Evaluation of wind farm effects on fatigue loads of an individual wind turbine at the EnBW Baltic 1 offshore wind farm

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Abstract. Turbulence in wake has special interest due to its strong connection with increment of fatigue loads. The aim of this paper is to evaluate the wind farm effects on fatigue loads of an individual wind turbine at the EnBW Baltic 1 offshore wind farm and compare the results with the statements suggested by IEC 61400-1 ed. 3 [1].
From measurements, the study provides strong evidence that considerable wake effects up to 15 rotor diameters (D) downstream are related to the increase of fatigue loads in the analyzed turbine. The influence of the behavior of the upstream wind turbine's thrust coefficient (C_T) can be observed in the analyzed curves for turbulence intensity and damage equivalent loads (DELs) in blade root flapwise and edgewise direction.

1 Introduction

Wind turbines extract energy from the turbulent wind and while doing so create additional turbulence [2], increasing the accumulated damage in the components of downstream wind turbines. The turbulence model based on wind velocity developed by Frandsen and suggested by the IEC 61400-1 ed. 3 in its Annex D is widely used to account for extra turbulence generated by neighboring wind turbines. In addition, Frandsen [3] suggests a model based on thrust coefficient (C_T). In this study, both models are briefly described and one year measured data from EnBW Baltic 1 offshore wind farm is analyzed. The evaluation of measurements includes the analysis of fatigue loads and turbulence intensity in function of velocity and direction of the incoming wind. The analysis is limited to blade root bending moments in flapwise and edgewise direction in free stream and wake flow conditions.

2 EnBW Baltic 1 offshore wind farm

The wind farm is situated in the Baltic Sea, 16 km north of the coast of the island Fischland Darß, and it is arranged in a triangular layout with an area of approximately 7 km^2, shown in Figure 1.

EnBW Baltic 1 comprises 21 wind turbines Siemens SWT 2.3-93 on monopile foundations in 16 to 19 m depth. This is a three-bladed model, upwind rotor with a diameter of 93 meters and a hub height of 67 m. The cut-in, rated, cut-out wind speeds are 4 m/s, 13-14 m/s and 25 m/s, respectively. The variable speed turbines have asynchronous generators with 2.3 MW capacity and are pitch-regulated, more details can be found in [4].

The meteorological information for the design-basis was obtained from three sources [5]: FINO-2 mast and two meteorological stations of the German Federal Maritime and Hydrographic Agency (BSH) i.e. Darßer Schwelle and Arkona Becken. The wind is mainly coming from southwest with a low turbulence intensity of 5% at 15 m/s [6], which is comparable to other offshore sites. Along this analysis, the used data was taken from the anemometers located on the turbines. The data was corrected by the developer of the project and validated with Lidar information on the site.

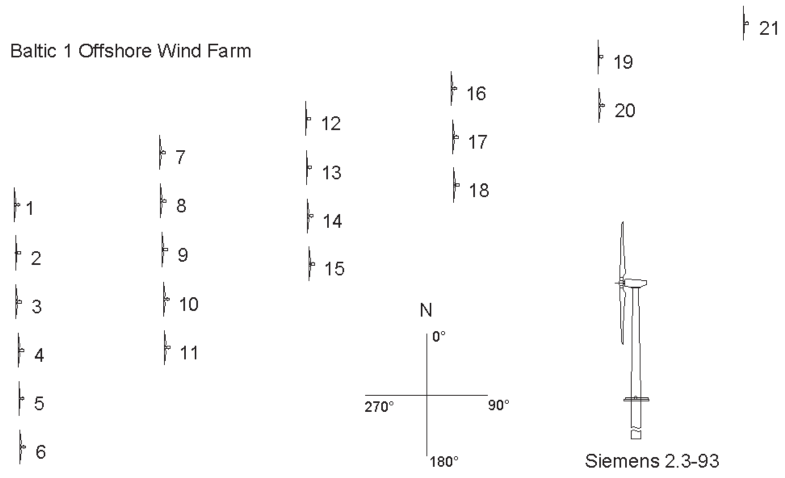

Figure 1. Layout of EnBW Baltic 1.

3 Turbulence intensity

Turbulence intensity is conceived as the instantaneous, random deviation of the mean wind speed [7]. According to Frandsen, turbulence in wake condition has two main components: ambient turbulence and turbulence added by the wake. The total turbulence modelled by Frandsen [3] is:

$$I_T = \sqrt{\frac{1}{\left(1.5 + \frac{0.8 \times D}{C_T}\right)^2} + I_0^2} \quad (1)$$

Where I_0 is the ambient turbulence modeled as σ/V_{hub}; σ is the standard deviation of the wind speed at V_{hub}; V_{hub} is the average of 10-minutes wind speed at hub height; D is the normalized distance between turbines in rotor diameters; C_T is the specific wind turbine thrust coefficient.

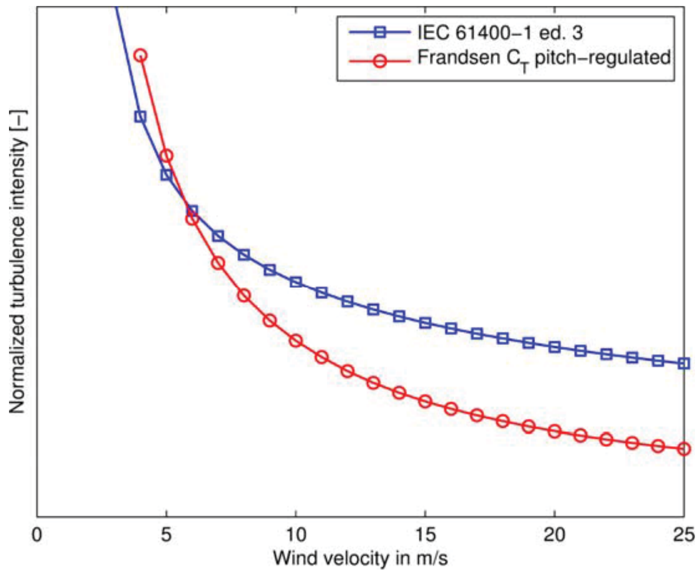

Figure 2. Normalized turbulence intensity for IEC and Frandsen model for pitch controlled turbine (measured), assuming 10 D and Normal Turbulence Model (NTM) turbulence reference (Iref) 0.16.

Meanwhile, the IEC 61400-1 ed. 3 [1] formulates I_T as in equation (2) , with *c* being a constant value equal to 1 m/s:

$$I_T = \sqrt{\frac{0.9 \times V_{hub}^2}{\left(1.5 + 0.3 \times D \times \sqrt{V_{hub} / c}\right)^2} + I_0^2} \quad (2)$$

Moreover, both models propose that the influence of neighboring turbines, with respect to the turbulence in wake, should be considered when they are located within 10 D [1].

4 Fatigue loads in wind turbines

As the wind speed is varying in time, the loads acting on the wind turbine blade are also varying and ultimately the stresses acting on the wind turbine blade are also changing. This leads to the fatigue of the different components in the wind turbine [8]. Turbulence is used as primary wind turbine design parameter, substantially describing the fatigue damage. In blades apart from the weight, turbulence is a main cause of material fatigue [7]. A large turbine nowadays can experience between 10^8 and 10^9 cycles over its lifetime [9]. Therefore, wind turbines suffer a huge number of cyclic loads and that is why they are known as the perfect “Fatigue Machine”. A general methodology to calculate fatigue loads in wind turbines can be found in [7].

For this research, it is assumed a generalized S-N fatigue slope $m = 10$ for blades, which is a widely used value for good performance on a basic unidirectional laminate material as glass fiber [10].

The number of load cycles that a component suffer is known as fractional damage and it is modelled as $d=n/N$ [9], where *n* is the number of constant amplitude cycles and *N* is the number of cycles to failure.

A convenient format to represent the variable spectrum loads that a wind turbine withstand is the damage equivalent load (DEL). The rainflow counting method is used to count and bin the load cycle time histories, converting the variable load spectra into constant range load spectra and it is modelled as follows:

$$DEL = \left[\sum_i \frac{S_i^m \times N_i}{N_{eq}} \right]^{1/m} \quad (3)$$

Where *S* is the stress range; an equivalent number of load cycles of $N_{eq}=10^7$ is normally used or the number of load cycles corresponding to 1 Hz. Nevertheless, for this study it will be referred to the number of load cycles corresponding to 50 Hz. In this study the damage equivalent load concept is used to compare different types of measured loads. In order to obtain an accurate basis for comparison the S-N slopes *m* must have the same numerical values.

5 Load measurement program in EnBW Baltic 1

Load measurements were performed at turbine 1 and 8. Several sensors installed in the two turbines, following the Standard IEC 61400-13, collected the data at various components e.g. blades and tower**.** In this study power production state is examined as Measure Load Case (MLC) which corresponds to Design Load Case (DLC) 1.2.

5.1 Fatigue analysis as function of wind velocity

The 10-minutes measured data acquired from turbine 1 is sampled at 50 Hz and is sorted in 1 m/s wind speed bins, from 4 to 17 ± 0.5 m/s. Three scenarios are analyzed in this section: free stream for directions going from 210° - 300° and wake condition at 90° and 180° directions are evaluated. Due to the different amount of 10-minutes filtered data at each wind speed bin and at each scenario, the mean DEL is computed. It has to be mentioned that over the 10-minute period, the variation in wake exposure due to wind direction changes, will contribute to the creation of few but large load cycles, due to low frequency turbulence added by those inflow variations.

Figure 3 shows that the flapwise damage equivalent load curves are mainly influenced by turbulence. It can be observed that for the upstream turbines referred to turbine 1 e.g. turbine 2 and 8, from rated wind speed on, the thrust coefficient varies due to the entry into operation of the pitch control, influencing the downstream turbulence. This action leads to a change in the full load behavior in turbine 1, tending the loads to decrease to the range of the mean DELs generated in free stream.

The analysis of the DELs in the edgewise direction is shown in Figure 4. The mean DELs in both wake conditions show similar values. On the other hand, compared with the analysis made in flapwise direction, the deviation between DELs in free stream and wake condition is lower since edgewise bending moment is driven mainly by gravity and torque. From rated speed the DELs tend to decrease based on what is explained in the previous paragraph.

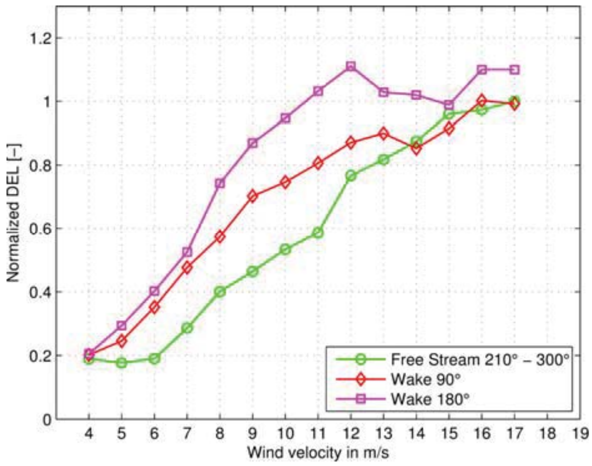

Figure 3. Mean flapwise DELs for free stream vs wake conditions.

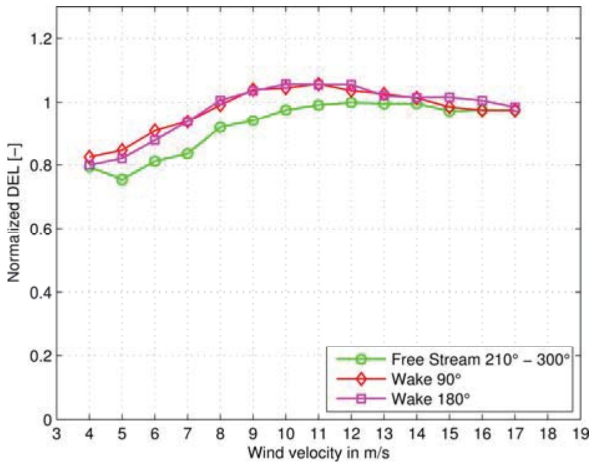

Figure 4. Mean edgewise DELs for free stream vs wake conditions.

5.2 Fatigue analysis as function of sectors

In this section, the wind directions are derived on the basis of turbine orientation. The polar wind direction 0°- 350° is covered with a resolution of 10°. The data analyzed are referred to wind speed values going from 4 to 20 m/s. Due to the different amount of 10-minutes filtered data at each sector, the mean values were computed. The values of turbulence intensity and DELs in flapwise direction are normalized based on the free stream data. To simplify the analysis, it is assumed that for every wind direction, turbine 1 is affected by only one other turbine of the wind farm, even though for some wind angle configurations turbine 1 is partially loaded by more than one wake.

According to the standard IEC-61400-1 ed. 3, the effects from "hidden" turbines do not need to be considered in wake analysis. Figure 5 and Figure 6 depict the distances and the angles between the analyzed turbine and its neighbors, respectively.

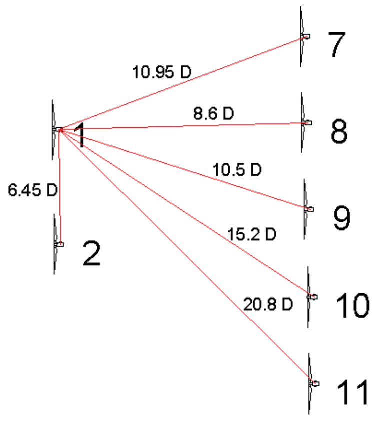

Figure 5. Normalized distances between turbine 1 and its neighbors.

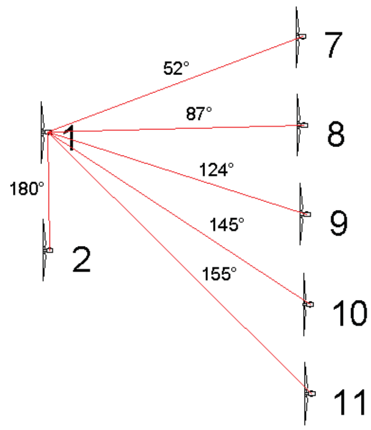

Figure 6. Angles between turbine 1 and its neighbors.

Figure 7 shows the mean turbulence intensities based on nacelle anemometer. In free stream, the turbulence intensity shows the least values. The highest sectorial turbulence intensity value is located at 180°, due to turbine 2, which is located 6.45 D from turbine 1, as it is depicted in Figure 5.

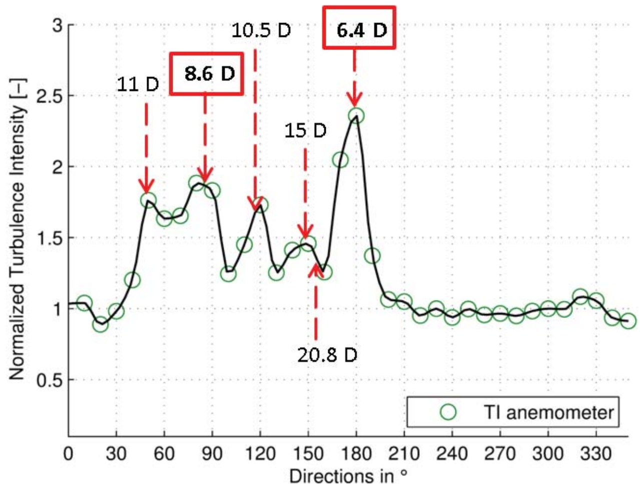

Figure 7. Normalized sectorial mean turbulence intensity in turbine 1. Values in rectangles show which sectors should be included to account for additional turbulence sources according to IEC 61400-1 ed. 3 Annex D.

Figure 7 shows five turbulence peaks affecting turbine 1 detailed in Table 1. The peaks located at 90° and 180°, corresponding to the turbines 8 and 2 respectively, are within the range to be considered as source of additional turbulence, as it is suggested by IEC 61400-1 ed. 3 – Annex D. It is also important to remark that even the turbulence coming from turbines installed at 20.8 D, does not decrease to the ambient turbulence level. This is probably due to at these positions, turbine 1 is partially loaded by more than one turbine.

Table 1. Sectorial turbulence intensity analysis of turbine 1

Location of turbulence intensity peaks	**Location of the neighbor turbines**	**Turbine number**	**Distance respecting the Turbine 1**	**Radio to free stream turbulence**
50°	52°	Turbine 07	10.9 D	1.75
90°	87°	Turbine 08	8.6 D	1.80
120°	124°	Turbine 09	10.5 D	1.65
140°	145°	Turbine 10	15.2 D	1.45
150°	155°	Turbine 11	20.8 D	1.30
180°	180°	Turbine 02	6.45 D	2.30

Figure 8 shows the sectorial mean turbulence intensity measured at turbine 1 and the NTM for an Iref of 0.16 correspondent to class A according to [1]. It can be observed that the thrust coefficient of the upstream turbine influences the turbulence curves seen by turbine 1. In partial load the turbulence intensity shows larger values for directions where the neighboring turbines are located closer, decreasing when the turbine upstream starts to pitch the blades from rated wind speed.

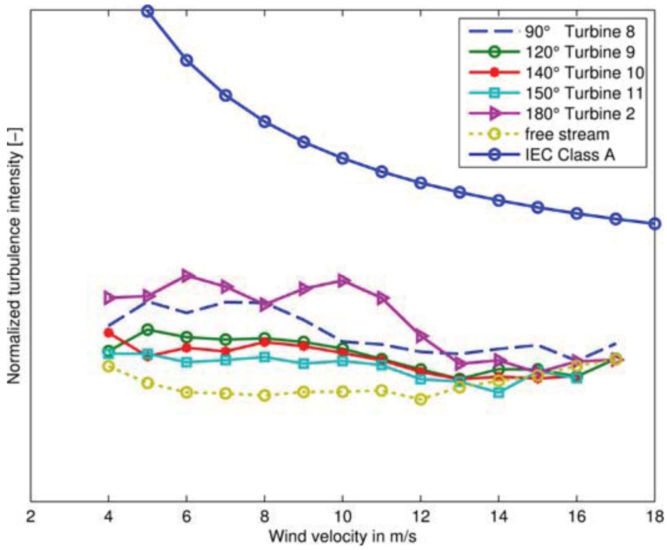

Figure 8. Sectorial measured mean turbulence intensities at turbine 1 according to the location of neighbor turbines and the NTM with Iref 0.16.

A partial load scenario at 8 ± 0.5 m/s in flapwise direction is depicted in Figure 9. With this figure, it can be seen the close connection between turbulence intensity and DELs in flapwise direction. Furthermore, as it was shown similarly in the previous turbulence analysis, there are DELs peaks related with turbines that are located at distances larger than 10 D e.g. 50°, 145°. At 155° where turbine 11 is located, the mean DELs are up to 1.3 times compared to the loads in the free stream conditions.

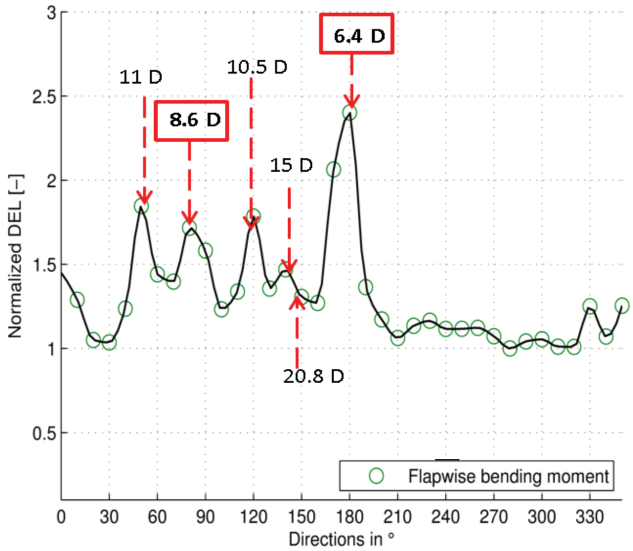

Figure 9. Mean DELs in flapwise direction at 8±0.5 m/s. Values in rectangles show which sectors should be included to account for additional turbulence sources according to IEC 61400-1 ed. 3 Annex D.

6 Discussion

The Standard IEC 61400-1 ed. 3 suggests to include the neighbor turbines that are located within 10 D for turbulence in wake. However, measurements show a considerable source of turbulence and loads caused by turbines located at distances up to 15 D for the MLC Power Production. From sectors, where a neighbor turbine is located within 20.8 D, mean DELs in flapwise direction and mean turbulence intensity do not decrease to the ambient conditions values. Nevertheless at this position, turbine 1 could be partially loaded by more than one turbine.

It was found in the measurements that the turbine's thrust coefficient C_T influences the behavior of the turbulence intensity and the mean DELs in partial load of the blade root in flapwise direction of the downstream turbine. Although the measured turbulence intensities are covered within the IEC 61400-1 ed. 3 model, the turbulence curves in wake conditions seem to be not well represented. In load analysis turbulence intensity plays an important role, therefore to achieve higher load accuracy, a model which can replicates the behavior of the turbulence intensity in wake conditions is necessary.

It is important to point that in blade design, other criteria are also considered e.g. buckling, ultimate stress, tower clearance. Therefore, in some cases, additional fatigue loading in the blades might not be critical, but indeed has to be considered.

Acknowledgments
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