Source: LM Wind Power - GE

Wind turbines

PHYS-E6572 Advanced Wind Power Technology L05

Timo Karlsson, Raul Prieto, based on material in Dipoli course by Petteri Antikainen and Andrea Vignaroli, Georg Böhmeke and other References

5.10.2018 L05 topics

- Wind turbine loads
- Design load cases
- Wind turbine control
- The safety and supervisory functions
- Noise control
- The Campbell diagram
- The rotor hub
- The nacelle
- The tower
- Applicable standards
- The certification process

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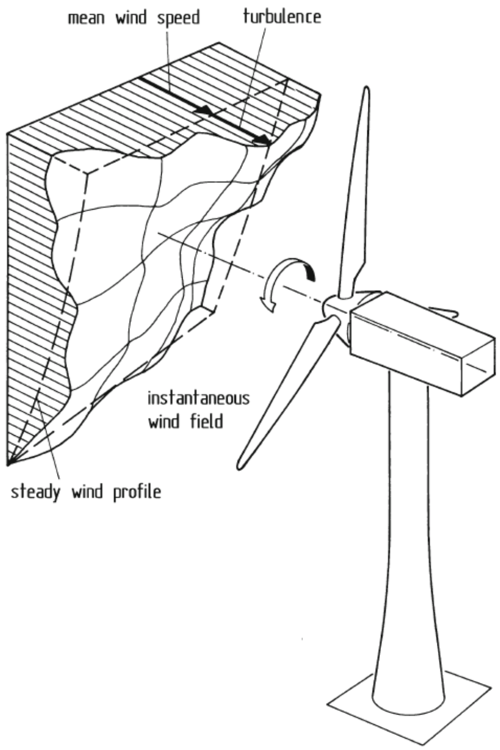
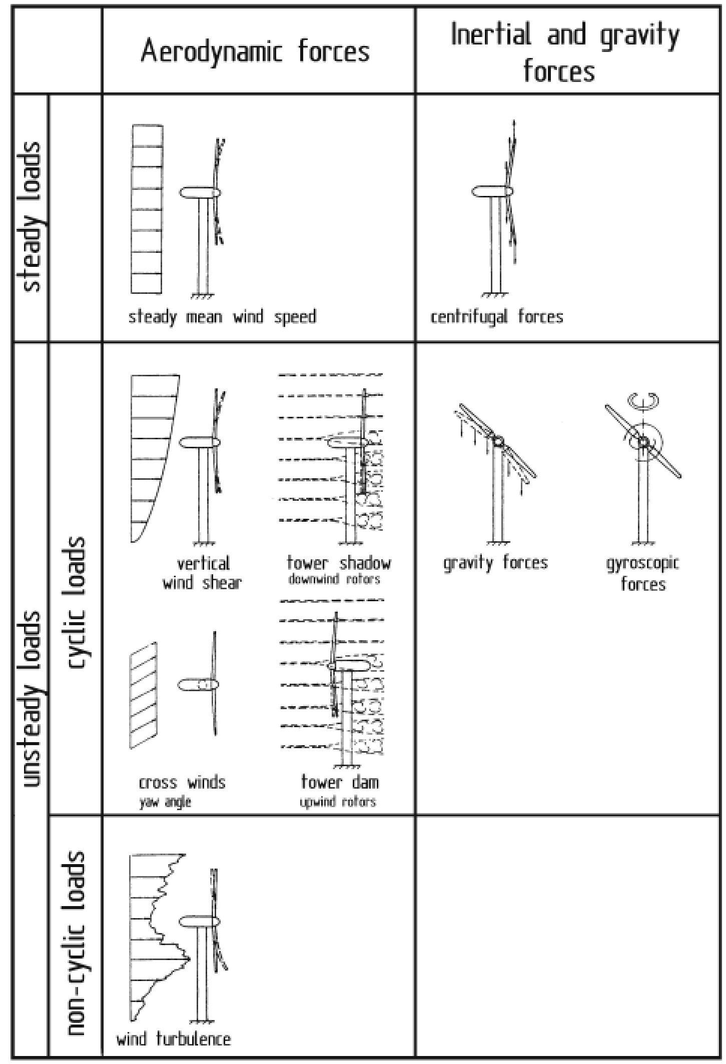
Wind turbine loads (I)

- During operation a wind turbine experiences a combination of steady and unsteady loads, caused by wind, gravity and inertia.





Source: Erich Hau "Wind Turbines" Ed 3.

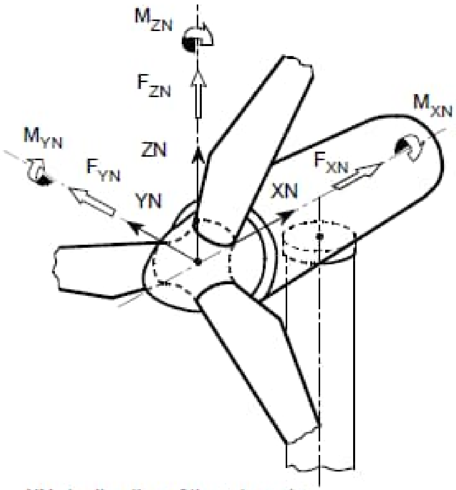
Wind turbine loads (II)

- In addition to normal operation, loading conditions corresponding to **transport, assembly , maintenance and repair** of the wind turbine need to be considered. For example contact loads due to interface with transport and lifting equipment

Blade yokes for offshore installation (Source: Liftra website)

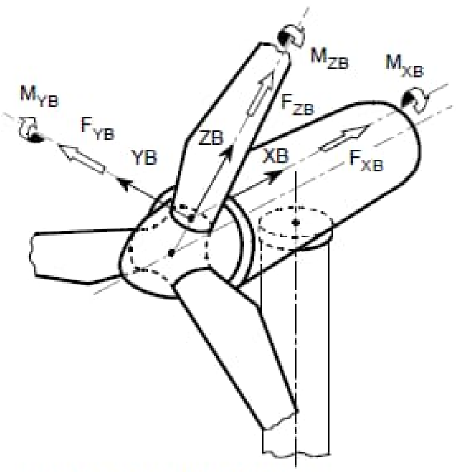
Coordinate systems for loads analysis (I)

F_x = Thrust
F_y = Shear force
F_z = Vertical force
M_x = "Power" moment
M_y = Tilt moment
M_z = Yaw moment



XN in direction of the rotor axis
ZN upwards perpendicular to XN
YN horizontally sideways, so that XN, YN, ZN rotate clockwise

Fig. 4.A.3 Hub coordinate system



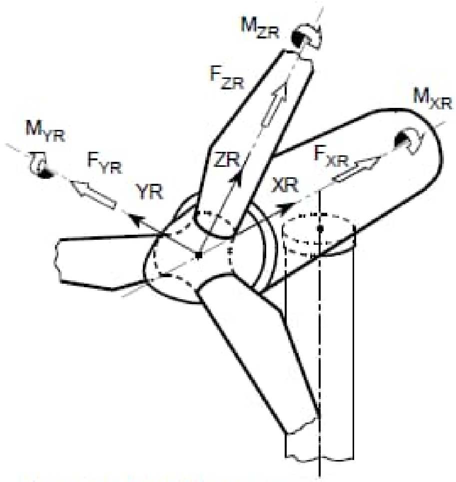
XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

Fig. 4.A.1 Blade coordinate system

F_x = Single blade Thrust
F_y = "In plane" tangential force
F_z = Axial force
M_x = Edgewise bending
M_y = Flapwise bending
M_z = Torsional moment

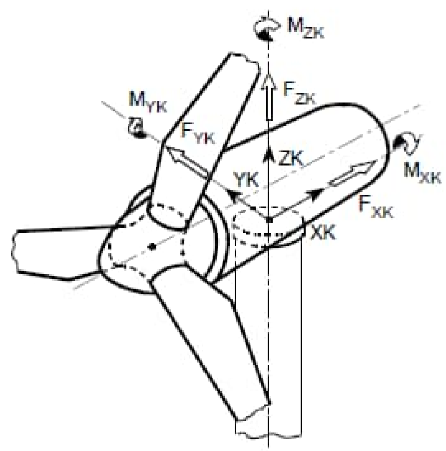
Source: GL Guideline for the Certification of Wind Turbines 2010

Coordinate systems for loads analysis (II)



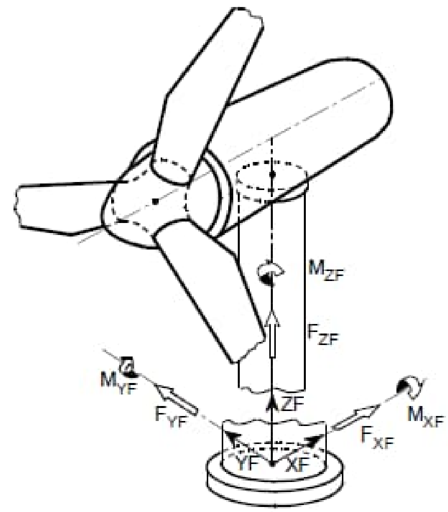
XR in direction of the rotor axis
ZR radially, orientated to rotor blade 1 and perpendicular to XR
YR perpendicular to XR, so that XR, YR, ZR rotate clockwise

Fig. 4.A.4 **Rotor coordinate system**



XK horizontal in direction of the rotor axis, fixed to nacelle
ZK vertically upwards
YK horizontally sideways, so that XK, YK, ZK rotate clockwise

Fig. 4.A.5 **Yaw bearing coordinate system**



XF horizontal
ZF vertically upwards in direction of the tower axis
YF horizontally sideways, so that XF, YF, ZF rotate clockwise

Fig. 4.A.6 **Tower coordinate system**

Source: GL Guideline for the Certification of Wind Turbines 2010

Wind turbine loads (III)

- **Fatigue loads**: Resulting from repetitive conditions during normal operation
- **Extreme-Ultimate loads**: Resulting from extreme wind events, and wind turbine/grid malfunction
- The Design Load Cases (**DLCs**) are used to produce the design loads of the wind turbine. They are regulated by standards (IEC) and certification Guidelines (for example DNVGL)
- DLCs are established sequences of events representative of realistic operation, which combine wind conditions, and operational status (grid and wind turbine).
- As a general principle, fatigue DLCs combine normal operation and normal wind conditions
- As a general principle, extreme DLCs combine:
  - operation with the occurrence of a fault (grid or wind turbine) with normal wind conditions, or
  - wind turbine operating as expected combined with extreme wind conditions

		Operational status	
		Normal Operation	Techn. Fault
Wind conditions	normal	Fatique	Ultimate loads
	extrem	Ultimate loads	

Criteria for the generation of design loads. Source: Erich Hau "Wind Turbines" Ed 3.

Wind turbine class

- **Wind turbine classes:** Wind turbine classes are related to the wind conditions used for the generation of their design loads.
- *”A plant designed for the wind turbine class with a reference wind speed **Vref** is so designed that it can withstand the environmental conditions in which the **10-min mean of the extreme wind speed with a recurrence period of 50 years** at hub height is equal to or less than Vref”*
- **Vave** is the annual average wind speed over many years at hub height
- **A** is the turbulence category for higher turbulence intensity (**B** for lower)
- **I15** is the characteristic value of the longitudinal turbulence intensity at 15m/s,
- **α** is called the slope parameter
- **σ1** is the longitudinal standard deviation of the wind speed fluctuations in the Normal Turbulence Model (NTM)

WTGS class	I	II	III	IV	
V_{ref} (m/s)	50	42.5	37.5	30	50-year annual wind speed (10 min., average at hub height)
V_{ave} (m/s)	10	8.5	7.5	6	1-year annual wind speed (10 min., average at hub height)
A I_{15} (-) α (-)	0.18 2	0.18 2	0.18 2	0.18 2	Characteristic turbulence, high at V_W = 15 m/s
B I_{15} (-) α (-)	0.16 3	0.16 3	0.16 3	0.16 3	Characteristic turbulence, low at V_W = 15 m/s

IEC 61400-1 Wind turbine classes. Source: Erich Hau ”Wind Turbines” Ed 3.

$$\sigma_1 = I_{15} \cdot (15\, m/s + \alpha\, v_{hub}\, (\alpha + 1))$$

IEC 61400-1 – Normal Turbulence Model (NTM). Source: GL Guideline for the Certification of Wind Turbines 2010

Offshore

- Aerodynamic loads are similar on onshore and offshore installations
- In offshore installation waves (in Finland also sea ice) create an additional source of load to the tower
- Structure interaction with soil needs to also be considered

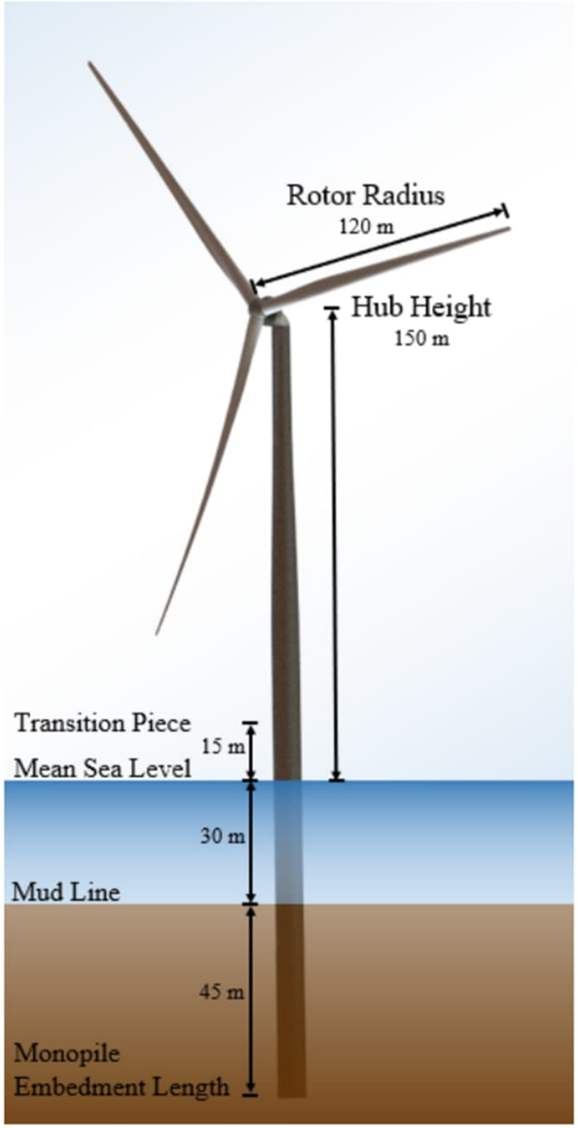
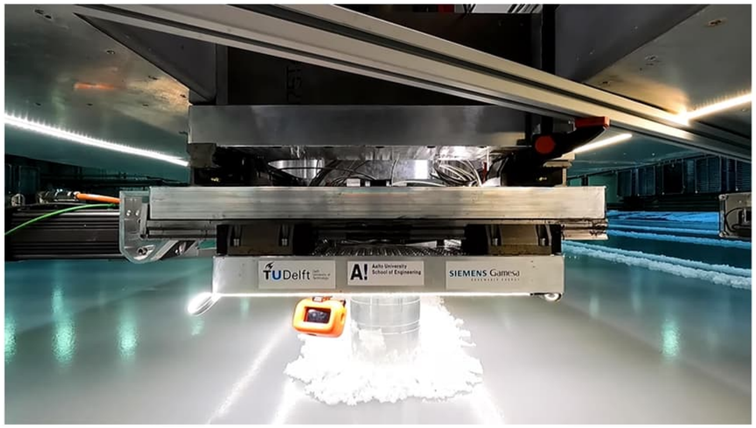


Figure 1-1. The IEA Wind 15-MW reference wind turbine



[Wind turbines versus ice in the world's largest ice tank - YouTube]

Offshore

- Floating platforms introduce new degrees of freedom to consider
- Waves can cause the structure to roll or rotate
- Rotation can be around any axis
- The turbine will also sway in the waves
- This will make the aerodynamic load calculation more complex

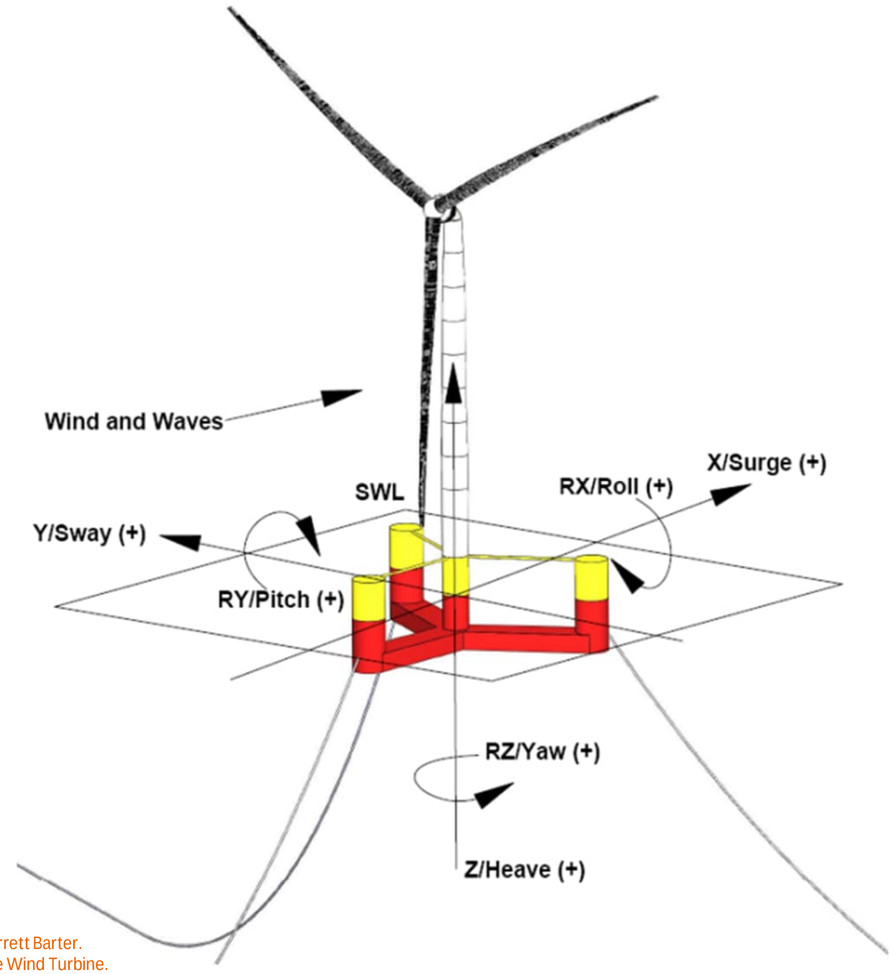


Figure 2. Floating offshore wind turbine reference coordinate system. *Figure courtesy of the University of Maine*

Allen, Christopher, Anthony Viselli, Habib Dagher, Andrew Goupee, Evan Gaertner, Nikhar Abbas, Matthew Hall, and Garrett Barter. Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-76773. https://www.nrel.gov/docs/fy20osti/76773.pdf

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Design Load Cases (I)

- The sets of Design Load Cases are defined in applicable standards: **IEC 61400-1** (Onshore) / IEC 61400-3 (Offshore) but also in Design guidelines which are specific to each Certification Body (For example the *”GL Guideline for the certification of Wind Turbines” of 2010*). The families of DLCs are :

- DLC 1.X – **Power production** with diverse wind conditions (NTM, ECD,NWP,EOG1, EOG50,EWS), including in some cases a **grid loss** event, or **ice formation**

- DLC 2.X – Normal wind conditions (NWP), plus an event of **wind turbine fault** such as control system failure, or safety system failure or other system.

- DLC 3.X – **Start-up** of the wind turbine with diverse wind conditions (NWP, EOG1)
- DLC 4.X – Normal **shut-down** of the wind turbine with diverse wind conditions (NWP, EOG1)
- DLC 5.X – **Emergency shut-down** of the wind turbine with diverse wind conditions (NWP, EOG1)

- DLC 6.X – **Parked turbine** (standstill or idling) with diverse wind conditions (EWM with 50 years recurrence period, NTM), including in some cases **grid loss** and extreme oblique inflow (yaw misalignment)
- DLC 7.X – **Parked turbine plus fault** (here the turbine is stand still as a result of the fault) combined with certain wind conditions (EWM with 1 year recurrence period)

- DLC 8.X – **Transport, erection maintenance and repair** with diverse wind conditions (NWP, EOG1)
- DLC 9.X – **Extended design situations**: severe ice formation, special grid failure cases (major fluctuations, short circuit, fault ride-through), wind farm influence, temperature influences, and earthquakes

Design load cases (II)

VTT

Table 4.3.2 Design load cases for extended design situations

Design situation	DLC	Wind conditions[1]		Other conditions	Type of analysis	Partial safety factors
Power production	9.1	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Ice formation	F / U	* / N
	9.2	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Grid failure	F / U	* / N
	9.3	NTM	$V_{in} \leq V_{hub} \leq V_{out}$	Wind farm influence	F / U	* / N
	9.4	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Temperature effects	F / U	* / N
	9.5	NTM	$V_{in} \leq V_{hub} \leq V_{out}$	Earthquake	U	**
	9.6	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Earthquake plus grid loss and, if applicable, activation of the safety system by vibration sensor	U	**
Parked (standstill or idling)	9.7	NWP	$V_{hub} = 0.8\ V_{ref}$	Earthquake and grid loss	U	**
	9.8	NWP	$V_{hub} = 0.8\ V_{ref}$	Temperature effects	U	N

* Partial safety factor for fatigue strength (see Section 4.3.5.2.2)
** Partial safety factor for earthquakes (see Section 4.3.5.4)
1 If no cut-out wind speed V_{out} is defined, V_{ref} shall be used.

Meaning of the abbreviations in Tables 4.3.1 and 4.3.2:

DLC	Design load case
ECD	Extreme coherent gust with direction change (see Section 4.2.3.2.5)
ECG	Extreme coherent gust (see Section 4.2.3.2.4)
EDC	Extreme direction change (see Section 4.2.3.2.3)
EOG	Extreme operating gust (see Section 4.2.3.2.2)
EWM	Extreme wind speed model (see Section 4.2.3.2.1)
EWS	Extreme wind shear (see Section 4.2.3.2.6)
Subscript	Recurrence period in years
NTM	Normal turbulence model (see Section 4.2.3.1.3)
NWP	Normal wind profile model (see Section 4.2.3.1.2)
F	Fatigue strength
U	Ultimate strength
N	Normal and extreme
A	Abnormal
T	Transport, erection, installation and maintenance

Table 4.3.1 Design load cases

Design situation	DLC	Wind conditions[1]		Other conditions	Type of analysis	Partial safety factors
1. Power production	1.1	NTM	$V_{in} \leq V_{hub} \leq V_{out}$		F / U	* / N
	1.2	omitted				
	1.3	ECD	$V_{in} \leq V_{hub} \leq V_r$		U	N
	1.4	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Grid loss	F / U	* / N
	1.5	EOG_1	$V_{in} \leq V_{hub} \leq V_{out}$	Grid loss	U	N
	1.6	EOG_{50}	$V_{in} \leq V_{hub} \leq V_{out}$		U	N
	1.7	EWS	$V_{in} \leq V_{hub} \leq V_{out}$		U	N
	1.8	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Ice formation	F / U	* / N
2. Power production plus occurrence of fault	2.1	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Fault in the control system	F / U	* / N
	2.2	NWP	$V_{in} \leq V_{hub} \leq V_{out}$	Fault in the safety system or preceding internal electrical fault	F / U	* / A
3. Start-up	3.1	NWP	$V_{in} \leq V_{hub} \leq V_{out}$		F / U	* / N
	3.2	EOG_1	$V_{in} \leq V_{hub} \leq V_{out}$		U	N
4. Normal shut-down	4.1	NWP	$V_{in} \leq V_{hub} \leq V_{out}$		F / U	* / N
	4.2	EOG_1	$V_{in} \leq V_{hub} \leq V_{out}$		U	N
5. Emergency shut-down	5.1	NWP	$V_{in} \leq V_{hub} \leq V_{out}$		U	N
6. Parked (standstill or idling)	6.1	EWM	Recurrence period 50 years		U	N
	6.2	EWM	Recurrence period 50 years	Grid loss	U	A
	6.3	EWM	Recurrence period 1 year	Extreme oblique inflow	U	N
	6.4	NTM	$V_{hub} < V_{in}$ *and* $V_{out} < V_{hub} < 0.8\ V_{ref}$		F / U	* / N
7. Parked plus fault conditions	7.1	EWM	Recurrence period 1 year		U	A
8. Transport, erection, maintenance and repair	8.1	EOG_1	$V_{hub} = V_T$ or NWP $V_{hub} = max$ *(EOG_1 based on V_T)*	To be specified by the manufacturer	U	T
	8.2	EWM	Recurrence period 1 year	Locked state	U	A

* Partial safety factor for fatigue strength (see Section 4.3.5.2.2)
1 If no cut-out wind speed V_{out} is defined, V_{ref} shall be used.

Source: GL Guideline for the Certification of Wind Turbines 2010

Grid loss: LVRT

- Loads in the drive train may be generated by grid disturbances (Low Voltage Ride Through, LVRT), control system (faults), wind gusts...

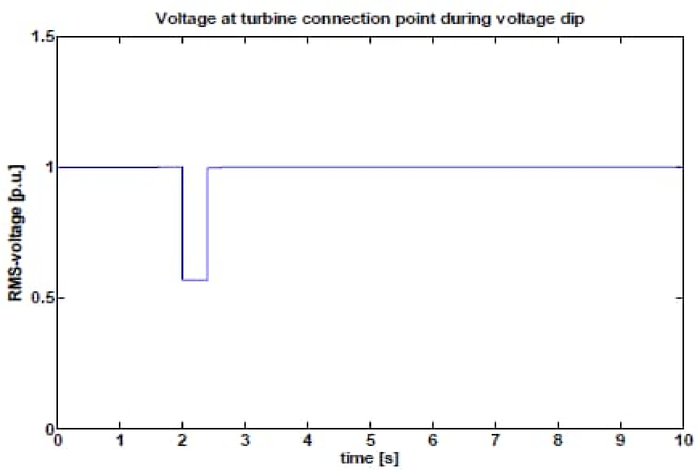


Figure 23: Voltage at turbine connection point during voltage dip

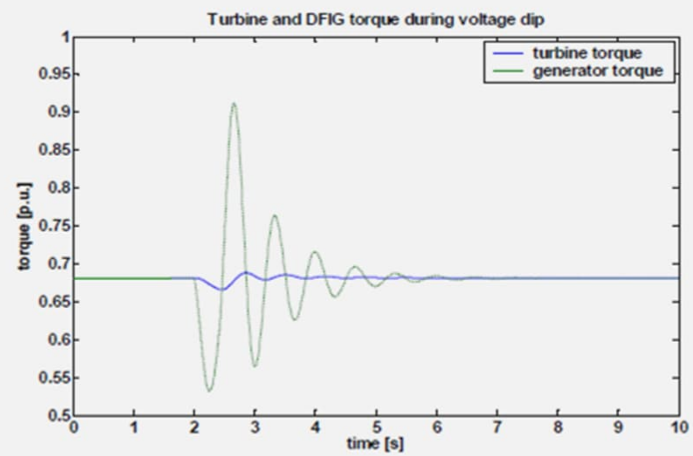


Figure 26: Turbine and DFIG torque during voltage dip

Source: Interaction between Electrical Grid Phenomena and the Wind Turbine's Behaviour, 2004

Extreme wind conditions

- A few examples of extreme wind conditions: left to right ECG, EDC, EOG also called "mexican hat"

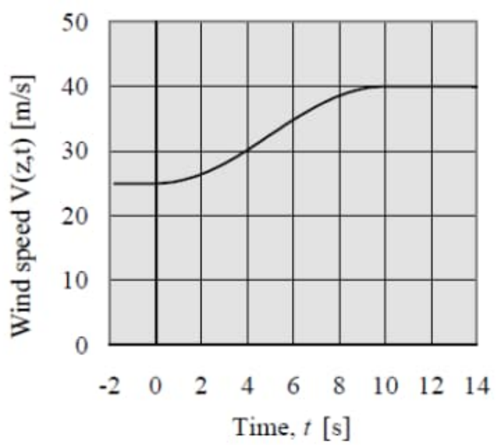


Fig. 4.2.5 **Example of an extreme coherent gust (V_{hub} = 25 m/s) (ECG)**

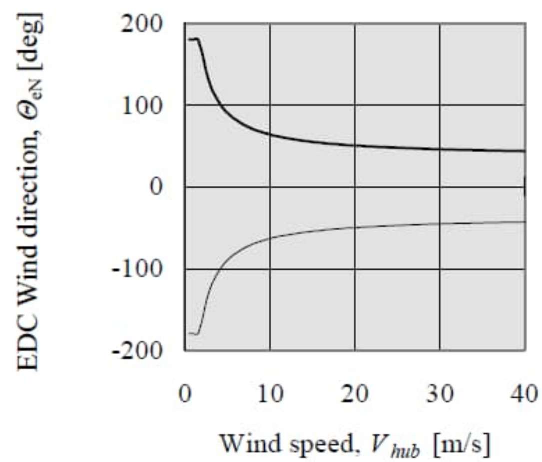


Fig. 4.2.3 **Example of the magnitude of the extreme direction change (N = 50, category A, D = 42 m, z_{hub} = 30 m)**

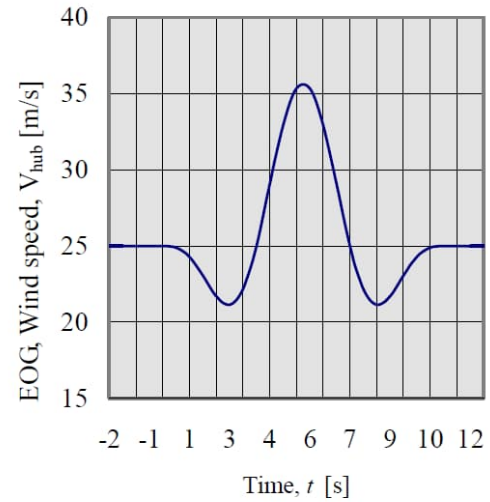


Fig. 4.2.2 **Example of an extreme operating gust (N = 1, category A, D = 42 m, z_{hub} = 30 m, V_{hub} = 25 m/s)**

Source: GL Guideline for the Certification of Wind Turbines 2010

Loads dataset: Extreme loads

- A loads dataset is a set of tables obtained from processing all the DLCs for the wind turbine. It summarizes the following key information:
  - The **extreme load** in each direction (Forces and Moments),
  - for **each location** in the turbine (blade stations, blade root, hub tower top, tower stations, tower base, etc),
  - using the relevant coordinate system
  - flagging the **specific DLC** causing that specific extreme load and listing the **contemporaneous loads** at the same station
  - the dataset also mentions the **partial safety factor for loads** being used to obtain the design values.
  - Fatigue **Damage Equivalent Loads** (DELs) (see next slide)

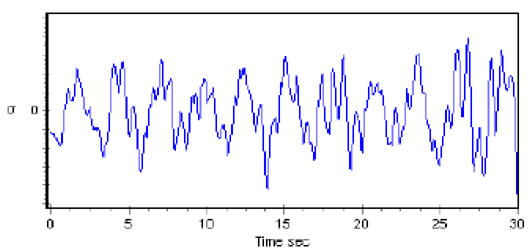
Table 5. Extreme-events for the blade 1 root moments – land.

Parameter	Type	File	RootMxc1 (kN·m)	RootMyc1 (kN·m)	RootMzc1 (kN·m)	Time (sec)
RootMxc1	Min	DLC1.3_0063_Land_24.0V0_S03.out	-7.48E+03	-2.13E+03	-1.68E+02	5.99E+02
RootMxc1	Max	DLC1.1_0061_Land_24.0V0_S01.out	1.11E+04	1.15E+04	-1.11E+02	5.66E+02
RootMyc1	Min	DLC1.4_0006_Land_ECD-R+20.out	1.93E+03	-6.81E+03	-2.24E+02	6.92E+01
RootMyc1	Max	DLC1.4_0002_Land_ECD+R.out	-7.78E+02	2.22E+04	1.18E+02	7.90E+01
RootMzc1	Min	DLC1.4_0006_Land_ECD-R+20.out	-1.75E+02	-5.18E+03	-2.81E+02	6.88E+01
RootMzc1	Max	DLC1.3_0038_Land_16.0V0_S02.out	-2.00E+03	1.77E+04	2.11E+02	1.53E+02

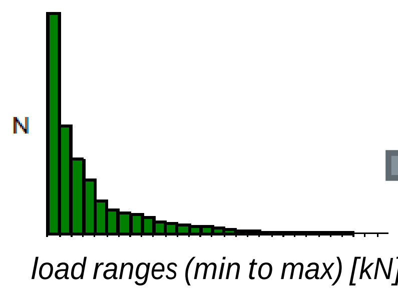
Example table from a loads dataset Source: J. Jonkman and M. Buhl "Loads Analysis of a Floating Offshore Wind Turbine Using Fully Coupled Simulation " NREL/CP-500-41714 GL Guideline for the Certification of Wind Turbines 2010

Loads dataset: Fatigue equivalent loads

- Fatigue loads are processed as follows:
- Use the DLCs representative of fatigue as defined by the standard /guideline
- Transform the load sequence of each load (force or moment) into a histogram of load ranges **Fi** (i=1 to **nbins**) and number of cycles for each bin **ni**, this is often called **Rainflow-counting** due to a popular algorithm used to perform this operation
- For each exponent **m** of the Wöhler curve (S-N curve), and using an **arbitrary value of N** (for example 10^6 cycles):



Time series for a certain load F



Histogram of load ranges for load

$$F_{DEL} = \left(\frac{\sum_{i=1}^{nbins} n_i F_i^m}{N} \right)^{1/m}$$

Loads dataset: Fatigue equivalent loads

- The damage equivalent loads are relevant in **comparison of different loads datasets**, for example to assess the effect of a design modification, to compare site specific loads versus the certification loads of the wind turbine.

Table 4.B.2 Recommended presentation of the calculation results of equivalent fatigue loads for various slope parameters of the S/N curve

Results of the fatigue load evaluation							
n_{Ref}		Fx	Fy	Fz	Mx	My	Mz
Slope parameter of the S/N curve m	m_a						
	m_b						
	m_c						
	m_d						
	m_e						
	m_f						
	m_g						
	m_h						
	m_i						
	m_j						

Source: GL Guideline for the Certification of Wind Turbines 2010

Fatigue analysis of structural components

- In order to analyse the fatigue of structural components, the time series of forces and moments are fed into the the structural model of the component (e.g. a FEM model) to obtain the distribution of stress ranges [MPa] at the critical component locations.
- The Fatigue Damage at the critical location is computed using the Palmgren-Miner rule fed with the design S-N curve of the material
- The design S-N curve depends on the characteristic resistance values of the materials (obtained from testing s statistically representative number of samples), and on the **partial safety factor** for material.

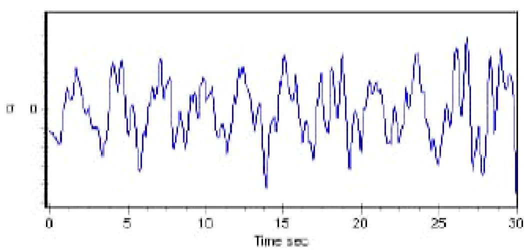


Figure C-1. Simulated time series of bending stress in the main shaft during production at 12 m/s.

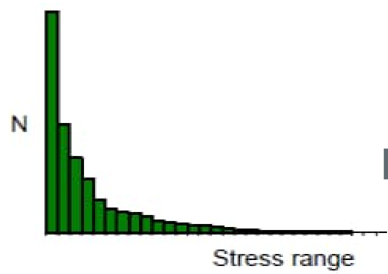


Figure C-2. Stress range distribution.

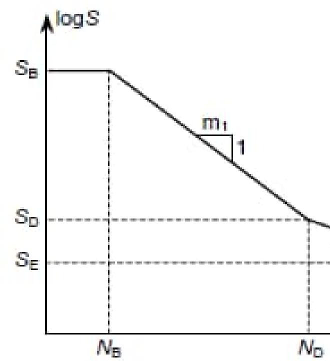


Figure C-3. S-N curve.

Palmgren-Miner rule

$$D = \sum_{i=1}^{k} \frac{\Delta n(S_i)}{N(S_i)}$$

S_E Endurance limit or ctt-off limit

S_D constant amplitude fatigue limit

S_B often set equal to the ultimate strength

Source: Guidelines fo Design of Wind Turbines – DNV/Risø, 2002

Structural analysis

- The ultimate limit state of a component correspond to the maximum load bearing capacity. Structural failure may be due to fracture (ultimate strength exceeded), or loss of stability (buckling), or fatigue
- Considering **design loads Fd** , **design stresses S**=S(Fd) , and **design Resistances Rd** , it is required that

$$S \leq R_d$$

- where

$$F_d = \gamma_F F_k \qquad (1.3.1)$$

where:

F_d design values of the loads

γ_F partial safety factors for the loads

F_k characteristic values of the loads. In this Guideline, the alternative term "representative value" is used in cases for which the characteristic value cannot easily be determined by statistical means.

(1) The partial safety factors for materials γ_M take into account the dependence on the type of material, the processing, component geometry and, if applicable, the influence of the manufacturing process on the strength.

(2) The design resistances R_d to be used for the strength analyses are derived by division of the characteristic strength R_k by the partial safety factor for materials as per equation 1.3.2.

$$R_d = R_k / \gamma_M \qquad (1.3.2)$$

Source: GL Guideline for the Certification of Wind Turbines 2010

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Wind turbine control (I)

- Goals:
  - Power regulation
  - Maximize energy capture
  - Maintain loads under acceptable limits
  - Noise control
  - Power quality in compliance with grid code
  - Operate in coordination with other turbines in the wind farm (Wind farm control)
- Challenges:
  - Challenging environment: Fluctuating wind, challenging to measure, wake flows
  - Large inertias, heavy and flexible components
  - Avoiding structure natural frequencies
  - Robust control (simulation model vs ”reality”)

Wind turbine control (II)

- The aerodynamic torque delivered by the rotor is opposed by a torque opposed by the generator. In between there is a gearbox with gear ratio Ngear. The resulting equation for the speed of the rotor (low speed shaft) is given by (e.g. Ngear=91 for a 91:1 gear ratio):

$$T_{aero} - N_{gear}T_{elec} = \left(I_{rotor} + N_{gear}^2 I_{gen}\right)\frac{d}{dt}(\omega_{rotor})$$

- The control system acts simultaneously on the **generator torque** and the **blade pitch** depending on the **control region** in which the turbine is operating. In the case of a generic control system for a DFIG machine, the regions are as follows:

  - Region 1 : Wind turbine **idling** before cut-in . Generator-torque **Telec = 0**, no power extracted
  - Region 1-1/2 : **Start-up** region: ngen $\leq$ nmin , the generator speed is below nmin
  - Region 2: Variable power with **optimal energy capture**. In this region the generator torque follows the rotational speed of the rotor to maintain the Optimal Tip Speed Ratio

    from equation:

$$P_{elec} = \eta.\frac{1}{2}.\rho.A.V^3.Cp(\lambda_{opt},\vartheta_{opt})$$

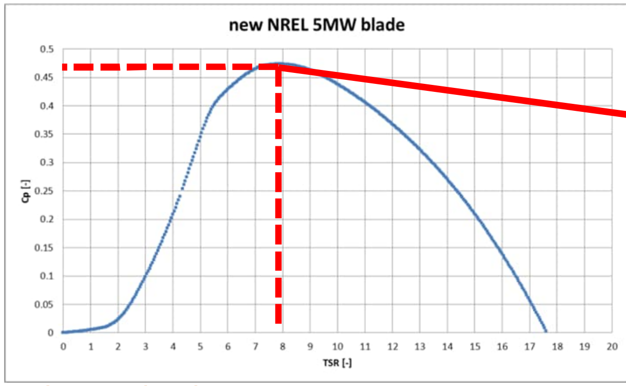
    it follows that in the optimal region the generator torque is proportional to the square of the filtered generator speed. K is called **Optimal Mode Gain**

$$T_{elec} = K.n_{gen}^2$$

  - Region 2-1/2: A transition region between optimal energy capture and rated power region. Control of turbine overspeed and rotor thrust clipping are important in this region
  - Region 3: **Rated power** region. P = Prated, and Telec is derived from the filtered generator angular velocity

$$T_{elec} = \frac{P_{rated}}{\omega_{gen}}$$

Wind turbine control (III)

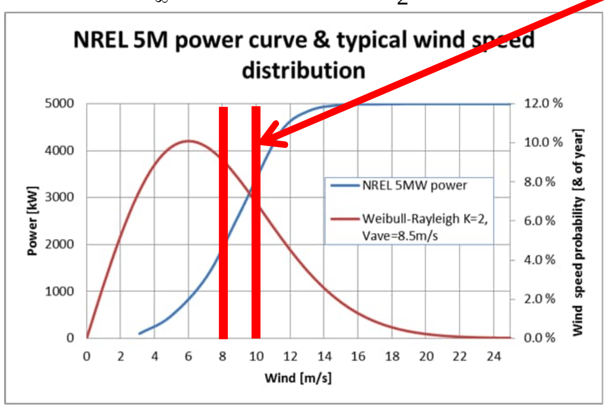


Tip speed ratio

$$\lambda = \frac{\omega R}{U_\infty}$$

Power coefficient

$$C_P = \frac{P}{\frac{1}{2}\rho U_\infty^3 A_d}$$



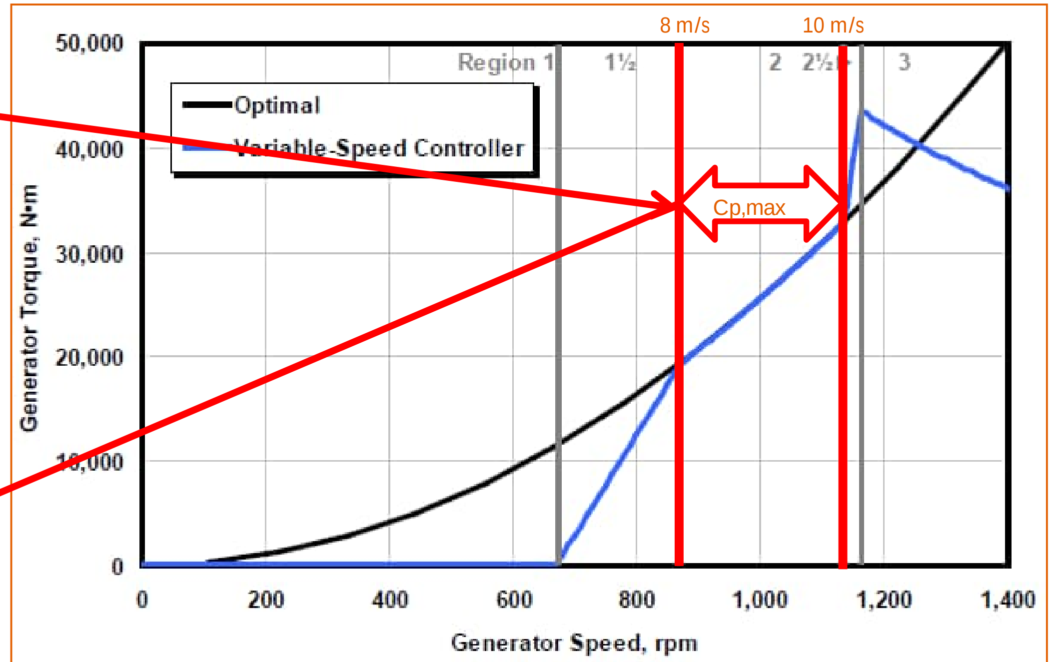
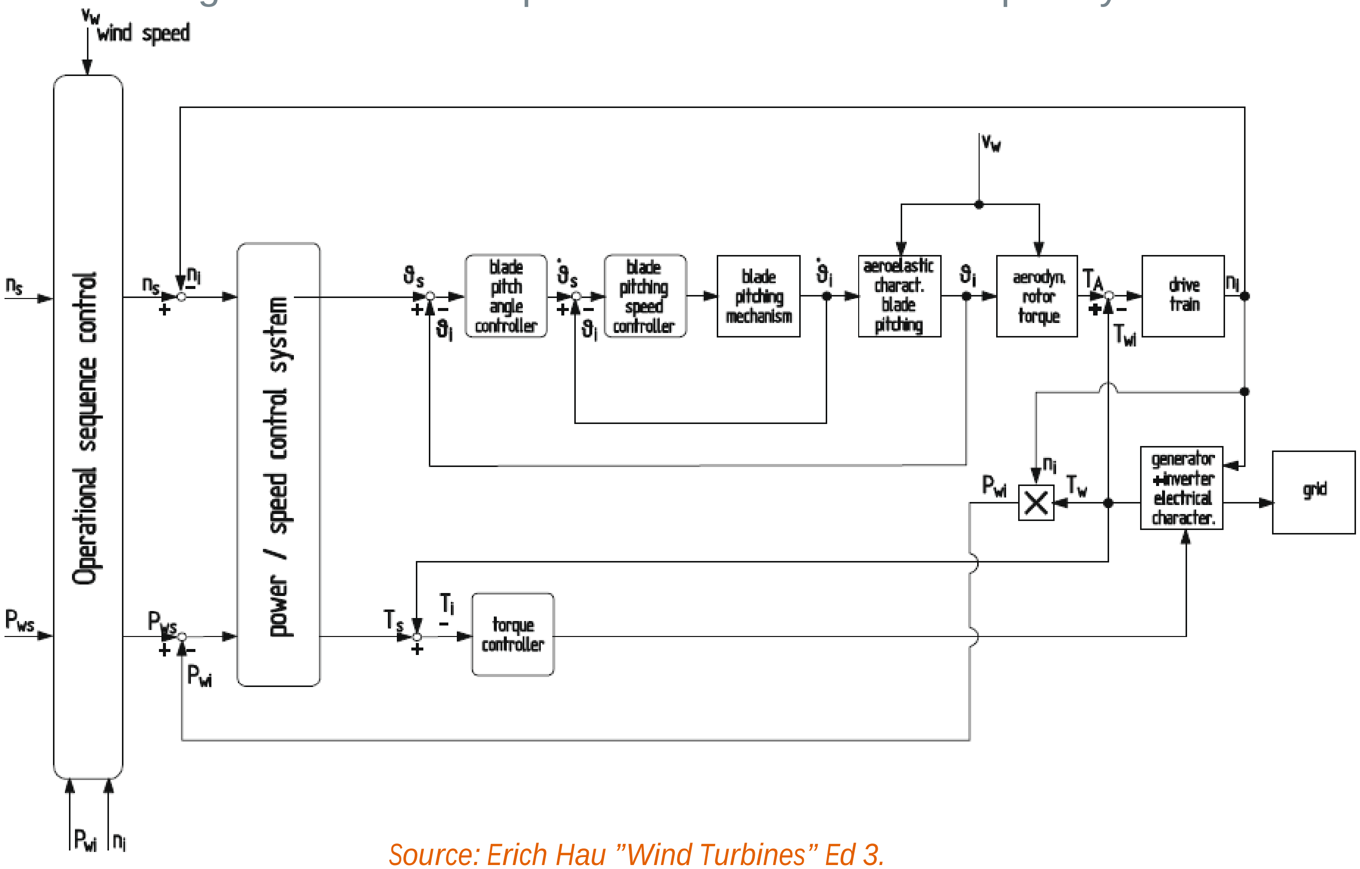


Figure 7-2. Torque-versus-speed response of the variable-speed controller

Source: Definition of a 5-MW Reference Wind Turbine for Offshore System Development, 2009

Wind turbine control (IV)

- Control structure of a generic variable-speed wind turbine with frequency converter



Source: Erich Hau "Wind Turbines" Ed 3.

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- Wind turbine loads
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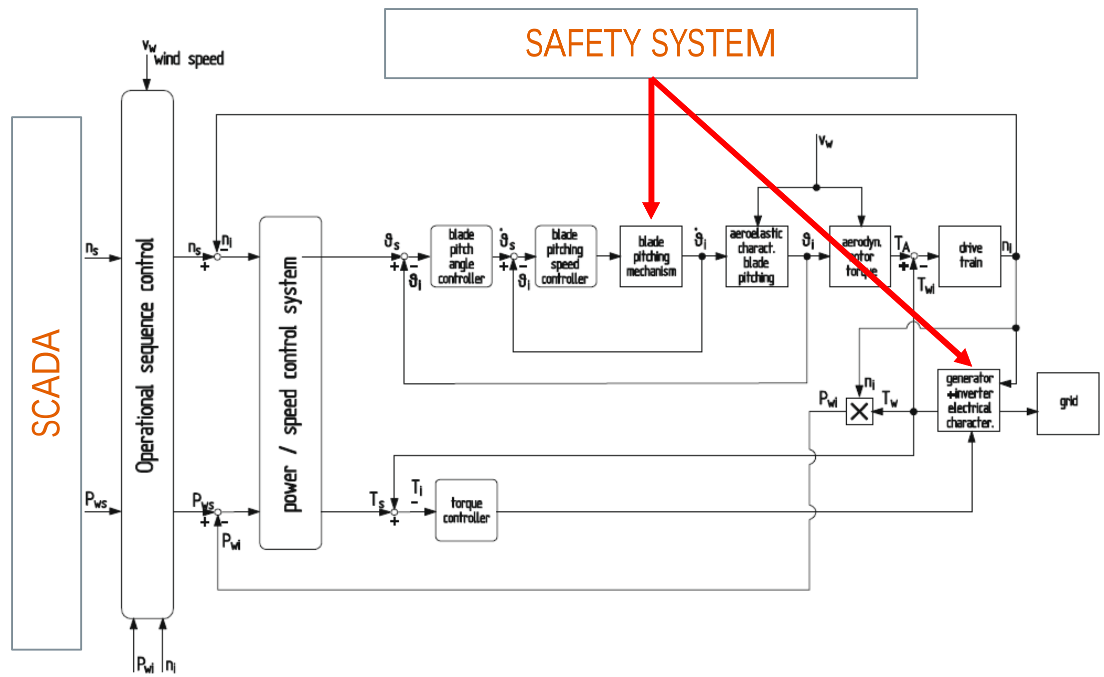
The safety and supervisory functions

- **1) Safety system:** Activates emergency stop in events
  - overspeed,
  - control system fault
  - excessive power or loads,
  - unusual vibration,
  - exceeding permissible temperatures (e.g. gearbox, generator)
  - exceeding limits related quality of power feeding into the grid
  - grid failure, vibrations, control system fault
  - cable twisting

- 2) **Dynamic control:** Control of pitch and torque

- 3) **Operational control**: switching among states in the operational sequency such as ”system check”, ”standstill” , ”start-up”, ”power production”, ”normal shutdown”, ”pause”, ”yawing” Also Yaw control to correct yaw misalignment.

- 4) **Supervisory Control And Data Acquisition** (SCADA). Strategic operation of the wind turbine / wind farm, for example a market driven curtailment.



Source: Erich Hau ”Wind Turbines” Ed 3.

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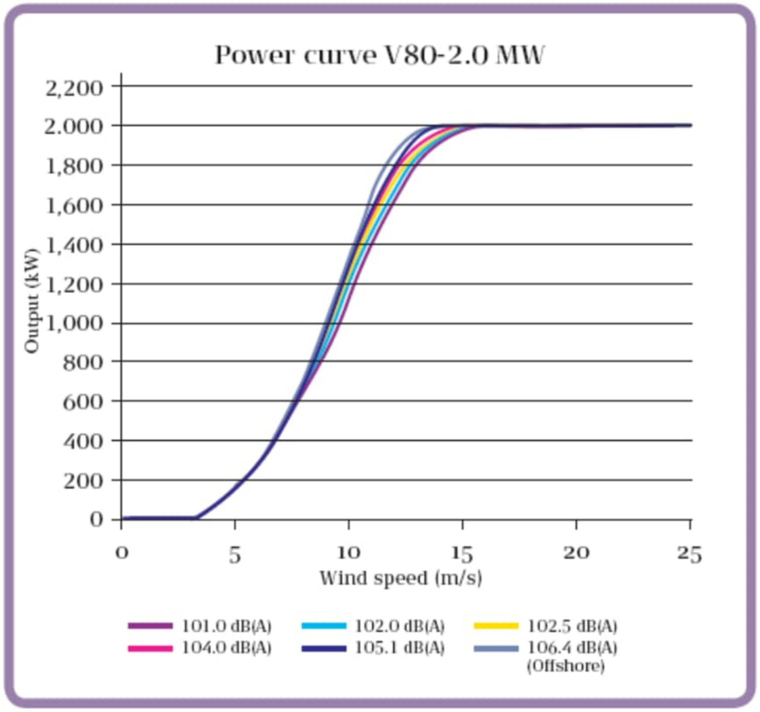
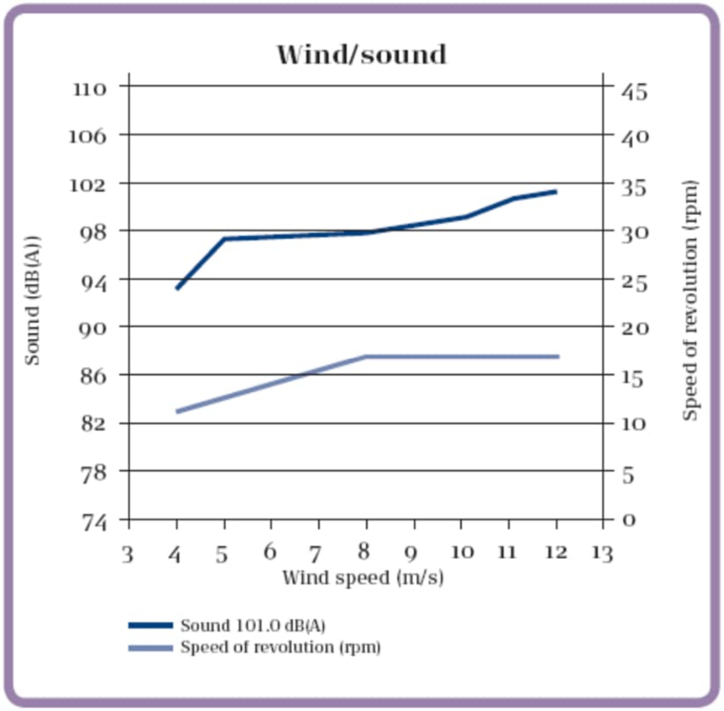
Noise control

- Noise is curtailed when necessary, typically by reducing the rotational speed of the rotor. This results in the wind turbine operating at slightly lower tip speed ratio than optimal, with a detrimental effect in the power curve





Source: Vestas

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Periodic behaviour of loads

- **Harmonic** loads:
  - Mass imbalance of the rotor, Aerodynamic imbalance (**1P loads – once per revolution** , and its harmonics 2P, 3P, 4P, 5P, 6P, 7P…)
- **Non-harmonic** periodic loads:
  - Wind shear, yaw misalignment, tower shadow (**3P loads** , and its harmonics 6P, 9P,…)
- Non-periodic **random** loading:
  - Small scale turbulence

The Campbel diagram (I)

- The Campbel diagram or resonance diagram shows interaction of the natural frequencies of the structure and key components vs the periodic loads
- Its purpose is to identify and avoid resonances, i.e. interaction between periodic load (or its harmonics) and key components in their natural frequency. Such event would result in a vibration with high Dynamic Amplification Factor
- The WKA-60 turbine experienced an umpleasant resonance between the tower 1st side-to-side frequency and the 2P at rated power.

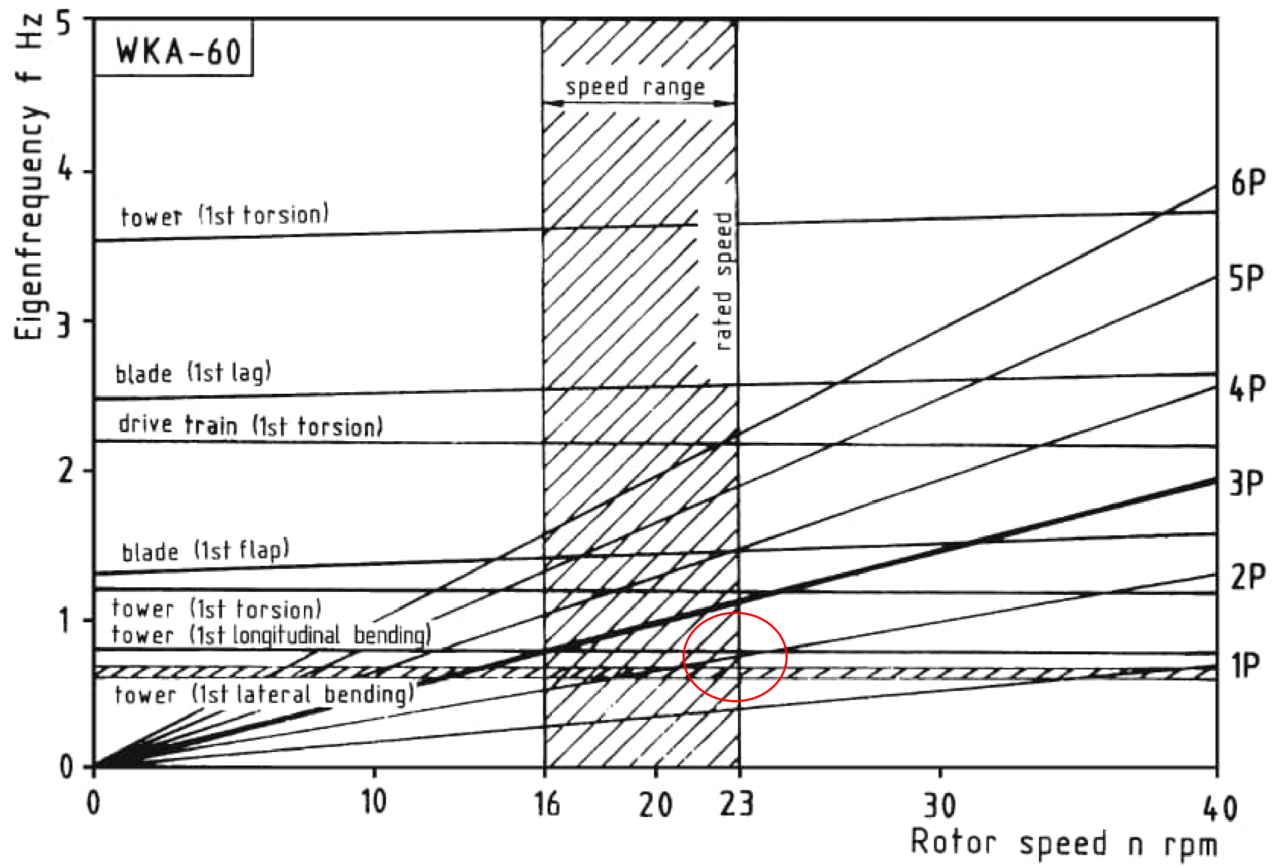
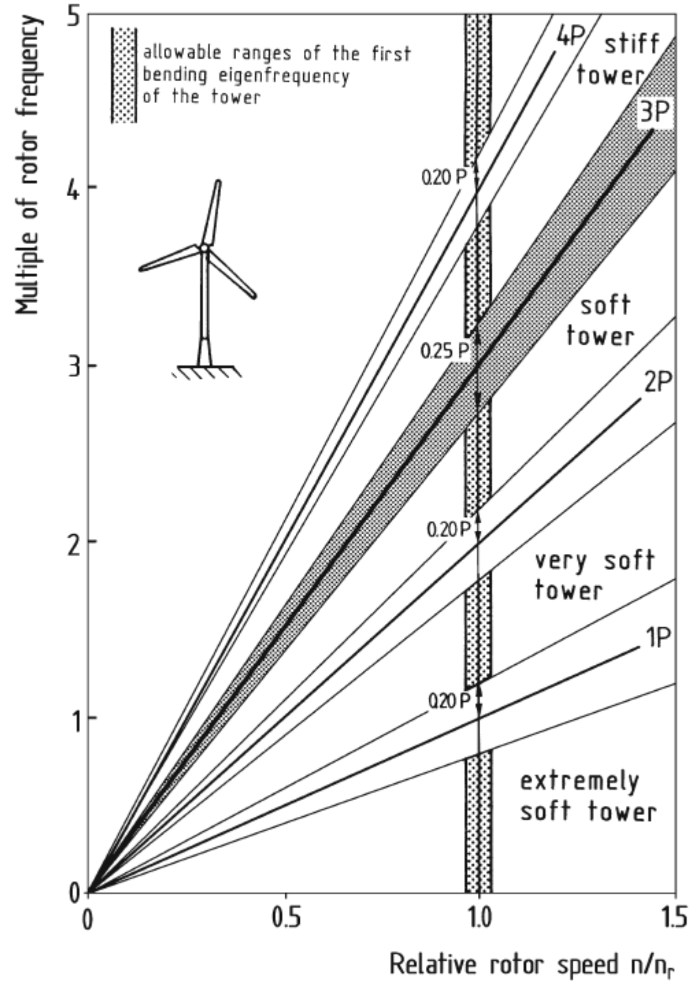


Fig. 7.26. Resonance diagram of the WKA-60 with variable speed three-bladed rotor on the up-wind side and soft tower

Source: Erich Hau "Wind Turbines" Ed 3.

The Campbel diagram (II)

- The figure shows an diagram of allowed regions for the first frequency of the foundation-tower-nacelle structure
- The foundation-tower-nacelle structure is named **extremely soft** when the first natural frequency (fore-aft and side-to side) are below **1P** at rated speed,
- and called **very soft** when such frequency is **between 1P and 2P** at rated speed,
- and called **soft** when such frequency is **between 2P and 3P** at rated speed,
- and called **stiff** when such frequency is above **3P** at rated speed.



Source: Erich Hau "Wind Turbines" Ed 3.

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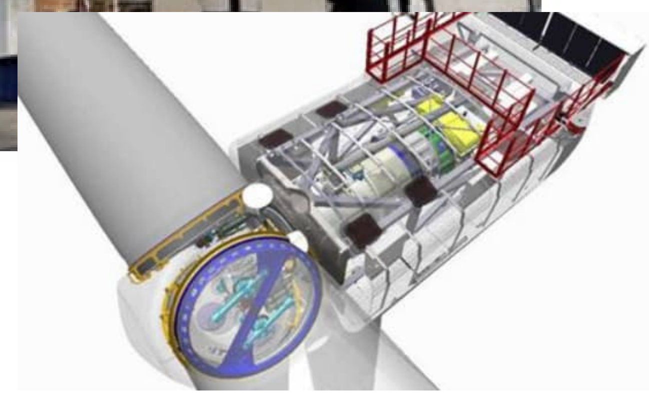
The rotor hub (I)

- The hub transfer the loads from the blades to the rotor bearing, and hosts the pitch system
- It is one of the most heavily stressed components in the wind turbine
- Generally a **cast steel** hub is used
- Spheroidal graphite cast iron is used due to the dynamic load spectrum
- Picture shows the hub of the Vestas V164. Note the presence of pitch actuators: two hydraulic cylinders per blade

- The hub materializes the rotor **cone angle** (between the blade longitudinal axis and the plane of the rotor bearing)



Source: Vestas , medium.com, Wind Power Monthly

The rotor hub (II)

- Interior of a hub, note the electric pitch drives and dedicated cabinets
- A hub cover made of glass fiber protects the hub structure from external environment

Source: Nordex

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The nacelle load carrying structure (I)

- The nacelle load carrying structure transfers the loads from the rotor to the tower via the yaw bearing
- Its design concept is closely linked the drive train architecture
- A classic concept uses a **welded or cast steel bedplate** as a support structure for the gearbox, front bearing, aft bearing and generator
- The nacelle load carrying structure also materializes the **tilt angle** between the rotor and the horizontal plane, which ensures enough blade tip clearance

Cast bedplate in a geared Nordex N80. Source: Nordex. Erich Hau "Wind Turbines" Ed 3.

The nacelle load carrying structure (II)

- An alternative concept is a **mainframe** which transfers the loads to the tower and hosts the drive train as a cantilever structure

Source: Meuselwitz Guss GmbH

The nacelle fairing

- The nacelle fairing protects the drive train and ancillaries from the weather
- It is typically manufactured in glass fiber, with access hatchs and doors to facilitate service of components

Servicing a gearbox in a modern geared offshore turbine
Source: Windpower monthly

Gearbox and main shaft replacement in an old wind turbine
Source: Windpower monthly

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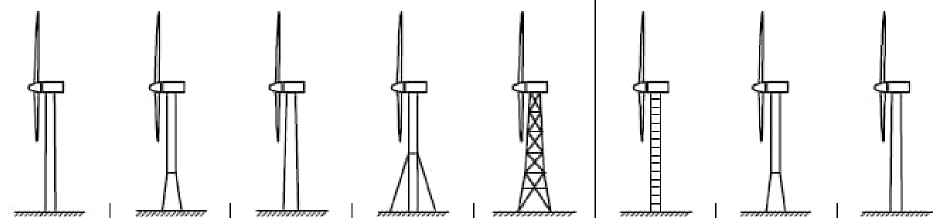
The tower (I)

- The tower holds the rotor high enough to ensure a strong and steady wind, and to enable a large rotor
- Each meter in height increases the annual energy production by ~ 0.5% - 1%
- It transfers the loads from the the yaw bearing to the foundation
- It hosts electrical and ancillary equipment, as well as a service elevator



Wind Turbine Rotor: 3 blade Diameter: 60 m Rotor speed: 23 rpm Towerhead mass: 180 t Hub height: 50 m Tower height: 46.6 m	Steel					Concrete		
	cylindrical	cylindrical with conical base	conical	cylindrical with guys	lattice	prefabricated prestressed	reinforced	prestressed
1st bending eigenfrequency Hz	0.567	0.577	0.570	0.551	0.60	0.65	0.941	0.947
Multiple of rated rotor speed P	1.48	1.51	1.49	1.44	1.57	1.70	2.45	2.47
Upper diameter m	3.5	3.5	3.5	2.5	3.5	3.5	3.5	3.5
Lower diameter m	3.5	7.1	4.4	2.5	11.6	3.5	8.4	5.5
Wall thickness mm	55 + 15 staged	25/15 staged	30/15 staged	20/15 staged	16/10	520/250 staged	300	300
Mass								
- Tower structure t	150	120	111	40	110	465	485	477
- Equipment t	22	22.5	22.8	20	22.5	21	22.5	22.5
Total mass t	172	142.5	133.8	60 guys	ca 120	486	507.5	499.5
Appr. cost relation %	100	90	85	95	70	60	60	80

Source: Erich Hau "Wind Turbines" Ed 3.

The tower (II)

- The steel tubular tower (with cylindrical segments of variable diameter) is frequently the most cost efective solution
- The highest tower full steel tower with 3 guy wires (Vestas V150-4.2MW, 175m hub height at Viinamaki)
- Concrete towers offer easy installation (”stacking” of rings) and long lifespans of 40+ years, but result in a larger foundation, and less wide manufacturing footprint.
- Hybrid towers (bottom part of concrete, upper part of steel) has been used by Max Bögl and Nordex for the 164m N131/3300

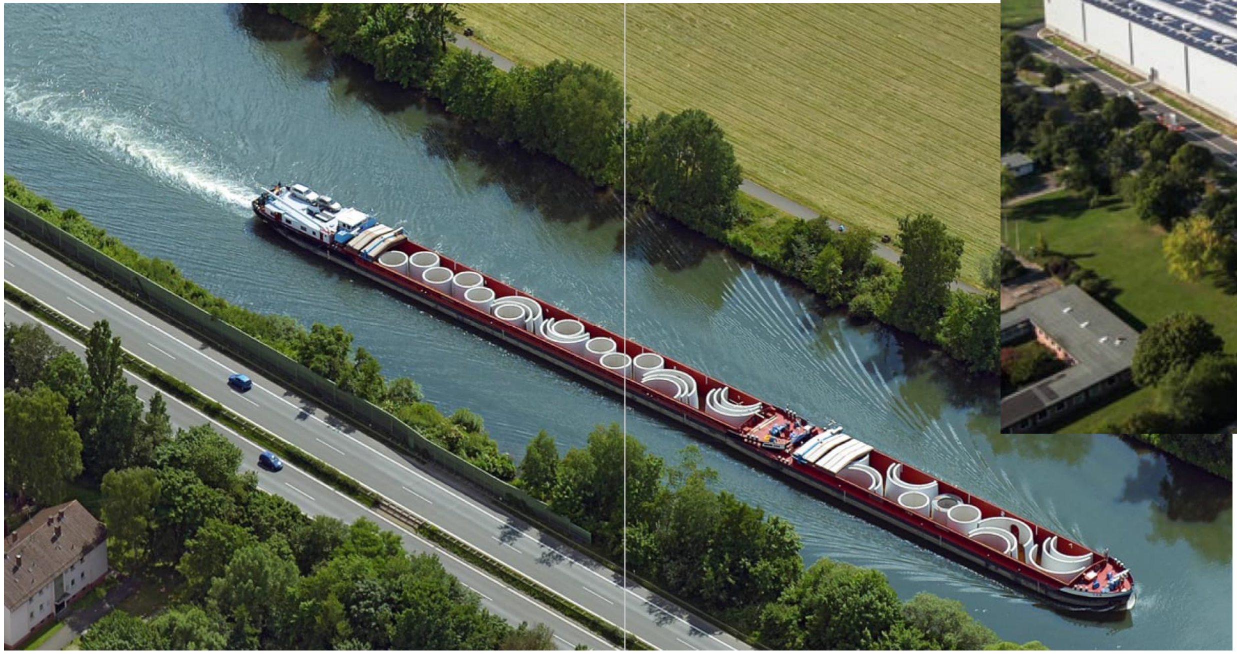
Source: Vestas, Wind Power Monthly

Source: Nordex, Wind Power Monthly

The tower (III)

- Ultimately the optimum tower for a target market a combined exercise of engineering and logistics costs

The pre-cast concrete components for the hybrid towers are shipped from the production site near the coast in Osterrönfeld in Schleswig-Holstein via the Kiel canal for the installation of wind power systems in North Germany and Scandinavia.



Source: Max Bögl

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Applicable standards (I)

- The Technical Committee TC88 of the International Electrotecnical Commission (IEC) creates and maintains the technical standards which wind energy products must fulfil:

- **IEC 61400-1** (2005-08) Ed. 3.0 + Amendement 1 (2010): Design requirements (soon to be replaced by Ed 4.0 as of Nov 2018)
- IEC 61400-2 (2006-03) Ed. 2.0 Design requirements for small wind turbines
- IEC 61400-3 (2009-02) Ed. 1.0 Design requirements for offshore wind turbines
- *IEC 61400-4 Ed. 1. Design requirements for wind turbine gearboxes, current* ISO 81400-4 (2006-04) Ed. 1.0
- *IEC 61400-5 Ed. 1.0 Rotor blades*
- IEC 61400-11 (2002-12) Ed. 2.0 + Amendment 1 (2006): Acoustic noise measurement techniques
- IEC 61400-12-1 (2005-12) Ed. 1.0 Power performance measurements of electricity producing wind turbines
- *IEC 61400-12-2 Ed. 1.0 Power performance of electricity producing wind turbines based on nacelle anemometry*
- *IEC 61400-12-3 Ed. 1.0 Wind farm power performance testing*
- IEC/TS 61400-13 (2001-06) Ed. 1.0: Measurement of mechanical loads
- IEC/TS 61400-14 (2005-03) Ed. 1.0 Declaration of apparent sound power level and tonality values
- IEC 61400-21 (2008-08) Ed. 2.0: Measurement and assessment of power quality characteristics of grid connected wind turbines
- IEC 61400-22 (2010-06) Ed. 1.0 Conformity testing and certification

Applicable standards (II)

- IEC/TS 61400-23 (2001-04) Ed. 1.0 Full-scale structural testing of rotor blades
- IEC 61400-24 (2010-06) Ed. 1.0 Lightning protection
- IEC 61400-25-1 (2006-12) Ed. 1.0 Communications for monitoring and control of wind power plants - Overall description of principles and models
- IEC 61400-25-2 (2006-12) Ed. 1.0 Communications for monitoring and control of wind power plants - Information models
- IEC 61400-25-3 (2006-12) Ed. 1.0 Communications for monitoring and control of wind power plants - Information exchange models
- IEC 61400-25-4 (2008-08) Ed. 1.0: Communications for monitoring and control of wind power plants - Mapping to communication profile
- IEC 61400-25-5 (2006-12) Ed. 1. Communications for monitoring and control of wind power plants - Conformance testing
- IEC 61400-25-6 (2010-11) Ed. 1.0 Communications for monitoring and control of wind power plants - Logical node classes and data classes for condition monitoring
- IEC/TS 61400-26-1 Ed. 1.0 Time based availability for wind turbines and wind turbine plants
- IEC 61400-27 Ed. 1.0 Electrical simulation models for wind power generation

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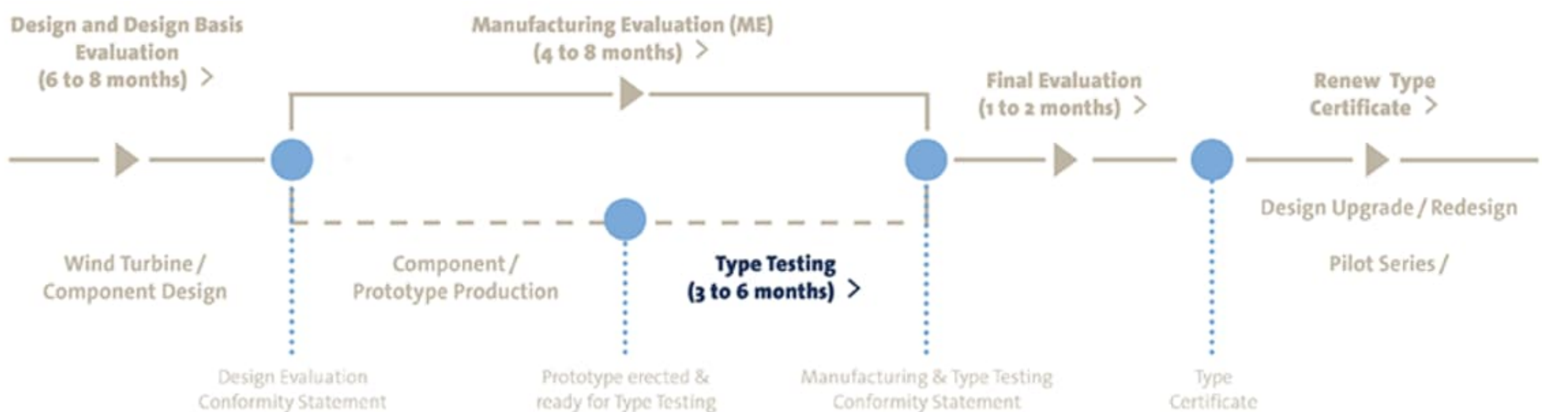
The certification process

- The certification process ensures that the product (wind turbine or component) is in compliance with relevant standards and rules, and is implemented in the reality as designed (DEWI).
- Also certification ensures that the product has low financial risk (“bankable”).

- **Certification bodies** are accredited organizations offering the certification process (DNVGL, TÜV, DEWI).



Timeline of the certification process following IEC-61400-22 according to DEWI Source: DEWI

- Certification process usually follows a “certification guideline”, this is:
  - A set of rules written by a certification body,
  - which is aligned to a standard,
  - and frequently provides more detail on the specific means to **show compliance** to that standard

References

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- ”Balance of Plant for wind projects” Univ. Strathclyde Energy Systems Research Unit
- Others (see image footnotes)

Source:
Max Bögl Wind AG,
Holger Hessenthaler,
NewAtlas.com