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Structural reliability aspects in design of wind turbines

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ABSTRACT: Reliability assessment, optimal design and optimal operation and maintenance of wind turbines are an area of significant interest for the fast growing wind turbine industry for sustainable production of energy. Offshore wind turbines in wind farms give special problems due to wake effects inside the farm. Reliability analysis and optimization of wind turbines require that the special conditions for wind turbine operation are taken into account. Control of the blades implies load reductions for large wind speeds and parking for high wind speeds. In this paper basic structural failure modes for wind turbines are described. Further, aspects are presented related to reliability-based optimization of wind turbines, assessment of optimal reliability level and operation and maintenance.

1 INTRODUCTION

The number and size of wind turbines are increasing fast these years. New typical wind turbines are 3-5 MW turbines with hub height 80-110 m and rotor diameter 100-150m. Offshore wind turbines are placed in wind farms with 50-100 wind turbines and loadings due to both wind, wave, current and ice besides harsh environmental attack implying corrosion etc. Onshore wind turbines are more and more placed in complex terrain with good wind conditions for energy production. Reliability analysis and optimization of wind turbines require that the special conditions for wind turbine operation are taken into account. Control of the blades implies load reductions for large wind speeds and parking for high wind speeds.

Optimal design of wind turbines should be obtained using a life-cycle approach where all relevant benefits and costs are included. Formulation of the associated general reliability-based optimization problem with a maximum acceptable probability of failure constraint is considered in this paper. Offshore wind turbines are characterized by a low risk of human injury in case of failure when compared to onshore wind turbines, and to civil engineering structures in general. It is then relevant to assess the minimum reliability level for the structural design on the basis of reliability-based cost optimization considering the whole life-cycle of the turbines without a reliability constraint. Especially for offshore wind turbines costs related to operation and maintenance can be significant and have to be included. One reason is that maintenance can only be performed under certain weather conditions.

Behind a wind turbine a wake is formed where the mean wind speed decreases and the turbulence intensity increases, (Frandsen 2005). The distance between the turbines is among other things dependent on the recovery of wind energy behind the neighboring turbines and the increased wind load. This paper describes the basic relationships of mean wind speed and turbulence intensity in wind turbine parks with emphasis on modeling the wind load. For offshore wind turbines also environmental loads from waves, ice and current can be significant.

The basic structural failure modes for wind turbines are fatigue failure in the tower – typically in welded steel connections; in the blades made of glass fiber and/or composites; and in the nacelle made of cast steel. Ultimate failure due to extreme load has to be considered in the tower, the blades, the nacelle and the foundation. The wind load effects depend highly on the chosen type of control (stall or pitch) in the operational mode, i.e. for mean wind speeds at hub height below 25 m/s. Also non-structural failure modes such as failure of electrical components and machine components e.g. gear boxes have to be considered because they influence the load on other structural components.

This paper describe some aspects for reliability analysis by structural reliability methods, see e.g. (Rackwitz 2002a) and optimization of wind turbines, including wind loads in wind farms, ultimate and fatigue failure modes, optimal reliability level and operation and maintenance.

2 WIND LOAD

For wind turbines in a wind farm the turbulence is increased significantly behind other wind turbines, and the wind velocity is decreased slightly. Figure 1 shows a typical layout of a small wind farm. In figure 2 from (Frandsen, 2005) data are shown obtained from this wind farm. It is seen that the wind load effect (flapwise blade bending moment) proportional to the standard deviation of the turbulence increase significantly behind other wind turbines.

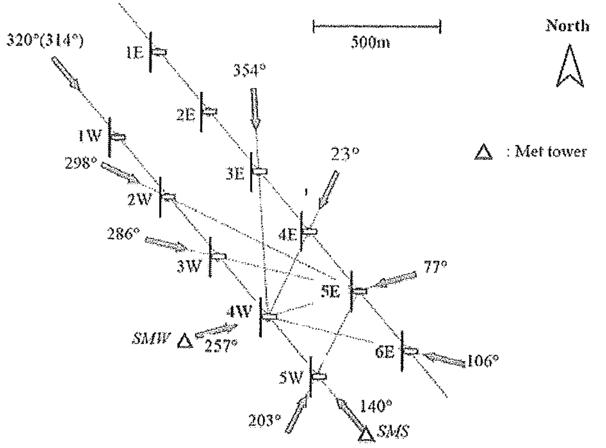

Figure 1. Layout of the Vindeby offshore wind farm - from (Frandsen, 2005).

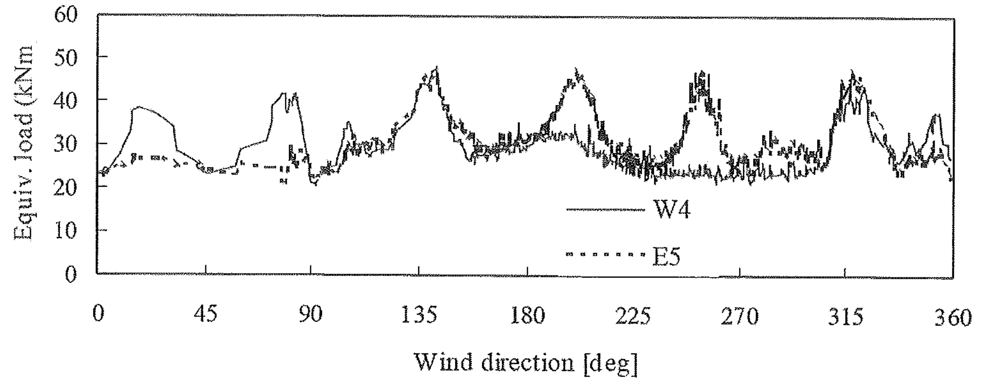

Figure 2. Equivalent load effect (flap-wise bending) for two wind turbines, 4W and 5E in figure 4, as function of wind direction, in the Vindeby wind farm, $8 < U < 9$ m/s - from (Frandsen, 2005).

As mentioned in the introduction, the operational mode of a wind turbine is important when modeling the wind load. The wind turbine is in *standstill* mode if the 10-minutes mean wind speed at hub height exceeds 25 m/s, and the wind load corresponds to the annual extreme wind load. At lower wind speeds the wind turbine is in the *operational*_mode and produces electricity. The wind velocity is at maximum 25 m/s. The maximum wind load is dependent on the control system (stall or pitch) of the wind turbine and the maximum turbulence intensity. Since the number of 10-minutes periods with wind velocity at the critical velocity smaller than or equal to the 25 m/s is in general large, the maximum wind load during operation is obtained from simulations of the wind velocity field in front of the wind turbine and the actual control system of the wind turbine. A distribution function is determined for the maximum wind load over the expected number of 10-minutes periods with wind velocity from approximately 10 m/s to 25 m/s.

3 LIMIT STATE EQUATIONS FOR STRUCTURAL RELIABILITY ASSESSMENT

3.1 *Probabilistic model for ULS failure*

For the typical structural failure mode 'bending failure of the tower' the limit state equation for a single wind turbine in *standstill mode* can be written, see (Tarp-Johansen et al. 2003) and (Sørensen and Tarp-Johansen 2005):

$$g_S(z_S, \mathbf{X}) = R(z_S) - Qh \qquad (1)$$

where h is the hub height and the bending moment resistance is $R = z_S X_R F_y$. z_S is the design variable in standstill mode (e.g. section modulus), F_y is the yield strength and X_R is the model uncertainty. The load effect is

$$Q = P\, C_T A\left(1 + 2k_p I c_{amp} X_{dyn}\right) X_{aero} X_{\exp} X_{st} X_{str} X_{sim} \qquad (2)$$

where $P = 0.5\rho V^2$ is the extreme mean wind pressure , U is the extreme annual mean wind velocity at hub height, $I = \sigma_u / V$ is the turbulence intensity at hub height, σ_u is the standard deviation of turbulence at hub height with standard deviation $\sigma[\sigma_u] = 2I_{15}$ and expected value $E[\sigma_u] = \hat{\sigma} - \sigma[\sigma_u]$, (Tarp-Johansen et al. 2003). I_{15} is the turbulence intensity corresponding to a mean wind speed equal to 15 m/s. The characteristic value $\hat{\sigma} = I_{15}(15 + aV)/(1 + a)$ is assumed to be a 90% quantile. All parameters are described in table 1.

In *operational mode*, the wind turbine is operating at a wind velocity which is maximum equal to 25 m/s. The limit state equation is written:

$$g_O(z_O, \mathbf{X}) = R(z_O) - Qh \qquad (3)$$

where the bending moment resistance is $R = z_O X_R F_y$ and the load effect is

$$Q = P\, C_T A\left(\eta + (1-\eta) T \frac{\sigma_u}{E[\sigma_u]} X_{dyn} X_{St} X_{ext} X_{sim}\right) X_{aero} X_{\exp} X_{str} \qquad (4)$$

z_O is the design variable in operation mode, η is a parameter modeling the mean response relative to the expected extreme response, $P = 0.5\rho V^2$ is the mean wind pressure at maximum operational wind velocity V = 25 m/s, T is the normalized annual extreme load during operation, which is assumed to be Gumbel distributed, see (Tarp-Johansen et al. 2002) and (Tarp-Johansen et al. 2003). All parameters are described in table 1.

Table 1. Example stochastic variables for local buckling failure mode. Variables denoted X model model-uncertainty. N: Normal, LN: Lognormal, G: Gumbel.

Variable		Distribution type	Mean value	COV	Characteristic value
h	Rotor height		70 m		
P	Annual maximum mean wind pressure - Standstill	G	538 kPa	0.23	98%
P	Operation mean wind pressure - Operation		$0.5\rho(25\text{m/s})^2$		
T	Annual maximum normalized operational wind load – Operation	G	$E[T]$	$COV[T]$	98%
σ_u	Standard deviation of turbulence - Standstill	LN			90%
σ_u	Standard deviation of turbulence - Operation	LN			90%
X_{wake}	Model uncertainty	LN	1	0.15	1
$C_T A$	Thrust coefficient × rotor disk area				
c_{amp}	Factor		1.35		
k_p	Peak factor		3.3		
$X_{\exp}$	Exposure (terrain)	LN	1	0.10	
X_{st}	Climate statistics	LN	1	0.05	1
X_{dyn}	Structural dynamics	LN	1	0.05	1
X_{aero}	Shape factor / model scale	G	1	0.10	1
X_{sim}	Simulation statistics – Standstill	N	1	0.05	1
X_{sim}	Simulation statistics - Operation	N	1	0.05	1
X_{ext}	Extrapolation – Operation	LN	1	0.05	1
X_{str}	Stress evaluation	LN	1	0.03	1
F_y	Yield stress	LN	240 MPa	0.05	5%
X_M	Resistance – model uncertainty	LN	1	0.03	1

In a *wind farm* the limit state equation for a wind turbine in *standstill* is the same as for a single wind turbine. In *operational mode* wakes behind wind turbines change the wind flow, see above. In the following it is assumed conservatively that the mean wind velocity is unchanged, and that the standard deviation of the turbulence is increased basically following the models recommended in (IEC 61400 2005). The limit state equation is written:

$$g_O(z_O, \mathbf{X}) = R(z_O) - Qh \qquad (5)$$

where the resistance is $R = z_O X_R F_y$ and the load effect is

$$Q = P\,C_T A(\eta + (1-\eta)TX_{dyn}X_{St}X_{ext}X_{sim}\sigma_u / E[\sigma_u])X_{aero}X_{\exp}X_{str} \qquad (6)$$

with $\hat{\sigma}_P^2 = \hat{\sigma}^2 + X_{wake} 0.9V^2 / \left(1.5 + 0.3d\sqrt{V/c}\right)^2$ as the characteristic value of σ_u equal to the 90% quantile and $c = 1$ m/s. $V\left[\sigma_{u,P}\right] = V\left[\sigma_u\right]$ is the coefficient of variation of standard deviation of turbulence, assumed to be the same as for one wind turbine in operation, X_W is a model uncertainty related to turbulence model in park conditions, modeled as a stochastic variable. The other parameters are described in table 1, based on (Tarp-Johansen et al. 2003) and (Sørensen and Tarp-Johansen 2005).

3.2 *Probabilistic models for fatigue failure*

Design and analysis for fatigue of especially welded steel details are assumed to be performed using linear and bilinear SN-curves, eventually with lower cut-off limit as e.g. used in (Eurocode 3, 2003). It is further assumed that Miner's rule with linear damage accumulation can be used. This could be considered acceptable for welded details, but for cast steel and glass fiber this assumption is questionable although it is used in practice. Fatigue contributions from events as start and stop of the wind turbine are not included in the following models.

A bilinear SN-curve is considered with slope change at $N_D = 5 \cdot 10^6$:

$$N = K_1 S^{-m_1} \text{ for } S \geq \Delta\sigma_D \tag{7}$$

$$N = K_2 S^{-m_2} \text{ for } S < \Delta\sigma_D \tag{8}$$

where N is the number of cycles to failure with constant stress range S, K_1, m_1 are material parameters for stress ranges $S \geq \Delta\sigma_D = \left(K_1 / 5 \cdot 10^6\right)^{1/m_1}$ and K_2, m_2 are material parameters for $S < \Delta\sigma_D$. For a wind turbine in free wind flow the limit state equation is written, see also (Sørensen et al. 2007):

$$g(t) = \Delta - \int_{U_{in}}^{U_{out}} \nu \cdot t \cdot D\left(m_1, m_2, \Delta\sigma_D; \sigma_{\Delta\sigma}, U\right) f_U(U) dU \tag{9}$$

where Δ is a stochastic variable modeling the model uncertainty related to Miner's rule, t is time in years and ν is the total number of fatigue load cycles per year (determined by e.g. Rainflow counting). U_{in} is the cut-in wind speed (typically 5 m/s) and U_{out} is the cut-out wind speed (typically 25 m/s). The expected damage rate given standard deviation of stress ranges, $\sigma_{\Delta\sigma}$ and mean wind speed U is

$$\begin{aligned} & D\left(m_1, m_2, \Delta\sigma_D; \sigma_{\Delta\sigma}, U\right) = \\ & \int_0^{\Delta\sigma_D} \frac{\left(X_W X_{SCF} s\right)^{m_2}}{K_2} f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right) ds + \int_{\Delta\sigma_D}^{\infty} \frac{\left(X_W X_{SCF} s\right)^{m_1}}{K_1} f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right) ds \end{aligned} \tag{10}$$

X_W is the model uncertainty related to wind load effects (exposure, assessment of lift and drag coefficients, dynamic response calculations) and X_{SCF} is the model uncertainty related to local stress analysis.

$f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right)$ is the density function for stress ranges given standard deviation, $\sigma_{\Delta\sigma}(U)$ at mean wind speed U. This distribution function can be obtained by e.g. Rainflow counting of response, and can e.g. be assumed to be Weibull distributed. Further, it is assumed that:

$$\sigma_{\Delta\sigma}(U) = \alpha_{\Delta\sigma}(U) \bar{\sigma}_u(U) / z \tag{11}$$

where $\alpha_{\Delta\sigma}(U)$ is an influence coefficient for stress ranges given mean wind speed U, $\bar{\sigma}_u(U)$ is the mean value of the standard deviation of the turbulence and z is a design parameter (e.g. proportional to cross sectional area) obtained from a design equation. A typical example of $\alpha_{\Delta\sigma}(U)$ is shown in figure 3, see also (Sørensen et al. 2007). The ratio is seen to be highly non-linear – due to the control system. An example of the number of load cycles in a 10 minutes period given mean wind speed is shown in figure 4 and indicates that $f_{\Delta\sigma}(s|\sigma_{\Delta\sigma}(U))$ can be approximated by a Weibull or Exponential distribution.

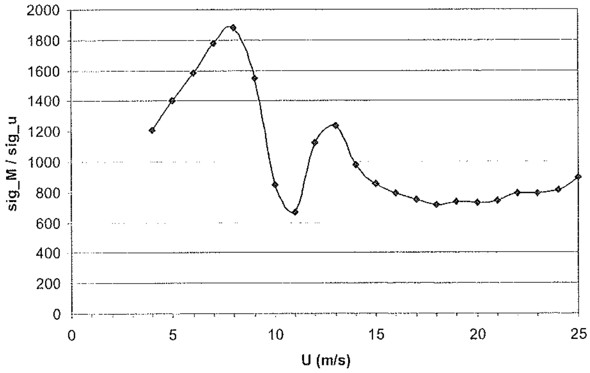

Figure 3. $\alpha_{\Delta\sigma}(U) = \sigma_{\Delta\sigma}(U)/\sigma_u(U)$ for mudline bending moment – pitch controlled wind turbine.

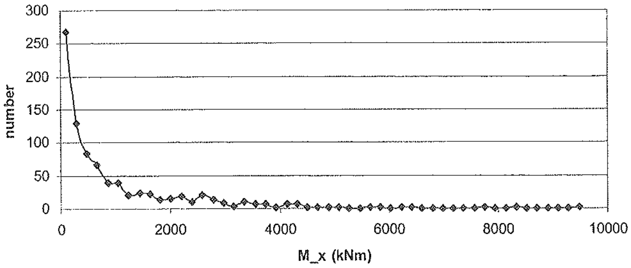

Figure 4. Number of load cycles in 10 minutes period for flap moment and mudline bending moment. Mean wind speed equal to 14 m/s.

For a wind turbine in a wind farm a limit state equation based on (IEC 61400-1 2005) can be written:

$$g(t) = \Delta - \int_{U_{in}}^{U_{out}} \nu \cdot t \cdot \left\{ \begin{matrix} (1 - N_W \cdot p_W) D(m_1, m_2, \Delta\sigma_D; \alpha_{\Delta\sigma}(U)\bar{\sigma}_u(U)/z, U) \\ + p_W \sum_{j=1}^{N_W} D(m_1, m_2, \Delta\sigma_D; \alpha_{\Delta\sigma}(U)\bar{\sigma}_{u,j}(U)/z, U) \end{matrix} \right\} f_U(U) dU \tag{12}$$

where N_W is the number of neighboring wind turbines and p_W is the probability of wake from a neighboring wind turbine (equal to 0.06). $\bar{\sigma}_{u,j}$ is the mean standard deviation of turbulence from neighboring wind turbine no j obtained from

$$\bar{\sigma}_{u,j}(U)^2 = \bar{\sigma}_u^2 + X_{wake} 0.9 \cdot U^2 / \left(1.5 + 0.3 d_j \sqrt{U/c}\right)^2 \tag{13}$$

d_j is the distance normalized by rotor diameter to neighboring wind turbine no j and c a constant equal to 1 m/s. An illustrative stochastic modeling is shown in Table 2.

Table 2. Stochastic model for fatigue failure mode.

Variable	Distribution	Expected value	Standard deviation
Δ	N	1	0.10
X_W	LN	1	0.15
X_{SCF}	LN	1	0.10
X_{wake}	LN	1	0.15
m_1	D	3	
$\log K_1$	N	determined from $\Delta\sigma_D$	0.22
m_2	D	5	
$\log K_2$	N	determined from $\Delta\sigma_D$	0.29
$\Delta\sigma_D$	D	71 MPa	

$\log K_1$ and $\log K_2$ are fully correlated

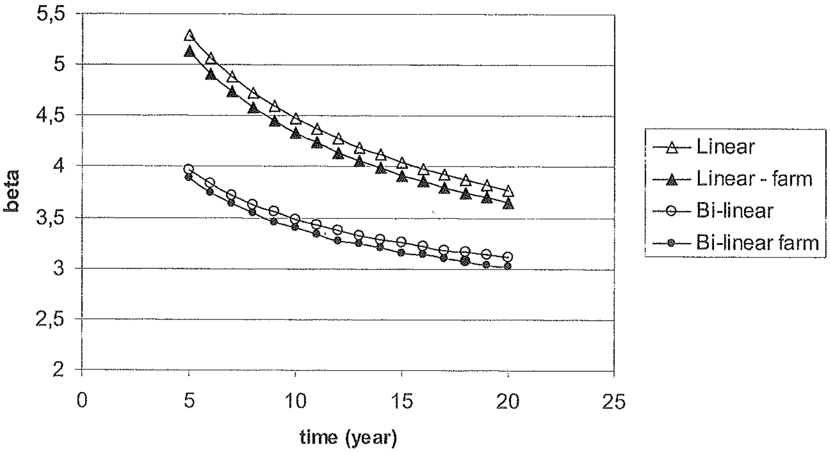

Figure 5. Annual reliability index as function of time for fatigue critical detail with mudline moment.

Figure 5 shows the annual reliability index as function of time for a fatigue critical detail with mudline moment obtained using the above limit states and stochastic modeling. It is seen that the reliability index β are smaller for the bi-linear SN-curve than for the linear SN-curve. The reliability decreases due to larger uncertainty on the lower part of the SN-curve and due to higher importance of the model uncertainties (X_W, X_{SCF}) at the lower part of the SN-curve (higher m value). The reliability level is seen to be slightly smaller for wind turbines in a wind farm than for single wind turbines.

4 TARGET RELIABILITY LEVEL FOR WIND TURBINES

For single wind turbines and for wind farms, the optimal design generally can be obtained using a life-cycle approach where all relevant benefits and costs are included. Basically the optimal design of wind turbines in a wind turbine park can be obtained from the optimization problem:

$$\begin{aligned} \max_z \quad & B(z) - \{C_I(z) + C_{\text{grid+transmission}}(z) + C_{\text{operation+maintenance}}(z) + C_F(z)\} \\ \text{s.t.} \quad & \Delta P_F(z) \le \Delta P_F^{\max} \end{aligned} \tag{14}$$

where z are the design variables including dimensions of the wind turbines (height, cross sectional dimensions, rotor diameter, ...,wind farm layout). B is the expected benefit from electricity production, C_{IN} is the initial production cost of the wind turbines (material, foundation, transportation and installation costs), $C_{\text{grid+transmission}}$ is the cost of grid and electricity transmission system, $C_{\text{operation+maintenance}}$ is the expected cost of operation and maintenance, C_F is the expected costs of eventual failure of wind turbines, ΔP_F is the annual probability of failure and $\Delta P_F^{\max}$ is the maximum acceptable annual probability of failure. For offshore wind turbines the probability of loss of human lives is often negligible. In these cases it can be relevant not to include the constraint and thus a purely monetary optimization is obtained.

If it can be assumed that the wind turbines are systematically reconstructed in case of failure, a slightly different formulation can be used. The direct failure costs is denoted C_F, the benefits per year are b, and the real rate of interest is r. Failure events are modeled by a Poisson process with rate λ. The optimal design is determined from the following optimization problem, see (Rackwitz, 2001b):

$$\begin{aligned} \max_{z} \quad & W(z) = \frac{b}{r\,C_0} - \frac{C_I(z)}{C_0} - \left(\frac{C_I(z)}{C_0} + \frac{C_F}{C_0} \right) \frac{\lambda \Delta P_F(z)}{r + \lambda \Delta P_F(z)} \\ \text{s.t.} \quad & \lambda \cdot \Delta P_F(z) \le \Delta P_F^{\max} \end{aligned} \qquad (15)$$

where C_0 is the reference initial cost corresponding to a reference design z_0. The optimal design z^* is determined by the solution to (15). If the constraint on the maximum acceptable probability of failure is omitted, then the corresponding value $\Delta P_F(z^*)$ can be considered the optimal annual probability of failure.

The failure rate λ and probability of failure can be estimated for the considered failure event, if a limit state equation, $g(X_1,...,X_n,z)$, and a stochastic model for the stochastic variables, $(X_1,...,X_n)$, are established. If more than one failure event is critical, then a series-parallel system model of the relevant failure modes can be used.

Representative examples show that the optimal reliability level corresponds to a reliability indices β approximately equal to 3 – 3.5, corresponding to a probability of failure per year equal to $2 \cdot 10^{-4}$ - 10^{-3}.

5 OPERATION AND MAINTENANCE (O&M)

Most new wind turbines and wind farms operate at acceptable levels of availability, especially those installed onshore. Limited experiences with offshore turbines indicate availability of the wind farms of 90% or even lower. The initial investment costs relative to energy production for wind farms are decreasing due to larger wind turbines. On the other hand, operation and maintenance costs of wind farms are a significant component of the relative production cost of electricity from wind energy (25 % in some cases, for offshore it can be more) implying that preventive and corrective maintenance requirements could be increasing.

Besides uncertainty related to the energy policy, the O&M costs of wind turbines are very important for the profitability of a wind farm. The initial investment costs of a wind power project are often well known, but the O&M costs have to be accumulated over the whole life of the wind farm and are very uncertain. Existing strategies for O&M are mainly based on experiences from other types of electricity production units, and therefore wind energy production could require use of new methods and technologies especially for off-shore wind farms.

For new turbines costs for unplanned (corrective exchange / repair of failed components) O&M are in the range of 0,005 – 0,010 €/kWh and for planned (preventive) O&M in the range of 0,003 – 0,009 €/kWh. Much higher values are obtained for lifetimes exceeding 10 years. Wind turbines are usually sold with a service contract during the first 5 years where the manufacturer has the risk of O&M costs. The owner has the real large uncertainty related to the O&M costs during the remaining life.

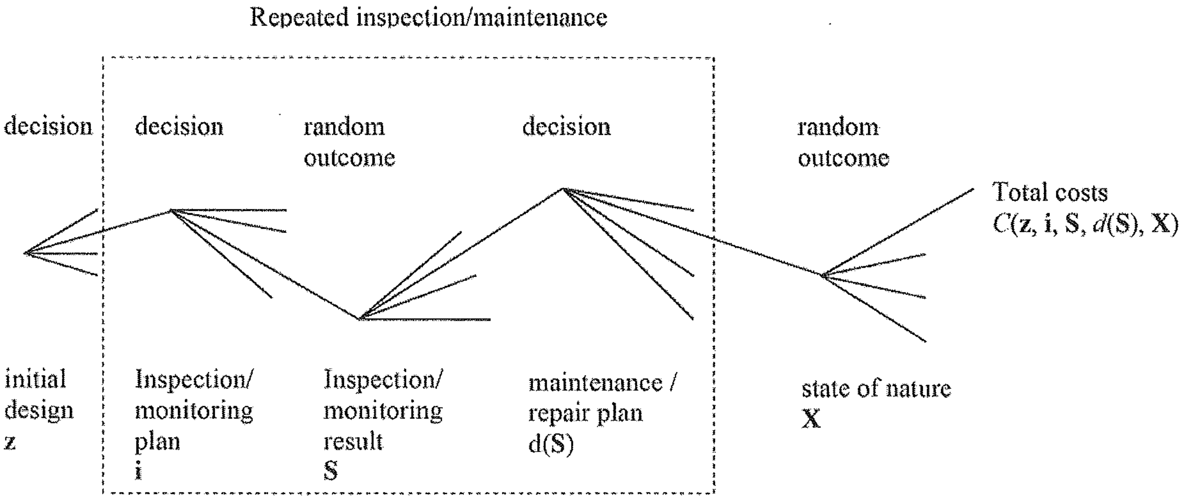

Figure 6. Decision tree for O&M decisions.

A rational way to decide on actions related to O&M is to use a risk-based approach based on pre-posterior Bayesian decision theory as formulated in e.g. (Raiffa and Schlaifer, 1961) and (Benjamin and Cornell, 1970), see decision tree in figure 6. The decision tree has the following nodes:

- Initial design where decision on size and design of the wind turbines and the wind farm is taken, represented by the design variables $\mathbf{z}$
- Repeated, sequential decisions / observations on
  - Inspection and condition monitoring plan for the remaining life, represented by the decision variables $\mathbf{i}$
  - Observation of result of inspection / monitoring, represented by random / unknown outcome $\mathbf{S}$
  - Decision on maintenance / repair based on observed inspection / monitoring result, represented by the decision rule $d(\mathbf{S})$
- Observation of random / unknown realization of state of nature, e.g. extreme wind speeds, represented by random variables $\mathbf{X}$

The total costs can be divided into initial construction investment, C_{IN}, monitoring / inspection costs, C_M, maintenance / repair costs, C_R, and eventual failure costs, C_F. The benefits from electricity production are denoted B. The optimal decision on design and operation & maintenance planning can be obtained from the optimization problem, where the total life-cycle expected costs-benefits are maximized with a constraint on the lowest acceptable reliability

$$\begin{aligned} &\max_{\mathbf{z},\mathbf{i},d} \quad C(\mathbf{z},\mathbf{i},d) = B - \left(C_{IN}(\mathbf{z}) + C_{IN}(\mathbf{z},\mathbf{i},d) + C_M(\mathbf{z},\mathbf{i},d) + C_R(\mathbf{z},\mathbf{i},d) + C_F(\mathbf{z},\mathbf{i},d)\right) \\ &\text{s.t.} \quad \Delta P_{F,t}(\mathbf{z},\mathbf{i},d) \le \Delta P_F^{\max} \qquad t = 1,2,\ldots,T_L \end{aligned} \tag{16}$$

$\Delta P_{F,t}$ is the annual probability of failure in year t and $\Delta P_F^{\max}$ is the maximum acceptable yearly failure probability which e.g. could be assessed based on Life Quality Index (LQI) considerations, see e.g. Rackwitz (2002).

6 CONCLUSIONS

Aspects for stochastic modeling of structural loads, strengths and models for wind turbines are described. Single wind turbines and wind turbines in wind farms with wake effects are discussed. Limit state equations are shown for fatigue limit states and for ultimate limit states.

Reliability-based cost-benefit optimization formulations for wind turbines are presented. Compared to onshore wind turbines offshore wind turbines are characterized by a very low risk of human injury in case of failure It is therefore relevant to assess the minimum reliability level for structural design on the basis of reliability-based cost optimization considering the whole life-cycle of the turbines without a reliability constraint.

Operation & maintenance (O&M) is very important for especially offshore wind turbines. A model for overall optimal planning is presented based on Bayesian decision theory. More research in this area is required, e.g. how to use information from condition monitoring, cost modelling and quantification of risks and uncertainties, include use of operating experience (failure data), logistic information (availability of access systems, crew, spare parts, etc.) and weather forecast (for planning of maintenance actions and for predicting energy output and limiting unbalance).

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