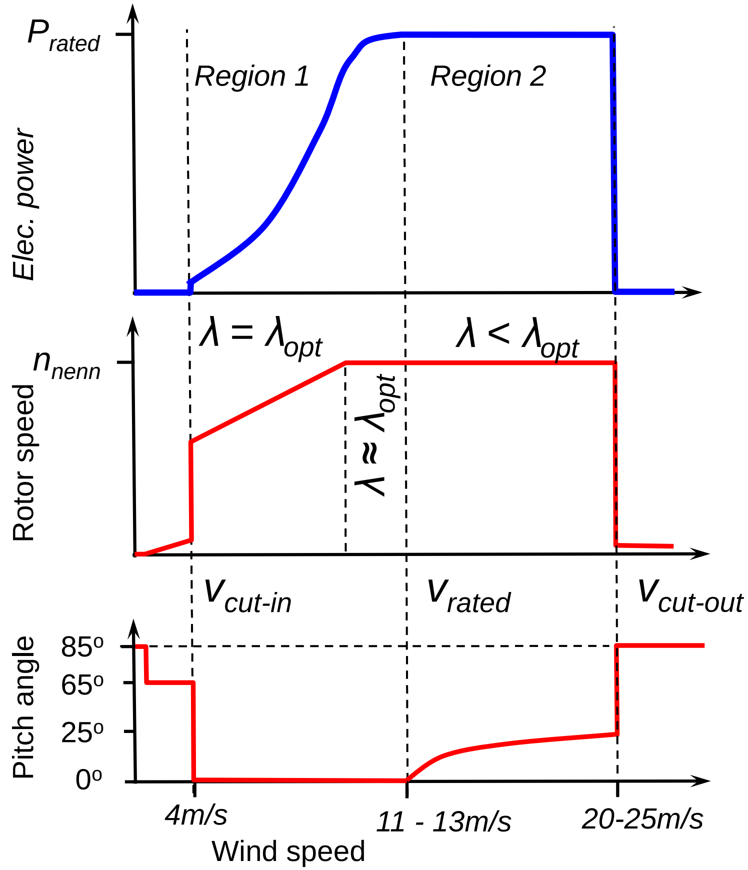
Design of Wind Energy Systems



Lecture 07
Wind Turbine Control

Prof. Dr. M. Kühn
Bernd Kuhnle

ForWind – Wind Energy Systems

Topics

- Regulations Strategies
- PID Controller
- Implementation in the turbine‘s operation
- Advanced Control
- Safety System
- Supervisory Control

Why turbine control?

For an optimal turbine operation:

- Maximal power conversion according to Betz
- Optimal inflow conditions at the blade sections

[Fotolia.com]

In case of unlimited turbine operation: $\Omega\uparrow \sim v$

[machinery.co.uk]

- Increase of centrifugal forces $\sim \Omega^2$
- Increase of thrust force $\sim \Omega^2$
- Increase of torque moment $\sim \Omega^2$
- Increase of power $\sim \Omega^3$

[NSW]

Regulation Strategies

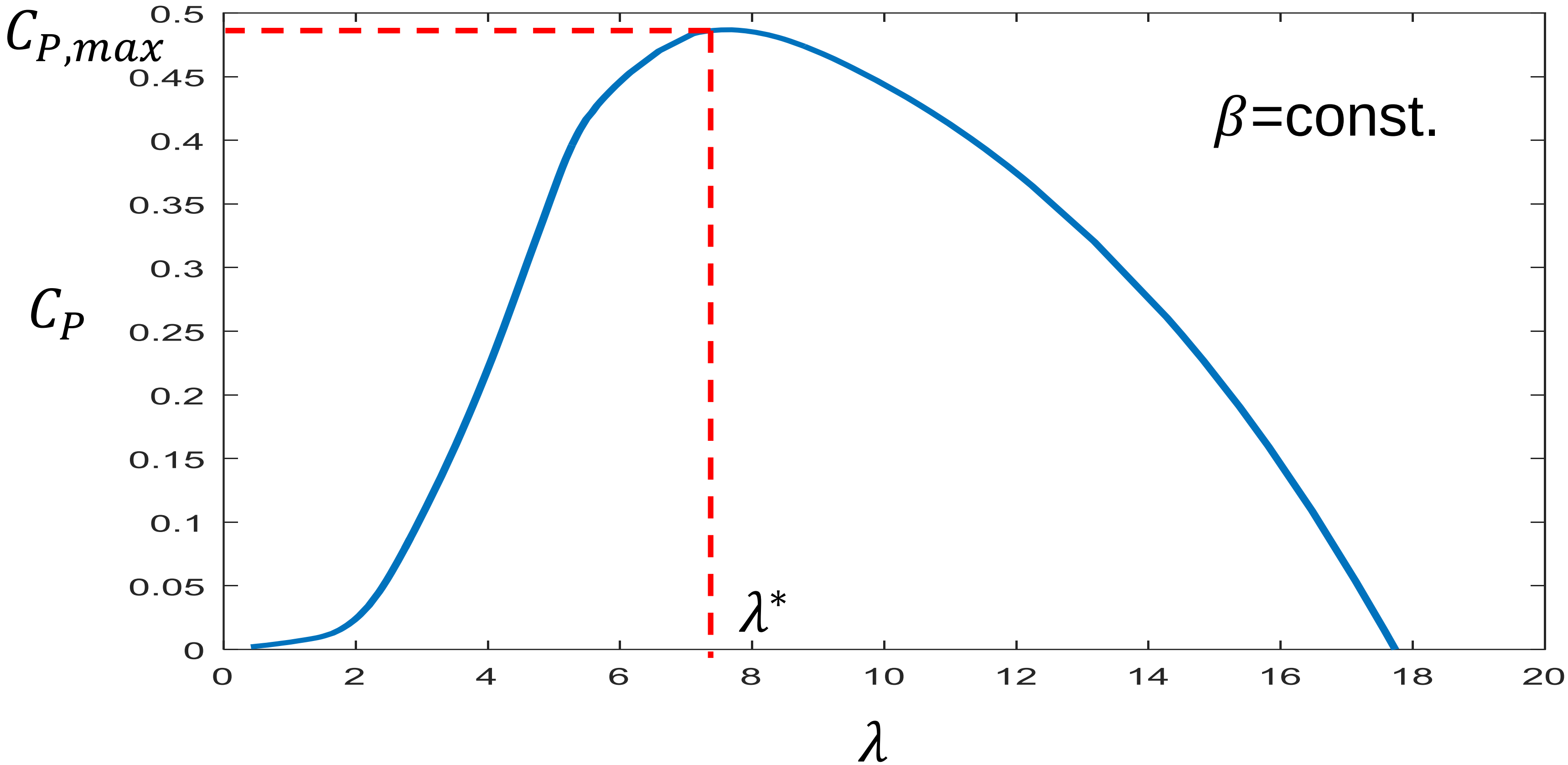
Basic wind turbine control strategies encompass:

- Constant Tip Speed Ratio (TSR) control
- Constant rotor speed control
- Below/Above rated wind speed control
- Variable-speed pitch-torque control

Regulation Strategies

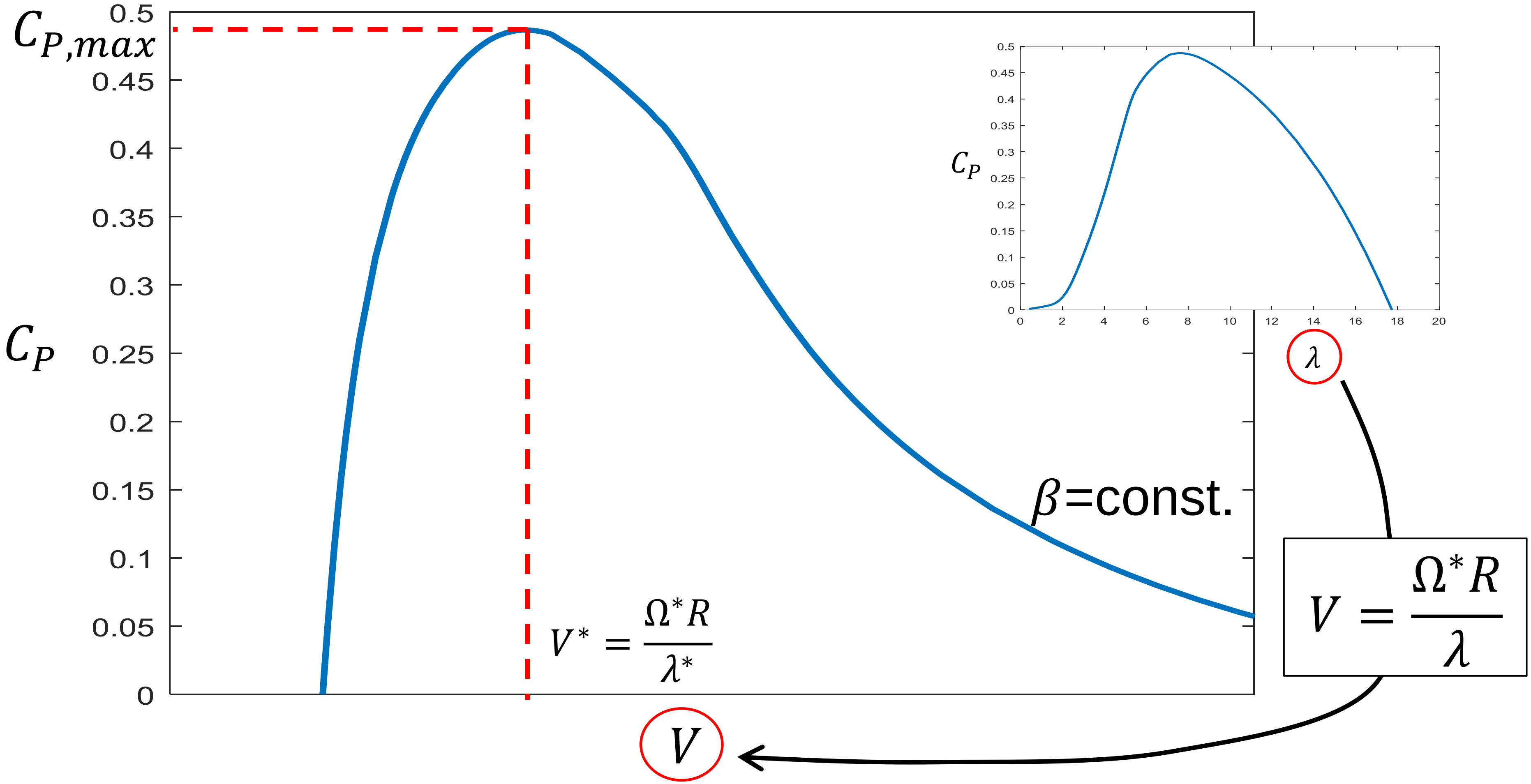
$$C_P = \frac{P_E}{0.5\rho\pi R^2 V^3} = f(\beta, \lambda, Re, M)$$

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



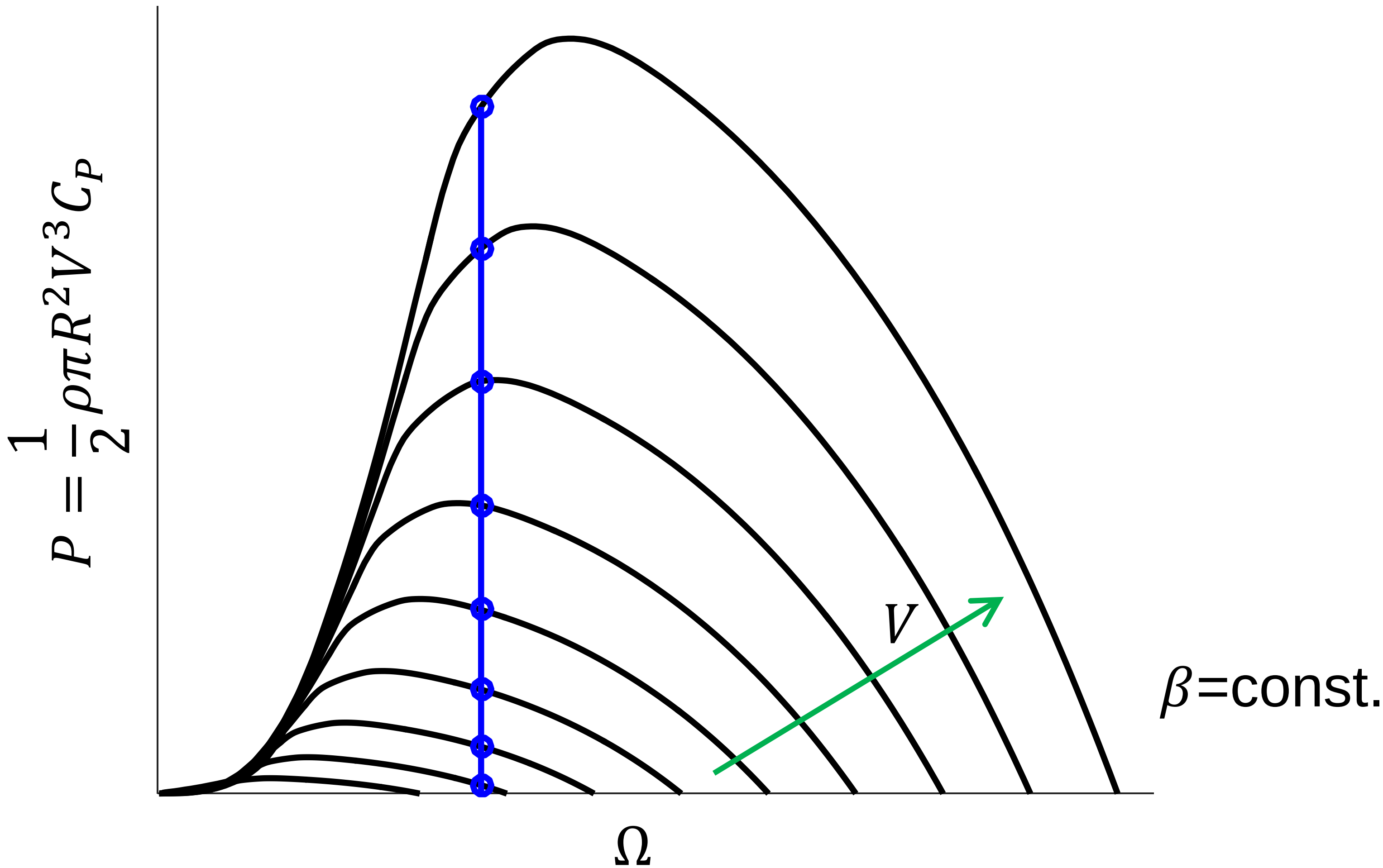
Regulation Strategies

Constant rotor speed, $\Omega = const = \Omega^*$,



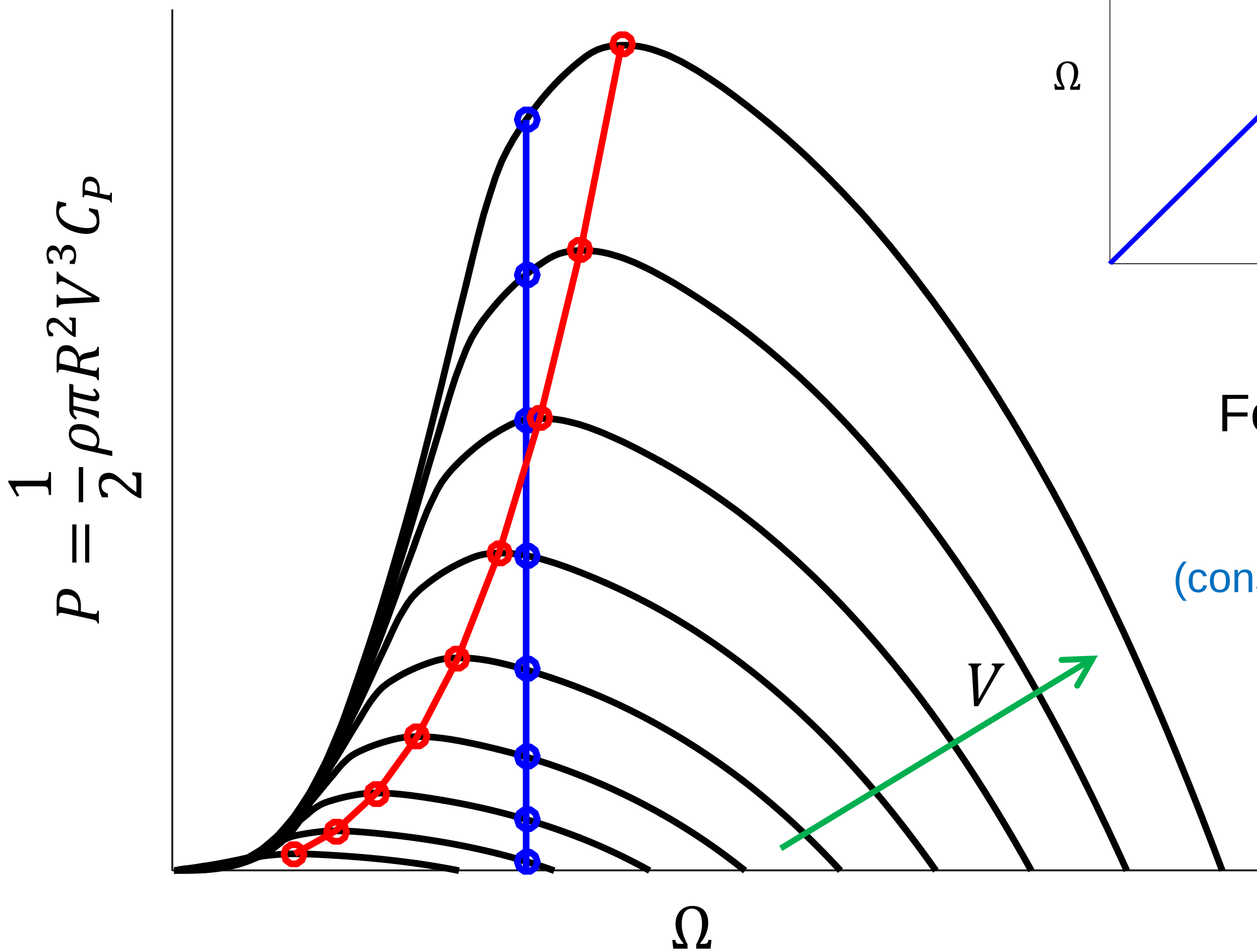
Regulation Strategies

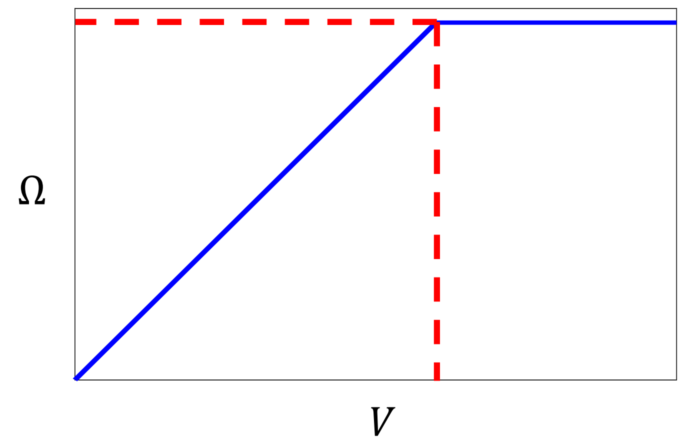
Constant rotor speed, $\Omega = const = \Omega^*$,



Regulation Strategies

Constant TSR, $\lambda = const = \lambda^*, \Omega = \frac{V\lambda^*}{R}$





For each wind speed:

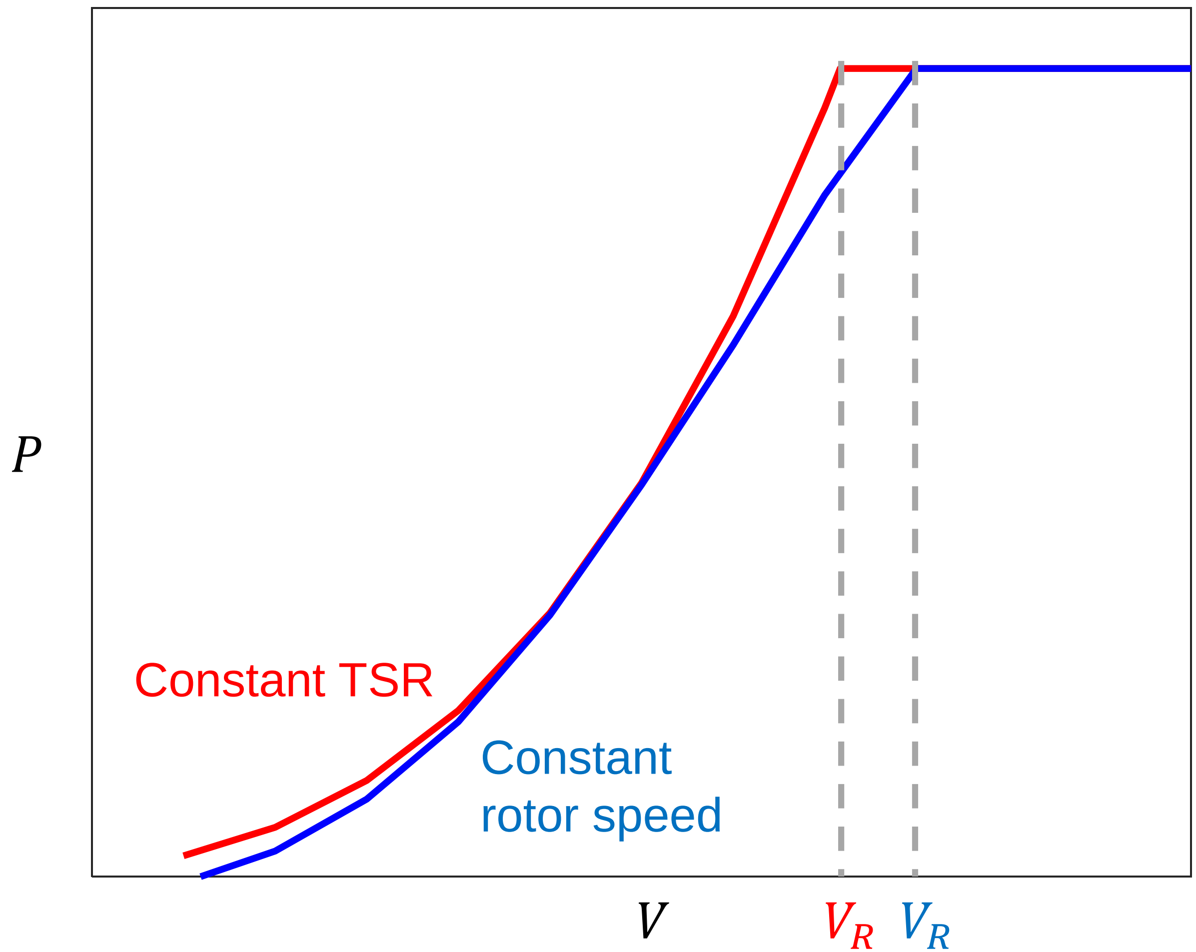
$C_P \leq C_P$

(const. RPM) (const. TSR)

β=const.

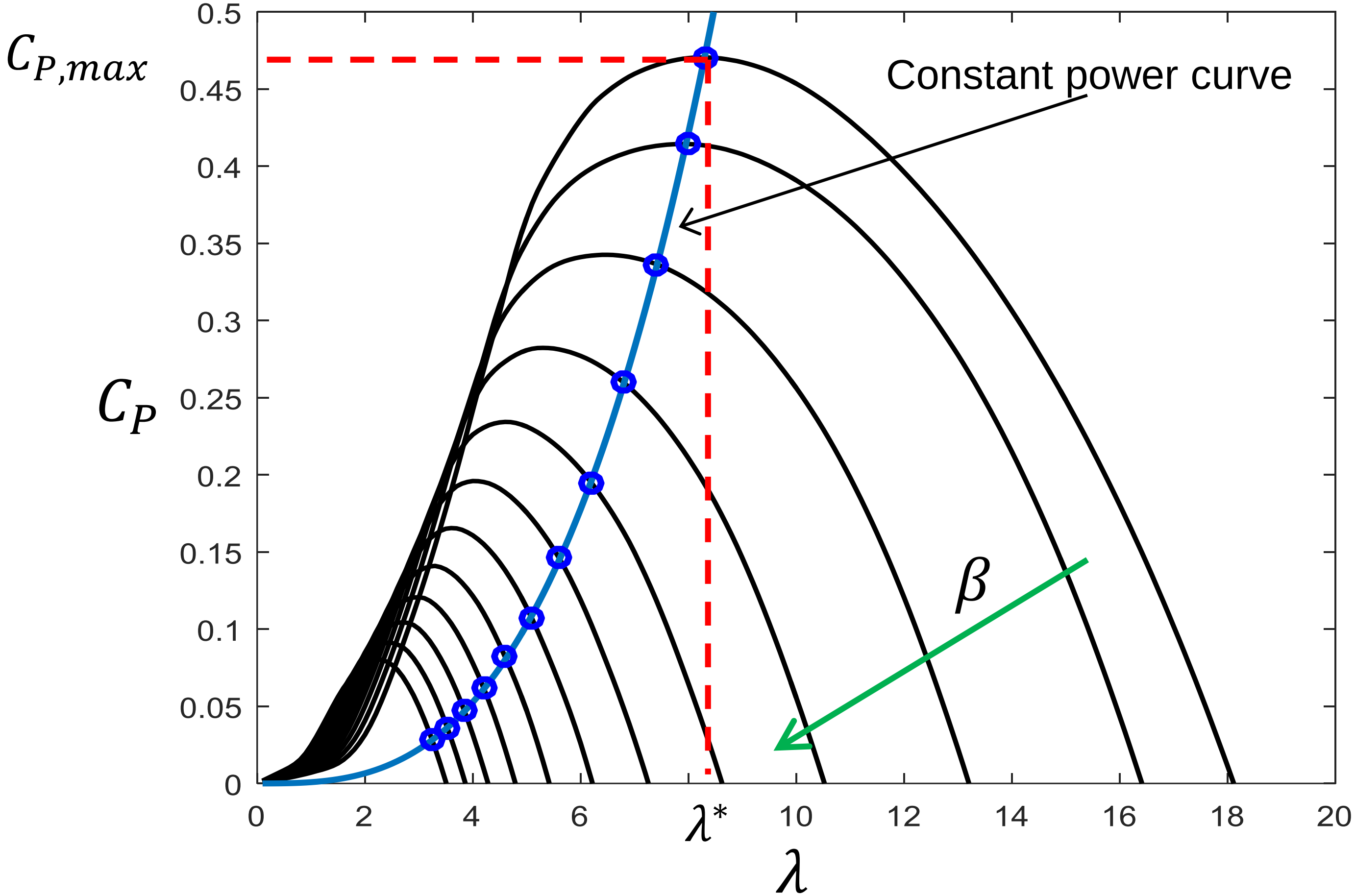
Regulation Strategies

Power-wind speed curve



Regulation Strategies

Region above rated speed: $V > V_R, P_E = P_R, \Omega = \Omega^*, T_G = T_R = \frac{P_R}{\Omega^*}$

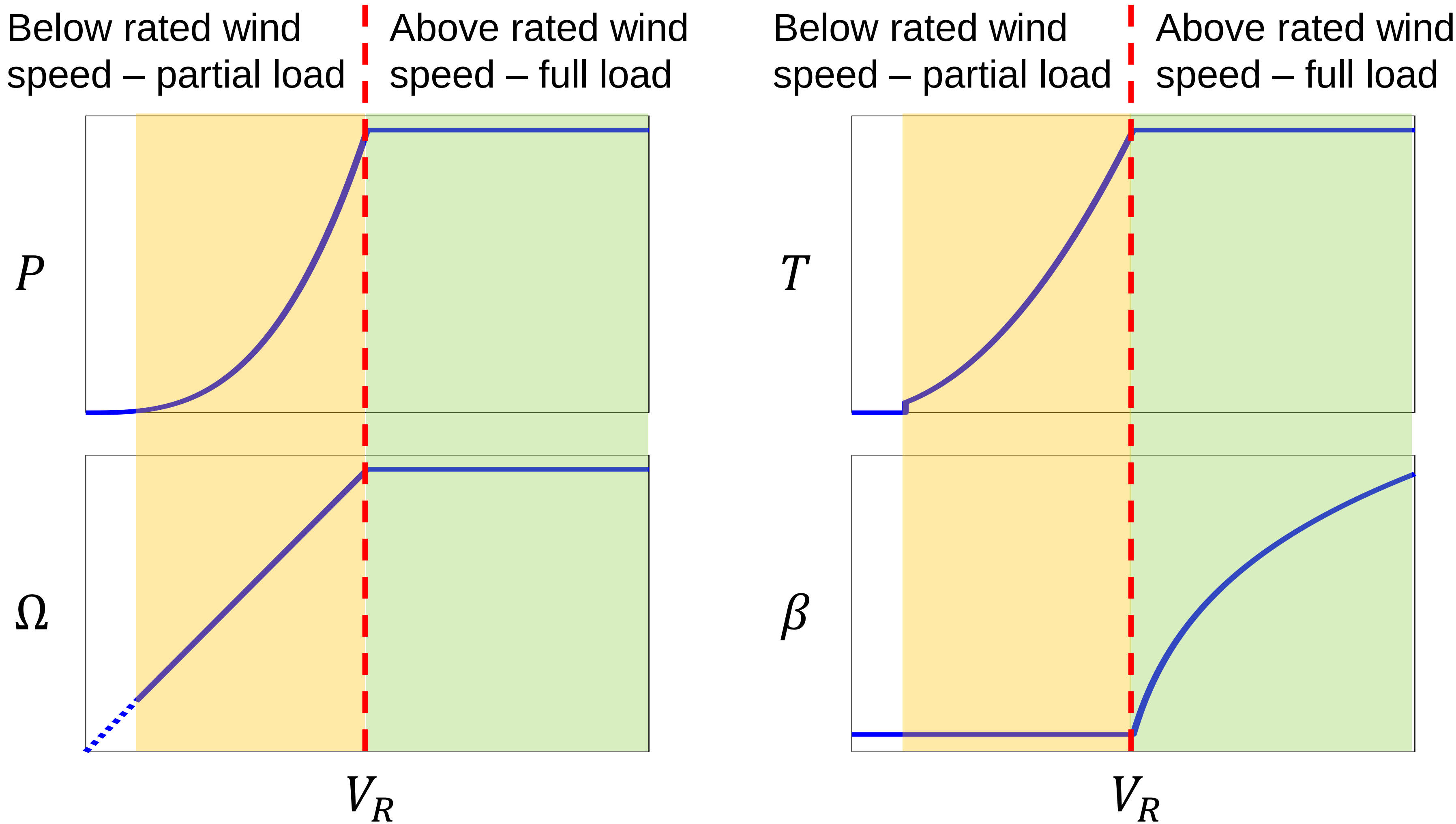


$$C_P = C_P^* \left(\frac{\lambda}{\lambda^*}\right)^3$$

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

Regulation Strategies

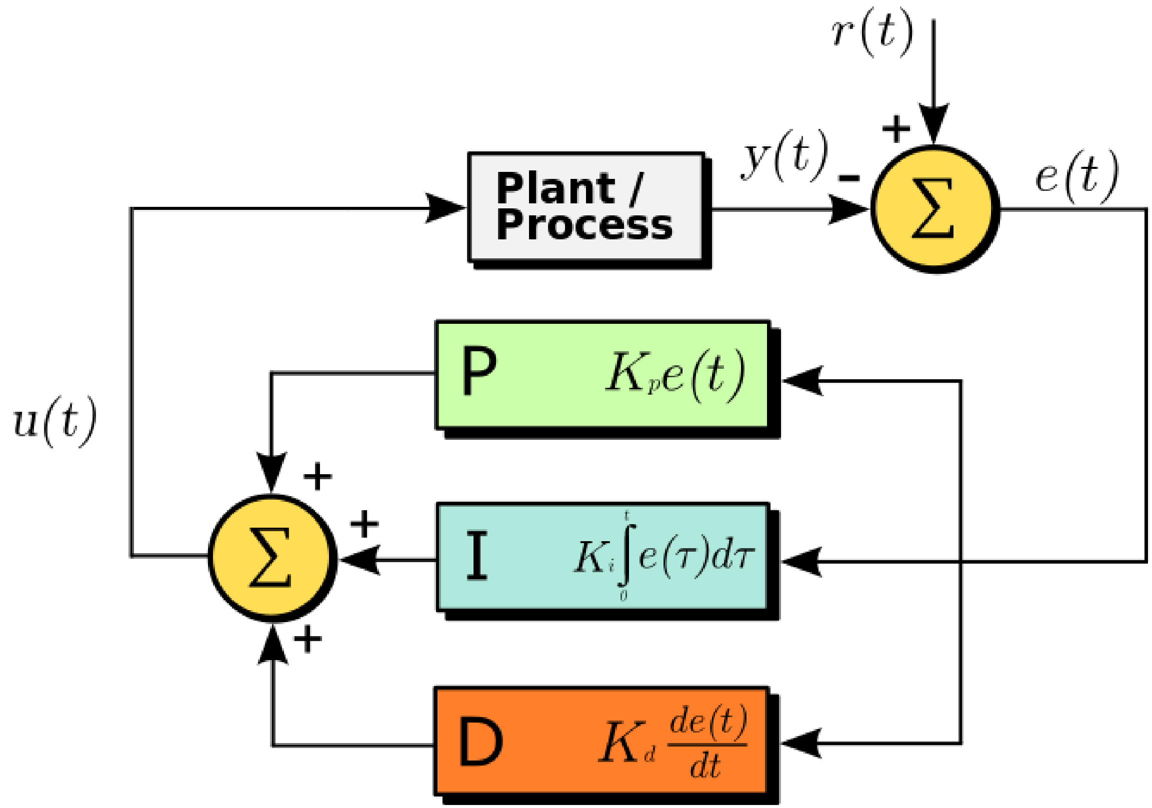
Variable-speed wind turbine with pitch/torque control



PID Controllers

The design of a proper control action for wind turbines is generally carried out by employing standard feedback control theory and so-called PID controllers.

- P-Term: Output, which is proportional to actual error.
- I-Term: Output, which is proportional to the magnitude and duration of the error.
- D-Term: Determines the slope of the error over time and predicts the upcoming behavior.

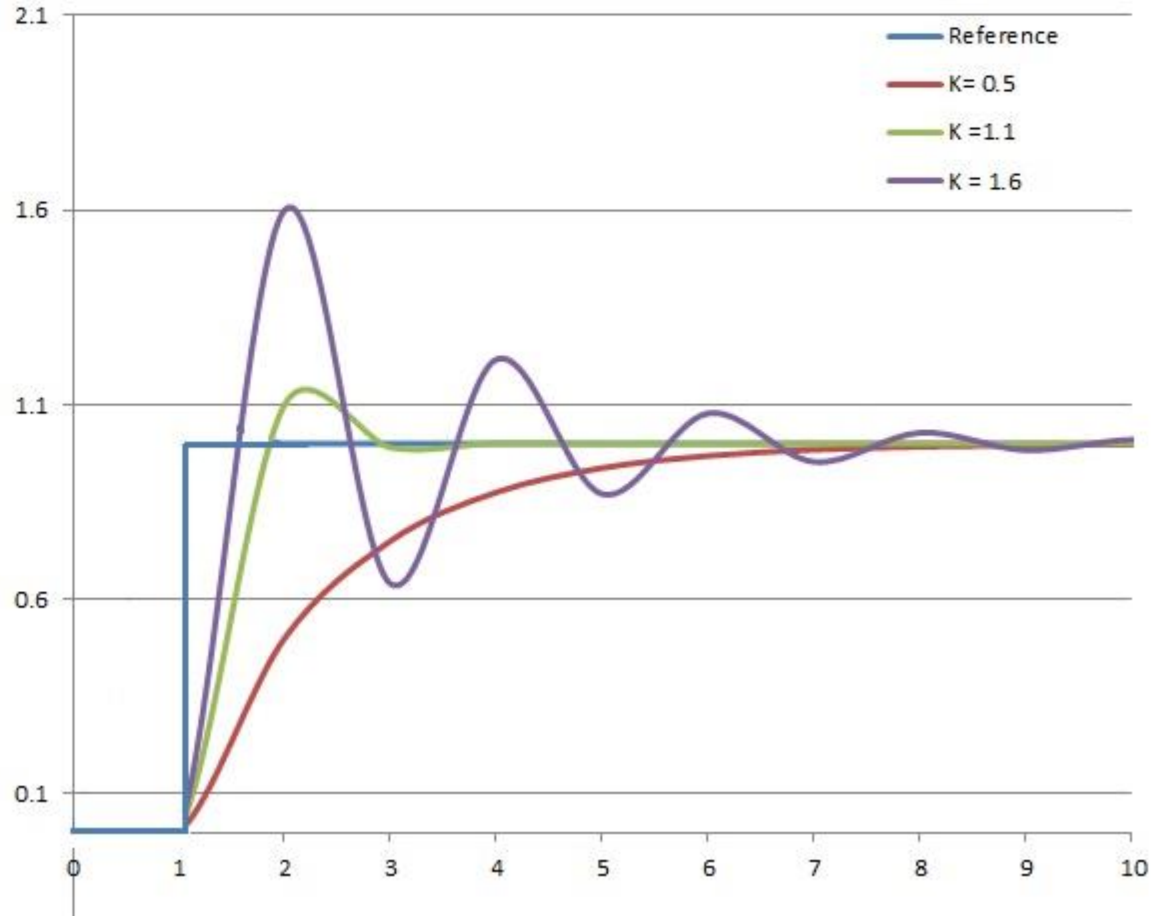


[Figure: wikipedia]

CARL VON OSSIETZKY universität OLDENBURG

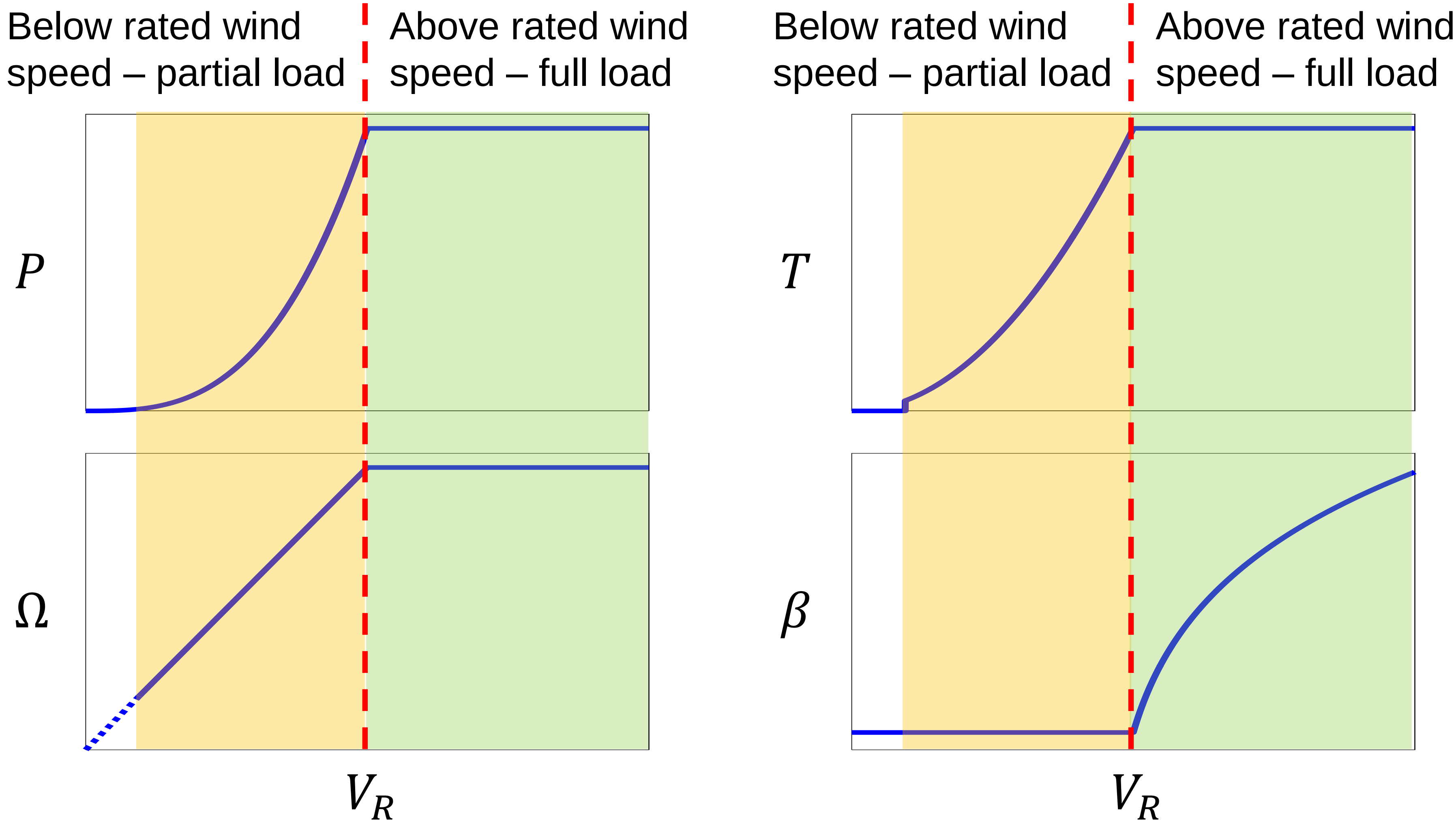
Example of influence of PID values

- Reaction of a system for a step response
- Here: varying proportional term



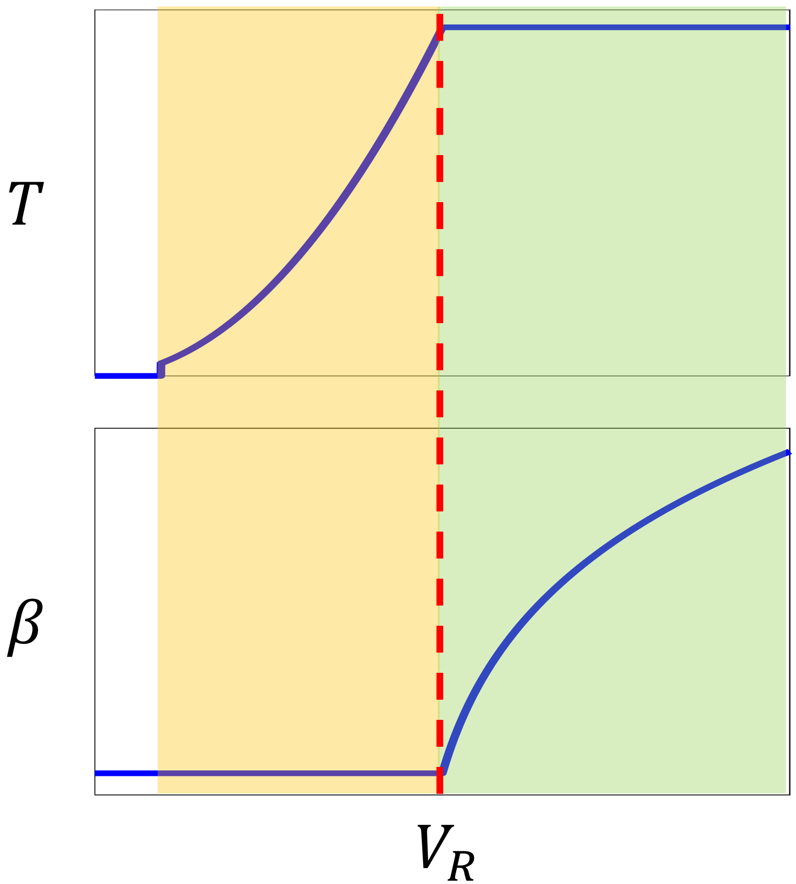
[Figure: wikipedia]

PID Controllers



PID Controllers

Torque and pitch demands are usually generated in isolation within two different regions of pertinence:



Generator torque below rated wind speed

$$
\begin{aligned}
T &= \frac{P}{\Omega} = \frac{1}{2}\rho\pi R^2 C_P^* \frac{V^3}{\Omega} \\
&= \frac{1}{2}\rho\pi R^3 \frac{C_P^*}{\lambda^{*3}}\Omega^2 \\
&= K_{opt}\Omega^2
\end{aligned}
$$

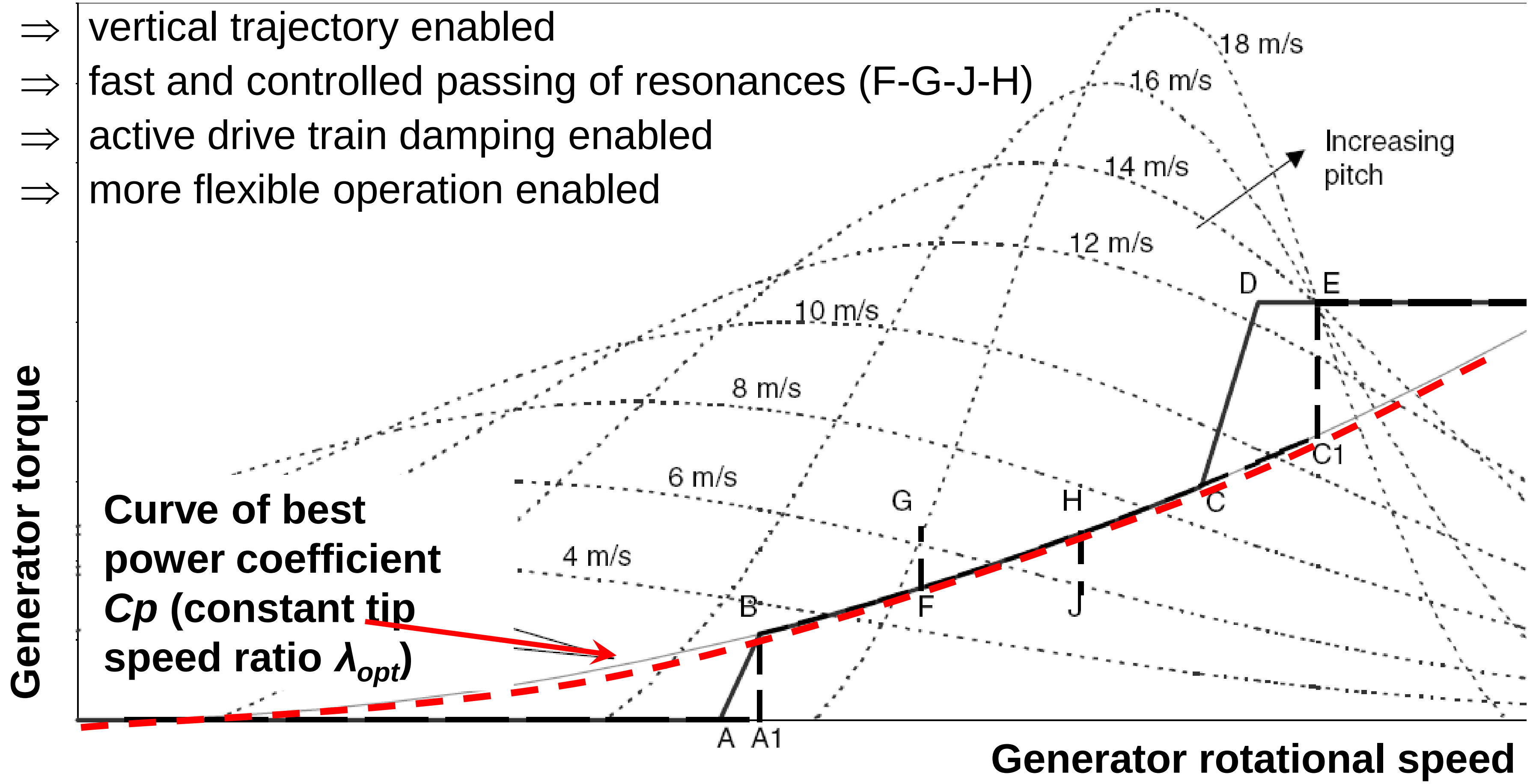
Collective pitch angle above rated wind speed determined by a PI(D) controller in order to keep rotor speed / electrical power at rated level

Typical torque-speed curve for torque control

Common control concepts:

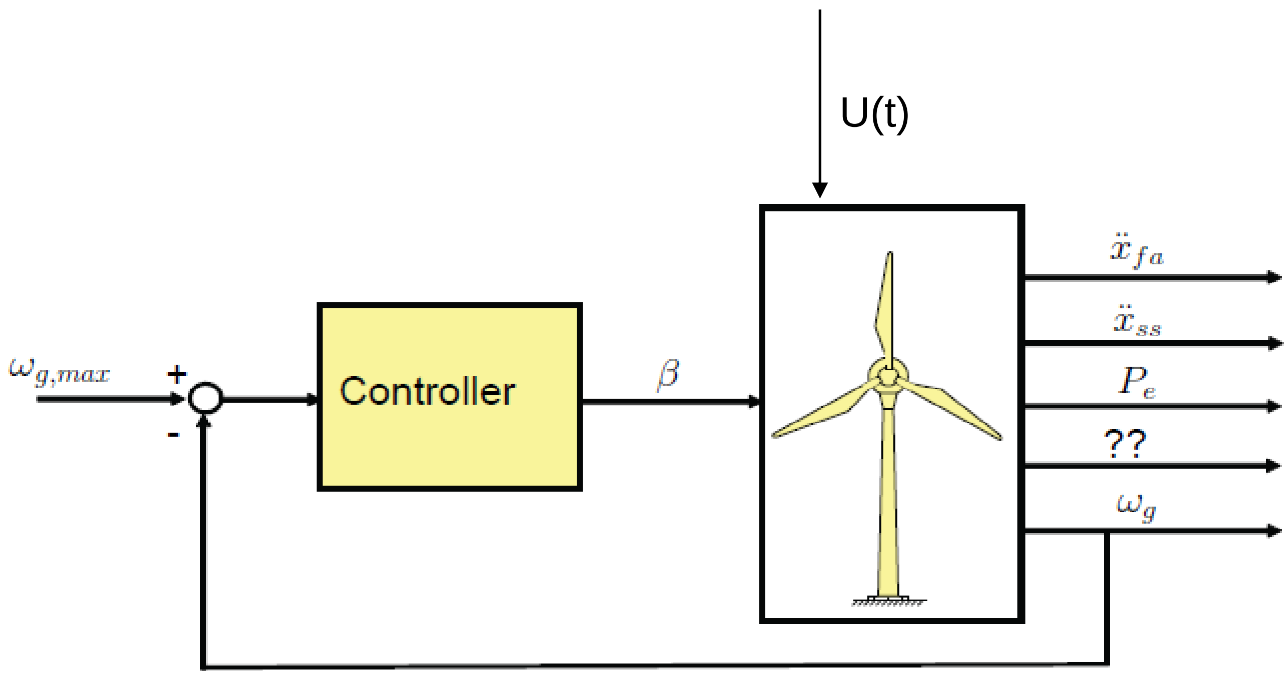
1. Steered guidance of a prescribed characteristics (e.g. A-B-C-D-E)
2. „controlled characteristics“ offer advantages:

⇒ vertical trajectory enabled
⇒ fast and controlled passing of resonances (F-G-J-H)
⇒ active drive train damping enabled
⇒ more flexible operation enabled



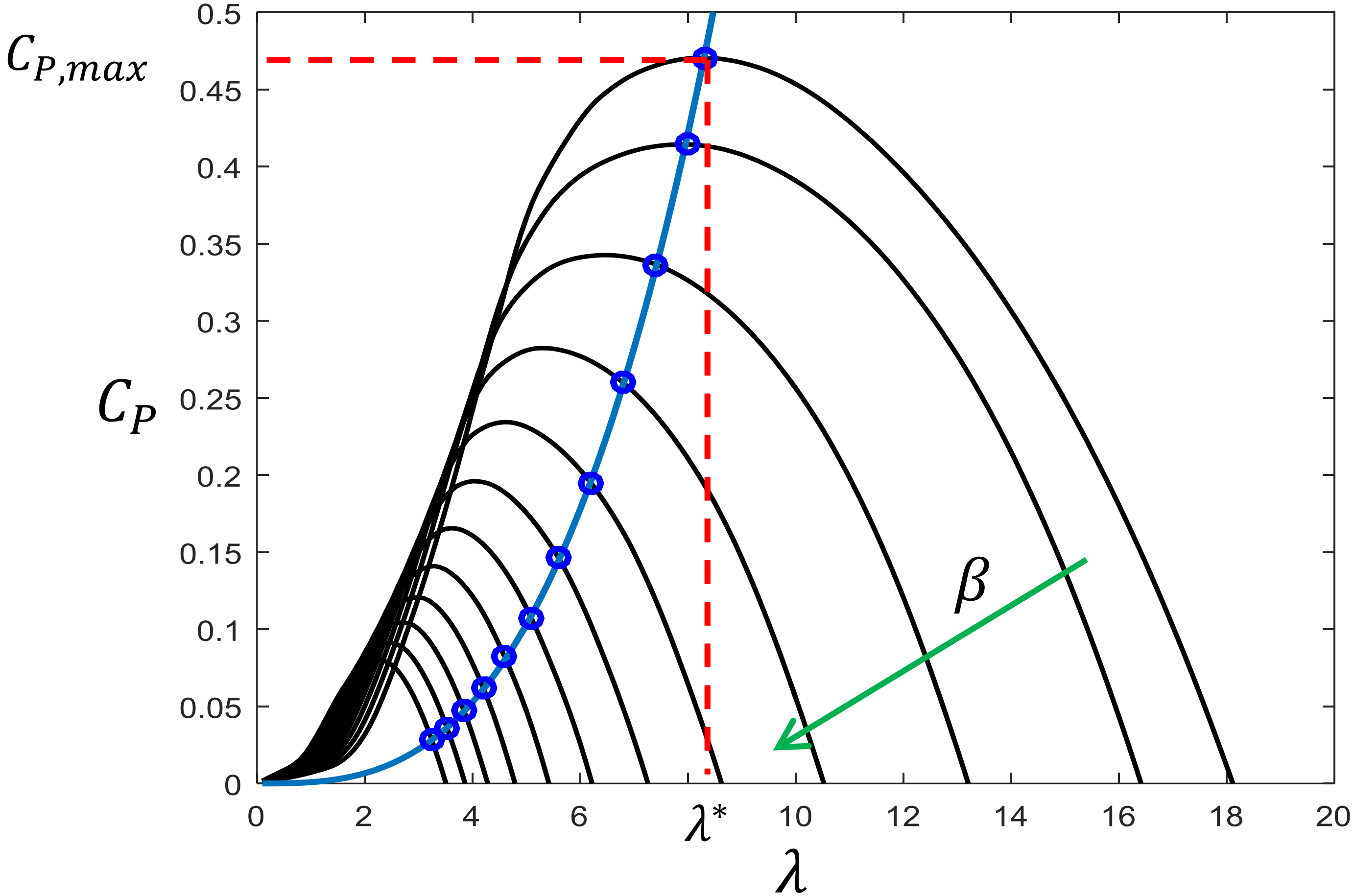
PID Controllers

The pitch activity can be modelled with a PI controller in the following way:



Regulation Strategies

Region above rated speed: $V > V_R, P_E = P_R, \Omega = \Omega^*, T_G = T_R = \frac{P_R}{\Omega^*}$



$$C_P = C_P^* \left(\frac{\lambda}{\lambda^*}\right)^3$$

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

Regulation Strategies

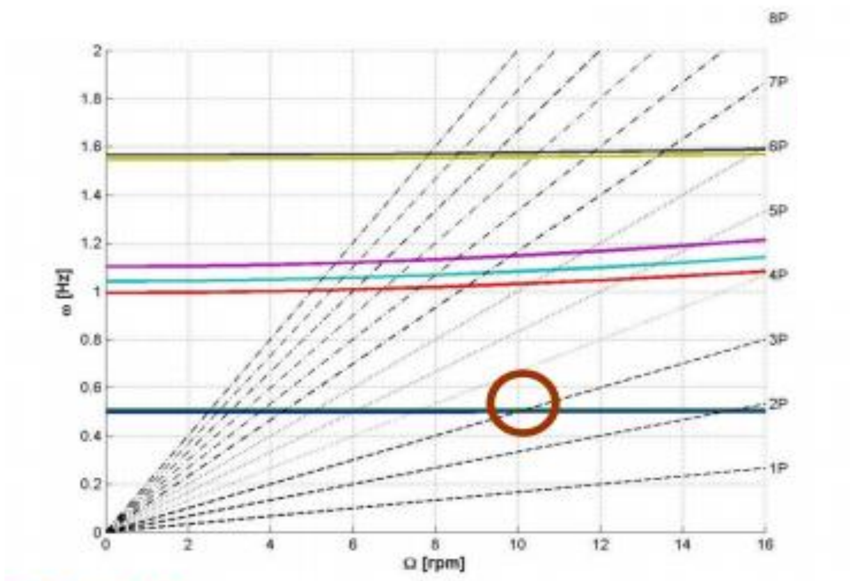
Further wind turbine control objectives may include:

- Fatigue load reduction in case of turbulent inflow,
- Mitigation of loads deriving from sudden wind gusts,
- By-passing particular resonant frequencies of the system,
- Reducing pitch actuator duty cycle.

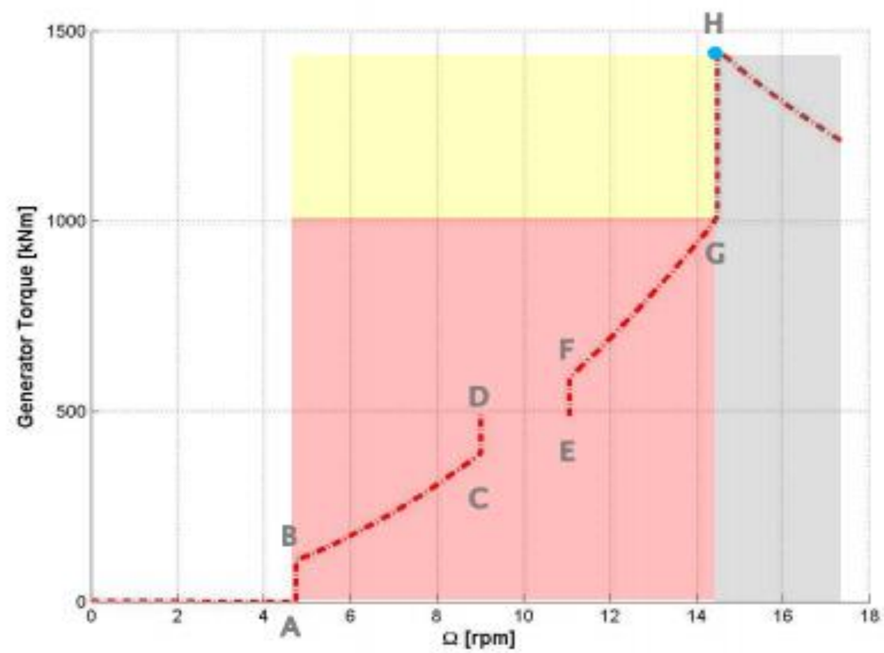
Generally, these additional goals should be achieved together with

- Maximizing energy capture, and
- Limiting power to the rated value.

Control adjustment to avoid resonances



Motivation: avoid operation at the intersection of nP harmonics and tower natural frequency.



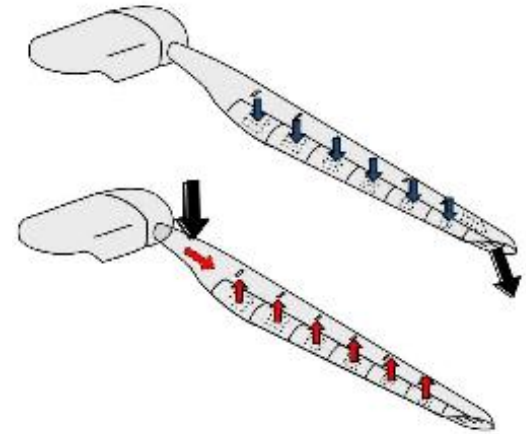
Solution:

- Speed range is split into two regions about the natural frequency.
- Each region constrained by vertical speed-torque ramp.
- PI torque control tracks vertical ramps.

Innovative control concepts

LiDAR feedforward control
[SWE Stuttgart]

Active smart blades (flaps)
[TU Delft]



Boundary layer control
[TU Delft]

2-bladed rotor, downwind,
advanced controls
[2-B Energy]

Passive control
e.g. bend-twist coupling

Advanced Control

Load reduction potential individual pitch control:

- fatigue at least 10 to 30%
- extreme loads: not yet, possible on longer term

Challenges

- reliable, robust sensor concepts
- system approach
- reliable control algorithms
- reliable pitch actuators

Fig. Vestas

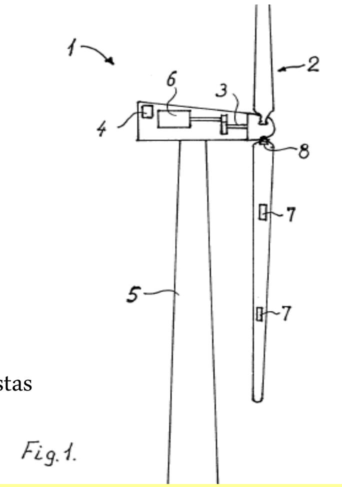


Fig. Vestas

Variable airfoil geometry (smart blades)

“Advanced Stall”?

?

Aeroelastic tailoring

Tower feedback control (individual pitch)

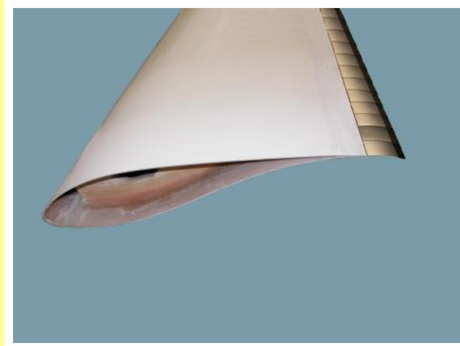
Individual pitch

Tower feedback control (collective pitch)

Tower vibration damper

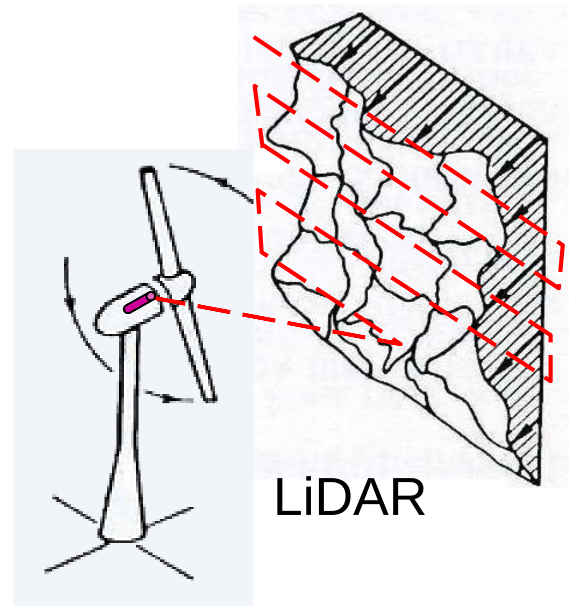
Peak shaver

Collective pitch

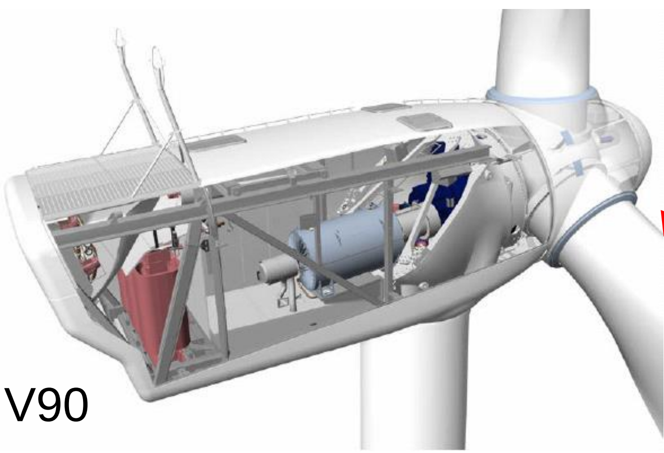


Advanced Control

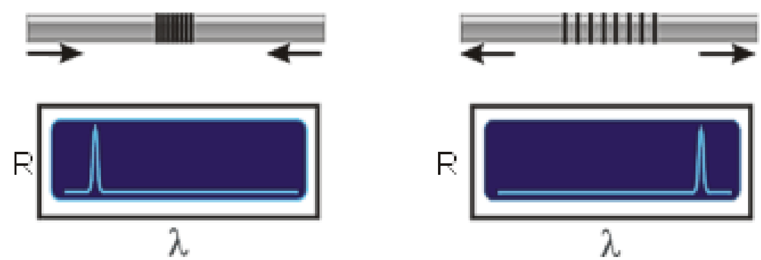
- *wind monitoring* (LiDAR = gust forecasting by laser)
- condition monitoring = damage monitoring
- *load monitoring* = stress monitoring
  - avoidance of over-loading
  - control based on actual real-time load effect
- *robust, optical sensors* (e.g. fibre bragg)
- individual blade pitch control



LiDAR



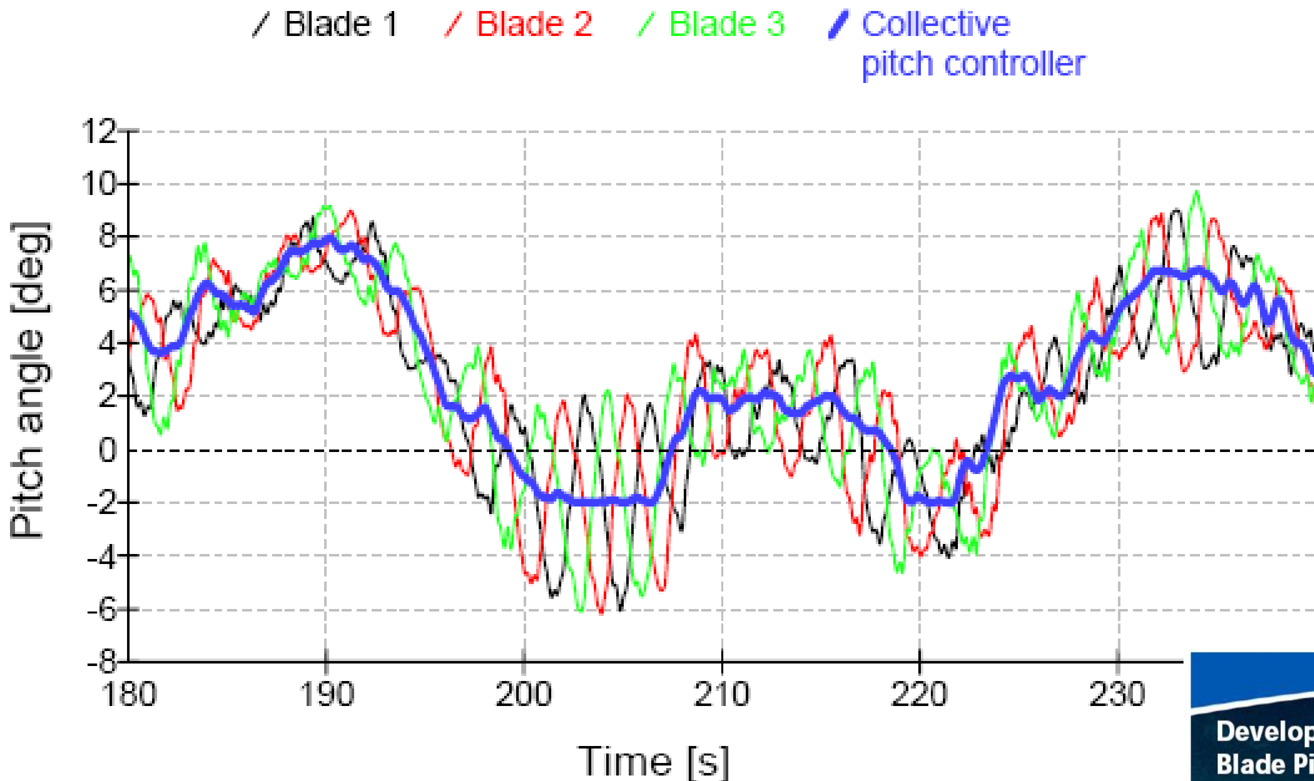
Vestas V90



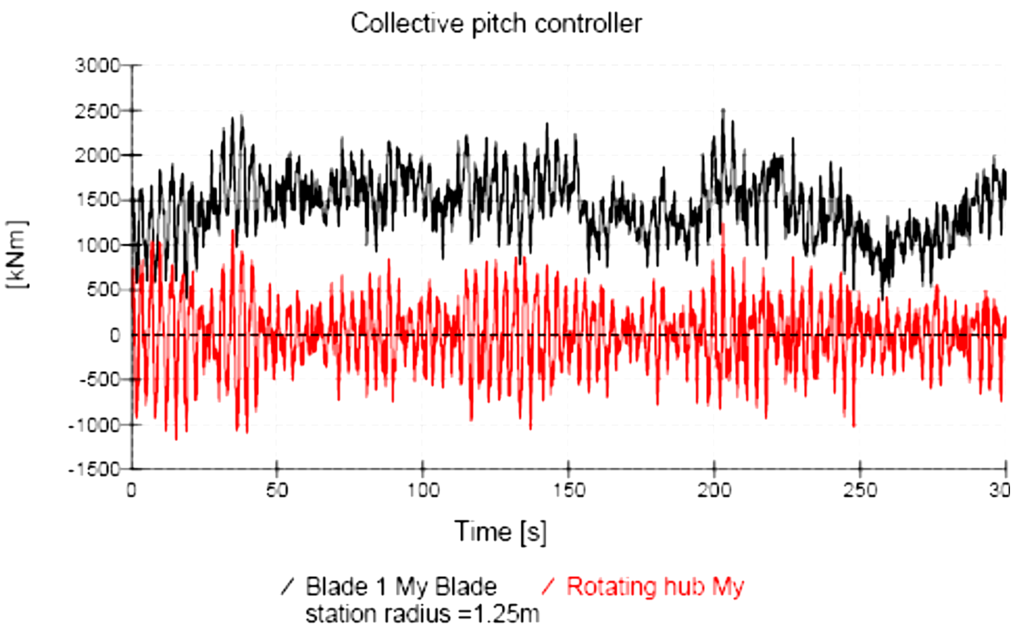
Fibre bragg effect at fibre prolongation

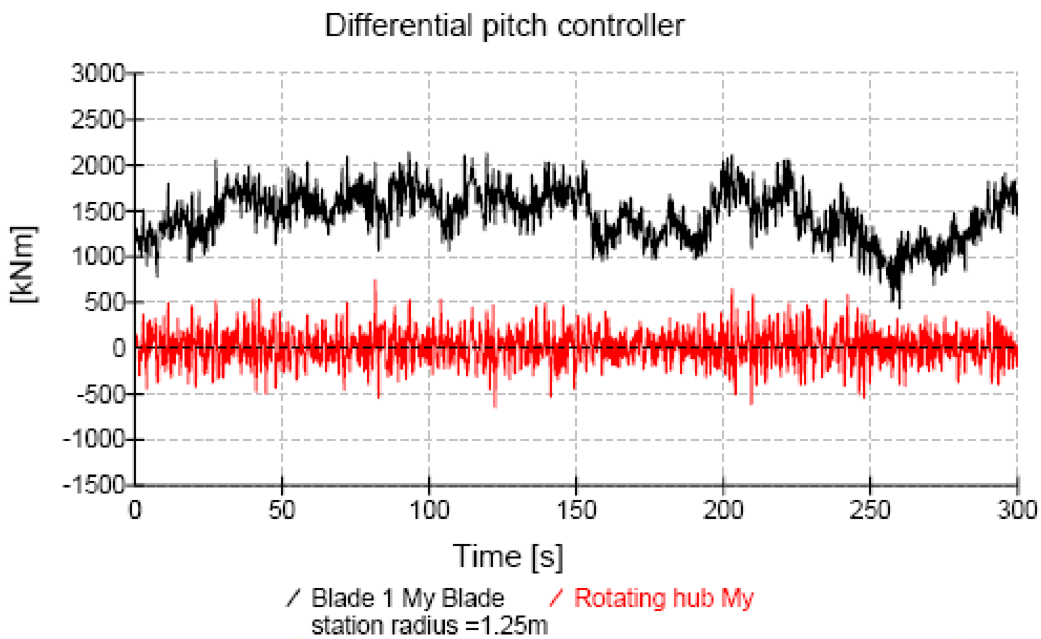
[www.smartfibres.com]

Individual Pitch Control



Reduction of blade and hub loads by individual pitch control (OPC)

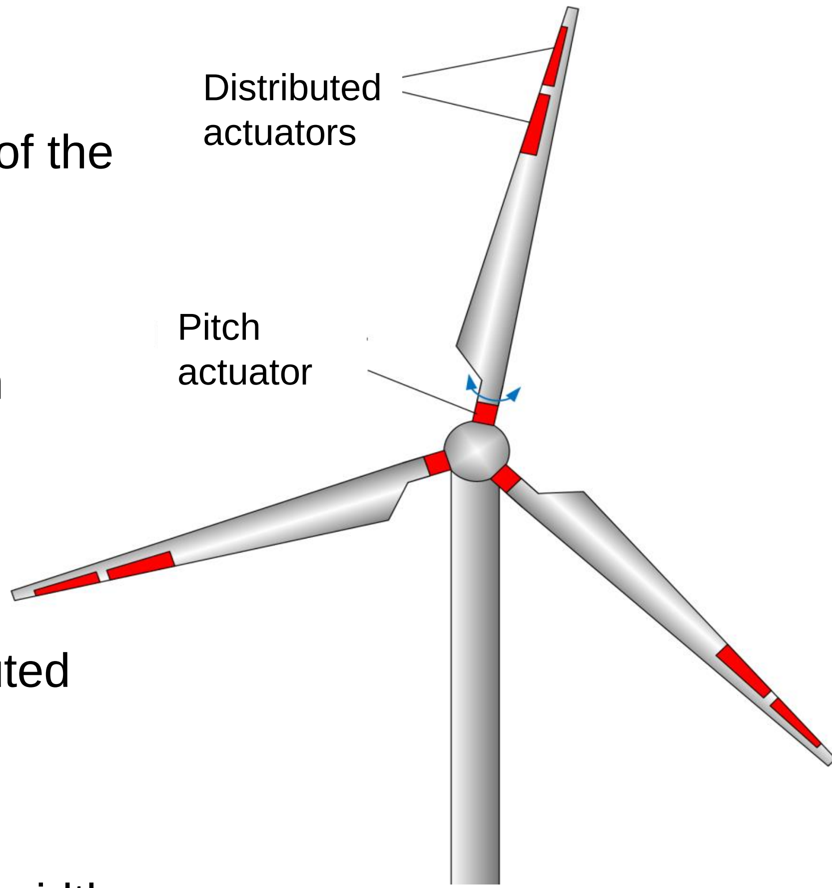


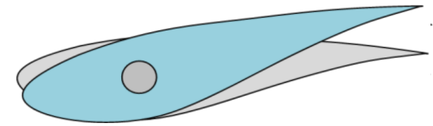


Pitch actuators and local actuators

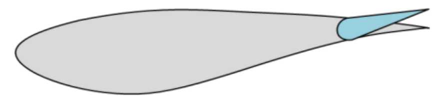
Power control via pitch of the blade
- collective
- slow
- Large angle bandwidth

Load control via distributed actuators
- indivual
- fast
- Limited actuation bandwidth

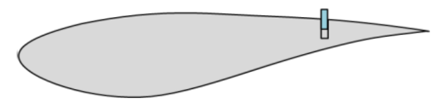




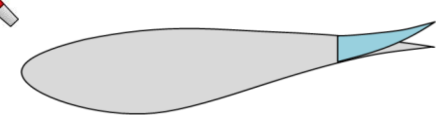
Moveable Blade Tips



Trailing Edge Flaps



Microtabs



Elastically deformable parts of the blade profile

[P. Caseitz, Regelung drehzahlvariabler Windenergieanlagen mit aerodynamisch aktiven Elementen - Smart Blades, BMU-Strategiegespräch 2012]

Supervisory Control

Main tasks:

- Operational managing and monitoring
- Diagnostics, safety
- Communication, reporting and data logging

Operational states:

- Idling
- Start-up
- Normal power production
- Normal shut-down
- Emergency shut-down

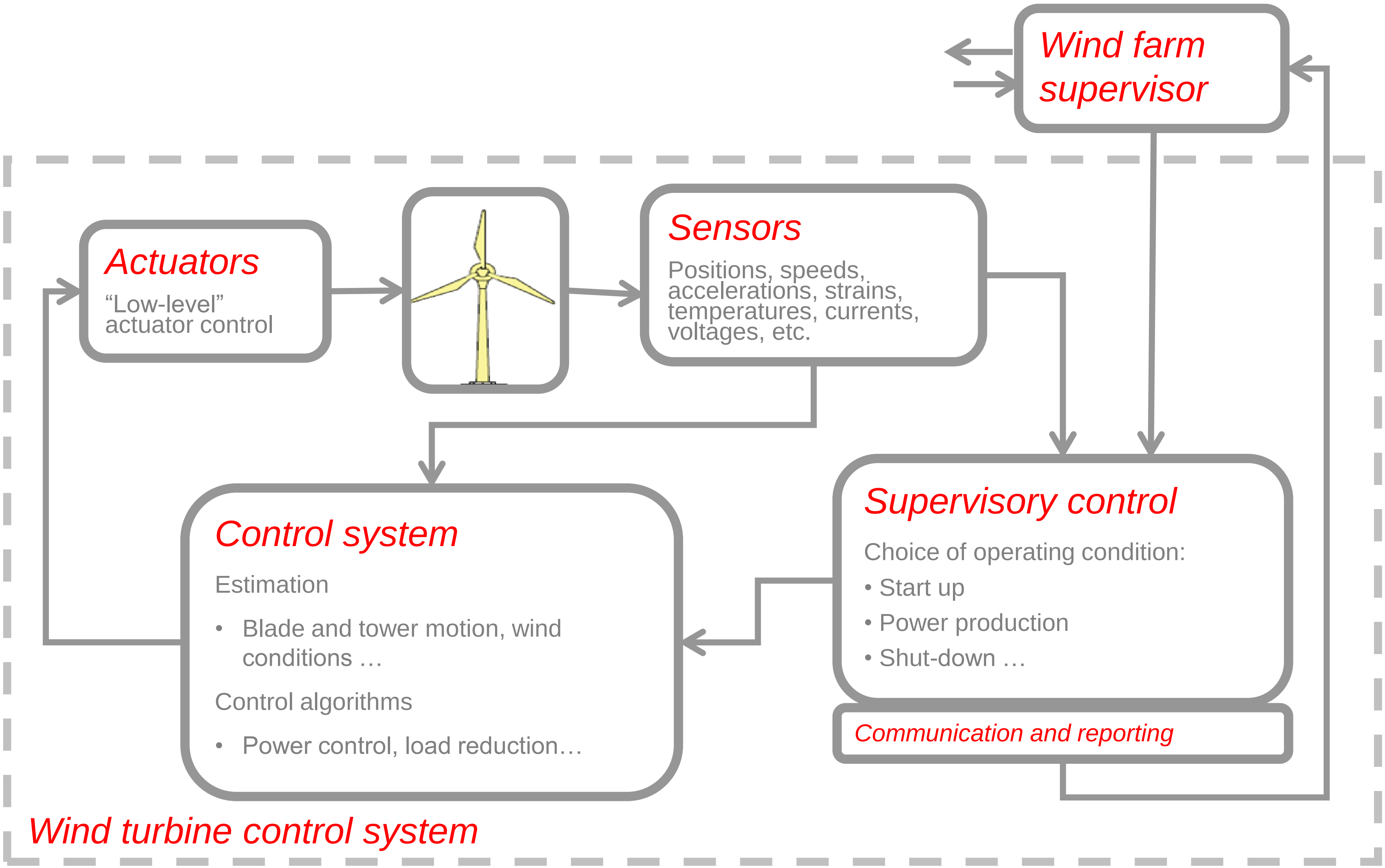
Main input data:

- Wind speed
- Rotor speed
- Blade pitch
- Electrical power
- Accelerations
- …

But, also

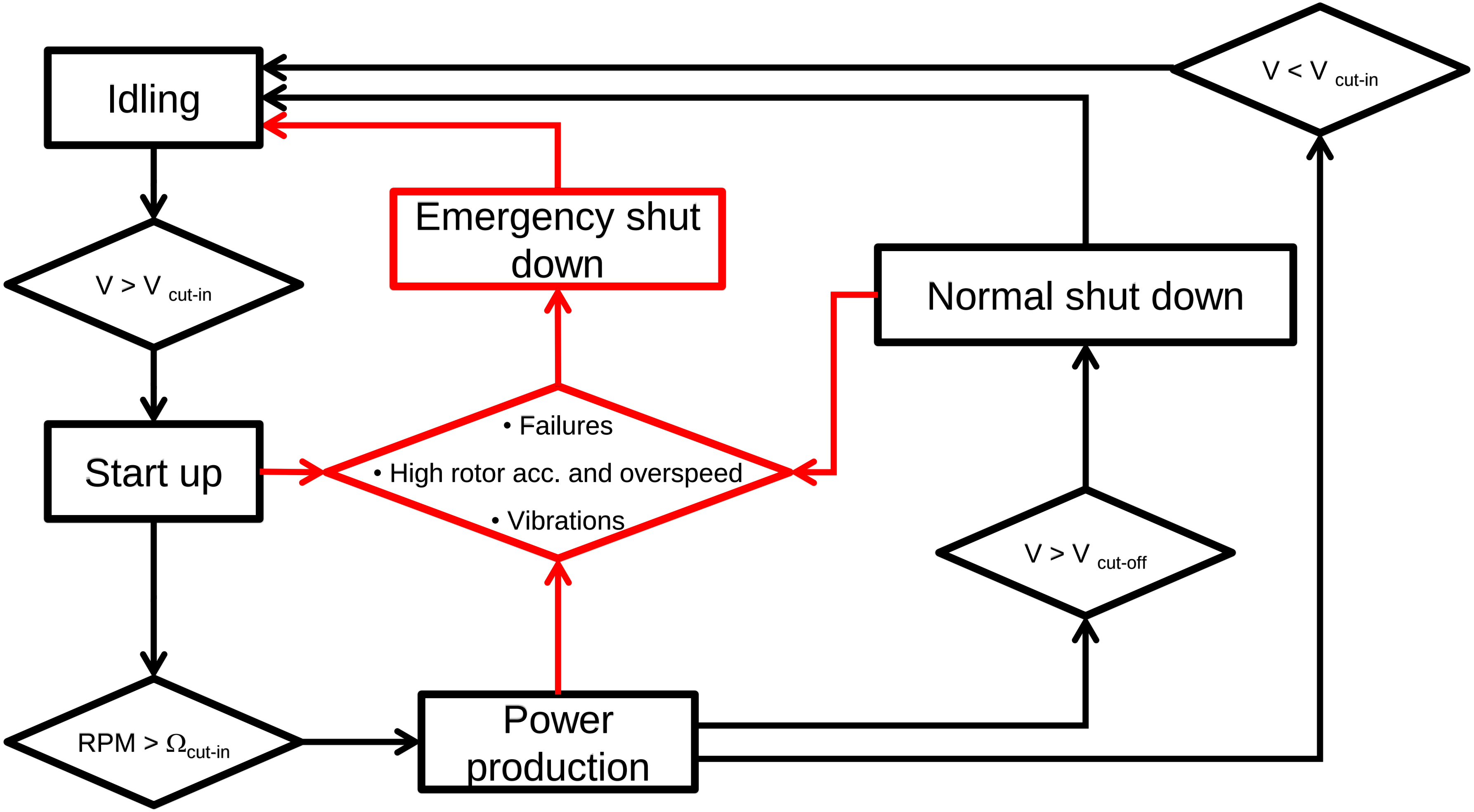
- Stresses, strains (blades, tower)
- Position, speed
- Lubricants properties and levels
- Icing conditions, humidity, …

Supervisory Control



Supervisory Control Logic

An exemplary monitoring logic may be sketched as follows:



Design principles of the safety system

- *„fail-safe“*

  i.e. in the event of failure, fails in a way that will cause no harm or at least a minimum of harm
- *redundant*

  i.e. at least two indipendent and redundant systens required, eached designed to bring the system back to a safe operational condition

  (Remark: „Fail-safe“ not necessary means redundant!)
- *„Low-level“*

  i.e. robust, as simple as possible, hard wired, direct impact
- *Autonomous system*

  i.e. watch dog function, triggers once system o.k. signal is interupted
- *Safety loop*

  i.e. triggered by any of many sensors in a connection in series

Braking systems: Examples

• regulations: primary and secondary braking system
• fail-safe-operation (voltage off $\Rightarrow$ brake on)
• triggering by safety loop

Stall:
-primary: airbrakes or blade tip brakes (or hydraulic brake at low speed shaft)
- secondary: hydraulic brake at high speed shaft

Typical active-stall turbine:
- primary : collective pitch control
- secondary: hydraulic brake at high speed shaft

Pitch-controlled turbine (example with electro-mech.pitch system):

- primary & secondary: *single*-blade pitching (autonomous battery-equipped for each blade, blades pitched independently)
- support: hydraulic brake at high speed shaft

Conclusions

- Turbine control
  - is necessary to achieve optimal energy yield
  - is needed to limit loads
- PID controllers are state-of-the practice in wind energy
- Operational control can, besides power, also optimise loads
- Supervisory control ensure safe operation of the turbine