International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 15, No. 2, June 2005, pp. 141–146

Reliability-based Optimization and Optimal Reliability Level of Offshore Wind Turbines

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Different formulations relevant for the reliability-based optimization of offshore wind turbines are presented, including different reconstruction policies in case of failure. Illustrative examples are presented and, as a part of the results, optimal reliability levels for the different failure modes are obtained as annual probabilities in the interval $2 \cdot 10^{-4}$–10^{-3}. Reliability-based inspection models for large offshore wind turbines are presented.

INTRODUCTION

Wind turbines for electricity production have been increasing drastically these past years both in production capability and in size. Offshore wind turbines with an electricity production of 3 to 5 MW are now being produced. The main failure modes are fatigue failure of wings, hub, shaft and main tower, local buckling of main tower, and foundation failure. This paper considers the reliability-based optimization of the tower and foundation.

Compared to onshore wind turbines and building structures, the risk of human injury is almost insignificant in case of failure of offshore wind turbines. One could then argue that the reliability of offshore wind turbines can be lower than for onshore turbines, and that the reliability level can be chosen on the basis of cost optimization considering the whole life-cycle of the turbines.

Different formulations are considered for the objective function, including benefits, building costs of the wind turbine, inspection and maintenance costs, and failure costs. Different reconstruction policies in case of failure are considered, including systematic reconstruction, no reconstruction, failure of the control system, and inspection and maintenance strategies. Illustrative examples for offshore wind turbines are presented and, as a part of the results, optimal reliability levels for the different failure modes are obtained.

FORMULATION OF RELIABILITY-BASED OPTIMIZATION PROBLEMS FOR WIND TURBINES

Reliability-based optimization problems can be formulated in different ways. First we consider the case where it is assumed that the control system is performing as expected, one single wind turbine is considered, and the wind turbine is systematically reconstructed in case of failure. Next, it is assumed that the wind turbine is not reconstructed in case of failure. This could for example be the case if new technologies have been developed, and rebuilding of the same type of wind turbine is not expected to be profitable. Important operations of a wind turbine, such as braking in case of high wind speeds, and yawing and pitching of pitch-regulated wind turbines, are within a control system. In this paper it is assumed that the control system can fail. Finally, inspection and maintenance are included in the formulation. In all cases a purely monetary optimization is considered, since it is assumed that for offshore wind turbines the probability of loss of human lives is negligible.

Systematical Rebuilding in Case of Failure

Here it is assumed that one wind turbine is considered, and that the wind turbine is systematically rebuilt in case of failure. The main design variables are denoted $\mathbf{z} = (z_1, \dots, z_N)$, that is, diameter and thickness of tower and main dimension of wings. The initial (building) costs are denoted $C_I(\mathbf{z})$, the direct failure costs are 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 probability of failure is $P_F(\mathbf{z})$, and the failure rate is $\lambda P_F(\mathbf{z})$.

The optimal design is determined from the following optimization problem (Rackwitz, 2001):

$$\begin{aligned} \max_{\mathbf{z}} W(\mathbf{z}) &= \frac{b}{rC_0} - \frac{C_I(\mathbf{z})}{C_0} - \left(\frac{C_I(\mathbf{z})}{C_0} + \frac{C_F}{C_0} \right) \frac{\lambda P_F(\mathbf{z})}{r + \lambda P_F(\mathbf{z})} \\ \text{s.t.} \quad & z_i^l \le z_i \le z_i^u, \quad i = 1, \dots, N \\ & \lambda P_F(\mathbf{z}) \le \Delta P_F^{\max} \end{aligned} \tag{1}$$

where $\mathbf{z}^l$ and $\mathbf{z}^u$ are lower and upper bounds on the design variables; C_0 is the reference initial cost of corresponding to a reference design $\mathbf{z}_0$; and $\Delta P_F^{\max}$ is the maximum acceptable failure rate, that is, with a reference time of 1 year. Regulators typically require this type of constraint.

The optimal design $\mathbf{z}^*$ is determined by the solution to Eq. 1. If the constraint on the maximum acceptable probability of failure is omitted, then the corresponding value $P_F(\mathbf{z}^*)$ can be considered the optimal probability of failure related to the failure event and the actual cost-benefit ratios used.

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

Received October 20, 2003; revised manuscript received by the editors February 8, 2005. The original version was submitted directly to the Journal.

KEY WORDS: Offshore wind turbines, reliability analysis, reliability-based optimization, reliability level.