Effective turbulence calculations using IEC 61400-1 Edition 3: Reaching consensus through dialogue and action

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Summary

Design turbulence intensity is a crucial factor for the design of wind turbine support structures, with particular relevance offshore, as well as for the project suitability of wind turbine models. For large offshore projects, wake effects play a major role in fatigue loading of turbines and their support structures. The standard IEC 61400-1 Edition 3 offers a method for calculation of "fatigue equivalent" turbulence intensity within large wind farms, but this is open to a range of interpretations giving a range of different results. At one end of the spectrum of interpretations, one can add significant costs to a project, or alternatively end up with a non-conservative design. The range of possible turbulence results are presented for all reasonable interpretations of the standard and knock-on effects for project costs and technical feasibility are evaluated. In this way, the importance of the detailed interpretation of the standard is highlighted with a view to instigating industry debate and agreement on a single consistent interpretation.

Keywords: *Offshore wind farms, IEC 61400-1 Edition 3, effective turbulence intensity, wake effects, fatigue loading, site-suitability, support structure design.*

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1. Introduction

The first offshore wind farms have been operating for more than 10 years, and at the end of 2009 the total installed capacity just exceeded 2 GW. The whole industry is about to take a giant leap forward with several gigawatts of capacity in the process of being contracted out for construction in 2010-2015. Some forecast 17 GW to be operating by 2015 [1].

While the projects installed to date are of relatively small size, larger gigawatt scale wind farms will soon be erected at sea.

Wind is one of the principal sources of structural loading for turbines and their support structures. Material fatigue is markedly governed by wind speed fluctuations, i.e. turbulence, and rotary motion, i.e. rotor mass and mass imbalance. In the offshore environment, ambient turbulence is typically low, often lower than onshore sites by a factor of two or greater. However, superposition of wakes from multiple turbines in large wind farms tends to add to the naturally occuring ambient turbulence. This “extra” ambient turbulence, along with discrete wake loading from adjacent turbines, increases equivalent loading on turbines compared to that on a single turbine in isolation.

A methodology for calculating fatigue equivalent loading from wake and non-wake situations in wind turbine clusters was introduced in IEC 61400-1 Edition 3 [2]. The model is based on work conducted by Sten Frandsen since 2000 and published wholly in [3].

It is argued in [3] that fatigue equivalent loading to which turbines are subject to in wind turbine clusters can be represented structurally by a change in turbulence intensity alone. A model is proposed to combine all loading situations by deriving an effective turbulence value for each wind speed bin. The model therefore authorises a significant reduction in the number of required computations for fatigue analysis in the design process. The combination of the wake and non-wake load cases for different components is achieved by way of a weighting method involving the slope of the considered material’s Wöhler curve.

Although this methodology inclusion in [2] is informative and therefore not compulsory, it has become commonly used for assessing the suitability of a particular turbine model for a particular project site and turbine layout. The methodology is also used to calculate specific turbine loads for design of support structures at offshore sites.

In this paper, any reasonable interpretive-doubt in the methodology presented in [2] is identified and the result and implications of the multiple possible interpretations are exposed. The results are presented and discussed primarily within the context of support structure design. Site-suitability implications for wind turbines are also discussed briefly.

2. Interpretation in IEC61400-1 Edition 3

The main areas of interpretive-doubt in the methodology as presented in Annex D of [2] are discussed below. In each area, two reasonable implementations are examined. It is noted that other reasonable interpretations may exist on top those presented below.

2.1. Characteristic view-angles

In [2], the methodology is presented for a uniform direction distribution although it is noted that a non-uniform distribution may also be used. Across all sectors, wake and non-wake loading situations must be weighted by the actual probability of the wind direction sector in which a particular loading occurs. However, no guidance is provided regarding the determination of wake sectors or view-angles θ_w.

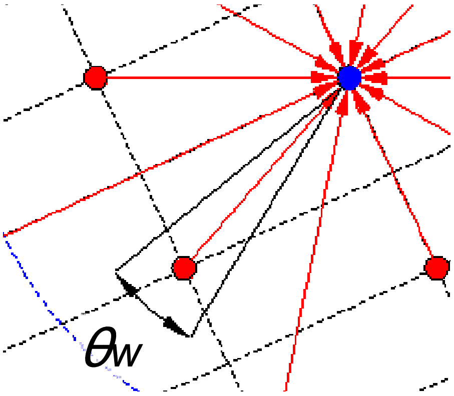

Figure 1: Wake sectors in which a downstream turbine is considered to be affected by the wake of the upwind turbine

The Park model [4] has been widely used across the wind industry for assessing wake situations in wind farm and the associated wake losses. View-angles θ_w in the Park model are calculated according to (Eq. 1) below.

$$\theta_W = atan(\frac{1}{s}) + atan(k) \qquad \text{(Eq. 1 - Park)}$$

Where:

- s - is equal to d/Do;
- d - is the downstream distance [m];
- D_0 - is the diameter of the wake producing turbine [m]; and
- k - is the Park decay constant.

Therefore, the calculation of waked sectors using this model is a reasonable implementation.

However in the research work published in [3], on which the methodology is based, a characteristic view-angle according to (Eq. 2) below is proposed.

$$\theta_W = \frac{1}{2}\left(atan(\frac{1}{s}) + 10^\circ\right) \qquad \text{(Eq. 2 - Frandsen)}$$

(Eq. 2) should therefore be used to calculate wake sectors in a manner which is consistent with the original research work by Frandsen. Depending on the wake decay factor assumed, view-angles according to (Eq. 1) are 10-70% greater than those of (Eq. 2) therefore the methodology presented in Annex D of IEC 61400-1 [2] should address the calculation of wake sectors.

2.2. Large wind farm correction

[3] suggests that inside large wind farms, the cumulative impact of wakes from numerous turbines tends to augment the ambient turbulence relative to that upwind of the wind farm. The increase is broadly associated to a reduction in mean wind speed and turbine-generated roughness.

[2] recommends that “when the number of wind turbines from the considered unit to the edge of the wind farm is more than 5” a correction of the ambient turbulence should be considered. In the Addendum [2] it is clarified that the correction shall not be applied in the centre-wake calculation for turbines sited within 10 rotor diameters of the turbine under consideration.

While this criterion is well defined and therefore straightforward to implement along the direction of turbine alignments for a regular layout, it leaves room for interpretation when departing from the main directions defining the layout.

At one end of the range of possible interpretations, one coarse but reasonably conservative implementation involves considering the correction at the wind farm level. If a project can be generically classified as a large wind farm i.e. one or several turbine locations are deeply embedded, the correction is applied globally irrespective of the actual position of each turbine in the wind farm or the wind direction. This is equivalent to considering that the wind farm is infinitely large.

At the other end of the range, a finer interpretation involves applying the correction selectively, in single degree direction sectors when the wakes of six or more turbines located beyond 10 rotor diameters (i.e. not for centre-wake calculations), impede on the rotor of the unit under consideration. The wake view-angles, θ_w, discussed in Section 2.1 may be considered for the purpose of determining the number of wakes arriving on a particular unit.

2.3. Other areas of interpretation

Other areas of interpretation exist although these have not been examined in this paper. In particular, the authors have met the following complications when implementing the methodology:

- Choice of view-angles for large wind farm correction sectors;
- Irregular layouts and the application of the large wind farm correction factor; and
- Application of the methodology for wind farms utilising multiple turbine models with different rotor diameters and thrust characteristics.

3. Case study

Permutations of the possible interpretations discussed in Sections 2.1 and 2.2 have been investigated in the context of a notional offshore project. Implications for structural design and site-suitability have also been assessed in this section.

The following project characteristics have been considered for the purpose of this case study:

- 130 turbine units
- Equilateral layout - 6D spacing
- Mean wind speed = 9.2 m/s
- Ambient turbulence I_{15} = 6.0%
- Typical northern European wind rose
- Park wake decay constant of k = 0.04

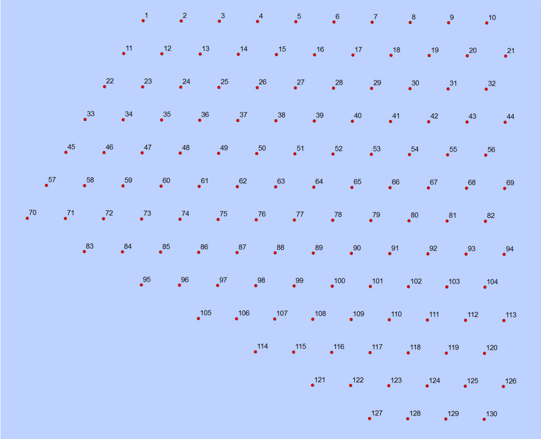

Figure 2: Wind farm layout investigated

3.1. Effective turbulence

Effective turbulence calculations have been completed for four different combinations of interpretations presented below:

		Large wind farm	
		Global	**Selective**
View-angles	**Frandsen**	◆	◆
	PARK	◆	◆

Table 1: Permutations of possible interpretations

A representative value of the Wöhler exponent of 4 for steel materials has been considered here. Higher Wöhler exponent would need to be investigated for other materials, in particular for composite materials used in wind turbine blades. However, for the purpose of assessing support structure implications for offshore turbines, a single Wöhler exponent has been considered.

Calculations have been implemented according to Addendum 88/339/CDV to IEC61400-1 Ed3. Results from those calculations are presented in Figure 3 for each combination and according to the colour code of Table 1.

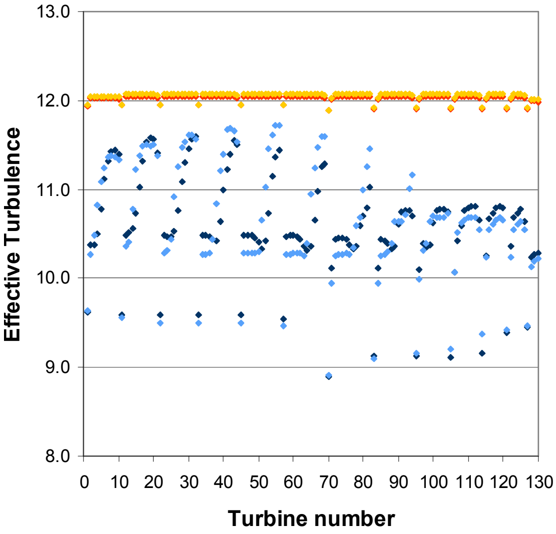

Figure 3: Effective turbulence [%] results at 15 m/s

It is evident from Figure 3 that different interpretations lead to significantly different results. Detailed interpretation of the large wind farm correction clearly has a major impact on the overall results. In the example presented here, the contribution from the corrected ambient turbulence tends to govern the overall results and tends to eclipse the individual centre-wake contributions. Differences in calculation of the view-angles therefore also become irrelevant.

An average difference of effective turbulence intensity of 1.5% results from the different implementations of the ambient turbulence correction. As anticipated, the largest deviations are produced for turbines at the periphery of the wind farm, with differences of up to 3% for some locations.

When a selective application of the large wind farm correction is implemented, the choice of view-angle calculation method does however become important and results in manifest differences for some wind turbine locations. It is noted that the layout spacings and wake decay constant used here for the Park model tend to undermine the real differences between the two view-angle calculation methods presented in Section 2.1. Smaller spacings and a higher wake decay constant, which may be applicable in an onshore context, would lead to much greater differences in the results.

A single turbine location was selected with the view of assessing the structural and site-suitability implications of differences in model interpretation. A location representative of the median difference between the highest and lowest turbulence intensity results was retained. The effective turbulence intensity distributions I_1 ("Frandsen" / "Global" in Table 1) and I_2 ("Frandsen" / "Selective") from the two extreme interpretations are presented in Figure 4 below.

At 15m/s, the two interpretations exhibit a difference of 1.8%. This difference reduces to 1% at wind speeds between 20 - 25m/s.

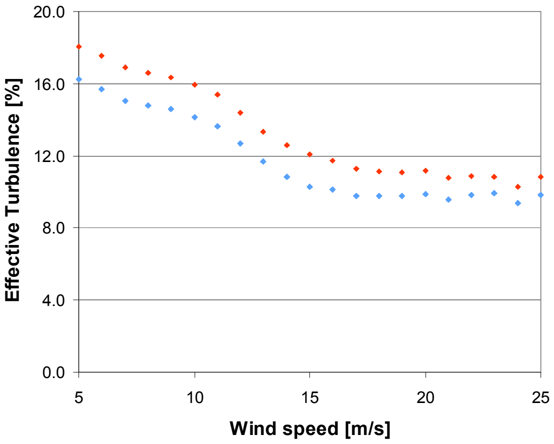

Figure 3: Effective turbulence intensities I_1 (Red) and I_2 (blue) for two interpretations of the standard

3.2. Equivalent loading

Support structure loads were calculated for a variable speed, pitch regulated 3.6MW wind turbine on a monopile support structure in 15m water depth. A numerical model of a generic 3.6MW turbine was created using the GH Bladed software, with the following characteristics:

Rated power	3.6	MW
Rotor diameter	107	m
Cut in wind speed	4	m/s
Rated wind speed	11	m/s
Cut out wind speed	25	m/s
Tower top mass	220000	kg

Table 2: Generic 3.6MW wind turbine parameters

Design load cases were performed according to the IEC offshore wind turbine design standard [3] using generic site conditions representative of a UK Round 3 offshore wind farm location. Two sets of load calculations including wave loads and soils were performed, one for each set of turbulence intensities presented in Section 3.1.

The lifetime fatigue loads were integrated using a Weibull distribution with site-specific annual mean wind speed of 9.2m/s. Damage equivalent loads were derived using Miner's rule with load assumed to be proportional to stress, using a reference frequency of 0.0158Hz corresponding to 1x10^7 cycles in 20 years. The damage equivalent loads presented in Table 3 are for the principal tower overturning moment Mz. Loads are given for an inverse S-N slope of 4, corresponding to the material properties of steel.

	DEL, Tower Mz (kNm) 1e7 Cycles in 20 years
Level (mLAT)	$\mathcal{U}(I_2)$ / $\mathcal{U}(I_1)$
-25.0	96.9%
-22	96.7%
-17	95.9%
-9.8	94.5%
-5.8	93.5%
-1.8	92.8%
1.7	92.3%
5.9	92.1%
10	92.2%
15	92.3%
21.7	92.3%
80.0	92.4%

Table 3: Monopile damage equivalent load results

A reduced set of extreme load cases was considered, selected as those expected to lead to design driving loads on the support structure. These included dlc1.6 (power production in severe sea state), dlc2.1 (power with control system fault) and dlc6.1 (idling in 50 year storm conditions). However most of the driving loads on the support structure came from dlc6.1 which is modelled using constant turbulence intensity, so little load reduction was experienced.

Damage equivalent loads were also determined for a variable speed, pitch regulated generic 5MW turbine on a jacket structure in water depth of 30m using GH Bladed.

Rated power	5	MW
Rotor diameter	128	m
Cut in wind speed	4	m/s
Rated wind speed	12	m/s
Cut out wind speed	30	m/s
Tower top mass	430000	kg

Table 4: Generic 5MW wind turbine parameters

Damage equivalent loads were derived using Miner's rule using a frequency of 1x10^7 cycles for a lifetime of 20 years and S-N curve with gradient m = 4.

3.3. Support-structure design

Structural analysis of a monopile type foundation was carried out using GL-GH in-house analysis software, along with the proprietary soil-structure interaction software Lpile. Two potential changes in structural design were investigated in response to reduction in loading described in section 3.2:

- Localised reduction in wall thickness of the structure (generally governed by fatigue loads)

- Reduction in pile embedment length. (generally governed by extreme loads)

Both of these will allow a decrease in structural weight and therefore cost. No other structural changes, such as changes to diameter, were investigated as they were considered to be unlikely given the limited reduction in loading.

The design philosophy embodied in the original design of the monopile foundation was followed, both in establishing a "baseline" analysis, using $\upsilon(I_1)$ loads, and then in re-optimising the design, using $\upsilon(I_2)$ loads. This replication of design philosophy included:

- Applying the same S-N curves [5] in the same areas

- Allowing the same wall thickness steps as the original foundation.

- Soil-structure analysis was carried out using the same method (Lpile) and using the same input parameters.

Wall thickness optimisation was carried out using in-house fatigue analysis software, whilst ensuring that the predicted fatigue life at all positions matched or exceeded the baseline fatigue life. Thickness reductions were possible in the tower and transition piece. However, no changes were possible in the monopile as any wall thickness reduction would have reduced the fatigue life below the baseline fatigue life.

The baseline and revised designs were then checked against the relevant ULS loads. A combination of a slight decrease in the ULS loads and the reduction in wall thicknesses arising from the FLS optimisation led to a slight increase in utilisation ratios. However, all utilisation ratios are well within acceptable limits, so the driving design case for the wall thicknesses was still the fatigue case.

The potential for reducing embedment length was checked using Lpile to check that monopile displacements were within acceptable limits. The reduction in the $\upsilon(I_2)$ loads led to minor reductions in monopile displacements. However, reducing the monopile embedment length of the revised design by just 1m led to monopile displacements which were in excess of baseline. Hence no reduction in pile embedment was deemed possible. Smaller reductions/refinements in embedment length would not be considered at this stage in the design process for the monopile embedment.

The final check was to ensure that the changes made did not greatly affect the dynamic response of the foundation. Significant changes in the foundation's natural frequency would change the response to dynamic loads and, in an extreme instance, require revision of wind turbine controller settings and a further load calculation. When the baseline and optimised designs were compared, their first natural frequencies were within 0.1Hz, so the loading was deemed to be valid for the optimised model.

In summary, the monopile structures investigation found that the mass of the tower and transition piece could be reduced due to the reduction in loading, but that the mass of the monopile could not be reduced. Results are summarised in Table 5 below.

	Primary Steel Mass (tonnes, % change)		
	$\mathcal{U}(I_1)$	$\mathcal{U}(I_2)$	$\mathcal{U}(I_2)$ / $\mathcal{U}(I_1)$
Tower	200	185	93%
Transition Piece	260	240	91.5%
Monopile	420	420	100%

Table 5: Monopile support-structure results

The generic 5MW turbine on a jacket was modelled using GH Bladed and GH in-house analysis software. In Bladed, the jacket and tower were modelled with the structure ending at the mudline – piles were not included in the model for this exercise. A spring system at the mudline comprising linear translational and rotational springs represented the soil profile.

Joint details and section sizes of braces were the focus for design to [5] and DNV-RP-C203 in FLS. A baseline case was determined using damage equivalent loads from I_1 effective turbulence distribution. This design was further optimised with reduced section thickness in the braces using in-house fatigue analysis software. The same procedure was implemented for revised damage equivalent loads calculated using the I_2 effective turbulence distribution.

Cast nodes were required for brace-to-leg connections in order for compliance in fatigue for both turbulence intensity cases. X-brace joints consist of fabricated forged tubulars to enable larger wall thicknesses to be used.

Primary steel masses for the two jacket designs are summarised in Table 6 below:

	Primary Steel Mass (tonnes, % change)		
	$\mathcal{U}(I_1)$	$\mathcal{U}(I_2)$	$\mathcal{U}(I_2)$ / $\mathcal{U}(I_1)$
Jacket	610	570	93%

Table 6: Jacket support-structure results

No change in pile weight is anticipated for the jacket.

4. Conclusions

Annex D of IEC 61400-1 Edition 3 [2] was reviewed and, for each area of reasonable interpretive-doubt identified, two different implementations were presented. Effective turbulence values were computed for the four resulting possible combinations of interpretations for a notional offshore wind project as a case study. It was shown that averaged across a wind farm a difference of effective turbulence intensity of 1.5% at 15m/s can result, depending on one's detailed interpretation of the standard. Fatigue load calculations were performed for the two sets of effective turbulence results exhibiting a difference of 1.8% at 15m/s. Loads were derived for a 3.6MW wind turbine model on a monopile support structure and for a 5MW turbine on a jacket support structure. The original designs of the monopile and of the jacket for the most onerous sets of loads were re-optimised based on the new loads.

A 4% reduction of the total primary steel weight of the support structure (tower, TP, monopile) for the 3.6MW turbine was estimated for the reduced set of loads based on the least onerous interpretation of the IEC standard. For the 5MW turbine jacket, a 7% reduction in primary steel weight was predicted. Fabrication costs for the support structures would be expected to decrease by 3% and 5% for the 3.6MW and 5MW turbines, respectively.

It is noted that individual support structure designs for each turbine location would be required to achieve the above cost reductions. In practice, the most onerous turbine load-set is generally considered for design of all support structures at an offshore wind farm in order to keep the number of individual designs relatively low for fabrication and installation reasons. The results presented in Figure 3 indicate a difference in effective turbulence of 0.5% (at 15m/s) for the most onerous turbine location between possible interpretations of the standard. That difference alone could impact support structure weights and costs by 1-2%.

The results of the analysis presented here indicate that effective turbulence results can vary significantly depending on the location of each turbine in the wind farm when a selective implementation of the large wind farm correction is considered. Since turbulence has a significant impact on support structure design and cost, there may be a case for considering a few turbulence cases in the design alongside the typical depth and soil properties cases.

Turbine suitability for a certain site and layout may also be impacted differently depending on specific interpretation of the standard. Intentionally conservative interpretations of the methodology may be considered by project owners or turbine suppliers in case of doubt, with wide-ranging implications for turbine selection, layout and project design.

It is hoped that this paper will serve to highlight the importance of the detailed interpretation of the methodology and instigate industry debate and agreement on a single consistent interpretation for the next revision of IEC standard.

References

1. MAKE Consulting, Market Outlook 2010, March 2010.

2. International Electrotechnical Commission (IEC) Standard 61400-1, Edition 3, *Design requirements,* 2005. Ed 3. Addendum 88/339/CDV 2008.

3. Sten T Frandsen, *Turbulence and turbulence-generated structural loading in wind turbine clusters*, Risø-R-1188(EN), 2005 and 2007.

4. P. Sanderhoff, PARK – User's Guide, *A PC-program for calculation of wind turbine park performance*, Risø-I-668(EN), Risø National Laboratory, 1993.

5. DNV-OS-J101 2008