December 2003 ECN-RX--04-002

An Approach to Optimizing the Structural Reliability and the Reliability of the Control and Safety System of Wind Turbines

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This report will be presented at the International Conference on Probabilistic Safety Assessment and

Management, June 14-18, 2004, Berlin, Germany

An Approach to Optimizing the Structural Reliability and the Reliability of the Control and Safety System of Wind Turbines

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1 Introduction

From the past experience one may anticipate that the reliability of the control and safety system of wind turbines (WTBs) for electric power generation is too low compared to the structural reliability. May the failure probabilities of these two sources of failure be balanced and may the total probability of failure be possibly reduced (optimized), then it must be expected that the price of the turbines may be reduced. Such a result would especially be relevant to the planned enlargement of the Danish offshore wind turbine farms. In this paper we explore whether such an imbalance is really present.

The problem of harmonizing the reliability among the subsystems or components in a system is not new and is referred to as the problem of reliability allocation. Usually this kind of problems is stated as an optimization problem, in which the objective function is the system reliability (to be maximized) subject to a set of constraints, among which monetary constraints play the major role. Another way is to minimise the cost of the system subject to providing the permissible level of the system reliability. In practice, for a more or less complex technical system it is often not feasible to solve the task mathematically due to a very high dimensionality and a large number of aspects that are difficult to formalize mathematically. To overcome this difficulty and still have a systemic approach to bringing the system reliability and safety to the desired level, simpler methodologies have been developed. For systems with a high potential risk for human beings and the environment the principle of eliminating weak points among the subsystems and components is employed. Reliability and risk analyses are used to identify weak points, and then proper measures (technical and organizational) are worked out to bring the performance of subsystems/components to the level attained by the other subsystems/components with higher levels of performance. That is, this approach is aimed at having a uniform reliability/risk among subsystems/components given the permissible level of reliability/risk is fulfilled. Sometimes this approach is referred to as the principle of the maximum of entropy with respect to the reliability among the subsystems/components. This is because the maximum of entropy is attained when the reliability is uniformly distributed over subsystems/components in a system.

Wind turbines are technical systems that do not expose high risks to human beings and the environment, and therefore their design is governed basically by economic considerations. This means that the harmonization of the structural reliability and the reliability of the control and safety system has to be sought taking into consideration the economic aspects of WTB's design and operation. Furthermore, the specific interrelation of the two kinds of reliability in the WTB introduces certain particularities that make this problem atypical.

2 A General Framework for the Approach

Let us introduce the following notation: SS stands for the safety system, $\boldsymbol{SF}$ denotes the event "a structural failure in the WTB", $\boldsymbol{SS}$ is the event "the SS works successfully on demand", $\overline{\boldsymbol{SS}}$ is the event "the SS fails on demand", P(·) is a probability, and $P(A|B)$ is a conditional probability of an event A happening given an event B has occurred.

A particularity of the work carried out is that a structural failure of the WTB is conditional on the performance of the SS. Thus, it can be written

$$P(\boldsymbol{SF}) = P(\boldsymbol{SF}|\boldsymbol{SS})\left(1 - P\left(\overline{\boldsymbol{SS}}\right)\right) + P\left(\boldsymbol{SF}\middle|\overline{\boldsymbol{SS}}\right)P\left(\overline{\boldsymbol{SS}}\right). \tag{1}$$

In this formula the terms $P(\boldsymbol{SF}|\boldsymbol{SS})$ and $P\left(\boldsymbol{SF}\middle|\overline{\boldsymbol{SS}}\right)$ characterize the structural reliability, which is dependent on the performance of the SS, and the terms $P(\boldsymbol{SS})$ and $P\left(\overline{\boldsymbol{SS}}\right)$ characterize the reliability/unreliability of the SS.

An aid in search for the approach to optimizing the structural reliability and the reliability of the SS could be the existence of some accepted permissible reliability values for WTBs. The Danish document "Rekommandation til Teknisk Grundlag" [1] (Recommendation for Technical Basis) contains such a value that could be made use of. The document states "The reliability of the safety system should be that high that the probability of failure of the safety system combined with the probability of a critical failure that requires the intervention of the safety system result in a probability of collapse which does not exceed a value of 0.0002 per WTB year." To mathematically implement this recommendation, one more event is to be introduced. It is of "a critical failure taking place". Denoting it by $\boldsymbol{D}$ (demand), allows writing the following inequality:

$$P\left(\boldsymbol{SF}\ \textbf{and}\ \boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}\right) = P\left(\boldsymbol{SF}\middle|\boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}\right)P\left(\overline{\boldsymbol{SS}}\middle|\boldsymbol{D}\right)P(\boldsymbol{D}) \le 0.0002\,.$$

Now the problem of designing the optimal WTB can be stated in general terms:

$$\min_{\Omega}(WTB\,\text{cost}) \tag{2}$$

subject to a set of constraints, one of which is

$$P\left(\boldsymbol{SF}\,\middle|\,\boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}\right)P\left(\overline{\boldsymbol{SS}}\,\middle|\,\boldsymbol{D}\right)P(\boldsymbol{D}) \le 0.0002. \tag{3}$$

The minimum of the objective function "*WTB* cost" is sought over the set of all possible design solutions, Ω, which includes possible design solutions for the structural parts of the WTB and the SS.

It is obvious that optimisation problem (2)-(3) can hardly be solved purely mathematically because of the existence of a large number of aspects to be taken into account. Therefore a feasible approach to attain the objective was developed.

3 A Feasible Approach

Formula (1) is a starting point to formalise the general framework of the approach, but it is not complete and ought to be further developed.

The intervention of the safety system is needed when there is a demand to trigger it. Thus, the probability of having a demand must be a constituent of formula (1). Let D={D_i}, $i = 1,\ldots, n$, denote a set of possible demands to bring the WTB to a safe condition, $\boldsymbol{D_i}$ the event "there is demand D_i to bring the WTB to a safe condition", and $\overline{\boldsymbol{D}}_i$ the event "there is no demand D_i to bring the WTB to a safe condition ". In general, we can consider that the set of possible demands D consists of 6 events [2]: (1) grid loss, (2) generator failure, (3) drive-line failure, (4) gearbox failure, (5) wind speed (ws) ≥ 25 m/s, and (6) failure of any component monitored by the microprocessor. Now the set of all possible conditioning events can be stated

$$\Theta = \left\{\boldsymbol{D}\ \textbf{and}\ \boldsymbol{SS}, \boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}, \overline{\boldsymbol{D}}\ \textbf{and}\ \boldsymbol{SS}, \overline{\boldsymbol{D}}\ \textbf{and}\ \overline{\boldsymbol{SS}}\right\}.$$

The elements of the set Θ are to be understood as follows. "***D* and *SS***" means that there is a demand to stop the WTB and the SS operates successfully, " $\boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}$ " means that there is a demand to stop the WTB and the SS fails, etc.

By taking this into account, formula (1) expands

$$\begin{aligned} P(\boldsymbol{SF}) = {} & P(\boldsymbol{SF}|\boldsymbol{SS}\ \textbf{and}\ \boldsymbol{D})P(\boldsymbol{SS}|\boldsymbol{D})P(\boldsymbol{D}) + P(\boldsymbol{SF}|\boldsymbol{SS}\ \textbf{and}\ \overline{\boldsymbol{D}})P(\boldsymbol{SS}|\overline{\boldsymbol{D}})P(\overline{\boldsymbol{D}}) + \\ & P(\boldsymbol{SF}|\overline{\boldsymbol{SS}}\ \textbf{and}\ \boldsymbol{D})P(\overline{\boldsymbol{SS}}|\boldsymbol{D})P(\boldsymbol{D}) + P(\boldsymbol{SF}|\overline{\boldsymbol{SS}}\ \textbf{and}\ \overline{\boldsymbol{D}})P(\overline{\boldsymbol{SS}}|\overline{\boldsymbol{D}})P(\overline{\boldsymbol{D}}) \end{aligned} \tag{4}$$

By taking into account that $\boldsymbol{D} = \bigcup_i \boldsymbol{D}_i$ and $\overline{\boldsymbol{D}} = \bigcup_i \overline{\boldsymbol{D}}_i$, one can see that all WTB subsystems are explicitly included in the formula. And this formula could be further developed up to the level of having the probabilities of the demands separately. If we had representative samples on the occurrences of all the demands (generator failure, drive-line failure, gear box failure, etc.), and if we could acquire data on the failure occurrences of the SS as a response to these demands, then the probability of having a structural failure could be assessed given the models for the assessment of the probabilities $P(\boldsymbol{SF}|\cdot)$ exist.

Considering model (4) feasible in principle and detailed enough to cover many aspects of the WTB design, there were a few obstacles to applying it. One of them was that failure records reported in the existing failure databases are not informative enough and often ambiguous to extract the needed information. One has to introduce some additional simplifications to overcome this problem. We made use of the fact that extreme wind conditions are regarded as the most often causes of WTB collapses, which is substantiated by the available failure records. Thus, extreme wind conditions (ws ≥ 25 m/s) were taken as a frequency dominating demand. Moreover, considering only extreme wind conditions in the analysis is reasonable in the sense that given the SS work successfully, then the WTB can collapse only under the condition of ws ≥ 25 m/s. After adopting this, formula (4) appears as follows:

$$\begin{aligned}
&P(\boldsymbol{SF}) \approx P(\boldsymbol{SF}|\boldsymbol{SS}\ \textbf{and}\ ws \geq 25)P(\boldsymbol{SS}|ws \geq 25)P(ws \geq 25) + \\
&P(\boldsymbol{SF}|\boldsymbol{SS}\ \textbf{and}\ \overline{ws \geq 25})P(\boldsymbol{SS}|\overline{ws \geq 25})(1 - P(ws \geq 25)) + \\
&P(\boldsymbol{SF}|\overline{\boldsymbol{SS}}\ \textbf{and}\ ws \geq 25)P(\overline{\boldsymbol{SS}}|ws \geq 25)P(ws \geq 25) + \\
&P(\boldsymbol{SF}|\overline{\boldsymbol{SS}}\ \textbf{and}\ \overline{ws \geq 25})P(\overline{\boldsymbol{SS}}|\overline{ws \geq 25})(1 - P(ws \geq 25)).
\end{aligned} \tag{5}$$

All the terms in formula (5) can be assessed in the following two ways. One way would be to use the existing reliability models to assess the structural (un)reliability, $P(\boldsymbol{SF}|\cdot)$, given the different conditioning events, and to assess the probabilities $P(\boldsymbol{SS}|\cdot)$ and $P(\overline{\boldsymbol{SS}}|\cdot)$. The probability $P(ws\ {}^{3}\ 25)$ can be assessed based on weather recorded data.

The other way would be to directly collect failure data on all the terms without the use of the existing models. The data needed can be retrieved from the existing failure records.

Expressions (4) and (5) along with (3) give a great deal of flexibility in choosing the constraints for optimizing the design of the WTB. For example, provided there were some desired value to be attained for the structural reliability, then (4) or (5) could be used to assess the existing level of structural reliability against the desired value. Condition (3) could be used as an additional constraint. The choice between (4) and (5) would be dictated by the existing failure data at hand and models. Formula (4) is a finer choice, but more data are needed to numerically evaluate it.

Denote by P^* the permissible probability of having the WTB exposed to a serious structural failure. Then, the general problem of designing the optimal WTB can be mathematically formulated as follows:

$$\min_{\Omega}(WTB\ \text{cost}) \tag{6}$$

subject to a set of constraints, two of which are

$$\begin{aligned}&P\left(\boldsymbol{SF}\middle|\boldsymbol{D}\ \textbf{and}\ \overline{\boldsymbol{SS}}\right)P\left(\overline{\boldsymbol{SS}}\middle|\boldsymbol{D}\right)P(\boldsymbol{D})\le 0.0002,\\&P(\boldsymbol{SF})\le P^{*},\end{aligned}\tag{7}$$

As seen from (4) $P(\boldsymbol{SF})$ depends on the (un)reliability of all WTB's systems, including the control and safety system. Thus, when designing and minimising the cost of the WTB and operational costs, the designer can choose such a design that fulfils requirement (7). Fulfilling this requirement can be achieved in many different ways. The designer could vary any of the terms in (6) and see which design delivers the minimum to the objective function (6) provided constraint (7) holds. It should be clear that behind certain numerical values for the terms in (4) and (5) there is a specific design solution.

In the following section an analysis of existing failure data is carried out and possible conclusions related to the subject of interest are drawn.

4 Insights Gained from the Data Analysis and Approach Developed

This section exemplifies the assessment of structural (un)reliability of the WTB based on the existing recorded failure data and gives some idea concerning the relationships between the reliability of the structure and the SS without solving the optimization problems.

By looking into formula (5) we can conclude that varying the probabilities of failures of the SS will have different effect compared to varying the probabilities characterising the structural reliability. To make this point more clear, let us consider an example of what kind of insight one can get by analysing the probabilities of wind turbine collapses. The data for this example are taken from the existing failure records for the period 1984-2000.

$P(\textbf{Sit.1})=P\left(\boldsymbol{SF}\middle|\boldsymbol{SS}\ \textbf{and}\ ws\ge 25\right)P\left(\boldsymbol{SS}\middle|ws\ge 25\right)P(ws\ge 25)=3{,}35\times10^{-5}$,

$P(\textbf{Sit.2})=P\left(\boldsymbol{SF}\middle|\boldsymbol{SS}\ \textbf{and}\ \overline{ws\ge 25}\right)P\left(\boldsymbol{SS}\middle|\overline{ws\ge 25}\right)(1-P(ws\ge 25))=2{,}01\times10^{-4}$,

$P(\textbf{Sit.3})=P\left(\boldsymbol{SF}\middle|\overline{\boldsymbol{SS}}\ \textbf{and}\ ws\ge 25\right)P\left(\overline{\boldsymbol{SS}}\middle|ws\ge 25\right)P(ws\ge 25)=3{,}68\times10^{-4}$, and

$P(\textbf{Sit.4})=P\left(\boldsymbol{SF}\middle|\overline{\boldsymbol{SS}}\ \textbf{and}\ \overline{ws\ge 25}\right)P\left(\overline{\boldsymbol{SS}}\middle|\overline{ws\ge 25}\right)(1-P(ws\ge 25))=3{,}35\times10^{-4}$.

Thus, $P(\boldsymbol{SF})=P(\textbf{Sit.1})+P(\textbf{Sit.2})+P(\textbf{Sit.3})+P(\textbf{Sit.4})=9{,}38\times10^{-4}$.

Then, let us assume that the probability of having blasts higher than 25 m/s per year is approximately equal to 0.1, which seems to our knowledge a realistic assumption.

Another assumption introduced is that of the WTB suffers a major structural failure (collapse) with surety given the SS does not properly work and wind speed is higher than or equal to 25 m/s. Formally, this means that $P\left(\boldsymbol{SF}\middle|\overline{\boldsymbol{SS}}\ \textbf{and}\ ws\ge 25\right)=1$.

Thus, applying these two assumptions to $P(\mathbf{Sit.3})$ we arrive at an equality $P(\mathbf{Sit.3}) = 1 \times P\left(\overline{\boldsymbol{SS}} \middle| ws \geq 25\right) \times 0.1 = 3{,}68 \times 10^{-4}$, from which we derive that $P\left(\overline{\boldsymbol{SS}} \middle| ws \geq 25\right) = 3{,}68 \times 10^{-3} \approx 4{,}00 \times 10^{-3}$.

Assuming also that the probability of failure of the SS does not depend of wind speed, we can obtain the assessments of all terms in the above expressions

$P(\mathbf{Sit.1}) = (3{,}36 \times 10^{-4}) \times 0{,}996 \times 0{,}1 \approx 3{,}35 \times 10^{-5}$,

$P(\mathbf{Sit.2}) = (2{,}24 \times 10^{-4}) \times 0{,}996 \times 0{,}9 \approx 2{,}01 \times 10^{-4}$,

$P(\mathbf{Sit.3}) = 1 \times 0{,}004 \times 0{,}1 \approx 3{,}68 \times 10^{-4}$, and $P(\mathbf{Sit.4}) = 0{,}1 \times 0{,}004 \times 0{,}9 \approx 3{,}35 \times 10^{-4}$

Now we will make a simple sensitivity analysis. First, let us see what would be the effect of reducing the unreliability of the SS as much as two times. That is, we are going to substitute the probability $P\left(\overline{\boldsymbol{SS}} \middle| ws \geq 25\right) = 3{,}68 \times 10^{-3}$ with $P\left(\overline{\boldsymbol{SS}} \middle| ws \geq 25\right) = 1{,}84 \times 10^{-3}$.

Recalculating the four probabilities brings us to the following result

$$P(\boldsymbol{SF}) = P(\mathbf{Sit.1}) + P(\mathbf{Sit.2}) + P(\mathbf{Sit.3}) + P(\mathbf{Sit.4}) = 5{,}87 \times 10^{-4}.$$

This result means that reducing the unreliability of the SS as much as two times reduces the probability of wind turbine collapses happening by approximately 1,6 times.

It has been checked that the effect of reducing the probability of major structural failures of WTBs by two times given the unreliability of the SS remains untouched, i.e., $P\left(\overline{\boldsymbol{SS}} \middle| ws \geq 25\right) = 3{,}68 \times 10^{-3}$, reduces the probability of wind turbine collapses happening by approximately 1,1. That is, the effect of raising the reliability of the SS is higher than that of raising structural reliability.

Then, the proper way to proceed would be to evaluate the costs of providing both a higher reliability of the SS and the structure. Based on the costs evaluated and the probabilities assessed it would not be a problem to make the right decision with respect to which measures are more effective and beneficial.

References

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