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Reliability of Offshore Wind Turbine Drivetrains based on Measured Shut-Down Events

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ABSTRACT

The key objective of this paper is to investigate the frequency of normal shutdowns to be used in the design stage of wind turbines, based on measurements at an offshore wind farm and thereby quantify their impact on the fatigue loads on the drivetrain and tower top. The measured shut-downs observed on a fully instrumented multi megawatt wind turbine located in an offshore wind farm are correlated with corresponding observations of shutdowns on surrounding wind turbines. The observed wind turbines have multiple shut-downs at high mean wind speeds. The normal shutdown is brought about by initiating blade pitching to feather and also sometimes using the generator torque as a brake mechanism. The shutdowns due to wind speed variation near cut-out are predicted using an Inverse First Order Reliability Model (IFORM) whereby an expected annual frequency of normal shutdowns at cut-out is put forth.

A simulation model of the wind turbine is set up in the aeroelastic software HAWC2, based on which the observed shut-downs are simulated, along with normal operation. The simulated tower top moments are compared with the measured loads, thereby quantifying the amplification in the loads due to the shutdown action. The IFORM determined frequency of shutdowns at cut-out mean wind speed is used as an input to the fatigue load computations in the drivetrain, by which, the resulting damage equivalent loads are analyzed to quantify their coefficient of variation for varying site specific wind conditions under both normal operation and with shutdowns. The maximum coefficient of variation (CoV) due to varying wind conditions was found on the low speed shaft torsion, but the shutdowns by themselves were not seen to significantly change the fatigue loads.

INTRODUCTION

Accurate prediction of different events in the operating life of the wind turbine is very important in the design of its constituent components. However many events such as the start-ups/shut-downs experienced by the wind turbine are not predicted during the design phase of the wind turbine and it may be relevant that a recommended frequency of such events is available for the designer. It is also important to understand the impact such events have on the fatigue life of the drivetrain as this is one of the components with a large number of failures (Asmus and Sietzler). Therefore to understand the effect of shutdowns, the number of such events observed on an offshore wind farm has been recorded, along with load measurements on the blade root, tower top and tower base. The measurement period during which the data was acquired spanned nearly 2 years from Apr 2012 to Feb 2013 and from Sept 2013 to Sept 2014 and which periods also accounted for several winter storms.

The drivetrain is defined as all components from the hub to the converter that is all elements that participate in the conversion of mechanical power to electrical power. Drivetrains are susceptible to failures in gearbox bearings, generator bearings, main bearings, gear teeth, generator windings, power electronics etc and therefore this sub system can be considered as most critical for the wind turbine life in terms of its overall reliability and structural integrity. There have been numerous investigations of drivetrain failures (Keller, Guo, Lacava and Link) and the reasons attributed to these are various (Maruqez-Dominquez, Sørensen and Rangel-Ramirez) from occurrence of faults, shutdowns/start-up fatigue, lubrication failure etc.

The gearbox design of the wind turbines on the farm are 3-stage planetary-helical and fitted with a fail-safe mechanical brake at the high-speed shaft. The generator is variable frequency asynchronous. Cut-in wind speed for the turbine is from 3m/s to 5 m/s and normal cut-out wind speed is 25 m/s. Some turbines today are fitted with a so called storm control where the turbine de-rates the power by pitching from mean wind speeds of 25 m/s and upwards. In many modern turbines, braking via a mechanical brake is minimized to decrease the cost of maintenance and control strategies are optimized to minimize loads in certain components. Under shut-down conditions, electrical torque control and braking can used to minimize vibrations in the gearbox (Xu, Xia, Hu, Li and Xu), (Wang, Yang, Yuan and Teichmann). The control for the present turbine in a shut-down may use generator torque braking from rated rpm and the blade pitch is varied.

The IEC 61400-1 Ed. 3 lists the minimum setup of load cases that need to be considered during the design of the wind turbine, amongst which are emergency shut-down design load case (DLC 5.1) , normal shut-down (DLC 4.1, 4.2) and normal start-ups (DLC 3.1, 3.2). The emergency shutdown load case contributes to ultimate design, while the normal shut-down and start-up cases contribute to both fatigue and ultimate design. For DLC 5.1, it is required that the wind turbine is brought to a halt in the quickest time possible, which usually implies that an additional brake on the main shaft is required besides the pitch action of the blades. For DLC 4.1, DLC 4.2, it is not required to have a brake torque since the turbine can be stopped by pitching the blades. However additional brake can be implemented using excess torque from the generator on the high speed side (HSS).

The fatigue loads on the wind turbine from normal shut-downs or start-ups are usually determined during the design phase by assuming indicative numbers and it is to be ascertained whether variation in these number of shutdowns is design driving for the drivetrain and if so, then the design of the bearings of the gearbox, generator, main bearing should consider these events, load and speed conditions much more carefully. However no publically available literature has so far been made on the frequency of shutdowns on an actual offshore wind farm and therefore such a study can provide a basis for future designers. The following sections propose a frequency of shutdowns based on measurements and address their effect on the fatigue damage.

WIND TURBINE AND SITE DESCRIPTION

The instrumented turbine is a variable speed, collective pitch controlled multi Megawatt machine that is mounted on a monopile foundation. The loads measured on the turbine and the SCADA system signals are logged as high frequency time series, from which additional statistics is processed. The SCADA system on the turbine transmits the rotational speed, anemometer wind speed, power production, blade pitch angle and turbine yaw direction. The nacelle top anemometer is benchmarked with a nacelle based LIDAR to ensure accurate mean wind speed measurements.

The main wind direction at the site is WSW, but the turbine under analysis is in wake in the main wind direction and facing free winds in SSE. The partial wind climate in SSE (frequency 10.4%) corresponds to an annual wind speed average of 9.9 m/s and a Weibull exponent k-parameter of 2.6. As a large part of the wind turbine operation is in the wake, the turbine is expected to endure high turbulence and consequently high fatigue loads and extreme loads, which can impact the reliability of the drivetrain. Further the wind farm site is exposed to storms that cross the Atlantic and therefore the turbine can experience mean wind speeds in excess of 20 m/s regularly in the winter months. This can lead to a large amount of start-up and shut-down operations at high mean wind speeds, whose effects are investigated herein.

SOFTWARE MODEL DESCRIPTION

The wind turbine model is developed as a multi-body finite element beam model in the aeroelastic simulation tool HAWC2 (Larsen and Hansen). The turbine is supported on a monopile structure at a mean water depth of 26m. As per information supplied by the turbine manufacturer, the modeled turbine component mass and the frequencies of the coupled structure are matched with the actual turbine structural mass and frequencies. The turbine controller is based on the in-house HAWC2 controller (Hansen and Henriksen), whereby the actual turbine mean-power curve and mean thrust curve are satisfactorily reproduced. A number of design load simulations under different operational conditions are performed in HAWC2 using environmental conditions measured on the offshore wind farm and following the IEC 61400-1 Ed.3 and IEC 61400-3 Ed.1 standards.

MEASURED SHUT-DOWN EVENTS AND THEIR SIMULATION

The IEC 61400-1 Ed. 3 load cases requires that normal shut-down and start-up events are examined for both extreme and fatigue loads and that emergency shut-downs are simulated to determine extreme loads. However the frequency of shut-downs as experienced by a wind turbine in general depends on the turbine control system and the site specific conditions and this frequency is to a large extent not known to the designer. Therefore it is valuable to document the frequency of shut-downs experienced by a state-of-the-art offshore wind turbine as a design guideline for wind turbine load simulations under similar conditions, especially since it can affect the fatigue damage on the turbine.

Due to the frequent occurrence of high mean wind speeds during the winter months, a measurement window spanning six months from September 2013 to February 2014 is initially considered, during which the start-up and shut-down events on the instrumented turbine was monitored. Figure 1 displays the histogram of the number of shut-downs experienced by the wind turbine in this period. A total of 34 shut-downs were experienced by the wind turbine, most of which can be considered as normal-shut downs.

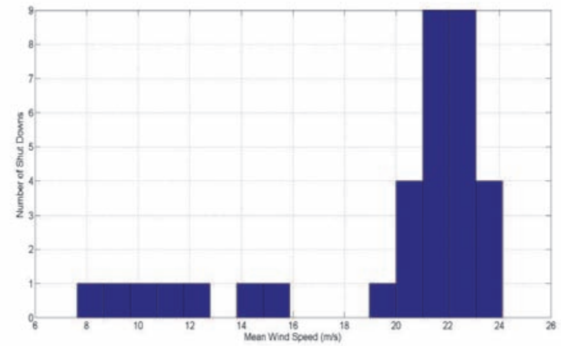

Figure 1 : Number of shut-downs recorded as a function of the 10-minute mean wind speed

As can be observed from Figure 1, the majority of the shut-downs, about 26 of them occur at mean wind speeds in excess of 21 m/s. The reasons for such shut-downs can be manifold, but herein the most frequent reason is attributed to short-term wind turbulence that causes the local 1-minute mean wind speeds in excess of 25m/s or a few due to rotor over speed and tower top vibrations.

In order to verify these number of shutdowns are not an isolated occurrence on one turbine, the SCADA measurements from four of the surrounding wind turbines have been collected, whereby the frequency of shutdowns is examined to see correlation with the instrumented turbine. The window of observation has also been widened and Table 1 lists the number of shutdowns in a 15 month period where data was available from all 5 turbines. Here R12 is the instrumented turbine corresponding to Fig. 1 and the remaining are surrounding turbines.

Table 1: Observed Shutdowns of different wind turbines in a 15 month period

Turbine	R11	R12	R22	R31	R32
No. of Shutdowns	84	91	94	77	62

From Table 1, it can be seen that the turbines R11, R12 and R22 show very similar trends of shutdowns and further they were seen to show similar spread with mean wind speed as shown in Fig. 1. It can be inferred from Table 1, that the mean shutdowns per year per turbine is 65, with a std. deviation of 11, where more than 50% of the shutdowns occur at high mean wind speeds in excess of 21m/s. This can of course be turbine controller dependent.

Figure 2 displays the recorded variation in wind speed as recorded by the calibrated nacelle anemometer, wherein it can be seen that wind speed has a linearly increasing trend wherein the mean wind speed is initially near 21m/s, but increases to a local one-minute mean of 25m/s, which results in the turbine shut-down. The 10-minute average wind speed for the plot in Figure 2 is near 23m/s. Figure 2 is characteristic of the wind speed profile in many shut-downs that occur near cut-out.

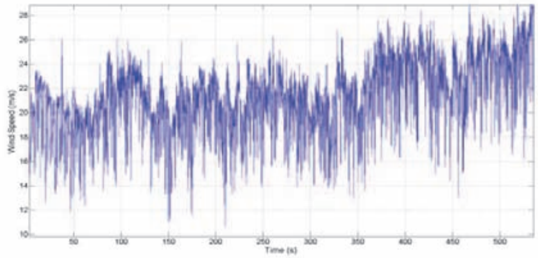

Figure 2: Measured Wind Speed Profile showing the variation in wind speed over short time

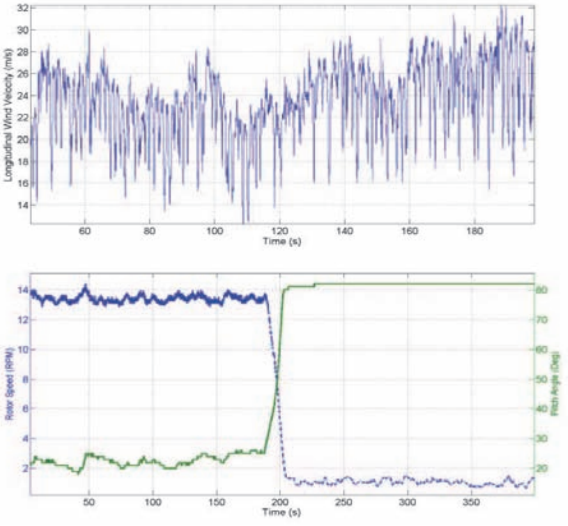

Figure 3 : Shut down at 23m/s mean wind speed with the corresponding wind velocity variation before the stop at 190s

Hence a shut-down at cut-out does not imply that the 10-minute average wind speed is at 25m/s, but that in a shorter interval the average wind speed is above 25 m/s.

A typical measured normal shut-down event that occurred during a wind speed ramp is depicted in Figure 3 where the rotor is brought to rest in about 14 seconds. The wind velocity variation before the stop again shows a gradual increase in the peak velocity and local mean. Based on the instant of shutdown, occurring around 195s in Fig.2, it can be seen that the instantaneous moving average of the wind speed is above 25m/s for about a minute before 195s, that is from approximately 130s onwards. The 1 minute mean before shut-down was 25.6 m/s, the 30-second mean was 26m/s and 10 second mean was 26.6 m/s. While the exact controller settings of the wind turbine were not available, in this paper a moving average greater than 25m/s for a duration of 1 minute was taken as representative of a normal shutdown.

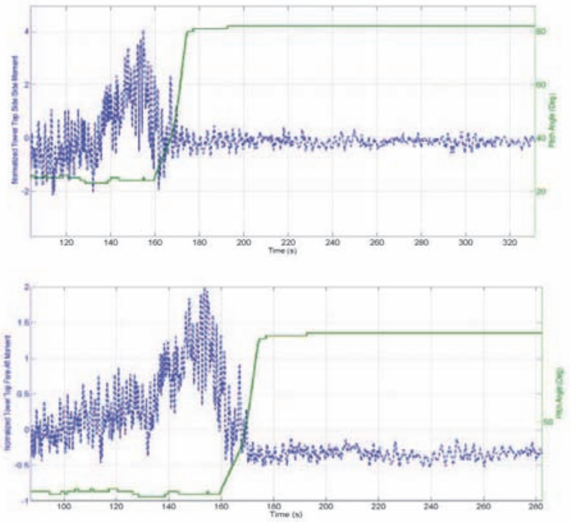

Figure 4: Measured amplification in tower top moments (1: Side-Side and 2: Fore-Aft) before one of the shut-downs

While Figure 3 reveals a shutdown due to high wind speed, there may be other reasons for the shutdown such as high tower top vibrations. Figure 4 depicts the normalized tower top fore-aft and side-side moment just before a shutdown and it can be seen that a large amplification in these moments occur as compared to a random sample taken a minute prior. Though the tower top moments show a large increase in magnitude, the tower base moments are only moderately affected due to the dominant role of the rotor thrust on the tower base moment as shown in Figure 5.

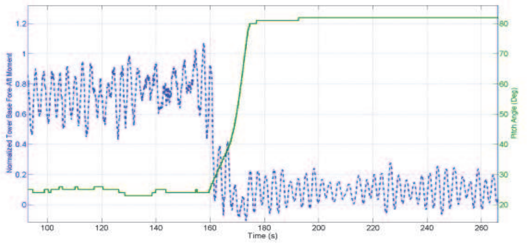

Figure 5: Measured rise in non-dimensional tower base fore-aft moment before shut-down which does not show large amplification

The type of pitch action seen in Figure 3 and Figure 4 are also observed in most of the 34 observed shut-downs in Figure 1 and represents a normal shutdown case representative of DLC 4.1 which is used in fatigue loads evaluation. The instrumented turbine loads do not measure the drivetrain shaft moments, but only the blade root moments, tower top moments and tower base moments. But at times, it is also possible that in some of the shutdowns the generator torque is used as a brake to decelerate the rotor during a shutdown and this can result in amplification in the tower side to side moment peak after shutdown. A brake initiated measured shutdown is shown in Figure 6, where the peak tower top side to side moment rises by 45% in comparison to the absolute maximum before shutdown in a 10 minute window.

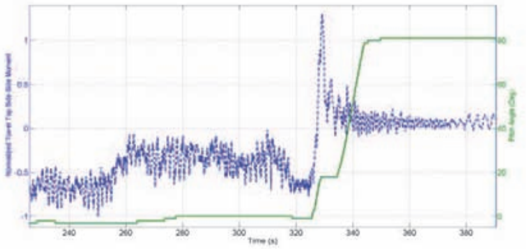

Figure 6: Measured non-dimensional amplification in tower top side-side moment after the shut-down

Based on the results in Figures 3-6, the shutdowns are simulated in HAWC2 to understand their effects on the low speed shaft torsion and tower top fatigue moments by realizing similar behavior as shown in the measured shut-downs. The HAWC2 simulation is run under turbine class 1B and three scenarios are simulated:

1) Normal DLC 1.2 as per the IEC 61400-3 which does not involve stops
2) DLC 4.1 which uses Normal stop procedures as applied under normal turbulence wind input with only pitch activity
3) A modified DLC 4.1 where the generator torque is used as a braking mechanism along with pitch activity.

A comparison of case 2 and case 3 above reveals that while the braking torque is seen to increase the simulated tower top side-side peak moments as shown in Fig. 7, the blade root edge moments are seen to be lowered than when using only pitch action to stop the turbine. Here the case with the brake was tuned so that the turbine comes to a standstill within 10 seconds. There a benefit of using the generator torque as a brake is to reduce the blade root edge moments during the shutdown as shown in Figure 8. Thus there is the potential that without using a generator brake torque, the normal shutdowns can result in significantly higher blade edge fatigue moments. Since the tower top side-side moments and the blade root edge moments show higher peaks near cut-out mean wind speed and since the frequency at cut-out is what is observed to be high on the wind farm, the effect on the fatigue moments, will be analyzed using shutdowns at cut-out.

In the subsequent sections in the paper, only the normal shutdowns due to wind speed exceeding cut-out will be investigated whereby the expected frequency of such shutdowns are predicted based on the Weibull probability of the mean wind speed combined with the probability of turbulence. The obtained frequency of shutdowns is then used in the estimated fatigue loads under normal shutdown simulations where there is no applied braking torque.

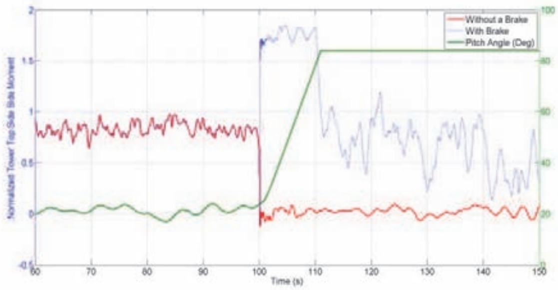

Figure 7: Effect of brake torque on the Simulated Tower Top Side-Side Moment compared with a shutdown with only pitch activity

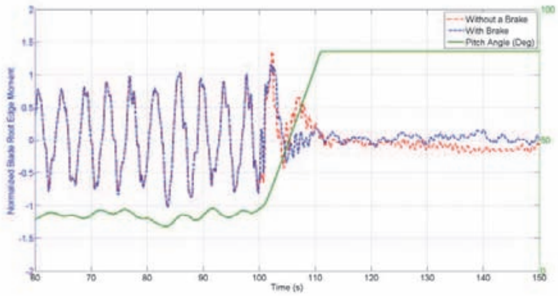

Figure 8: Effect of brake torque on the simulated blade root edge moment compared with a shutdown with only pitch activity

EXPECTED FREQUENCY OF SHUT DOWN EVENTS

As ascertained from Figure 1 and Table 1, the number of shut-downs near the shut-down mean wind speed (25 m/s) is of the order of 50 per year. Also considering from Figure 2, many of the shut-downs occur from instantaneous mean wind speed progression from about 22m/s to 25 m/s within a 10 minute period. Further from the results of the previous section, the effect of such shut-downs can induce high torsional moments on the tower top side to side bending moments, LSS torsion or blade root edge moments, which can be detrimental to the integrity of the structure, if the events occur frequently. From an extreme load point of view, each occurrence of the shut-down is an opportunity for a load level crossing and in this aspect the frequency of occurrence of a shut-down is very similar to the load extrapolation process demanded for DLC 1.1. The load extrapolation is done with regards to the probability of exceedance of a 50 year load level due to the interaction of wind turbulence with the rotor. The normal shut-downs are a similar interaction wherein a level crossing can occur and then the level crossings may be taken to follow a Poisson process.

Therefore a pertinent design parameter is to understand is the target annual frequency of shut-downs near cut-out wind speed, which is consistent with the target reliability of the structure. Though, the IEC 61400-1 Ed.3 wind turbine design standards do not prescribe definite allowable shutdown frequencies, some of the certification guidelines such as the GL-2010 (Germanischer Lloyd) guideline stipulate an annual frequency of 1000 normal shut-downs at cut-in and 50 normal shut-downs at cut-out. However, where wind conditions are the cause, frequency of shut downs allowable at mean wind speeds near cut-out and cut-in should be based on the probability of the mean wind speed to be at cut-in or cut-out. Such an estimate can provide a better site specific design limit.

Based on the Inverse First Order Reliability Model (IFORM), the probability of occurrence of different events can be made conditional on the environmental parameters and other turbine stochastic parameters, whereby a desired target of the joint probability can be met in normal space. The mean wind speed profile is assumed to follow a Weibull distribution. Even though the IEC 61400-1 standard allows deterministic wind profiles to estimate the extreme loads from a shut-down event, in reality the wind is turbulent such as shown in Figure 2 and Figure 3. Keeping the focus to only shutdowns caused by wind speeds above the cut-out limit, the probability of a shut-down event near the mean wind speed for cut-out is analyzed as conditional on the probability of that mean wind speed and the turbulence level. Other factors such as the control settings of the turbine can also be significant, but are not analyzed here due to lack of specific information from manufacturers.

The annual target probability of exceedance assumed in wind turbine design is 0.02 corresponding to a 50 year return period. Using the Rosenblatt transformation (Rosenblatt) to convert to normally distributed space, the number of shut-downs to be considered in the design space to satisfy a given exceedance criteria can be formulated as

$$F_V{}^2 + F_{\sigma|v}{}^2 + F_{\vartheta|\sigma|v}^2 = \beta^2$$

$$F_V = \Phi^{-1}(P_v) \; and \; F_{W|v} = \Phi^{-1}\left(P_{\sigma|v}\right) \qquad \text{-(1)}$$

Where Φ indicates the normal CDF and P($\sigma|v$) is the cumulative distribution of the 10-minute wind turbulence conditional on the 10-minute mean wind speed, *V*, which is Weibull distributed (P_v) and $F_{\vartheta|\sigma|v}$ is the probability of a given number of shut-downs in a 10-minute window, which is considered normally distributed, conditional on the mean wind speed and turbulence. Based on taking the shutdowns as mutually independent occurrences and only conditional on the mean wind speed turbulence, the *N*-year- probability of exceeding f_s shutdowns per year is ~ $1/(N.f_s)$

Consequently,

$$F_{\vartheta|\sigma|v} = \Phi^{-1}\left(1/(N.f_s) \right) \qquad \text{-(2)}$$

Even though the normal turbulence level used in the IEC 61400-1 Ed. 3 is the 90% quantile, the turbine under investigation was under wake situations about 89% of its operational time and further most of the shutdowns were seen under storm conditions. Therefore a 98% turbulence with a short-term exceedance probability of 0.02 is used, in Eq. (1). A bin size of 3m/s is assumed, that is a shut-down at cut-out can occur at a 10-minute mean in the range 23m/s -26m/s.

In Eq. (1), a β, which corresponds to the number of 10 minute periods in *N* years can be used, but herein the annual frequency of shut-downs is evaluated. The observed wind conditions from the wind farm, i.e., with the Weibull parameters of annual average wind speed of 9.9 and exponent of 2.6, when evaluated in Eq. (1) provides the annual frequency of shutdowns at cut-out of 25m/s as 10 and the expected number shut-downs above a mean wind speed of 23m/s as 85, which is of the same order as observed from Figure 1 of about 52 annual shutdowns with the mean wind speed greater than 23m/s.

This estimate is strongly dependent on the tail of the Weibull distribution where lower the exponent, the higher the numbers of probable shut-downs due to exceeding the cut-out wind speed. Figure 9 shows the number of possible shut-downs as a function of the Weibull Exponent, wherein using a the traditional Rayleigh exponent of 2 provides the estimate of 251 possible annual shut-down events at cut-out, where the cut-out is defined by a trend in the mean wind speed over 10 minutes, where a 1 minute mean may exceed 25m/s. Hence the number of wind related shut-downs to be considered can vary significantly based on site specific conditions as shown in Figure 9. As mentioned earlier, GL-2010 guidelines prescribe about 1000 shut-downs at cut-in and 50 annual shut-downs at cut-out. If the above analysis of estimating the number of shut-downs based on the Weibull probability of mean wind speed is made, then about 1000 annual shut-downs can be expected at the present site specific wind conditions at cut-in. However, if the Rayleigh wind distribution is used, then about 1900 shut-downs at cut-in of 3m/s can be expected.

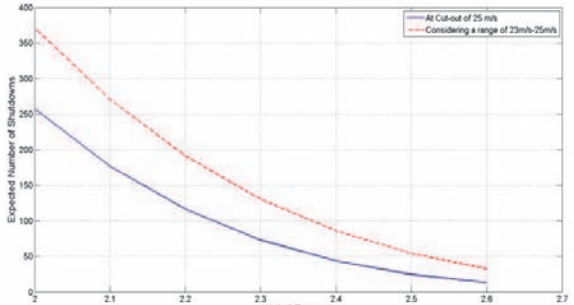

Figure 9: Number of Expected Shut-downs at cut-out mean wind speed when considering cut-out as 25m/s and when using a larger range of mean wind speeds (23m/s-26m/s)

At all other mean wind speeds between cut-in to cut-out, the probability of shut-down is strongly dependent on the turbine control system parameters and the likelihood of various faults and therefore the Weibull analysis provided above is not applicable.

ANALYSIS OF FATIGUE DAMAGE EQUIVALENT LOADS

The fatigue on structures is based on standard S-N curves, wherein the number of cycles for failure, *N* at a load (or stress) amplitude ΔS is expressed as

$$N = K\left(\Delta S\right)^{-m} \qquad \text{- (3)}$$

where *K* and *m* are material parameters. However there are significant uncertainties in the evaluation of the fatigue load level and in the material properties. The Miner's rule (Maruqez-Dominquez, Sørensen and Rangel-Ramirez) is used to ascertain when the damage in the material reaches unity, which implies failure. Such a basic methodology for fatigue failure can also possess several uncertainties.

The damage limit state equation for the Miners rule is:

$$\Delta - \sum_i \frac{n_i}{K} \gamma_{Mf} \gamma_{Ff} \Delta S_i^{\ m} = g(t) <= 0 \qquad \text{- (4)}$$

and the annual probability of failure $P_F(t)$ is normalized by the survival probability in *t* years is given by

$$P_F(t) = (P(g(t) \leq 0) - P(g(t-1) \leq 0))/(1 - \mathrm{P}(\mathrm{g}(\mathrm{t}-1) \leq 0)$$

The Miners sum Δ is usually assumed to be Log-normal distributed with a coefficient of variation of 25%. The partial safety factors γ_{Mf}, γ_{Ff}, are due to material parameter variability and the fatigue load variability. Herein we are focused on the variability of the fatigue load only and therefore the coefficient of variation leading to γ_{Ff} is to be determined with the added focus on fatigue damage under shut-down events. The usual coefficient of variation assumed when determining the safety factor γ_{Ff} is of the order of 20% based on the normal operational fatigue cycle evaluation methods employed. It is to be determined, if the variability in wind conditions leading to shutdowns causes as greater coefficient of variation in the fatigue load.

Simulating the loads on the wind turbine in normal operation and with shut-downs at cut-out in normal turbulence, the fatigue loads on the tower top, blade root and driveshaft were assessed at different Weibull exponents for the wind distribution over 20 year operational period. Figure 10 depicts the variation in the tower top side-to-side fatigue moment at cut-out as a function of the Weibull exponent computed using simulations for shut-downs at cut-out, which reveals a large difference in the shutdown loads based on the wind conditions used. This is also reflected in the number of shutdown cycles compared to the overall cycles at cut-out as also depicted in Fig. 10. However this needs to be compared with the overall fatigue during normal operation to quantify its significance.

Table 2: Coefficient of variation of Fatigue Loads in Eq. (4) due to Weibull wind exponent variation

Load Sensor	CoV without shutdown	CoV with shutdown
Blade Edge moment	1.6%	1.7%
Tower Top SS moment	6.4%	6.6%
LSS Torsion	8%	8.8 %
LSS Bending	1.3%	1.4 %

The coefficient of variation of the cumulative damage equivalent loads over the lifetime is estimated by computing the fatigue in normal operation and then comparing the results with the fatigue computed with the additional loads due to shutdowns occurring at cut-out.

Table 2 describes the coefficient of variation of the fatigue damage equivalent loads, based on varying Weibull wind parameters; the higher fatigue cycles being for the Rayleigh wind distribution. Thus table 2 displays that the coefficient of variation in the tower top side-side damage equivalent moment and LSS bending with shutdowns at cut-out is significantly greater than when the fatigue is assessed without shut-downs. All the coefficients of variation in Table 2 when computed without shutdowns are of the order of 1%-8%. The blade edge moment and low speed shaft bending are driven more by inertial forcing rather than wind action and hence the low CoV to wind variations may be expected. Further the coefficients of variation with shutdowns is still of the same order as the normal operation case and well within the 20% that is used in computing γ_{Ff} in Eq. (4). However at cut-in, the number of shutdown cycles (~1000 - 1900) in Figure 9 may also result in a larger uncertainty in fatigue loads especially if the rotor speed at cut-in is near the 3P frequency. However since no shutdowns or start-ups at cut-in were recorded from the observed wind turbines and since these events are much more controller dependent, these are not investigated herein.

The Rayleigh wind distribution leads to the largest expected number of shutdowns and it is only the low speed shaft torsion that shows some uncertainty to the site specific wind conditions. Since this might also affect the loads on the components of the gearbox, an additional coefficient of variation of about 5%-8% on the Miners sum, γ_{Mf} may be considered in Eq. 4 to take into account this uncertainty.

CONCLUSIONS

The number of shutdowns and start-ups under high mean wind speeds was investigated by measuring the actual shutdowns of 5 different wind turbines in an offshore wind farm, The observed shutdowns at cut-out showed an increasing mean wind speed trend before shutdown, which implied that shutdowns were possible even if the 10 minute average wind speed was 22m/s-23m/s since the one minute mean can exceed 25m/s causing the turbine to shut down. The turbine shutdowns may also be due to other reasons such as tower top vibrations.

The measured tower top loads showed high peak extremes during some of the shutdowns indicating that a brake torque may be used on occasion which leads to significant fatigue or extreme loads on the tower top. The fatigue loads were simulated in the HAWC2 aeroelastic software during normal operation and during shutdowns, whereby the effect of including the fatigue damage equivalent loads due to shutdown at cut-out was quantified at different Weibull mean wind speed profiles. The frequency of shutdowns was predicted based on an IFORM approach where the shutdown frequency at cut-in and cut-out was conditional on the mean wind speed and turbulence probability.

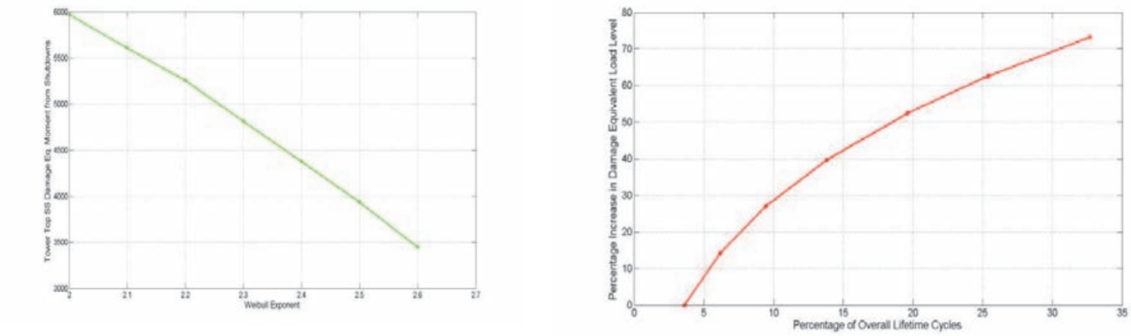

Figure 10 : Variation in the tower top Side-to-Side Damage Equivalent Moment at cut-out with the Weibull Exponent and its percentage increase with increased number of shut downs at cut-out

The obtained results were found to tally with the observed number of shutdowns in the wind farm at cut-out at the measured mean wind Weibull parameters. It was found that there can be significant variation in the frequency of shutdowns due to varying Weibull wind parameters, but this was not found to significantly affect the damage equivalent loads. The overall coefficient of variation in the damage equivalent loads on the blades, tower top and driveshaft bending due to Weibull wind parameter variation was very low, but the drivetrain shaft torsion was affected with a CoV of 8%. In general, the shutdowns are also dependent on the turbine specific controller settings.

Based on the results, it is recommended that for drivetrain design 1) the designer uses site specific wind conditions for fatigue computation along with the expected frequency of shutdowns at cut-in and cut-out. 2) If the site specific wind conditions are not known, then at least 1900 annual shutdowns at cut-in and 250 annual shutdowns at cut-out should be used 3) The coefficient of variation of fatigue loads was well within the 20% range that is usually accounted for in the partial safety factors for fatigue loads, but the design limit for the Miners rule may be varied by 5%-8% for drivetrain component design studies.

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