Further progress with field testing of individual pitch control

E. Bossanyi*, A Wright+ and P Fleming+

*Garrad Hassan & Partners Ltd., St Vincent's Works, Silverthorne Lane, Bristol, BS2 0QD, UK
Tel: +44 (0)117 972 9900, Fax: +44 (0)117 972 9901, Email ervin.bossanyi@garradhassan.com

+ National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, Colorado 80401, USA.
Tel: +1 303-384-6928, email alan_wright@nrel.gov

Summary

An important task in the EU "UPWIND" project is to use field tests to demonstrate that the important load reductions predicted with individual pitch control (IPC) can really be achieved in practice. This is vital for increasing confidence of turbine designers to use IPC in their new designs, to improve cost-effectiveness. As well as reducing asymmetrical out of plane loading on three-bladed machines, IPC can also be used on two-bladed machines as an alternative to a mechanical teeter hinge. The NREL test site provides an excellent opportunity to test IPC on both the two-bladed (CART2) and three-bladed (CART3) turbines. At the same time, the efficacy of fore-aft tower damping (FATD) by means of collective pitch control will also be demonstrated.

State-of-the-art control algorithms for both the CART2 and CART3 have been designed, including both IPC and FATD in addition to the normal speed regulation. The CART2 controller has been implemented on the turbine's control computer, and some early results have now been obtained. With no need for adjustments of any significance, the very first results already demonstrated good performance, as presented in this paper.

The new CART3 controller has also been implemented on the control computer, but its use is awaiting the completion of turbine commissioning. First results for this turbine are now expected in late spring 2010.

Introduction

A major goal of UPWIND is to investigate the feasibility of very large offshore turbines. Both two and three-bladed turbines have been proposed for this, since some of the main environmental impact objections to two-bladed turbines are less relevant in the offshore environment. In both cases the use of IPC has the potential to improve the cost-effectiveness significantly, and in the two-bladed case it can be used to replace the potentially troublesome teeter hinge. A previous paper has already demonstrated these benefits using Bladed simulations [1]. This paper describes the field testing project undertaken at NREL using the CART turbines and presents the initial results, which already demonstrate conclusively that the IPC works as expected.

This provides the confidence required to design new turbines to make use of the load reductions expected with IPC, including any re-optimisation of the blade and the rest of the turbine which might help to take full advantage of the new loading regime.

The field tests also confirm the operation of the tower damping feedback, although field tests on other machines have previously already confirmed this [2].

Another paper [3] contains the first results from the CART2 turbine. The results in this paper have been updated to include some further datasets and additional analysis.

The CART turbines

As part of the EU 6th Framework integrated project "UPWIND", these field tests were originally conceived on a commercial European turbine, but commercial considerations prevented this from going ahead. A new programme was therefore conceived in 2008, making use of two research turbines at NREL in USA, both 42m diameter and rated at 660 kW: the two-bladed CART2 and the three-bladed CART3. Although these are a bit small and commercially unrepresentative, they are quite adequate for the required proof of principle, and have the advantage of being very accessible and free of commercial problems to prevent publication of results.

The principles of IPC apply equally to two and three-bladed turbines, since the fundamental control action is calculated after first transforming to the non-rotating reference frame, and it is therefore largely independent of the number of blades. For two-bladed turbines, the 1P rotating control action also reduces the 2P loads which dominate fatigue in the non-rotating frame. For three-bladed turbines the dominant non-rotating fatigue loads are at 3P, and to reduce these requires additional second-harmonic IPC action [1]. The CART3 provides the opportunity to test this aspect.

When applied to a two-bladed machine, the IPC is intended to reduce blade root loads sufficiently to obviate the need for a teeter hinge. Although a teeter hinge can in principle reduce the normal hub moments even more, the possibility of end stop impacts in extreme conditions can never be discounted, and this can produce very severe extreme loads. The CART2 is actually a teetered machine, but for these tests the teeter hinge was locked by means of a teeter brake. A small amount of intermittent slippage of the brake was found to occur, but this was not sufficient to affect the conclusions.

Controller design

Power production controllers including IPC and FATD were designed for both the CART2 and CART3 turbines. These are state-of-the-art controllers representative of those now being used for commercial turbines. Following simulation testing using GH Bladed [1], the new CART2 controller was installed in the turbine in early 2009, but a gearbox failure delayed the start of field testing until November 2009. There followed a winter wind season with unusually low winds, so that first data was not obtained until early February 2010. The very first results already demonstrated good performance of the advanced load reduction features of the controller, as shown below.

With three blades, the CART3 provides the opportunity to test both 1P and 2P IPC. The algorithm for this turbine was designed and tested in GH Bladed simulations, and is already installed on the CART3 control computer. However the control system for this turbine is new and commissioning has to be completed before the field tests can begin. This is expected to be in late spring 2010. Meanwhile the control computer is also connected to the NREL simulation code FAST, which was used to provide further validation of the algorithm prior to switching over to the real turbine.

For the field testing, the IPC and FATD action can be switched on and off during operation without affecting speed regulation, so by comparing test data with and without the advanced features, the load reduction can be quantified across a variety of wind conditions.

Implementation

The CART2 baseline controller at NREL is compiled from C and runs on a DOS computer. The new power production algorithm was embedded within the existing controller code. This already included the supervisory control, which hands over control to the new algorithm when a certain rotational speed is reached, but continues to monitor for faults, and resumes control for shutdowns.

The CART3 baseline controller was implemented much more recently using LabView, and the new power production algorithm was embedded into it in a similar way, again integrating it with the existing supervisory control. The implementation was tested using the NREL simulation code FAST, linked in to LabView in place of the real turbine. Field tests with the new controller had not yet begun at the time of writing, as commissioning of the baseline controller had not yet been completed.

Instrumentation

The sensor inputs to the control algorithm were:

- Rotor speed
- Rotor azimuth
- Generator speed
- Flapwise and edgewise blade root strain gauges (conventional type)
- Fore-aft nacelle acceleration
- Pitch angles

The following additional sensors were also used in evaluating the field test results:

- Wind speed and direction at hub height on nearby met mast
- Tower base bending strain gauges in two directions: E/W and N/S
- Nacelle yaw position
- Teeter angle
- Generator power

A number of internal controller variables were also logged, including the switching variable which defines whether the IPC and FATD features are active

Control loops tested

The new control algorithm designed for CART2 included the following control features:

1. Drive train damper.
2. Speed regulation by torque (below rated).
3. Speed regulation by collective pitch (above rated).
4. Interaction between loops 2 and 3 around rated.
5. Fore-aft tower damping by collective pitch.
6. 1P individual pitch control using blade root strain gauges.

Features 5 and (more especially) 6 were the focus of the field tests. The performance of features 2, 3 and 4 was not quantified, but these were observed to work very well from the start, and needed no adjustment. The design of the drive train damper (feature 1) depends on precise knowledge of the drive train dynamics, which was not available: normally the generator speed is used as input, but filtered rotor speed was found to work better. No attempt was made to optimise this feature since the problems are well understood and were not the focus of this exercise.

The advanced features 5 and 6 would normally be phased out in low winds, since the already low loading levels do not justify the additional pitch action required to reduce them further. For these tests however, these features were enabled at all wind speeds so as to maximize the amount of useful data obtained.

CART2 test results

All recorded datasets were 10 minutes in length. Headers were created to allow each dataset to be plotted and post-processed using Bladed.

First results

Figure 1 plots four variables from dataset 02050340 measured on 4th February 2010, just to illustrate the entirely satisfactory operation of the speed regulation below and above rated.

When the tower feedback feature was switched on, a problem was immediately apparent: the acceleration signal had a large mean offset (which is clearly not physical if the turbine is staying in the same place). The integrator in the FATD algorithm was then causing the pitch angle to drift away, causing loss of power. If the pitch drifted to negative angles, the blades would stall and the IPC would work badly, as predicted by simulations. The problem is illustrated in Figure 2 (part of dataset 01240204 from 3rd February 2010).

This problem was very easily fixed by passing the acceleration signal through a 0.1 Hz high pass filter: this removed the offset with little effect on the phase of the remaining signal. After this change, both the IPC and FATD were found to work well, as the following results illustrate.

First some time series results are presented, comparing two datasets with similar wind conditions, both measured on 4th February 2010: dataset 02050253 with IPC and FATD switched ‘OFF’, and dataset 02050317 with both features switched ‘ON’ (Figure 3).

Clearly the wind speed is not identical in the two cases, and is dropping off towards the end in case ‘ON’. Fine pitch is reached (-1º) and the speed and power start to fall. The individual pitch action is clearly visible. The load reduction in the ‘ON’ case is not immediately obvious in the time histories. To assess this, Bladed post-processing was used to resolve the flapwise and edgewise bending moments with pitch angle to give the out of plane moment, and the N/S and E/W tower base bending moments with yaw position to give the fore-aft moment (the yaw position signal was very noisy and first had to be cleaned up by removing spikes and filtering). Furthermore, the blade root My signals were combined to give the hub rotating My (ignoring the small additional moment due to differences in blade root Fx force), and also transformed to stationary co-ordinates using the azimuth position, to give hub fixed My and Mz (ignoring any possible differences in blade Mz pitch moment). Spectra of these signals then immediately reveal the expected changes in loading.

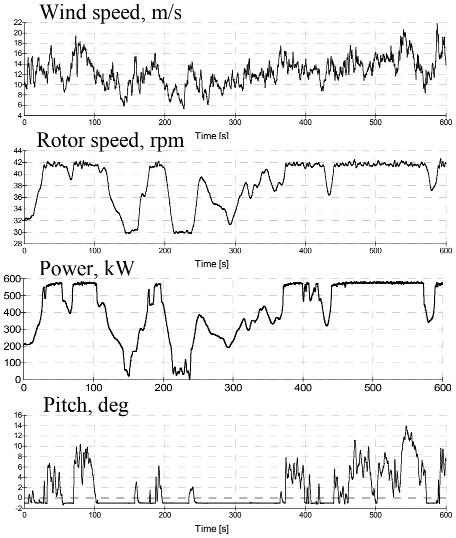

Figure 1: Speed regulation around rated

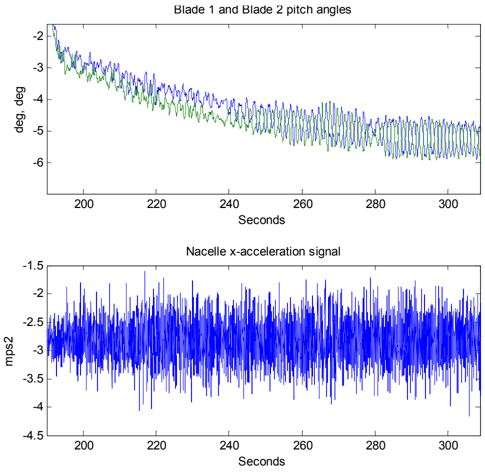

Figure 2: Effect of acceleration offset

Although the ‘ON’ case has a lower mean wind speed, it has a significantly higher turbulence intensity as shown in Table 1. Two more cases have therefore also been included in the subsequent analysis, selected to have similar wind speeds and turbulence intensities, but in this case slightly lower in the ‘ON’ case. The characteristics of these datasets are also in Table 1. The table also includes an estimate of the wind shear, obtained by roughly fitting to the mean wind speeds measured at the four anemometer heights on the met mast, at heights of 3, 15, 36.6 and 58. 2m.

Looking first at the tower damping, Figure 4 shows the spectrum of tower base fore-aft bending moment for these four cases, with the thicker lines representing the two ‘ON’ cases. A clear reduction is seen on both ‘ON’ cases at the first tower frequency around 0.9 Hz, confirming that the damping algorithm is working as intended. The low frequency levels are more variable, lower in one ‘ON’ case and higher in the other; this is simply caused by the range of the wind speed variations during the sample, not by the controller dynamics (more dips below rated occurred in the first ‘ON’ case, and since the maximum thrust occurs at rated this gave rise to more periods of higher mean thrust in this case, as is clearly shown in Figure 3; for the 12 m/s cases, the ‘OFF’ case suffered from bigger wind speed dips right down to 6 m/s, compared to 8 m/s for the ‘ON’ case).

Turning to the IPC performance, Figure 5. compares the spectra of blade root out of plane bending moment. The low frequency increase in the ‘ON’ case occurs for exactly the same reason due to the increased thrust loading at rated, but the complete removal of the 1P peak at 0.7 Hz is exactly as predicted in simulations, confirming that the IPC is working perfectly as intended.

The rotating hub My is calculated as the difference between the out of plane moments at the two blade roots, so the low frequency effects due to gross thrust variations cancel out. This is essentially the main shaft bending moment, and as shown in Figure 6, the dominant 1P load peak is again removed exactly as expected.

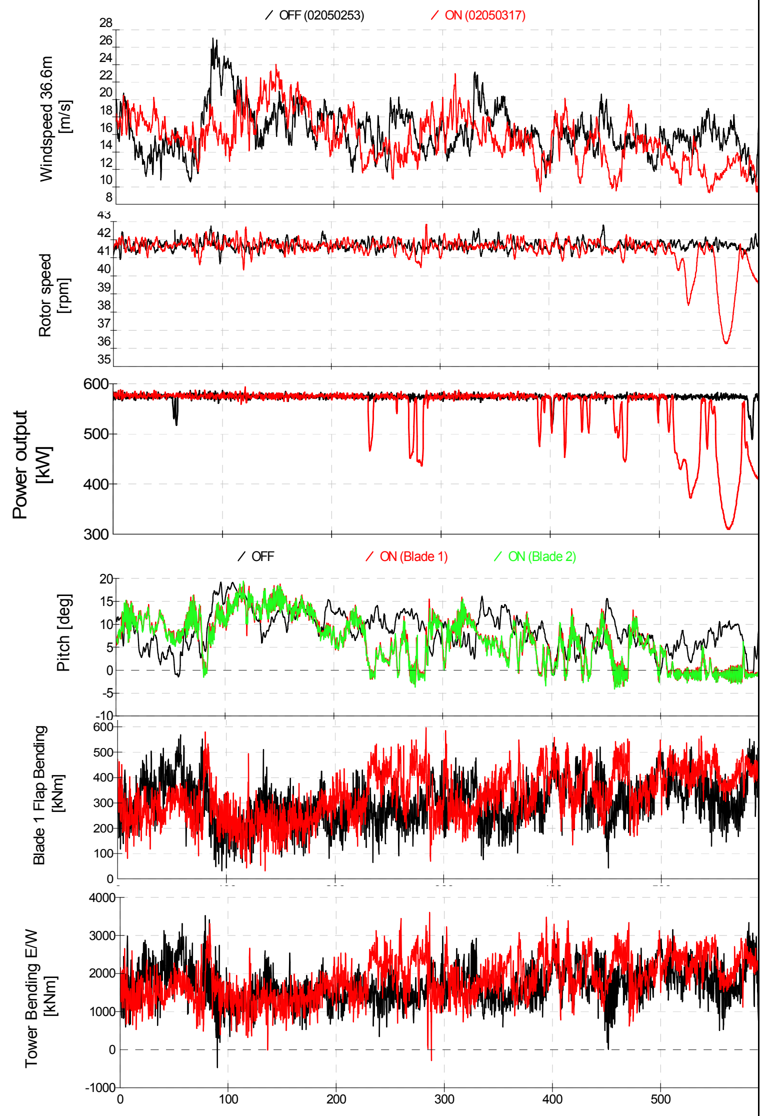

Figure 3: First results with and without IPC and FATD: 600s datasets near rated

The hub fixed Mz or yawing moment is shown in Figure 7 (the fixed My or nodding moment behaves in a very similar way). These moments are normally dominated by the peak at blade passing frequency, 2P (here 1.4 Hz). As predicted, the IPC successfully removes the 0P (low frequency) and 2P peaks in the non-rotating loads (although in one case the 0P reduction is small). Unlike in simulation results, there is a clear 1P peak in all four datasets, which implies some kind of significant imbalance. There may be some inherent rotor imbalance, but in this special case a likely source of such large imbalance is the slippage of the teeter brake, shown by the teeter angle plots in Figure 8. The rotor is occasionally knocked to a small teeter angle, where it sticks for a while: then centrifugal force causes a steady offset in the rotating My, which would appear as a 1P peak in the non-rotating moment (note that in the 'OFF' case there are also many periods when the rotor is actually teetering continuously against the brake; these periods might not be expected to contribute to the 1P peak in Mz).

The IPC is of course achieved at the cost of additional 1P Pitch activity. As Figure 9 shows, this is entirely concentrated at 1P, again agreeing well with simulations.

Dataset	Mean wind direction (deg)	Mean wind speed (m/s)	Standard deviation (m/s)	Turbulence intensity (%)	Estimated shear exponent
02050253 (OFF)	276.698	16.3807	2.61317	15.95	.09
02050317 (ON)	284.246	15.481	2.85928	18.47	.14
02050340 (OFF)	289.563	12.4217	2.67643	21.55	.13
02020007 (ON)	277.872	12.0926	2.50302	20.70	.08

Table 1: Sample datasets for comparison

Below rated, both IPC and FATD cause the pitch to be constantly moving with respect to the optimum 'fine pitch' value, which in principle should cause a small loss of power output. However simulations have shown any such loss is very small. Since the wind is different for each dataset it would be very difficult to confirm this from the data in Figure 3 for example. However this is addressed further in the next section.

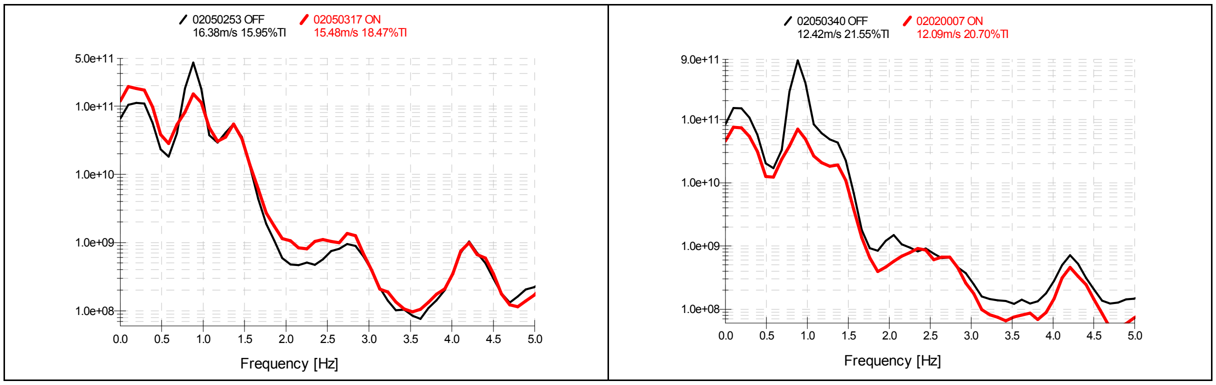

Figure 4: Tower base moment: two comparisons

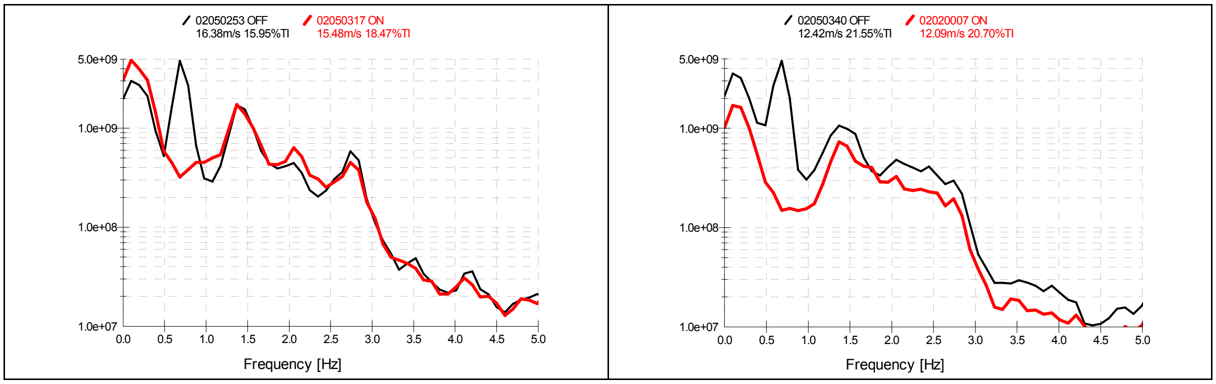

Figure 5: Blade root My moment: two comparisons

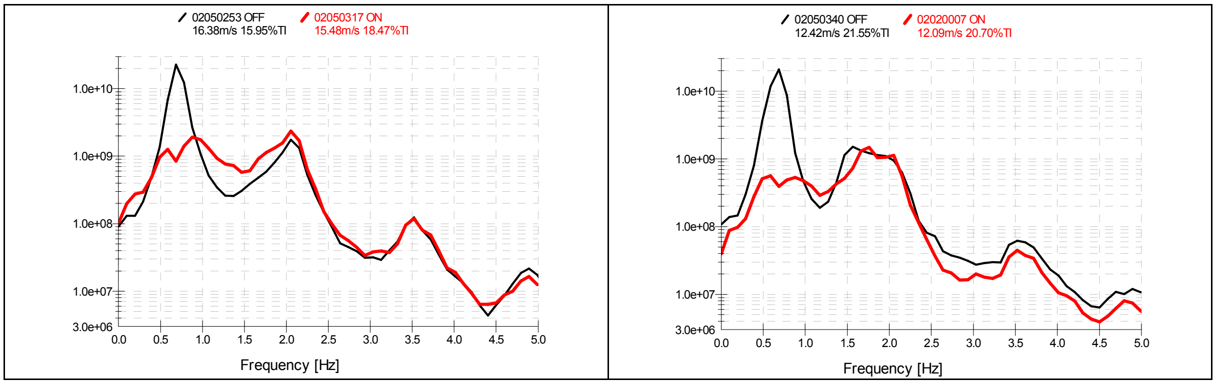

Figure 6: Shaft My moment: two comparisons

Further results

The above results are for just four 10-minute datasets, two without and two with IPC and FATD, chosen because they have similar wind speeds. This already demonstrates fairly conclusively that these load reducing features work well, confirming previous simulation results. For a more complete assessment, a whole series of 10-minute datasets were processed to estimate the reduction in key damage equivalent loads and also to confirm that the loss of power production is negligible.

Some 73 ten-minute datasets were collected on days with sufficient wind in February and March 2010 (1st, 4th and 15th February, and 5th, 11th and 12th March). A number were not useful as the wind speed was falling away, and in some the turbine was only operating for part of the time, although some extracts of less than 10 minutes were still usable from these. Also a procedural error meant the fine pitch was incorrect in the later ‘ON’ cases, which would have slightly reduced the energy output in these cases.

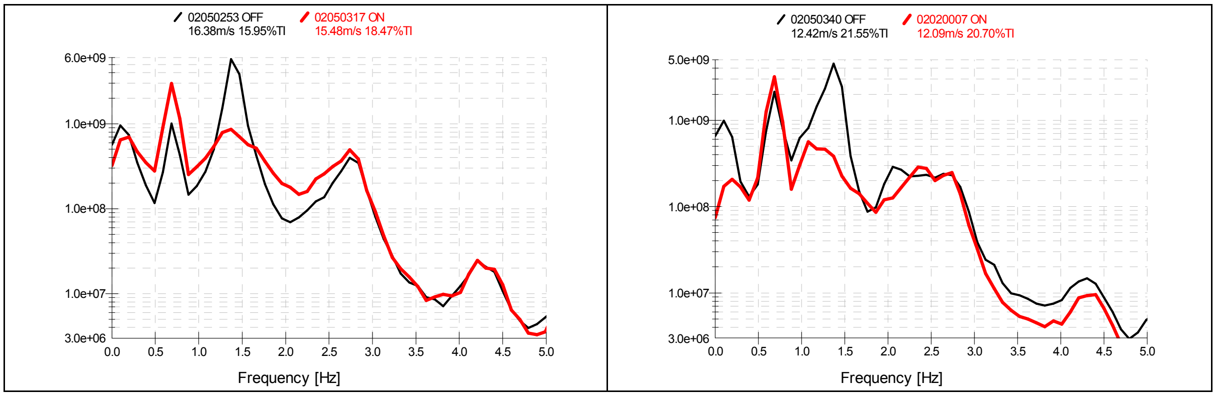

Figure 7: Hub fixed Mz (yaw) moment: two comparisons

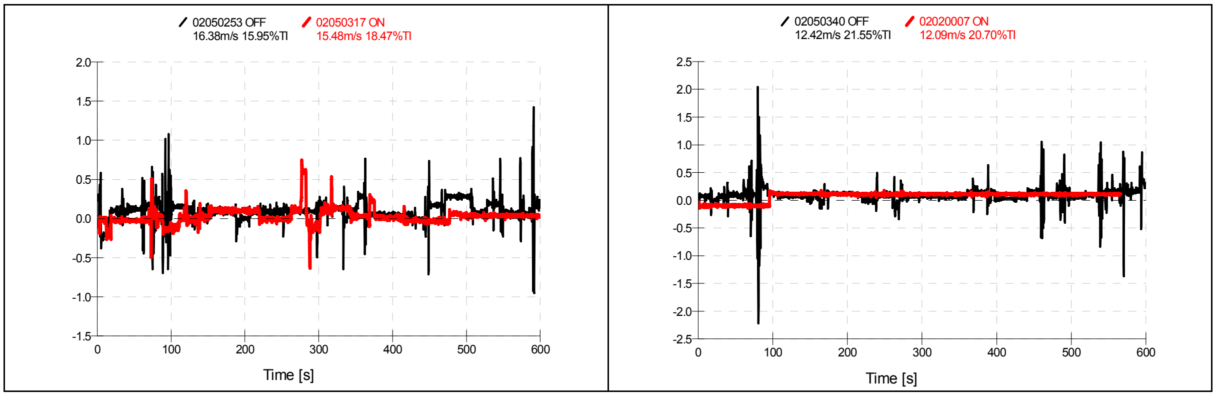

Figure 8: Teeter angles

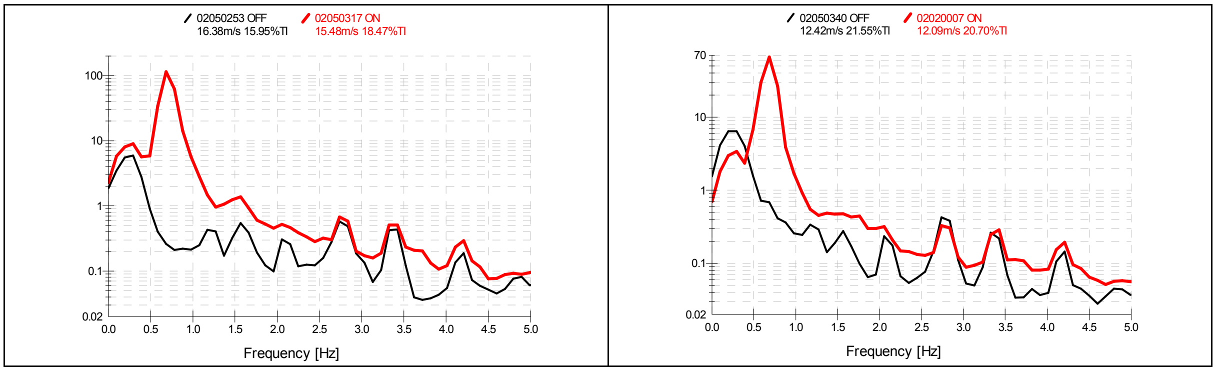

Figure 9: Pitch rate spectra

For each dataset the met mast mean wind speed and turbulence intensity at the hub height was calculated. Only datasets with turbulence intensities within the range 15% - 25% and more than 300s in length are included in the results below; this means 23 ‘OFF’ datasets and 27 ‘ON’.

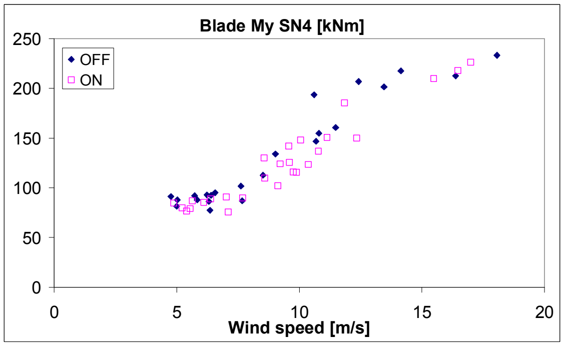

Figure 10: DELs, Blade root My

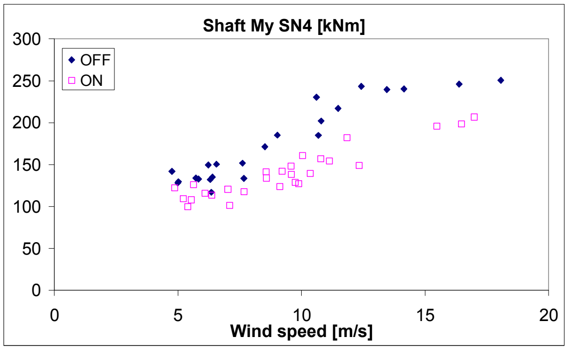

Figure 11: DELs, Hub My

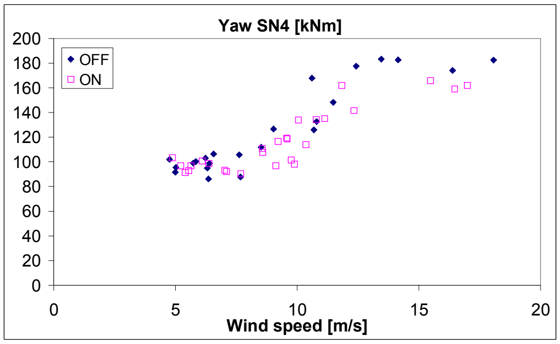

Figure 12: DELs, Hub yaw Mz

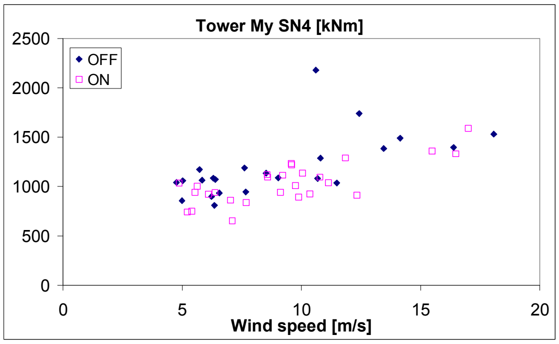

Figure 13: DELs, Tower base My

These datasets were then processed in Bladed to calculate the 1Hz damage equivalent loads as a measure of fatigue damage, using Wöhler exponent 4 (appropriate for steel). Figure 11 shows very clearly the reduction in damage equivalent load for the rotating hub My caused by the IPC. For other loads, the reduction is perhaps less clear because of the influence of low-frequency differences, and also the 1P loading due to teeter brake slippage as mentioned above, so more data is still required to quantify the differences more precisely above the ‘noise’. Nevertheless the load reductions are already clearly apparent. The blade root My moment is shown in Figure 10, Figure 12 shows the fixed hub yaw moment Mz as reduced by IPC (the nodding moment is similar), and Figure 13 shows the reduction in tower fore-aft bending caused by FATD.

The wide variation of turbulence intensities between datasets further masks the differences. An attempt was made to account for this by binning the results into wind speed and turbulence intensity bins, calculating the mean DEL for ‘OFF’ and ‘ON’ cases in each bin, and calculating the difference between these means. Differences can only be calculated if the bin is populated with at least one ‘OFF’ and one ‘ON’ case. The results are shown in Figure 14 to Figure 17, with 2 m/s and 5% turbulence intensity bins. Although these bins are still rather too broad, the load reductions are generally quite clear, but there are already very few datasets per bin so it is not possible to use narrower bins. The most crucial bins from 12 – 16 m/s are empty, highlighting the need for more data in this region; the 16-18 m/s bin only contains three points, two ‘ON’ cases both with higher wind speed and turbulence intensity than the single ‘OFF’ case. The numbers of points per bin are listed in Table 2, with grey shading for bins where no comparison was possible.

Finally in Figure 18 the mean power output for each dataset is plotted, as a check that any loss of power output due to the additional pitch action is small. Again there is not enough data to quantify the differences in a statistically meaningful way, but certainly there is no indication of any significant loss of performance – if anything, the graph suggests an increase in performance around 8 - 13 m/s.

It is conceivable that a reduction in tower vibration for instance might actually help to keep the aerodynamic performance closer to optimum. The binned results tend to confirm this, apart from the first bin which is distorted by the fine pitch error of over 2 degrees in some of the 'ON' datasets which was referred to earlier. The coarseness of the wind speed bins is also a factor, as the mean wind speeds can differ by up to 2 m/s within each bin.

	Turbulence: 15-20%		Turbulence: 20-25%	
	OFF	ON	OFF	ON
4-6 m/s	2	1	3	4
6-8 m/s	6	1	1	4
8-10 m/s	1	6	1	2
10-12 m/s	3	3	1	2
12-14 m/s	0	1	2	0
14-16 m/s	0	1	1	0
16-18 m/s	1	2	0	0
18-20 m/s	1	0	0	0

Table 2: Points available per bin

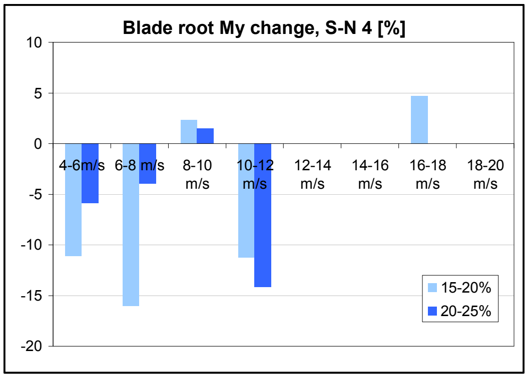

Figure 14: DEL change, Blade root My

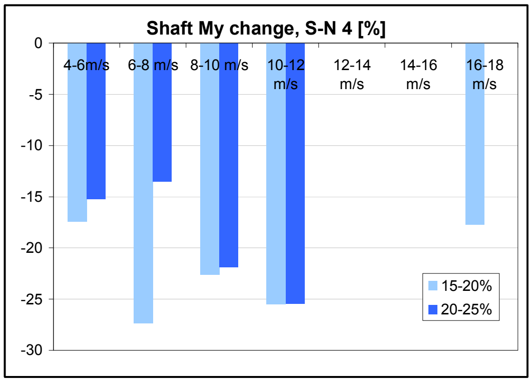

Figure 15: DEL change, Hub My

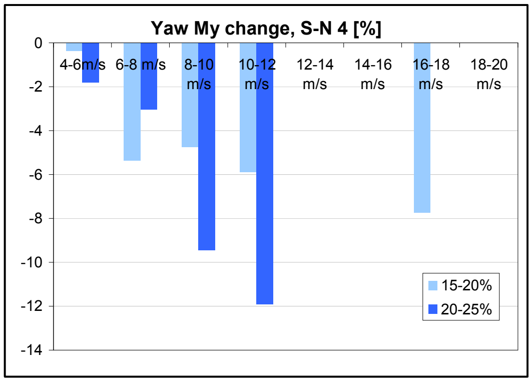

Figure 16: DEL change, Hub yaw Mz

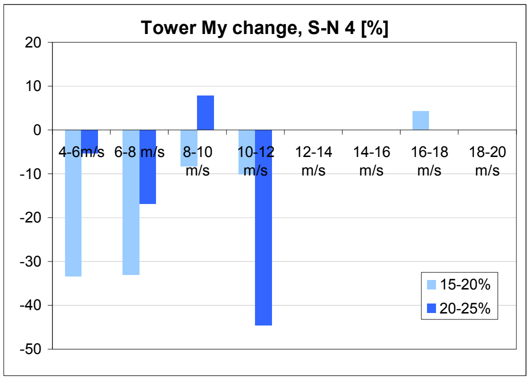

Figure 17: DEL change, Tower base My

CART3 progress

The new controller has been designed and its performance tested in both Bladed and FAST simulations. It will allow verification of both 1P and 2P IPC for a three-bladed turbine, as well as further verification of FATD. Simulation results in Figure 19 show the 1P and 2P reduction in rotating loads, and in the non-rotating loads the reductions due to IPC at 0P and 3P (see [1]), and the effect of tower damping is also visible at the 0.8 Hz tower frequency. The algorithm is implemented in the turbine controller and the testing is ready to begin as soon as the turbine has been fully commissioned. These activities are all awaiting suitable wind speeds at the site.

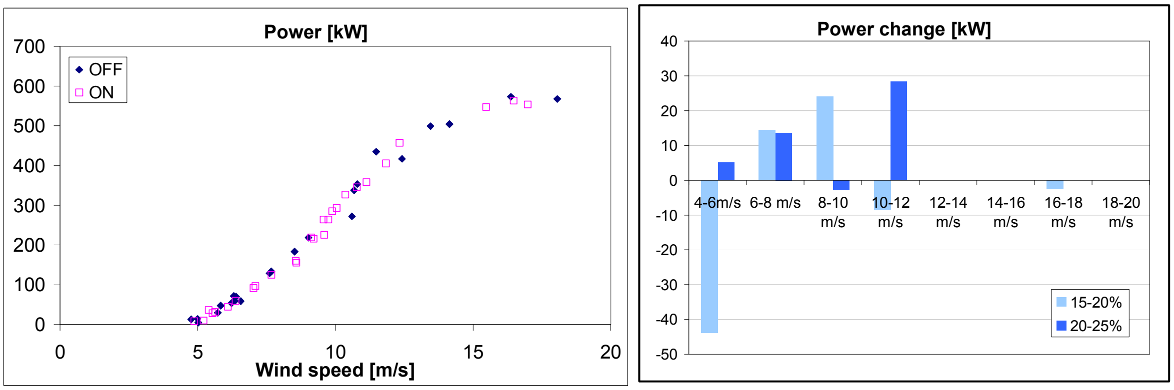

Figure 18: Power output

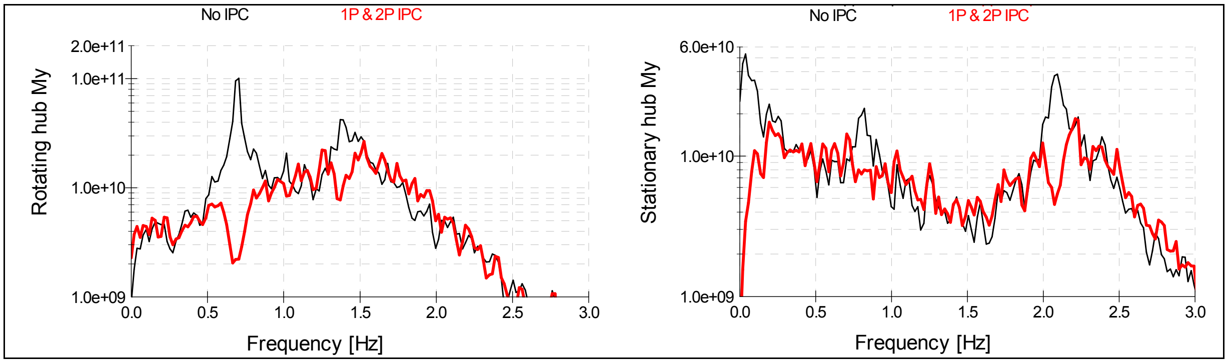

Figure 19: CART3 simulation results

Conclusions

The data available so far from the CART2 field tests already gives a very clear indication that both the individual pitch control and the fore-aft tower damping algorithms are working as expected, and that the load reductions predicted by simulations should be realised in practice. The fact that no adjustments of any significance needed to be made to the algorithms or the parameter values confirms that these controller features are robust, and should provide the necessary confidence for turbine designers to able to use these techniques as an integral part of turbine design in future. The results also confirm that the load reductions are achieved without significant loss of energy output.

After a winter of disappointing winds, it is hoped that some further periods of above-rated wind speed will be experienced on site while the turbine remains available for these tests. This would allow the benefits to be quantified more precisely over a wider range of conditions of wind speed and turbulence intensity.

References

[1] Field testing of individual pitch control on the NREL CART-2 wind turbine, E. Bossanyi, A. Wright, proc. European Wind Energy Conference 2009.

[2] Damping of tower motions via pitch control – theory and practice, M. Rossetti, E. Bossanyi, proc. European Wind Energy Conference 2004.

[3] Progress with field testing of individual pitch control, E. Bossanyi and A Wright, Proc. Torque 2010: The Science of making Torque from Wind, CRES, June 2010.

Acknowledgements

This work has been carried out under the 6th Framework Integrated Project “Upwind”. The financial support from the European Commission is gratefully acknowledged.