# Field testing of individual pitch control on the NREL CART-2 wind turbine

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## Summary

This paper is concerned with field testing of an individual pitch controller on the CART-2 research turbine at NREL. The project is being carried out as part of the EU “UPWIND” project.

A power production controller has been designed for the test turbine, which includes an independent individual pitch control (IPC) algorithm which can easily be switched in and out during operation. The turbine is already instrumented with well-calibrated blade root strain gauges, and by comparing test data with and without the IPC, the load reduction will be quantified. This is a 2-bladed teetered turbine, but with the teetering locked by a brake the tests should demonstrate that IPC can be used instead of teeter to reduce the hub moments. It is hoped that the three-bladed CART-3 turbine can subsequently be made available for a similar field test in early 2010. 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. A tower damping algorithm using collective pitch control has also been designed, and will be tested at the same time.

This paper presents simulation results demonstrating the control principles to be tested. The intention was to also present some preliminary field test results, but administrative problems have unfortunately delayed the start of testing, which is now expected to begin during the second quarter of 2009.

## Introduction

For some years, detailed simulation studies have shown that individual pitch control (IPC) can be an effective way to reduce fatigue loading on a wind turbine, and some commercial turbines are now being designed to make use of this technique to improve overall cost-effectiveness. However, to increase confidence in the technique there is a need for field tests to demonstrate conclusively that the load reductions can be achieved in practice. Under the EU “UPWIND” project, a project has been set up to design, implement and test an IPC algorithm on the two-bladed CART-2 research turbine at NREL, with the intention to repeat similar tests on the three-bladed CART-3 turbine a year later.

## The NREL turbines

Two turbines are available at NREL, each 42 m diameter with an output of 660 kW. The CART-2 has two blades and a teetered hub, while the CART-3 is a conventional three-bladed machine. Although not fully representative of modern multi-MW designs, these turbines should be adequate for proof of principle. As research turbines, they have the advantage of being very accessible with minimum fuss, and without problems of commercial sensitivity to prevent publication of results.

The CART-2 is fully ready and operational. Being two-bladed, it is rather less representative of commercial turbines than the CART-3. However it is still relevant, because two-bladed turbines are definitely still seen as a potential option for large offshore machines where problems of high tip speed, noise and visual aesthetics are less significant. It is also relevant because the advanced control principles to be tested (both IPC and tower damping) are actually just the same, irrespective of the number of blades.

The CART-2 is fitted with conventional strain gauges, but these are very stable, robust and well calibrated. This is partly because of the mounting position, made possible by the spindle bearings used for pitching, which also results in very low pitch bearing friction and very fast actuator response, very suitable for IPC. This is excellent for proving the control principles, even if it does not allow experience to be built up with the use of fibre-optic load sensors (which are more likely to be chosen for commercial applications) or the effect on more conventional pitch actuation systems.

The CART-2 is also teetered, but for these tests the teeter will be locked using the teeter brake.

The CART-3 is more representative of commercial turbines and is physically ready, but it requires completion of the control system by NREL before it can be used. However it is planned to be ready in early 2010.

## Programme

Following agreement of the principles of this co-operative project between GH and NREL, a power production control algorithm was designed by GH, and tested in detailed non-linear simulations using the *Bladed* software with turbulent wind input. Some results of these simulations are reported in this paper. Unfortunately the first measurements, originally planned to start early in 2009, are not yet available due to administrative delays, but these are now resolved and it is hoped that the measurements will be able to begin in the next few weeks.

A similar algorithm will then be designed for the CART-3 and tested in simulations, ready for implementation and field testing in early 2010.

## The CART-2 controller

A *Bladed* model of the CART-2 turbine was built from information supplied by NREL [1]. Linearised models were derived from this at a number of operating points, and used as the starting point for control tuning.

The power production control algorithm to be tested on the CART-2 is based on up-to-date principles regularly used by GH for commercial controller design work [2], [3]. It includes the following features:

- Optimal power production, maintaining peak Cp over the whole nominal operating speed range
- Speed regulation by interacting PI-based torque and collective pitch control loops
- Drive train damping filter in torque controller
- Damping of fore-aft tower vibration by collective pitch control
- PI-based 1P individual pitch control to reduce rotating and non-rotating loads

The tuning of the control loops has been carried out using classical design techniques. Although the controller as a whole has several measured input signals and several output demands, it can easily be divided into a series of largely decoupled single-input, single-output loops for which classical methods are well suited. Where the loops are not fully decoupled, for example the collective pitch control loops for rotor speed and tower vibration, a good coupled solution can be reached after only a very small number of iterations with each loop in turn. In many ways this is more practical than using multivariable methods.

## Simulation results

A selection of key simulation results is presented below, to illustrate the operation of the advanced features of the controller. Simulations at 18m/s and 24m/s mean wind speeds are illustrated, with 20% turbulence intensity in each case.

The effect of the fore-aft tower damping using collective pitch control is well illustrated by a spectrum of tower base overturning moment (My), in Figure 1. The large peak at the first mode frequency of about 0.87 Hz is virtually eliminated when the damping action is introduced. Although this effect has previously been demonstrated in field tests [4], the opportunity will be taken to use the CART-2 field tests for further confirmation.

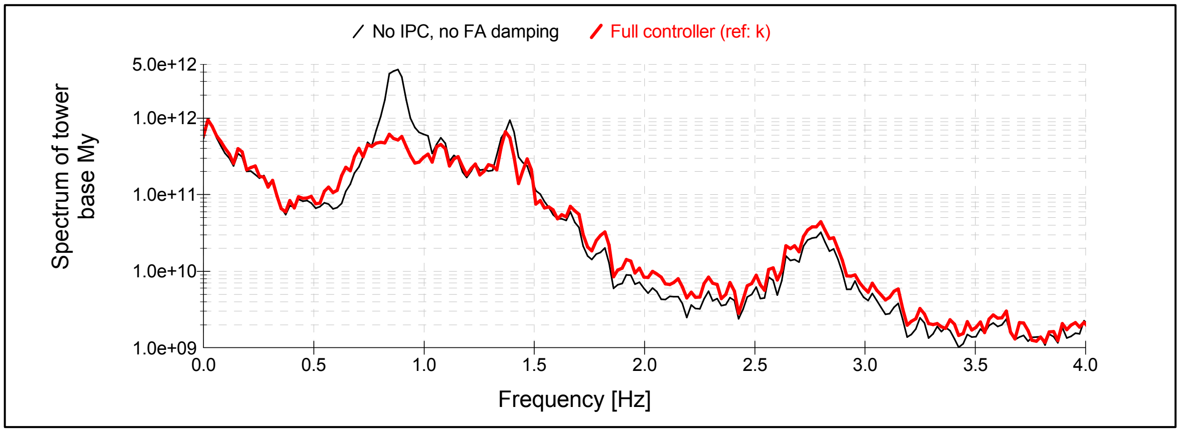


**Figure 1: Effect of tower damper at 18 m/s**

The following figures demonstrate the effect of IPC. The main effect is to reduce the once-per-revolution (1P) loading on the rotating components; the blade root out of plane moment and the hub teeter moment are shown in Figure 2 and Figure 3 respectively, and the fatigue-dominant 1P spike (about 0.7 Hz) in the spectrum is effectively removed, hopefully eliminating the need for a teetered hub.

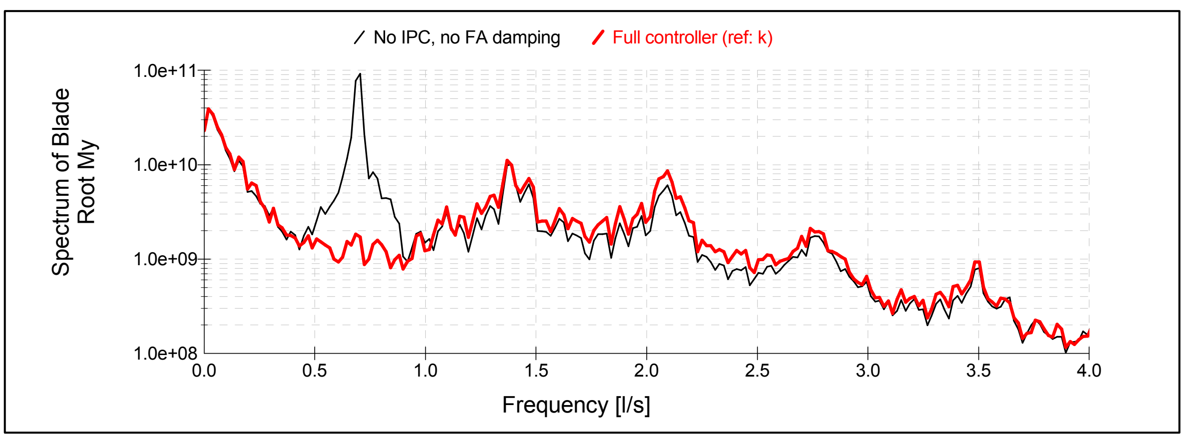


**Figure 2: Effect of IPC at 18 m/s: Blade root out of plane moment (My)**

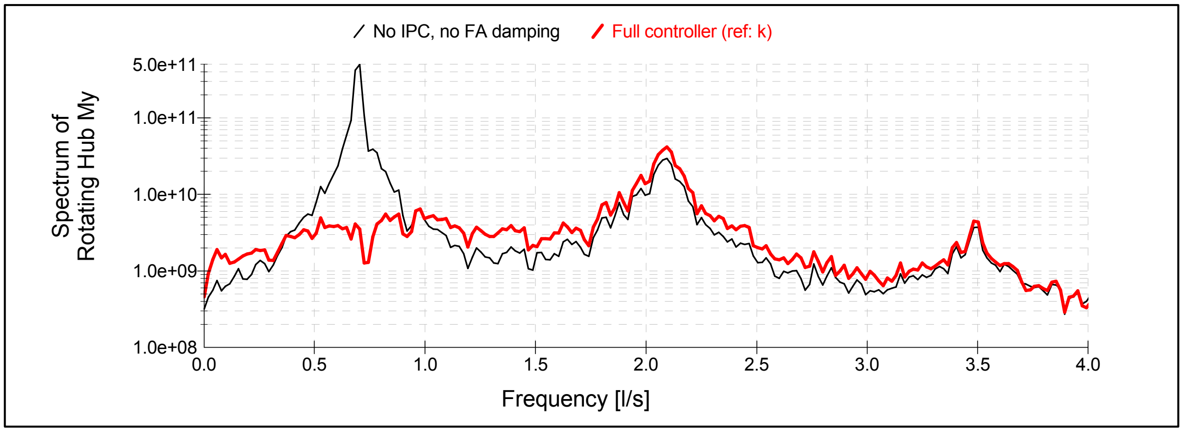


**Figure 3: Effect of IPC at 18 m/s: Rotating hub out of plane (teeter) moment (My)**

The 1P loading component on the rotor, when transformed to the non-rotating reference frame, results in loading contributions at 0P and 2P. However the dominant source of fatigue loading on the non-rotating components is also at 2P on a two-bladed turbine, since this is also the blade passing frequency. Therefore the 1P IPC action on the rotating blades also significantly reduces the fatigue loading on the non-rotating components. This is illustrated in Figure 4 for the yaw bearing Mz (yawing) moment – a similar effect is seen on the nodding (My) moment. This is contrast to a three-bladed turbine, where the dominant fatigue loading is at 3P, and is therefore not significantly reduced by IPC at 1P.

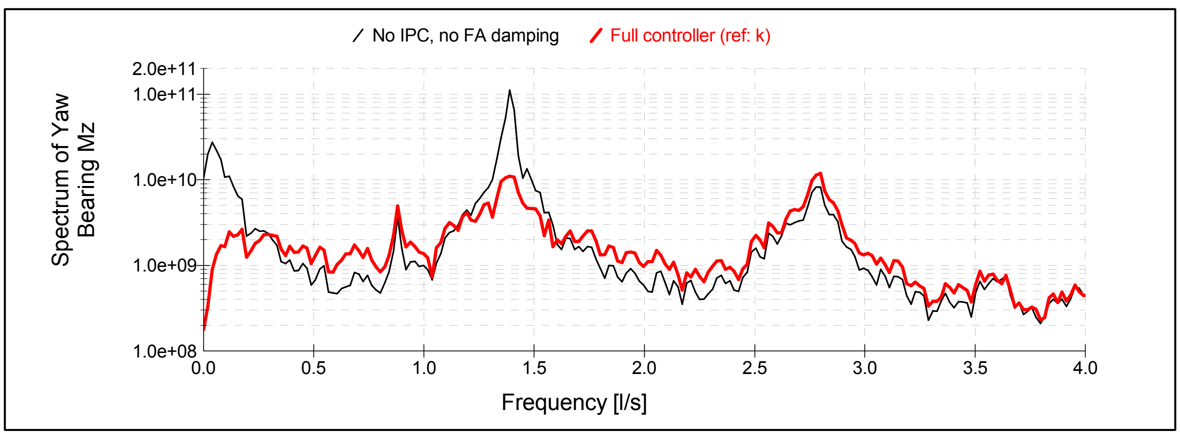


**Figure 4: Effect of IPC at 18 m/s: Yaw moment (Mz)**

The removal of the low frequency peak in Figure 4 also means that the slow variations due to gradual changes in wind speed and direction are removed. The combined effect means a significant reduction in peak values of this load, implying also a reduction in the duty required of the yaw motors when they are required to yaw the turbine.

The IPC of course requires a significant amount of pitch activity at 1P on the individual blades, with implications for the design of the pitch actuators and pitch bearings. The pitch actuators will be working harder, although the peak torque duty will not be different and may even be reduced in typical turbines, because reduced blade root loads mean that there is less pitch bearing friction to work against. The pitch action is illustrated by the pitch rate spectrum in Figure 6, with a sample time history shown in Figure 7. Any extra pitch action due to the fore-aft tower damping at 0.87 Hz is not discernible; the additional action is concentrated at 1P and is due to the IPC.

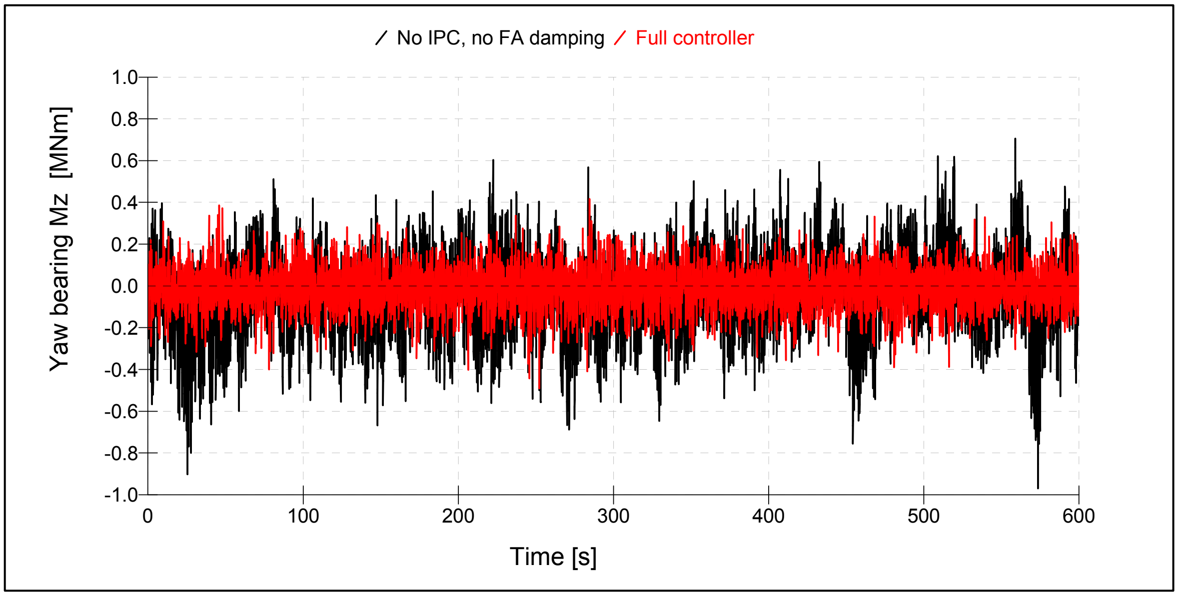


**Figure 5: Effect of IPC at 24 m/s: Yaw moment (Mz) as time history**

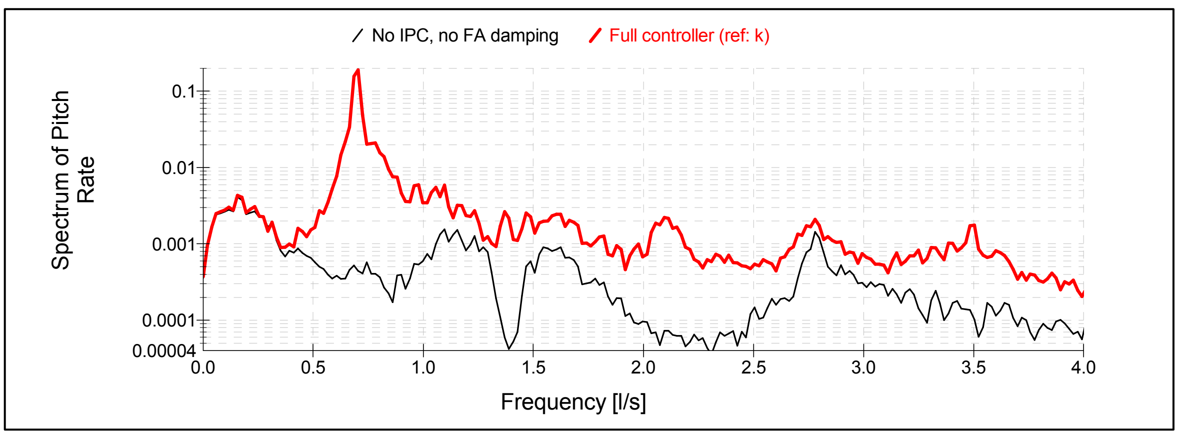


**Figure 6: Effect of IPC at 18 m/s: Pitch rate spectrum**

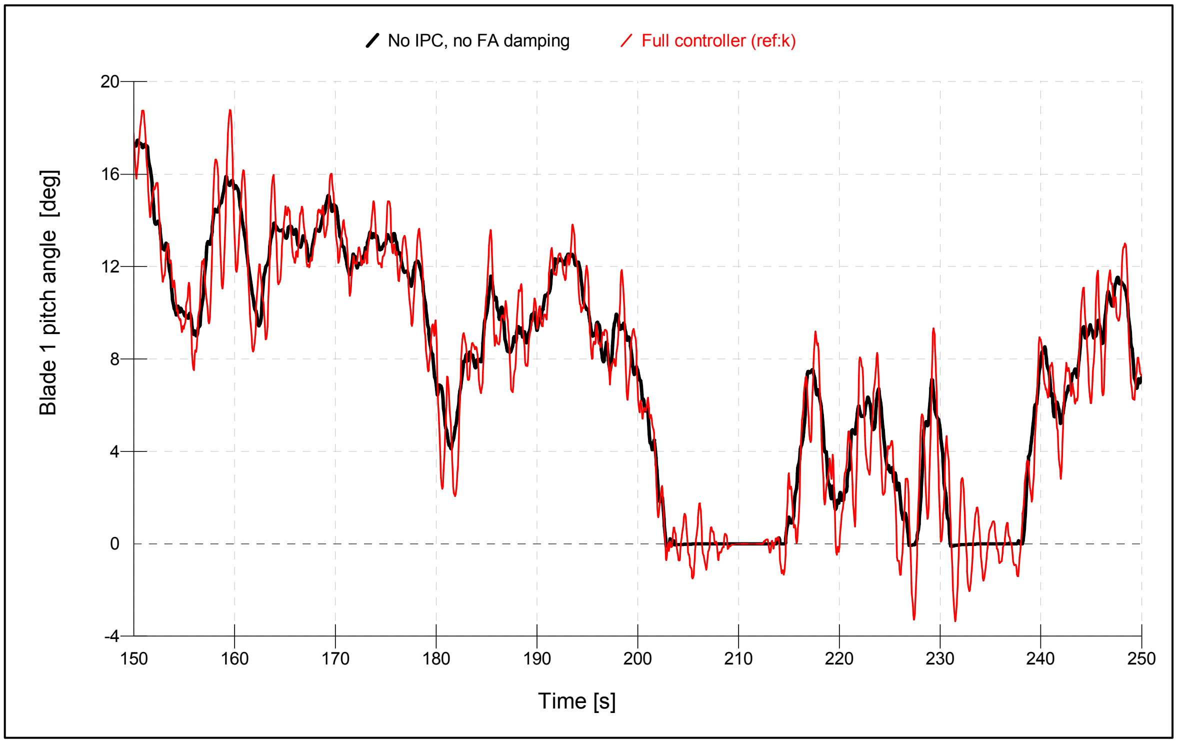


**Figure 7: Effect of IPC at 18 m/s: Pitch rate time history**

## IPC with two and three blades

The IPC control action is calculated in the non-rotating frame, in two axes (e.g. horizontal and vertical), and this is not in any way dependent on the number of blades. The number of blades is embodied in the rotational transformations: one to transform the blade root load measurements into the non-rotating frame, and a reverse transformation to transform the pitch demands back into the rotating frame (Figure 8).

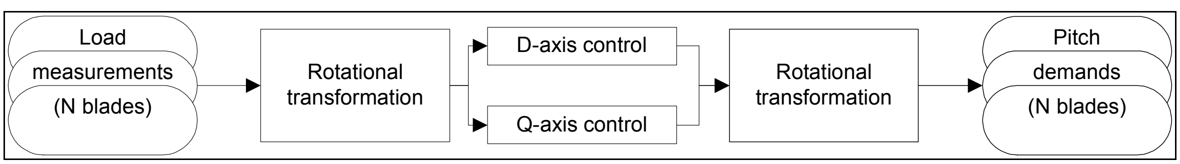


**Figure 8: IPC in the fixed frame of reference**

The transformations are easily generalised to any number of blades B. The forward transformation is

$$\begin{bmatrix} L_d \\ L_q \end{bmatrix} = \frac{2}{B} \begin{bmatrix} \cos(\varphi) & \cos(\varphi + 2\pi/B) & \cos(\varphi + 4\pi/B) & \dots \\ \sin(\varphi) & \sin(\varphi + 2\pi/B) & \sin(\varphi + 4\pi/B) & \dots \end{bmatrix} \begin{bmatrix} L_a \\ L_b \\ L_c \\ \dots \end{bmatrix}$$

and the corresponding reverse transformation is

$$\begin{bmatrix} L_a \\ L_b \\ L_c \\ \cdots \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ \cos(\phi + 2\pi/B) & \sin(\phi + 2\pi/B) \\ \cos(\phi + 4\pi/B) & \sin(\phi + 4\pi/B) \\ \cdots & \cdots \end{bmatrix} \begin{bmatrix} L_d \\ L_q \end{bmatrix}$$

The above simulation results have demonstrated that on a two-bladed turbine, the 1P IPC action reduces both the 1P rotating and the 2P non-rotating fatigue loads. On a three-bladed machine, the non-rotating fatigue loads are at 3P, so to reduce these requires additional (second harmonic) individual pitch control action at 2P in the rotating frame, since this will reduce non-rotating loads at 3P (and also at 1P, but this is not important). IPC action at higher harmonics is also possible, but probably unnecessary. Figure 9 shows how the second harmonic (2P) IPC is implemented, in principle.

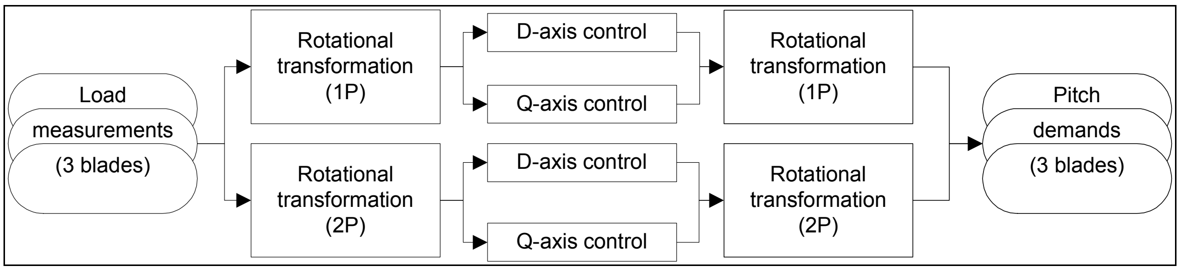


**Figure 9: Addition of second harmonic IPC**

The transformations for the higher harmonics are exactly as above but with the arguments to the sin and cos functions multiplied by the harmonic number.

The CART-3 turbine will provide the opportunity for field testing of both 1P and 2P IPC. The CART-3 algorithm is not yet designed, but a similar algorithm has already been designed for the Upwind 5MW reference turbine [5], and some simulation results for this fictitious turbine are shown here for illustration. These are at a mean wind speed of 19 m/s, with 16.7% turbulence intensity. Sample spectral analysis results in Figure 10 and Figure 11 show how the rotating loads are reduced at both 1P and 2P, while the non-rotating loads are reduced at 0P and 3P: the 1P IPC reduces them at 0P and 2P (but 2P is not important), and the 2P IPC reduces them at 1P (not important) and 3P (very important). The 2P IPC introduces some additional pitch action at 2P, but significantly less that the 1P action.

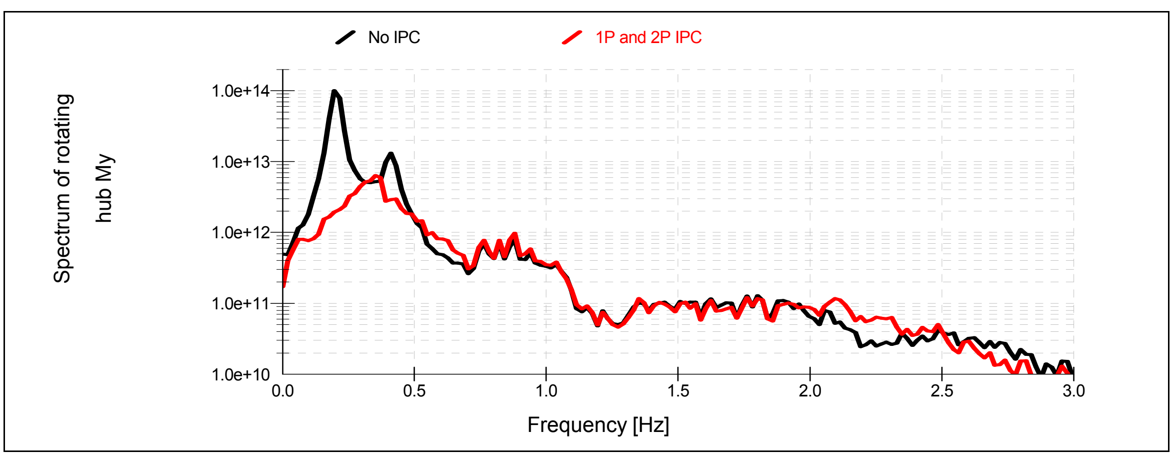


**Figure 10: Effect of 1P and 2P IPC for the Upwind 5MW turbine: rotating loads**

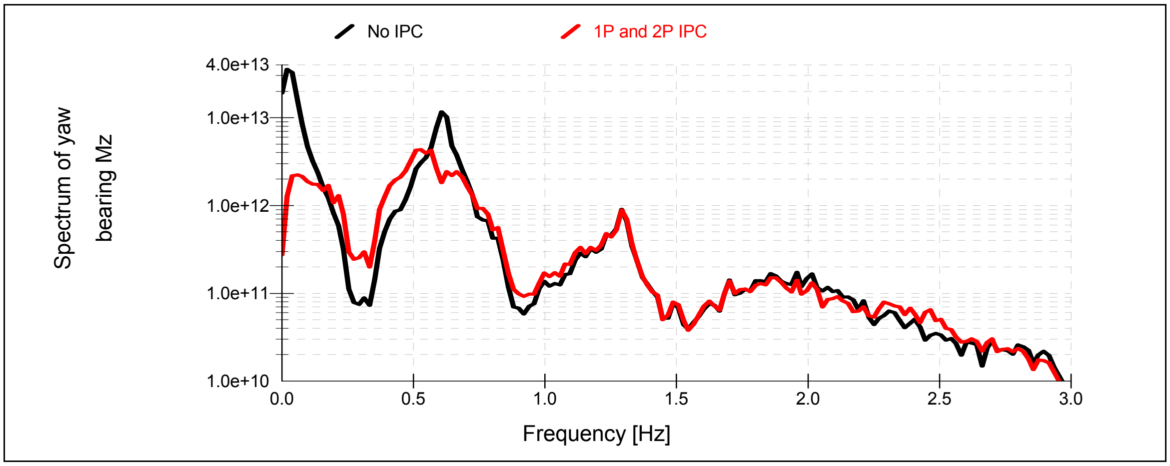


**Figure 11: Effect of 1P and 2P IPC for the Upwind 5MW turbine: non-rotating loads**

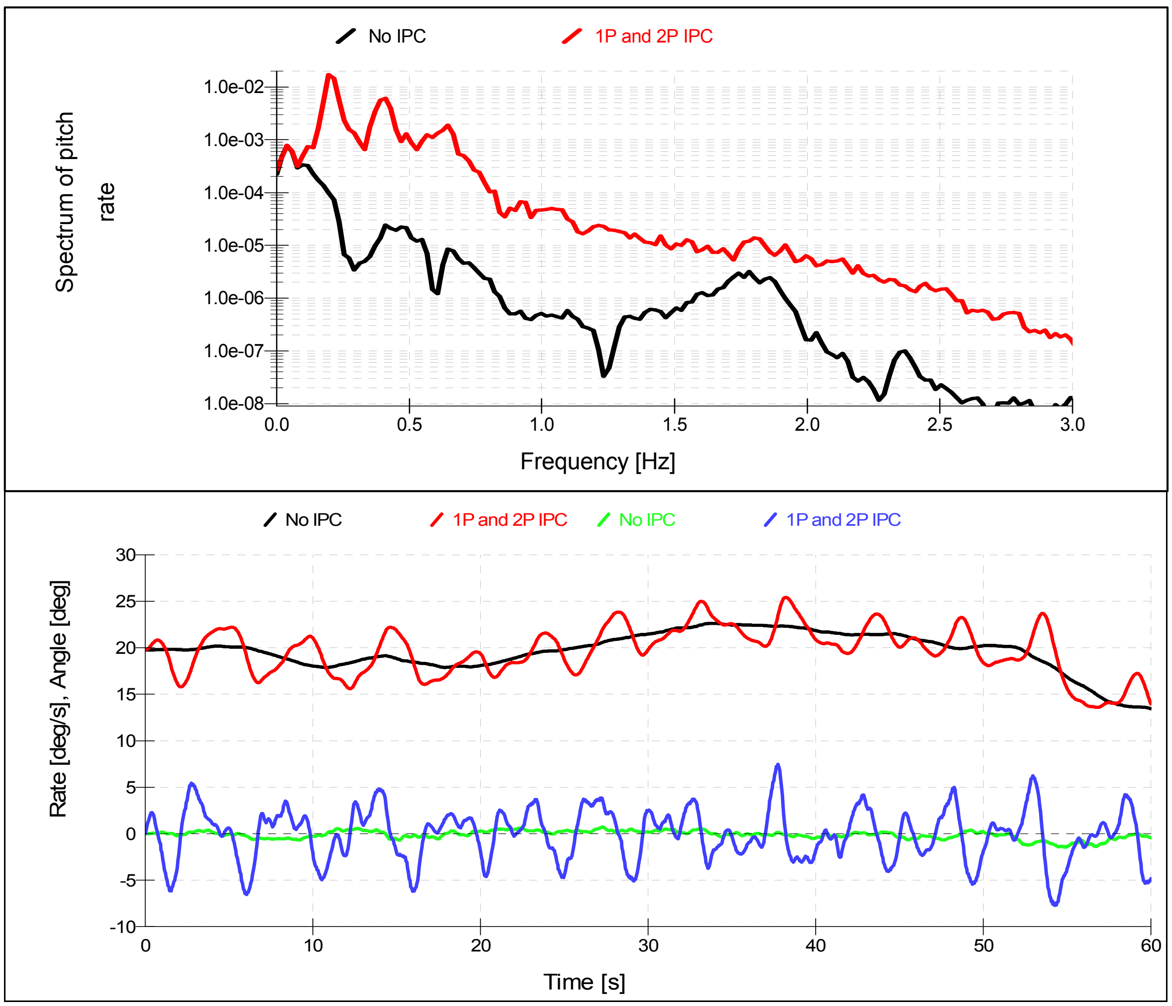


**Figure 12: Effect of 1P and 2P IPC for the Upwind 5MW turbine: pitch action**

## Conclusions

A programme of field testing has been set up, using the CART turbines at NREL, with the start of testing scheduled to start early in 2009. The aim of the field tests is to demonstrate that certain advanced control objectives, already demonstrated by means of simulation results, can be realised in practice. In advance of the first test results, this paper explains the features to be tested and uses the simulation results to illustrate their expected effects. The main control objectives to be tested are as follows:

Measurements on the CART-2:

- That measured nacelle acceleration can be used in the collective pitch controller to reduce fore-aft tower vibrations and loading,
- That IPC can be used instead of a teeter hinge on a 2-bladed turbine to reduce the 1P loads in rotating components,
- That IPC on a 2-bladed turbine also reduces the 2P fatigue loading on non-rotating components.

Measurements on the CART-3:

- That measured nacelle acceleration can be used in the collective pitch controller to reduce fore-aft tower vibrations and loading,
- That IPC at 1P can be used to reduce the 1P loads in rotating components,
- That IPC at 2P can additionally be used to reduce the 3P fatigue loads on non-rotating components.

The CART-2 controller has been designed and tested in simulations. Field measurements are due to start soon, with 1P IPC and tower fore-aft damping. The CART-3 field measurements are due to take place in 2010, with 1P and 2P IPC and tower fore-aft damping. Although the controller has not yet been designed, the principles have been proven in simulations using the 5MW Upwind reference turbine.

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