Probabilistic Safety Assessment of Offshore Wind Turbines

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Cover: Windturbines on the ocean © Zentilia

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Content

1 Introduction

Institute of Concrete Construction
Michael Hansen, Boso Schmidt

Electricity from offshore wind turbines will make an important contribution to tomorrow's energy policy. In Germany, offshore capacities of about 2.2 Gigawatt in the North Sea are planned or under construction.
Optimized and robust support structures for Offshore Wind Turbines (OWT) are essential to make offshore wind energy economically promising. These structures have to be designed against extreme loads as well as fatigue loads. The design principles have to ensure a long working life and an extremely low failure rate.
Actually, there are different utilized concepts in engineering standards. But these existing design concepts are based on insufficient data for research.
Based on the results of this inter disciplinary project, the central question of the design process should be answered: What is the probability of failure in the current design of OWT? Of course, former international researches tried to find results for similar questions. But in this current project we would like to detect possible optimizations for the structural design. By using probabilistic methods, the probabilities of failure will be calculated.
The existing failure modes of the support structure will be consolidated, relevant failure modes and the resulting probability of failure will be determined. Based on these data, the support structure shall be improved. In addition to the determination of safety elements for the civil engineering, safety and reliability assessments of the mechanical and electronical components of the OWT will be considered.
The involved institutes within the Leibniz Universität Hannover (LUH), shown in Figure 1, belong to three different faculties and are members of Forwind [1], the joint Center for Wind Energy Research of the universities in northern Germany.

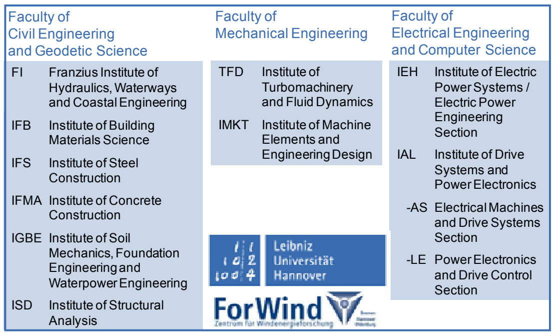

Figure 1: Project partners

These institutes operate in different work packages (WP) and are bound through WP 1 by means of equal methodology and tools (Figure 2).

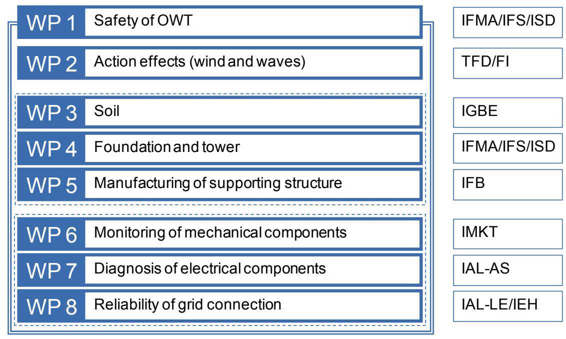

Figure 2: Work packages (WP)

WP 2 deals with action effects of wind and waves. On the one hand, additional aerodynamic loads on the rotor caused by the interaction between tower and rotor blades will be considered. On the other hand, dominant and significant sea state parameters as well as wave-breaking probabilities have to be taken into account.
The tower-foundation-interaction as well as differentiated material properties will be investigated in WP 3 to WP 5. First of all, statistical parameters for actions and resistances will be identified. In the next step, a Finite-Element-calculation coupled with a probabilistic investigation of the substructure will be prepared. Several substructure concepts will be taken into account. Of course, incoming parameters are lined up between other WPs.
In WP 6, the development and optimization of monitoring systems and

diagnostic systems for bearings and screw connections are focused.
WP 7 and WP 8 concern with the mechanical and electrical examination. In WP 7 it is aimed to dimension and to realize prototypes of two diagnostic systems. Hence, the influence of the generator type and the power electronic components will be evaluated.
In WP 8 different grid connection topologies will be evaluated. The two involved institutes are specialized in the generator, its frequency, converter and the grid connection.
The process of risk-examinations fundamentally depends on available input data. The statistical parameters of wind and waves are calculated from the measured values delivered from the research platforms. On the research platforms in the North Sea and the Baltic Sea, a comprehensive series of measurements and investigations are being performed, cf. Figure 3.

Figure 3: Research platforms in the North Sea [2]

In 2010, the first German offshore wind farm *alpha ventus* in the North Sea was installed near the location of the research platform FINO1 [3] at a water depth of about 30 m. The loadings like the design wave and wind were measured using the preexisting research platform.
Offshore wind energy farms are planned at locations of different water depths. Thus, they require appropriate types of support structures.

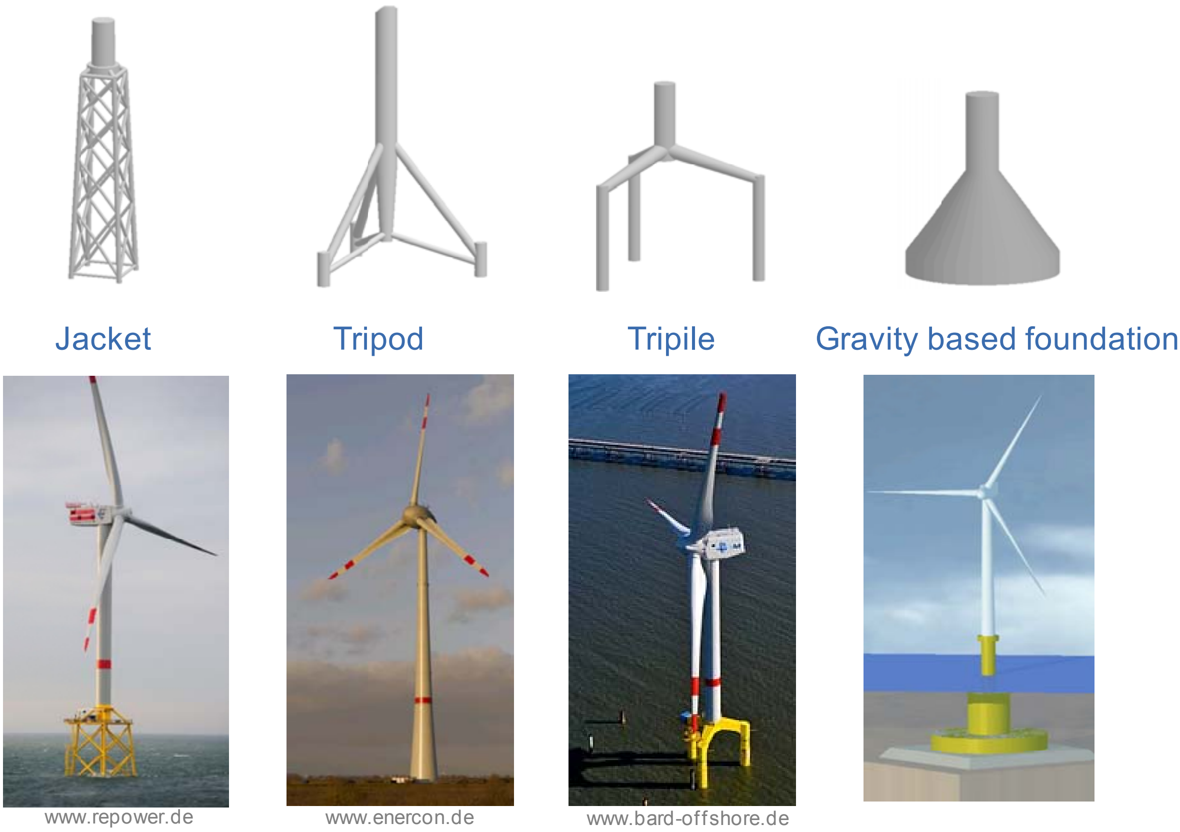

Figure 4: Types of foundation

Monopile foundations and gravity-based foundations are favored in shallow and moderate water depths while braced towers (e. g. tripod or jacket structure) are considered to be more advantageous in deeper water, cf. Figure 4.
The current research activities take advantage from previously gained knowledge from other research projects like GIGAWIND [4]. The whole OWT structure has to be analyzed with respect to the safety level. Thus, probabilistic methods should be implemented and are applied to verify the OWT safety level. The aim is to create a framework for probabilistic design concepts of OWTs. Therefore, nearly all project partners will use the same probabilistic tools described in chapter 2.1.2.
Incoming parameters like wind velocity in different sections, wave characteristics like heights and frequencies and flow velocities are measured at measurement platforms in the German Bight (cf. Figure 3) and the Baltic Sea. At FINO 1 [3], a measurement mast at a height of up to 100 m above sea level was installed on the platform. Measurement data have been recorded since 2003. This large pool of data is used to analyze the important statistical parameters, see Figure 5. For example, the design parameters of the significant actions are analyzed. The wave loads acting on the supporting structure will be calculated with appropriate models. The correlations between wind and wave loads and statistical parameters for the resistance models like material strength or characteristic values of soil properties will be determined in relationship to studies conducted in GIGAWIND [4].
Of course, the dynamic behavior of the support structure is important for the design of offshore wind turbines and has to be investigated. The dynamic behavior of moored structures in rough sea is usually analyzed by means of simplified mathematical models. The calculation of hydrodynamic loading has to be performed for hydrodynamic transparent foundations as well as for compact foundations. The most common model applied for calculating the loads of slender structures is Morison's equation.

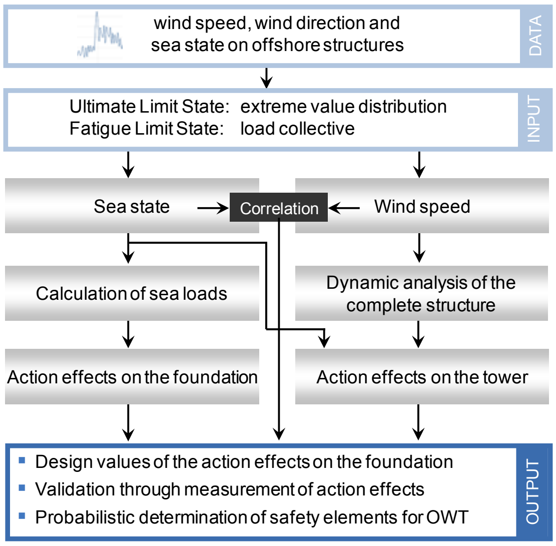

Figure 5: Analysis concept

In case of compact foundations, the interaction between wave, current and structures has to be analyzed by use of diffraction theory. The hydrodynamic loads on the structure will be obtained by integration of the local surface loads.
In the current research project, during reliability analysis, different Limit State equation will be performed. Within a fault tree analysis, the results for several limit states will be connected. Optionally, the tools used for probabilistic calculation enable multiple limit state calculations simultaneously.

References

[1] ForWind www.forwind.de

[2] http://www.dena.de/

[3] http://www.fino-offshore.de/

[4] GIGAWIND www.gigawind.de

2 Work Packages (WP)

2.1 Safety of Offshore Wind Turbines (WP 1)

Institute of Concrete Construction
Michael Hansen, Boso Schmidt

The objective target of current examinations is to obtain a design approach for offshore wind turbines (OWTs) based on an holistic probabilistic analysis regarding the practicable probability of failure. Therefore, about 30 researchers of three faculties are involved. These researchers will work on individual and team objectives. They are brought together within work package one (WP 1).

2.1.1 Motivation

Reliability analyses are appropriate in civil engineering code development, cf. [1]. Consequently, characteristic values and safety factors for predefined safety classes can be determined. Unlike deterministic examinations, random parameters are taken into account in probabilistic methods. Thus, statements about the frequency of occurrence of several limit states are possible. The importance and sensitivity of the included parameters can be evaluated, too.

In the actual design of OWT structures, random parameters are substituted by characteristic loads and safety factors. These values are taken from codes for buildings or from guidelines for Onshore Wind Turbines, such as [2]. Within probabilistic examinations, the essential design parameters ought to be implicated with their statistical values to receive safe and efficient structures. Former research projects deal with the failure probabilities of Wind Turbine components like blade fails or tower fails. In the current project the whole tower with the tower-foundation-interaction is focused.

The economy of structures and buildings depends on the investment costs (construction costs) and the costs of failure, cf. Figure 1. The failure of OWT can concern the whole structure as well as just several parts of the electrical or mechanical components. In an holistic design concept, the concerning risks and follow-up costs for environmental damage have to be considered. Finally, the risk R given with eq. (1) has to be lower than the socially justifiable limited risk R_{lim}.

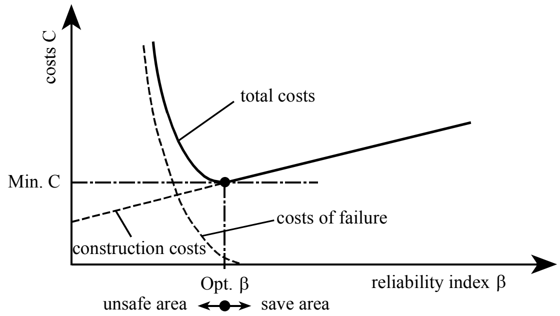

Figure 1: Development of costs, [3]-[5]

$$R = V_f \cdot P_f \leq R_{\lim} \quad (1)$$

where:

R	risk
V_f	consequences of failure
P_f	probability of failure
R_{lim}	limited risk

A probabilistic approach is suitable to classify the reliability of the analyzed structure. Thus, it should be possible to optimize the reliability and economic investment of OWTs.

2.1.2 Approach

Reliability analysis normally is very expensive. Lots of calculations have to be performed to get prediction about the probability of failure. Thus, appropriate methods and programs have to be detected for suitable analyses.

Codes and guidelines

A brief history and general comparison of different guidelines which may be used for the design of OWT support structures are given in [6]-[8]. These guidelines have been developed by organizations such as International Electrotechnical Commission

(IEC), Germanischer Lloyd (GL), Det Norske Veritas (DNV), International Standardisation Organisation (ISO) and the American Petroleum Institute (API).

In [7] the guidelines developed by API and IEC are compared in general terms based on the extent of their applicability and fundamental differences for OWT support structure design. The API and IEC guidelines are also compared on the basis of the levels of reliability inherent in their design methodologies for a monopile.

The limitation of target reliability levels is developed on economic optimization, cf. [1], [9]-[12]. The target failure probability for OWTs has to be predefined. Wind turbine structures are unmanned and imply much less risk to human life than onshore structures. Therefore, they can be designed based on a lower safety class. The codified characteristic loads in codes are given as 50-year values [13] or 100-year values [14]. Furthermore, wind turbine structures are expected to be dominated by wind turbine loads which are of other nature than the wave loads. However, wave loads are assumed to be dominating for structures designed according to [14].

During revision of [13] in 2007 different examinations were carried out. It has been concluded with consensus in the wind industry that the minimum requirements for structural safety are identical on land and offshore [6].

Reliability Methods

Various methods of reliability analysis are used. These methods are different with regard to their degree of precision (Level of Sophistication, [3]). The semi-probabilistic method also called partial safety concept introduced internationally by [15] and nationally by [16] is a method of the so-called Level I at which characteristic values of actions and resistances are transferred into design values by means of partial factors. These partial safety factors are calculated by Level II methods. The Level II methods (e.g. First Order Reliability Method, shortened FORM) are based on the mean average value and the statistical spread being two characteristics of random distributions of mechanic parameters (basic values). More exact results are achieved applying Level III methods like the Numeric Integration and the Monte-Carlo Method. Performing Stochastic Optimization and Robust Design Optimization, sampling methods (e. g. Importance sampling using design point ISPUD or Latin hypercube sampling LHS) or Adaptive Response Surface Method ARSM are used, cf. [3], [17].

Applying approximation procedures like FORM, comparisons and sensitivity analyses are possible. Based on the probability of failure, the Hasofer-Lind second moment reliability index β and the sensitivity factors of actions and resistances, it is possible to appraise rough values for the safety elements like the partial safety factors ([9], [10], [3]-[5]). To obtain certain statements about the probability of failure of the structure more precise probability methods are necessary. With regard to non-linear limit state functions and non-linear calculations of the structure, the ARSM will be used. The consequences of varying design concerning the construction have to be included in a risk-based analysis. A comparison between various OWT constructions with regard to costs and risks of each structure should indicate the best solution. The results of these calculations enable specifying safety elements for the OWT design. On this way, a practicable risk-based design concept is aimed, e. g. with advanced partial safety factors for different design conditions.

More detailed explanations about reliability methods are given in [3], [18], for example.

Reliability Modeling of OWT

Each OWT is modeled as a system of different components which are divided into two groups:

- Structural members such as tower and foundation (WP 3-5) or blades (WP 2). For these parts, limit state equations can be formulated defining failure or unacceptable behavior. The parameters in these equations are modeled by use of stochastic variables.
- Mechanical (WP 6) and electrical (WP 7-8) components where the reliability is estimated using classical reliability models e. g. FMEA (Failure Mode and Effect Analysis) or FTA (Failure Tree Analysis).

Uncertainties

In reliability analysis, several kinds of uncertainties have to be considered, see Figure 2. Uncertainties modeled by stochastic variables are divided into four groups. Inherent uncertainties are related to the randomness of a quantity (e. g. expected wave height or annual maximum wind speed). Model uncertainties are related to imperfect knowledge or idealizations of the mathematical or physical models used for the uncertainty (e. g. distribution fittings, models for bearing behavior). Furthermore, there are dimension uncertainties related to imperfect dimensions (e. g. geometrical quantity) and statistical uncertainties related to the limited sample sizes of observed quantities. Human errors will not be included, because they cannot be approached by use of probability methods.

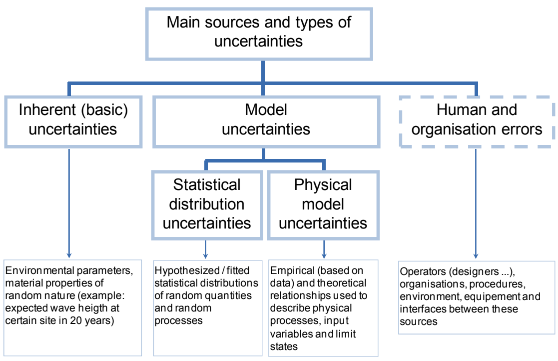

Figure 2: Uncertainties

2.1.3 State of work

The WP 1 is characterized by a common use of methodical approaches and agreed databases. For that purpose, a central database is applied, which will be enlarged regularly. The statistical values, which are required in probabilistic determination, can be taken from this database. In civil engineering, these are statistical values of the resistance on the one hand and statistical values of the loads on the other. The statistical values of the parameters, which are required for the resistance models of the support structure, are valid on- and offshore in a similar manner. They were investigated in the past and, therefore, the database contains an overview of statistical values from literature.

Considering the whole support structure and its environmental conditions, soil parameters are essential. These parameters are highly dependent on the OWT location. For the location of the research platform FINO 1 [19], an overview of the statistical values is contained in the database.

In addition to the material and soil properties, the dimensions of the components represent a further value of influence. In this case, we use data from closed research projects such as GIGAWIND [20].

The statistical distributions of essential load parameters for OWT are known hardly. To determine the statistical values of these input parameters, the meteorological- and hydrological measurements of the research platforms FINO are used (cf. chapter 1). For the statistical analysis of the loads on an OWT, it is important to use a distribution, which approximates a dataset or the associated histogram suitably. In civil engineering, the range of low occurrence probability is important. That's why the upper quantiles of a probability distribution are important to determine the reliability. In civil engineering, the Gumbel distribution as a distribution of extreme values is

appropriate to discribe climate loads. Further distribution-types are the Weibull- or the Rayleigh distribution.
Comparatively, for wind speed measurement data from FINO 1 [19] an analysis using Gumbel distribution was performed (cf. chapter 2.4.3). This distribution allows for an extrapolation to extreme values. Thus it is possible to determine characteristic loads with a recurrence period of 50 years (shown in Figure 3), according to current codes like [13], [21].

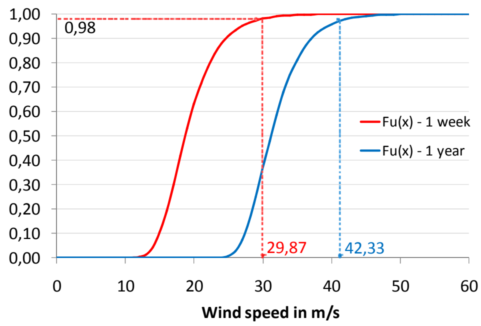

Figure 3: Distribution function of the weekly- and annual extreme value distribution $F_u(x)$ of the wind speed at 100 m above water level and the 98% quantile (recurrence period of 50 years)

As a common use of probability methods is intended, in all WPs, the software *OptiSlang*© [17] is provided for all project members. *OptiSlang*© [17] contains a lot of probabilistic methods. Further a combination of non-linear Finite-Element-calculation with probabilistic methods like FORM or ARSM is possible. The statistical distributions of the input-parameters are calculated based on the statistical values of the applied database.

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2.2 Action Effects of Wind and Waves (WP 2)

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The interaction of loads and structures influenced by several components are essential input parameters of probabilistic investigations. For offshore wind turbines (OWTs) these effects are mainly caused by aerodynamic wind loads and hydrodynamic wave loads. Therefore, in this work package characteristic parameters of the loads and the resistance of OWTs will be determined. As a common database the wind and wave measurements at FINO 1 are used.

2.2.1 Motivation (TFD)

For the design of several mechanical components of OWTs it is necessary to consider aeroelastic effects on the entire structure. Some of these effects can be coupling between the main shaft torsion and the edgewise bending of the blades or the interaction between the tower and the rotor flapwise bending. A detailed description of the loading of wind turbines is given for example in [1,2,3]. Previous works at the Institute of Turbomachinery and Fluid Dynamics have shown that the interaction between the tower and the rotor blades causes additional aerodynamic loads on the rotor which change the load history of the blades. These additional loads are unsteady flapwise and edgewise moments. Furthermore, the rotor blades cause additional lateral tower loads [4,5,6]. Unsteady loading of OWTs is also induced by wind shear, turbulence and waves.

In order to reach an acceptable reliability and safety, there are standards and guidelines for the design of OWTs, e.g. *Design Requirements of Offshore Wind Turbines* [7], *Guideline for the Certification of Offshore Wind Turbines* [8], and *Design and Manufacture of Wind Turbine Blades, Offshore and Onshore Wind Turbines* [9]. These, some other standards, and guidelines tend to give general procedures for safe design, but are not very specific [10]. Therefore, probabilistic methods are required for developing a cost optimized OWT with high reliability and low probabilities of failure. So it is also possible to adjust the safety requirements of the design to specific sites and to calculate individual failure probabilities for OWTs [11].

In IEC 61400-1 [12] the individual wind turbine components are divided into three component classes. Wind turbine blades are normally designed in component class 2 corresponding to the normal consequence with a probability of failure $P_f=10^{-3}$ and a reliability factor $\beta=3.09$ [13]. This implies the following partial safety factors used in IEC 61400-1 for fatigue design of wind turbine blades:

Table 1: Partial safety factors for fatigue design of composite material [12]

Partial Safety Factor	IEC 61400-1
Material properties	1.20
Consequences of failure	1.15
Load	1.00

In the literature there are several publications dealing with failure probabilities caused by fatigue and ultimate loading in connection with wind turbine blades. An overview of previous works is given in [10]. Further works are for example [13,14,15].

In this part of work package 2 the failure probability of rotor blades of OWTs due to aerodynamic loads will be determined. Therefore, failures as a result of fatigue and ultimate loading will be investigated.

2.2.2 Approach (TFD)

Initially a failure mode and effect analysis (FMEA) of an OWT will be done. A FMEA is an analytical method to identify weak points of systems or processes in order to prevent failures and to improve the technical reliability. In this project the objective of the FMEA is to identify several failure modes of OWTs and their effects. Thereby, the main focus is on the rotor and the drive train components. As far as possible, the results of the FMEA should be considered in the aeroelastic modelling. The aeroelastic behaviour of OWTs will be determined by taking into account stochastic wind fields at offshore locations and given structure characteristics. On the one hand aeroelastic models of OWTs consist of an aerodynamic part to determine the wind loads and on the other hand of a structural dynamic part to calculate the dynamic response of the OWT. 3D turbulent, stochastic wind fields will be generated based on the FINO 1 data. The aim is to investigate the impact of both the wind field parameters and the structure characteristics on the aeroelastic behaviour of OWTs and on the probability of failure. Furthermore, the sensitivity of the natural frequencies due to variations of material and/or geometric properties will be investigated. It will be assumed that material properties follow a normal distribution. In order to describe variations of geometry parameters within the manufacturing tolerances a uniform distribution will be assumed [16].

For the investigations the aeroelastic model of a 5 MW OWT [17], which was developed at the National Renewable Energy Laboratory (NREL), will be used. The wind fields will be generated with the computer programme TurbSim [18] and the turbine response will be computed with the aeroelastic simulation software FAST [19].

In IEC 61400-1/ -3 [7,12] several design load cases for OWTs exist:

- Power production
- Power production plus occurrence of fault
- Start-up
- Normal shut-down
- Emergency shut-down
- Parked
- Parked and fault conditions
- Transport, assembly maintenance and repair

In this work package the main focus is on the turbine response in an operating state (power production) to determine the probability of failure due to fatigue and ultimate loads. Especially design load case (DLC) 1.1 and DLC 1.2 which are classified in the IEC standard [7,12] will be considered in this work package.

2.2.3 State of Work (TFD)

Up to now, an extensive literature research has been carried out with the main topics:

- Standards and guidelines for the design of OWT
- Probabilistic design of wind turbines, especially for wind turbine blades
- Fatigue and ultimate loads
- Calibration of partial safety factors

The FMEA is not entirely concluded yet. As mentioned above, the main focus of the FMEA is on the rotor and the drive train components. Because of missing data of an existing OWT, the FMEA is mainly done on the basis of published information.

Furthermore, investigations of the influence of wind field parameters on the aeroelastic behaviour and on the loads of OWTs are still in progress.

2.2.4 Motivation (FI)

Extreme hydrodynamic loads on OWTs result principally from breaking waves, which cause severe impact on offshore structures and induce significant singular stresses as well as vibration and therefore discrete degradation of the support structure, see Figure 1 and 2.

Figure 1: Norwegian tanker WILSTAR hit by a huge wave in the Agulhas current, Sourth Africa in 1974 [20].

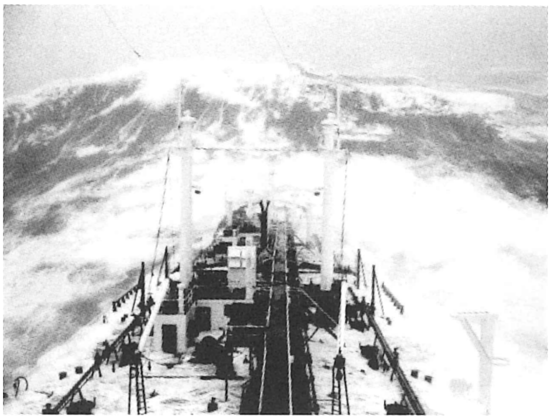

Figure 2: Tanker Stolt Surf in heavy seas, 1977 [20].

The relevant loads for a design base depend decisively on the prevalent sea state, i.e. the geometry of breaking waves in a storm. All influencing factors vary strongly in the natural sea state. For an efficient design of OWTs, dominant and significant sea state parameters as well as wave-breaking probabilities must be considered.

2.2.5 Approach (FI)

Therefore, validations with measured and computed hindcast data records are necessary and investigations on the laboratory scale are indispensable. In the first step sea state direction, heights and occurrence of wave trains in the North Sea can be analyzed. The second step deals with the wave-breaking probability, which is investigated by means of laboratory experiments in the 3D wave basin of the Franzius-Institute to quantify the scatter of the influencing factors. The varying input parameters are i.a. the significant wave height H_S, the peak period T_P, the phase angle φ and the spreading angle α.

Several authors have investigated the statistical properties of wave-breaking by different measurement methods (visual or acoustical observation, wave gauges, etc.) in nature, in a controlled wave tank environment or numerically. However, most of the experiments were performed with monochromatic waves, few with random seas and less with three-dimensional seas.
To investigate the wave-breaking probability, a criterion to define the breaking of a wave crest has to be chosen. Common wave-breaking criteria are:

- Wave steepness
- Dynamic criterion

Wave Steepness

The wave steepness is the ratio of wave height H and period T. The most widely known wave steepness threshold is the limiting steepness for a Stokes wave, analytically derived by Michel [21], for which a wave crest breaks when the wave height exceeds 14.2 % of the Stokes limiting wave length. However, several tests on breaking of irregular waves were conducted in wave flumes (see [22], [23] and [24]) and it was found that the observed number of random breaking

waves is much greater than the theoretically computed based on [21].
The wave steepness criterion may be written as:

$$H \geq \beta g T^2 \qquad (1)$$

where β is a constant. Ochi and Tsai [22] showed in their tests that β is 0.020 while Xu et al. [23] and Ramberg and Griffin [24] obtained 0.019 and 0.021, respectively. These mentioned wave-breaking parameters underlie wide scatter in natural seas and they can be described with joint probability density functions. Based on Eq. (1) with β = 0.020 and the joint probability density function analytically developed for waves with a non-narrow-band spectrum by Cavanié et al. [25], the wave-breaking probability is given in the following:

$$Pr\{breaking\ wave, Type\ I\} = \frac{p_I^2}{p_I^2 + p_{II}} \int_0^\infty \int_{\alpha\left(\frac{\bar{T}_m^2}{\sqrt{m_0}}\right)\lambda^2}^\infty f\big((\nu,\lambda) d\nu d\lambda\big) \qquad (2)$$

Type I is referring to a wave breaking along the excursion as it crosses the zero-line, see [22].

Dynamic Criterion

The dynamic criterion describes the vertical component of surface acceleration exceeding a certain threshold $\geq \alpha g$ with α as an unknown constant according to Srokosz [26]. Srokosz derives the wave-breaking probability as:

$$Pr\{breaking\} = e^{-\frac{\alpha^2 g^2}{2m_4}} \qquad (3)$$

However, all these results were based on the observations of two-dimensional deep water waves. The applicability of these results to three-dimensional wave fields is not validated yet. Therefore, in this part of the work package the directional behavior of wave-breaking characteristics and probability will be investigated. Prior investigations with three-dimensional wave fields were conducted by She et al. [27]. Found from the results of the tests by [27] it is shown that the i.a. wave height and crest-front steepness, at breaking, are strongly dependent on the angular spreading. In [27] it is written: “In general, the greater the spreading angle, the bigger are the breakers.”

2.2.6 State of Work (FI)

The intended laboratory investigations will take place in the rebuilt wave basin of the Franzius-Institute in Hannover - Marienwerder. The wave basin is 40 x 24 m large and features a new three-dimensional sea state generating wavemaker. The maximum water depth is 0.80 m and the maximum wave height of directional sea state is 0.40 m. The installation of the snake wave maker with 72 single blades is currently in progress, see Figure 3.

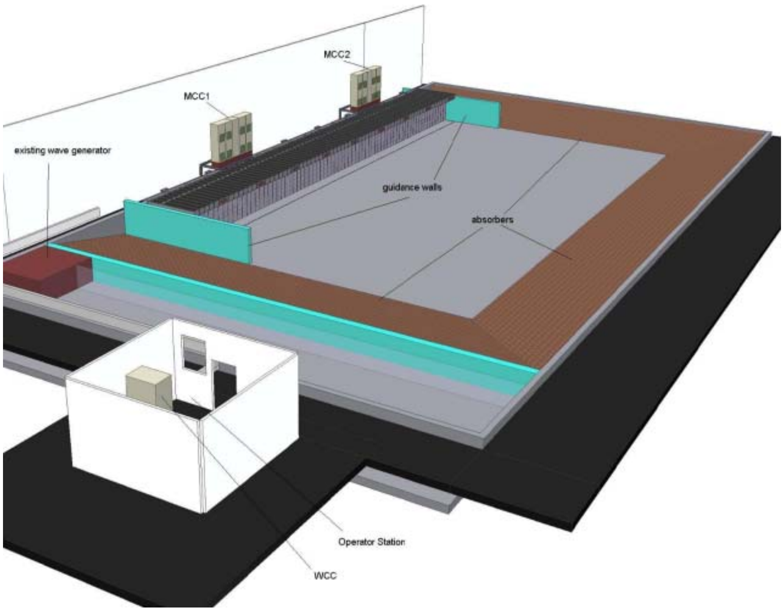

Figure 3: Wave basin with 3D snake wavemaker (source: Bosch Rexroth).

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2.3 Soil (WP 3)

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Martin Achmus, Kirill Schmoor

The aim of this work package is to establish a probabilistic based design approach for OWT foundations. One of the major tasks is to develop a model to present the ground soil performance.

2.3.1 Motivation

To carry out reliability analyses of OWT it is necessary to implement the ground into a stochastic model. The development of this process is shown in Fig. 1. The final design model results from several sources of uncertainties and errors as listed below:

Spatial Variability:
Due to the soil heterogeneity there is a significant spatial variability of soil properties. These uncertainties which affect the design are specified by the "spatial variability".

Measurement Error:
Uncertainties which come from in situ measurements errors or from laboratory tests are covered by "measurement errors".

Transformation Error:
It is often necessary to transform one parameter to obtain the required one, for example to calculate the mobilized friction angle (φ') from the cone penetration test (q_c). This uncertainty which results from transforming parameters is specified by the "transformation error".

2.3.2 Approach

The general working steps foreseen in the project are shown in Fig. 2.

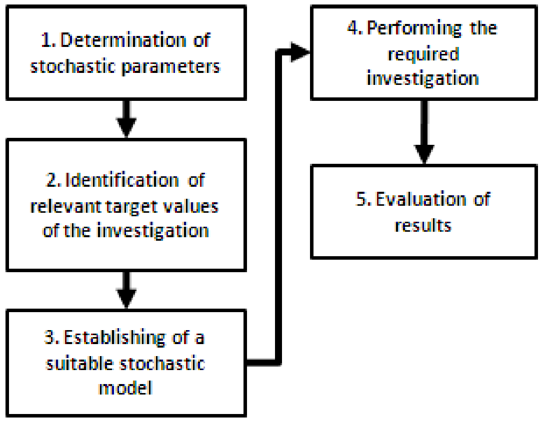

Figure 2: Working steps in the project

A suitable approach to model variability of soil properties is shown in Eq. (1):

$$z(\boldsymbol{x}) = t(\boldsymbol{x}) + w(\boldsymbol{x}) \qquad (1)$$

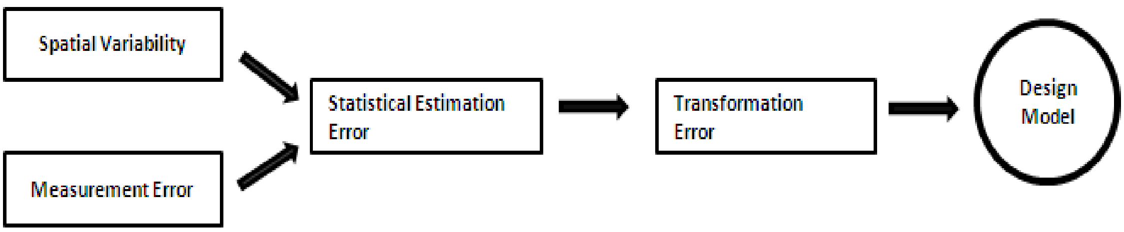

Figure 1: Development of the design model

These errors could arise from measurement equipment or from operator.

Statistical Estimation Error:
Mostly there is only limited information available about the in situ soil properties. By establishing statistical parameters from these data uncertainty results due to approximation errors. However this error can be decreased with increasing data.

in which z is the soil property, t is a trend function, w is a fluctuating component and $\boldsymbol{x} = (x_1, x_2, x_3)$ specifies the spatial position. In most cases $w(\boldsymbol{x})$ can be modeled as a stationary (*or homogeneous*) and isotropic random field [8]. Due to stationarity the probability density function of a soil property is independent of spatial position, it depends only on the relative position. This implies that the mean and covariance of the random field are constant in space. Isotropic behavior implies that the random field is invariant due to axis rotation. Hence two points affect each other only by their relative distance between them and not by their relative orientation to each other.

By taking the "measurement error" $e(\boldsymbol{x})$ into account the ground model $z_m(\boldsymbol{x})$ is described by Eq. (2). By applying a transformation function $T(\cdot,\varepsilon)$ with the "transformation error" ε the final design ground model $z_d(\boldsymbol{x})$ can be obtained from Eq. (3):

$$z_m(\boldsymbol{x}) = z(\boldsymbol{x}) + e(\boldsymbol{x}) \tag{2}$$

$$z_d(\boldsymbol{x}) = T(z_m(\boldsymbol{x}), \varepsilon) \tag{3}$$

Fig. 3 shows three possible modeling examples of a homogeneous soil profile. These simple models can also be modified to adapt more complex soil profiles like layered soil [3].

- Type I:
  Constant trend and constant variance
- Type II:
  Linear trend and constant variance
- Type III:
  Linear trend and constant COV

As a result of geological and environmental processes it can be expected that when two points are close to each other, that their soil properties are related to each other. This could be covered by modeling the random field as a correlated random field with a specified correlation length θ. The determination of the correlation length is in fact complicated. However, it generally arises that the horizontal correlation length is much larger than the vertical one. In Fig. 4 two typical correlation functions of the distance between two points Δx for a correlation length $\theta = 1.0\,m$ are shown. Uncertainty due to variation of the correlation length should also be taken into account for performing reliability analyses.

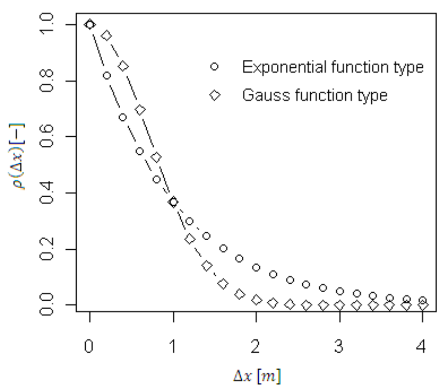

Figure 4: Correlation functions

Probabilistic investigations of a bearing capacity problem by Griffiths et al. (2002) [2] have shown that the correlation length has a non-negligible influence on the bearing capacity which consequently affects the failure probability.

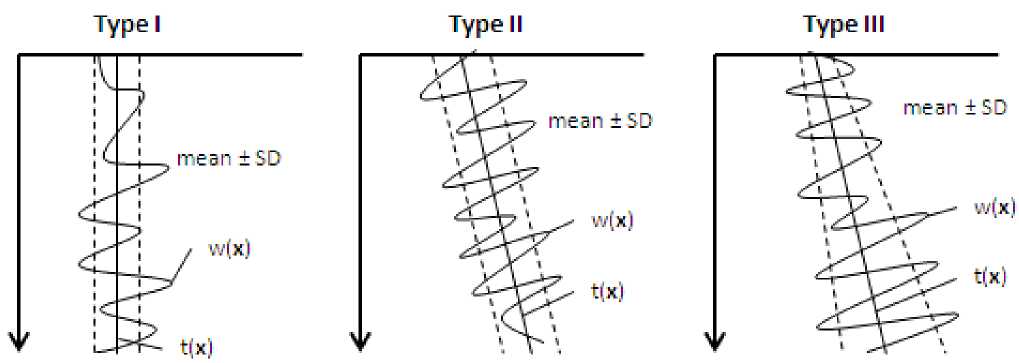

Figure 3: Different types of ground models

	Soil Property	Spatial Variability COV [%] COV_s	Measurment Error COV [%] COV_m	Transformation Error SD [°]	Total COV [%] COV_t
Cohesionless soil	φ'	$6-13$	13		$10.0-17.7$
	φ' (from q_c)	$20-60$	$5-15$	2.8	$2.6-7.9$
	γ'	10	$1-2$		$10.0-10.2$
	q_c	$20-60$	$5-15$		$20.6-61.8$
Cohesive soil	φ'	$5-14$	$18-26$		$18.7-29.5$
	φ' (from q_c)	$20-60$	$5-15$	2.8	$4.9-14.8$
	c'	$15-60$	30		$33.5-67.1$
	s_u	$20-40$	20		$28.3-44.7$
	γ'	10	$1-2$		$10.0-10.2$
	q_c	$20-60$	$5-15$		$20.6-61.8$

φ', effective friction angle; γ', effective unit weight; q_c, CPT tip resistance; c', cohesion; s_u, undrained shear strength

Table 1: Range of COV for common soil properties [4],[5],[6]

2.3.3 State of Work

Referring to Fig. 2 the first step has been completed. However, this step can also be updated during coming steps.

A realistic determination of the stochastic soil properties and their distributions is very important for performing reliability analyses, since these input properties reflect the quality of the final design. Fellin et Oberguggenberger (2003) [1] showed by simple modeled probabilistic analyses of slope stability that the factor of safety is sensitive to the assumed distribution type.

Phoon et Kulhawy (1999) [5], [6] summarized the range of spatial variability, measurement errors and transformation errors for some common soil properties by reviewing different literature. Nottrodt (1991) [4] summarized stochastic parameters of soil properties on the basis of several investigations too. By merging these results an approach to quantify the coefficient of variation (COV) for several sources of uncertainties is shown in Tab. 1.

It is important to mention that the COV of spatial variability COV_s is determined from detrended data sets according to Eq. (1). The total COV of spatial variability and measurement errors can be computed by Eq. (4). The total COV by implying transformation errors depends on the transformation codes which are listed in [6].

$$COV_t^{\,2} = COV_s^{\,2} + COV_m^{\,2} \tag{4}$$

The introduced COV in Tab. 1 should not be seen as fixed values. Rather they could be combined with in situ measurements values by applying “Bayesian Updating” technique [7]. Hence these values could be used as a-priori values.

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2.4 Foundation and Support Structure (WP 4)

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Institute of Structural Analysis
Rana Meyering, Martin Kohlmeier, Tanja Grießmann, Raimund Rolfes

Institute of Concrete Construction
Michael Hansen, Boso Schmidt

Work Package 4 (WP 4) deals with the design and optimization of support structures of Offshore Wind Turbines (OWTs) with respect to probabilistic methods. According to the relevant German guideline of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschiffahrt und Hydrographie – BSH) [1] support structures of Offshore Wind Turbines can be subdivided into different parts, as depicted in Figure 1. Investigations of WP 4 focus on the support structure consisting of substructure, tower and foundation.

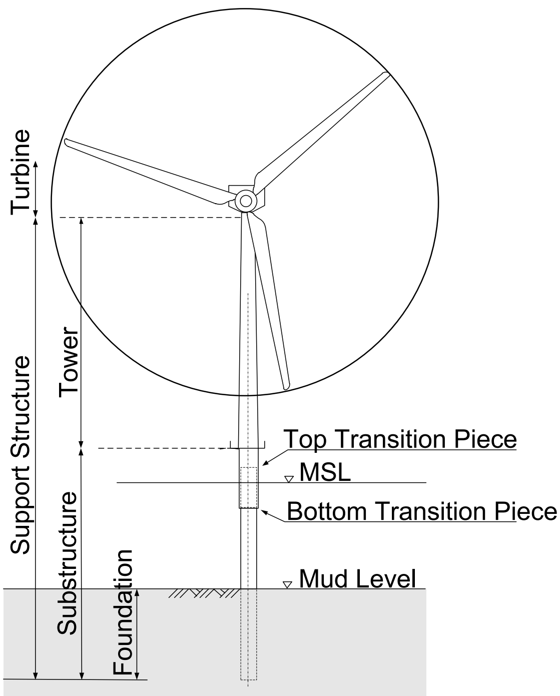

Figure 1: Offshore Wind Energy Converter

2.4.1 Motivation

Due to political aims and agreements to reduce the CO_2 emissions the renewable energies have been developed intensively in the last decade. Beside geothermal, photovoltaic and biomass wind energy has great potential to fulfill politically set aims. In the northern part of Europe offshore wind energy will be one of the leading renewable technologies due to limited onshore locations. The German government and surrounding countries plan to install numerous offshore wind farms in the North and Baltic Sea.

The design and construction of OWTs is regulated within different international and national standards. OWTs built in the German territorial exclusive economic zone have to be approved by the BSH [1]. This German design standard allows to use different technical codes for the design as e.g. regulations of the Germanischer Lloyd [2], the Det Norske Veritas [3], the American Petroleum Institute [4], the German guideline of the DIBt [5], and IEC 61400 [6]. Furthermore, national and European standards for the structural design are valid e.g. DIN 18800 [7], DIN 1055 [8], DIN 1045 [9], Eurocode 2 [10] and 3 [11]. Within these standards the design process for Offshore Wind Energy Converters is based on knowledge and standards from offshore constructions within the oil and gas industry. Moreover, the regulations were influenced by experience gained from constructing onshore wind turbines.

With regard to the named standards the assessment is based on the so-called semi-probabilistic safety concept. Hence, the design concept includes partial safety factors for loads and material strengths in different limit states. By comparing the load action or resulting stresses with the material strengths in combination with given safety factors the main task of the design is achieved. The partial safety factors ensure a certain safety distance between loading effect and resistance of the material by reducing the material strength and increasing the loading effect. Considering those effects, an adequate safety level can be assured.

Valid standards state deterministic values for the partial safety factors as well as for material parameters. With regard to realistic conditions material properties are afflicted with uncertainties and scatter. Usually the partial safety factors take into account for these scattering effects resulting from uncertainties of loading and material properties. Approved and recommended safety factors for offshore wind converters result from standardized factors for OWTs. These kind of offshore structures are characterized by a very low risk of human injury in case of failure compared to Onshore Wind Energy Converters, and to civil engineering structures in general. Identical safety factors have to be applied for onshore and offshore support structures for significantly different circumstances. Consequently, there is a need to investigate in the assessment of offshore structures regarding scattering of material and load conditions. In order to identify the real safety distance between resistance and loading effect for offshore support structures of wind converters calculations based on statistical distributions are to be conducted.

The reliability analysis will be carried out by using probabilistic methods as for example the First Order Reliability Method (FORM) or the Response Surface Method (RSM). The First or Second Order Reliability Methods only have nominal character and only can be used to compare the outcomes. Other reliability methods like the response surface method enable to get more information about the reliability of the system. As a result the most likely mode of failure and the failure probability of the structure can be identified. Determination of the probability failure affords to generate failure trees for variable support structures. In the end, gained knowledge and results may be introduced to assessment procedures of OWTs.

2.4.2 Approach

To estimate the failure probability of support structures of OWTs several steps need to be taken.

Figure 2 shows a process flow for the working intervals to reach the aim of the project a probabilistic analysis of the support structure of an OWT.

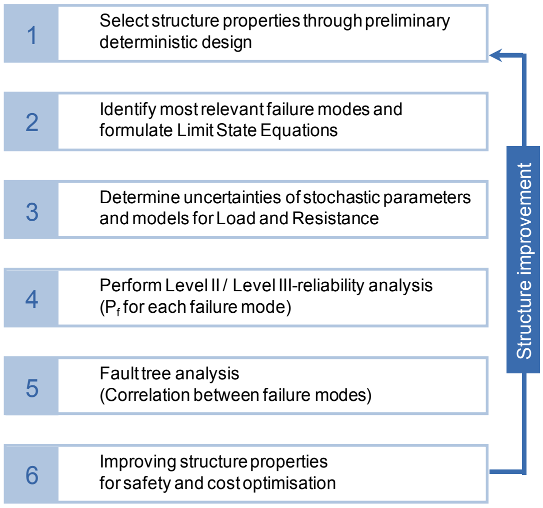

Figure 2: Process flow of WP4

Before probabilistic methods can be applied to the structure, its structural data have to be established in the first interval based on a deterministic design. Depending on environmental conditions as e.g. the water depth, there are varying possible types of support structures that can be built. With regard to varying complexity of support structures the first structure to be analyzed needs to be selected carefully. Beside structural details, load actions and material parameters are to be set. OWTs are mainly exposed to dynamical wind and wave loadings. Further effects result from environmental and operating loads. Beside the structural data the input parameters for load actions are to be known. Therefore, available measurement data will be interpreted to use for a probabilistic design.

Based on the deterministic design procedure the decisive failure modes are to be assessed for selected constructions. Examples of ultimate limit failure modes can be local or global buckling failure of the tower or fatigue failure of details in the substructure. By means of these failure modes the limit state function can be defined. The limit state function is one of the decisive parameters that influences probabilistic design.

In order to implement and carry out a probabilistic design within the next working step the statistical parameters for material properties and loading are to be identified. Compiled statistical parameters and constructional details need to reflect realistic assumptions. In order to assure correct input parameters for the probabilistic design, the chosen parameters will be adapted with industry representatives.

The probabilistic assessment is separated into different steps. With the aid of numerical models of the chosen support structure and the statistical input parameters, in a first step the number of parameters should be reduced by conducting a sensitivity analysis. For this working step the special software OptiSLang® [12] is used. This software is compatible with already established numerical program systems ANSYS® [13]. Reduction and identification of decisive parameters has to be done to achieve an adequate and acceptable calculation time. Subsequently a robustness analysis verifies the model. The last step within this procedure would be to conduct a reliability analysis and optimization of the model. Within the calculation procedure for every failure mode the failure probability P_f is going to be examined. By identifying the correlation between the failure modes, so called failure trees could be established. In the focus of working group 4 is the determination of failure probability for decisive failure modes for different support structure of offshore wind turbines. By using statistical parameters for resistance and loading effects including a probabilistic concept, the assessment procedure and design codes and even the construction might be optimized in the end.

2.4.3 State of Work

The project partners of WP 4 in cooperation with WP 3 and 5 agreed to analyze in a first step a monopile. A monopile is compared to other sub-structures relatively uncomplicated to model and calculate. Monopile foundations consist of a steel tube which is driven or drilled into the seabed. The connection between tower and drilled pile is realized by a transition piece, see Figure 1. The steel tube of the transition piece is slid over the driven pile. The annulus between the two steel tubes is filled with a high performance grout. Statistical parameters resulting from the grouting process under realistic offshore conditions and the grout material will be delivered from WP 5. In addition statistical parameters and distributions considering soil properties will be set in WP 3.

Subsequent to calculations and analysis of the monopile substructure different substructures may be optimized with probabilistic methods. Possible substructures are tripod, jacket, tripile, and gravity based substructures, Figure 3 and 4.

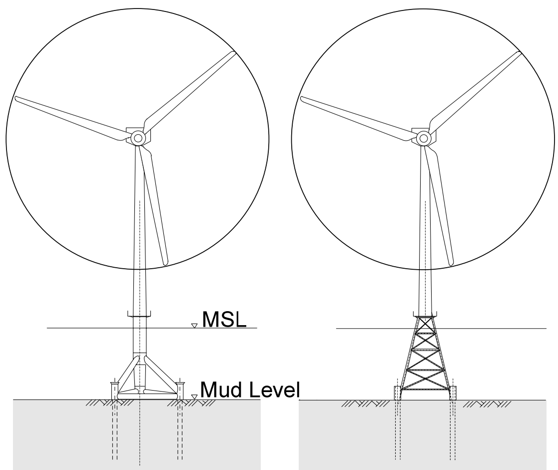

Figure 3: Tripod and jacket structure

Beside the predefinition of the support structure types, a probabilistic design of wind turbines requires definition of the input parameters. Therefore the uncertain parameters such as dimensional imperfections and material properties need to be set carefully within the stochastic modelling.

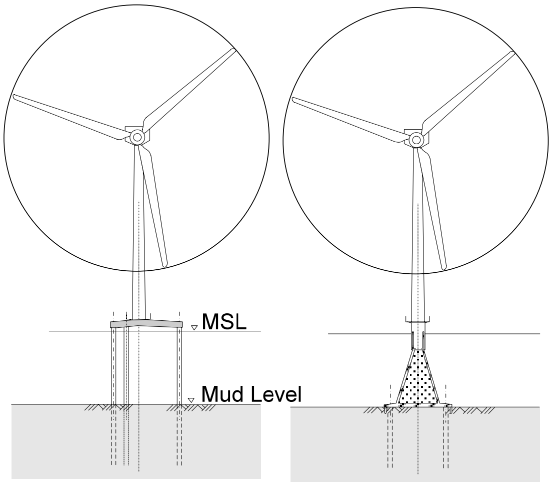

Figure 4: Tripile and gravity based structure

For the materials concrete and steel stochastic model parameters as standard deviation, type of distribution and coefficient of variance (COV) were compiled resulting from recommendations within approved literature.

Steel

Steel components within wind energy converter systems are primarily the tower and the tubes used for the transition piece and the drilled pile. Depending on the importance of structural member, type of load, and stress level, it can be differentiated between the three component categories secondary, primary, and special structural members. According to the GL standard [2] secondary structural members are components of marginal importance to the support structure as e.g. stairs and mountings for cables. Whereas, primary and special structural members are of significant importance to operational safety and overall integrity of the structure. Special components are exposed to extraordinary conditions such as stress concentrations or multi-axial stresses due to the geometrical shape.

Beside the component definitions the steel strength can be separated into normal steel strength with yield stress up to 285 N/mm², higher strength steel with yield strength over 285 N/mm² up to 380 N/mm², and high strength steels with a yield strength over 380 N/mm². Due to fatigue resistance the yield strength should not exceed 355 N/mm². For further information on appropriate steel materials concerning structural components reference is made to [2]. The type of distribution for yield strength and Young`s modulus of steel is lognormal as recently published literature states [14]. The mean value depends on the chosen steel strength.

Concrete

The statistical evaluation of the characteristic values of concrete strength is not new. However, in cause of more high-grade materials and manufacturing methods today's results can be different from the previous knowledge. The statistical spread of the concrete compressive strength was detected in [15] with an almost constant middle standard deviation of about 5.0 N/mm^2 which is approximately independent of the middle compressive strength. A distinction is carried out for different concrete strength classes in consideration of different production types. Thus, in [16] [17] there are given different statistic parameters for concrete elements out of job-mixed concrete at the building site, concrete from precast concrete factories or precast concrete units.

Also the distribution which is used in probabilistic analyses has to be predefined. In literature for a parent population of concrete compressive cube strength the gaussian distribution is indicated as the best description of measurements. This distribution has to be converted into a lognormal distribution to avoid senseless negative strength values.Due to an unreasonably high mathematical effort it is not practicable to use other statistical distributions even if they may match better existing measurements.

Loading

Equal to statistical values considering resistance, statistical values for loading effects were ascertained. In order to perform realistic reliability-based calculations wind and wave data from the measuring platform FINO1 were evaluated. FINO1 is a research platform in the North Sea which records measurement data from wave height, wave direction and wind velocities at different heights. Since 2003 data is registered in a great database, cf. Chapter 1.

Evaluated wind data is jointly agreed between different WP. The wave data will be addressed by WP2.

Theoretical Knowledge and Software

The project partners intensified the subject of probabilistic methods. A workshop with the topic “Risk analysis and Management” as well as the course for the software OptiSLang [12] was visited to deepen the understanding of probabilistic methods and software.

With the learned applications of the software OptiSlang the use of the software was intensified. Relatively simple models were implemented in the finite element program ANSYS. An interface allows to couple ANSYS and OptiSLang [12]. The modelled structure can be included in the software OptiSLang [12].

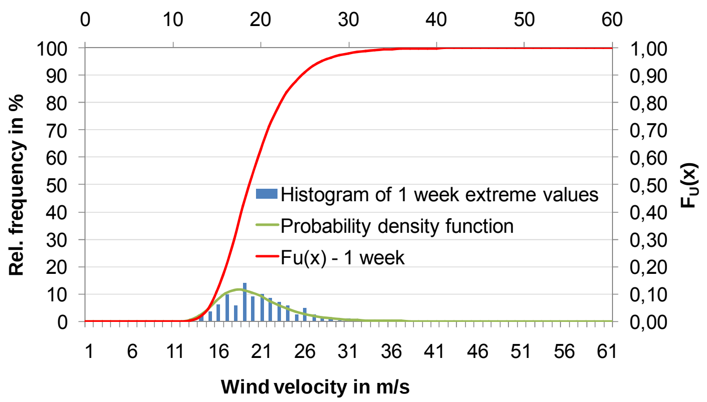

Figure 5: Histogram, distribution function Fu(x) (Gumbel) and probability density function (Gumbel) of one week extreme values for the wind velocity in 100 m above sea level

The available wind data considering mean values of 10-min intervals within the period 2004/01/01– 2010/02/01 were determined. In a first analysis the Gumbel function was chosen to depict the wind velocity distribution. For this, mean values and standard deviation were identified in different heights up to 100 m above sea level, Figure 5. As expected the increase of characteristic wind speeds with increasing height can be observed. The wind speed profile depending on height shall be determined next.

Thus the sensitivity analysis and the optimization of the modeled structure could be accomplished.

The sensitivity analysis gives the opportunity to reduce the statistical parameter set, Figure 6. With the optimization methods as e.g. the Adaptive Response Surface Method (ARSM) a best design can be determined. Further stochastic analyses give the reliability of the structure.

By starting to analyze simple models the calculation methods can be tested and effective methods might be exposed.

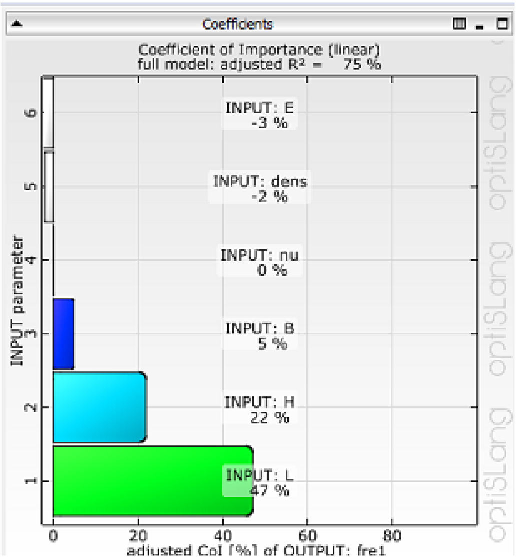

Figure 6: Most important design parameters acc. to sensitivity analysis

2.4.4 Summary and Outlook

The aim of work package 4 (WP 4) is to optimize the support structure of an OWT using probabilistic methods.

Therefore, stochastic model parameters for the materials concrete and steel were compiled, also wind and wave data from the measuring platform FINO1 were evaluated. The selected parameters will be adjusted in the context of a Workshop with industry representatives.

Furthermore, the software OptiSLang [12] will be used to obtain a reliability analysis of the support structure of an OWT. Therefore, simple models with the software ANSYS and OptiSlang were implemented to get more knowledge about probabilistic calculation methods.

Upcoming work will be to organize a Workshop with industry partners, enhance the complexity of the models and test the software and options of calculation. The first support structure under research will be the monopile followed by the jacket structure.

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2.5 In-Situ Assembly (WP 5)

Institute of Building Materials Science
Ludger Lohaus, Michael Werner

2.5.1 Motivation

Support structures and turbines of offshore wind turbines (OWTs) are segmental prefabricated onshore what offers the possibility to monitor the production and ensure the quality. Contrary to this, the foundation and the connection elements between the support structure and the foundation are manufactured offshore. Frequently a so-called grouted-joint is used. The gap between the pile and the sleeve is filled with a high performance mortar called “grout”. These grouted joint connections are used in almost all kinds of offshore structures.

The main problem during the installation process is the application of the grout under offshore conditions. Due to the inaccessibility of the application site, it is difficult to establish an effective quality control and quality management system what induces a high safety factor in the design of the grouted joint connection.

2.5.2 Approach

In this work package “supporting structure production in situ”, the risk factors of the grouted joints during the application process will be evaluated taking the material behavior of the grout into account. Furthermore, concepts used for monitoring and minimization of defects in the execution will also be considered.

2.5.3 State of Work

A literature study showed that there is nearly no usable literature and information available containing work experience from the construction process of OWTs.

This applies especially to the construction of the grouted joint. The executing companies offer only some basic information considering the construction process as well as some basic material properties.

Information about work experience is available to a minor degree from the oil-industry. However, it must be taken into account that the grout connections are mainly used under the water level. Contrary to oil rigs the location of the grouted joints depends on the kind of the substructure. Grouted joints in the alternating water level are mostly used for monopile-constructions. For tripod and jacket constructions the connection is generally under the sea level. Tripile-constructions use connections to the foundation-piles above the see level.

Different to oil rigs where mostly normal strength grouts are used in batteries of pile-sleeve connections are OWTs. Here, basically single connections with high and ultra-high strength grouts are used.

Furthermore the load behavior is not comparable to the behavior of oil rigs because of the filigree structure and additional dynamic loads caused by the turbine.

The grouted joint is one of most important part for the stability of the OWT and is heavily prone to failures because of the application process offshore [1]. The study showed that this fact is only taken into minor account in established standards due to the complex offshore execution process of the OWTs.

Table 1 shows a selection of focused areas related to grouted joints in different established standards. These areas are material properties, quality control and, application process as well as geometrical properties.

This small selection of areas shows how complex the application process is and which complications can occur. To evaluate the influences of possible difficulties a fault tree analysis is currently carried out.

Therefore the different kind of supporting structures had to be divided into major groups considering the different variants of grouted joints. The place of the connection

Table 1: Selected requirements for grouted joints of established standards.

Standards/requirement **material properties/ compressive strength**	**Health Safety Execution [6]**	**GL Wind [5]**	**API-Rules [2]**	**Det Norsk Veritas [3][4]**
laboratory testing with in situ conditions			X	X
in situ testing	X		X	X
in situ sampling	X		X	
composition of the mixture	X			X
water-cement ratio	X			
consistency		X		
values for temperature		X		X
application process/quality control:				
cleaning of the steel surfaces				X
complete filled connection				
quality control with tools	X	X	X	X
quality control by documentation		X		X
control of the annulus seal				X
continues filling			X	X
spare parts for the components		X		X
geometrical properties:				X

is of great importance regarding the application system and the mixture of the grout.

Figure 1 shows some criteria which have to be taken into account to develop an application process, the material properties and the quality control. The knowledge which kind of supporting structure is used is not enough. Additional essential information are the geometry of the connection, if sheer keys are present and if a fiber content in the grout is reasonable.

The evaluation of risk factors basically depends on the application methods and the used mixtures and materials.

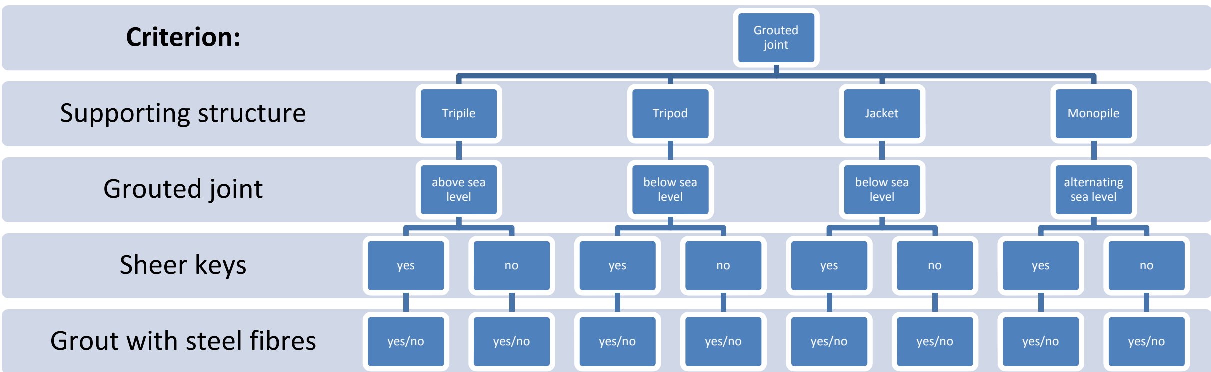

Figure 1: Criteria for the application process and the grout given by the construction design.

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2.6 Monitoring of Mechanical Components (WP 6)

IMKT (Institute for Machine Elements, Engineering Design and Tribology)
Gerhard Poll, Sebastian Otto

In addition to the determination of safety elements for the civil engineering, safety- and reliability assessments of the mechanical and electronical components of the offshore wind turbines (OWT) will be considered.
The aim of work package 6 is the development and optimization of monitoring systems and diagnosis systems for bearings and screw connections. These systems should be applicable to OWT.

2.6.1 Motivation

The mechanical power train of wind energy systems is subjected to various non stationary loads and speeds due to quickly changing operating conditions. These include sudden short time events like short circuits on the electric end and wind gusts on the rotor end. It is important to correctly be able to predict the effects of such events on the reliability and service life of mechanical components such as gears and bearings in order to avoid costly premature damage.
According to statistical analysis made by the German Wind Energy Institute (DEWI), different components of the wind turbine are causing different costs of maintenance. Figure 1 shows the statistical costs of maintenance of onshore wind turbines during an operation period of 20 years.

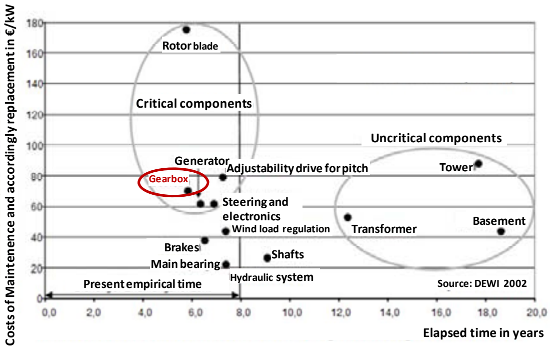

Figure 1: Costs of maintenance on wind turbines [1]

This figure clarifies that rotor blades, generator, adjustability drive for pitch, steering, electronics and the gearbox of a wind turbine are critical components for maintenance and replacement during early years of operation. All these critical components belong to the power train. The gearbox is a very important part of the power train, because it positioned between rotor blades and generator. It changes low speed and high torque of the rotor blades to high speed and low torque for the generator. Figures 2 and 3 are showing configuration of a typical power train and its components in a wind turbine.

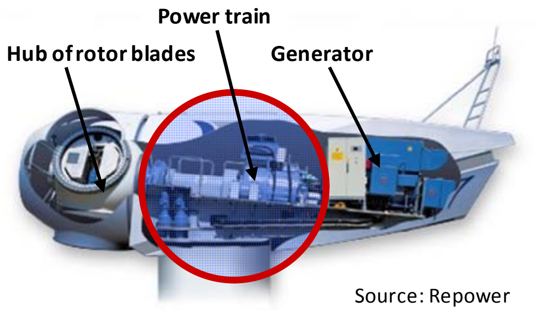

Figure 2: Configuration of a wind turbine [2]

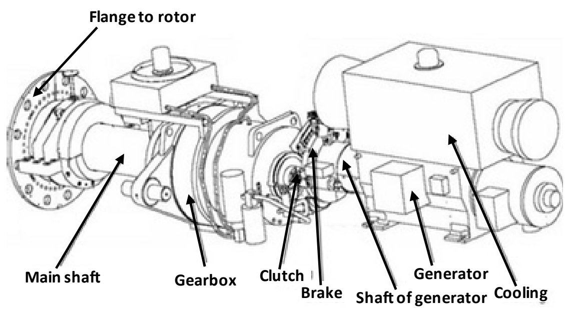

Figure 3: Power train of a wind turbine [1]

On the one hand according to the characteristic of wind the gearbox is loaded by changing speed and changing forces, on the other hand also the characteristic of the generator influences the loads of all components of the gearbox. A typical gearbox is designed with a ratio of transmission about 0.01. The gearbox consists of different sized gear wheels (including a planetary transmission), shafts and large size bearings. During the last years there have been some early failures on bearings mounted in the gearbox. Maintenance and accordingly changing of damaged bearings of the gearbox means high effort and costs especially for OWT.

The reliability of many mechanical components of wind turbines and possibly of OWT can be increased by control monitoring. This facilitates a better prediction of damages to bearings or gear wheels. In Addition to existing monitoring systems the aim of this project is the development and optimization of further suitable monitoring tools for early detection of damages. These tools should monitor damages to slow-rotating large size bearings and detect the preload of screw connections by integrated sensors.

If it is possible to measure the preload of important screw connections it might also be possible to measure forces that load bearings mounted in the gearbox.

2.6.2 Approach

For monitoring of damages on dynamic slow-rotating large size bearings existing diagnosis systems have to be developed further. For testing large size bearings with dynamic speed and dynamic load a large size bearing test rig is at IMKT's disposal. This test rig is depicted in the following figure.

Figure 4: Large size bearing test rig at Institute for Machine Elements, Engineering Design and Tribology of Leibniz University Hannover

It is intended for experimental investigations with large size bearings under various conditions, especially those that may cause unexpected bearing damages or failures in practical applications. The test rig accommodates one test bearing (red color in fig. 4). This bearing can operate with different speeds, radial and axial forces as well as tilting moments and misalignments, both static and dynamic. The following picture shows an overall view of the test rig.

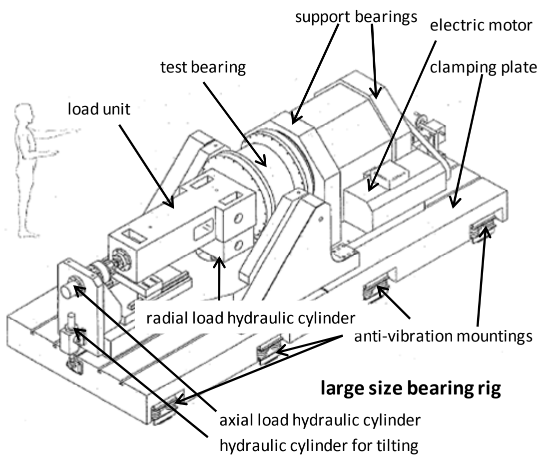

Figure 5: Components of large size bearing test rig

Fatigue life with different loads and speeds of small bearings can be tested at several small test rigs at IMKT. For the analysis of fatigue life the Weibull calculation method in combination with the maximum likelihood method is used.

Preload of screw connections

The preload of screw connections can be monitored by special grommets or pressure blocks with integrated thin film sensors. The Fraunhofer Institute IST from Braunschweig has developed a system of grommets with special thin film piezoresistive sensors that are able to measure forces pushing the grommet (see F_V at figure 6).

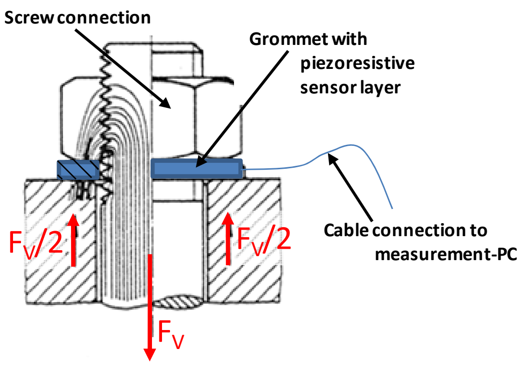

Figure 6: Screw connection with piezoresistive sensor [on the basis of 3]

The piezoresistive system consists of three thin film layers that are put on a substrate. Figure 7 shows the schematic configuration of these layers.

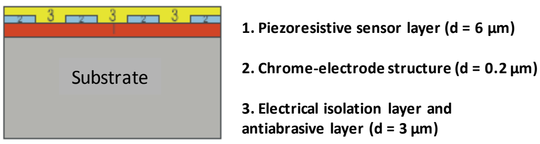

Figure 7: Schematic configuration of sensor layers [on the basis of 4]

First, the piezoresistive sensor layer is put on the substrate. The second layer is a structured chrome electrode. These two layers are covered by an electrical isolation layer and an antiabrasive layer. It is possible to apply this system to different geometrical forms and dimensions.

For using the sensor it has to be cabled and calibrated to a measurement-PC. In future it might be possible to use RFID-chips for a wireless connection.

As a result of the cable connection it is important to use a special counter profile disc with suited cavities (see figure 8).

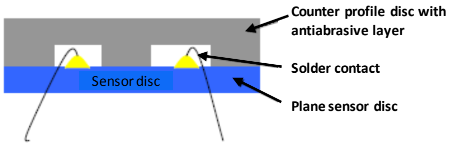

Figure 8: Schematic graph of installation condition [on the basis of 4]

In this way the preload F_V of the connection can be controlled easier during mounting. As a consequence of settling progresses and dynamic external forces the actual preload can vary.

During the operation of mechanical components the forces of the screw connections can be recorded and the preloads of the mechanical components can be detected by using this new system of sensor grommets. This makes it possible to monitor the necessary preload of screws permanently.

The aim of the project is to test and adjust the measuring method for use on OWT. Bearing test rigs are presenting a suitable possibility for purposive testing of this method under defined conditions. The testing and adjusting of this system to bearing test rigs will be done in two main steps:

1. Adjusting and testing the system in a load unit with springs mounted in a test rig for small cylinder roller bearings (d_{shaft} = 30 mm). This allows using the system under defined constant load. In this way it is possible to evaluate long time behavior and temperature influence on the measurement.

2. Adjusting and testing the system on selected screws of the large size bearing test rig (d_{shaft} = 260 mm). The test rig enables testing under constant or dynamic conditions with higher forces.

Step 1:

Figure 9 depicts the test head of IMKT's four cylinder roller bearing test rig. This test head is characterized by a constant load that is discharged radial into four equal test bearings with rotating inner ring. The constant force is applied by a prestressed spring unit. It is possible to put a piezoresistive load sensor into the power train to measure and control the real forces during running the test bearings with constant radial forces.

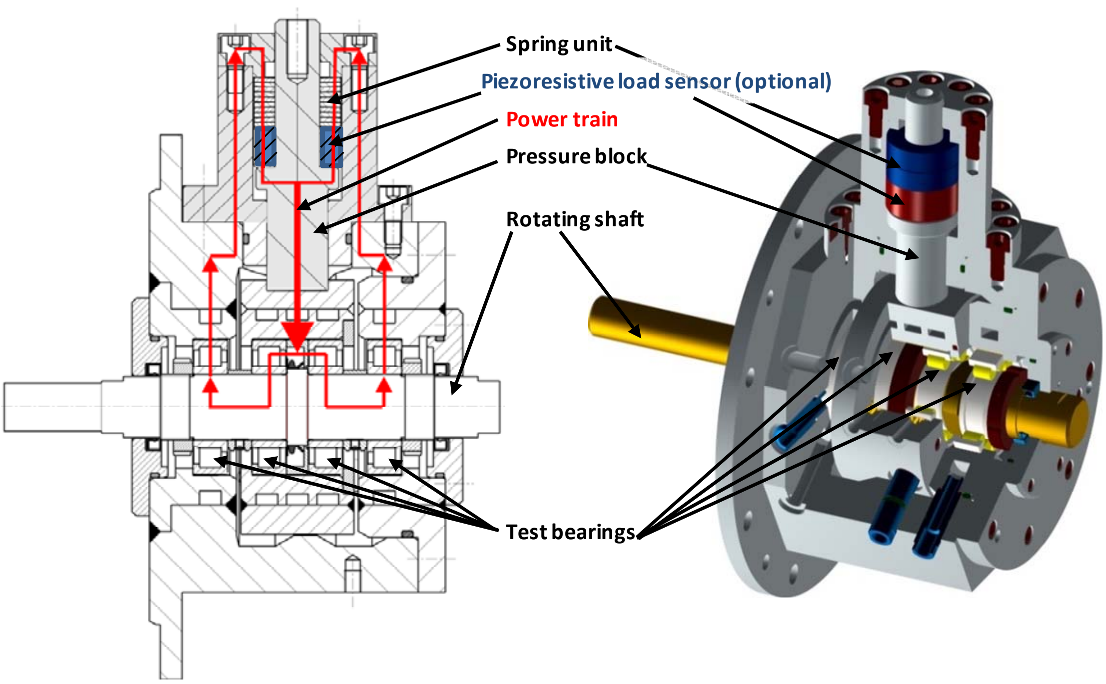

Figure 9: Test head of four cylinder roller bearing test rig (d_{shaft} = 30 mm).

A special tool allows calibrating the spring unit and the piezoresistive load sensor by using a hydraulic press and a reference load cell. The load of the prestressed spring unit can be varied by changing the number of springs and by using pressure rings with different heights. The following figure shows this tool.

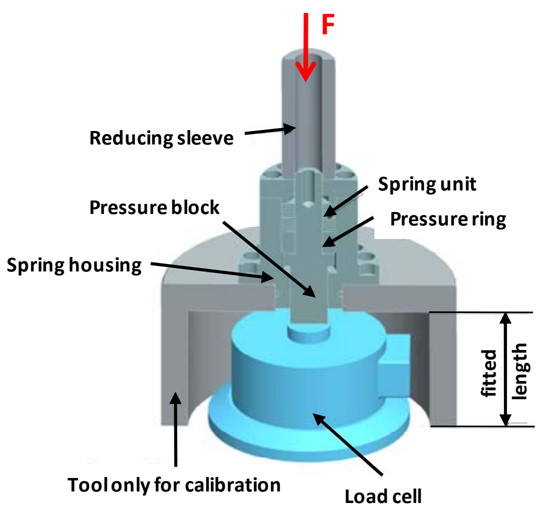

Figure 10: Tool for calibration of springs and load sensor [5]

Instead of the shown pressure ring it is also possible to put in the piezoresistive load sensor.

Step 2:

The large size bearing test rig allows testing bearings that are normally mounted in gearboxes of wind turbines. It is possible to test these bearings under defined conditions. After having tested the piezoresistive load sensor system in a test rig for small bearings under constant conditions this system should be adjusted to conditions in the large size bearing test rig. The idea is to measure forces of chosen screw connections under defined dynamic conditions. By having notice of the forces of these screws it might be possible to calculate the real forces applied to the test bearing. The test rig allows testing interference between forces of screw connections and forces applied to test bearing. Figure 11 shows an example of a screw connection on a bearing seat of a large size bearing at the test rig.

Figure 11: Screw connection on bearing seat at large size bearing test rig

If this method works it might also be possible to measure and record forces on bearings mounted in gearboxes of OWT. If these bearings are damaged early it is possible to evaluate interference between forces given to the bearing and fatigue life. On the one hand this is very important according to the dynamic characteristic of the wind with low wind speeds and possible overloads and on the other hand according to the influence of the generator.

Condition monitoring system

The fatigue life of rolling element bearings depending on the load history, which even includes singular events, is actually being studied at IMKT both experimentally and theoretically. This allows for more precise life prediction in the field. High shock loads and skidding between rollers and raceways, both circumferentially and axially are to be taken into account. The existing standardized life prediction methods are not sufficiently validated under such conditions and appear to be unable to explain a number of failures observed in practice. To complement the experimental and theoretical investigations, additional studies are planned to measure the operational conditions of bearings in the real application.

Condition monitoring plays a vital role in all the experimental work. Methods are being developed to detect failures reliably in a very early state. These will later on be applicable for the supervision of wind power plants in regular service.

Existing condition monitoring systems still have problems with early detection of beginning roller bearing damages of bearings mounted in gearboxes. This is basically caused by insufficient provision for dynamic speeds of wind turbines. The following figure shows a typical damage at the outer ring raceway of a cylinder roller bearing.

Figure 12: Pitting at outer ring of cylinder roller bearing

Present systems are successfully used for stations with constant speeds. High

dynamic variability of speed demands special tools of evaluation and an exact consideration of the geometry of the gearbox. It is a challenge to adapt a condition monitoring system to slow rotating large size bearings. [6]
In figure 13 the mounted and adjusted condition monitoring system at the four bearing test rig is shown. This system uses a FFT in combination with an envelope curve analysis for detection of roller bearing damages.

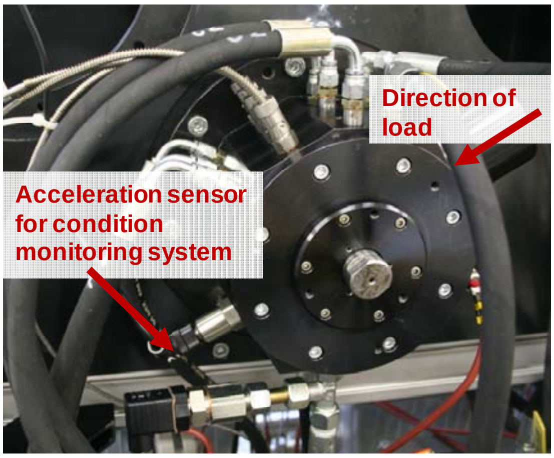

Figure 13: Condition monitoring system at IMKT's four bearing test rig

New methods like this system could realize great improvement according to a condition monitoring for bearings with varying speed.

2.6.3 State of Work

Preload of screw connections

The described system for measuring the preload of a prestressed spring unit in the four bearing test rig is just being manufactured. Next steps will be mounting, calibration and testing of this system under constant and defined conditions.

Condition monitoring system

The described system has been developed and adjusted at the four bearing test rig, too. This system enables to detect damages at roller bearings or roller bearing elements early, precise and with varying speed. It is also possible to locate the position of damage. A next important step will be the installation, adjustment and testing (under defined conditions) of this system at the large size bearing test rig.

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2.7 Diagnostic Systems for Electronic Systems (WP 7)

Institute of Drive Systems and Power Electronics
Meike Wehner

2.7.1 Motivation

Faults and defects in electrical machines, such as winding faults, short circuit faults, break of squirrel cages or rotor imbalances, result in characteristical changes of the electromagnetic air gap field, whose dependency on position and time was investigated in previous works at IAL-AS.

Using sensors such as exploring coils, the local dependence acts as a filter supporting the detection of a fault or defect with high distance between the signal in normal and fault mode as well as the type of fault by signal frequency.

In theory, the sensor signals are assumed to be zero in faultless wind turbines. In industrial applications, the signal fluctuation as well as the reachable ratio of the signal at fault beginning and the value of faultless generators has to be evaluated. Otherwise, the influence of the generator type and the power electronic components concerning reliability has to be researched.

Their influence of the generator type (doubly fed induction generator, electrical or permanent magnet synchronous generator) as well as the influence of power electronic components concerning reliability of failure diagnosis has to be examined, too.

For this reason two diagnostic systems will be dimensioned and realized in prototypes. Finally, the measuring data are evaluated, and based in this, appropriate design criteria are elaborated for this kind of diagnostic systems.

2.7.1 Approach

For the application in wind energy plants, two generator types are in common use. Besides doubly-fed induction machines, permanent magnet synchronous machines have been used more and more during the last years. In a first step, a search coil system for 4-phase doubly-fed induction machines with a power of $\mathrm{P} = 900\,\mathrm{kW}$ shall be dimensioned. The resulting air-gap field and the induced voltages are analyzed based on rotating field theory by using the institute-specific program ALFRED.

Table 1: Generator data

Generator type	Doubly fed induction machine
Electric Power	$P = 900\ kW$
Number of pol pairs	$2p = 4$
Number of stator slots	$N_1 = 72$

2.7.2 State of Work

Dimensioning of a Search Coil System

In optimally dimensioned search coil systems, no voltage should be induced during normal operation, and in fault mode, the measuring voltage should increase with the disturbance value. In addition, a clear identification of the fault type should be possible. In general, measuring signals are the more significant, the more disturbances are previously eliminated by a measuring sensor. For this reason, the arrangement of the search coils is of great importance.

In [1,2,3], comprehensive investigations have been made concerning the appropriate arrangement of search coils in an air gap. The width of the search coils as well as their location along the circumference of the machine give information about all important characteristics of the air-gap field: size, spatial distribution (number of pole pairs), frequency and type of field (alternating field, circulating field or elliptic rotating field) [3].

Fault detection via search coil systems is made by using reference fields, whose

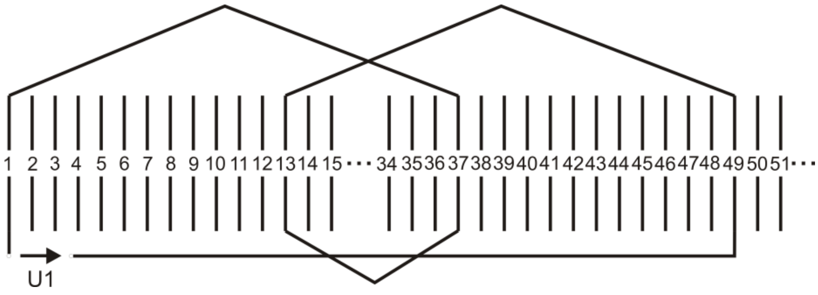

Figure 1: Position of Search Coils

number of pole pairs, it is useful to dimension the search coil system for a preferably low-pole field. As described in [1], fields of static and dynamic eccentricities only produce components with amplitudes of the number of pole pairs $\nu = p \pm 1$. For this reason, the reference number of pole pairs ν_R

$$\nu_R = p + 1 \quad \vee \quad \nu_R = p - 1 \quad (1)$$

should be selected. The number of turns of the search coil system increases proportionally to the reference number of pole pairs. For a minimum number of turns in the search coil system, the reference number of pole pairs of $\nu_R = 1$ is selected for the case ($p = 2$) described here.

According to [3], practical variants for search coil systems are designed with two- to four-slot windings, whereby the number of turns increases with the number of slots per pole and per phase. Variants with two-slot windings are recommended as a good compromise between the number of conductors and the selectivity. According to

$$z_W = 2 \cdot \nu_R \quad (2)$$

the two-slot winding selected here consists of $z_W = 2$ windings. The width of search coils are $W_M = 36$ slots with

$$W_M = \frac{\pi}{\nu_R} \quad (3)$$

By shifting two adjacent conductors τ, one of the symmetrical components can be suppressed, in order to increase the selectivity of the search coil. In order to suppress all fields of the number of pole pairs $\nu = g \cdot \nu_U$, the shift must be

$$\tau = g \frac{N_1}{2\nu_U} \quad (1).$$

To be able to place the search coil in the slot wedges of the stator slots, the distances between the measuring conductors must always be a multiple of a stator slot pitch. The number of the equally spaced slots of a search coil is defined as $\widetilde{N}_1$ and depends on the field component to be suppressed

$$\tilde{N}_1 = 2 \cdot \nu_U \quad (5)$$

For a complete suppression of all multiples of $\nu_U = 3\,\nu_R$, the following is valid: $\widetilde{N_1} = 6, \tau = 12$ slots. Figure 1 shows the winding distribution in stator slots. In this case, a suppression of the multiples of $\nu = 5\,\nu_R$ $\nu = 5\,\nu_R$ is not possible with a two-slot winding, since $\tau = 7{,}2$. In [3], the possibility to evenly suppress $\nu = 3\,\nu_R$ and $\nu = 5\,\nu_R$ with $\nu_U = 4\,\nu_R$ is described.

Via Fourier analysis, the relevant field components are filtered from the resulting induced voltage. Different faults, however, lead to identical induction frequencies. Winding faults as well as static eccentricities induce for example fault fields with line frequency. In addition, the induced voltage depends on its arbitrary location between fault location and coil system. In order to avoid this local dependence, the voltage components are separated from each other by using multi-.

Table 2: Fault Indicator [2]

	Measured variable		
Fault type	f	$U_1;\ U_2$	$U_m; U_g$
Winding fault	$f = f_1$	$U_1 \neq 0;\ U_2 \neq U_1 \neq 0$	$U_m \neq 0; U_g \neq 0$
Static eccentricity	$f = f_1$	$U_1 \neq 0;\ U_2 = U_1$	$U_m \neq 0; U_g = 0$
Dynamic eccentricity	$f = f_1\left\{1 \pm \left(\frac{1}{p}\right)(1-s)\right\}$	$U_1 \neq 0;\ U_2 = U_1$	
Rotor unbalances	$f = f_1\left\{\left(\frac{\nu}{p}\right)(1-s) \pm s\right\}$	$U_1 \neq 0;\ U_2 = U_1$	

phase search coil systems, segregating the symmetrical components with respect to their location. For this purpose, m_M identical search coils are equally arranged and shifted towards each other along the circumference. Just search coil systems with $m_M = 2$ or $m_M = 3$ phases are of practical use here, since the total number of turns is the m_M - fold number of turns of a phase.
Here, a two-phase search coil system is used. The two phases have to be shifted towards each other by half a pole pitch:

$$\varphi_M = \frac{\pi}{2\nu_R} = \frac{\pi}{2} \quad (6)$$

The line-frequency negative-sequence component of the measuring voltage indicates a winding fault, since the positive-sequence component can also be caused by static eccentricity.
Table 2 contains all important characteristics necessary for the diagnosis of the voltage induced in the two coil systems. One voltage component characterizes the eccentricity. In case of two components, as well as indicate a winding fault [4].

Simulation

The diagnosis is carried out for a three-phase motor with $2p = 4$ poles and $N_1 = 72$ stator slots. The dimensioning of the search coil system described in the previous section is indicated in Table 3. Analysis is done by using an institute-specific calculation program, which in accordance with the mathematical derivations [3] and based on the rotating field theory determines the resulting air-gap field as well as the voltages induced in the search coil system.
Figure 2 shows the voltages induced in the search coil described for static eccentricities of 10% to 20% of the air-gap width. The amplitude of the voltage increases proportionally to the eccentricity and is thus a measure for the amount of eccentricity.

Table 3: Dimensioning of search coil

Reference number of pole pairs	$\nu_R = 1$
Spatial harmonic to be suppressed	$\nu_U = 3\,\nu_R$
Winding factor of search coil system	$\xi_M = 0{,}8660$
Coil pitch of search coil system	$W_M = 36$
Shift of two equal conductors	$\tau = 12$
Number of turns of search coil system	$w_M = 4$

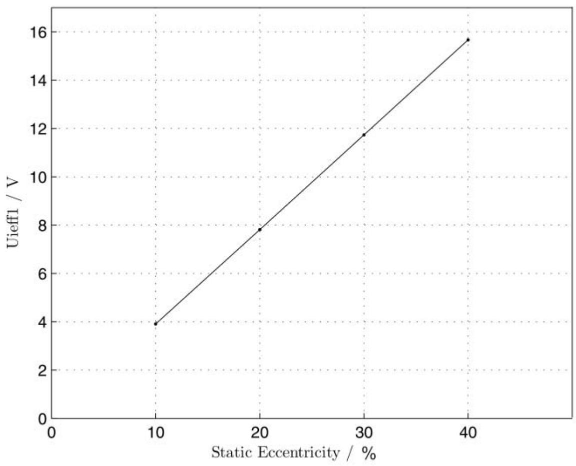

Figure 2: Induced Voltages for different eccentricities

The frequency analysis of the voltage induced for a static eccentricity of 30% of the air-gap width leads to frequency components with uneven multiples of line frequency, the amplitude being largest at line frequency. For the measuring-relevant line frequency, the separation of the induced voltage in its symmetrical components shows a pure positive-sequence component.

The detection of interturn failures and inter-phase short circuits is of great importance, since they can possibly provoke large stator currents. As a consequence, the winding and the complete active part of the machine may thermally be affected [3].

An interturn failure was simulated with a fault current of $I_{fe} = 1000\ A$. Only significant voltages with line frequency are induced. As described in Table [2], the negative-sequence component of the measuring voltage serves as indicator of a winding fault, because the positive-sequence component can also be caused by static eccentricity.

Conclusion

The results show that winding faults and eccentricities lead to significant changes of the air-gap field, the analysis of which thus being an appropriate means to detect them.

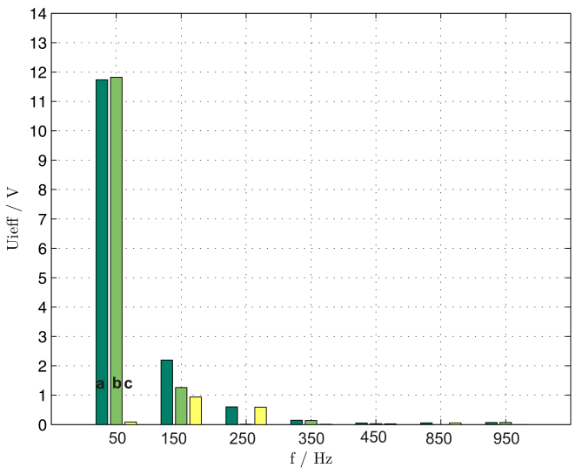

Figure 3: Frequency analysis of the voltage induced for a static eccentricity of 30%; a: induced resulting voltage b: positive sequence component, c: negative sequence component

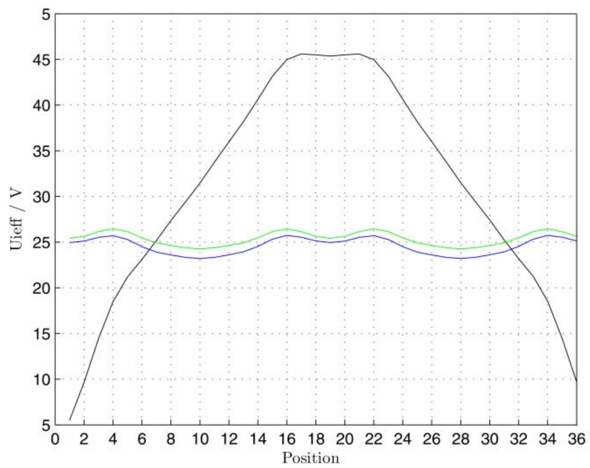

Figure 4: Induced Voltage for an interturn failure

Fault detection can be done by using adequately dimensioned search coils, so that only harmonic fields are induced which are theoretically not induced during normal mode. Nevertheless, it must be considered, that even during normal mode unavoidable residual eccentricities may induce a level of disturbance in the search coils of existing machines.

The most important reason for voltage distortions are unavoidable inaccuracies during the manufacturing process. So even small deviations when displacing the search coils will lead to a winding factor unequal zero for the main magnetizing field of the machine during normal mode and provoke an induced voltage of large amplitude.

In this respect, further research work has to investigate to which extent inaccuracies during the manufacturing process affect the level of disturbance.

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2.8 Reliability of the Grid Connection (WP 8)

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Felix Fuchs

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Regarding the probabilistic safety of offshore wind turbines, the electrical system and the grid connection cannot be neglected. Together with work package 6 and 7, mechanical and electrical examination is covered.
The work package 8 is a collaboration between the Institute for Drive Systems and Power Electronics and the Institute of Electric Power Systems. The overall aim is to evaluate different grid connection topologies from the probabilistic point of view concerning the reliability. The two mentioned institutes are on the one hand specialized in the generator and its frequency converter and on the other hand in the grid connection itself.
The probabilistic reliability model of the whole electrical system will be implemented by the Power System side-while the Institute for Drive Systems and Power Electronics delivers reliability models for power electronics and filter elements within the grid connection.

2.8.1 Motivation

In the field of electrical power supply the reliability of the system plays an important role. For the investor the breakdown of a wind turbine always means losses by reason of costs of repair and loss of (financial) compensation for electricity fed into the grid. Especially in the field of offshore wind parks a breakdown leads inevitably to longer breakdown times, because repairing takes longer due to hindered availability. In Fig. 1 it can be seen, that the higher the power of the wind turbines becomes, the more often the electrical part of the system fails. It is thus most important to investigate the reliability of the electrical system of large (offshore) wind turbines and their grid connection. The wind as a stochastic factor is an important input factor that determines load cycles and stress of the wind turbine. This gives also a motivation to examine the system from a probabilistic point of view.

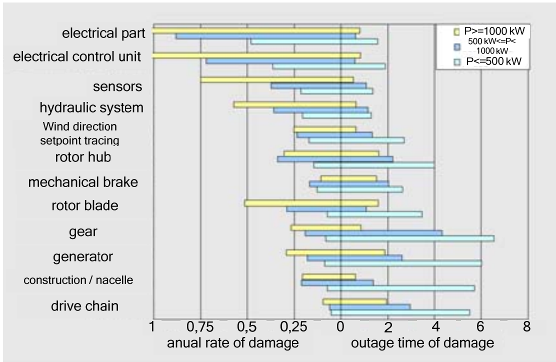

Figure 1: frequency of damage and corresponding outage time of wind power plants sorted by components for different output power (from [1])

2.8.2 Approach

In Fig. 2, the topology of an offshore wind park ,its internal interconnection and its connection to onshore can be seen.

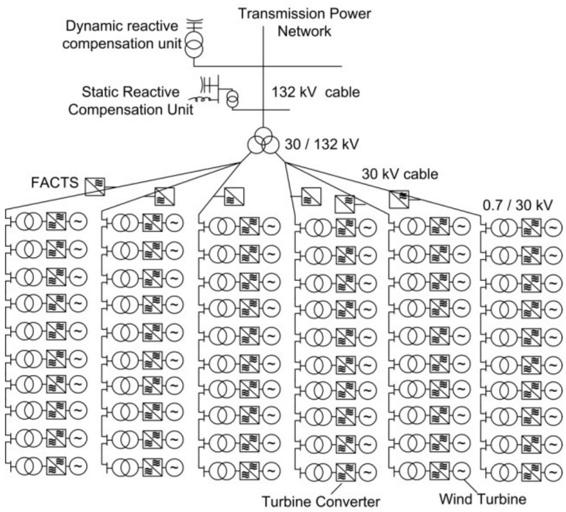

Figure 2: Example of the grid connection of an offshore wind park (in part from [2]).

Each wind turbine has a frequency converter, some filters and a step up transformer. Other frequency converters control the power flow within the offshore

grid (FACTS). Another step up transformer (30 kV /132 kV) gives the high voltage for transmitting the power through a sea cable to an onshore grid connection point. Compensation units (reactive compensation) help controlling the power flow. An alternative way to transmit the power onshore is a high voltage DC (HVDC) connection.
This overall system is in the focus of work package 8. All parts of the offshore grid concerning power electronics (frequency converters) and filters (capacitors, chokes) are covered by the Institute for Drive Systems and Power Electronics. Models giving information about their failure performance will be built. It is the aim to get a probabilistic model for the whole grid connection for computing the reliability. This will be done by the Institute of Electric Power Systems.

2.8.3 State of Work

From the side of the Institute for Drive Systems and Power Electronics, at first, the focus of the project lies on the frequency converter of an offshore wind turbine. In further steps, other frequency converters and filter elements will be considered. The weak elements of the chain in a wind turbine are the power semiconductor modules of the frequency converter [4]. So, the first aim is to get a probabilistic reliability model for the failure of the power semiconductors of the turbine converter. In offshore wind turbines, two topologies of generator-converter systems exist: The so-called doubly-fed induction generator (DFIG) and the permanent magnet synchronous generator (PMSG). Both will be analysed in this project. The influence of operation statistics on the lifetime of power semiconductor modules in DFIG was investigated first. The most important factor influencing their lifetime is the varying junction temperature [4]. The junction temperature is dependent on the power flowing through the converter. With the software Matlab/Simulink/PLECS, it is possible to simulate the junction temperature variation of the semiconductors.
A general sketch of the utilized procedure is shown in Fig. 3.

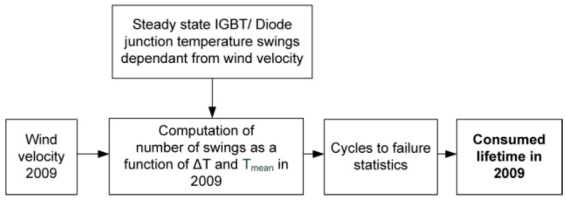

Figure 3: Procedure for lifetime estimation of module.

First, the junction temperature swings of the module (power semiconductors) over the wind velocity are computed in steady state operation. In the next step, the wind velocity data for 2009 (from the FINO station [3]) is taken. From this data, the operating time in 2009 for each wind velocity is calculated. The number of cycles with different temperature swing frequency and mean temperature is calculated. This is fed into a “cycles to failure statistic” for the power semiconductor modules (in a first step taken from the LESIT project [9]). For every wind velocity (discretized by 0,1m/s) the consumed percentual lifetime is computed. This is summed up linearly to a consumed lifetime in 2009.
The simulation model [6] is extended with the thermal equivalent circuit of a standard low voltage module taken from its data sheet. A standard cooling system with the ambient temperature set to 70 degree is chosen. The equivalent thermal circuit of an IGBT (Insulate Gate Bipolar Transistor) module can be seen in Fig. 4.

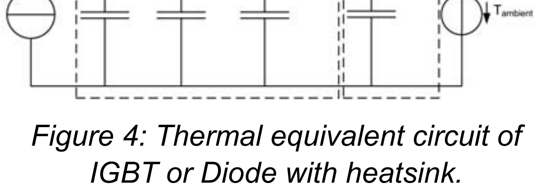

Figure 4: Thermal equivalent circuit of IGBT or Diode with heatsink.

As input of this circuit, the dissipation power P_v of the semiconductors must be computed. It is composed of temperature dependent turn off, turn on and conducting losses specified by the data sheet.

For first results, a simulation model of a 1.5 MW DFIG is taken (for system parameters see Tab. 1). The control system always tracks the maximum of the c_p-characteristic of the wind turbine assumed (fixed pitch angle [1]). The final analysis will be extended to a 5 MW DFIG system. Until here, relatively high switching frequencies are assumed, which will be adjusted, too.

Table 1: System Data.

Symbol	Quantity	Value
P	Rated Power	1,5 MW
P_{conv}	Rated Power of Converter	~0,5MW
U_L	Line voltage (phase-to-phase, rms)	400 V
ω	Grid frequency	2π50Hz
p	Pole Pairs	2
C_{DC}	DC link capacitance	38 *m*F
$f_{S,grid}$	Switching frequency grid side converter	5 kHz
$f_{S,machine}$	Switching frequency machine side converter	10 kHz
J	Inertia	5 kg m²
n	Gearbox ratio	1:75,71
R	Turbine radius	35 m
v_{rated}	Rated wind speed	12 m/s

An example junction temperature swing of the machine side converter is shown in Fig. 5 for a wind velocity vwind=10,5 m/s.

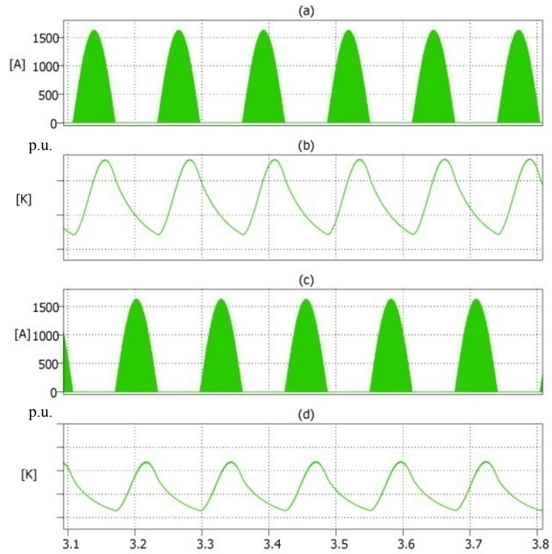

Figure 5: Steady state at vwind=10,5m/s (a) Current through IGBT of machine side converter, (b) Junction temperature of IGBT, (c) Current through antiparallel diode, (d) Junction temperature of diode

It can be seen that in steady state the temperature oscillates with the frequency of the rotor current. The following results will verify this observation.

The junction temperature of the IGBT and diode of one phase leg is taken and mean, minimum and maximum values are extracted. The preliminary results are shown in Fig. 6. In the first row, mean value, temperature swing and period of the temperature swing of the grid side converter plotted over the wind velocity is shown. The second row shows the same values for the machine side converter. The upper curve is always assigned to the examined IGBT, the lower one is that of the diode of the chosen phase leg. It can be seen that the period of the temperature swing corresponds to the frequency of the output current in both converters. For the grid side the grid frequency (50 Hz) can be seen, for the machine side, it differs with changing slip (and the corresponding rotor frequency) of the machine. It can be seen, that the mean temperature of the semiconductors of the grid side converter does not change significantly. Also the temperature swing in (b) is not critical, which is seen when calculating lifetime consumption. Considering the machine side converter, the temperature swings are much higher. It can be seen that at a wind velocity of 9.1 m/s the mean temperature, the temperature swing and the temperature frequency have a maximum. This is caused by the synchronous operating point of the DFIG. In this point currents with very low frequency are injected into the rotor. One IGBT is holding the whole current. The temperature swing becomes intolerable for the semiconductors. This operating point is critical for the machine side converter.

A preliminary lifetime assessment is done by taking a “cycles to failure statistic” from the LESIT project [6]. It is in the focus to examine several cycles to failure relationships ([7]). The relationship between cycles to fail and the mean junction temperature and ΔT from [6] is:

$$N_f(x) = 640 \Delta T_j^{-5} \quad e^{\frac{Q}{R \cdot T_m}} \qquad (1)$$

with $Q = 7{,}8 \cdot 10^4 \ \mathrm{Jmol^{-1}}$ and $R = 8{,}314 \ \mathrm{J/mol \cdot K}$. The consumed lifetime over the wind speed of the machine side converter as preliminary result can be seen in Fig. 7 (the grid side converter is not critical). It can be seen that most of the lifetime is consumed around a wind speed of v_{wind} = 9m/s

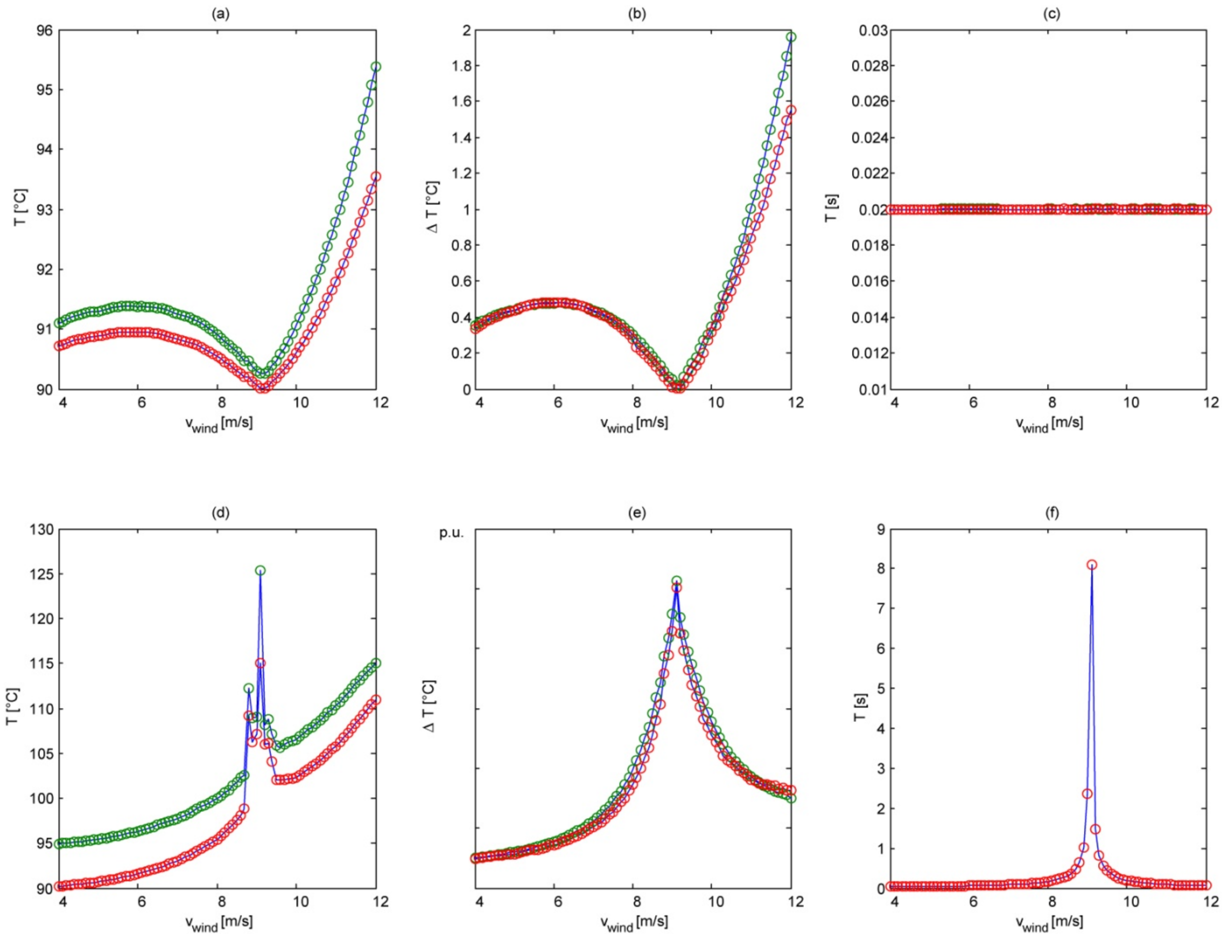

Figure 6: Preliminary Results (red: diode, green: IGBT): (a) mean junction temperature of grid side converter over wind velocity (b) junction temperature swing of grid side converter over wind velocity (c) period of temperature swing of grid side converter (d) mean junction temperature of machine side converter over wind velocity (e) junction temperature swing of machine side converter over wind velocity (f) period of temperature swing of machine side converter over wind velocity

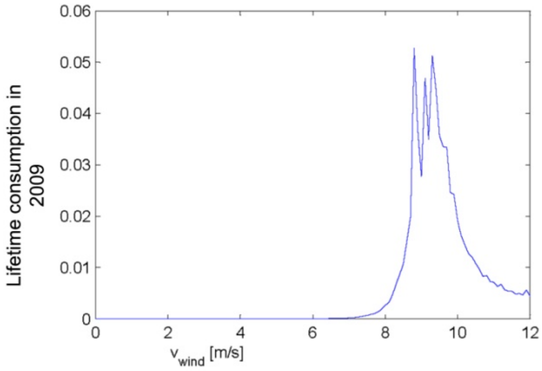

Figure 7: Lifetime consumption over wind velocity

(synchronous operating point). This underlines the need of a control strategy that avoids driving the turbine in synchronous operating point.
The further steps of the project will be:

- As already mentioned above, the synchronous operating point is avoided while driving a DFIG wind turbine. This will be considered when estimating the lifetime of the DFIG.
- The consideration will be extended to full load operating area.
- In extension, a 5 MW DFIG system will be examined.

In a next step, it is focused to consider the dynamic operation of DFIG. Here, rain flow counting algorithms will be utilized to extract temperature swings caused by wind fluctuation [7]. Finally, a reliability model for the converter of the DFIG system will be built.
Further the converter of the PMSG will be analyzed. The results will integrated in the reliability model for the whole grid connection

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3 Summary

Institute of Concrete Construction
Michael Hansen, Boso Schmidt

The objective targets of this project are to obtain adjusted environmental actions on Offshore Wind Turbines and to determine the safety elements for the design with respect to a harmonized safety level.

Performing networked investigations, the project partners get parameters for the intended probabilistic approximations. The numerical calculations have to account for the whole load-bearing structure of Offshore Wind Turbines (OWT). The probabilistic analyses have to be developed and implemented on a representative design of typically used OWT foundations.

The research platforms in the sea offers to analyze the statistical parameters of wind and waves.

Another part is to optimize monitoring systems and diagnostic systems for bearings and screw connections by means of experimental investigations.

Different diagnostic systems for the power electronic components as well as different grid connection topologies will be evaluated, too.

Probabilistic methods shall be used because conventional deterministic design methods recognize uncertainty implicitly and unequally. Up to now this is addressed by conservative safety factors to calculate worst predictable scenarios.

Finally, probabilistic analysis will be used to check failure modes, the overall vulnerability and weakness of the structure in a transparent way.

4 Literature

4.1 Publication List

4.1.1 Reviewed Articles

Schmidt, B.; Hansen, M.; Rolfes, R.; Schaumann, P.:
Energiegewinnung auf hoher See – Sicherheit und Zuverlässigkeit von Offshore-Windenergieanlagen.
AlumniCampus Ausgabe 5 2010, Hannover, 2010.

Schmidt, B.; Hansen, M.; Rolfes, R.; Schaumann, P.:
Energiegewinnung auf hoher See – Sicherheit und Zuverlässigkeit von Offshore-Windenergieanlagen.
Unimagazin 03/04 2010, Hannover, 2010.

4.1.2 Reviewed Conference Contributions

Grünberg, J.; Hansen, M.:
Design Approach for Offshore Wind Turbines.
Joint IABSE-fib Conference on: Codes in Structural Engineering. Developments and Needs for International Practice. Cavtat, Dubrovnic-Neretva County, Croatia, 3-5 May 2010.

Schmidt, B.:
Probabilistische Sicherheitsbewertung von Offshore-Windenergieanlagen.
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4.2 Diploma, Master and Bachelor Theses

Ghassen, C.:
Modellierung und Modalanalyse einer Offshore- Windenergieanlage vom Typ REpower
Master Thesis
ISD Mai 2010

Knöfel, S.:
Strukturdynamische Analyse einer Jacket-Tragstruktur mittels Finite-Elemente- und Mehrkörpersimulation zur Verifikation eines Gesamtsimulationspakets für Offshore-Windenergieanlagen
Master Thesis
ISD Dezember 2010

Spieker, H.:
Semi-analytische, probabilistische Analyse der Beullast dünnwandiger Faserverbund-zylinder
Project Thesis
ISD März 2009