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Extreme wind speed ramp events: A measurement-based approach for improving the modelling of ultimate loads for wind turbine design

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Abstract. Ramp events, i.e., significant changes in wind speed in a short time period, have become critically important to end-users. However, only a few studies address their impact on wind turbine loads. To the best of the authors' knowledge, these results have not yet been validated with measurements. Therefore, this paper aims to investigate the impact of extreme wind speed ramps on ultimate wind turbine loads using eight months of offshore measurements. We also compare the measured loads with simulations following the International Electrotechnical Commission (IEC) extreme turbulence model, in order to improve the modelling of ultimate loads. This is because events with a 10-min horizontal wind speed standard deviation higher than the prescribed IEC turbulence class, in line with other research, are primarily associated with ramp events. They are found to be design driving for the blade root flap-wise moments below and beyond rated wind speed, but not in the transition region. The high-frequency analysis of these moments showed a sudden pitch transition from the inactive to the active region. In general, the loads associated with ramp events did not exceed the simulations. In addition, non-ramp related extreme loads around rated wind speed, which exceeded the simulations, were associated with standard deviations slightly above the normal turbulence model (NTM) of IEC for a waked turbine, indicating the impact of wake added turbulence. In conclusion, for the ultimate load analysis, the wind speed time series should include a sudden pitch transition from the inactive to the active region in addition to wake added turbulence.

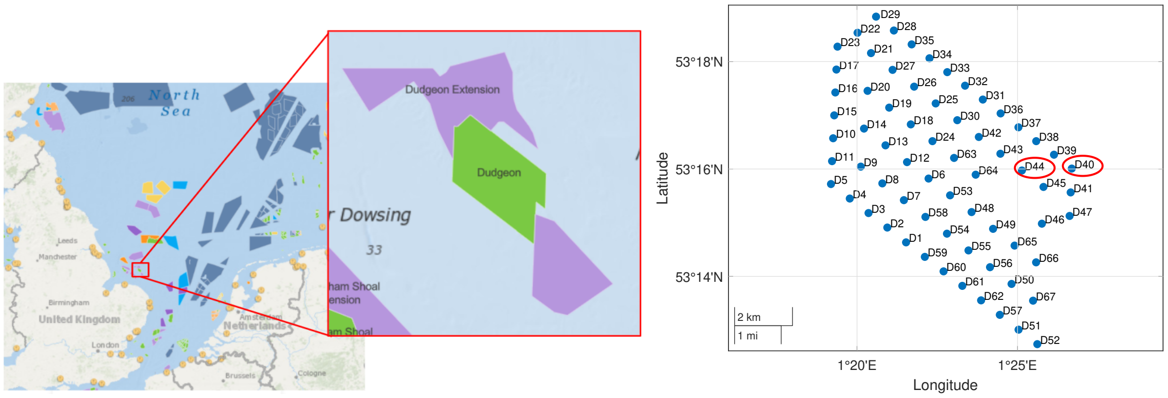
1. Introduction

The widely used International Electrotechnical Commission (IEC) 61400 standard [1] specifies design load cases (DLCs) to engineer a turbine with a certain reliability level. These DLCs provide the ultimate loads that a wind turbine may experience, among others, due to extreme horizontal turbulence, wind shear, or wind gusts [2]. However, none of the load cases deal with wind speed ramp events (i.e. a sudden and significant shift in wind speed in a short period of time) and only a few papers address their impact on loads. The existing studies have identified that 10-min horizontal wind speed standard deviations (σ_u) exceed the prescribed IEC extreme turbulence model (ETM), claiming it is not a conservative approach [3, 4]. These events were found to be associated with wind speed ramps of temporal scales from a few minutes to hours and thus, not related to turbulence. Ramp events are highly intermittent in nature and represent non-Gaussian inflow. Therefore, they can impact the extreme wind turbine loads significantly [5]. In Hannesdóttir *et al.* [3], the authors observed almost simultaneously wind speed ramps at two met masts, 400 m apart, showing that their length scale is longer than the turbulence scale. They simulated loads induced from observed ramp-like events and compared them with loads based on IEC ETM model (i.e. Design load case (DLC) 1.3). This DLC simulates the normal operation of a wind turbine under extreme turbulence. In their research, the authors found that tower-base fore-aft bending moments that are associated with ramp events exceed the IEC DLC 1.3 moments for wind speeds of 8-16 m/s (that starts below and exceed beyond rated wind speed, leading to higher thrust force). Nonetheless, to the best of the authors' knowledge, the results are not yet validated with load measurements. Therefore, further research based on real measurements is needed to substantiate the existing findings and to investigate the real impact of ramp events on wind turbine design.

This paper aims to investigate the influence of wind speed ramp events on extreme loads of offshore wind turbines using eight months of measurements. Subsequently, these measured ultimate loads are compared with simulations following the IEC DLC 1.3 to understand how effectively DLC 1.3 predicts ramp-induced loads and overall ultimate loads.

2. Site description, measurements and load simulations

For the ultimate load analysis we analyse a dataset from the Dudgeon wind farm. This offshore wind farm is located 32 km off the coast of Cromer, in the North Sea, UK (see Figure 1(a)). It consists of 67 Siemens 6MW pitch-regulated wind turbines, of which 'D40' and 'D44' (highlighted in red circles of Figure 1(b)) are fully instrumented turbines to provide load measurements.



(a) Map of Dudgeon wind farm

(b) Dudgeon wind farm's layout

Figure 1: Overview of the Dudgeon wind farm

2.1. Measurements and filtering

The calibrated 10-min statistics and high-frequency (25 Hz) data of the blade root, tower top and tower base moments are provided by SGRE, from the Power Load Measurement (PLM) system. In addition, wind speed, rotational speed of the rotor, pitch, and yaw angle data are also available for this study. The wind speed measurements are obtained from a nacelle mounted cup anemometer. Thus, the readings are affected by the modified wind speed variability due to the rotation of the rotor. Therefore, it is important to note that the available TI and 10-min average wind speed measurements deviates from free flow.

These measurements are filtered for normal operation conditions for the different wind turbine control regions. Region 1 $\frac{1}{2}$ is a start-up region, region 2 is partial load and in region 3, power is kept constant at the rated power by increasing the pitch activity. Transition of controller from region 2 to 3 is indicated by region $2\frac{1}{2}$. Detailed information can be found in Ranka *et al.* [6].

2.2. Load simulation environment

In addition, load simulations datasets of DLC 1.2 and 1.3 are also available. SGRE simulates the wind turbine loads by using the Bonus energy Horizontal axis wind turbine Code (BHawC). It is a non-linear aeroelastic tool used for dynamic analysis and load calculations of horizontal axis wind turbines. For this study, simulations were performed by tuning the structural parameters of the aeroelastic model with the calibrated sensor readings of the turbine D40 from the Dudgeon wind farm. The available bending moments were simulated at the sections corresponding to the sensor locations on the actual wind turbine, i.e. near the blade root, tower top, and tower base.

Simulations were performed for six turbulent seeds per wind speed bin indicating six different wind time series with nearly similar statistical values. The 10-min time series of a sampling frequency of 25 Hz were based on the NTM and ETM model, for DLC 1.2 and 1.3 respectively. For this study, the wind and wave directions were assumed to be perfectly aligned, i.e. 0^o misalignment. Further information is available in the IEC 61400-3 standard [7].

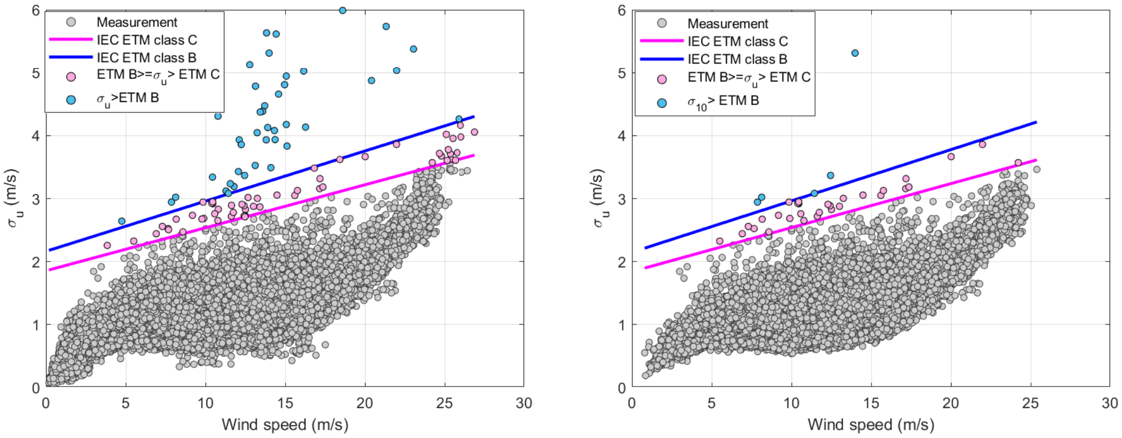
3. Methodology

Hannesdóttir *et al.* [3] found that the extreme horizontal wind speed fluctuations which exceed the prescribed IEC ETM are related to wind speed ramps. These events also lead to higher tower base fore-aft moments for specific wind speed bins. Therefore, a similar approach is used in this paper, to detect and analyse extreme ramp events and their impact on wind turbine loads. The IEC ETM σ_u is defined as:

$$\sigma_u = c * I_{ref} * (0.072(\frac{u_{ave}}{c} + 3)(\frac{u}{c} - 4) + 10) \tag{1}$$

where $c = 2$ m/s, I_{ref} is 0.12 and 0.14 for class C and B, respectively [1]. u_{ave} is taken as average of entire available wind speed dataset.

Figure 2(a) represents the variation in horizontal wind speed standard deviation for the whole unfiltered dataset. As observed, the site conditions of the Dudgeon wind farm fall under the IEC turbulence class C. The number of extreme events drop drastically after filtering the wind speed data (see Figure 2(b)) w.r.t. the availability of bending moments. Thus, in order to draw substantial conclusions, events with 10-min wind speed standard deviation higher than 90% of the IEC ETM class C were considered for analysis of extreme ramp events. It should be noted that in Hannesdóttir *et al.* [3], the authors only considered events higher than the ETM class B, as their work was based on data from an onshore (near-coastal) site using ten years of high-frequency measurements.



(a) Unfiltered (raw data)

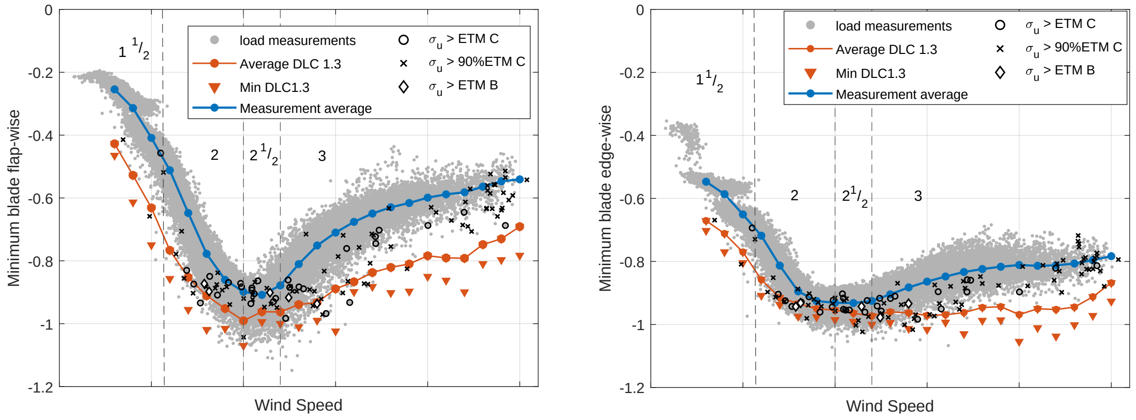
(b) Filtered

Figure 2: Extreme observed horizontal wind speed standard deviations (σ_u) compared to IEC ETM class C and class B. Grey dots correspond to raw measurements, pink dots denote $\sigma_u >$ IEC ETM class C and blue dots indicate $\sigma_u >$ IEC ETM class B. Data in figure (b) is filtered w.r.t. data availability of the bending moments, and wind turbine shut-down and power curtailment cases are discarded.

4. Results

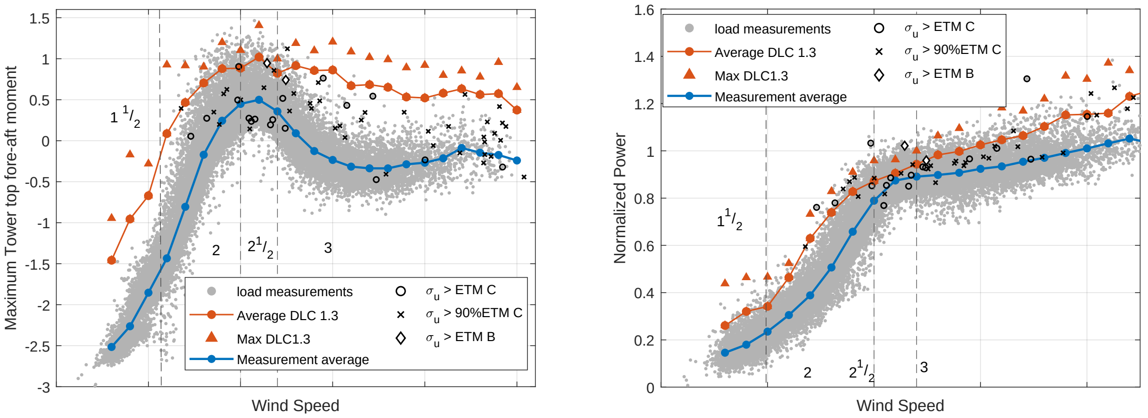
Before investigating the influence of ramp events on extreme loads of an offshore wind turbine, it was ensured that the measurements were well calibrated w.r.t the aeroelastic simulations. In this regard, simulation results of DLC 1.2 and DLC 1.3 were compared against the measured 10-min minimum blade root, maximum tower top and base moments. The selection of 10-min extreme moments as either minimum or maximum moments is based on the local coordinate system of that turbine component. The IEC DLC 1.2 calculates loads experienced by a turbine due to normal atmospheric turbulence during its operational lifetime. In general, these results satisfactorily match, concluding that the model is a good representative of the measured loads and no significant calibration uncertainties are involved. As DLC 1.3 simulates the loads caused by the ETM, the average of its maximum (or minimum) results is validated with the extreme measurements. DLC 1.3 loads satisfactorily followed the extreme 1% measured moments. Detailed information can be found in Ranka *et al.* [6].

Following that, the influence of the ramp events is analysed on the blade root, tower top and base moments (see figures 3 and 4). The negative values of the extreme blade moments are associated with the orientation of the local blade coordinate system. The detected extreme wind speed ramp events are highlighted with black markers and are divided based on their turbulence intensity levels. The comparatively lower number of these events for the tower bending moments is due to the lower availability of the tower data compared to the blades data. The blue and orange lines represent the average of the measured and the DLC 1.3 simulation loads, respectively, per wind speed bin. The triangles indicate the extreme simulation loads per wind speed. All graphs are divided into four separate control regimes. These events are likely to govern higher loads in region 3, whereas in the region $2\frac{1}{2}$, extreme fluctuations mainly fall near the average loads. This can be associated with the increased pitch activity around the rated wind speed region. In comparison with the simulation results, the loads associated with extreme fluctuation events show, in general, lower (in absolute terms) values than the respective extreme moments of DLC 1.3, except for some of the wind speed bins of tower top side-side moments.

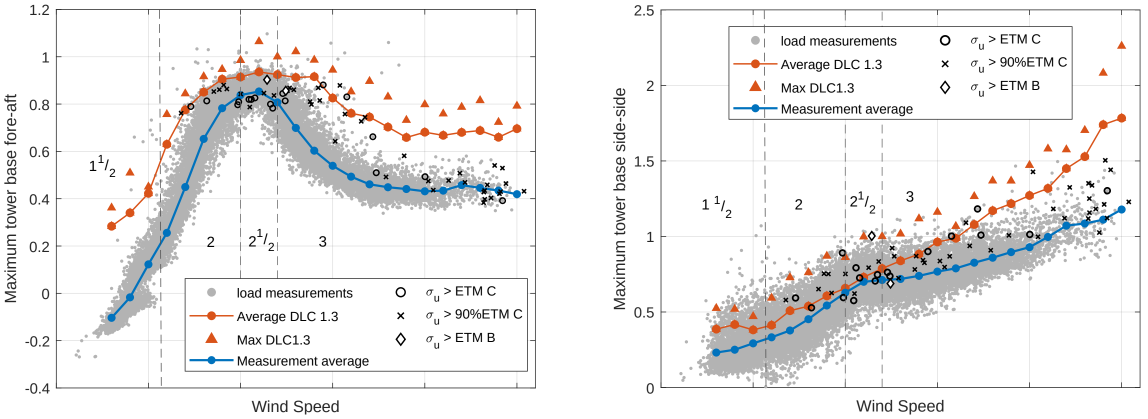


(a) Minimum Blade root flap-wise moment (b) Minimum Blade root edge-wise moment

Figure 3: Influence of extreme ramps on the minimum blade root flap-wise and edge-wise moments. Values are normalized with the absolute minimum DLC 1.3 moment at rated wind speed.



(a) Maximum Tower top fore-aft moment (b) Maximum Tower top side-side moment



(c) Maximum Tower base fore-aft moment (d) Maximum Tower base side-side moment

Figure 4: Influence of extreme ramp events on the maximum tower top and base moments. All moments are normalized with the absolute maximum DLC 1.3 moment at rated wind speed.

Aside from the extreme ramp events, some of the measured loads near the regions $2\frac{1}{2}$ and 3 exceed the extreme loads predicted by the DLC 1.3. To determine the plausible cause of higher or lower loads in each region, a few interesting events are selected for high-frequency analysis based on their turbulence level intensity or extreme loads higher than DLC 1.3.

4.1. An event of σ_u > IEC ETM B

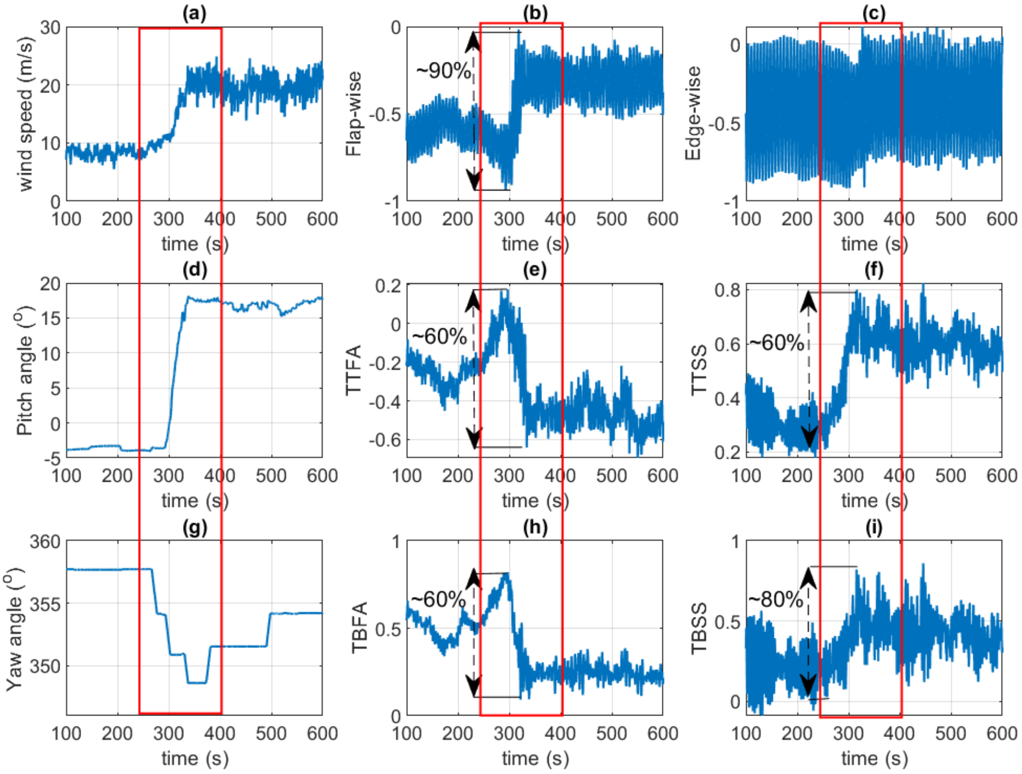


Figure 5: Time series of different turbine signals for an event of σ_u > IEC ETM B. Red boxes highlight the timing at which the wind speed ramp occurs. All moments are normalized with the absolute maximum DLC 1.3 moment at rated wind speed.

At first, an event of turbulence level higher than IEC ETM B is selected, for which an explicit ramp-like increase is observed. This is highlighted by red boxes in Figure 5. The wind speed time series (see Figure 5(a)) initially showed a gradual increase around 300 s followed by a sudden increase. Around this time, fluctuation intensity of the ramp event is lower compared to the no-ramp region. Interestingly, the tower top side-side moment showed a similar pattern (see Figure 5(f)), but with a shorter rise time as power reaches the rated capacity. The ramp-like increase is also observed in other bending moments and pitch angle around the same time, indicating that the length scale is of the order of the turbine size. When the blade started pitching (see Figure 5(d)), a sudden peak in the tower fore-aft and blade root flap-wise moments is observed before they drop (see Figure 5(b), (e) and (h)). Yet, the moments do not reach extreme values because of the faster pitch response to a comparatively longer ramp duration. In other words, as explained in Bierbooms [8], as the rise time of the ramp events is much longer than the time constant of the controller activity, the ramp-related variations were well handled by the controller. Moreover, approximately a 90% drop in the blade root flap-wise moment, a 80% rise in the tower base side-side moment and a 60% drop (or rise) in the other moments is observed in less than 50 s, except for the blade edge-wise moment.

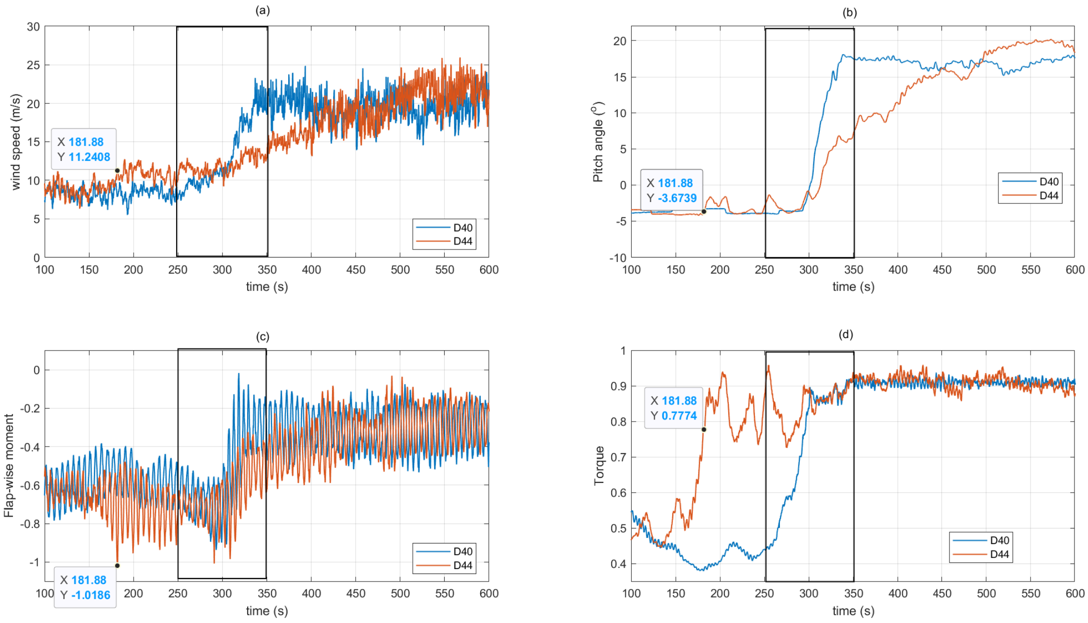


Figure 6: Time series of D40 and D44 measurements of an extreme event. The black box highlights the ramp event observed in D40. X and Y coordinates show the time and other signals value at the local minimum blade root flap-wise moment, respectively. All moments are normalized with the absolute maximum DLC 1.3 moment at rated wind speed.

Figure 6 compares time series of this event at turbine D40 and D44 for the same 10-min duration. A ramp event at D44 showed a longer time duration to reach the same wind speed level as the turbine D40 (see Figure 6), which could be a result of wake effects (see Figure 1(b)). Despite the slower ramp-rate, the blade root flap-wise bending moment is lower (higher in absolute terms) for turbine D44 than D40. Moreover, the local minimum value in the specified 10-min duration is not associated with a ramp event, but with wind speed fluctuations near rated wind speed. This leads to a sudden pitch transition from inactive to active, which can be observed in the pitch curve around the minimum blade root bending moment (see Figure 6(b) in orange). The torque time series of D44 showed higher fluctuation compared to gradual ramp-like variations for turbine D40. The comparatively higher turbulence at turbine D44 may be associated with the wake added turbulence, as D44 is in the wakes of turbines D37 and D38 (see Figure 1(b)) for northerly winds (assuming no yaw misalignment). In Kelly *et al.* [9], the author also found that higher extreme loads were observed for downstream wind turbines than for upstream turbines based on constrained simulations with ramp-like wind speeds. Thus, if a no-ramp region is near rated wind speed and involves sudden fluctuations demanding pitch activation, this can result in higher loads than DLC 1.3 in the wind speed bin.

4.2. An event of $\sigma_u > \text{IEC ETM C}$

For the selected event, the 10-min minimum (maximum in absolute terms) measured flap-wise moment is observed close to the minimum from DLC 1.3, for the specific wind speed bin. When compared time series of similar wind speed statistics, they showed a similar ramp-like decrease (approximately at the same time, see Figure 7(a)). However, the simulation wind speed consists of higher fluctuations. Thus, in this case, the resulted blade root flap-wise bending moment from simulations showed lower minimum value than measurements (see Figure 7(c)). Similar to previous events, the minimum blade root flap-wise moment also occurred when the blade pitched from the inactive to the active region (see Figure 7(b)). Around this time, a sudden transition in torque activity is also observed. Thus, it can be said that the DLC 1.3 satisfactorily predicts the moments related to such time series.

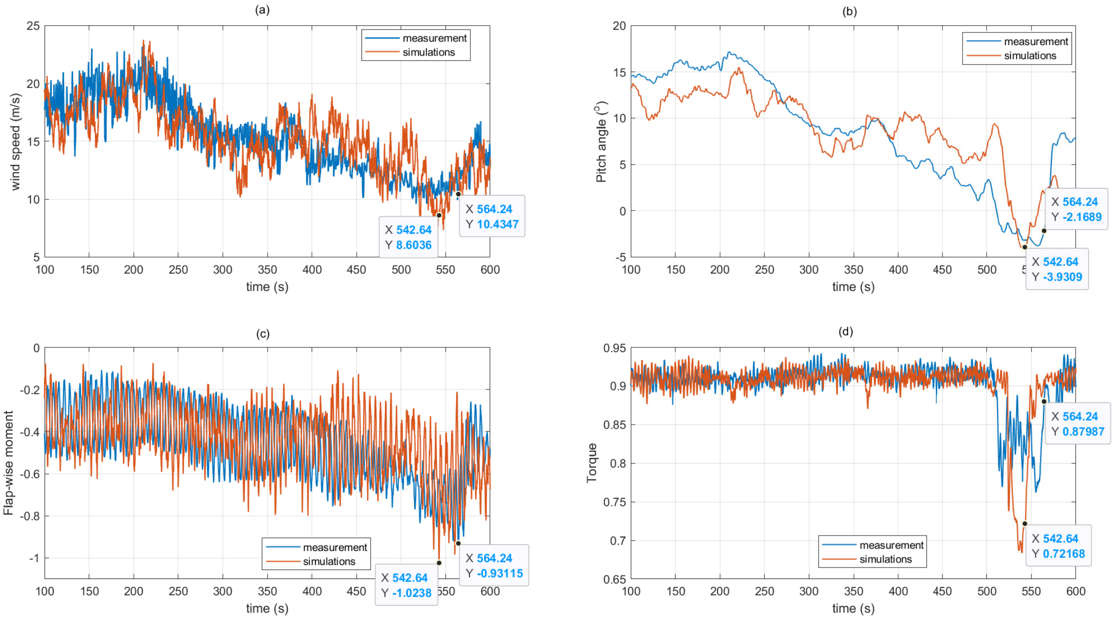


Figure 7: Comparison of measurements and DLC 1.3 time series of similar wind speed statistics. X and Y coordinates show the time and other signals value at the indicated blade root flap-wise moment, respectively.

4.3. An event of the minimum blade root flap-wise moment

This event corresponds to the lowest (highest in absolute terms) measured blade root flap-wise moment in the entire duration. It showed a considerably lower turbulence level than IEC ETM. In comparison with the NTM time series of similar wind speed statistics, the selected events showed a slightly higher turbulence intensity (see Figure 8(a)). We relate this to the fact that the analysed wind turbine was in the wake of an upstream turbine. One can argue that the measured wind speed time series may include added blade passing fluctuations (see subsection 2.1). However, the measured rotational speed is given as an input to the control system. The comparison of power spectral density (PSD) plots revealed the higher fluctuation frequency present in the measured rotational speed than the simulations. The observations in (Figure 8(d)) suggest that the increased fluctuations near rated rotational speed and the observed higher energy in the high-frequency region are the reasons for the higher loads (more information can be found in Ranka *et al.* [6])

In addition, as the 10-min average wind speed is near rated wind speed, any slight change in the wind speed could lead to a transition of pitch control from the inactive to the active region within a few seconds. Thus, in a similar manner, a sudden pitch transition from the inactive to the active region, in addition to wake added turbulence, leads to higher loads (see Figure 8(b)).

One can argue that the exceeding blade root flap-wise moments should be compared with 10-min minimum DLC 1.1 moments, because DLC 1.1 yields ultimate loads experienced by NTM in 50-years recurring time. However, IEC DLC 1.3 is designed such that the ultimate loads from DLC 1.1 should not exceed DLC 1.3 [1], i.e. DLC 1.3 includes the ultimate loads from DLC 1.1.

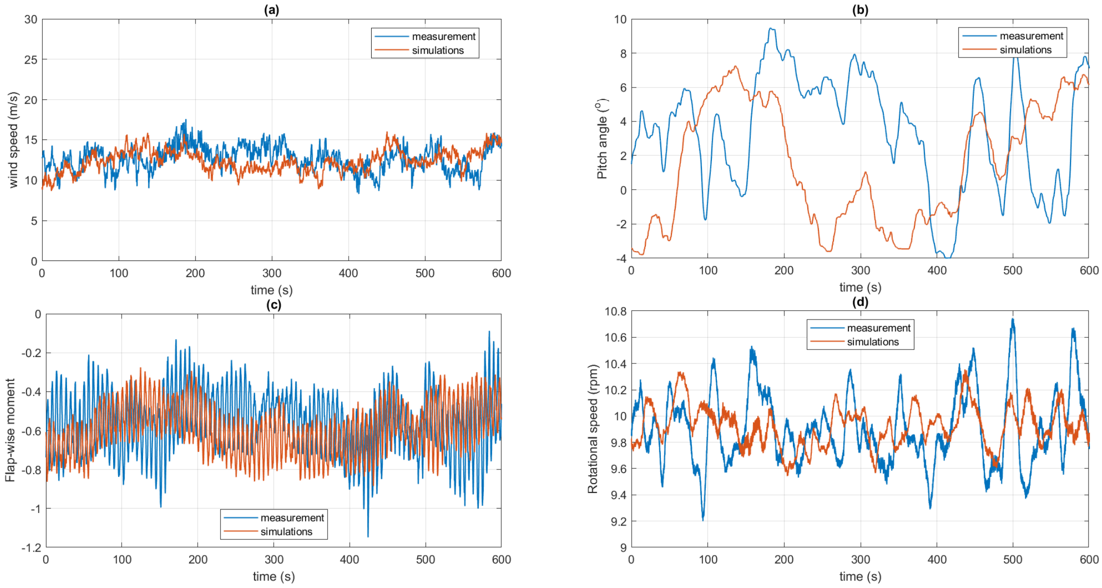


Figure 8: Comparison of measurements and DLC 1.2 time series of similar wind speed statistics. All moments are normalized with the absolute maximum DLC 1.3 moment at rated wind speed.

5. Discussion

Ramp-related loads that exceed IEC ETM guidelines showed a significant impact on the maximum (minimum for blades) bending moments in the regions 2 and 3, i.e. below and above rated wind speed. Yet, no such impact was observed in the region $2\frac{1}{2}$ (transition region), which can be because of the increased controller activities.

The tower side-side moments, induced by the extreme ramp events exceeding IEC ETM Class B, outperformed DLC 1.3 simulations in few of the wind speed bins. By contrast, the constrained simulations of Hannesdóttir *et al.* [3] showed higher values than the IEC ones for the tower base fore-aft and blade root flap-wise moments. It should be noted that the site conditions, simulation environment, turbine parameters, and designed controller may be different and lead to different results. Also, in Hannesdóttir *et al.* [3], the authors used 10-years of measurements, while our data is only 8 months.

The high-frequency analysis of the blade root flap-wise moments revealed that the extreme bending moments per wind speed bin are mainly caused by a sudden transition of pitch angle from inactive to the active region. Therefore, extreme loads over the wind speed range, except in the region $2\frac{1}{2}$ (and close to it), were governed by ETM or ramp events that lead to pitch transition. In region $2\frac{1}{2}$, the extreme loads were observed for lower turbulence than the ETM but higher than the NTM, and in particular, for the case of wake added turbulence. These increased fluctuations which occurred when the pitch was active did not result in high loads. Therefore, for the ultimate load analysis, the wind speed time series of the simulation model should involve a sudden transition of a pitch from inactive to the active region.

It has been attempted to ascribe e.g. a frontal system, to the observed wind speed ramps based on surface pressure maps. Unfortunately, the resolution of the available weather maps were not good enough to do so. This leaves it open whether the wind speed ramps are related to turbulence or to a meso-scale phenomenon. Note that in Bierbooms [8] ramp like gusts, similar to Figure 6(a), have been simulated by means of an ordinary wind field simulation package (i.e. assuming turbulence to be Gaussian).

6. Conclusions

This paper investigates the impact of ramp events on ultimate wind turbine loads based on eight months of measurements data, followed by their comparison with simulations. The measured loads associated with extreme wind speed ramps did not outperform the simulations based on IEC ETM, except for the tower side-side moments. The high-frequency analysis of the blade root moments has shown that the extreme moments per wind speed bin are mainly caused by a sudden fluctuation in the wind speed time series leading to the transition of the pitch angle from the inactive to the active region. Therefore, it can be concluded that the extreme blade root flap-wise moments over the wind speed range, except near rated wind speed, are governed by extreme turbulence or ramp events, which involve pitch transition. The extreme loads around rated wind speed that exceeded the DLC 1.3 loads were associated with a wind speed standard deviation close to the one from IEC NTM, but with higher fluctuation frequency, which can be related to wake added turbulence. These loads also involved pitch transitions. Ramp-like wind speeds in combination with such turbulence (involving pitch transition) showed higher loads than the DLC 1.3 loads. Based on the findings, it can be concluded that, for the ultimate load analysis, a wind speed time series should include a sudden transition of the pitch angle from the inactive to the active region, in addition to wake added turbulence.

Future work should include a similar analysis on turbine D44 for a longer period, as the turbine is constantly under wake. The IEC design standards can be improved for extreme loads by including design cases for ramp-related and wake-induced loads (non-Gaussian inflow conditions). The findings also imply the scope for a smarter pitch control to attenuate the extreme loads.

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