# IEC 61400-1

Edition 3.0   2010-10

# INTERNATIONAL STANDARD

AMENDMENT 1

**Wind turbines –**
**Part 1: Design requirements**

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**AMENDMENT 1**

**Wind turbines –**
**Part 1: Design requirements**

# FOREWORD

This amendment has been prepared by IEC technical committee 88: Wind turbines.

The text of this amendment is based on the following documents:

| FDIS | Report on voting |
|------|------------------|
| 88/374/FDIS | 88/378/RVD |

Full information on the voting for the approval of this amendment can be found in the report on voting indicated in the above table.

The committee has decided that the contents of this amendment and the base publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version may be issued at a later date.

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## 2 Normative references

*Replace the existing list of normative references by the following new list:*

IEC 60204-1, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V a.c. or 1 500 V d.c. and not exceeding 36 kV*

IEC 60364 (all parts), *Low-voltage electrical installations*

IEC 60364-5-54, *Electrical installations of buildings – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements, protective conductors and protective bonding conductors*

IEC 60721-2-1, *Classification of environmental conditions – Part 2: Environmental conditions appearing in nature – Temperature and humidity*

IEC 61000-6-1, *Electromagnetic compatibility (EMC) – Part 6-1: Generic standards – Immunity for residential, commercial and light-industrial environments*

IEC 61000-6-2, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments*

IEC 61000-6-4, *Electromagnetic compatibility (EMC) – Part 6-4: Generic standards – Emission standard for industrial environments*

IEC 61400-2, *Wind turbines – Part 2: Design requirements for small wind turbines*

IEC 61400-21, *Wind turbines – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines*

IEC 61400-24, *Wind turbines – Part 24: Lightning protection*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

ISO 76:2006, *Rolling bearings – Static load ratings*

ISO 281, *Rolling bearings – Dynamic load ratings and rating life*

ISO 2394:1998, *General principles on reliability for structures*

ISO 2533:1975, *Standard atmosphere*

ISO 4354, *Wind actions on structures*

ISO 6336-2, *Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:2006, *Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength*

ISO 81400-4, *Wind turbines – Part 4: Design and specification of gearboxes*

# 3 Terms and definitions

## 3.26 – limit state

*Replace* ISO 2394 *by* 2.2.9 of ISO 2394.

## 3.55 – ultimate limit state

*Replace* ISO 2394 *by* 2.2.10 of ISO 2394.

# 4 Symbols and abbreviated terms

## 4.1 Symbols and units

*Switch the definitions of $\sigma_2$ and $\sigma_3$. The vertical wind velocity standard deviation should be $\sigma_3$, not $\sigma_2$.*

# 6 External conditions

## 6.3.1.3 Normal turbulence model (NTM)

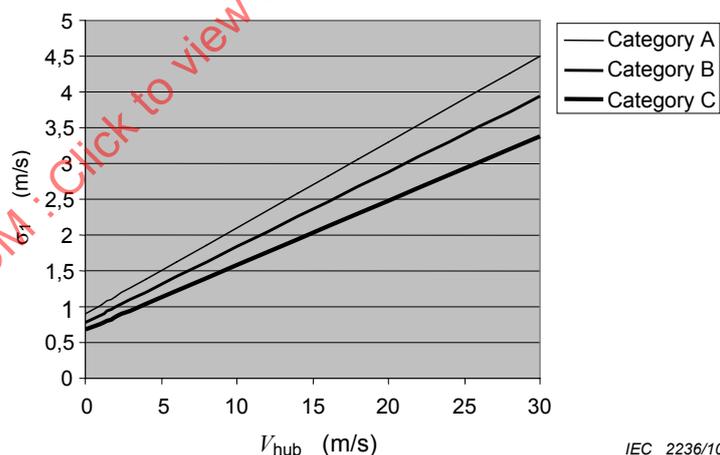*Replace the existing Figures 1a and 1b by the following new figures:*



IEC 2236/10

**Figure 1a –Turbulence standard deviation for the normal turbulence model (NTM)**
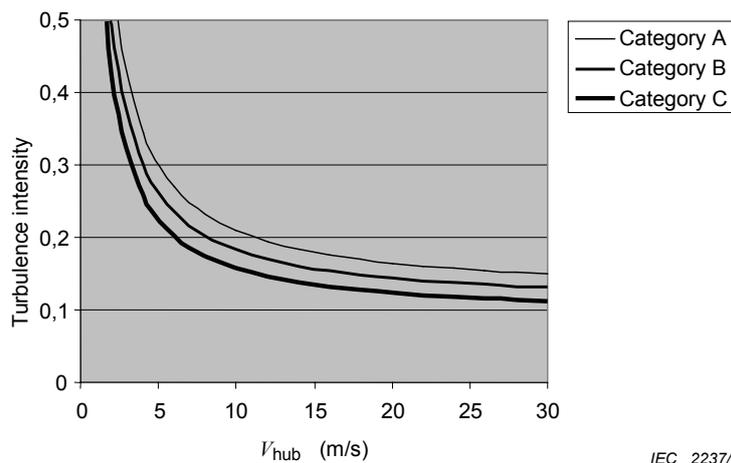
IEC   2237/10

**Figure 1b – Turbulence intensity for the normal turbulence model (NTM)**

### 6.3.2.6   Extreme wind shear (EWS)

*Replace the number 2,5 in equations (26) and (27) to 2,5 [m/s]. (The number 2,5 in equations (26) and (27) is not dimensionless.)*

## 7   Structural design

### 7.4.2   Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 – 2.4)

*Add, as 2nd paragraph, the following new text:*

As an alternative to the specification of DLC 2.3 above and in Table 2, DLC 2.3 may instead be considered as a normal event (i.e. a partial safety factor for load of 1,35) to be analyzed using stochastic wind simulations (NTM - $V_{in}<V_{hub}<V_{out}$) combined with an internal or external electrical system fault (including loss of electrical network connection). In this case, 12 response simulations shall be carried out for each considered mean wind speed. For each response simulation, the extreme response after the electrical fault has occurred is sampled. The fault must be introduced after the effect of initial conditions has become negligible. For each mean wind speed, a nominal extreme response is evaluated as the mean of the 12 sampled extreme responses plus three times the standard deviation of the 12 samples. The characteristic response value for DLC 2.3 is determined as the extreme value among the nominal extreme responses.

### 7.5   Load calculations

*Add, after second paragraph, the following new text:*

When turbulent winds are used for dynamic simulations, attention should be given to the grid resolution regarding the spatial[1] and time resolution.

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[1] Concerning the spatial resolution, the maximum distance between adjacent points should be smaller than 25 % of $Λ1$ (Equation (5)) and no larger than 15 % of the rotor diameter. This distance is meant to be the diagonal distance between points in each grid cell defined by four points. In the case of a non-uniform grid, an average value over the rotor surface of the distance between grid points can be considered as the representative spatial resolution, but this distance should always decrease towards the blade tip.

*Replace the last paragraph by the following new text:*

Ultimate load components may also be combined in a conservative manner assuming the extreme component values occur simultaneously. In case this option is pursued, both minimum and maximum extreme component values shall be applied in all possible combinations to avoid introducing non-conservatism.

Guidance for the derivation of extreme design loads from contemporaneous loads taken from a number of stochastic realisations is given in Annex H.

### 7.6.1.2 Partial safety factor for consequence of failure and component classes

*Add, after the bullets defining the component classes, the following new text:*

The consequences of failure factor shall be included in the test load when performing tests as for example full scale blade testing.

### 7.6.2 Ultimate strength analysis

*Replace equation (31) by the following new equation:*

$$\gamma_f F_k \leq \frac{1}{\gamma_n} \cdot \frac{1}{\gamma_m} f_k \tag{31}$$

*Add the following new paragraph after equation (31):*

Note that $\gamma_n$ is a consequence of failure factor and shall not be treated as a safety factor on materials.

*Delete the last sentence in 5th paragraph ("For guidance see Annex F") and insert, after the 5th paragraph, the following two paragraphs:*

Data used in extrapolation methods shall be extracted from time series of turbine simulations of at least 10 min in length over the operating range of the turbine for DLC 1.1. A minimum of 15 simulations is required for each wind speed from ($V_{rated} - 2$ m/s) to cut-out and six simulations are required for each wind speed below ($V_{rated} - 2$ m/s). When extracting data, the designer must consider the effect of independence between peaks on the extrapolation and minimize dependence when possible. The designer shall aggregate data and probability distributions to form a consistent long-term distribution. To ensure stable estimation of long-term loads, a convergence criterion shall be applied to a probability fractile less than the mode of the data for either the short-term or long-term exceedance distributions. For guidance, see Annex F.

The characteristic value for blade root in-plane and out-of-plane moments and tip deflection may be determined by a simplified procedure[2]. The characteristic value may then be determined by calculating the mean of the extremes for each 10-min bin and using the largest value, multiplied by an extrapolation factor of 1,5, while maintaining the partial load factor for statistical load extrapolation, see Table 3.

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[2] This approach is considered conservative for 3-bladed upwind wind turbines. Caution should be exercised for other wind turbine concepts.

### 7.6.2.1 Partial safety factor for loads

*Replace the existing formula in the footnote of Table 3 by the following new formula:*

$$\varsigma = \begin{cases} 1 - \left| \dfrac{F_{\text{gravity}}}{F_{\text{k}}} \right|; & \left| F_{\text{gravity}} \right| \leq \left| F_{\text{k}} \right| \\ 0; & \left| F_{\text{gravity}} \right| > \left| F_{\text{k}} \right| \end{cases}$$

*Add the following new text after Table 3:*

The approach in 7.6.1.1, where the partial safety factor for loads is applied to the load response, assumes that a proper representation of the dynamic response is of prime concern. For foundations or where a proper representation of non-linear material behaviour or geometrical non-linearities or both are of primary concern, the design load response $S_{\text{d}}$ shall be obtained from a structural analysis for the combination of the design loads $F_{\text{d}}$, where the design load is obtained by multiplication of the characteristic loads $F_{\text{k}}$ by the specified partial load factor $\gamma_{\text{f}}$ for favourable and unfavourable loads,

$$F_{\text{d}} = \gamma_{\text{f}} F_{\text{k}}$$

The load responses in the tower at the interface (shear forces and bending moments) factored with $\gamma_{\text{f}}$ from Table 3 shall be applied as boundary conditions.

For gravity foundations, the limit states considering overall stability (rigid body motion with no failure in soil) and bearing capacity of soil and foundation shall be regarded and calculated according to a recognized standard. In general, a partial safety factor of $\gamma_{\text{f}}$ = 1,1 for unfavourable permanent loads and $\gamma_{\text{f}}$ = 0,9 for favourable permanent loads shall be applied for foundation load, backfilling and buoyancy. If it can be demonstrated by respective quality management and surveillance that the foundation material densities specified in the design documentation are met on site, a partial safety factor for permanent foundation load $\gamma_{\text{f}}$ = 1,0 can be used for the limit states regarding bearing capacity of soil and foundation. If buoyancy is calculated equal to a terrain water level, a partial safety factor for buoyancy $\gamma_{\text{f}}$ = 1,0 can be applied.

Alternatively, the check of capacity of soil and foundation can be based on a partial safety factor $\gamma_{\text{f}}$ = 1,0 for both favourable and unfavourable permanent loads and the check of overall stability can be based on a partial safety factor of $\gamma_{\text{f}}$ = 1,1 for unfavourable permanent loads and $\gamma_{\text{f}}$ = 0,9 for favourable permanent loads, using in all cases conservative estimates of weights or densities defined as 5 % / 95 % fractiles. The lower fractile is to be used when the load is favourable. Otherwise, the upper fractile is to be used.

### 7.6.5 Critical deflection analysis

*Replace the existing text by the following new text:*

#### 7.6.5.1 General

It shall be verified that no deflections affecting structural integrity occur in the design conditions detailed in Table 2.

The maximum elastic deflection in the unfavourable direction shall be determined for the load cases detailed in Table 2 using the characteristic loads. The resulting deflection is then multiplied by the combined partial safety factor for loads, materials and consequences of failure.

- Partial safety factor for loads

The values of $\gamma_{\text{f}}$ shall be chosen from Table 3.

- Partial safety factor for the elastic properties of materials

The value of $\gamma_m$ shall be 1,1 except when the elastic properties of the component in question have been determined by testing and monitoring in which case it may be reduced. Particular attention shall be paid to geometrical uncertainties and the accuracy of the deflection calculation method.

- Partial safety factor for consequences of failure

Component class 1: $\gamma_n$ = 1,0

Component class 2: $\gamma_n$ = 1,0

Component class 3: $\gamma_n$ = 1,3.

The elastic deflection shall then be added to the un-deflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference.

### 7.6.5.2 Blade (tip) deflection

One of the most important considerations is to verify that no mechanical interference between blade and tower will occur.

In general, blade deflections have to be calculated for the ultimate load cases as well as for the fatigue load cases. The deflections caused by the ultimate load cases can be calculated based on beam models, FE models or the like. All relevant load cases from Table 2 have to be taken into account with the relevant partial load safety factors.

Moreover, for load case 1.1 extrapolation of tip deflection is mandatory according to 7.4.1. Here direct dynamic deflection analysis can be used. The exceedance probability in the most unfavourable direction shall be the same for the characteristic deflection as for the characteristic load. The characteristic deflection is then to be multiplied by the combined safety factor for loads, materials and consequences of failure and be added to the un-deflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference.

## 9 Mechanical systems

### 9.4 Main gearbox

*Replace the existing text by the following new text:*

The main gearbox shall be designed according to ISO 81400-4, until a similar document is published in the IEC 61400 series.

### 9.5 Yaw system

*Replace the second paragraph by the following new text:*

Any motors shall comply with relevant parts of Clause 10.

Non-redundant parts of the gear system such as the final yaw gear shall be considered as component class 2. When multiple yaw drives ensure sufficient redundancy in the yaw gear system, and easy replacement is possible, the reduction gearbox and the final drive pinion may be considered to be in component class 1.

The safety against pitting shall be determined in accordance with ISO 6336-2. The application of the upper limit curve (1) for life factor $Z_{NT}$, which allows limited pitting, is permissible. Sufficient tooth bending strength shall be proven in accordance with ISO 6336-3. The reverse

bending loads on gear teeth shall be considered in accordance with ISO 6336-3 Annex B. Minimum values for $S_F$ and $S_H$ are specified in Table 5. These values must be achieved by using characteristic loads $F_k$ Hence they include the partial safety factor for consequences, $\gamma_n$, materials, $\gamma_m$ and loads, $\gamma_f$.

**Table 5 – Minimum required safety factor $S_H$ and $S_F$ for the yaw gear system**

|  | Component class 1 | Component class 2 |
|---|---|---|
| Surface durability (pitting) | $s_H \geq 1,0$ | $s_H \geq 1,1$ |
| Tooth bending fatigue strength | $s_F \geq 1,1$ | $s_F \geq 1,25$ |
| Static bending strength | $s_F \geq 1,0$ | $s_F \geq 1,2$ |

Lower safety factors may be applicable in cases where efficient monitoring is implemented. If safety factors below 1,0 are applied, then the maintenance manual must reflect anticipated replacement intervals.

# 10   Electrical system

## 10.5   Earth system

*Replace, in the first paragraph*, IEC 61024-1 *by* IEC 62305-3.

## 10.6   Lightning protection

*Replace* IEC 61024-1 *by* IEC 62305-3.

## 10.9   Protection against lightning electromagnetic fields

*Replace, in the first paragraph,* IEC 61312-1 *by* IEC 62305-4.

# 11   Assessment of a wind turbine for site-specific conditions

## 11.2   Assessment of the topographical complexity of a site

*Replace the text of this subclause by the following new text:*

The complexity of the site is characterised by the slope of the terrain and variations of the terrain topography from a plane.

To obtain the slope of the terrain, planes are defined that fit the terrain within specific distances and sector amplitudes for all wind direction sectors around the wind turbine and pass through the tower base. The slope, used in Table 4, denotes the slopes of the different mean lines of sectors passing through the tower bases and contained in the fitted planes. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between the fitted plane and the terrain at the surface points.

**Table 4 – Terrain complexity indicators**

| Distance range from wind turbine | Sector amplitude | Maximum slope of fitted plane | Maximum terrain variation[3] |
|---|---|---|---|
| < 5 $z_{hub}$ | 360° | | < 0,3 $z_{hub}$ |
| < 10 $z_{hub}$ | 30° | < 10° | < 0,6 $z_{hub}$ |
| < 20 $z_{hub}$ | 30° | | < 1,2 $z_{hub}$ |

The resolution of surface grids used for terrain complexity assessment must not exceed the smallest of 1,5 $z_{hub}$ and 100 m.

The site shall be considered complex, if 15 % of the energy in the wind comes from sectors that fail to conform to the criteria in Table 4 and homogeneous, if less than 5 % of the energy in the wind comes from sectors that fail to conform.

A complexity index $i_c$ is defined, such that $i_c$ = 0 when less than 5 % of the energy comes from complex sectors, and $i_c$ = 1 when more than 15 % of the energy comes from complex sectors. In between, $i_c$ varies linearly.

## 11.4 Assessment of wake effects from neighbouring wind turbines

*Add the following new text after the 3rd paragraph:*

Generally, the effective turbulence for fatigue and various ultimate loads cannot be assumed to be the same.

*Delete the 4th paragraph to the end of the subclause.*

## 11.9 Assessment of structural integrity by reference to wind data

*Replace the existing footnote 18 by the following new footnote:*

[18] The effect of complex terrain may be included by additional multiplication with a turbulence structure correction parameter $C_{CT}$ defined as

$$C_{CT} = \frac{\sqrt{1 + (\hat{\sigma}_2 / \hat{\sigma}_1)^2 + (\hat{\sigma}_3 / \hat{\sigma}_1)^2}}{1,375}$$

where ratios of the estimated standard deviations, $\hat{\sigma}_i$, correspond to hub height values. Where there are no site data for the components of turbulence and the terrain is complex, results of modelling or $C_{CT}$ = 1+0,15 $i_c$, where $i_c$ is the complexity index defined in Subclause 11.2, may be used.

*Replace the 5th paragraph to the end of the subclause by the following new text:*

An adequate assessment of wake effects[4] can be performed by verifying that the turbulence standard deviation $\sigma_1$ from the normal turbulence model is greater or equal to the estimated 90 % fractile of the turbulence standard deviation (including both ambient and wake

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3 The check criteria is considered fulfilled if the requisite fails over a surface less than 5 $z_{hub}^2$.

4 This approach can also be used for the assessment of sector-wise varying turbulence, alone or in combination with wake turbulence. The standard deviation $\hat{\sigma}_\sigma$ of $\hat{\sigma}$ may be determined as the average of the sector-wise values.

turbulence) between the wind speeds $0{,}2\ V_{\text{ref}}$ and $0{,}4\ V_{\text{ref}}$ (or when the turbine properties are known, between $0{,}6\ V_{\text{r}}$ and $V_{\text{out}}$), i.e.:

$$\sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} \tag{35}$$

Guidance for calculating $I_{\text{eff}}$ can be found in Annex D.

Furthermore, it shall be demonstrated that the site specific horizontal shear due to partial wakes does not exceed EWS in 6.3.2.6 and that the site specific extreme turbulence[5], including the wake effects, does not exceed the ETM model in 6.3.2.3. For determination of the site specific turbulence, the site specific conditions, the frequency of the wake situations and wind farm layout shall be accounted for.

## 11.10 Assessment of structural integrity by load calculations with reference to site specific conditions

*Replace the 2ⁿᵈ paragraph to the end of the subclause by the following new text:*

Where there are no site data for the components of turbulence and the terrain is complex, it shall be assumed that the lateral and upward turbulence standard deviations relative to the longitudinal component are equal to 1,0 and 0,7, respectively.

In the case of wake effects, it shall be verified that structural integrity is not compromised for ultimate and fatigue limit states. For fatigue limit state in DLC 1.2 $\sigma_1$ in the normal turbulence, model is replaced by an appropriate wake turbulence model, e.g. $I_{\text{eff}}$, found in Annex D.

For ultimate limit state analysis, DLC 1.1 or DLC 1.3, as well as DLC 1.5, shall be applied with site specific conditions including wake effects represented by appropriate models. NTM for ULS loads can be set to characteristic ambient turbulence inside large farms as defined in Annex D, Equation (D.4).

Since for fatigue load calculations, $I_{\text{eff}}$ as defined in Annex D depends on the Wöhler curve exponent $m$ of the material of the considered component, the loads on structural components with other material properties shall either be recalculated or assessed with the appropriate value of $m$.

## Annex B – Turbulence models

### B.1 Mann (1994) uniform shear turbulence model

*Replace the equation defining $C_2$ by the following new equation:*

$$C_2 = \frac{k_2 k_0^{\,2}}{\left(k_1^{\,2} + k_2^{\,2}\right)^{3/2}}\,\arctan\!\left(\frac{\beta(k)k_1\sqrt{k_1^{\,2}+k_2^{\,2}}}{k_0^{\,2}-\left(k_3+\beta(k)k_1\right)k_1\beta(k)}\right)$$

---

[5] The site specific extreme turbulence may be represented by the maximum centre wake turbulence in the most severe direction.

## Annex D – Wake and wind farm turbulence

*Replace the existing text of Annex D by the following new text:*

### D.1   Wake effects

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity $I_{\text{eff}}$, Frandsen (2007). The effective turbulence intensity – conditioned on hub height mean wind speed - may be defined as

$$I_{\text{eff}}(V_{\text{hub}}) = \left\{ \int_0^{2\pi} p(\theta|V_{\text{hub}})I^m(\theta|V_{\text{hub})}d\theta \right\}^{\frac{1}{m}} \tag{D.1}$$

where

$V_{\text{hub}}$ is the wind speed at hub height;

$p$ is the probability density function of wind direction;

$I$ is the turbulence intensity of the combined ambient and wake flows from wind direction $\theta$, and

$m$ is the Wöhler (SN-curve) exponent for the considered material.

In the following, a uniform distribution $p(\theta|V_{hub})$ is assumed. It is also acceptable to adjust the formulas for other than uniform distribution[6]. No reduction in mean wind speed inside the wind farm shall be assumed.

If $\min\{d_l\} \geq 10\ D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_c}{V_{\text{hub}}} \tag{D.2}$$

If $\min\{d_l\} < 10\ D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}} \left[ (1 - N\ p_{\text{w}})\hat{\sigma}_c^m + p_{\text{w}} \sum_{i=1}^{N} \hat{\sigma}_{\text{T}}^m(d_i) \right]^{\frac{1}{m}}; p_{\text{w}} = 0,06 \tag{D.3}$$

where

$\hat{\sigma}_c = \hat{\sigma} + 1,28\hat{\sigma}_\sigma$ is the characteristic ambient turbulence standard deviation;

$\hat{\sigma}$    is the estimated ambient turbulence standard deviation;

---

[6]   In the case of non-uniform distribution or non-grid wind farm layout, the formula must be modified accordingly, maintaining the concept implied in the more general formula D.1, it must be taken into consideration for each neighbor affecting wind turbine, the sector disturbed and their associated probability of occurrence conditioned on hub height mean wind speed.

$\hat{\sigma}_\sigma$ is the estimated standard deviation of the ambient turbulence standard deviation;

$\hat{\sigma}_T = \sqrt{\dfrac{V_{hub}^2}{\left(1{,}5 + \dfrac{0{,}8 d_i}{\sqrt{C_T}}\right)^2} + \hat{\sigma}_c^2}$ is the characteristic value of the maximum center-wake, hub height

turbulence standard deviation ($\hat{\sigma}_c$ shall not account for farm generated ambient turbulence);

$C_T$ is the characteristic value of the wind turbine thrust coefficient for the corresponding hub height wind velocity. If the thrust coefficient for the neighbouring wind turbines are not known, a generic value $C_T = 7\,c\,/V_{hub}$ can be used;

$d_i$ is the distance, normalised by rotor diameter, to neighbouring wind turbine no. i;

c is a constant equal to 1 m/s;

$I_{eff}$ is the effective turbulence intensity;

$N$ is the number of neighbouring wind turbines; and

$m$ is the Wöhler curve exponent corresponding to the material of the considered structural component.

Wake effects from wind turbines "hidden" behind other machines need not be considered, for example in a row, only wakes from the two units closest to the machine in question are to be taken into account. Dependent on wind farm configuration, the number of nearest wind turbines to be included in the calculation of $I_{eff}$ is as given in Table D.1.

The wind farm configurations are illustrated in Figure D.1 for the case "Inside a wind farm with more than 2 rows".

**Table D.1 – Number of nearest wind turbine to be considered**

| Wind farm configuration | N |
|---|---|
| 2 wind turbines | 1 |
| 1 row | 2 |
| 2 rows | 5 |
| Inside a wind farm with more than 2 rows | 8 |

Inside large wind farms, wind turbines tend to generate their own ambient turbulence. Thus, when

a) the number of wind turbines from the considered unit to the "edge" of the wind farm is more than 5, or

b) the spacing in the rows perpendicular to the predominant wind direction is less than 3$D$,
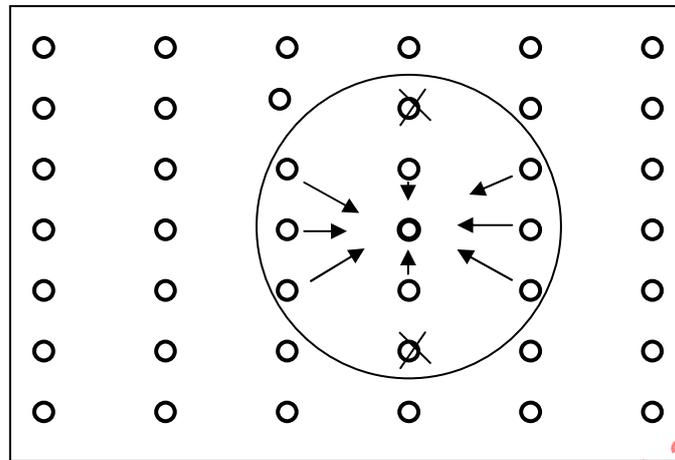
then the following characteristic ambient turbulence shall be assumed instead of $\hat{\sigma}_c$ except in the expression for $\hat{\sigma}_T$:

$$\tilde{\sigma}'_c = \tfrac{1}{2}\left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma}\right) + 1{,}28\,\hat{\sigma}_\sigma \tag{D.4}$$

where

$$\hat{\sigma}_w = \frac{0{,}36\,V_{hub}}{1 + 0{,}2\sqrt{d_r d_f / C_T}} \tag{D.5}$$

In which $d_r$ and $d_f$ are separations in rotor diameters in rows and separation between rows, respectively.



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**Figure D.1 – Configuration – Inside a wind farm with more than 2 rows**

## D.2     Reference documents

FRANDSEN S. (2007) *Turbulence and turbulence generated loading in wind turbine clusters*, Risø report R-1188.

## Annex F – Statistical extrapolation of loads for ultimate strength analysis

*Replace the existing text of Annex F by the following new text:*

### F.1   General

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the component material. Assuming that local stresses are related to the loading so that the stress progressively increases with increased loading, the strength of a structural component can be defined in terms of an ultimate load that causes failure. Given the service loading, the adequacy of the structure can be assessed by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, loading depends on the turbulent wind inflow for a variety of wind conditions. Thus, it is necessary to analyze the extreme values of the loading on a statistical basis in order to determine a suitable characteristic load.

For a given wind condition, it is reasonable to model the short-term load response as a stationary random process. Given that loads can be represented as such processes, methods are described in the following for the extraction of data for extrapolation and load extrapolation. Convergence criteria also are proposed and an alternative for estimating the long-term loads using the Inverse first-order reliability method (IFORM) is given.

The methods have been tested for a 3-bladed horizontal-axis upwind turbine. Special attention may be necessary for other wind turbine concepts and/or control schemes including load feedback. More information and guidance can be found in [1][7].

### F.2   Data extraction for extrapolation

Data used in extrapolation methods are extracted from time series of turbine simulation over the operating range of the turbine in specified wind conditions. Data may be extracted by choosing the global individual response extremes from each simulation or some subset created by breaking the simulation into blocks of equal time or ensuring a minimum time separation between extremes.

Establishing independence among the individual load response extremes is important for some methods of extrapolation. When extracting, the designer must consider the effect of independence between peaks on the extrapolation and minimize dependence when possible. If the method chosen for extrapolation is sensitive to independence assumption (e.g. the method involves transforming probability functions between time bases), the designer should attempt to statistically test for independence.

A simple approach to ensure independence is to assume that the global extreme in each ten-minute simulation or local extremes from intervals no shorter than three response cycles are independent and thus require a minimum time separation between individual response extremes of three response cycles (defined by three mean crossings over the block size). If a systematic statistical approach is desired, the designer may test for independence using standard estimation techniques (e.g. [5],[6]) and then minimize dependence in a controlled manner.

Peak over threshold methods may also be employed, but the designer must be careful that truncation errors and correlation introduced by the threshold do not influence the shape of the empirical distribution dramatically.

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7   Figures in square brackets refer to Clause F.6.

## F.3 Load extrapolation methods

### F.3.1 General

The suggested approaches of extrapolation of extreme events for determination of the 50-year load of a wind turbine can be divided into the following procedures.

a) Parametric fitting and aggregation afterwards

Subdivision of the operational range of the turbine into discrete wind speeds and performance of time domain simulations at the normal turbulence (NTM) level. Estimation of an extreme value (parametric) distribution [2] for every wind speed realization. Aggregation of all distributions according to the long-term distribution function of the mean wind speed. Prediction of the 50-year value of the aggregated distribution function. For global extreme from ten-minute simulations, the probability of the 50-year load is $3,8 \times 10^{-7}$.

b) Data aggregation first and fitting afterwards

Subdivision of the operational range of the turbine into discrete wind speeds and performance of time domain simulations at normal turbulence (NTM) level. Aggregation of all relevant extremes from all time series according to the long-term distribution function of the mean wind speed within the operational range of the turbine. Estimation of one (aggregated) distribution function for all extremes. Prediction of the 50-year value from the resulting distribution function.

Two different cases are regarded for aggregation of simulated short-term distributions of extremes for a specific observation period $T$ into an empirical distribution of the long-term extremes for the same period: extrapolation from global extremes, and from local extremes.

### F.3.2 Global extremes

The short-term distribution of global extremes in the observation period, $T$, is denoted

$$F_{short-term}(s \mid V;T) \tag{F.1}$$

where $s$ stands for load response. From this, and by use of the long-term distribution of the mean wind speeds, the long-term distribution of extreme values is obtained:

$$F_{long-term}(s;T) = \int_{V_{in}}^{V_{out}} F_{short-term}(s \mid V;T) f(V) dV \tag{F.2}$$

The extreme load response, $s_r$, of the desired return period, $T_r$, is obtained from the following equation:

$$F_{long-term}(s_r;T) = 1 - \frac{1}{N}, \quad N = \frac{T_r}{T} \tag{F.3}$$

The practical implementation of these formulas would typically be to use discrete wind speed values. Then one has

$$F_{long-term}(s;T) \approx \sum_{k=1}^{M} F_{short-term}(s \mid V_k;T) p_k, \quad p_k = f(V_k)\Delta V_k, V_{in} \le V_1 < ... < V_M \le V_{out} \tag{F.4}$$

The distribution $F_{\text{short-term}}$ is obtained by fitting to the empirical distribution:

$$F_{short-term}\left(S_{ki} \mid V_k\right) = \frac{r_i}{n_k + 1}, i = 1,...,n_k \tag{F.5}$$

where $s_{ki}$ denotes the $i^{\text{th}}$ extreme value sample from wind speed $k$ and $r_i$ is $s_{ki}$'s rank among the $n_k$ extremes arising from wind speed $k$. For the following developments, it is worth noting that an equivalent expression for the empirical distribution by use of a summation is

$$F_{short-term}\left(S_{ki} \mid V_k\right) = \sum_{j=1}^{n_k} \frac{1}{n_k + 1} I\left(S_{kj} - S_{ki}\right), i = 1,...,n_k \tag{F.6}$$

where an indicator function $I(x)$ has the expression:

$$I(x) = \begin{cases} 1 \ \ for \ \ x \le 0 \\ 0 \ \ for \ \ x > 0 \end{cases} \tag{F.7}$$

The task of the indicator function is to pick out all values less than or equal $s_{ki}$ in order that they can contribute to the empirical probability of having values less than or equal $s_{ki}$. Note that the specific definition of the indicator function ensures that the event that identical extreme values should be realized is accounted for.

### F.3.3  Local extremes

Now the short-term distribution of global extremes in the observation period, $T$, is obtained from $n(V)$ independent local extreme values in the period (assuming the extremes are positive, otherwise a change of sign may be made):

$$F_{short-term}(s \mid V;T) = F_{local}(s \mid V;T)^{n(V)} \tag{F.8}$$

The long-term distribution, defined in (F.9), and the extreme load response, $s_r$, of the desired return period, $T_r$, are established as described in the previous subclause. Strictly, $n$ should be a random number for which a distribution (dependent on $V$) must be assumed. However, $n$ has for wind turbine applications limited variation compared to its mean value. Consequently, replacing $n$ by its mean value (conditional on $V$), as implicitly done above, is sufficiently accurate. The approximation may be accepted if, when applying the formulas proposed in the following, one uses an $s$-value representative of the wind speeds that contribute most to the specific load response under consideration. Based on the approximation one has the following expressions:

$$F_{long-term}(s;T) = \int_{V_{in}}^{V_{out}} F_{local}(s \mid V;T)^n f(V) dV \tag{F.9}$$

$$F_{long-term}(s_r;T) = 1 - \frac{1}{N}, \ \ N = \frac{T_r}{T} \tag{F.10}$$

### F.3.4 Long-term empirical distributions

There are advantages to aggregating data from all wind speeds and then fitting a distribution to the combined data. One method for accomplishing this is to compute a number of simulations, where the number of simulations per bin is determined by the Weibull (or appropriate) distribution of wind speed.

$$N_{sims}(V_k) \approx N_{total}p_k, \quad p_k = f(V_k)\Delta V_k, V_{in} \leq V_1 < ... < V_M \leq V_{out} \tag{F.11}$$

Once simulations are completed and maxima are extracted, all maxima from all wind speeds are combined into a single distribution and ranked such that

$$F_{long-term}(S_i) = \frac{r_i}{n_k + 1}, i = 1,...,n_{total} \tag{F.12}$$

where $s_i$ denotes the $i^{th}$ extreme value sample over all wind speeds and $r_i$ is $s_i$'s rank among the $n_{total}$ extremes arising from the combined distribution.

One potential disadvantage of this method is that loads that are dominated by high wind speeds may have very few simulations from which to extract large extreme values in the tail of the empirical distribution. To address this issue, additional long-term distributions can be calculated using additional simulations for the low probability wind speed bins. The total simulation time per bin must follow the original wind speed distribution. But, a number of new long-term empirical distributions can be formed using randomly bootstrapped data from all bins, in which a large number of simulations are available. Once a number of long-term distributions are formed, they can be averaged to form a single aggregate long-term distribution that can be used for extrapolation to lower probability levels.

## F.4 Convergence criteria

### F.4.1 General

In the context of turbine extreme loads, the importance of different wind speeds varies depending on the load that is being extrapolated. Some loads are dominated by wind speeds near rated while others are dominated near cut-out or other wind speeds. It is important that the designer examines the dominant wind speeds closely to ensure that a sufficient number of simulations are carried out to ensure stability of the method. A minimum of 15 simulations is necessary for each wind speed from $(V_{rated} - 2$ m/s) to cut-out and six simulations are necessary for each wind speed with $V$ below $(V_{rated} - 2$ m/s).

In addition to a minimum number of simulations for the wind speeds $(V_{rated} - 2$ m/s) to cut-out, an additional convergence criterion shall also be applied according to 7.6.2. The recommended number of simulations is determined by calculating a confidence interval for the resulting empirical distribution. The number of simulations deemed sufficient is that for which the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile. This interval may be estimated using bootstrapping methods [3], the binomial estimation method [4], or it may be inherently estimated as a part of the extrapolation method employed.

If the extremes are obtained using any other method (e.g., block maxima) that results in $m$ extremes per 10-minute simulation, on average, then the 84 % fractile above needs to be replaced by $p^*$ where

$$p^* = (0,84)^{1/m} \tag{F.13}$$

The convergence criterion should be applied individually to each short-term load distribution whether the long-term distribution is to be established using aggregation of wind speed data before fitting or whether fitting parametric distributions to data from each wind speed is carried out before aggregation.

In the procedure that involves aggregation before fitting, empirical long-term distributions for the loads following aggregation of all wind speed bins can be established by making use of similar convergence criteria as proposed above for short-term distributions. The appropriate fractile at which to impose the convergence criterion should be higher than the fractile corresponding to any apparent "knee" (often observed) in the empirical long-term distribution to ensure that convergence is checked closer to the tail of this empirical distribution.

### F.4.2   Load fractile estimate

The desired load fractile, $\hat{L}_p$, corresponding to a non-exceedance probability, $p$, is estimated as follows.

Rank order all the loads data such that $S_1 \leq S_2 \leq \ldots \leq S_m$ if we have $m$ such values from simulations. Note that $m$ will be equal to the number of simulations if global maxima are used.

For any specified $p$, make sure it is possible to find some integer $i$ (where $2 \leq i \leq m$), such that

$$\frac{i-1}{m+1} \leq p \leq \frac{i}{m+1} \tag{F.14}$$

A sufficient number of extremes, $m$, must be available (for which a sufficient number of simulations will have to be run) so that the above inequality results and a value of $i$ found.

The load fractile estimate is then computed by (linear) interpolation as follows:

$$\hat{S}_p = S_{i-1} + [p(m+1)-(i-1)](S_i - S_{i-1}) ; \text{ where } 2 \leq i \leq m \tag{F.15}$$

### F.4.3   Confidence bounds

Confidence bounds are estimated such that the 90 % confidence interval on the 84 % fractile, $\hat{S}_{0.84}$, is as follows.

$$\frac{\hat{S}_{0.84,0.05} - \hat{S}_{0.84,0.95}}{\hat{S}_{0.84}} < 0{,}15 \tag{F.16}$$

The interval, $\left\langle \hat{S}_{0.84,0.05}, \hat{S}_{0.84,0.95} \right\rangle$, represents the desired 90 % confidence interval.

### F.4.4 Confidence intervals based on bootstrapping

Using the bootstrap procedure to form confidence intervals, [3] and [7], begins with taking the initial set of data on $p$ global maxima ($m_1$, $m_2$, $m_{3,}$ $m_4$, $m_5$ ... $m_p$) and randomly resampling these data with replacement to form a new set ($m_1^*$, $m_2^*$, $m_3^*$, $m_4^*$, $m_5^*$ ... $m_p^*$) or a bootstrap resampling of the same size as the original sample. Note that bootstrap resamplings will be composed of repeated values from the original sample since, for each resampling, data are sampled randomly with replacement. The process is repeated so as to form a large number, $N_b$, of bootstrap resamplings. From each of these sets of $p$ data, individual estimates of the 84 % fractile can be obtained. From these $N_b$ estimates, constituting the set, ($l_1$, $l_2$, $l_3$, $l_4$, $l_5$ . . . $l_{N_b}$), confidence intervals can be found in the usual manner by ordering the data. These can then be used for the numerator of Equation (F.16). The estimate of the 84 % fractile that is obtained from the original data represents the denominator of Equation (F.16).

A minimum number of 25 bootstrap resamplings may be sufficient to determine an reasonable estimate of confidence bounds. However, a larger number closer to 5 000 will lead to more reliable estimates.

### F.4.5 Confidence Intervals based on the binomial distribution

Confidence intervals based on the binomial distribution ([7]) are computationally less intensive than those computed using the bootstrap procedure. This saving is simplified by tabulating parameters for calculating a binomial confidence interval that will result for most common situations. For the load fractile equal to 0,84 and 90 % confidence interval, Table F.1 provides values of $k^*$ and $l^*$ as well as two other values, $A$ and $B$, needed for interpolating the estimate confidence bounds in Equation (F.17), below. The number of simulations is of the order of 15 to 35 for each wind speed bin.

**Table F.1 – Parameters needed to establish binomial-based confidence intervals**

| | No. of simulations | $k^*$ | $l^*$ | $A$ | $B$ |
|---|---|---|---|---|---|
| **For 90 % confidence interval on the 84th percentile load** | 15 | 9 | 14 | 0,50 | 0,32 |
| | 16 | 10 | 15 | 0,27 | 0,19 |
| | 17 | 11 | 16 | 0,10 | 0,03 |
| | 18 | 11 | 16 | 0,87 | 0,96 |
| | 19 | 12 | 17 | 0,58 | 0,90 |
| | 20 | 13 | 18 | 0,35 | 0,83 |
| | 21 | 14 | 19 | 0,16 | 0,76 |
| | 22 | 14 | 20 | 1,00 | 0,69 |
| | 23 | 15 | 21 | 0,69 | 0,60 |
| | 24 | 16 | 22 | 0,45 | 0,50 |
| | 25 | 17 | 23 | 0,25 | 0,39 |
| | 26 | 18 | 24 | 0,08 | 0,26 |
| | 27 | 18 | 25 | 0,85 | 0,12 |
| | 28 | 19 | 25 | 0,58 | 0,98 |
| | 29 | 20 | 26 | 0,36 | 0,91 |
| | 30 | 21 | 27 | 0,18 | 0,83 |
| | 31 | 22 | 28 | 0,02 | 0,75 |
| | 32 | 22 | 29 | 0,75 | 0,66 |
| | 33 | 23 | 30 | 0,51 | 0,56 |
| | 34 | 24 | 31 | 0,31 | 0,44 |
| | 35 | 25 | 32 | 0,13 | 0,32 |

The parameters in Table F.1 are used with a design equation that is tailored to give the 90 % confidence interval for the 84th percentile ten-minute maximum. The design equation can be written as follows:

$$(x_l - x_k) = (x_{l^*} - x_{k^*}) + B(x_{(l+1)^*} - x_{l^*}) - A(x_{(k+1)^*} - x_{k^*})$$ (F.17)

where $l^*$, $k^*$, $A$, and $B$ are as given in Table F.1 as a function of the number of simulations run and $x_{l^*}$, $x_{(l+1)^*}$, $x_{k^*}$, and $x_{(k+1)^*}$ are obtained from the rank-ordered simulated extremes. This estimate can then be inserted into Equation (F.16) to determine if the convergence criteria are met, where

$$\hat{S}_{0.84,0.05} - \hat{S}_{0.84,0.95} \approx x_l - x_k$$ (F.18)

## F.5 Inverse first-order reliability method (IFORM)

An alternative to typical loads extrapolation methods is the use of IFORM to estimate long-term loads. In this method, turbulence and wind turbine response simulations are carried out for NTM conditions. A minimum of 15 simulations should be carried out for wind speeds ($V_{rated}$ − 2 m/s) to cut-out. The wind speed(s) that yields the highest load is(are) then identified. Extrapolation of the short-term load distributions to a probability level consistent with the definition of a 50-year return period yields the 50-year load for use with DLC 1.1.

The convergence criteria for IFORM should be the same as for the other extrapolation methods, except that the designer need only estimate confidence intervals for the load distributions from identified important wind speeds (often only one).

The theory for the use of the inverse FORM (IFORM) technique (which relies on transformation of physical random variables to standard normal random variables [8]) is well-documented, see e.g. [9], and can be applied to estimate long-term wind turbine loading under NTM conditions.

In order to implement IFORM for wind turbine extreme loads, use the following steps.

a) Carry out 15 simulations for the wind speed bins ($V_{rated}$ − 2 m/s) to cut-out.

b) Identify which bins yield the largest load maxima.

c) Refine the search by performing another 15 simulations for the bins identified in step b). Again, identify the design dominating wind speed(s), $v^*$, which produce the largest loads. Ensure that the number of simulations at the important wind speed ($s$) is sufficient such that the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile.

d) Perform short-term analysis only for the bin(s) identified in step c). The desired fractile of the load distribution for this bin is derived and depends on the target probability level.

Using Rayleigh CDF, compute $U_1 = \Phi^{-1}[F_V(v^*)]$.

For probability of exceedance in 10 min once in 50 years, $p_T = 3{,}8 \times 10^{-7}$. This corresponds to $\beta = 4{,}95$.

Solve $U_2 = [\beta^2 - U_1^2]^{1/2}$.

Derive the load fractile $P_S = \Phi(U_2)$, see Table F.2.

The long term load is the $P_S$ fractile of the short-term distribution for the wind speed bin, $v^*$. To reach the appropriate fractile, extrapolation may be required.

**Table F.2 – Short-term load exceedance probabilities as a function of hub-height wind speed for different wind turbine classes for use with the IFORM procedure**

| $v^*$ [m/s] | 1-$P_S$,class I | 1-$P_S$,class II | 1-$P_S$,class III |
|---|---|---|---|
| 5 | 5.77E-07 | 4.74E-07 | 4.16E-07 |
| 6 | 3.85E-07 | 3.72E-07 | 3.73E-07 |
| 7 | 3.87E-07 | 4.14E-07 | 4.55E-07 |
| 8 | 5.13E-07 | 5.93E-07 | 7.02E-07 |
| 9 | 8.50E-07 | 1.05E-06 | 1.33E-06 |
| 10 | 1.71E-06 | 2.25E-06 | 3.03E-06 |
| 11 | 4.14E-06 | 5.79E-06 | 8.24E-06 |
| 12 | 4.83E-07 | 4.14E-07 | 3.81E-07 |
| 13 | 3.71E-07 | 3.80E-07 | 4.07E-07 |
| 14 | 4.52E-07 | 5.22E-07 | 6.22E-07 |
| 15 | 7.66E-07 | 9.73E-07 | 1.27E-06 |
| 16 | 1.71E-06 | 2.37E-06 | 3.37E-06 |
| 17 | 4.93E-06 | 7.41E-06 | 1.14E-05 |
| 18 | 1.81E-05 | 2.95E-05 | 4.93E-05 |
| 19 | 4.32E-07 | 3.85E-07 | 3.71E-07 |
| 20 | 3.81E-07 | 4.14E-07 | 4.73E-07 |
| 21 | 5.64E-07 | 7.02E-07 | 9.10E-07 |
| 22 | 1.23E-06 | 1.71E-06 | 2.48E-06 |
| 23 | 3.72E-06 | 5.79E-06 | 9.31E-06 |
| 24 | 1.55E-05 | 2.67E-05 | 4.76E-05 |
| 25 | 8.80E-05 | 1.68E-04 | 3.34E-04 |

## F.6  Reference documents

[1]  Wind Energy, Vol. 11, Number 6, November-December 2008, Special Issue on Design Load Definition

[2]  MORIARTY, P.J., HOLLEY, W.E., BUTTERFIELD, S.P. (2004) "Extrapolation of Extreme and Fatigue Loads Using Probabilistic Methods", NREL-NWTC, Golden, CO.

[3]  EFRON, B. and TIBSHIRANI, R. J., (1993) "An Introduction to the Bootstrap", Chapman and Hall, New York.

[4]  HOGG, R. V. and CRAIG, A. T., (1995) "Introduction to Mathematical Statistics", 5th Ed., Prentice Hall, Englewood Cliffs, New Jersey.

[5]  HOEFFDING, W., (1948) "A Non-Parametric Test of Independence," The Annals of Mathematical Statistics, Vol. 19, No. 4, pp. 546-557.