# Extrapolation of Extreme Response for Wind Turbines based on FieldMeasurements

Toft, Henrik Stensgaard; Sørensen, John Dalsgaard

*Published in:*
Safety, Reliability and Risk of Structures, Infrastructures and Engineering Systems

*Publication date:*
2009

*Document Version*
Publisher's PDF, also known as Version of record

# Extrapolation of Extreme Response for Wind Turbines based on Field Measurements

H.S. Toft
*Aalborg University, Denmark*

J.D. Sørensen
*Aalborg University, Denmark*
*Risø-DTU, Denmark*

ABSTRACT: The characteristic loads on wind turbines during operation are among others dependent on the mean wind speed, the turbulence intensity and the type and settings of the control system. These parameters must be taken into account in the assessment of the characteristic load. The characteristic load is normally determined by statistical extrapolation of the simulated response during operation according to IEC 61400-1 2005. However, this method assumes that the individual 10 min. time series are independent and that peaks extracted are independent. In the present paper two new methods for loads extrapolation are presented. The first method is based on the same assumptions as the existing method but the statistical extrapolation is only performed for a limited number of mean wind speeds where the extreme load is likely to occur. For the second method the mean wind speeds are divided into storms which are assumed independent and the characteristic loads are determined from the extreme load in each storm.

## 1 INTRODUCTION

The methods for load extrapolation during operation of wind turbines have in recent years been widely discussed within the wind turbine industry. For wind turbines the extreme load can occur both in the standstill position and during operation, where the magnitude of the loads is influenced by larger turbulence and the control system. The fact that the limit state condition can occur during operation makes a precise and robust method for determination of the characteristic load necessary.

With the wind turbine standard IEC 61400-1 3.edition 2005 it is recommended that the characteristic load during operation is determined by extrapolation of the response. The method for extrapolation of the response given in the standard is based on (Moriarty, Holley & Butterfield 2002) and uses the Peak Over Threshold (POT) method to extract extremes from simulated time series of the response. (Ragan & Manuel 2008) have also used only the global maxima from each 10 min. simulation of the response to estimate the extreme load. Other methods such as stochastic process models where the simulated time series are used to estimate the stochastic process have been studied (Ragan & Manuel 2008) and (Peeringa 2003). However, in all cases the POT-method seems to give the best results.

Load extrapolation according to (IEC 61400-1 2005) is based on the assumption that the individual extremes and the individual 10 min. time series are independent. (Ragan & Manuel 2008) studied the correlation between the individual extremes within 10 min. time series and found that the correlation was weak. The extreme load during operation is among others dependent on the mean wind speed, the turbulence intensity and the type and settings of the control system. The correlation in the extreme load must for this reason be a combination of the correlation for these parameters i.e. also the correlation between 10 min. periods.

In (Cook 1982) and (Coles & Walshaw 1994) a correlation length in the range of 48-60 hours has been used for the mean wind speed. Correlation in the turbulence can according to (Dyrbye & Hansen 1996) be approximated by a exponential function leading to a correlation length in the range of 10-20 sec. For the control system the correlation will be dependent on how fast the wind turbine can e.g. pitch the blades. The correlation length will typically be in the range of a few seconds if the control system is active. Thereby is the correlation for the extreme load a combination of very different time scales.

In the present paper two different methods for load extrapolation for wind turbines during operation are proposed. The first method is based on the same assumptions as the existing method but the statistical extrapolation is only performed for a limited number of mean wind speeds where the extreme load is likely to occur. The second method uses a continuous sample of field measurements instead of simulated or measured 10 min. time series. The continuous measurements are divided into storms which are assumed independent in the load extrapolation. The load extrapolation is performed based on the extreme response in each storm. For both methods the characteristic response is obtained by a numerical example and compared to the characteristic load calculated according to (IEC 61400-1 2005).

## 2 LOAD EXTRAPOLATION ACCORDING TO IEC 61400-1

The characteristic response which according to (IEC 61400-1 2005) should have a recurrence period of 50 years is determined from extrapolation of stochastic simulations of the wind turbine during operation. The extrapolation is according to (IEC 61400-1 2005) performed for 6 – 10 min. simulations at each mean wind speed between the cut-in and cut-out wind speed (typically $U_{in} = 4$ m/s and $U_{out} = 25$ m/s).

For each 10 min. time series the local extremes are extracted by the POT-method using a threshold equal to the mean plus 1.4 times the standard deviation based on (Moriarty, Holley & Butterfield 2004). In (Ragan & Manuel 2008) the optimal threshold is estimated from the mean square error which leads to a higher threshold. The distribution function for the local extremes is chosen to a 3-parameter Weibull distribution according to (IEC 61400-1 2005). Different distribution functions such as the Gumbel and Pareto distributions have been considered in (Moriarty, Holley & Butterfield 2004) and (Ragan & Manuel 2008). However, the 3-parameter Weibull distribution seems to give the best estimate. The distribution function for the local ($T = 10$ min.) extreme response $l$ is written

$$F_{local}\left(l \mid T,U\right) = 1 - \exp\left(-\left(\frac{l-\gamma}{\beta}\right)^{\alpha}\right) \tag{1}$$

where $\alpha, \beta, \gamma$ are parameters in the distribution. The distribution parameters are obtained for mean wind speeds $U$ in the interval $U_{in} \le U \le U_{out}$. The distribution parameters are determined by the Maximum-Likelihood Method by which the individual parameters become asymptotically (minimum 25-30 data) normally distributed stochastic variables with expected value equal to the Maximum-Likelihood estimators and covariance matrix equal to, see (Lindley 1976).

$$\mathbf{C}_{\alpha,\beta} = \left[-\mathbf{H}\right]^{-1} = \begin{bmatrix} \sigma_\alpha^2 & \rho_{\alpha\beta}\sigma_\alpha\sigma_\beta \\ \rho_{\alpha\beta}\sigma_\alpha\sigma_\beta & \sigma_\beta^2 \end{bmatrix} \tag{2}$$

where $\mathbf{H}$ is the Hessian matrix of the Log-Likelihood function and $\sigma$ is the standard deviation for each of the distribution parameters in (1). $\rho$ is the correlation between the distribution parameters. Notice that the distribution parameter $\gamma$ is not included in the Maximum-Likelihood optimization – but could easily be so. Using the Maximum-Likelihood Method and the Hessian Matrix it is possible to take the statistical uncertainty into account when estimating the 50 year response.

The short-term distribution of the global extremes is determined from the local distribution by assuming that the individual extremes are independent. This assumption has been studied by (Ragan & Manuel 2008) who found a weak correlation between the extremes. At (Boulder Meeting 2007) several presenters have used a separation time in the range of 5-15 sec. to secure that the individual peaks are independent. In (IEC 61400-1 2005) no separation time between the peaks is recommended. The short-term distribution for the global 10 min. extremes is given by

$$F_{short-term}\left(l \mid T,U\right) = F_{local}\left(l \mid T,U\right)^{n(U)} \tag{3}$$

where $n(U)$ is the expected number of extremes at mean wind speed $U$ within each time series $T$.

The long-term distribution of the response is determined from the short-term distribution by integrating over the mean wind speeds given by the distribution function $f_U(U)$.

$$F_{long-term}\left(l \mid T\right) = \int_{U_{in}}^{U_{out}} F_{local}\left(l \mid T,U\right)^{n(U)} f_U\left(U\right) dU \tag{4}$$

According to (IEC 61400-1 2005) the characteristic response is determined as

$$F_{long-term}\left(l_c \mid T\right) = 1 - \frac{T}{60 \cdot 24 \cdot 365 \cdot T_r} \tag{5}$$

where $T$ is the length of the time series in minutes (10 min.) and $T_r$ is the recurrence period in years (50 years). The quantile corresponding to the characteristic value is based on the assumption that the individual 10 min. time series are independent and that the wind speed always is between $U_{in}$ and $U_{out}$.

By modelling the distribution parameters in the local Weibull distribution (1) as stochastic variables and solving the long-term distribution in (4) for the probability in (5) the characteristic value including statistical uncertainty can be found. The equation can be solved using e.g. FORM (First Order Reliability Method) techniques, see e.g. (Madsen, Krenk & Lind 2006).

## 3 DEFINITION OF A STORM

The extreme response for wind turbines during operation does normally occur around the nominal wind speed (typically $U_{nom} = 15$ m/s) or the cut-out wind speed. For normal civil engineering structures a storm is characterized by extreme wind speeds.

However, for wind turbines a storm should include all the wind speeds for which the response can become critical. In figures 1 and 2 the mean wind speed and the maximum flap bending moment for each 10 min. time series are given for a stall and a pitch controlled wind turbine.

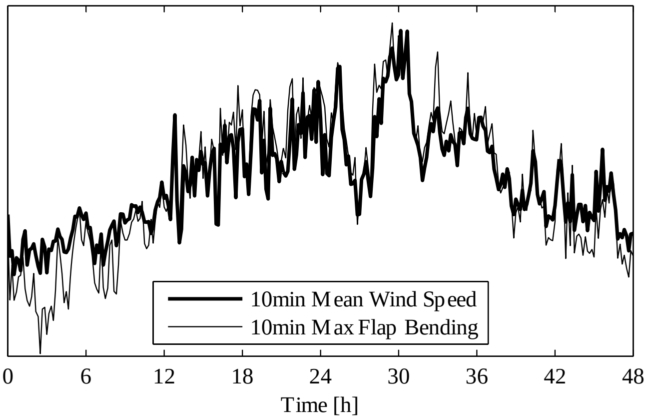


Figure 1: Mean wind speed and max flap bending moment within each 10 min. time series for a stall controlled wind turbine.

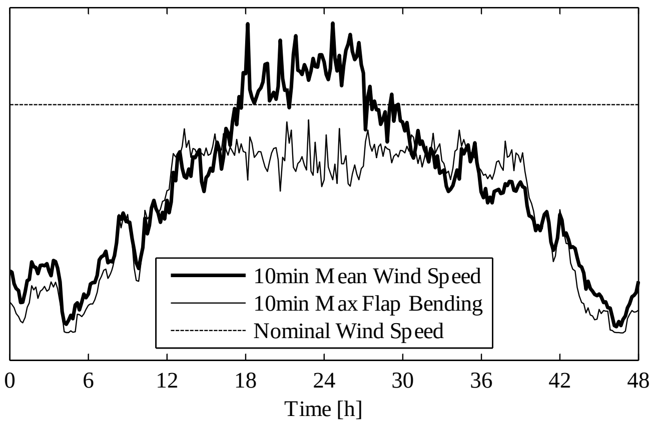


Figure 2: Mean wind speed and max flap bending moment within each 10 min. time series for a pitch controlled wind turbine.

From figure 1 it is seen that the maximum flap bending moment follows the mean wind speed closely for a stall controlled wind turbine. For the pitch controlled wind turbine in figure 2 the same behaviour is seen for small wind speeds. However, at mean wind speeds close to the nominal wind speed the flap bending moment seems to reach a constant level.

For pitch controlled wind turbines the pitch position of the blades is normally close to zero degrees for wind speeds less than the nominal wind speed. However, for wind speeds higher than the nominal wind speed the control system becomes active and the pitch position of the blades is adjusted. The mean wind speed where gusts in the wind from turbulence can lead to pitch active is in the following denoted the storm wind speed $U_{storm}$ (10 min. mean wind speed). It is assumed that the largest loads will occur for mean wind speeds above the storm wind speed corresponding to mean wind speeds where the control system is or can become active.

The storm wind speed can be determined based on the mean value for the standard deviation of the turbulence which according to (IEC 61400-1 2005) is estimated by

$$\sigma_1 = I_{ref}\left(0.75U_{storm} + c\right) \quad (6)$$

where $I_{ref}$ is the reference turbulence intensity at 15 m/s and $c = 3.8$ m/s is a constant. All wind speeds are specified at hub height.

By requiring that the maximum gust for the storm wind speed is less than the nominal wind speed $U_{nom}$ the storm wind speed can be determined by

$$U_{storm} = U_{nom} - k_p\sigma_1 \quad (7)$$

where the wind speed is assumed to be a Gaussian process and peak factor is assumed to be $k_p = 3.5$ as for the wind pressure.

In order to secure independence of the individual storms, two storms are combined to one if the wind speed between the two storms are not below 80% of the storm wind speed $U_{storm}$. (Tromans & Vanderschuren 1995) have used this approach for calculating the maximum response in an offshore structure from waves. For the offshore structure the maximum response was closely related to the maximum wave height and for this reason the 80% was defined from the lowest peak wave height. For wind turbines during operation the maximum response is only partly related to the wind speed and for this reason the 80% has been related to the storm wind speed.

The independence of storms is also secured by applying a minimum time separation between the individual storms. If a storm was characterized by an extreme wind speed as for civil engineering structures the separation time would be assumed to be 48-60 hours according to (Cook 1982) and (Coles & Walshaw 1994). However, because the storm wind speed $U_{storm}$ is rather common to occur at least at severe sites it has been chosen to use a separation time on 2 hours. The correct separation time in order to obtain independent storm should be further studied.

## 4 LOAD EXTRAPOLATION BASED ON STATISTICAL EXTRAPOLATION OF THE RESPONSE IN STORMS

The first method for load extrapolation based on storms is based on the already existing method given in (IEC 61400-1 2005). However, instead of performing a statistical extrapolation of the response for all wind speeds between $U_{in}$ and $U_{out}$ the following method only uses the wind speeds between $U_{storm}$ and $U_{out}$. However, the amount of measured or simulated 10 min. time series should be significant increased compared to the 6 – 10 min. time series used in (IEC 61400-1 2005).

For each of the mean wind speeds between $U_{storm}$ and $U_{out}$ a local distribution function for the maximum response is obtained by the Peak Over Threshold method. The threshold value is chosen so that only the 30 largest extremes are used. The extremes should be well separated in time in order to secure independence. The distribution function for the local extreme response $l$ is assumed 3-parameter Weibull distributed as in formula (1).

The reference time $T$ is in the following assumed to be 10 min., but other reference times such as one hour or one year could also be used. The short-term distribution for the global 10 min. extremes is given by formula (3). The parameter $n(U)$ which is the expected number of extremes at mean wind speed $U$ within time $T$ will be reduced compared to the method in (IEC 61400-1 2005) because less extremes are extracted from longer time series.

The long-term distribution of the response is determined by integrating over the mean wind speeds in a storm given by the distribution function $f_U(U\,|\,S)$ where $S$ denotes a storm.

$$F_{long-term}(l\,|\,T,S) = \int_{U_{storm}}^{U_{out}} F_{local}(l\,|\,T,U)^{n(U)} f_U(U\,|\,S)\,dU \quad (8)$$

The characteristic value for the extreme response can be determined from a given probability as in section 2 by assuming that the individual 10 min. time series are independent. However, in section 2 the length of the time series $T$ was compared to the total time in the return period. In this case $T$ is only compared to the time where the mean wind speed corresponds to a storm because only these mean wind speeds are taken into account. The probability is given by:

$$F_{long-term}(l_c\,|\,T,S) = 1 - \frac{T}{60 \cdot T_s \cdot \eta \cdot T_r} \quad (9)$$

where $T_s$ is the average duration of a storm in hours and $\eta$ is the expected number of storms per year. Both $T_s$ and $\eta$ should be determined from measurements of the wind speed at the given site.

The present method assumes that the individual 10 min. time series are independent and that the extremes used for determine the short-term distribution are independent. These assumptions are the same as for the method in (IEC 61400-1 2005). However, because the extremes used for determining the short-term distribution are obtained from many 10 min. time series and well separated in time the assumption of independents of the extremes is better satisfied.

If the characteristic response is determined from simulations, simulations for mean wind speeds between $U_{in}$ and $U_{storm}$ can be omitted, but additional simulations should be performed for mean wind speeds between $U_{storm}$ and $U_{out}$. The additional simulations are required in order to get a good estimation of the short-term distribution and secure independence of the local extremes.

## 5 LOAD EXTRAPOLATION BASED ON EXTREME RESPONSE IN STORMS

In order to secure that the extracted extremes from the time series are independent the following method breaks the measured time series into storms as defined in section 3. It is assumed that the individual storms can be considered as independent. Breaking a measured time series into storms to secure independence has previously been used by (Soares & Scotto 2004) to estimate the significant wave height at a given location.

A distribution function for the extreme response can be obtained by extracting the extreme response from each storm. For the storms that contain the 30 largest extremes a distribution function is fitted to the extreme response. The 30 largest extremes have been chosen in order ignore the smallest extremes and still have a representative dataset for the extremes. The extreme response can be fitted to either a 3-parameter Weibull distribution or a Gumbel distribution.

$$F_{response}(l\,|\,S) = 1 - \exp\left(-\left(\frac{l-\gamma}{\beta}\right)^{\alpha}\right) \qquad l \ge \gamma \quad (10)$$

$$F_{response}(l\,|\,S) = \exp\left(-\exp\left(-\alpha\left(l-\beta\right)\right)\right) \quad (11)$$

where $S$ indicates a storm and $\alpha,\beta,\gamma$ are parameters in the distributions and determined by the Maximum-Likelihood Method in order to take the statistical uncertainty into account.

The characteristic value for the extreme response can be calculated for the probability given by:

$$F_{response}(l_c\,|\,S) = 1 - \frac{1}{\lambda T_r} \quad (12)$$

where $\lambda$ is the number of data per year. In section 6 the characteristic load is calculated for both the Weibull and the Gumbel distributions.

In order to calculate the characteristic load with the present method it is necessary to have a long time series of wind speed and structural response. In the example below these data are provided by measurements. However, long time series could also be established based on simulations or by fitting a generic load model, see e.g. (Tromans & Vanderschuren 1995).

## 6 NUMERICAL EXAMPLE

In the present section the characteristic load with and without statistical uncertainty is calculated according to (IEC 61400-1 2005), see section 2, and the methods for load extrapolation given in sections 4 and 5.

The load extrapolation is performed based on measured time series for the structural response of a stall controlled wind turbine. In the following only the structural response corresponding to the flap bending moment is considered. A similar comparison of the 3 methods should be performed for other structural responses and for a pitch controlled wind turbine. The characteristic response is calculated based on the extremes in the raw time series which is sampled with approximate 35 Hz. The correct characteristic response will probably be an average over a short time period. In the following is only the relative magnitude of the characteristic response for three methods compared for which reason the raw time series is used.

The dataset is measured over 68 days in winter and spring and contains 52 days of complete measurements. The wind distribution for the given site is measured as 10 min. mean values over a period of 4 years. The wind distribution is modelled by a 2-parameter Weibull distribution, see figure 3 where the distribution has been compared to the IEC Class III site given in (IEC 61400-1 2005). The site is in general less severe than the IEC Class III site.

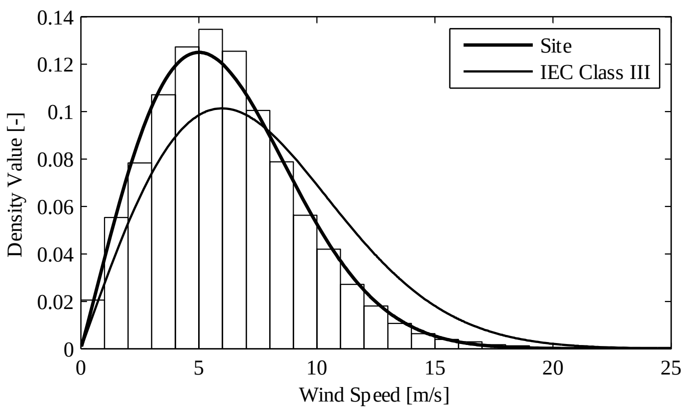

Figure 3: Probability distribution function for mean wind speed.

The turbulence intensity in the main wind direction at the site is calculated to $I = 0.120$ for a mean wind speed on 15 m/s. For the IEC Class C the reference turbulence intensity at 15 m/s is assumed to be $I_{ref} = 0.12$ and the site thereby has the same turbulence climate.

### 6.1 *Statistical extrapolation IEC 61400-1*

In the following the characteristic load is calculated based on the method given in (IEC 61400-1 2005), see also section 2.

Based on the measured time series 6 – 10 min. time series are used from each mean wind speed between 4 and 15 m/s. In general, the method should use wind speeds in the range from 4 to 25 m/s but in the measuring period there is only 2 – 10 min. time series with mean wind speeds above 15 m/s. The 6 – 10 min. time series are picked randomly between all the measured time series at each mean wind speed. However, measured time series containing measurement errors have not been used.

The calculated characteristic loads with a return period of 50 years are calculated for two different threshold values:

- Mean value plus 1.4 standard deviations (1.4)
- Mean value plus 2.0 standard deviations (2.0)

The characteristic load has been calculated for two threshold values in order to determine the influence of the threshold value on the characteristic load. As stated in section 2 several authors recommend a higher threshold value than the 1.4 used in (IEC 61400-1 2005).

In order to secure that the individual peaks are independent a separation time between the peaks on 10 sec. has been added. The separation time is chosen according to (Boulder meeting 2007). In table 1 the calculated characteristic loads with a return period on 50 years are given both with and without statistical uncertainties. The characteristic loads are all normalized with the characteristic load for a threshold value of 1.4 without statistical uncertainty.

Table 1. Characteristic loads IEC 61400-1.

| Threshold | Characteristic load | |
|---|---|---|
| | without stat. unc. | with stat. unc. |
| 1.4 | 1.000 | 1.037 |
| 2.0 | 1.041 | 1.091 |

From table 1, it is seen that the characteristic load increases 4.1% when the threshold value is increased from 1.4 to 2.0. The statistical uncertainty is in the range of 3.7 to 4.9% and increases with higher threshold value. The increase in statistical uncertainty is due to extraction of fewer extremes from the time series leading to a more uncertain fit of the short-term distribution.

The probability for exceeding a given load is given in figure 4 for a threshold value on the mean plus 1.4 standard deviations.

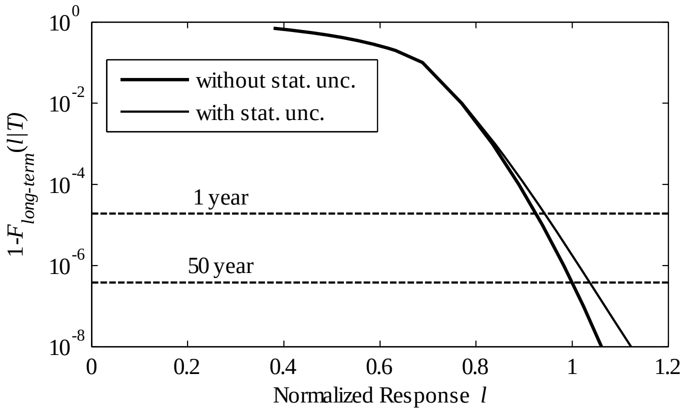

Figure 4: Probability of load exceedance with and without statistical uncertainties.

## 6.2 *Storm*

The stall controlled wind turbine considered in this example does not as a pitch controlled wind turbine have a nominal wind speed where it reach the nominal power. The number of storms and the mean length of a storm are dependent on the nominal wind speeds and the turbulence intensity. The following sensitivity analysis is based on 4 years of measured 10 min. mean wind speeds.

In table 2 the storm wind speed $U_{storm}$ is calculated for different typical nominal wind speeds $U_{nom}$. The average number of storms per year $\eta$ and the average length of a storm $T_s$ are also given.

Table 2. Storm wind speed, average number of storms and average length of storms for different nominal wind speeds.

| Nominal wind speed $U_{nom}$ | Storm wind speed $U_{storm}$ | Storms per year $\eta$ | Length of storm $T_s$ |
|---|---|---|---|
| 14 m/s | 9.5 m/s | 202 | 8.0 h |
| 15 m/s | 10.2 m/s | 165 | 7.4 h |
| 16 m/s | 11.0 m/s | 135 | 6.7 h |

From table 2 it is seen that both the average number of storms and the average length of the storms decrease with higher nominal wind speed. The influence of the separation time between two individual storms on the number of storms and the length of a storm is given in table 3. The nominal wind speed is assumed to be $U_{nom} = 15$ m/s leading to a storm wind speed on $U_{storm} = 10.2$ m/s.

Table 3. Average number of storms and average length of storms for different separation times.

| Separation time | Storms per year $\eta$ | Length of storm $T_s$ |
|---|---|---|
| 0 h | 198 | 6.0 h |
| 2 h | 165 | 7.4 h |
| 4 h | 141 | 9.2 h |

A higher separation time between the individual storm leads to less storms because storm that is less separated is combined to one storm. Higher separation time also give an increase in the average storm length. The last parameter used to characterize a storm is that two storms are combined to one if the mean wind speed between them not is below 80% of the storm wind speed $U_{storm}$ (In the following denoted $P_{storm}$). Sensitivity analysis with this parameter is performed in table 4, where a separation time on 2 hours has been used.

Table 4. Average number of storms and average length of storms for different separation wind speeds in percent.

| Wind speed $P_{storm}$ | Storms per year $\eta$ | Length of storm $T_s$ |
|---|---|---|
| 70 % | 140 | 9.4 h |
| 80 % | 165 | 7.4 h |
| 90 % | 177 | 6.7 h |

From table 4 it is seen that the average number of storms increases when $P_{storm}$ are increased. However, the average length of the storms decreases when $P_{storm}$ are increased. The separation time and the wind speed between the storms $P_{storm}$ therefore have the same influence on the average number of storms and the average length of a storm.

## 6.3 *Statistical extrapolation of the response in storms*

The method for statistical extrapolation of the response in storms is examined in section 4. The characteristic load is calculated by determining a short-term distribution for the response at each mean wind speed in a storm.

In the following a storm is characterized by having a wind speed $U_{storm}$ greater than 10.2 m/s corresponding to a nominal wind speed $U_{nom} = 15$ m/s and a turbulence intensity $I = 0.12$.

The short-term distribution for the response is obtained from the 30 largest extreme at each mean wind speed. In order to make the extremes independent it is assumed that they separate not less than 10 min. Because the amount of measured data is limited the short-term distribution has only been determined for mean wind speeds between 10 and 14 m/s. In general, the method should use wind speeds in the range from 10 to 25 m/s but for high wind speed is has not been possible to extract 30 extremes separated by minimum 10 min.

In order to determine the characteristic load with a 50 year return period the average number of storms per year $\eta$ and the average length of a storm $T_s$ must be used. In the present case these parameters are determined from 4 years of wind speed measurements at the site.

In table 5 the characteristic load is given when both 25 and 30 extremes are extracted at each mean wind speed in order to determine the short-term distribution. All loads are normalized with the characteristic load calculated for IEC 61400-1 without statistical uncertainty in table 1.

Table 5. Characteristic loads statistical extrapolation of the response in storms.

| Number of extremes | Characteristic load without stat. unc. | Characteristic load with stat. unc. |
|---|---|---|
| 25 | 1.029 | 1.232 |
| 30 | 1.025 | 1.162 |

The characteristic load without statistical uncertainty is hardly influenced whether 25 or 30 extremes are used at each mean wind speed to determine the short-term distribution. However, the characteristic load with statistical uncertainty is significantly reduced by using more extremes.

The loads calculated without statistical uncertainty in the present method are in the same range as the characteristic loads calculated using (IEC 61400-1 2005) and a threshold value on 1.4 and 2.0. The two methods are based on the same assumptions about independence of the 10 min. time series. But the present method fulfils the requirements about independence of the local extremes better than the method in (IEC 61400-1 2005) because less extremes are extracted from a longer time series.

### 6.4 *Extreme response in storms*

The method for load extrapolation based on the extreme response in storms is described in section 5. The characteristic load is determined by extrapolation of the extreme responses in each storm.

In the following is a storm characterized by having a wind speed $U_{storm}$ greater than 10.2 m/s corresponding to a nominal wind speed $U_{nom} = 15$ m/s and a turbulence intensity $I = 0.12$. The time separation is assumed to 2 hours and two storms are combined to one if the mean wind speed is not below 80% of the storm wind speed.

In section 5 it was stated that the load extrapolation should be performed based on the extreme response in the 30 most severe storms. However, based on the measurements and the definition of a storm it has only been possible to extract 25 storms and thereby 25 extreme responses. Because of the limited amount of measurements it has not been possible to perform a sensitivity analysis for the characteristic load with respect to the definition of a storm.

In table 6 the characteristic load is given by assuming both a 3-parameter Weibull and a Gumbel distribution for the extreme response. In figure 5 the fit of the two distribution functions is given. All loads are all normalized with the characteristic load calculated for IEC 61400-1 without statistical uncertainty in table 1.

Table 6. Characteristic loads for extreme response in storms.

| Distribution | Characteristic load without stat. unc. | Characteristic load with stat. unc. |
|---|---|---|
| Weibull | 1.106 | 1.348 |
| Gumbel | 1.303 | 1.401 |

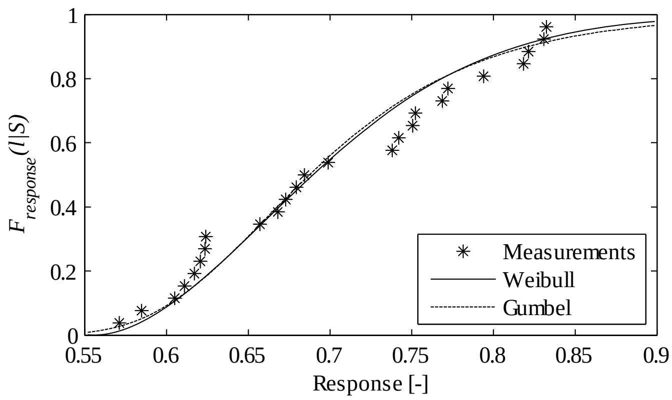


Figure 5: Fit of probability distribution for extreme response in storms.

From table 6 it is seen that the choice of distribution function has a significant influence on the characteristic load. The Gumbel distribution gives a higher characteristic load because it has a thicker tail than the Weibull distribution. With statistical uncertainty the difference in characteristic loads are smaller but still significant.

The present method leads to significant higher characteristic loads than the previous two methods. The higher loads can be due to that the 10 min. time series, which the two present methods assume independent, are not completely independent.

## 7 CONCLUSION

In the present paper two new methods for load extrapolation during operation for wind turbines are presented.

The first method is based on statistical extrapolation of the extreme response for mean wind speeds above the storm wind speed $U_{storm}$. The storm wind speed is determined based on the nominal wind speed for the wind turbine and the turbulence intensity. The method assumes that the individual 10 min. time series are independent and that the extremes used for extrapolation are independent. The calculated characteristic load is approximate 3% higher than using the method in (IEC 61400-1 2005) with a threshold value on 1.4. However, the method gives smaller loads than the (IEC 61400-1 2005) method with a threshold value on 2.0.

The second method breaks the measured time series into storms which are assumed independent. The characteristic load is determined by extrapolation of the largest extreme in each storm and both a 3-parameter Weibull distribution and a Gumbel distribution have been used for fitting the extremes. The characteristic loads calculated by the Gumbel distribution are approximate 18% higher than for the Weibull distribution. The choice of distribution function should be further studied but based on the present study the Weibull distribution is recommended. In general, the method leads to characteristic loads which are 10 – 30% higher than (IEC 61400-1 2005). The significant increase in the characteristic load by using this method can be due to that the assumptions of independents in the (IEC 61400-1 2005) method are not satisfied.

Based on the present study it is recommended that load extrapolation for wind turbines during operation is performed by the second method where the characteristic load is determined based on the extreme loads in each storm. The advantage of this method is that the load extrapolation is performed based on independent extremes leading to a statistically more accurate determination of the characteristic load. The drawback of the method is the large amount of measurement or simulations required in order to perform the load extrapolation.

## 8 ACKNOWLEDGEMENT

The work presented in this paper is part of the project “Probabilistic design of wind turbines” supported by the Danish Research Agency, grant no. 2104-05-0075. The financial support is greatly appreciated.

## 9 REFERENCES

Boulder Meeting. Load Extrapolation Evaluation Exercise LE$^3$, Meeting 23-25 April 2007, NREL Boulder, Colorodo, USA.

Coles, S. G. & Walshaw, D. 1994, "Directional Modeling of Extreme Wind Speeds", *Applied Statistics-Journal of the Royal Statistical Society Series C*, vol. 43, no. 1, pp. 139-157.

Cook, N. J. 1982, "Towards Better Estimation of Extreme Winds", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 9, no. 3, pp. 295-323.

Dyrbye, C. D. & Hansen, S. O. 1996, *Wind Loads on Structures* Wiley.

Madsen, H. O., Krenk, S., & Lind, N. C. 2006, *Methods of Structural Safety* Dover Publications, Inc..

IEC 61400-1. Wind turbines - Part1: Design requirements. 3$^{rd}$ edition. 2005.

Lindley, D. V. 1976, *Introduction to Probability and Statistics from a Baysian Viewpoint* Cambridge University Press, Cambridge.

Moriarty, P. J., Holley, W. E., & Butterfield, S. 2002, "Effect of turbulence variation on extreme loads prediction for wind turbines", *Journal of Solar Energy Engineering-Transactions of the Asme*, vol. 124, no. 4, pp. 387-395.

Moriarty, P. J., Holley, W. E., & Butterfield, S. 2004, *Extrapolation of Extreme and Fatigue Loads Using Probabilistic Methods*, NREL - National Renewable Energy Laboratory, NREL/TP-500-34421.

Peeringa, J. M. 2003, Extrapolation of extreme responses of a multi megawatt wind turbine ECN-C-03-131.

Ragan, P. & Manuel, L. 2008, "Statistical extrapolation methods for estimating wind turbine extreme loads", *Journal of Solar Energy Engineering-Transactions of the Asme*, vol. 130, no. 3.

Soares, C. G. & Scotto, M. G. 2004, "Application of the r largest-order statistics for long-term predictions of significant wave height", *Coastal Engineering*, vol. 51, no. 5-6, pp. 387-394.

Tromans, P. S. & Vanderschuren, L. 1995, "Response Based Design Conditions in the North Sea: Application of a New Method", in *27$^{th}$ Offshore Technology Conference*.