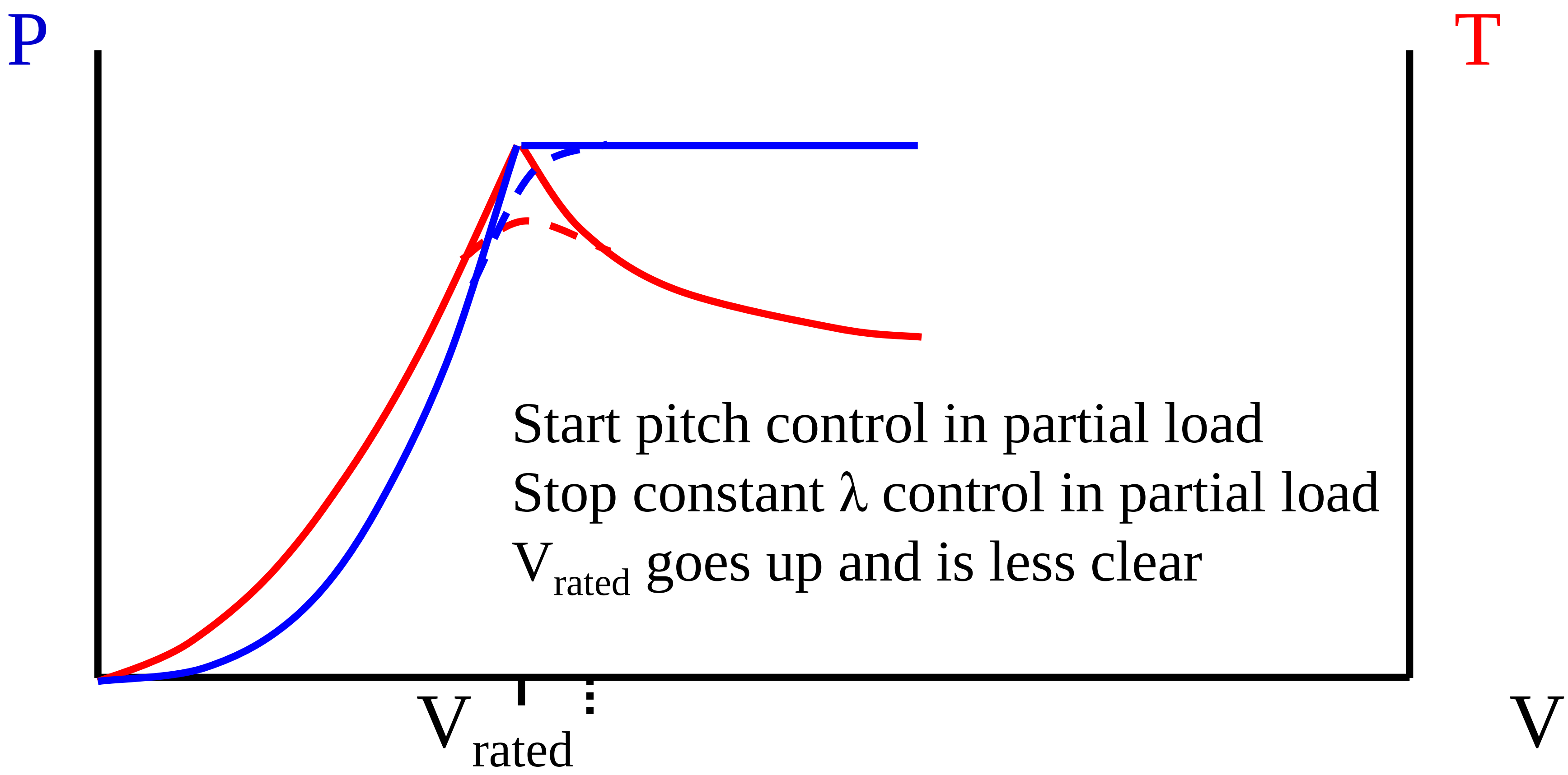
Load alleviation: Peak shaving



Energy production

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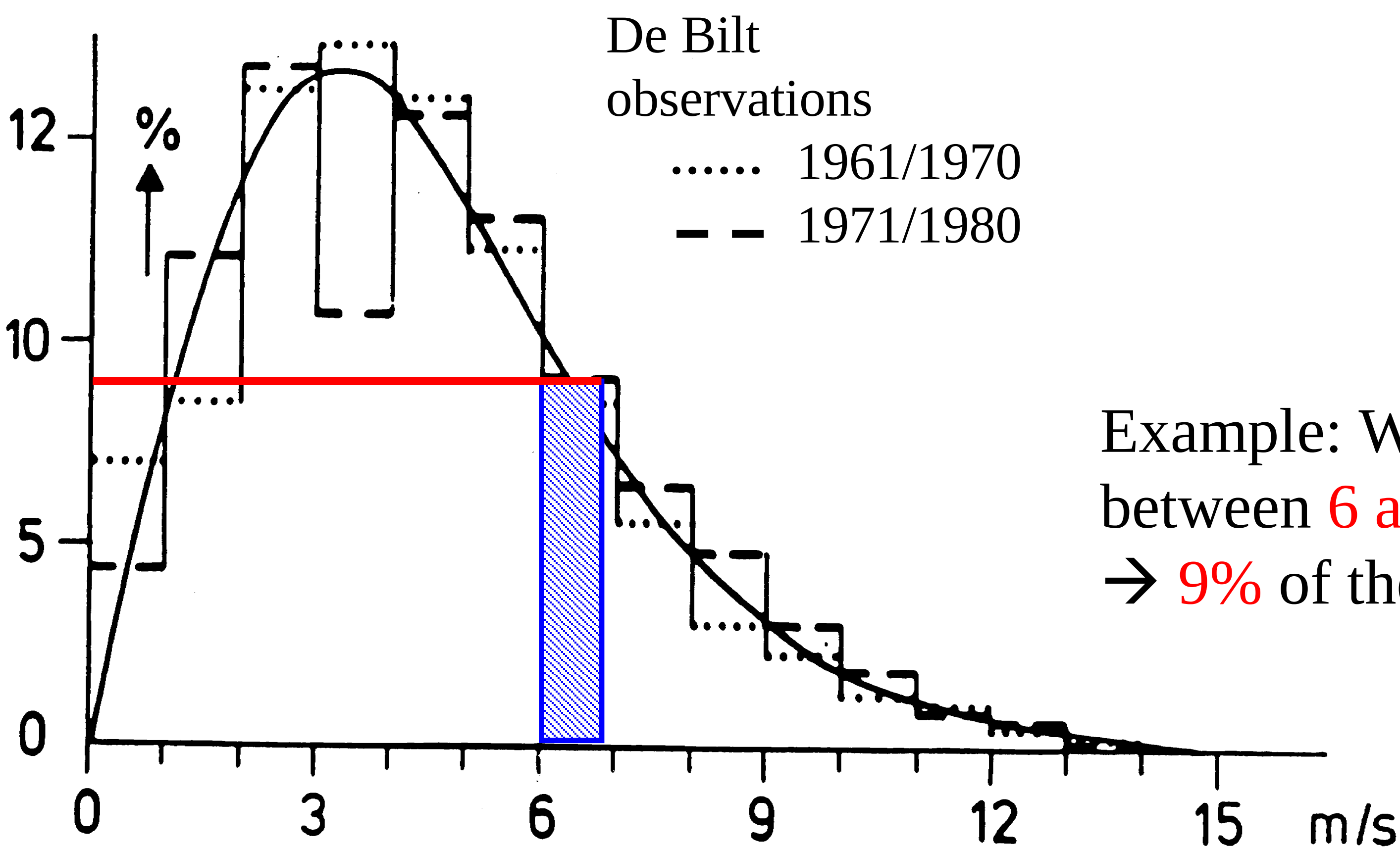
Wind speed distribution



Example: Wind speed between 6 and 7 m/s → 9% of the time

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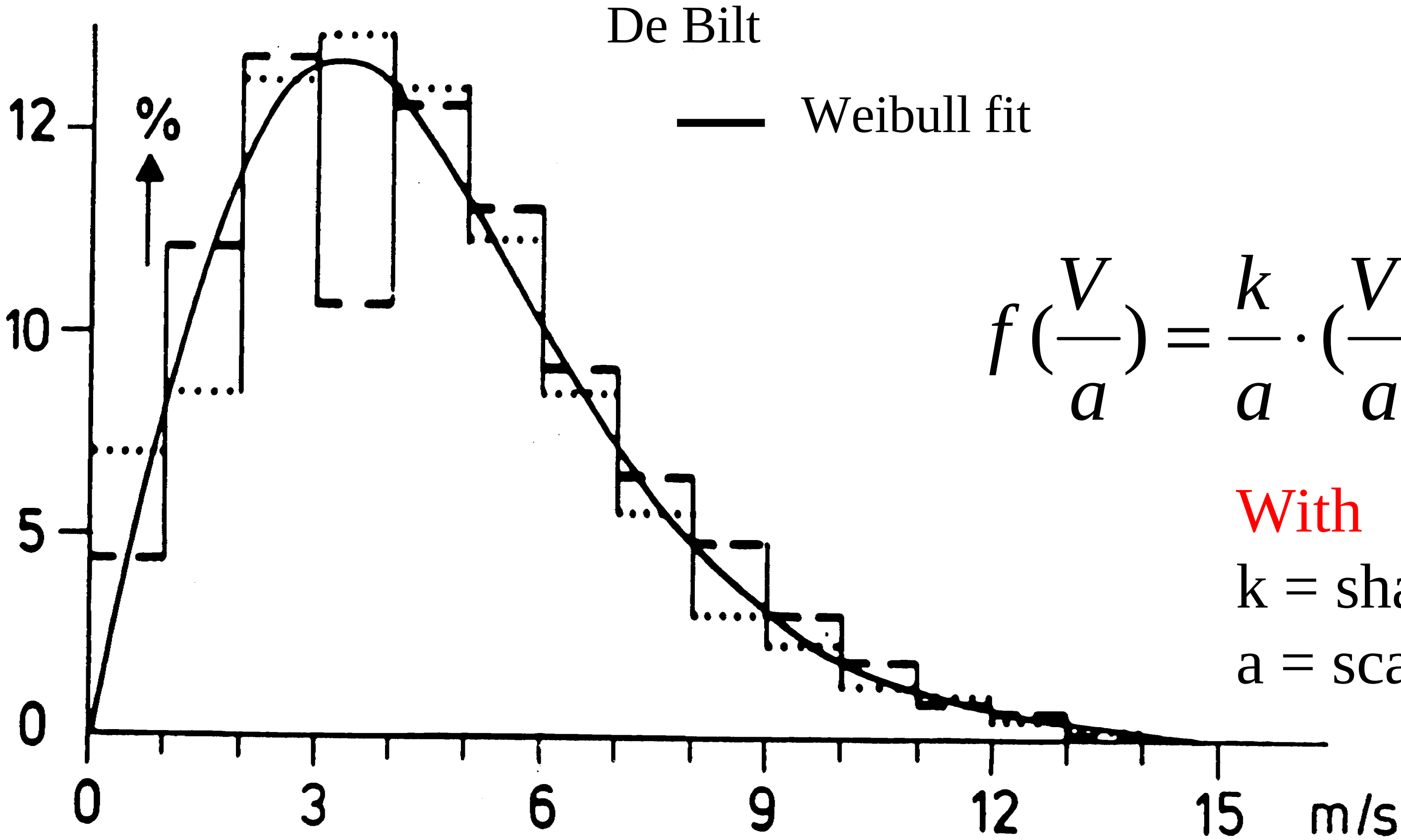
Weibull distribution



$$f\left(\frac{V}{a}\right) = \frac{k}{a} \cdot \left(\frac{V}{a}\right)^{k-1} \cdot e^{-\left(\frac{V}{a}\right)^{k}}$$

With
k = shape factor
a = scale factor

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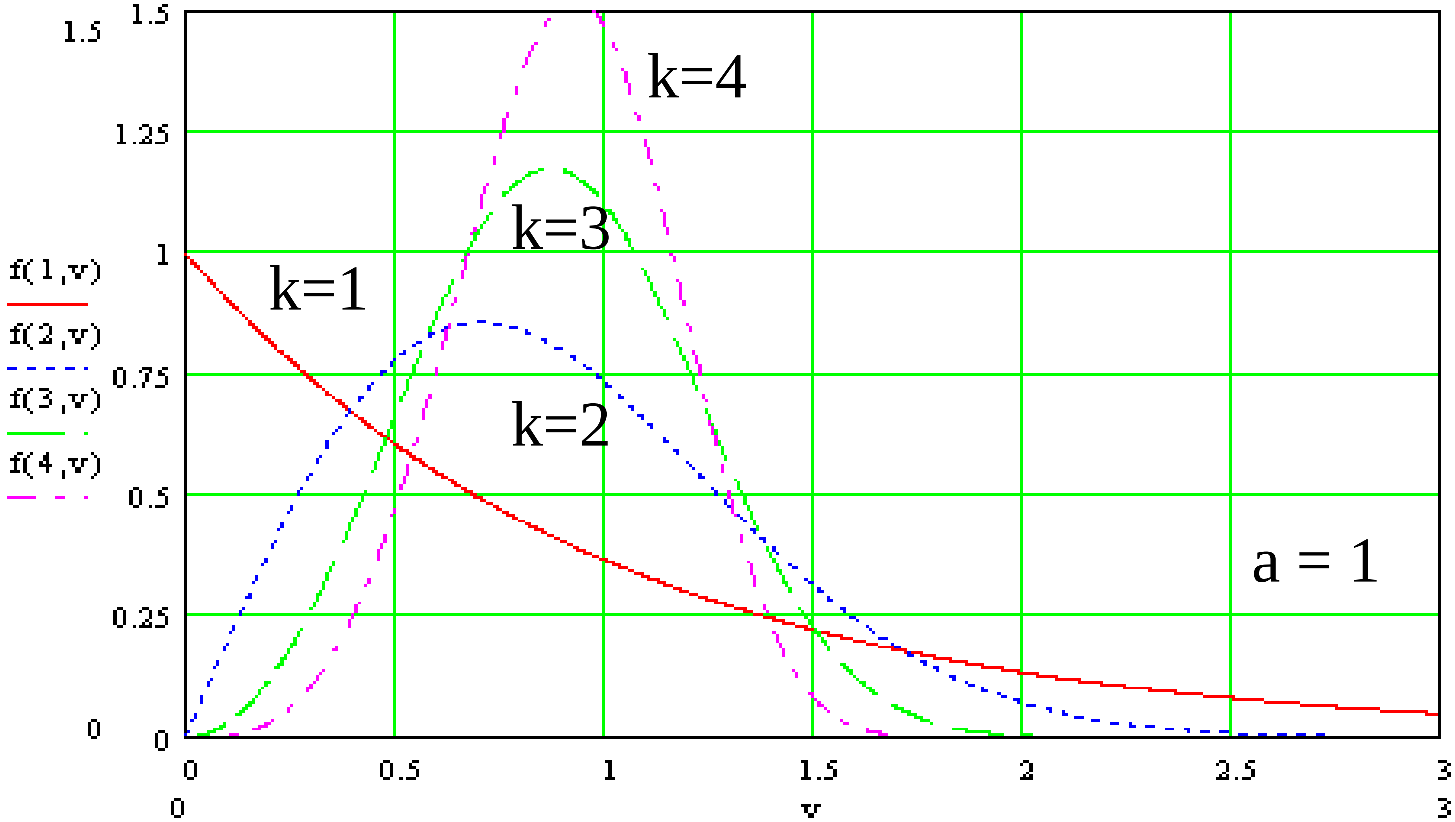
Weibull distribution: examples



Shape factor vs average wind speed

$$a = \frac{V_{avg}}{\Gamma(1+\frac{1}{k})}$$

With
a = Weibull scale factor
V_{avg} = Annual average wind speed
Γ = Gamma function

$$\Gamma(\alpha) = \int_0^\infty \beta^{\alpha-1} e^{-\beta} d\beta$$

$$\Gamma(1+\frac{1}{k}) \approx \left(0.568 + \frac{0.434}{k}\right)^{\frac{1}{k}}$$

Example

$$\Gamma(1+\frac{1}{k}) \approx 0.886$$

➔ $V_{avg} > a$

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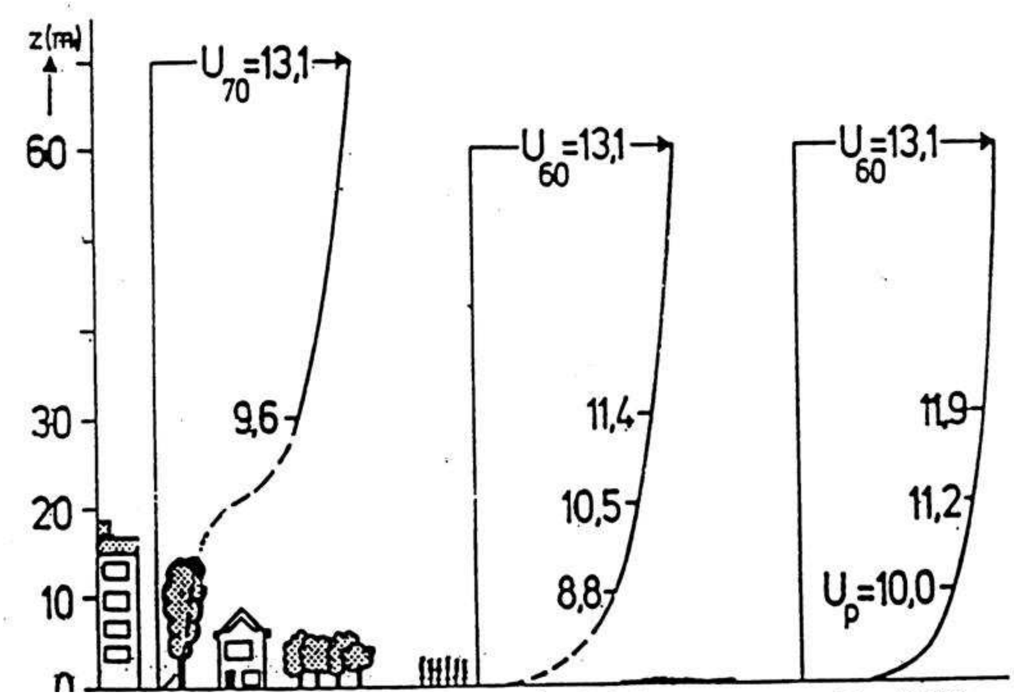
Wind speed vs height



Power law

$$v(h) = v(h_{ref}) \cdot \left(\frac{h}{h_{ref}} \right)^{\alpha}$$

Offshore $\alpha \approx 0.08 - 0.14$

Guideline $\alpha = 0.11$

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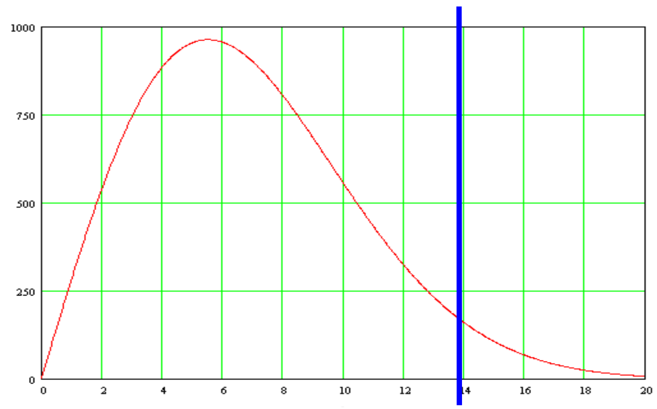
Calculation of annual yield

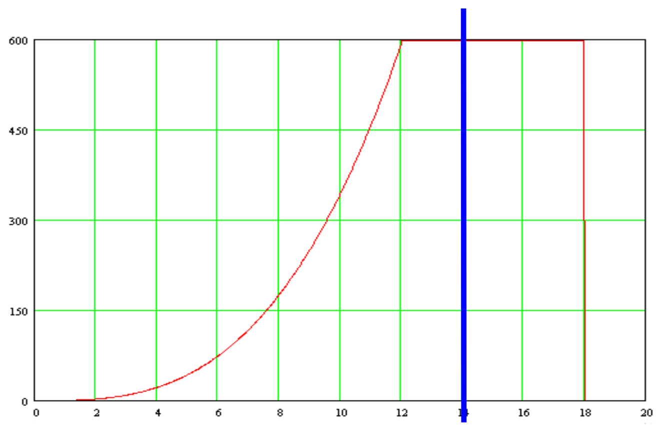
$$E_{Turbine} = T \int_{V_{ci}}^{V_{co}} P_{el}(V) \cdot f(V) dV$$

T (hours/(m/s))



X

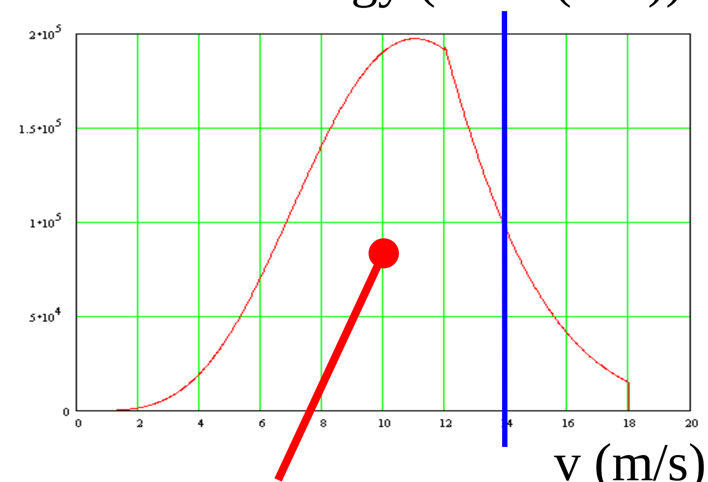
Power (kW)



v (m/s)

=

Contribution to energy (kWh/(m/s))



v (m/s)

Total area = energy production in one year

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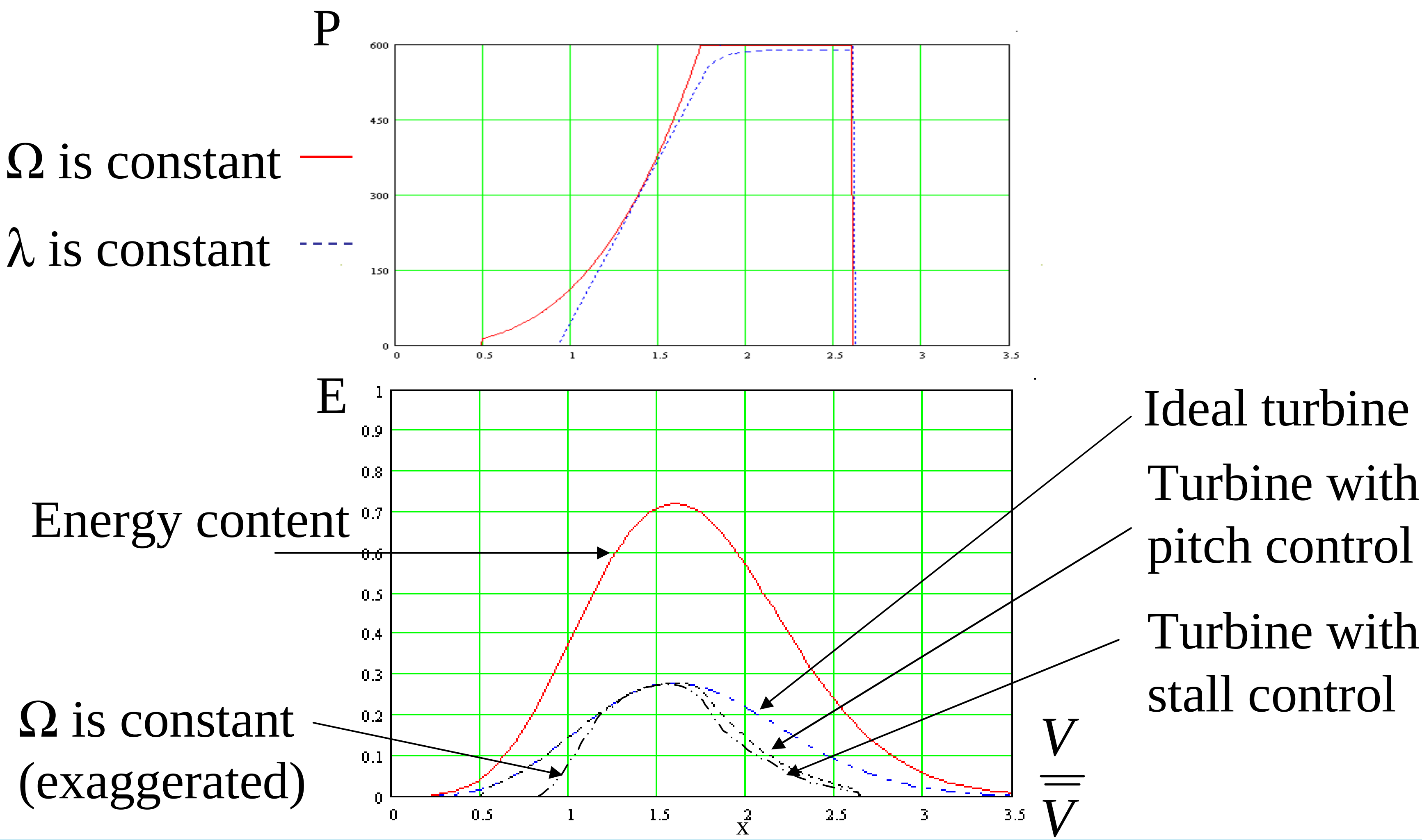
Energetic efficiency (1)



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Energetic efficiency (2)

V_{cut-in}	:	Hardly affects E, only interest is public perception
Speed control	:	Some effect on E
Pitch/stall	:	Some effect on E
$V_{cut-out}$	:	Limited effect on E, primarily determined by loads
V_{rated}	:	Has largest influence on E

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Capacity factor (1)

Yearly energy production

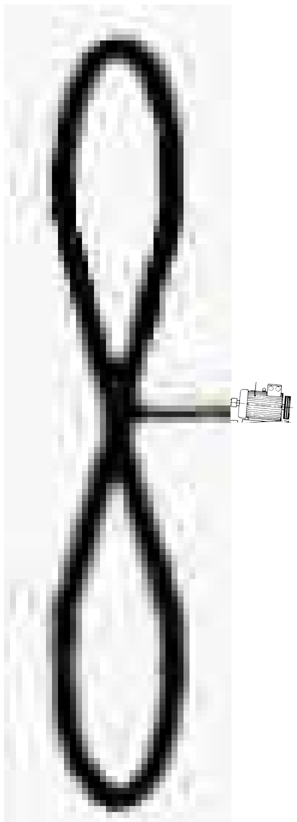
$$E = T\int_{V_{ci}}^{V_{co}} P_{el}(V)\cdot f(V)dV$$

The same yearly production would be generated in an equivalent amount of time $T_{equivalent}$ running at full power:

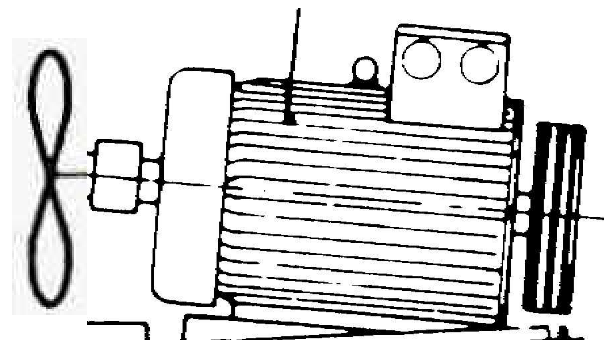
$$E = P_{rated}T_{equivalent}$$

$$cf = \frac{T_{equivalent}}{T_{year}}$$ is called the capacity factor

Capacity factor (2)



cf ≈ 1



cf ≈ 0

A high capacity factor is not necessarily good!

There is an economic optimum

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Characteristic values for cf

First generation turbines: cf ≈ 0.2
Present generation: cf ≈ 0.25 - 0.3
Offshore wind farms: cf ≈ 0.35 - 0.45

For comparison
The capacity factor of all the power generation ability mounted in the Netherlands :

$$cf = \frac{\text{total electricity consumption}}{\text{maximum electricity production} \cdot 8760} \approx 0.5$$

(8760 is the number of hours in a year)

Energy losses

$$P(V)_{\text{Electrical}} = P(V)_{\text{Aero}} \cdot \eta_{\text{Drive train}} \cdot \eta_{\text{Generator}} \cdot \eta_{\text{Conversion}}$$

P-V curve of manufacturer includes these losses

Additional farm related losses:

- Availability of the turbines
- Availability of the electrical infrastructure
- Aerodynamic farm losses (wakes)
- Transformation and transmission losses

Sources

- Models
- Guestimates (literature)

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Estimating energy production (1)

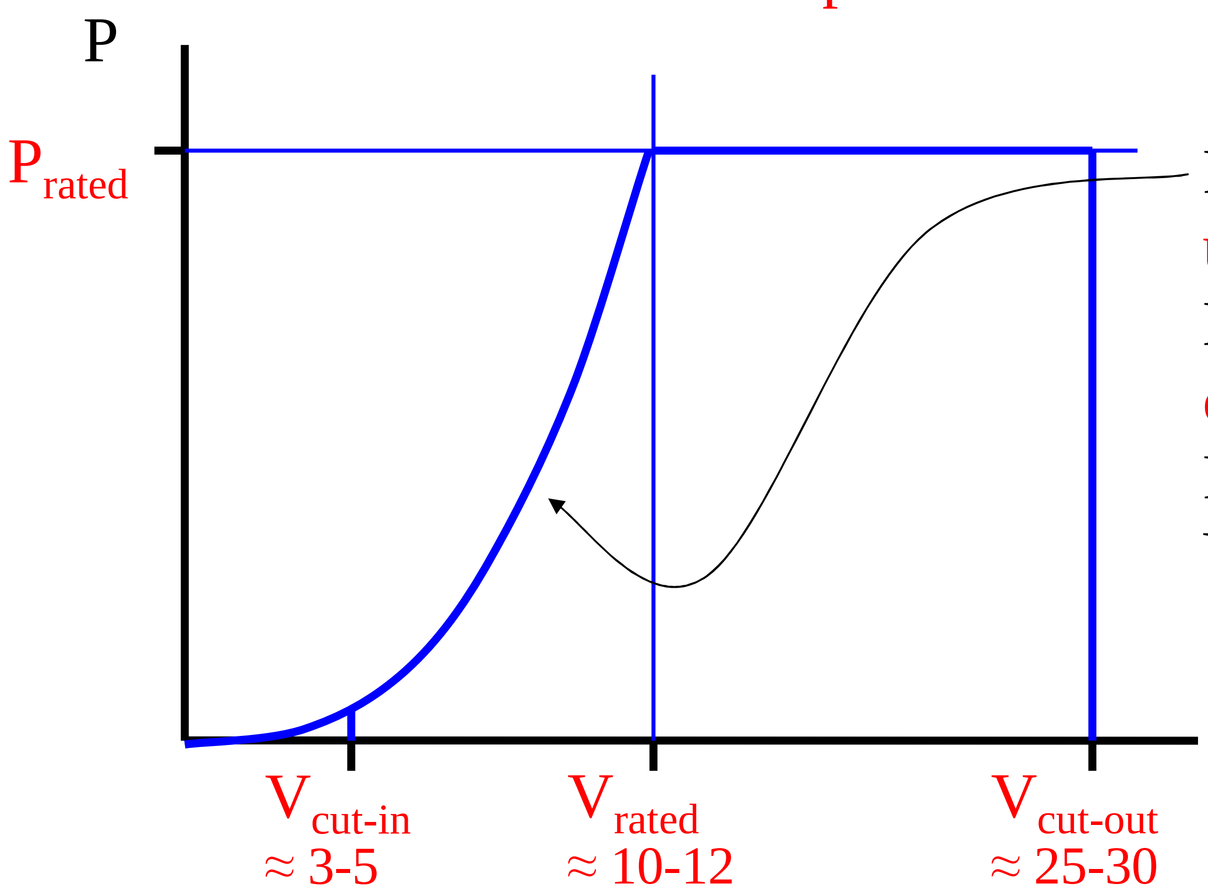
Energy yield =
number of hours/year * installed power * capacity factor

e.g.: 8760 h * 108 MW * 0.35 ≈ 331 GWh / y
for offshore wind park Egmond aan Zee
(Average Dutch household: 3.2 MWh / y)

Only applicable for order of magnitude guess !!
Wind speed distribution (based on data) indispensable

Estimating energy production (2a)

Estimate power curve



$P = \frac{1}{8} \rho C_p V^3 \pi D^2$

use

D and estimate of C_p

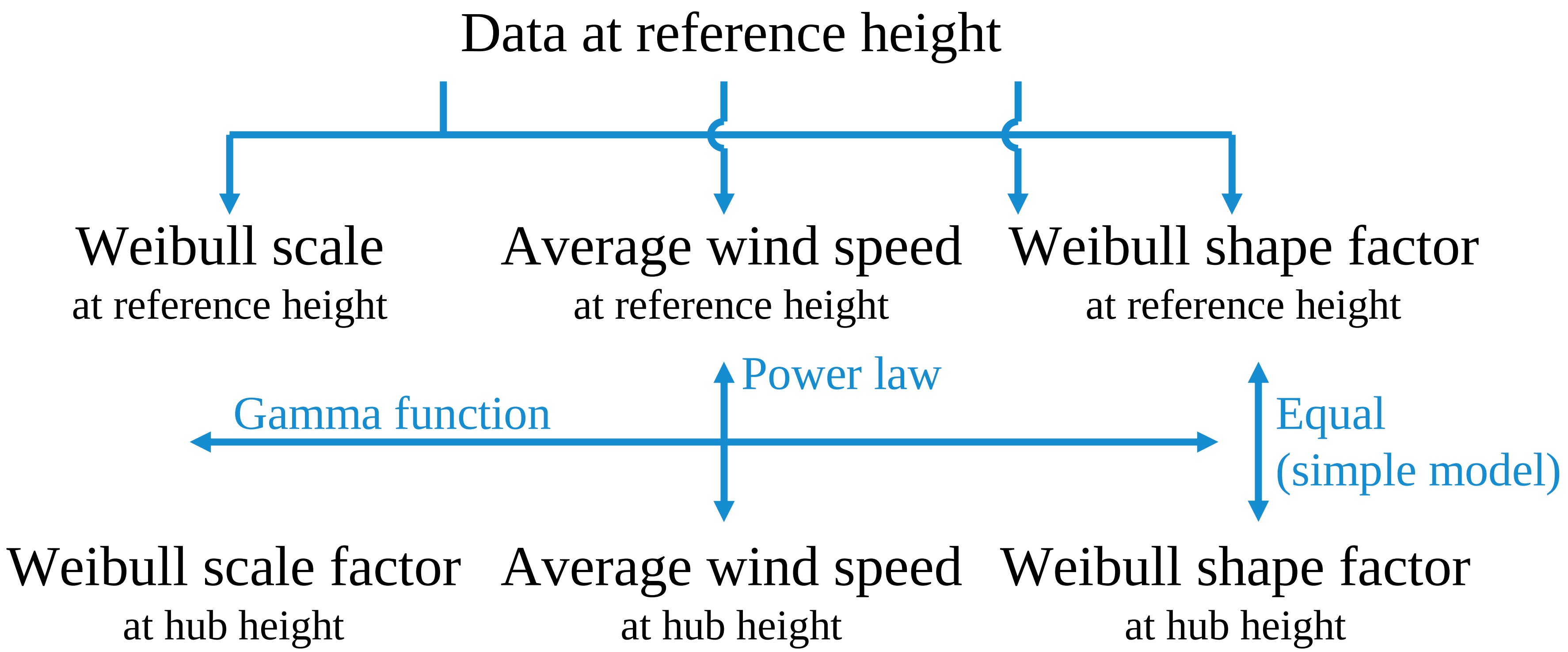
or

P_{rated} and

$V_{rated} \approx$ 10-12 m/s

Estimating energy production (2b)

Estimate wind speed distribution



TU Delft

Turbine technology

2007-2008

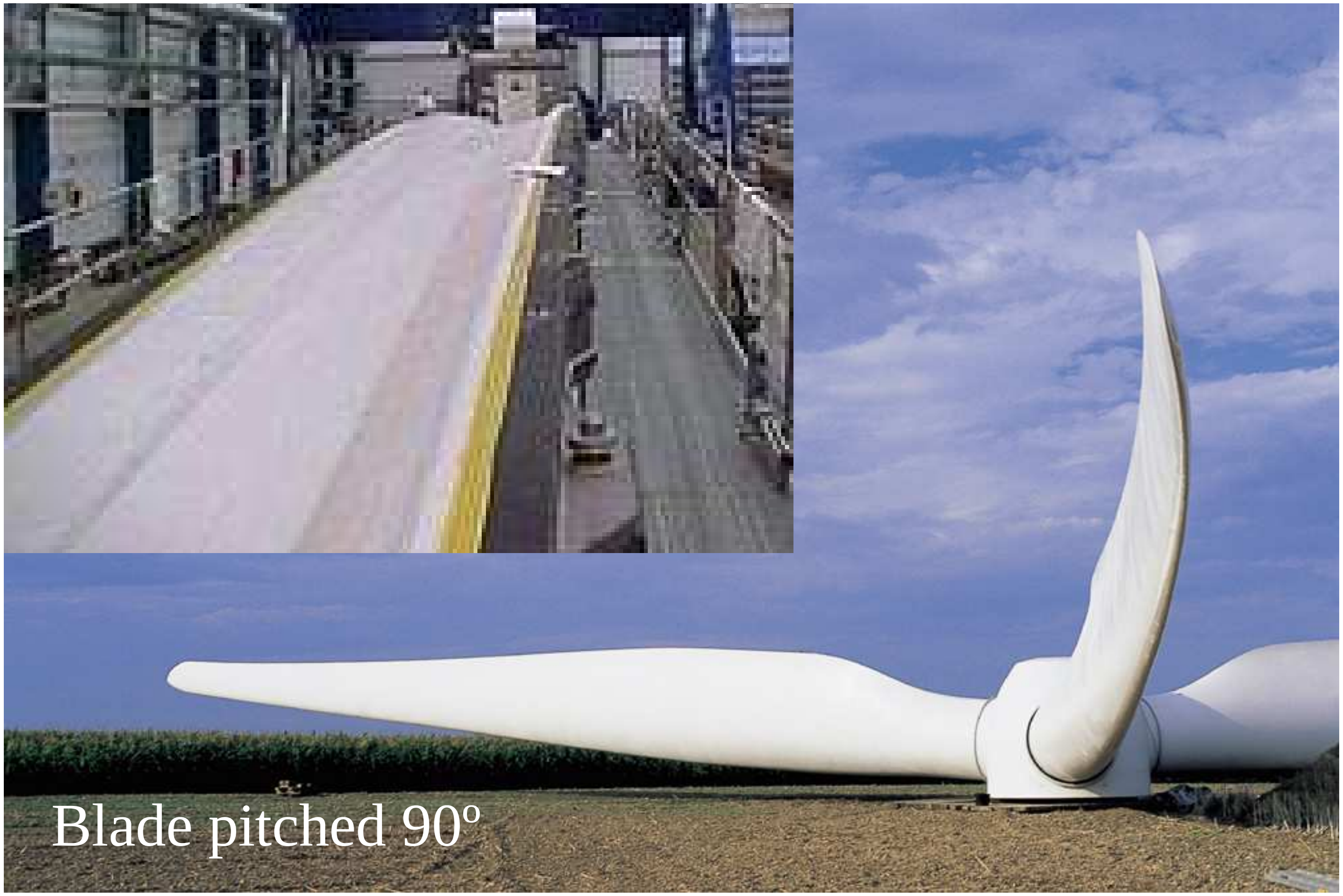
Blades

2007-2008

Blades

Composite
One-piece
Flexible
Skin / spar
T-bolts

Large blades: pre-bending in mould



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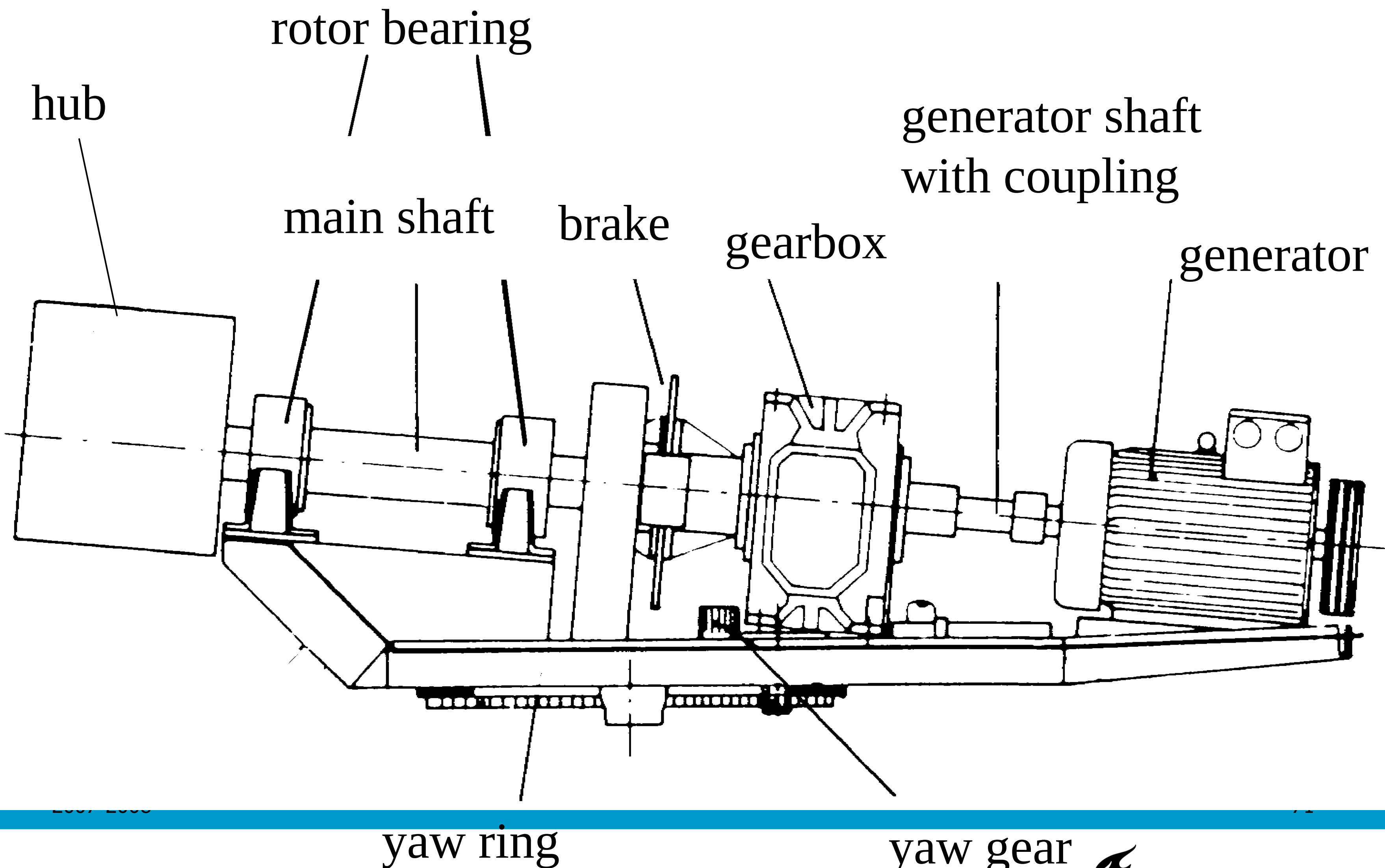
Overview of the drive train

Drive train (with gearbox)



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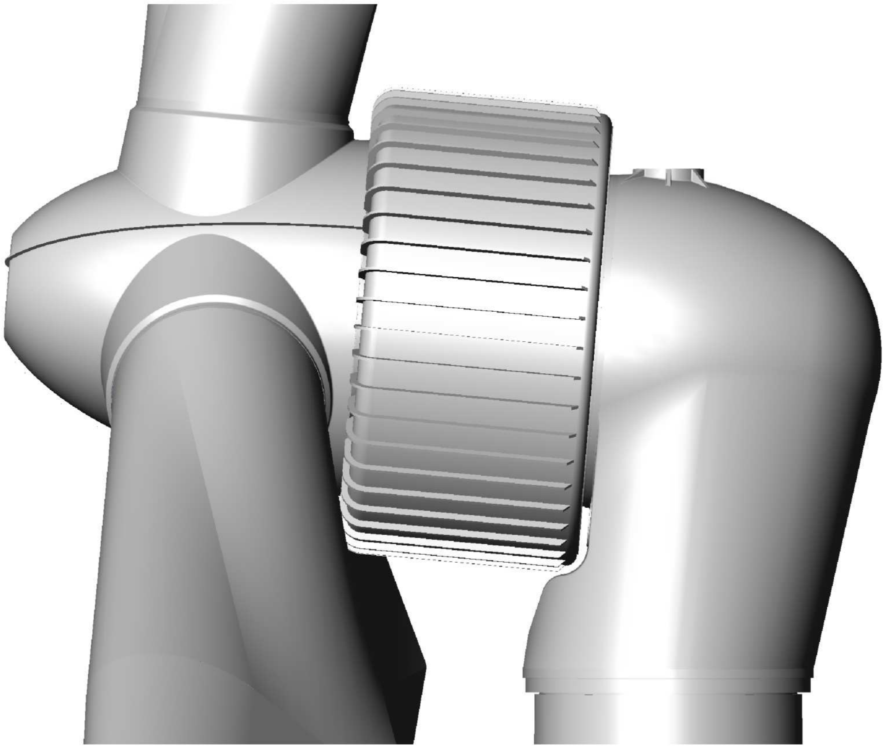
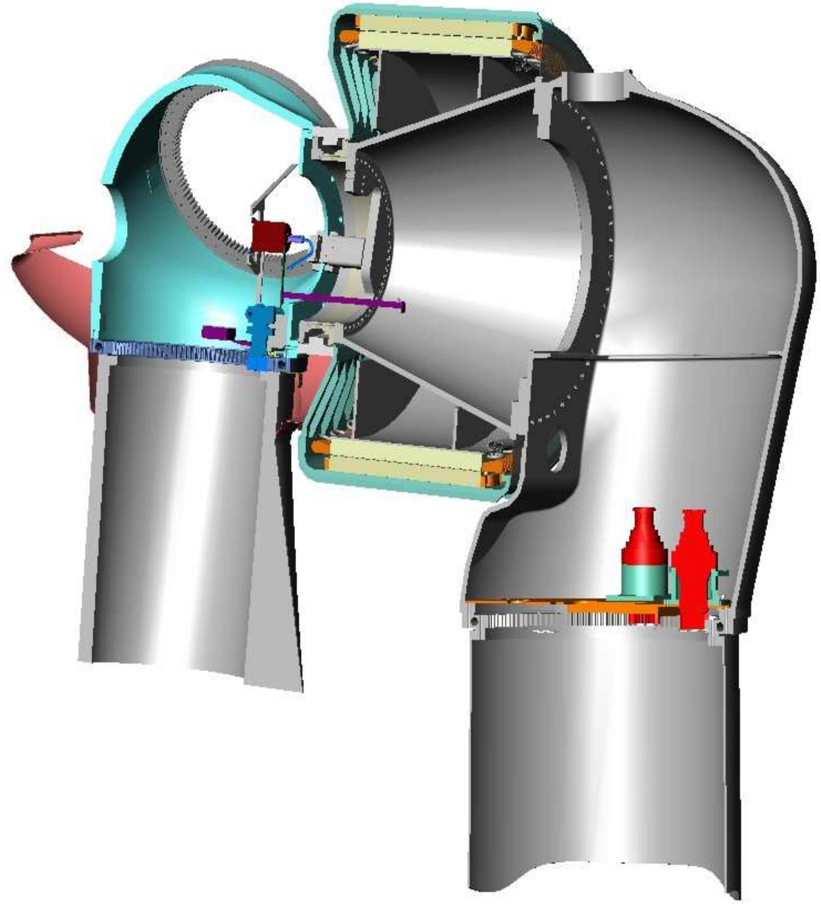
Drive train without gear: direct drive





Zephyros 2 MW turbine

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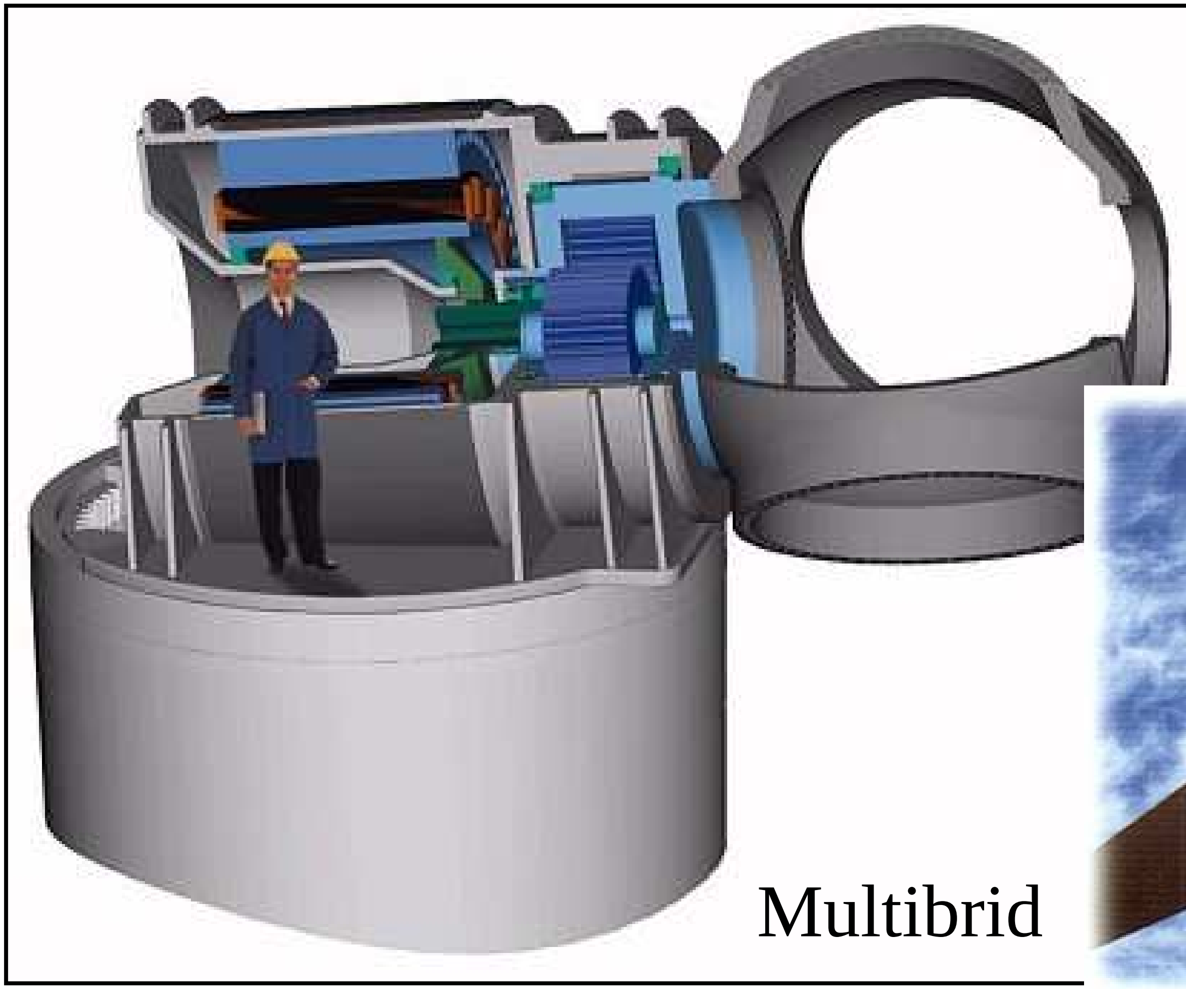
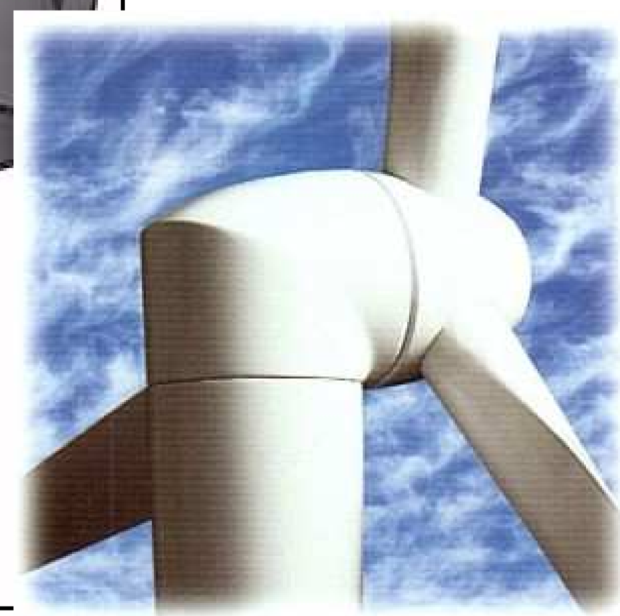
Compact drive train



1-stage gearbox, medium speed generator, direct hub-gear-generator connections



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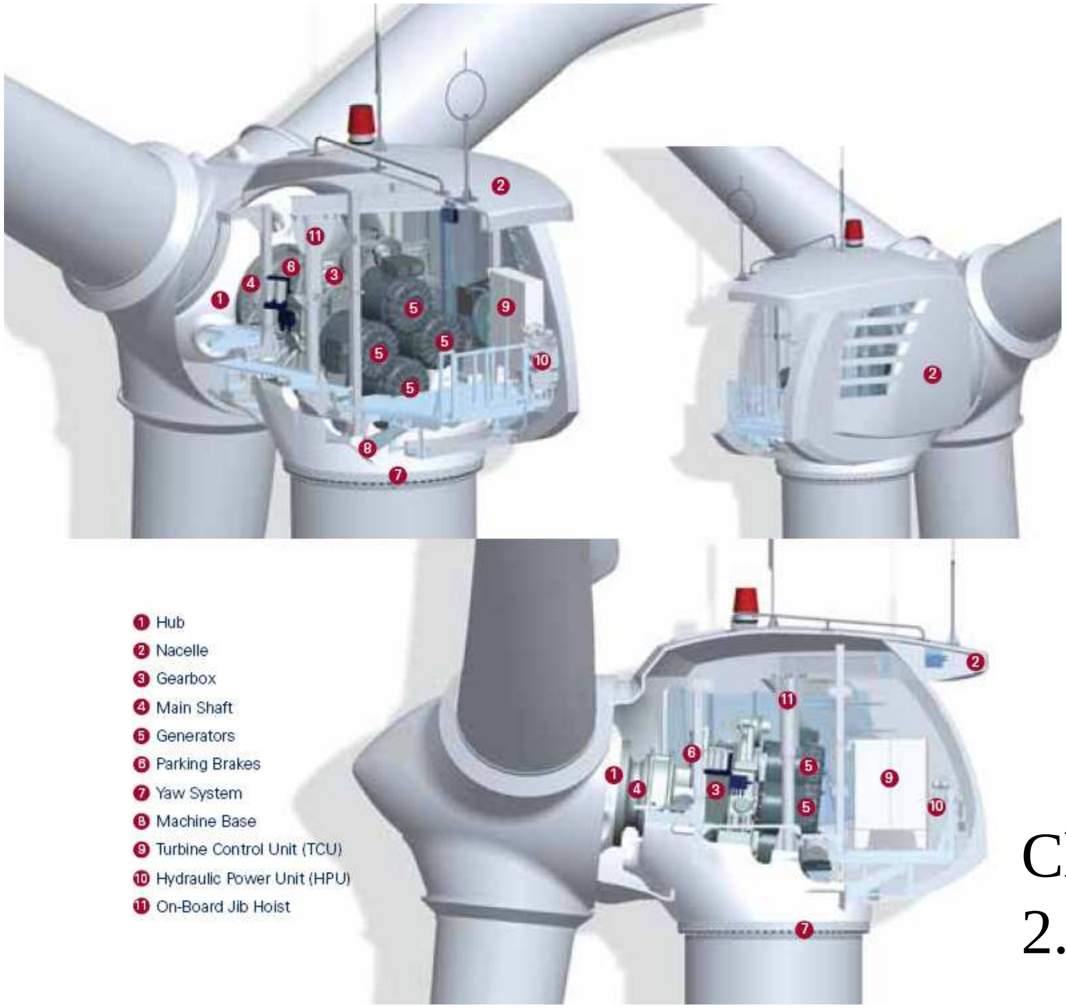
Gearbox & generator



Clipper Liberty
2.5 MW

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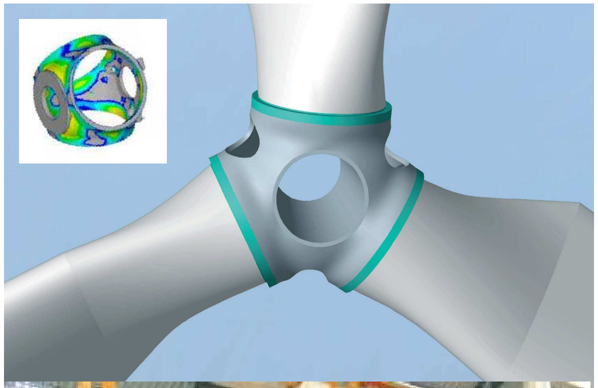
Hub

2007-2008

Hub

Hub and cover



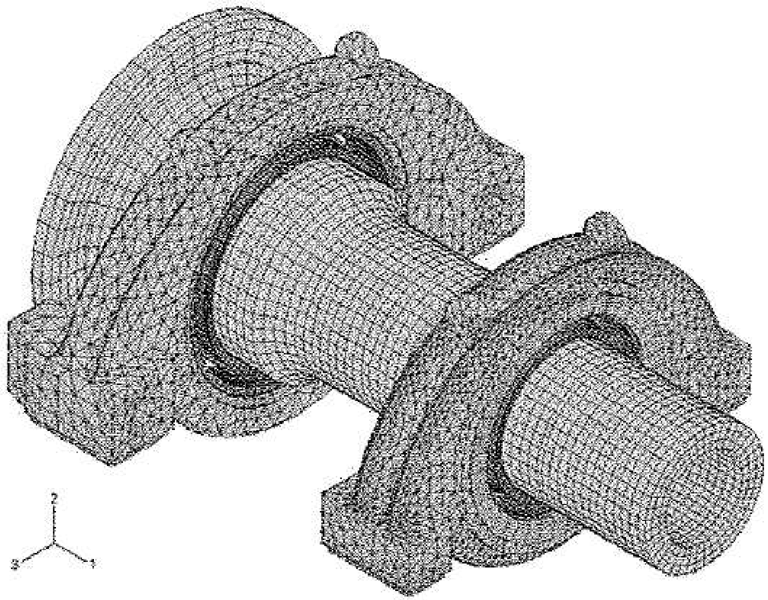
Composite
aerodynamic cover

Cast-iron hub for rotor loads

Main shaft and bearings

2007-2008

Double and single bearings



Rotating main shaft

Direct connection to hub

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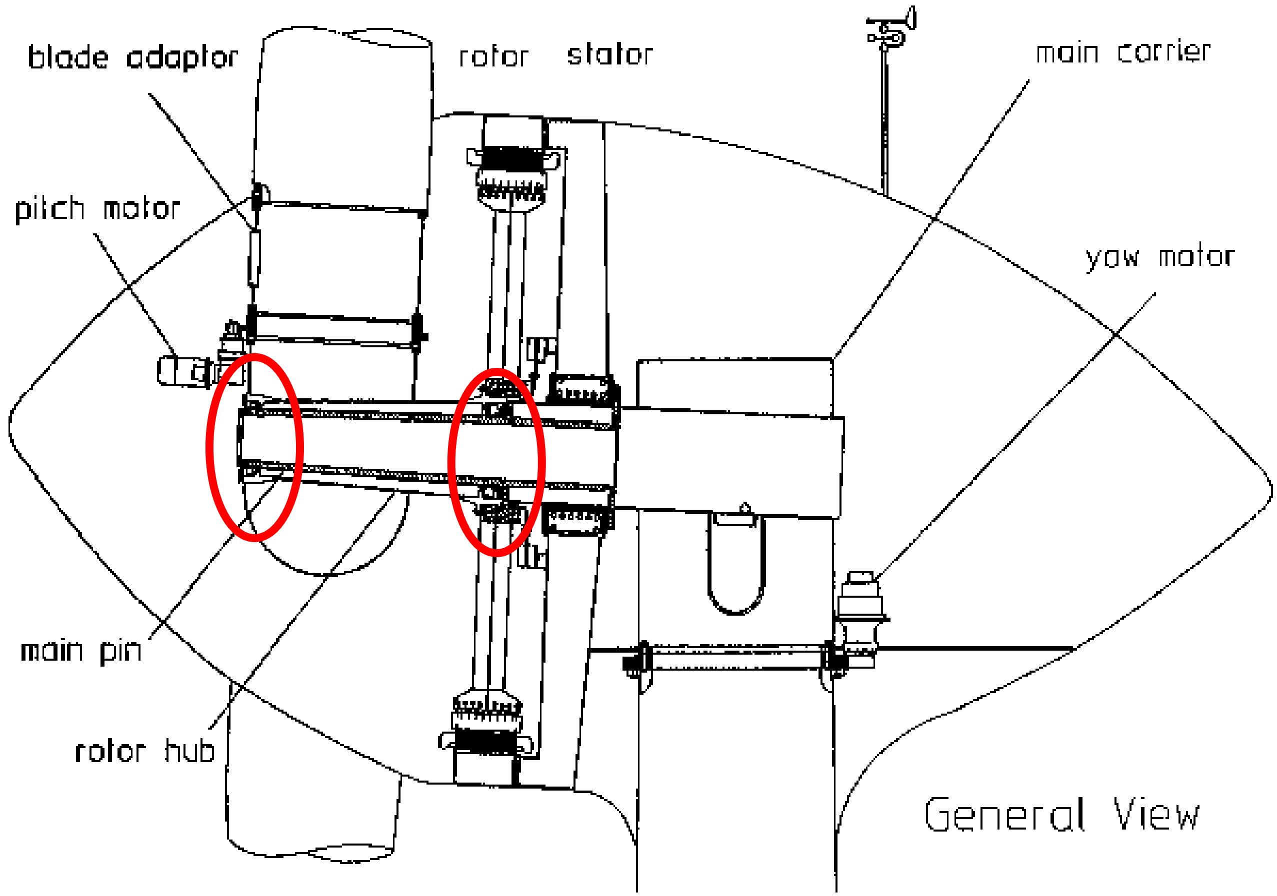
Bearings on fixed axle pin



Gearbox

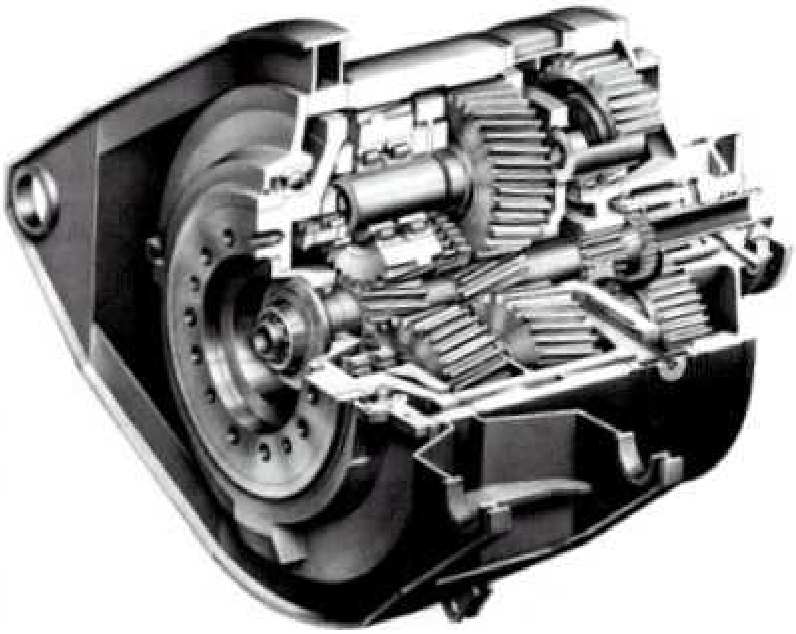
2007-2008

type of transmission

Parallel

Simple

Planetary



Compact for high power

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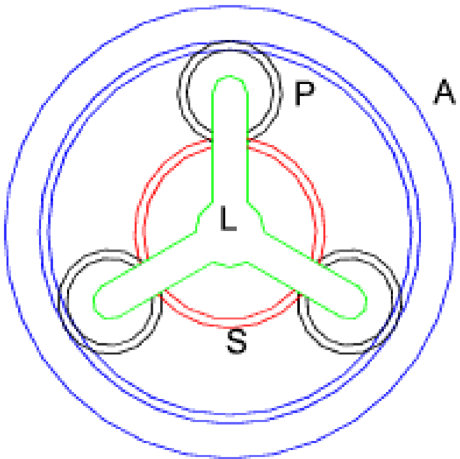
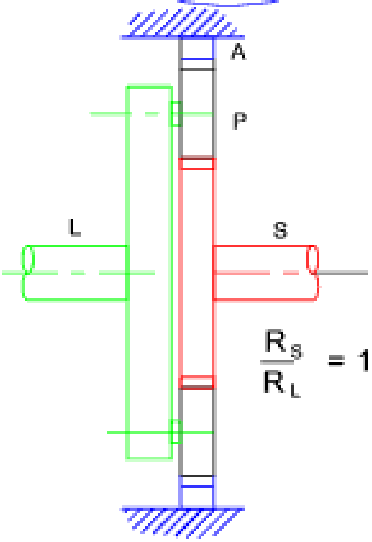
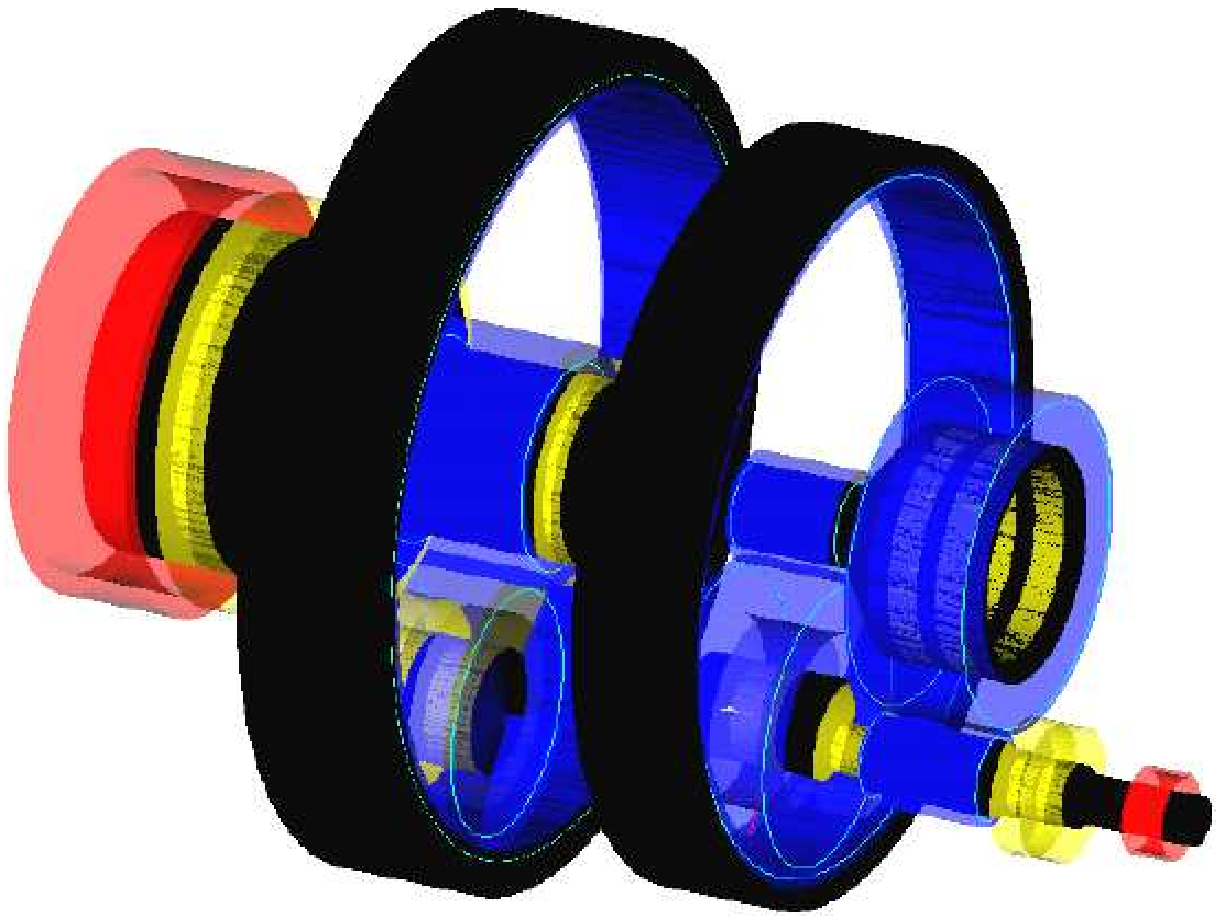
Gearbox – planetary & parallel stages





$$\frac{R_S}{R_L} = 1 + \frac{N_A}{N_S}$$



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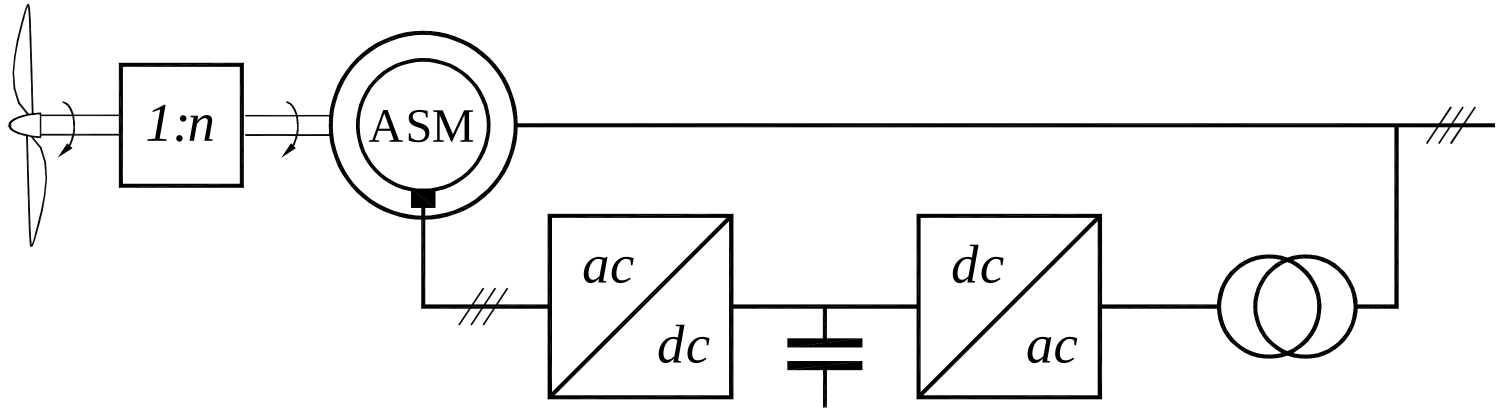
Generator

Doubly fed generator

Partly variable speed
Fed rotor
Inverters needed



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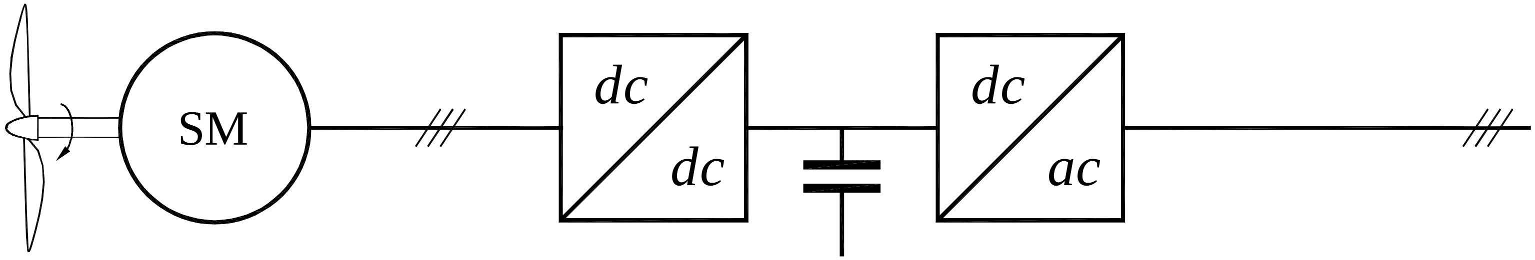
Direct drive (synchronous) generator

ENERCON 4.5 – 6 MW

Full variable speed
Rotor windings for magnetic field
Inverters needed

Low speed:
(Very) big diameters needed



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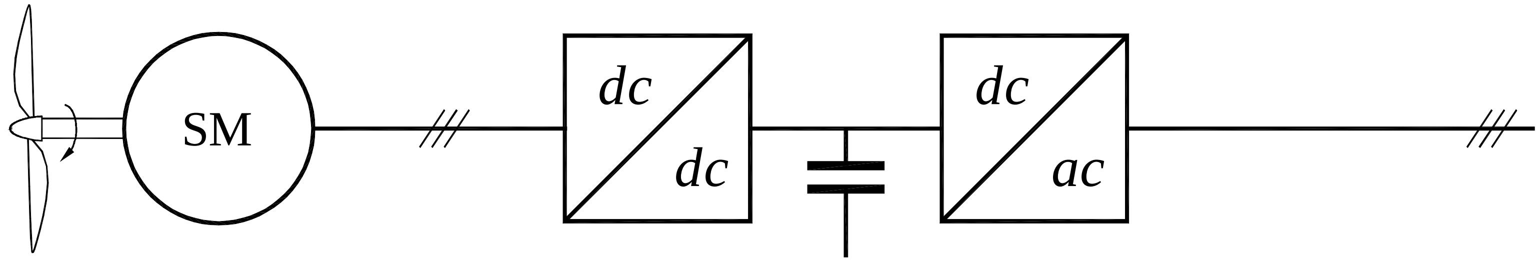
Permanent magnet generator

Full variable speed
No rotor windings
Inverters needed

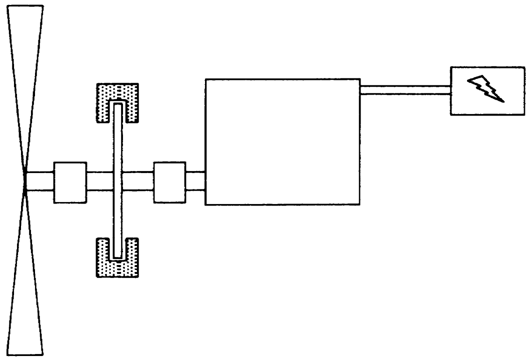


TU Delft

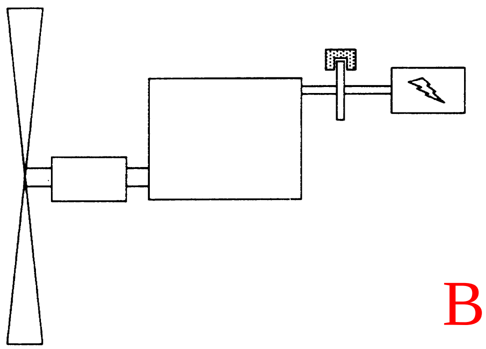
Brakes

2007-2008

Location of (fail-safe) brakes



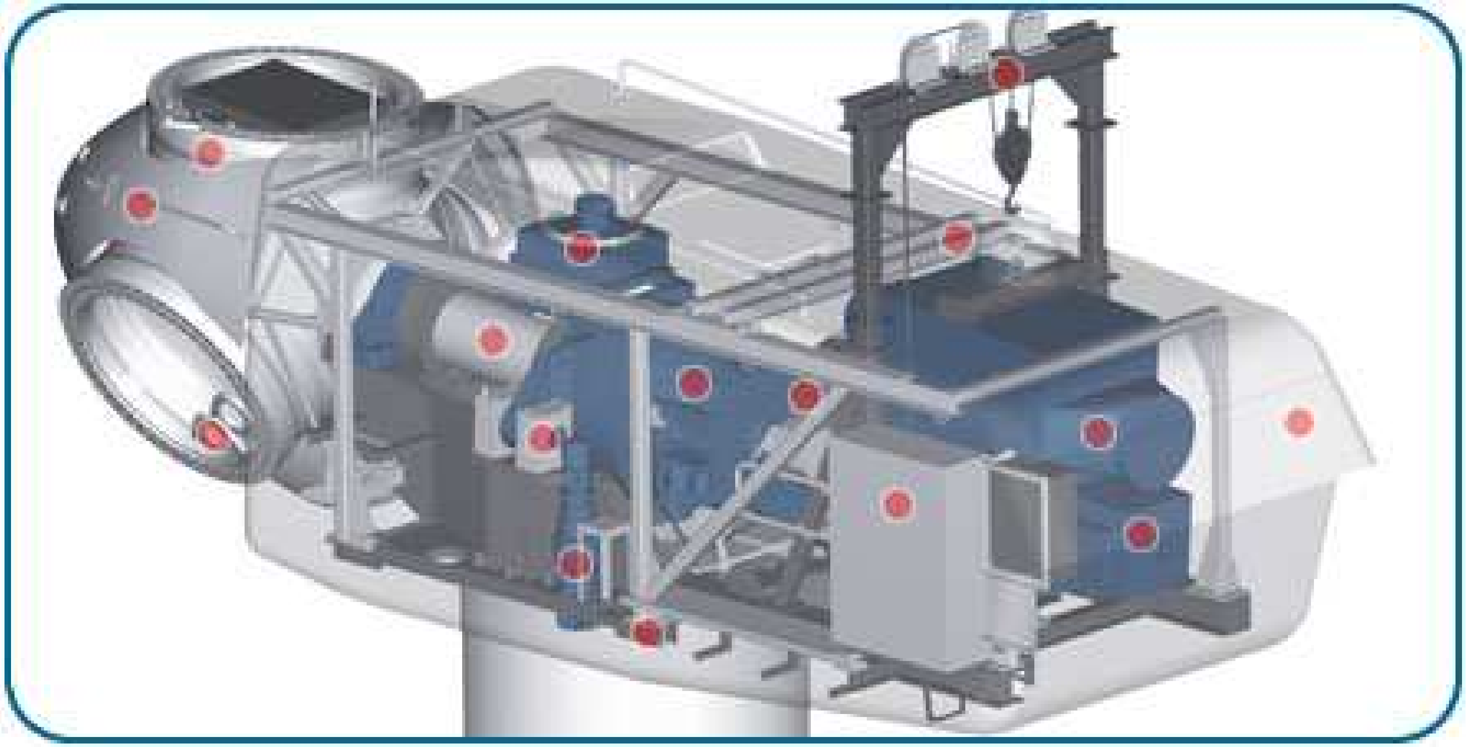
- brake located on slow shaft
(rotor shaft has double bearings)



- brake located on fast shaft

Brakes are actively released (hydraulics)
and passively clamped (springs)

Aerodynamic brake



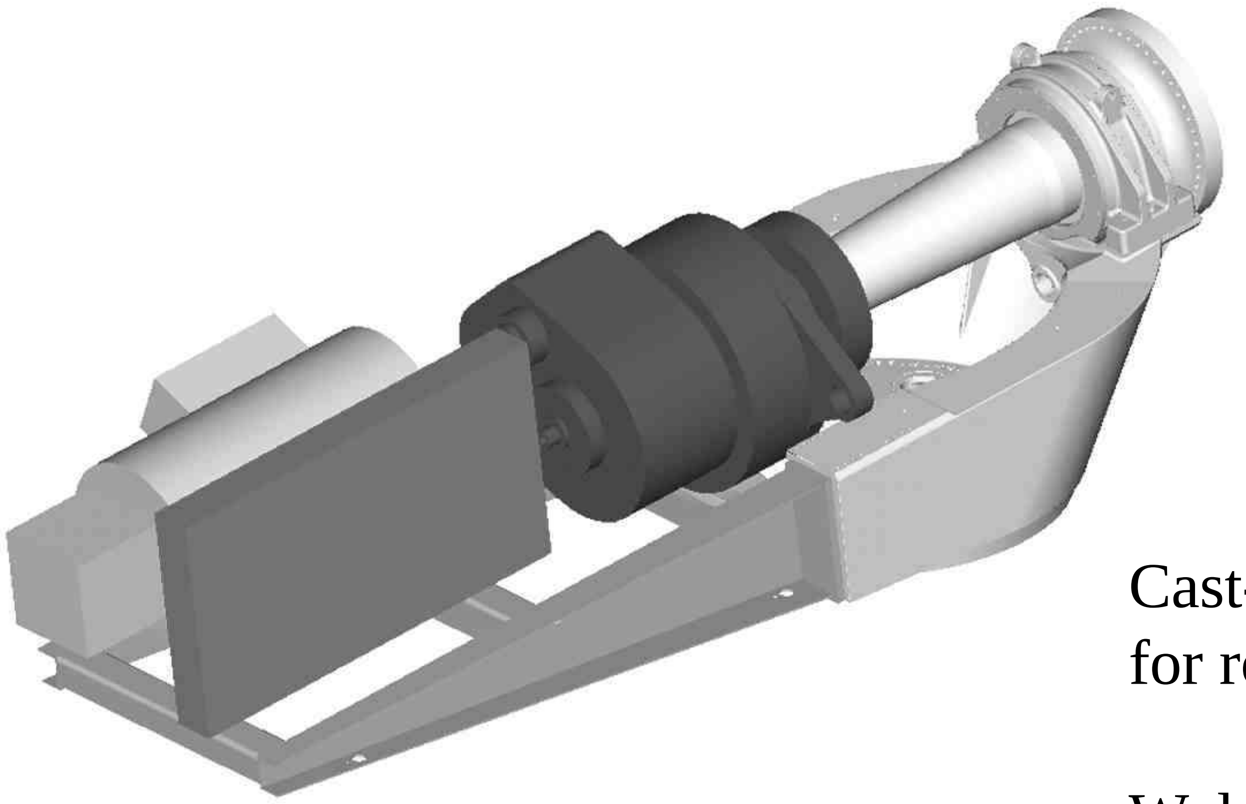
- Each blade can pitch individually to brake
- Only mechanical parking brake

TU Delft

Bedplate / Main frame

2007-2008

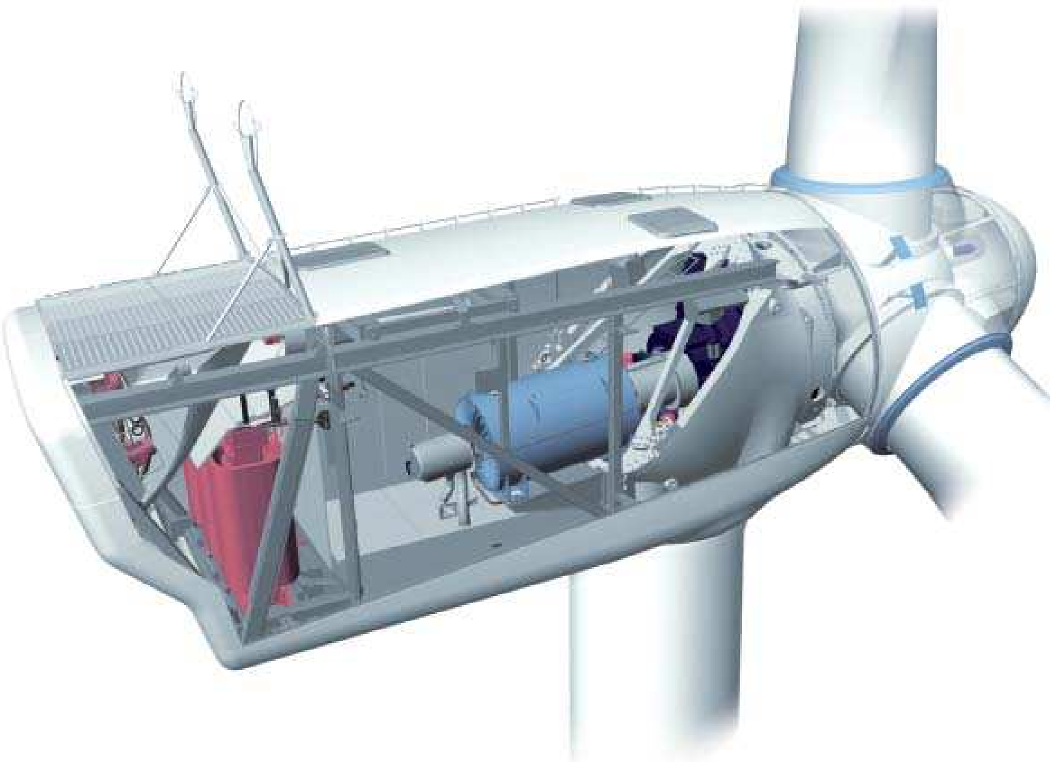
Traditional bedplate

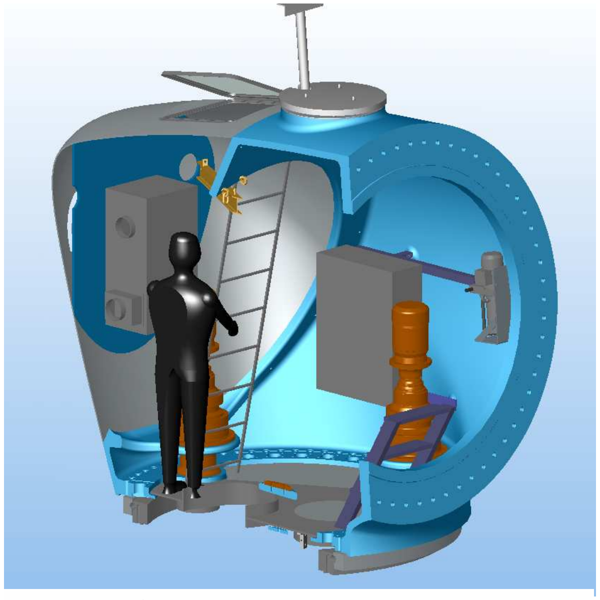


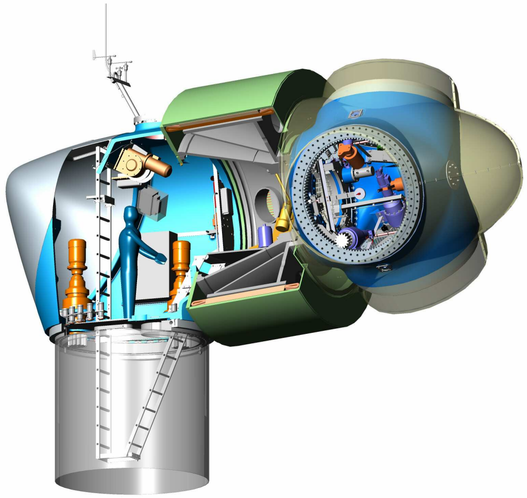
Cast-iron mainframe for rotor loads

Welded frame to carry other components

Compact frames







TU Delft

Yaw system

2007-2008

Yaw system

Bearing
Engines
Gearboxes
Yaw brakes

Cable twist counter &
pull switch (redundancy)

TU Delft

Control

State of the art

- Variable speed (restricted in US through patent)
- Pitch control

Future advances

- Individual pitch
- Smart rotors

Multi-MW turbines in the market

≥ 5MW (prototypes)

GE 3.6 – 3.6s
Enercon E-112
REpower 5M
Multibrid M5000
Siemens SWT-3.6-107

2007-2008

GE 3.6 – 3.6s (3.6 MW)

First prototype:	April 2002
Rotor:	104 m
Gearbox:	3-stage (PPE)
Generator:	Asynchronous
	Doubly-fed
Inverter:	Partial (30%)

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Enercon E-112 (4.5 MW)

First prototype:	August 2002
Rotor:	114 m
Gearbox:	No
Generator:	Synchronous
	Wound rotor
Inverter:	Full (100%)

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REpower 5M (5 MW)

First prototype:	November 2004
Rotor:	126 m
Gearbox:	3-stage (PPE)
Generator:	Asynchronous
	Doubly-fed
Inverter:	Partial (30%)

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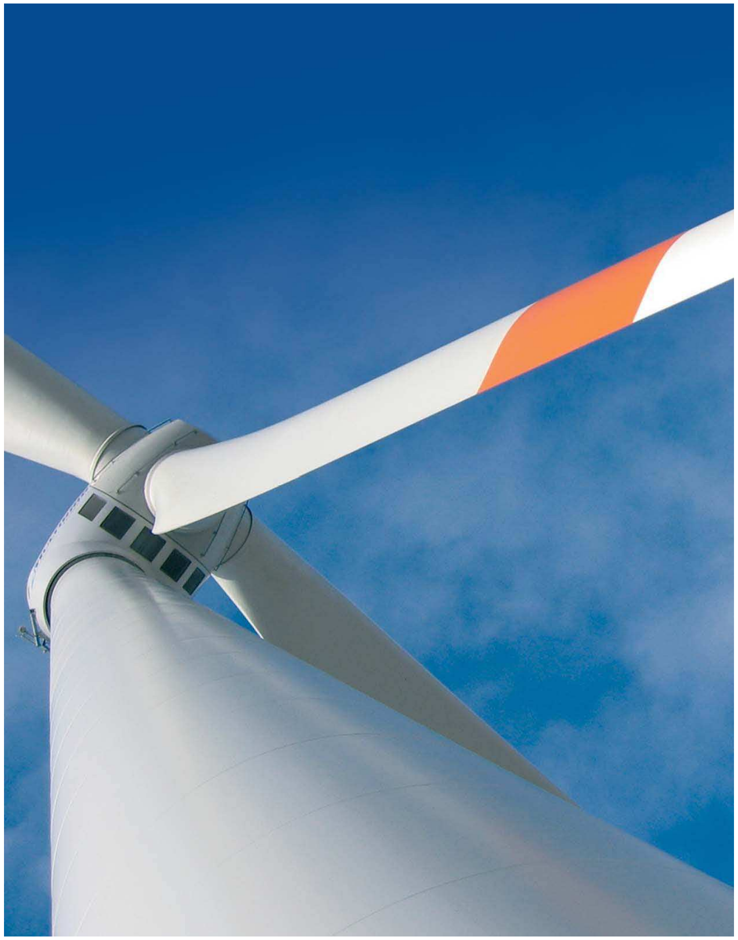
Multibrid M5000 (5MW)



First prototype:	December 2004
Rotor:	116 m
Gearbox:	1-stage (Planet)
Generator:	Synchronous
	Permanent Magnet
Inverter:	Full (100%)

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Siemens SWT-3.6-107 (3.6 MW)

First prototype:	December 2004
Rotor:	107 m
Gearbox:	3-stage (PPE)
Generator:	Asynchronous
	Squirrel cage
Inverter:	Full (100%)

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Future developments

- Announced by leading manufacturers
  - Vestas V120 (4.5 MW)
  - Upgrade Enercon E-112 → E-126 (?? MW)
- Developers involvement
  - Bard Engineering – Bard VM (5 MW)
  - Econcern – DarwinD (4.5 MW)
- No end to scale and concept evolution

TU Delft