BeFORECAST

Deliverable: Potential grid and power impacts of advanced turbine controllers

Deliverable No.: D5.5

This project has received funding from the Energy Transition Fund of the Belgian Federal Public Service for Economy, SMEs, and Energy (FOD Economie, KMO, Middenstand en Energie)

DOCUMENT CONTROL SHEET

DOCUMENT INFORMATION	
Document title	Potential grid and power impacts of advanced turbine controllers
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Deliverable No.	D5.5
Work Package No.	WP5
Dissemination level	Public
Date of issue	6/10/2025

DOCUMENT SUMMARY

Modern high-megawatt offshore machines (>7MW) adopt complex controller schemes. Several examples of advanced control are performed (e.g. individual). These controller actions can be triggered in response to environmental loading. However, information about the presence of such advanced controller schemes in the field is less documented in the public domain. In this task we lay the foundation to gain insights in the presence of such advanced controller actions in the Belgian offshore wind farms. In total, three different actions are highlighted, of which one particular one is chosen to further investigate within NREL FAST software simulations to assess its impact on turbine loading. Nevertheless, the developed framework offers the capability of investigate other control cases as well.

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1 Introduction

Modern high-megawatt offshore machines (>7MW) adopt complex controller schemes. Several examples of advanced control are performed (e.g. individual). These controller actions can be triggered in response to environmental loading. However, information about the presence and impact of such advanced controller schemes in the field is less documented in the public domain. In this task we lay the foundation to gain insights in the presence of such advanced controller actions in the Belgian offshore wind farms. In total, three different actions are highlighted, of which one particular one is chosen to further investigate within NREL FAST software simulations to assess its impact on turbine loading.

In particular, the following actions are identified:

- Individual pitch control (IPC): Independent control of the pitch angle of each blade to reduce the load changes on the turbine blades
- Active Tower Damper (ATD) system: Modulation of the active power of the wind turbine to guarantee the structural integrity of these assets
- Grid curtailments: The reduction of the wind farm power output by request of the grid operator or balance responsible party, for example to balance supply and demand

In this document, the main focus for load simulations is on the last control action, as the first two are currently being investigated in a dedicated research project (cSBO FOOS). Furthermore, this is also the control action where feedback can most easily be incorporated by the operators and grid operator, as the first two actions are controller settings governed by the manufacturer, whereas the third one is prescribed by the local parties in the value chain (e.g. Parkwind, Otary, Norther, CPower, Elia). Nevertheless, the developed framework offers the capability to investigate other control cases as well, as all require to use FAST in a dynamic manner based on the time series captured in the scada data.

1.1 Structure

To meet the above-mentioned goals, Section 2 delves into detail on the performed control actions. Afterwards, Section 3 investigates the loading during grid curtailments, focusing on the manner on how the grid curtailment is performed and its effect on the damage equivalent load at the level of the main bearing and blade roots.

2 Controller actions in the Belgian offshore zone

This section gives a brief overview of the control actions that are currently being performed in the Belgian offshore zone. It should be mentioned that not all wind farms apply these control schemes; only the most recent generation of wind turbines (>7MW) has started adopting these, and even then, there are large differences between the manufacturers.

2.1 Individual pitch control

The rotor blades are subject to periodic bending forces due to their rotation. These bending forces are acting in two ways:

1. Edgewise bending in the direction of the rotor movement
2. Second flap wise bending in the direction perpendicular to the plane of movement.

The rotation of the blades modulates these forces, with as modulation frequencies multiples of the rotational speed of the turbine. Individual pitch control attempts to compensate for these modulations, typically focusing on the fundamental harmonic (1P component). This controller action is typically applied at high wind speeds where the turbine is actively pitching. This means that it has little to no effect on the power production of the wind turbine, since rated power is maintained. Therefore, this control action is normally of no major concern for grid stability.

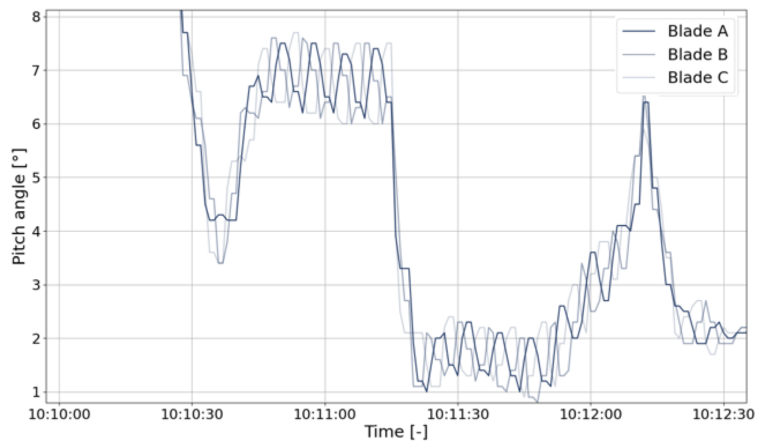

Figure 1: Example of a time series where individual pitch control is performed.

2.2 Active tower damper system

Wind and wave loads cause structural vibrations of offshore wind turbine structures. An Active Tower Damper (ATD) system is designed to dampen these vibrations, in order to guarantee the structural integrity of these assets. With these control actions, the generator torque, and therefore the active power of the wind turbine, is modulated at frequencies that are critical for machine lifetime. These modulations are typically in the order of 100kW for a single wind turbine. Depending on whether these constructively or destructively interfere across the wind farm, this means the introduction of oscillations at critical grid frequencies within the EU (0.1Hz-0.3 Hz). These oscillations can result in critical situations like grid instability, system split, and collapse. With new generations of wind turbines with even higher rated capacity, and the construction of new farms within the PEZ, these are a bigger concern for grid stability.

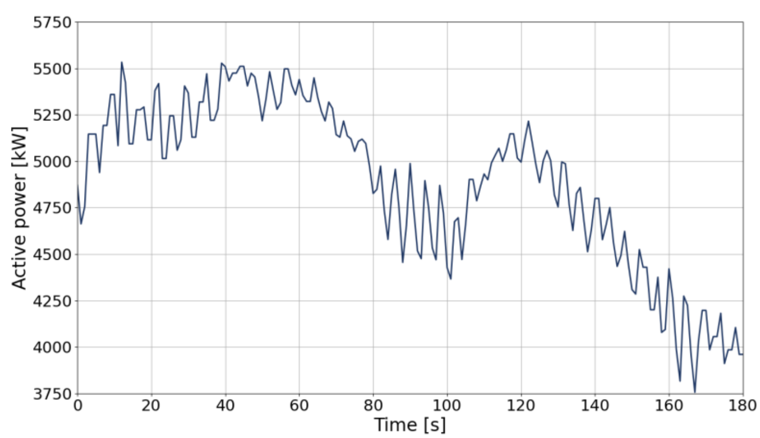

Figure 2: Example of a time series where the active tower damper system is active

2.3 Grid curtailments

The previously discussed control actions are programmed by the manufacturer at the level of the individual turbines. On the other hand, grid curtailments are actions which are imposed by the grid operator or balance responsible party. This is also a control action where the main trigger is not to reduce the turbine loading, but to comply with grid constraints (e.g. balancing supply and demand). The timespan of these actions is typically also larger than the aforementioned ones (timescale of several minutes versus several seconds). These two aforementioned aspects mean that there is an opportunity to investigate the influence of these curtailments on wind turbine component loading, and to see if the actions can be modified to better preserve machine lifetime, while maintaining a similar effect on the grid. This is investigated in the following section.

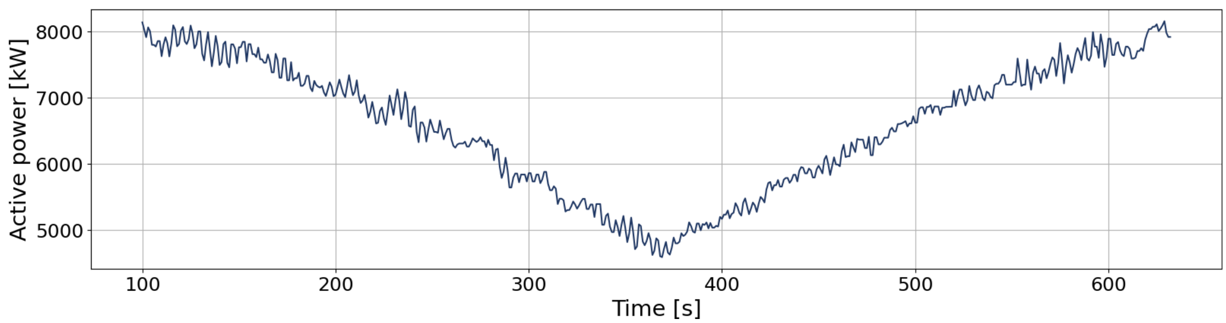

Figure 3: Example of a time series of a single turbine during a grid curtailment

3 Investigation of turbine component loading during curtailments

To assess the wind turbine loading during dynamic events, three steps are needed:

- **Insights into representative curtailment events to simulate:** This is essential to ensure that relevant events are investigated, and allows to assess the sensitivity of different parameters within their typical range (Section 3.1)
- **Capability to simulate dynamic events using OpenFAST**: Typically, OpenFAST can only cope with static setpoint modifications (constant across the simulation). Within the development branch of OpenFAST, dynamic changes have nevertheless been made possible using either ZMQ or open loop control. (Section 3.2)
- **Coupling between the generated curtailment events and the OpenFAST control framework** (Section 3.2)

3.1 Assessment of typical curtailment actions

In order to ensure that representative simulations are performed, the scada-1s data is analyzed to annotate the different curtailment events. These events are afterwards post-processed to extract several statistics, such as:

- Duration of the event [min]
- Slope of the event [kW/min]
- Energy loss during event [kWh]
- Minimum setpoint during event [kW]

Example of time series where these statistics were extracted from, are seen in Figure 4.

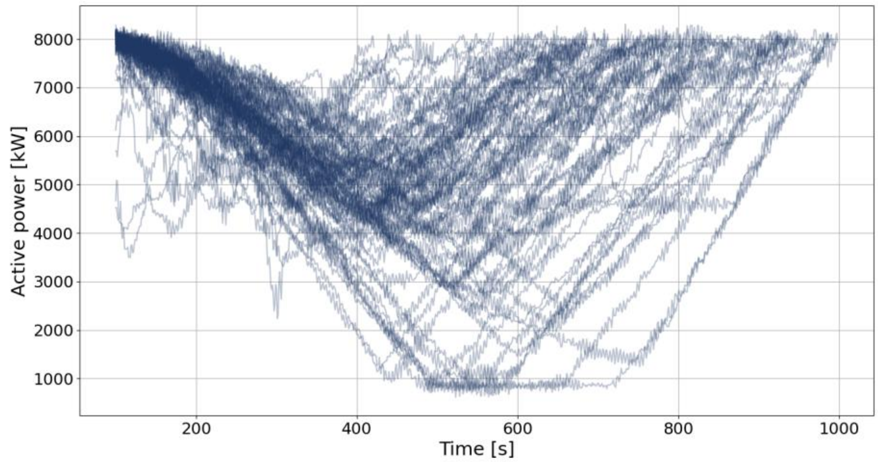

Figure 4: Example of a subset of different curtailment events at rated power extracted from scada-1s data

3.2 Assessment of turbine loading

3.2.1 Methodology

The previous section discussed the extraction of typical curtailment events for the analyzed Belgian wind farm. This section uses these results to assess the turbine loading at the level of different machine components using OpenFAST. To this end, OpenFAST can either be coupled (1) directly to the scada data, or (2) to a simulator that generates curtailment events. This simulator has as main advantage that sensitivity studies can easily be performed for all considered parameters, whereas we are limited to the observed events when working directly with scada data. Therefore, we opt to use this simulator based on the typical curtailment parameters we see in the Belgian offshore zone. An example of different events with the same energy loss, minimum energy setpoint, and duration, but different slopes can be seen in Figure 5. A framework is then established that couples these power profiles with OpenFAST using open loop control.

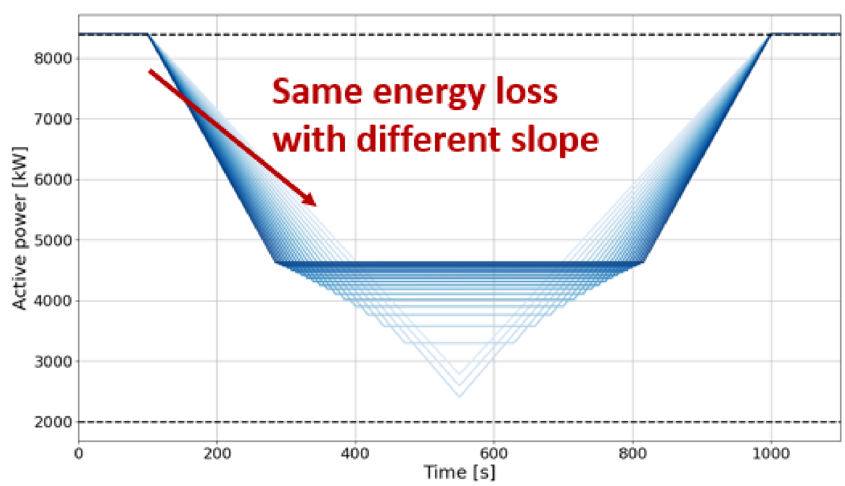

Figure 5: Example of simulated events with the same energy loss, minimum energy setpoint, and duration, but different slopes. Darker colours indicate higher slopes.

After the definition of the setpoint to track, the simulation is executed and post processed to calculate the damage at the level of different components (e.g. main bearing).

3.2.2 Results

This section discusses the results of the performed sensitivity analysis. First, Section 3.2.2.1 showcases a proof of concept with four different power profiles realizing the same power reduction in order to gain insight into its influence on the damage equivalent loading across the window.

Afterward, a more in-depth study is performed by deploying over 200 simulations on the cluster. Although a significant number of load signals (blades, bearings, tower, etc.) have been calculated within the performed simulations, this report opts to focus on the change in loading at the level of the main bearing and the blade root.

3.2.2.1 Proof of concept

In the initial proof of concept, four different power profiles are compared with one another: an exponential, flat bottom, linear, and fractional window. All windows achieve the same power reduction over a ten-minute time window. It is then of interest to investigate the variability in loading between these different reference profiles.

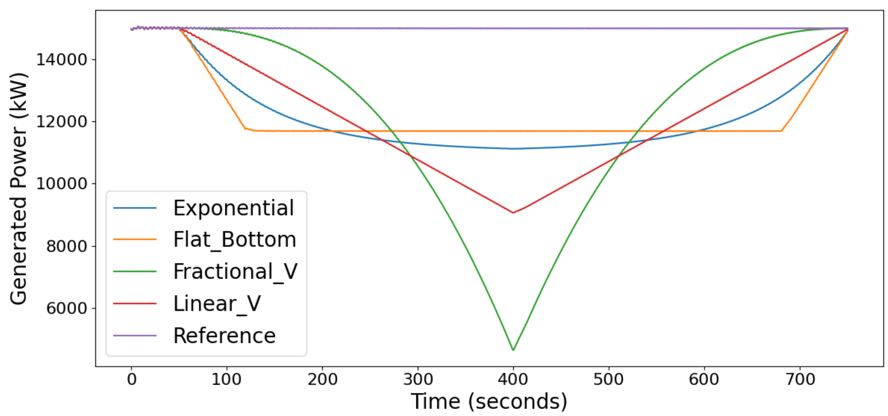

Figure 6: Different power profiles simulated to assess the impact of the curtailment shape on main bearing loading.

For each of the events, load series are calculated using OpenFAST. Rainflow counting is then applied, based on which the damage equivalent load (DEL) is calculated using the Palmgren-Miner Rule **(**ISO 281). To assess the impact of the control action, the loading is compared with a reference simulation where no setpoint changes occur (purple line in Figure 6), allowing to assess the relative change due to control. This is shown in Figure 7, where the change is both normalized with respect to time (left) and energy production (right) at the level of the main bearing. It can be noted that all curtailments achieve an absolute reduction in damage, although the magnitude differs. This is more noticeable when normalizing the damages with respect to the energy production, where it can be noted that the "fractional V" profile results in higher damage per energy compared to the reference, whereas the other three profiles also achieve a reduction here. The largest reduction is achieved with the flat bottom and exponential profiles. It can be seen that compared to the other two profiles, these shapes reduce the power output more aggressively near the start of the event (between 100s and 300s), allowing to reach a constant setpoint more quickly. On the other hand, the two other profiles perform setpoint changes throughout the entire event, which results in a higher DEL. Although it is not shown in this report, a similar analysis was performed for the blade roots, based on which identical conclusions were drawn.

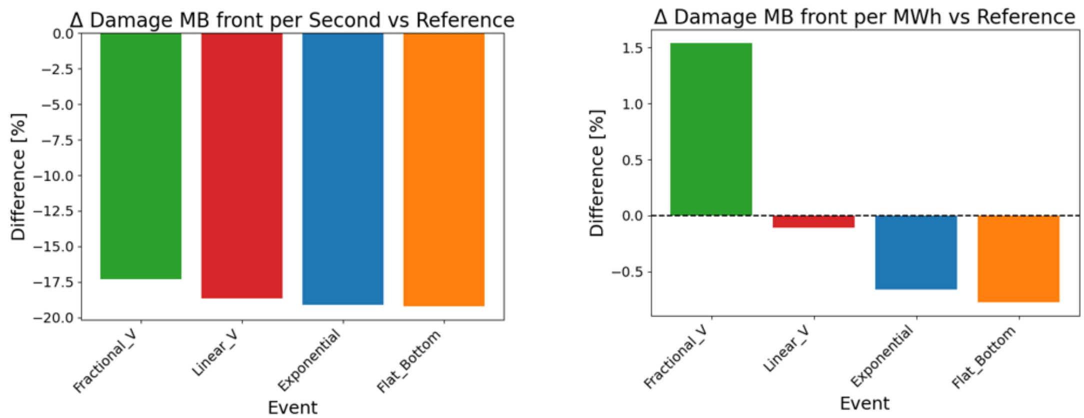

Figure 7: Change in main bearing (front) loading as a function of time (Left) and energy production (Right).

Based on this proof of concept, it can be concluded that the way the curtailment is being performed influences the impact at the level of the machine components. However, the different windows illustrated in this section can all be parameterized in different manners, which will further impact their shape. To further gain insight into this, the next section performs a more in-depth study on the linear profile. This particular profile is chosen as it is parameterizable using easily interpretable parameters, i.e. linear slope, power reduction, and minimum setpoint.

3.2.2.2 Sensitivity analysis

To gain more insights into the effect of different curtailment speeds (slope, in kW/min) and energy reduction (in %), the code is factorized and deployed as dockers on the VUB cluster. More than 200 simulations have been performed with different curtailment parameters to gain insight into the sensitivity, of which a subset can be seen in Figure 8.

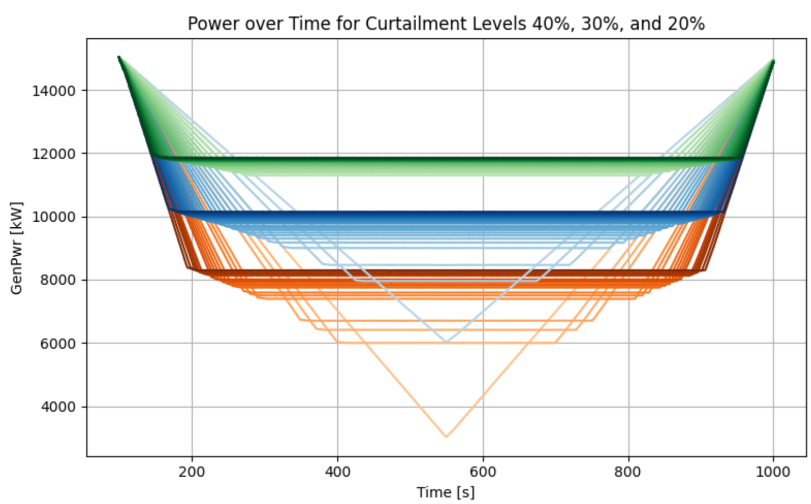

Figure 8: Different time series showcasing curtailments realizing three different energy reductions (20%, green; 30%, blue; 40%, orange). For each of the reduction levels, different curtailment rates (kW/min) are simulated.

Figure 9 shows the outcomes of this analysis, focusing on the DEL of the main bearing as a function of the two illustrated parameters. It should be noted that not all parameter variations are possible. For example, it is not possible to achieve a high energy reduction in case a low curtailment rate is imposed. This explains the lack of data near the top left of the graph. It can be noted that in general, lower DELs are achieved when imposing faster curtailment rates. In this case, more aggressive control actions are performed near the beginning of the event, but constant setpoints are obtained more quickly. It can moreover also be noted that the DEL increases when increasing the curtailment amount. Minimum DELs are observed for curtailment amounts of around 15%.

These results highlight the importance of the proper choice of curtailment shapes to optimally operate the wind turbines, as the difference in DEL is up to 35% within the investigated parameter range, which can be significant to the component lifetime. It should furthermore be mentioned that it is important to consider the entire machine during this analysis, whereas this document solely focuses on two specific machine components (main bearing and blade), as the impact of curtailment events might be different for different components.

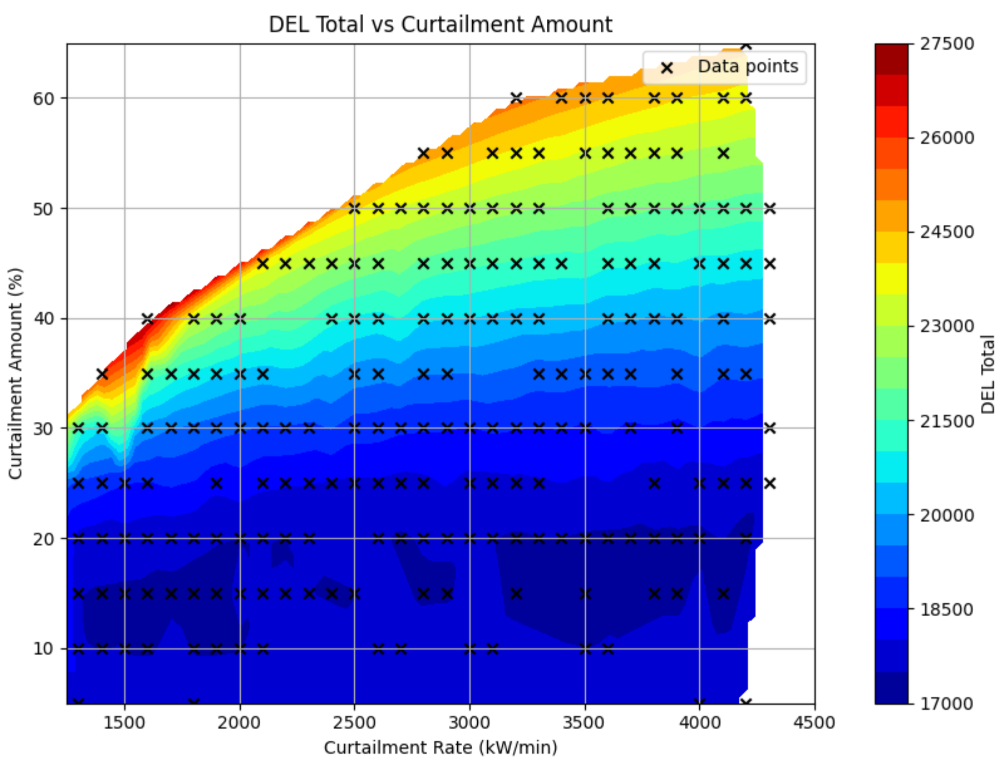

Figure 9: Damage equivalent load as a function of the amount of achieved energy reduction and the allowed rate of energy reduction.

4 Conclusions

This report has given an overview of the different control actions that are at present day performed on modern wind turbines. Among these, grid curtailments have been investigated into more depth. To assess the impact of these events at the level of the turbine components, simulations have been performed. Concretely, the following steps have been realized:

(a) Establishing a framework in OpenFAST that can cope with dynamic setpoints in terms of power and/or pitch.
(b) Establishing a simulator that can simulate different curtailment events in a parameterized manner, which is coupled with (a)

Based on this, a sensitivity analysis has been performed on the VUB cluster, focusing mainly on assessing the influence of the curtailment rate and realized energy reduction on the damage equivalent load at the level of the bearing.

5 References and dissemination

Conferences

Gebel, Jakob "Impact of Grid Services on Fatigue Life of Offshore Wind Turbine Components." *Wind Energy Science Conference (June 24th – 27th 2025), Nantes, France*