The Impact of Site Conditions on the Turbine Suitability

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ABSTRACT SUMMARY

Installation of wind turbines in a given configuration will lead to site conditions that differ from the external design conditions assumed during turbine design and certification. Based on a generic turbine load simulation model, site-specific load calculations are performed for different sets of site conditions and the influence of these parameters on the site-specific loads is evaluated. The site-specific loading levels are then compared to the design loads. Additionally, the expected lifetime of the turbines is also estimated. The results show significant deviations in loading and consequently in expected lifetime as a function of the site conditions assumed.

OBJECTIVES & MOTIVATION

Micro-siting wind turbines in a given layout will invariably create site conditions which differ from the external conditions assumed during turbine design and certification. Due to the fact that modern turbines are mostly designed for generic turbine classes defined in standards, the suitability of the selected turbine type at a given site must be guaranteed. When planning a wind project it must be ensured that the technical integrity of the individual wind turbines is not threatened (Figure 1). Often this is done by a simple judgment of the site conditions with respect to the external design conditions. As site conditions become more complex and further deviate from the external conditions in the design standards this approach becomes increasingly unreliable. The most scientific and accurate solution is thus to use the site conditions to calculate the actual site-specific loads and compare these to the design loads. For this paper a generic turbine load simulation model is used and a site-specific load calculation is performed. Based on the calculated results the influence of the site parameters on the site-specific loads is evaluated and discussed.

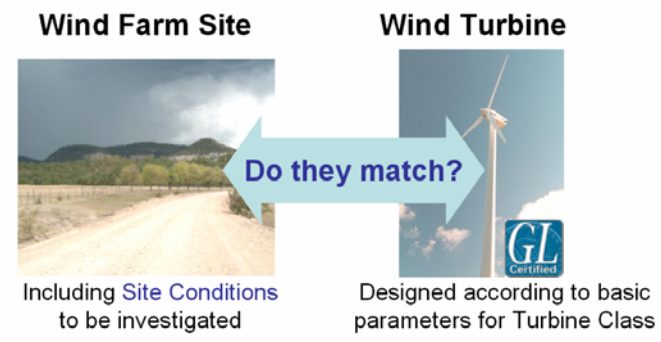

Figure 1: Is the Chosen Turbine Suitable for the Site?

ASSUMPTIONS & METHODOLOGY

For this paper a generic turbine load simulation model is used and an example wind turbine layout is investigated. Four sets of typical environmental conditions are assumed, with site condition parameters varied individually to visualize their respective degrees of influence on loads.

Turbine Type

Fatigue loads are estimated using the load simulation model of a generic 2-MW wind turbine prepared for this study (see Table 1). The fatigue load calculations assume a three-bladed system, with the rotor arranged on the windward side with power output limitation by blade adjustment and active yaw. All relevant parameters of a control and safety system are taken into account during the power production and idling load cases. Additionally also the shut-down and start-up procedures are taken into account by simulating the relevant DLCs.

Table 1: Turbine Geometry and Control Data

Turbine Geometry Data	
Rotor diameter	75 m
Hub height	100 m
Tower diameter top	2.5 m
Tower diameter bottom	4.0 m

Turbine Control Data	
Cut in wind speed	4m/s
Cut out wind speed	25m/s
Rated wind speed	13m/s

The turbine was assumed to be designed according to IEC WTG Class II A (IEC 2nd Edition). All external design conditions have therefore been assumed as defined in the standard. The most important conditions are presented in Table 2.

Table 2: Turbine Design Conditions

Design Conditions IEC II A (2nd Edition)	
Mean Wind Speed	8.5m/s
Turbulence Intensity (Characteristic)	18%
Vertical Wind Shear	0.2

Wind Farm Configuration

The assumed wind farm comprises 11 wind turbines, the layout of which is depicted in Figure 2. The wind farm configuration selected is in line with industry standards and best practices for onshore project layouts in terms of inter-turbine spacing. The normalised distances (distance / rotor diameter) are summarised in Table 3.

Table 3: Normalized Distances of Wind Farm Layout

Normalized Distances
3.10
3.14
3.22
3.23
3.53
3.69
4.00
4.54

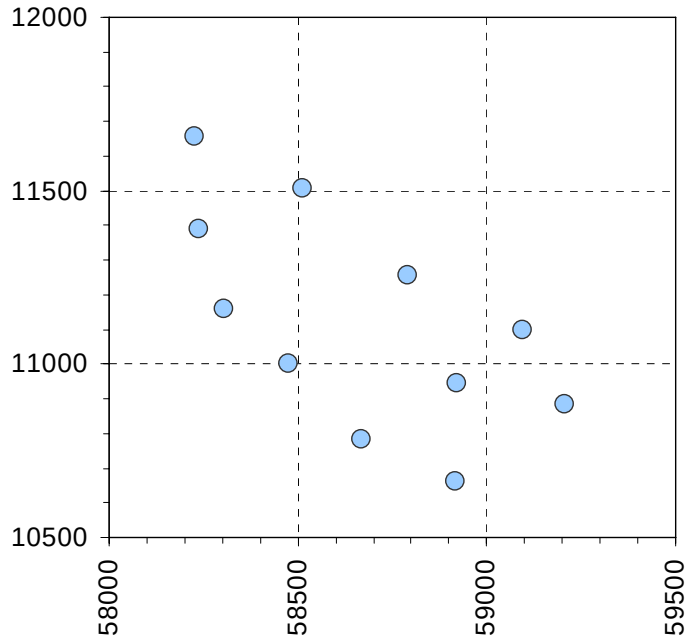

Figure 2: Wind Farm Layout

Turbine Load Calculation

For the fatigue load examination, calculations are performed in consideration of the site-specific wind speed distribution (Weibull), wind direction distribution (wind rose), air density, characteristic (ambient) turbulence intensity, turbine locations, and the wind farm influence (wake effects).

The influence of the wind turbines themselves on the loads is considered in the calculations using the method of Sten Frandsen. In this manner, the wake effects within the wind farm are quantified in order to correct the characteristic (ambient) site turbulence intensity to a design value ("effective turbulence intensity"). The calculated values of the effective turbulence intensity are used for the wind field modelling and to perform the fatigue load calculations. For these calculations a three-dimensional turbulent wind field is used. Idling below cut-in and above cut-out wind speed is considered. Additionally also the shut-down and start-up procedures are taken into account by simulating the relevant DLCs.

The calculations are based on IEC 61400-1 2nd edition "Wind turbine generator systems – Part 1: Safety requirements" (1999), as most turbines installed at onshore sites are designed and certified according to this standard. For the fatigue load calculation different parameters of interest are varied in an analytical study.

In order to compare the influence of different parameters on loads, four different combinations of mean wind speed, characteristic turbulence intensity and vertical wind shear (Hellmann exponent) values are considered to calculate the site-specific loads under each of four case scenarios. These sets of assumed site conditions are outlined in Table 4.

Table 4: Site Conditions for Different Calculations

Case A: V=6.5m/s, char. TI=16%, α=0.15
Case B: V=10.5m/s, char. TI=16%, α=0.25
Case C: V=6.5m/s, char. TI=20%, α=0.15
Case D: V=10.5m/s, char. TI=20%, α=0.25

These three parameters have been chosen as they are expected to affect the loading level in a non-linear way; the site suitability and turbine lifetime are difficult to predict without performing a load calculation.

RESULTS

The resulting load cycles of the simulated time histories for the site conditions are quantified using the Rainflow counting method. This is performed using the associated wind speed distribution for each of the simulated cases for a 20-year lifetime. These load spectra are converted, assuming S/N-curve slopes of m = 4 and m = 10 and a reference number of load cycles of $N_{ref} = 1.0 * 10^7$, into damage-equivalent constant-range load spectra for relevant load components.

The site-specific loads for selected components of the wind turbine structure are compared directly to the design loads. The margin is calculated as given in Equation 1.

$$MARGIN = \left(\frac{DEL_Site}{DEL_IEC} \right) \qquad \text{Equation 1}$$

In this equation *DEL_Site* is the site-specific damage equivalent load and *DEL_IEC* is the design load, respectively. The load deviations for the major components are presented as a bar chart in Figure 3. The horizontal red line represents equivalency with respect to the design loads.

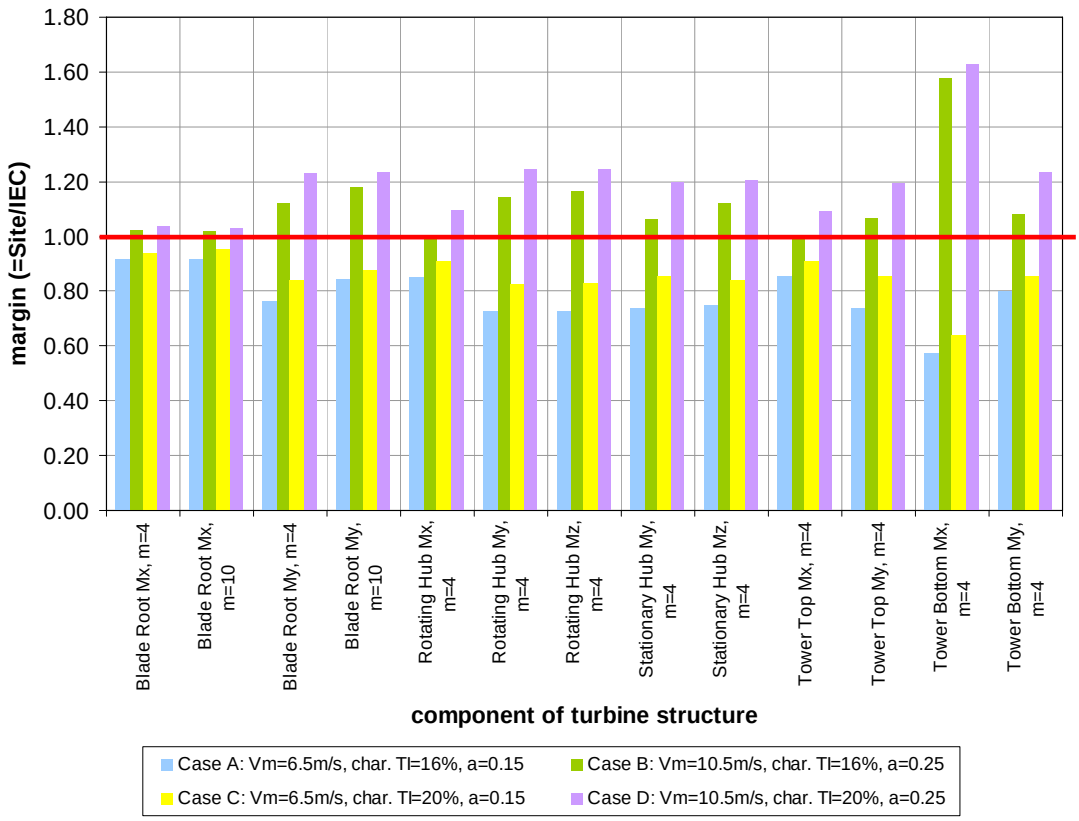

Figure 3: Load Deviations for Relevant Components

The calculated site-specific loads with respect to design loads for various turbine components under each of the 4 case scenarios show significant variation. For example, it can be observed that the Tower Bottom loads are much higher than the other components. The influence of Woehler slopes is also evident.

Subsequently, the effects of loads on turbine service life (lifetime) are analysed. In this context, the resulting damage equivalent loads – for each of the four wind condition scenarios and their corresponding input parameters – are used to calculate the expected lifetimes of major components. This calculation was performed by dividing the assumed typical design lifetime of 20 years by the ratio of site-specific damage equivalent loads to design loads to the power of *m* (to take into account the Woehler slope), as summarised in Equation 2.

$$LIFETIME = \frac{20\,years}{\left(\frac{DEL_Site}{DEL_IEC}\right)^{m}} \qquad \text{Equation 2}$$

For this exercise the expected lifetimes of all evaluated wind turbine components are averaged to deduct the mean lifetime for the whole wind turbine structure. The results for each case scenario are given in Table 4.

Table 4: Calculated Lifetimes for Different Cases

	lifetime (years)
Case A:	40
Case B:	17
Case C:	30
Case D:	15

CONCLUSIONS

The present study seeks to analyse the influence of three meteorological parameters – mean wind speed, turbulence intensity and vertical wind shear – on turbine fatigue loads and in turn on expected turbine lifetime.

For Case A the reduced wind speed and turbulence intensity with respect to the design conditions increases the lifetime significantly. The analytical lifetime for the turbine doubles when the site shows such a set of environmental conditions.

In Case B the influence of the increased wind speed and vertical wind shear is clearly visible: load levels for most of the components increase and the mean value of the calculated lifetime is reduced to 17 years.

In Case C the increase in turbulence intensity does not affect the fatigue loads as much as the decrease in wind speed, as the overall load level was reduced with respect to the design load level. The calculated lifetime therefore increases accordingly.

Case D shows the severe effects of high turbulence and high wind loading in combination with a high vertical wind shear. Loading levels increase for all components and the calculated lifetime is reduced to 15 years.

Summarising the results of all analysed cases, it can be observed that for these site conditions it is revealed how the deviations in site conditions affect the wind turbine fatigue loads as well as the connected turbine fatigue life. From the calculated lifetimes the following deductions can be made:

- Lifetime increases with decreased turbulence intensity
- Lifetime increases with decreased wind speed

When planning and designing a wind farm project, the technical integrity of individual wind turbines and in turn the suitability of the proposed turbine type in the proposed turbine layout must be ensured. In this context, attention should be given to the site conditions and particularly to their influence on turbine fatigue loading. The results of this study reveal that even slight under- or overestimations in mean wind speed, turbulence intensity or vertical wind shear can have a serious effect on turbine loads, which have a direct bearing on the lifetime of the turbines. Higher values for any of the aforementioned parameters may result in a reduction in the typically expected service life of 20 years, thereby curbing the project's profitability or even rendering the undertaking economically impractical.

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