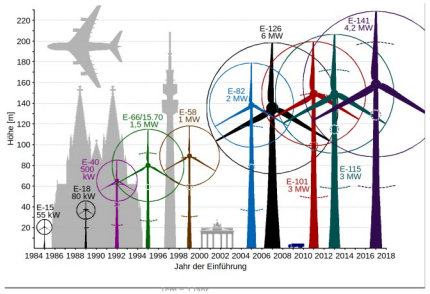
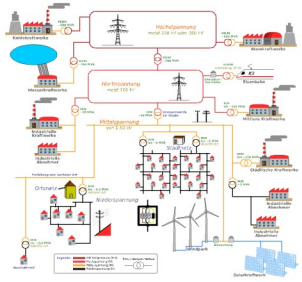
Industrial Practice of Wind Turbine Control

Prof. Dr.-Ing. Jens Geisler

June 23, 2020





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Agenda

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- Setting the Scope and a bit of History
- Requirements for Modern Wind Turbines
- Control System Hardware
- Control System Software Architecture
- Development Process
- Future Developments

Setting the Scope and a bit of History

The Predominant Commercial Turbine Type

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- Horizontal axis wind turbine (HAWT)
- Three blades
- Upwind
- With and without gearbox
- Electric generator
  - Permanent magnet, synchronous
  - Doubly-fed induction
  - Asynchronous
- Active Converter

(Source: © 2000 Nordex)

The Ancestor of modern HAWTs

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- Wind powered machinery known for millennia
- 1887 first turbine to produce electricity
- The Gedser turbine: prototype for the "Danish Model"
  - 1957 by Johannes Juul
  - 200kW
- Mixed developments followed
- Smaller, mass-produced turbines prevailed
- Evolution in small increments led to today's very uniform turbine design

(Source: Elektrizitätsmuseum, Bjerringbro)

No Controller Necessary

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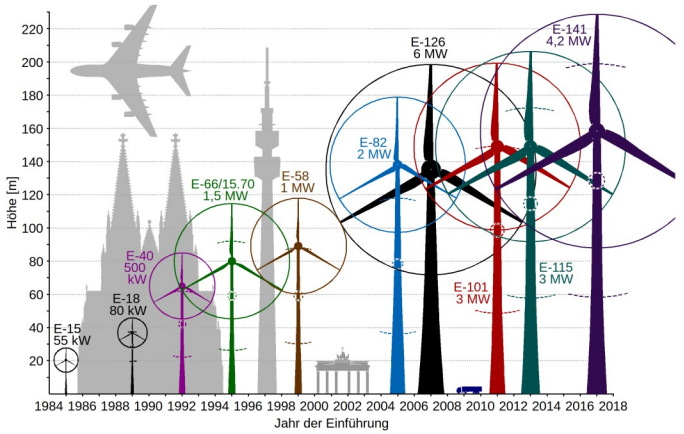
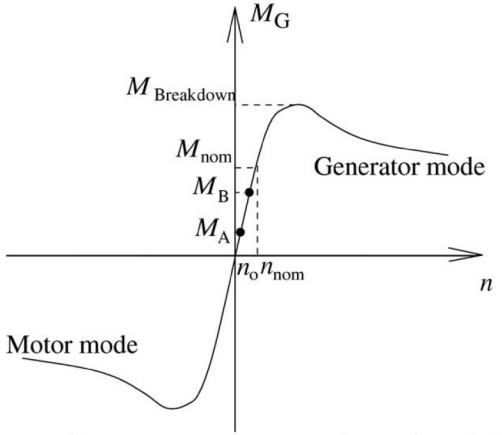
- Size and technology evolved together
- Control was mostly mechanical or inherent
  - Stall regulated rotor power
  - Implicit torque-speed curve of asynchronous generator
  - Electro-mechanical yaw alignment
  - Aerodynamic tip breaks
- Simplicity and a fail-safe design were drivers of the economic success



(Source: Jahobr / CC0 2015)



(Source: Hansen, Aerodynamics of...)

Requirements for Modern Wind Turbines

Harvesting Wind

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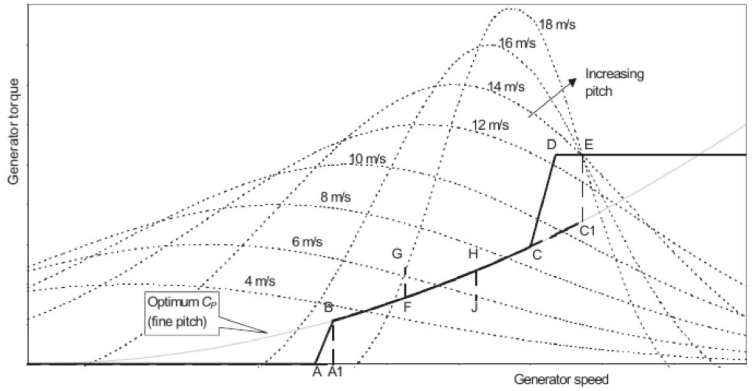
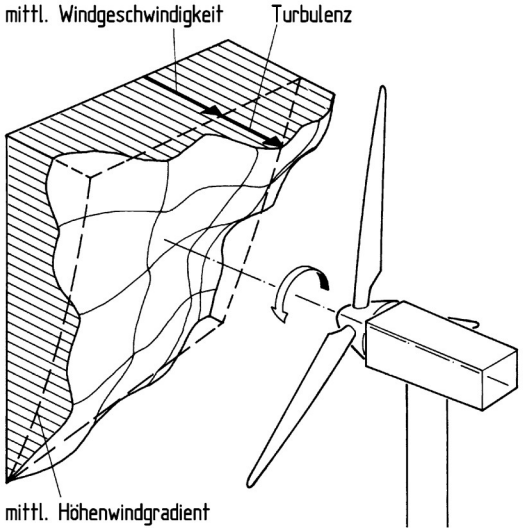
- Partial load (generator control)
  - Minimum wind necessary to startup
  - Variable speed for optimal harvesting
  - Maximum speed for economic design
- Full load (blade angle control)
  - Too much wind must not be harvested
  - Extreme wind shutdown
- Transition region critical
- Alignment of rotor perpendicular to wind
- Every 0.1% of annual energy production (AEP) counts
- Wind is unknown
- Turbulence is not always the same



(Source: Burton, Wind Energy Handbook)



(Source: Hau, Windkraftanlagen)

Load Reduction

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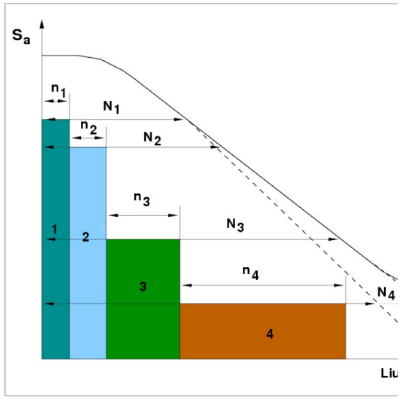
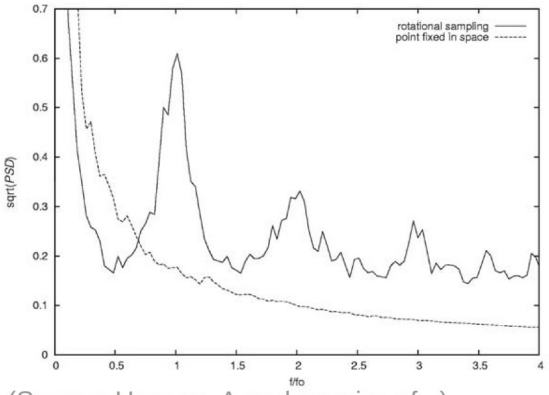
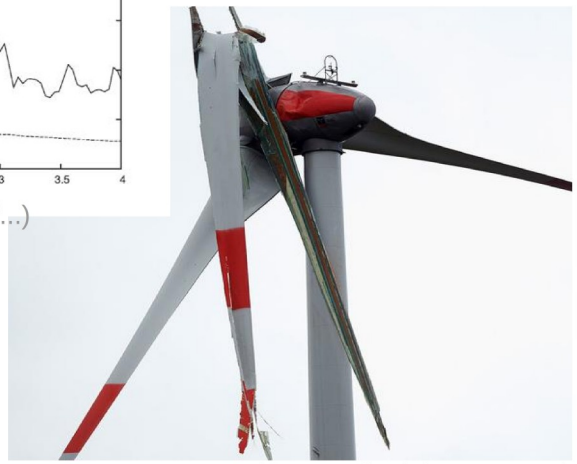
- *Wind is the **reference** and the main **disturbance***
- *Torque always goes along with thrust*
- All components are affected
- Fatigue loads
  - Eigenoscillations
  - Stochastic excitation
  - Rotational sampling
  - Adversarial control action
- Extreme loads
  - Hard to predict but fatal
  - Rare, thus conservative avoidance uneconomical
  - Component faults



(Source:S. Fischer, CC-BY-SA)



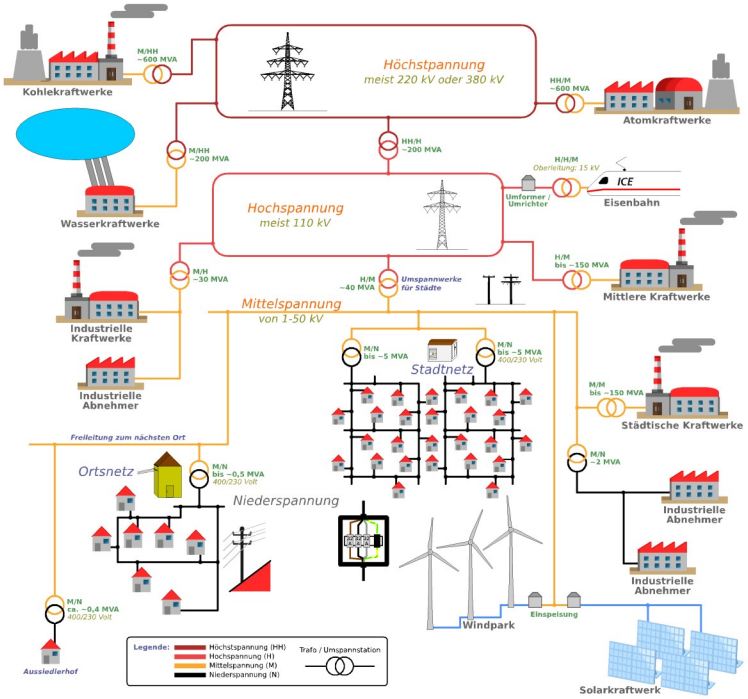
(Source: Hansen, Aerodynamics of...)



(Source:dpa/Thomas Frey)

Grid Support

- Voltage support
  - Large reactive power capability is
    - standard requirement
    - in conflict with active power production
- Frequency stability
  - Over-frequency requires power reduction
  - Under-frequency requires power increase
- Resilience
  - Frequency deviations
  - Voltage drops (Fault Ride Through)



(Source: Stefan Riepl / Vector: Mrmw / CC0)

Environmental Aspects

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- Outbound
  - Sound and noise immissions
  - Bat protection
  - Radar interference
  - Aircraft warning vs. light emission
- Inbound
  - Temperature variations
  - Icing of the blades
  - Sand, dust and rain
  - Terrain, wind-direction and turbine wake
  - General interaction within a wind farm

(Source:DOI: 10.1016/j.rser.2016.06.080)

(Source: Mora, 2017: A Transition from ...)

Added Values

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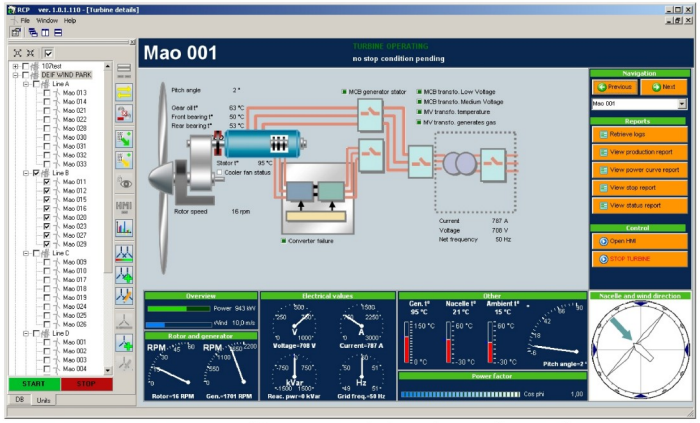
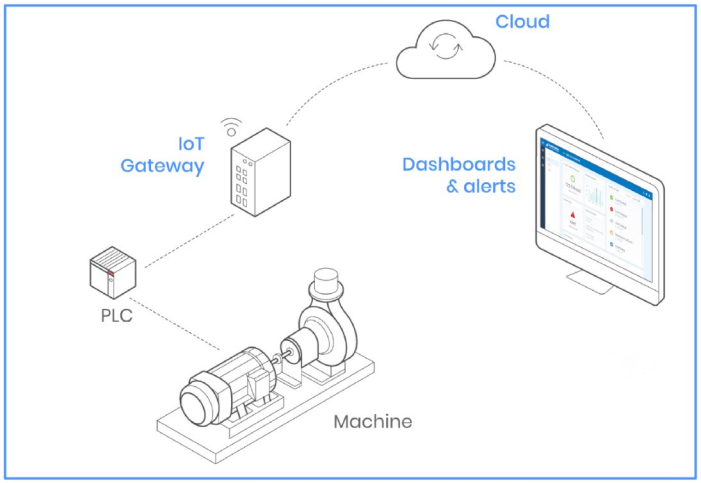
- HMI, remote access, user roles
- Standardized communication and control interfaces
- Parameter / variant management
- Current and history of events
- Fault and prefault detection and identification
- Condition monitoring
- Data collection
- Data and statistics visualization
- Data aggregation



(Source: sielcosistemi.wordpress.com)

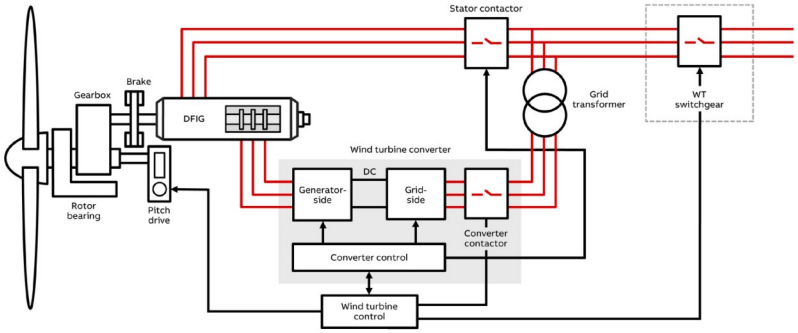


(Source: seebo.com)

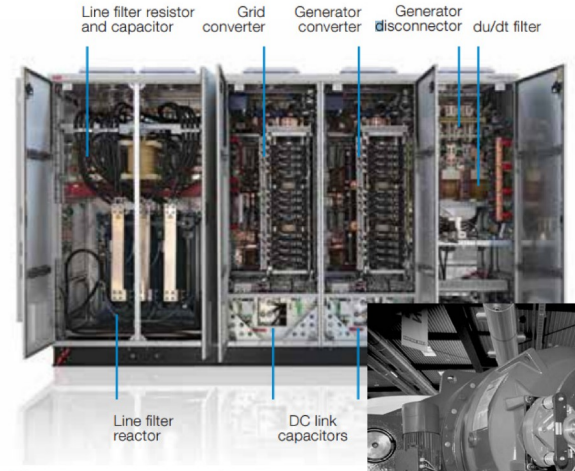
Control System Hardware

Actuators

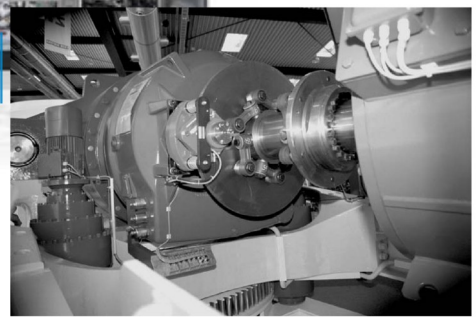
- Individual blade pitch drives
  - DC motors
  - Hydraulic
- Machine-side and grid-side inverter
- Breaks, breaking chopper
- Yaw drives
- Cooling fans and pumps
- Blade heating
  - Hot air
  - Heating foil
- (Semi-) active tower dampers
- Noise canceling speakers
- House load and UPS



(Source: ABB)



(Source: qats.com)



(Source: Hau, Windkraftanlagen)

Sensors

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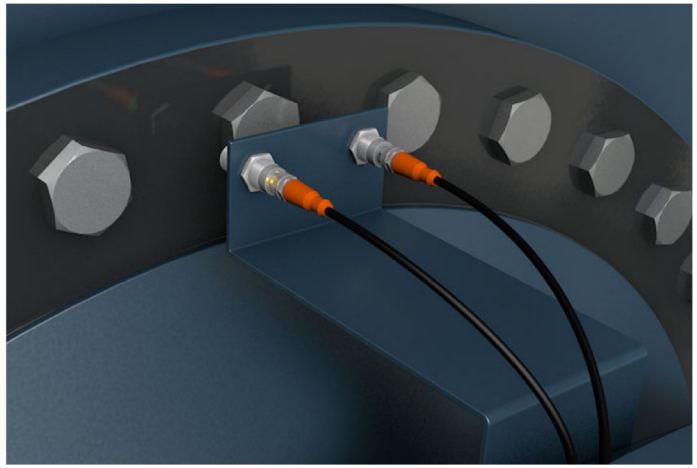
- Wind and air
  - Anemometer
  - Wind vane
  - Temperature
  - Rain, mist, icing, lightning
- Drive train
  - Speed, several, redundant
  - Blade, rotor and yaw position
  - Electrical torque
  - Tower acceleration
  - Blade bending

(Source: Getty Images)

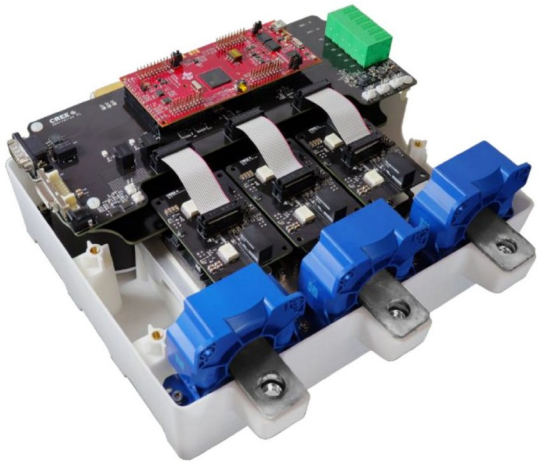


(Source: ifm)

Sensors

- Grid
  - Voltage
  - Frequency
  - Active and reactive power
  - Harmonics
- Components
  - Temperatures
  - Vibrations
  - Voltage
  - Currents
  - Activation, end-stops

(Source: Hau, Windkraftanlagen)



(Source: wolfspeed.com)

Processors

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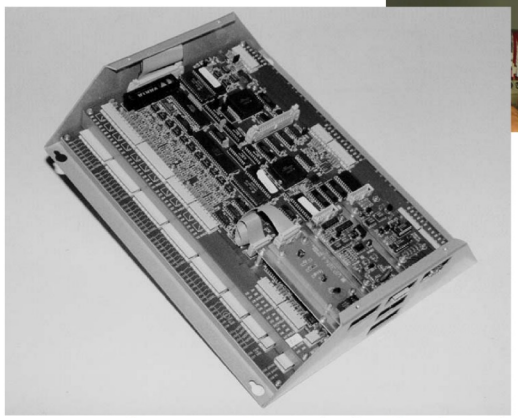
- Main PLC
  - Main control loop(s) up to ~10Hz
  - SCADA
  - Component control (fans, pumps, etc.)
  - HMI, Parameters, Events
  - Communication
- Inverter controller
  - Machine-side, grid-side
  - High-level control
  - Independent HMI
  - Pulse-generation

(Source: DEIF)



(Source: Hau, Windkraftanlagen)

Processors

- Hub controller
  - Blade position control
  - Battery management
  - Independent safety-functions
- Safety Logic Controller (SLC)
  - (Partial) replacement of safety-chain
  - Tamper-proofing
- Semi-active components, e.g. UPS
- Additional instrumentation, e.g. LIDAR
- Wind farm controller

(Source: Hau, Windkraftanlagen)

(Source: Bachmann)

Additional Equipment

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- Safety-chain
- Mechanical vibration switches
- Communication Equipment
  - Switches, WiFi
  - Fiber connectors
  - 4G
  - Special purpose grid operator protocols
- Circuit breakers
- Power meters
- Physical access control
- Cameras
- Local HMI, operating panels

(Source: nordseeone.com)

(Source: betonbau.com)

Control System Software Architecture

Main PLC

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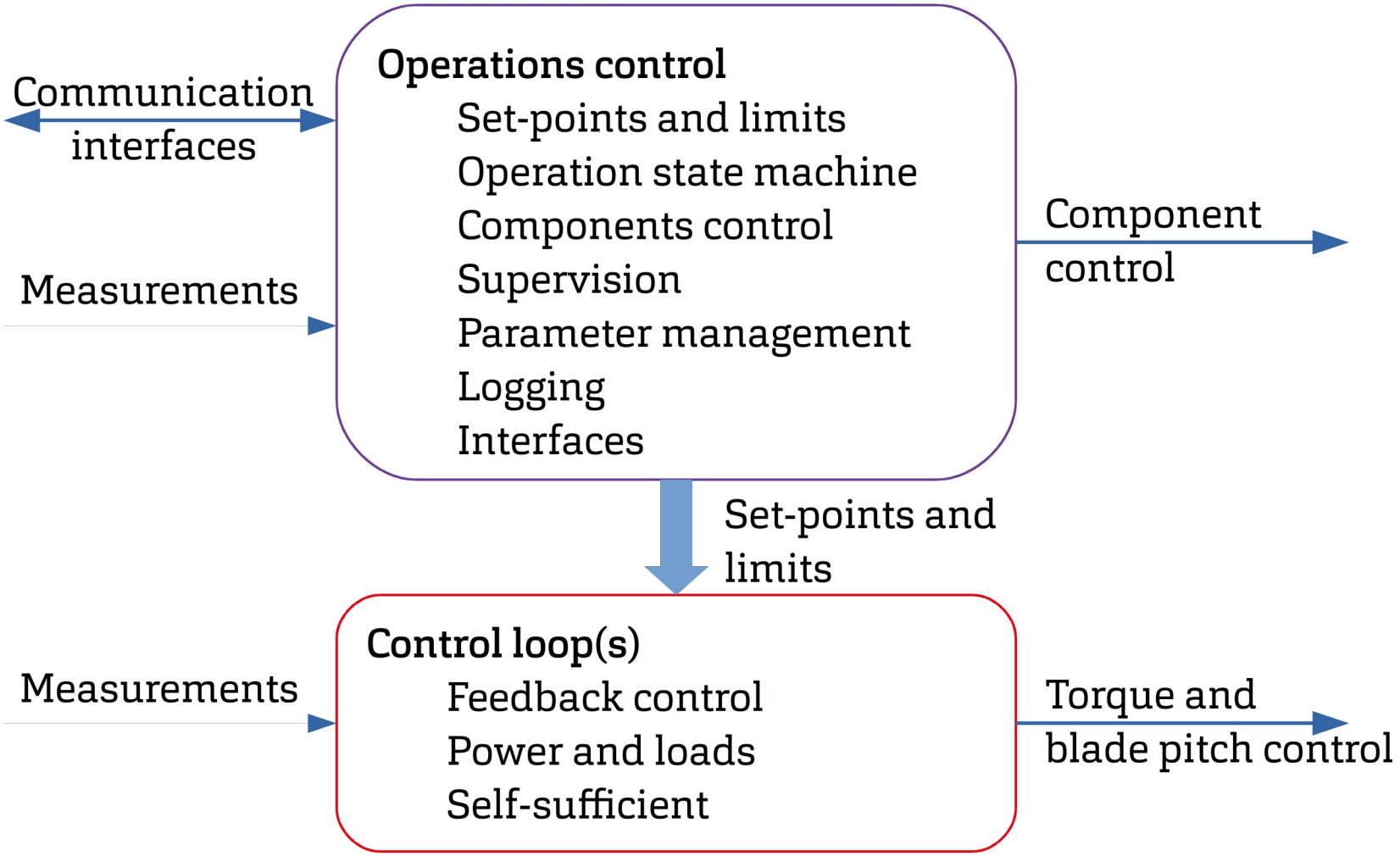

Closed Loop Control

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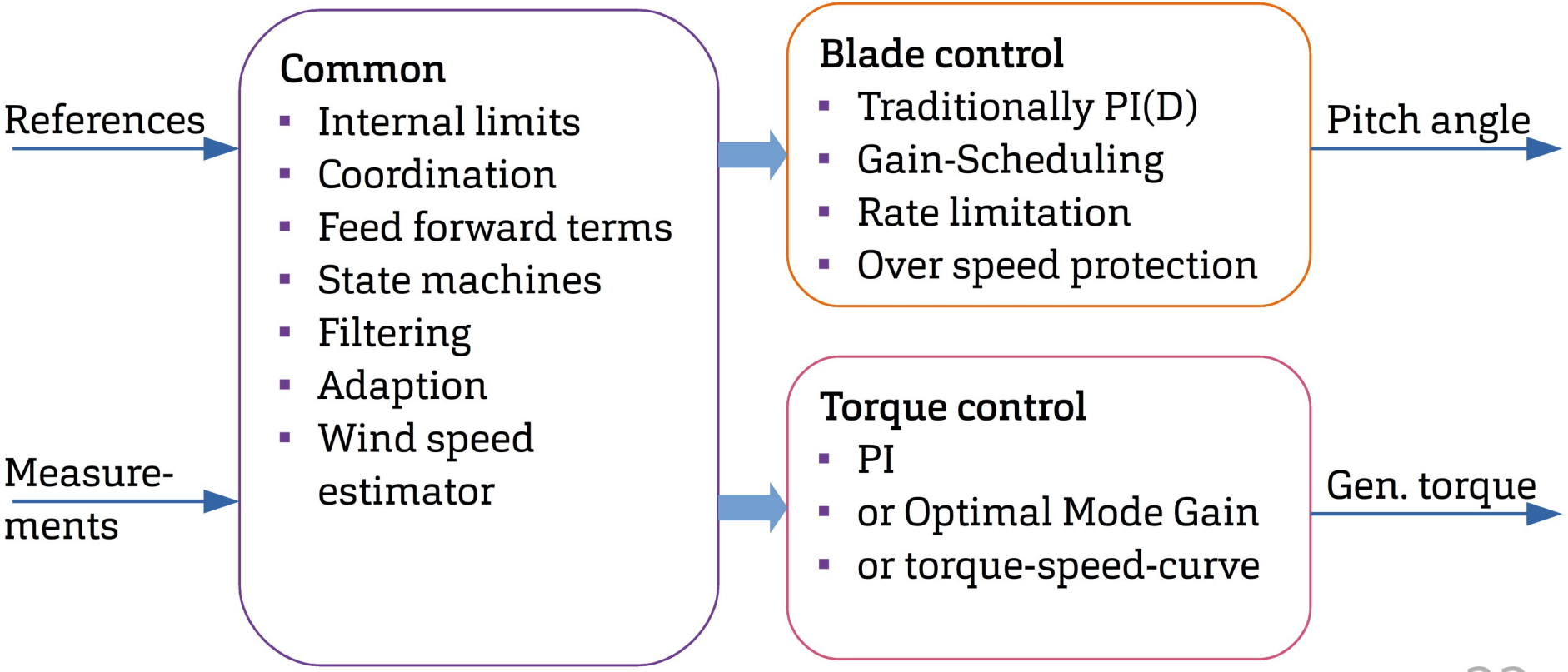
- Drive train over actuated
- Pitch and torque limited to mutually exclusive regions



Many Added Functions for Loads

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- Power and speed reductions according to reference
- Drive train damping via torque
- Tower damping
  - Longitudinal (fore-aft)
  - Lateral (side-side)
  - Via pitch and/or torque
- Individual Pitch control (IPC)
  - Reduce excitation from inhomogeneous wind field
  - Support yawing
- Gust mitigation
- Blade tip clearance
- Avoid resonances at certain speeds

(Source: Hau, Windkraftanlagen)

… for the Grid and the Environment

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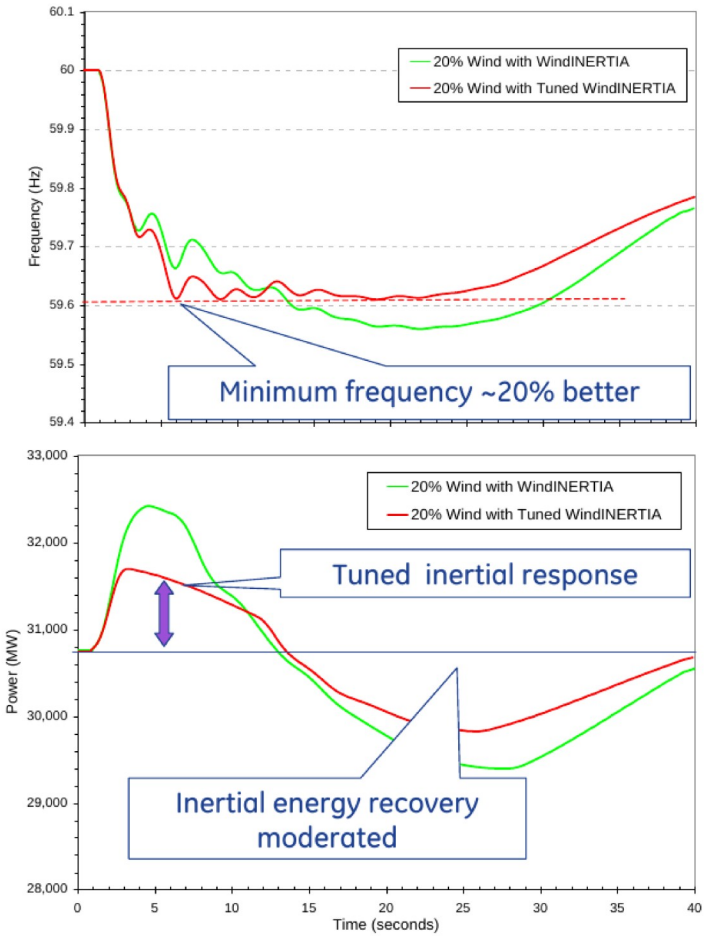
Grid

- Low voltage ride through (LVRT)
- Additional power boost for short duration
  - Partial load: power from kinetic energy of rotor
  - Full load: power from wind via pitching in
- Fast active power regulation into and out of curtailments
- Keep active power steady or follow linear ramps
- High wind ride through

Environment

- Noise reduction: special speed profile
- Avoidance of gear box resonance



(Source: GE, Nicholas Miller)

Development Process

Closed Loop Engineering

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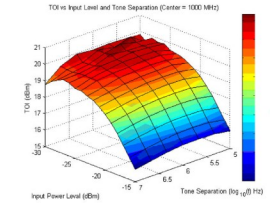
- New turbine types
- New functions / features
- Parameter tuning / adaption
- Pre-studies
- Internal consulting
- Planning
- Field support
- Model improvements
- Research projects



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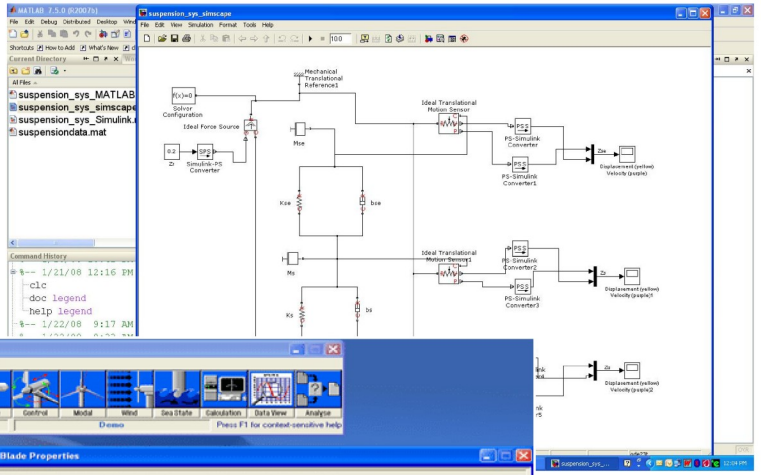
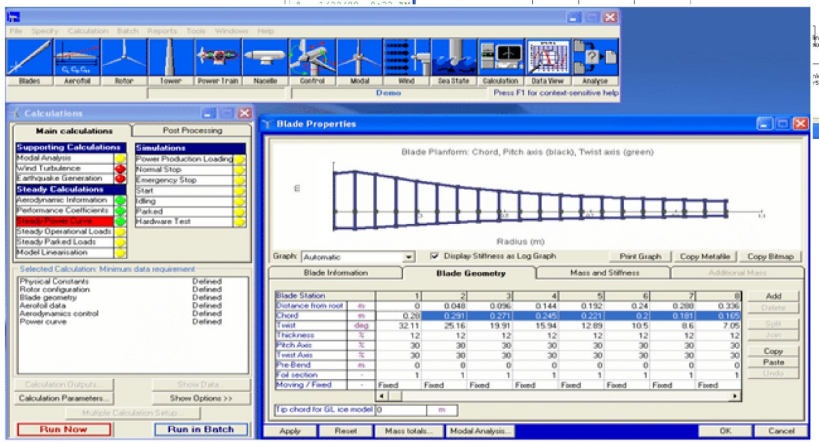


(Source: mathworks.com)



(Source: dnvgl.com)

Closed Loop Engineering

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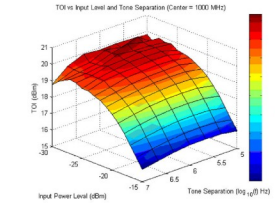
- **Requirements analysis and shaping**
- Function specifications
- Development in Simulink
- Co-simulation with special model
- **Validation**
- Hand coding + auto-code, integration
- Parameter definition
- Documentation, internal and external
- **Testing**
- Certification
- Series maintenance



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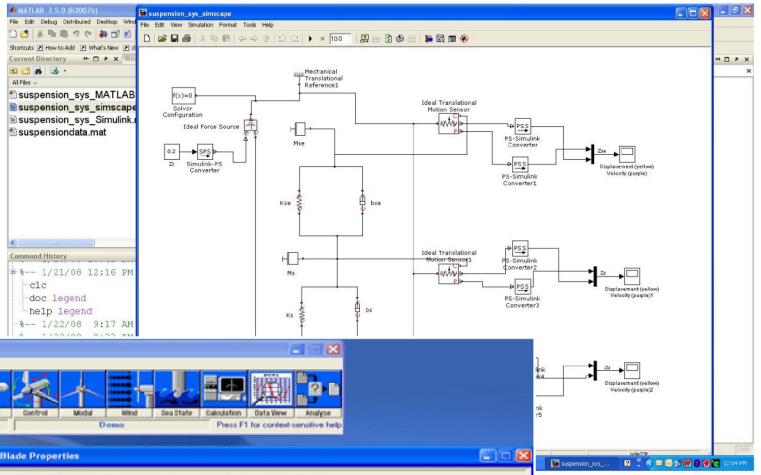

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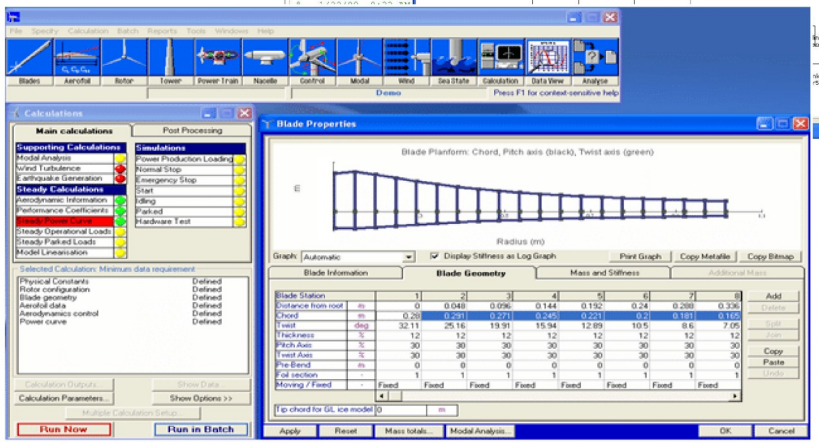

(Source: dnvgl.com)

“Loads and Controls”

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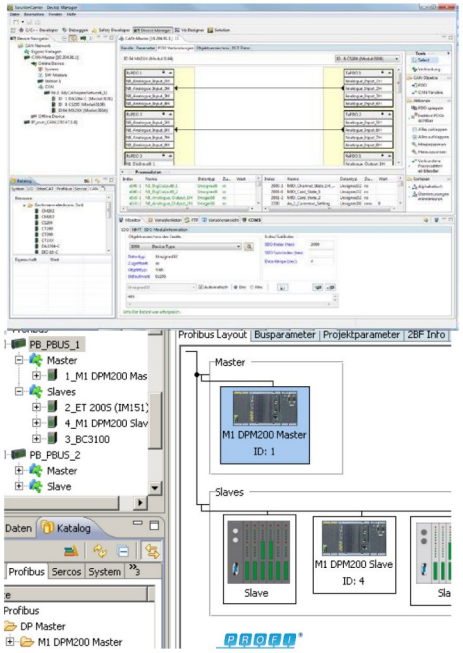
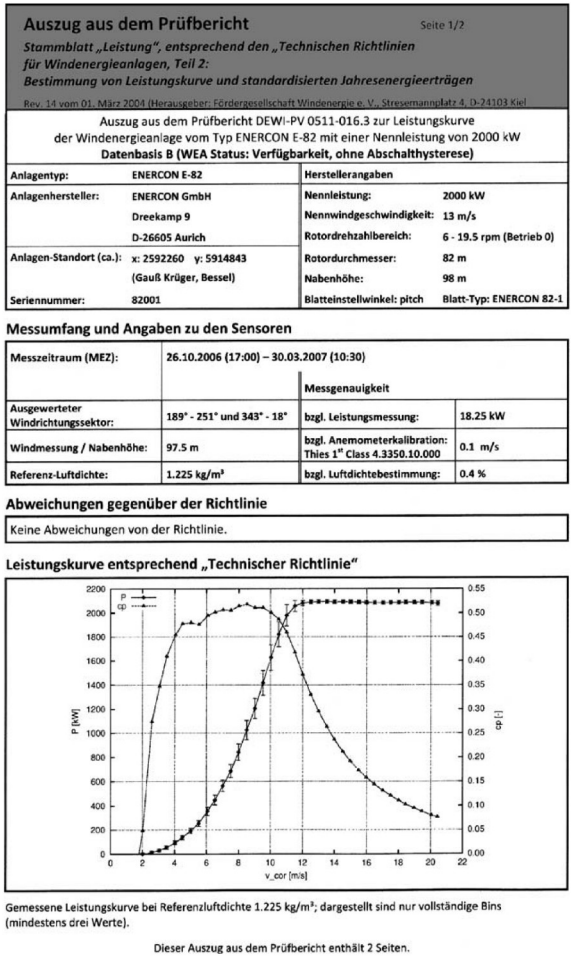
- **Operations control**
  - Cross functional communication
  - Specification of functions
  - Testing
  - Prototype commissioning
- Automation (software coding)
- Sensor specialists
- Wind farm controller
- **Load analysis and certification**
  - Massive time domain simulations
  - Design Load Cases (DLC)
  - Comparison against component limits
  - Approx. 10,000 time series à 10 Min.
  - Approx. 200GB data
- Aerodynamics, blade design
- Grid operator models



(Source: Bachmann)



Auszug aus dem Prüfbericht Seite 1/2

Stammblatt „Leistung“, entsprechend den „Technischen Richtlinien für Windenergieanlagen, Teil 2: Bestimmung von Leistungskurve und standardisierten Jahresenergieerträgen

Rev. 14 vom 01. März 2004 (Herausgeber: Fördergesellschaft Windenergie e. V., Stresemannplatz 4, D-24103 Kiel

Auszug aus dem Prüfbericht DEWI-PV 0511-016.3 zur Leistungskurve der Windenergieanlage vom Typ ENERCON E-82 mit einer Nennleistung von 2000 kW

Datenbasis B (WEA Status: Verfügbarkeit, ohne Abschalthysterese)

Anlagentyp:	ENERCON E-82	Herstellerangaben	
Anlagenhersteller:	ENERCON GmbH Dreekamp 9 D-26605 Aurich	Nennleistung: Nennwindgeschwindigkeit: Rotordrehzahlbereich:	2000 kW 13 m/s 6 - 19.5 rpm (Betrieb 0)
Anlagen-Standort (ca.):	x: 2592260 y: 5914843 (Gauß Krüger, Bessel)	Rotordurchmesser: Nabenhöhe:	82 m 98 m
Seriennummer:	82001	Blatteinstellwinkel: pitch	Blatt-Typ: ENERCON 82-1

Messumfang und Angaben zu den Sensoren

Messzeitraum (MEZ):	26.10.2006 (17:00) – 30.03.2007 (10:30)		
		Messgenauigkeit	
Ausgewerteter Windrichtungssektor:	189° - 251° und 343° - 18°	bzgl. Leistungsmessung:	18.25 kW
Windmessung / Nabenhöhe:	97.5 m	bzgl. Anemometerkalibration: Thies 1st Class 4.3350.10.000	0.1 m/s
Referenz-Luftdichte:	1.225 kg/m³	bzgl. Luftdichtebestimmung:	0.4 %

Abweichungen gegenüber der Richtlinie

Keine Abweichungen von der Richtlinie.

Leistungskurve entsprechend „Technischer Richtlinie“

Gemessene Leistungskurve bei Referenzluftdichte 1.225 kg/m³; dargestellt sind nur vollständige Bins (mindestens drei Werte).

Dieser Auszug aus dem Prüfbericht enthält 2 Seiten.

(Source: Hau, Windkraftanlagen)

Future Developments

Standardization vs. Diversification

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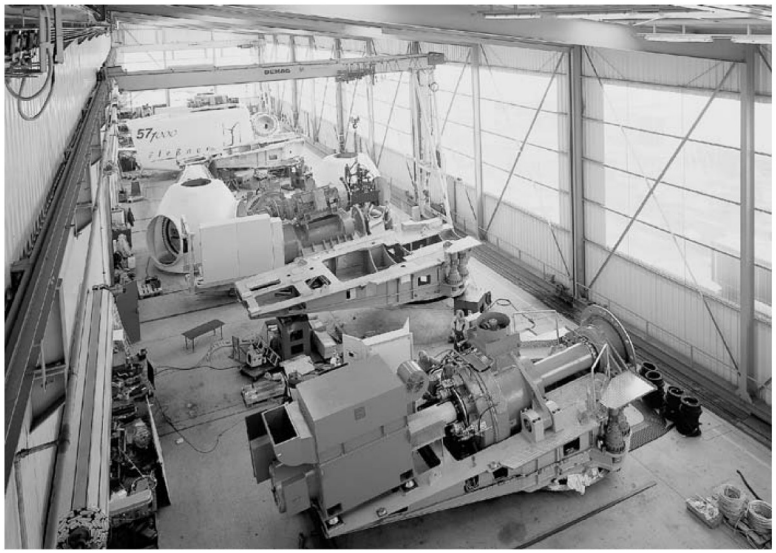
- Trend towards commercial owners
  - Bigger wind farms, esp. off-shore
  - More money for economics of scale
- Highly competitive market
  - Pressure for cost-saving
  - Consolidation of manufacturers
  - vs.
  - Continuously evolving technology
  - Highly specialized project configuration
- Wind is a very locally diverse and volatile resource
- **Adaptive and self-learning technologies to the rescue?**



(Source: Hau, Windkraftanlagen)

Smarter is better

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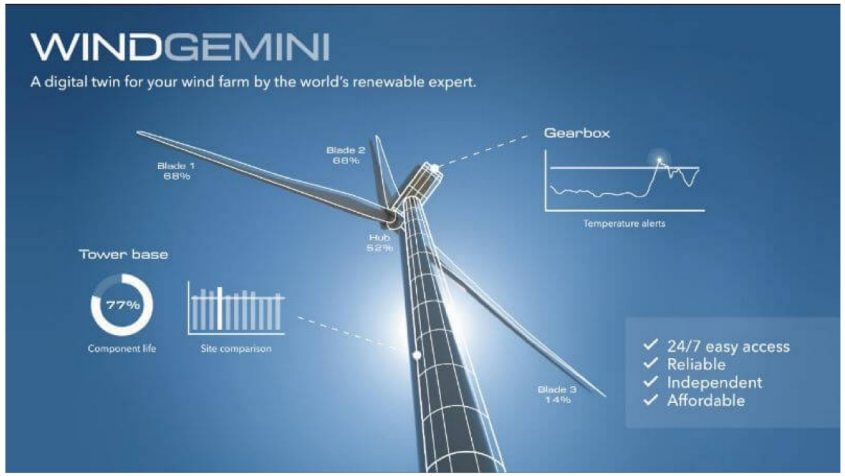
- Adaption to use every power reserve
  - Turbulence
  - Temperature
  - Grid condition
  - Life time loads
- Learning from others
  - Big (fleet) Data
  - Automatic tuning and calibration
- Improved health
  - Predictive maintenance
  - Digital twin



(Source: windpowerengineering.com)

(Source: GE)

From Power Source to Power Plant

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- **100% renewable energy is not possible**
- (Without storage)
- The simplest form of storage is over-capacity
- No individual turbines, only power plants
- Or virtual power plants
- Coordination of capacities and possibly also consumers
- Paradigm change from “all you can harvest” to ”what the market needs”
- More flexible distribution of life time vs energy

(Source: lifeboat.com)

(Source: nawindpower.com)

Thanks for listening

Prof. Dr.-Ing. Jens
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https://hs-flensburg.de/hochschule/personen/geisler