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"Integrated Wind Turbine Design"

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Abstract: This document presents a state-of-the-art power production controller design for the UPWIND 5MW reference turbine.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				Confidentiality				Accessibility	
S0	Approved/Released	●		**R0**	General public	●		Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	●
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1. Introduction

This report presents a state-of-the-art power production controller design for the UPWIND 5MW reference turbine.

The turbine is a generic 126 m diameter 3-bladed offshore turbine of fairly conventional design. Although not representative of any one particular turbine, it is fairly representative of typical commercial turbines in this class. The hub height is 90m above the nominal surface, with a sea depth of 20m. Figure 1.1 provides an illustration of the basic proportions of the turbine, and the key operational parameters are summarised in Table 1.

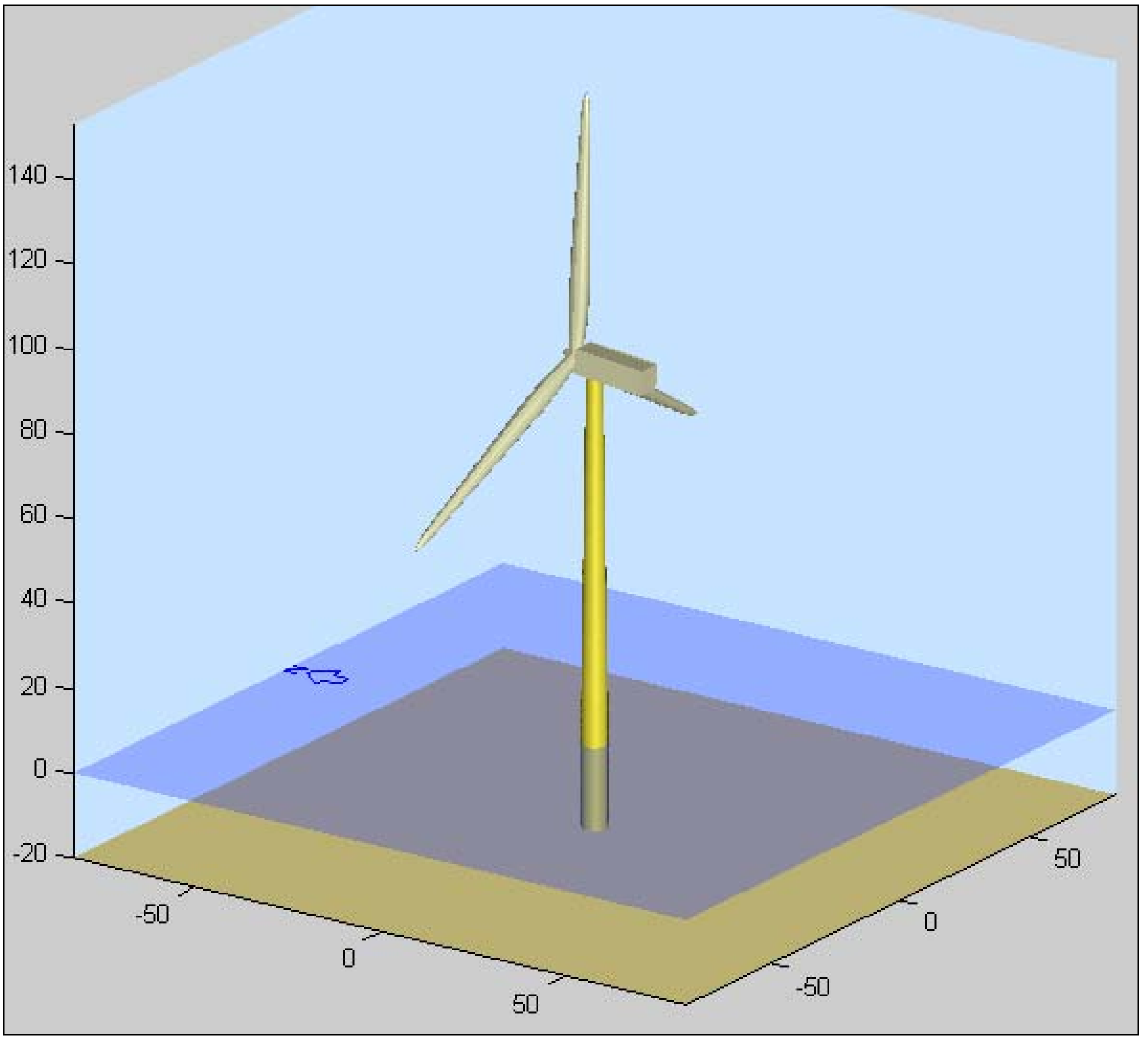

Figure 1.1: The 5 MW reference turbine

Rotor diameter	126	m
Number of blades	3	
Hub height	90	m
Tilt angle of rotor to horizontal	5	deg
Cone angle of rotor	-2.5	deg
Rotor overhang	5	m
Gearbox ratio	97	
Rotational sense of rotor, viewed from upwind	Clockwise	
Position of rotor relative to tower	Upwind	
Aerodynamic control	Full span pitch	
Generator	Variable speed	
Cut in wind speed	4	m/s
Rated wind speed	11.3	m/s
Cutout wind speed	25	m/s
Rated rotational speed	12.1	rpm

Table 1: Key operational parameters

In accordance with widespread current practice, the power production control is based on the principles of variable rotor speed with full-span pitchable blades which pitch in the feathering direction. The turbine reaches its rated power of 5 MW at the rated wind speed of 11.3 m/s. The main principles of the controller are based on previous work [1], [2].

The controller presented in this report is based on the following principles:

- Optimisation of power production below rated wind speed, by allowing the rotor speed to vary in proportion to wind speed until the maximum operational rotor speed of 12.1 rpm is reached, subject to a speed exclusion zone to prevent excitation of the first vibrational tower mode by the blade passing frequency (3P).
- Nominally constant speed operation at 12.1 rpm, using speed regulation by torque control below rated and by collective pitch control above rated.
- Modification of generator torque control to help with damping of torsional resonance in the drive train.
- Combined torque and pitch control to ensure smooth transitions at rated and maximise energy capture.
- Modification of collective pitch control in response to nacelle acceleration, to help with damping of fore-aft tower vibration.
- 1P individual pitch control to reduce asymmetric rotor loads, especially 1P loads on rotating components and low frequency loads on non-rotating components.
- 2P individual pitch control to reduce 3P fatigue loads on non-rotating components.

The controller design has been carried out using classical linear control design methods applied to a high-order linearised model of the turbine dynamics at a number of operating points. The controller has then been tested in detailed non-linear turbulent simulations and further adjusted, using some non-linear controller features where appropriate, to achieve a satisfactory controller performance across a range of operating conditions.

This report describes the various elements of the controller in more detail, and presents some simulation results to demonstrate the performance in different operating conditions.

2. Details of the controller design

The turbine operates at variable speed, using a generator and variable speed drive capable of delivering any demanded level of torque (within limits) at the generator air-gap. This torque control has a high bandwidth, so the demanded torque is achieved at the air-gap with only a short delay, which has been ignored in this particular study. By controlling this torque, the speed of the rotor can be regulated to any desired level. In low winds the speed is adjusted to maintain maximum energy capture, until the design value of the maximum steady-state rotational speed is reached. Thereafter the torque is controlled to keep the speed constant at this maximum value, until rated torque and power are reached at the rated wind speed. In higher winds the rated power is maintained and collective blade pitch control then takes over the speed regulation.

In addition to this primary duty, both the torque and pitch control actions are modified dynamically in order to reduce certain loads: both by reducing applied loads and by providing additional damping for certain important structural resonances of the system.

2.1 Optimisation of power production below rated

The turbine rotor achieves its maximum aerodynamic efficiency (Cp = 0.486) at a tip speed ratio of about 7.8. While this optimum tip speed ratio is maintained, the rotor speed must change in proportion to the wind speed, the torque will change with the square of the wind speed, and hence also with the square of the rotor speed, and the power will change with the cube of the wind or rotor speed. Although this represents a steady-state relationship, in practice, it is possible to maintain optimum tip speed ratio fairly well simply by setting the generator torque to be proportional to the square of the measured generator speed.

Figure 2.1 shows the torque-speed operating curve of the turbine. Below the rated generator speed of 1173.7 rpm, the curve is quadratic as explained above. Starting from the definition of the power coefficient Cp, the curve is easily calculated as follows:

$$Q_d = K_\lambda \, \omega_g^2$$

where

$K_\lambda = \pi \rho R^5 Cp(\lambda) / 2 \lambda^3 G^3$
ρ = air density
R = rotor radius
λ = desired tip speed ratio
$C_p(\lambda)$ = Power coefficient at tip speed ratio λ
G = gearbox ratio

Because the turbine rotor has a finite inertia, it is not possible to maintain peak C_p at all times since the rotor cannot change speed fast enough to follow rapid changes in wind speed. However the strategy described above works reasonably well provided the rotor is not unusually heavy, and the C_p - λ curve does not have too sharp a peak so that variations away from optimum tip speed ratio do not cause a large drop in Cp. More dynamic algorithms are possible which compensate for the inertia, for example by adding a torque term proportional to acceleration, but the gain in energy is usually very small, and not sufficient to compensate for the very large power and torque variations which are required to achieve this.

Once rated generator speed is reached, the speed-torque curve is a vertical line, which therefore cannot be implemented by means of any function or look-up table which simply gives the torque as a static function of speed. In this region a PI (proportional plus integral) controller has been designed to maintain the desired speed by varying the torque demand in response to measured generator speed. The gains for this controller have been obtained using linear control design techniques. Some variation of the rotor speed about the set-point is desirable: this gives a ‘softer’ response with slower variations in torque and power than if the speed were constrained to follow the set-point very tightly. This can be achieved by suitable choice of PI gains.

Figure 2.1 also shows an “exclusion zone” in the region of approximately 450 to 650 rpm. This zone is centred on a rotor speed of about 5.6 rpm, at which speed the 3P blade passing frequency is 0.28 Hz, which corresponds to the first tower bending mode. If the rotor operates at this speed for any length of time, the excitation of this tower mode by the 3P forcing frequency can cause the tower vibration to build up unacceptably. Therefore the speed range is divided into two regions, above and below tower resonance, as shown. Each region is bounded by a constant speed characteristic, which is implemented using the same PI controller as is used at the upper speed limit, although the gains are reduced as a linear function of speed since this allows the resulting power variations to be smaller while the quality of speed regulation is amply good enough. When the controller determines that it is time to cross the exclusion zone, the speed set-point is simply ramped through the exclusion zone at a fixed rate, and the PI controller causes the speed to follow the moving set-point.

Transitions between the quadratic characteristic and the vertical PI sections are very straightforwardly handled: the PI controller is simply acting all the time, but the quadratic curve acts as a (varying) torque limit applied to the output of the PI controller (with full integrator desaturation). This results in a completely smooth transition. The speed set-point is switched between the upper and lower limits of the region when the actual speed passes the mid-point of the region; since the torque is constrained to follow the quadratic curve at this time, this transition is also completely smooth.

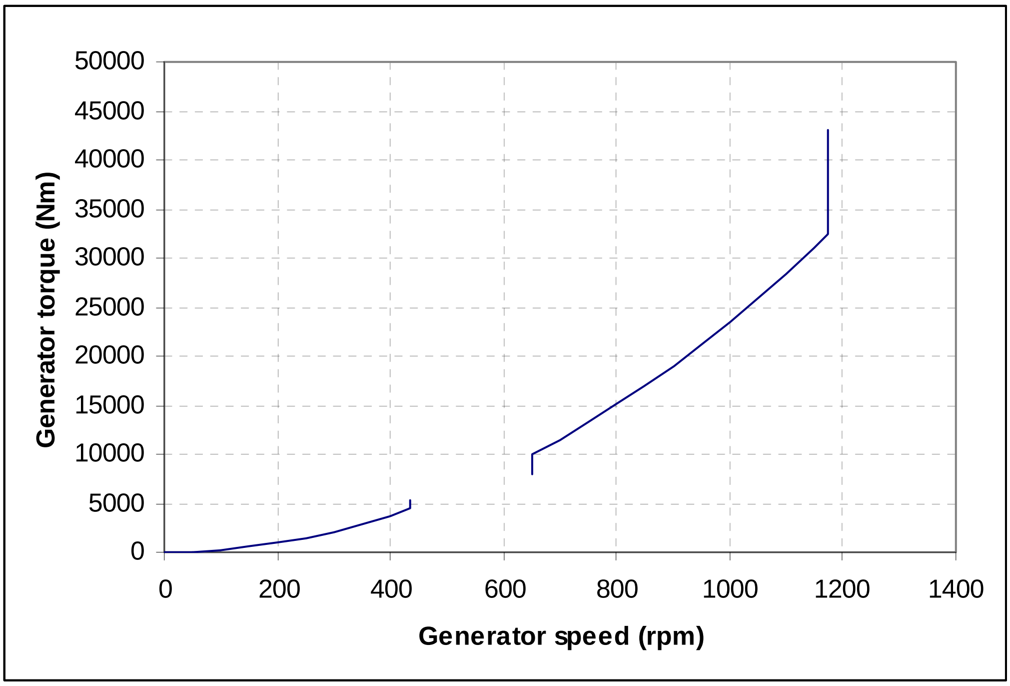

Figure 2.1: The steady-state torque-speed curve

In the constant speed regions, it is possible in principle to change the blade pitch angle slightly as a function of low-pass-filtered power level, used as a proxy for wind speed, in order to maximise the energy capture when operating away from the peak of the Cp curve. However there is little to be gained in this case, so the pitch angle is held constant at zero degrees over the whole of the below-rated range.

2.2 Damping of torsional vibrations

In the above-rated region the generator torque may be held nominally constant, or alternatively the power can be held constant in which case the torque demand is given a small variation in inverse proportion to speed variations about the set-point. In principle this has a slight destabilising effect on the speed control, but in practice this may not be severe. In this case the constant power option has been adopted as the power quality is thereby improved.

In variable speed turbines, the torsional modes of the drive train are usually very lightly damped during normal operation. The in-plane blade vibrations provide very little aerodynamic damping, and structural damping will be small, as will be any mechanical damping from the gearbox or generator. If the generator torque is held constant, this will not provide any damping, and in fact with the constant power option there is a slight negative damping effect. However there can be very significant excitation of these lightly damped modes, leading to large oscillatory torques at the gearbox particularly at the frequency of the first drive train torsional mode, sometimes coupling significantly with in-plane rotor vibrations and side-side tower modes. Any methods for introducing additional mechanical damping will involve additional component cost. Fortunately it is straightforward to provide very significant damping through the controller, by modifying the nominal generator torque demand with an additional term which adds a small ripple at the appropriate frequency or frequencies. As long as the phase is correct, this will have the required damping effect. This damping term is usually obtained by passing the measured generator speed through a suitably tuned bandpass filter.

In this case, a fourth-order filter was designed to provide the damping effect. It was designed using classical methods in discrete time, taking into account an assumed one-timestep controller delay, and is implemented as a discrete transfer function. For convenience, the filter has been converted into two continuous-time second-order bandpass filters in parallel which, when discretised using the bilinear or Tutsin approximation, result in the same discrete transfer function. The continuous-time representation of the damping filter can be expressed as the transfer function

$$K_1 \frac{2\varsigma_1 s/\omega_1}{1+2\varsigma_1 s/\omega_1 + s^2/\omega_1^2} + K_2 \frac{2\varsigma_2 s/\omega_2 (1+\tau_2)}{1+2\varsigma_2 s/\omega_2 + s^2/\omega_2^2}$$

with the following parameter values:

K_1	1560	Nms/rad	K_2	1625	Nms/rad
ω_1	24.20	rad/s	ω_2	8.998	rad/s
ζ_1	0.132	-	ζ_2	0.5041	-
			τ_2	0.0138	s

An amplitude limit of 1.8 kNm at the generator is imposed on the damping torque, corresponding to 220 kW in power, but the limit is unlikely to be reached.

The effect of the damping filter is illustrated in a full turbulent wind simulation in Figure 2.2, which is for a mean wind speed of 13 m/s with 19% turbulence intensity. Without the damping filter, the drive train is actually unstable in torsion at this wind speed, with a rapidly-developing oscillation which would cause severe gearbox damage and leads rapidly to turbine shut-down. The damping filter has a dramatic effect, stabilising the drive train and giving a rather smooth gearbox torque. The damping ripple can be seen on the power signal, and is rather small.

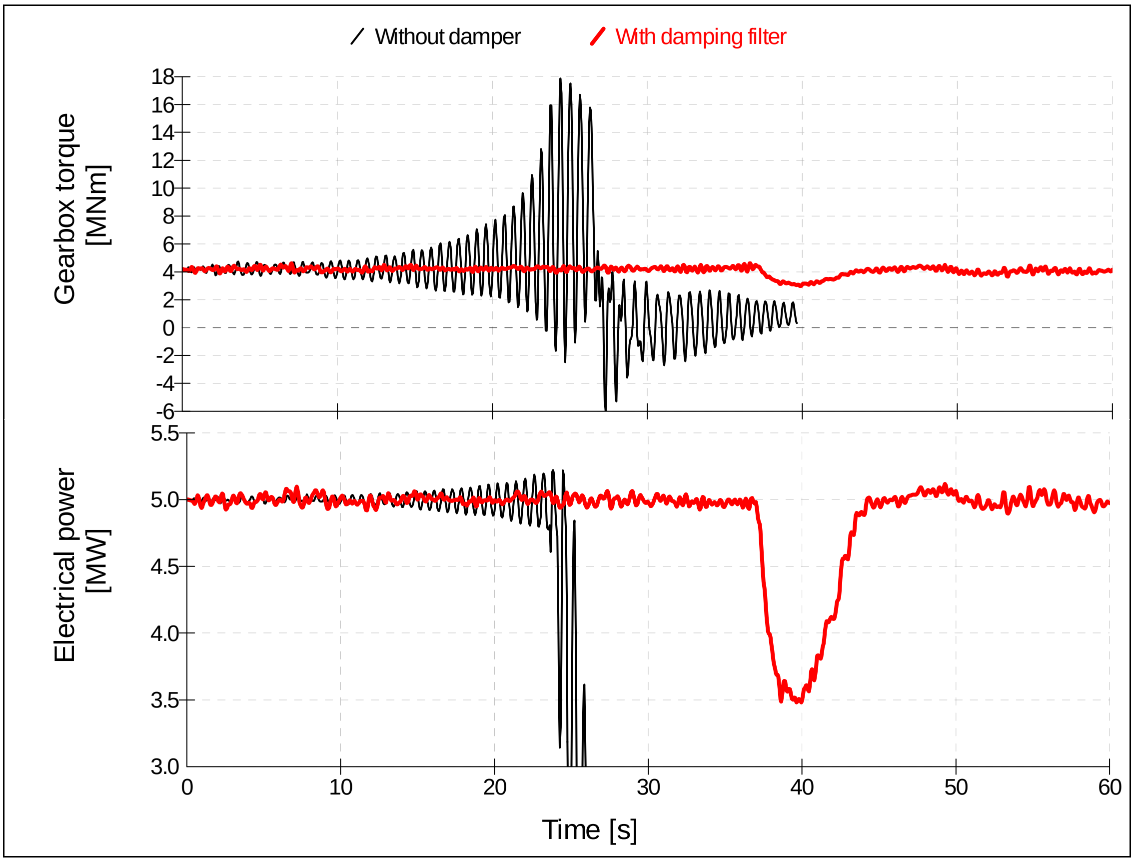

Figure 2.2: The effect of the drive train damping filter

2.3 The PI torque controller

On the vertical sections of Figure 2.1, speed regulation is achieved by means of a PI controller reacting to speed error and outputting a generator torque demand. The design of the PI controller is relatively straightforward: the bandwidth need not be too high, allowing some speed variation about the set-point rather than demanding large torque variations to control the speed more tightly. The controller parameters are:

Proportional gain	4200	Nms/rad
Integral gain	2100	Nm/rad

Once again this controller was tuned in discrete time. The torque limits at the top and bottom of each vertical section of Figure 2.1 are implemented using full integrator desaturation, to prevent integrator wind-up at the limits. For the torque controller, including the drive train damping filter, a 10 ms timestep has been used.

2.4 The PI collective pitch controller

Once rated torque is reached, the speed regulation duty is taken over by the pitch controller, again using a PI-based controller to generate a pitch position demand from the speed error. The tuning of this controller is rather more critical, for a number of reasons. Firstly, adjusting the blade pitch influences not only the aerodynamic torque but also the rotor thrust, so while regulating the speed the resulting thrust variations can cause excitation of fore-aft tower vibrations, particularly at the first mode frequency. Furthermore the pitch controller reacts significantly to variations in rotor speed at 3P (blade passing frequency), but this response is not useful so a notch filter in series with the PI controller has been introduced at this frequency (about 0.6 Hz). A second notch filter at 1.3 Hz was also found to be beneficial, as well as a low-pass filter to prevent unnecessary high frequency pitch action. The nominal PI controller gains are:

Proportional gain	0.0135	s
Integral gain	0.00453	-

However, the aerodynamic response of the blade varies significantly with pitch angle, so the gains have to be changed as a function of the pitch angle in order to maintain good response with adequate stability margins across the whole range of above-rated wind speeds. Thus a high gain is needed close to rated wind speed, where the aerodynamic torque is insensitive to pitch angle, but in higher winds the sensitivity increases, more or less in proportion to the pitch angle. This has been compensated by *dividing* both PI gains by a factor which varies linearly from 1.0 at fine pitch (0º) to 3.5 at 25º and above.

Each notch filter can be represented in continuous time by a transfer function of the form

$$\frac{1 + 2\zeta_1 s/\omega_1 + s^2/\omega_1^2}{1 + 2\zeta_2 s/\omega_2 + s^2/\omega_2^2}$$

The following parameters are used for the two notches:

Notch A: $\omega_1 = \omega_2 = 3.8$ rad/s, $\zeta_1 = 0$, $\zeta_2 = 0.15$.
Notch B: $\omega_1 = \omega_2 = 8.2$ rad/s, $\zeta_1 = 0$, $\zeta_2 = 0.2$.

The low-pass filter can be represented by:

$$\frac{1}{1 + 2\zeta s/\omega + s^2/\omega^2}$$

with $\omega = 10$ rad/s and $\zeta = 1$.

As before, this controller was tuned in discrete time, with full integrator desaturation to prevent integrator wind-up at the fine pitch limit, and also at the pitch rate limits of ± 8º/s. The above continuous-time representations assume that the bilinear or Tutsin approximation is used to discretise them. For the pitch controller, a 100 ms timestep has been used.

2.5 Tower vibration damping

Since variations in pitch angle cause changes in rotor thrust, it is possible to use this to help damp fore-aft tower vibrations. If the fore-aft acceleration is measured by an accelerometer in the nacelle, this signal can used to calculate a modification to the PI collective pitch demand such that the resulting thrust variations have a damping effect on the tower by opposing the tower top motion. Once again classical methods can be used to design this feedback. However, this makes the collective pitch controller into a two-input, single-output controller:

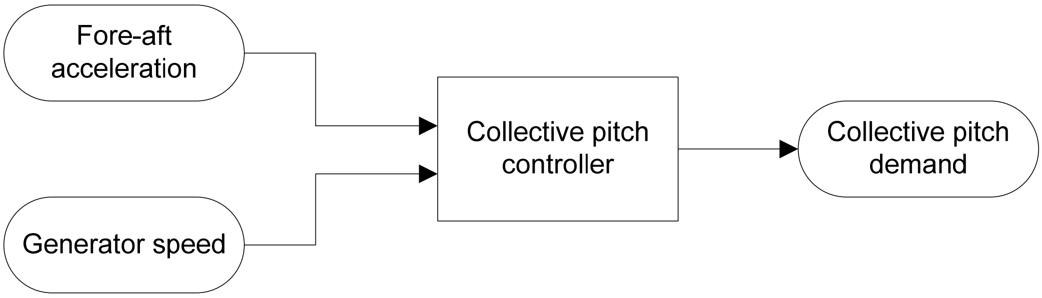

Figure 2.3: Overview of collective pitch controller

Since there can be significant interaction between the two loops, tuning them in isolation from each other may not result in optimal performance. However, even with classical methods, it is actually straightforward to tune one loop in isolation as a single-input, single-output (SISO) controller, and include this loop as part of the plant model for tuning the other loop. This process is then iterated until both tunings are satisfactory. In fact only one or two iterations are usually required in practice, making this approach quite straightforward.

In this case the final controller consisted of the speed loop described in Section 2.4, together with an acceleration loop which consists of a second-order filter in series with an integrator. The overall gain is 0.0454 rad.s/m, and the filter has the form

$$\frac{1+2\zeta_1 s/\omega_1+s^2/\omega_1^2}{1+2\zeta_2 s/\omega_2+s^2/\omega_2^2}$$

with the parameters values ω_1 = 1.17 rad/s, ω_2 = 1.9 rad/s, ζ_1 = 0.69, ζ_2 = 1.0. The output is limited by the $\pm$8º/s rate limits. Note that this tower damping can continue to act below rated, when the PI controller is saturated at its fine pitch limit. However in low winds the tower loading is not severe and additional pitch action to reduce it further is probably unwarranted. Therefore a gain schedule is applied to the acceleration feedback term, such that the full action at rated power is reduced linearly to zero at 80% of rated power. The power used for this gain schedule is actually the product of measured generator speed and torque demand, passed through a 0.5s first order lag filter.

For this particular turbine, the intrinsic aerodynamic damping of the tower vibration appears to be rather higher than is usually the case, so in fact the tower damping loop has little effect in this case. However it has been left in place as an example of state-of-the-art controller technology which in the case of most turbines is actually of very significant benefit.

2.6 Interaction between the torque and pitch controllers

Since both pitch and torque controllers are controlling the speed of rotation to the same set point, it is necessary to implement some logic to ensure that torque control is disabled above rated and pitch control is disabled below rated. This has been done by operating both controllers in parallel, but with some additional torque terms in the pitch controller to make it saturate at fine pitch below rated, and a ‘ratchet’ on the lower torque limit to ensure that the torque demand cannot fall until fine pitch is reached. This technique ensures that

a) the pitch demand saturates at fine pitch when the torque is below rated
b) the torque demand saturates at rated torque when the pitch is above fine pitch
c) the pitch can start to act if the wind is rising rapidly towards rated, to prevent a transient overspeed when the torque hits the upper limit

d) the torque will stay at rated during transient wind lulls: the rotor kinetic energy then keeps the power at rated, preventing frequent power dips around and above rated wind speed.

The additional torque terms in the pitch controller are actually based on the difference between actual power and rated power (where power is defined as the product of measured generator speed and torque demand), and are actually a proportional term to help the pitch to start acting below rated if the power is rising fast, and an integral term to bias the pitch towards fine when the power is below rated. The proportional gain is 1.0e-7 rad/W, and the integral term is 0.5e-7 rad/Ws. The algorithm is designed so that both PI controllers share the same integrator and wind-up prevention.

2.7 Additional non-linear pitch control term

In addition to the speed regulation PI controller and tower acceleration feedback, a further contribution to the pitch position demand is added on to increase the response to sudden gusts. This term depends on both the speed error and its rate of change, which is obtained by first difference in combination with a first-order lag to prevent over-reaction to signal noise. Each contribution is normalised by a scale factor, and the sum of the resulting terms is calculated. Any excess over 1.0 is multiplied by a gain factor to give a contribution to pitch rate demand. Multiplying by the timestep gives the increment in pitch position demand. This logic results in additional pitch action when the generator speed error is large, positive and increasing. In normal circumstances, the additional pitch action remains zero. The parameters used for this control action were selected to ensure that this is the case for standard turbulent wind simulations, while still helping to prevent overspeeding during severe gusts.

The relevant parameters are as follows:

Time constant for first order lag (PitNonLinTau) = 0.05 s
Scale factor for speed error (Err0) = 25 rad/s
Scale factor for rate of change of speed error (ErrDot0) = 10 rad/s^2
Gain (PitNonLin1) = 0.15 rad/s

2.8 The individual pitch controller

The individual pitch controller generates an additional zero-mean pitch demand for each blade which is added to the collective pitch demand derived as above. The individual pitch action is calculated from measured blade root bending moments in such a way as to minimise the asymmetrical out of plane loads across the rotor produced by inhomogeneity of turbulence, wind shear, yaw misalignment, tower shadow, aerodynamic asymmetry of the rotor etc. The basic theory is described in [2], where a rotational transformation is used to transform the measured blade root moments in the rotating reference frame into two orthogonal axes in the non-rotating reference frame, which may be called the D (direct) and Q (quadrature) axes by analogy with electrical machine theory (Park's transformation). The same process is used in helicopter control, where it is known as the Coleman transformation. The transformed loads in the two axes may be thought of as representing the asymmetrical load components in the horizontal and vertical directions. A PI controller for each axis then generates a pitch demand, and an inverse rotation transformation then generates the appropriate individual pitch demands for the three blades in the rotating reference frame of the rotor. The measured loads in this case are the blade root out of plane bending moments, which would normally be derived from flapwise and edgewise moments measured with fibre-optic sensors, resolved through the pitch angle at each point in time. The individual pitch control is then used to minimise the asymmetrical out of plane loads. The basic scheme is shown in Figure 2.4.

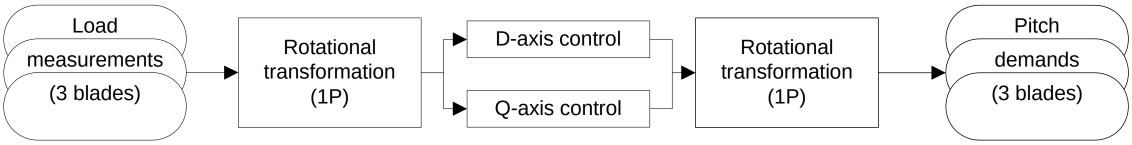

Figure 2.4: Individual pitch control – schematic

The rotational transformation can be written as

$$\begin{bmatrix} L_d \\ L_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\varphi) & \cos(\varphi + 2\pi/3) & \cos(\varphi + 4\pi/3) \\ \sin(\varphi) & \sin(\varphi + 2\pi/3) & \sin(\varphi + 4\pi/3) \end{bmatrix} \begin{bmatrix} L_a \\ L_b \\ L_c \end{bmatrix}$$

where φ is the rotor azimuth angle, and the corresponding reverse transformation is

$$\begin{bmatrix} L_a \\ L_b \\ L_c \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ \cos(\phi + 2\pi/3) & \sin(\phi + 2\pi/3) \\ \cos(\phi + 4\pi/3) & \sin(\phi + 4\pi/3) \end{bmatrix} \begin{bmatrix} L_d \\ L_q \end{bmatrix}$$

An offset ωT (ω is the rotational frequency) can be added to the azimuth angle in the reverse transformation to compensate for any time lag T caused for example by the controller timestep and any signal delays between the controller and the pitch actuators.

The D-axis controller consists basically of a PI controller, which regulates the D-axis load to the set-point which is normally zero. The Q-axis controller does the same for the Q-axis load. The two controllers are normally designed to be the same as each other, as in this case, although they can be different to account for differences due to, for example, yaw system or tower dynamics. Non-zero set-points can be used if required to generate a yawing moment (which could be used to yaw the machine) or a nodding moment, but for present purposes zero set-points are used.

A notch filter tuned to the rotational frequency (1P) is placed in series which each PI controller.

The inverse transformation generates 1P pitch actions at the three blades which compensate for the 1P loading which dominates fatigue loading of the blades and shaft, caused mainly by rotational sampling of turbulence together with wind shear, yaw misalignment, tower shadow, imbalance, etc. In the non-rotating frame of reference, e.g. for the yaw bearing, nacelle and tower, it is the low frequency variations in nodding and yawing moments which are compensated. While this reduces the peak moments, so that the yaw motor duty is reduced for example, it does not have much effect on the 3P (blade passing frequency) loads which dominate the fatigue on these components.

However it is possible to reduce this 3P loading by means of additional second-harmonic individual pitch control, which operates in parallel with the existing or first-harmonic individual pitch control – see Figure 2.5. In this case the rotational transformations are still the same, but with all angles (the arguments of the sin and cos functions) doubled.

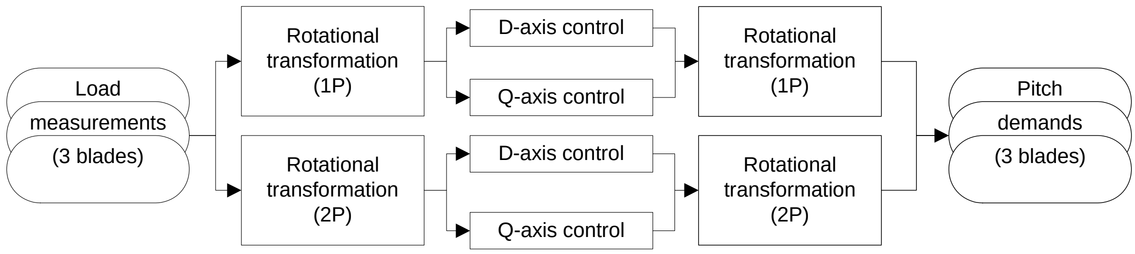

Figure 2.5: Addition of second harmonic individual pitch control

This will reduce any 2P loads on the rotating components, but more importantly, when transformed to the non-rotating frame, it reduces the 3P load loads which dominate the fatigue on the non-rotating components.

To be precise, the first-harmonic individual pitch reduces both the low frequency (0P) and the 2P loads in the non-rotating frame, of which only the 0P loads are important, while the second-harmonic individual pitch reduces both the 1P and 3P loads in the non-rotating frame, of which only the 3P loads are important.

All the PI controllers are subject to limits on their outputs, which after transforming to the rotating frame means that the maximum amplitude of the near-sinusoidal individual pitch action is limited. A limit of 5º for each axis has been set here, but it is not often reached. The PI limits can be reduced to zero to phase out the individual pitch control, for example in low winds where the additional pitch action cannot be justified. In this case the PI limits are ramped down to zero at and below 80% of nominal power output.

3. Sample simulation results

This section presents some sample simulation results to illustrate the performance of the controller. Where appropriate the effect of the 'advanced' features are demonstrated by comparing results with and without individual pitch control and fore-aft tower damping.

Figure 3.1 shows how the controller achieves smooth transitions between below-rated and above-rated operation. Speed regulation at 12 rpm is maintained, whether by torque or collective pitch control. The phasing-out of individual pitch control and fore-aft tower damping at lower power levels is clearly seen; when they are active however, they have a negligible effect on the power output. This figure also shows that the tower fore-aft motion is already well damped, so the additional damping effect of the pitch controller is not important.

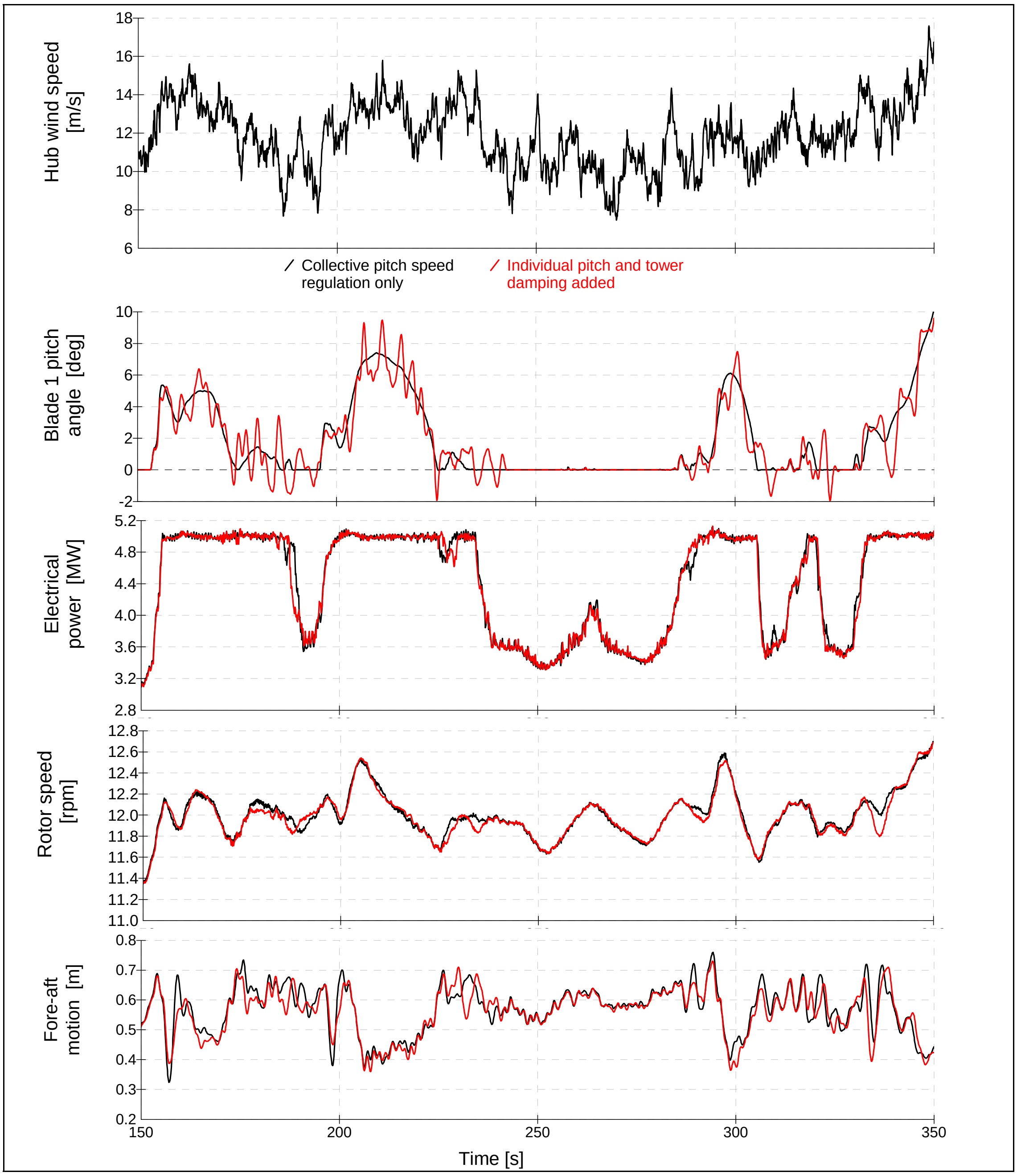

Figure 3.1: Transitions above and below rated wind speed

Figure 3.2 demonstrates the effect of the non-linear term described in Section 2.7 in significantly reducing both the overspeed and the tower vibration resulting from the IEC edition 2 extreme operational gust at cut-out wind speed. This feature is also beneficial for the extreme gust at rated wind speed, without effecting normal operation in turbulent wind at any wind speed.

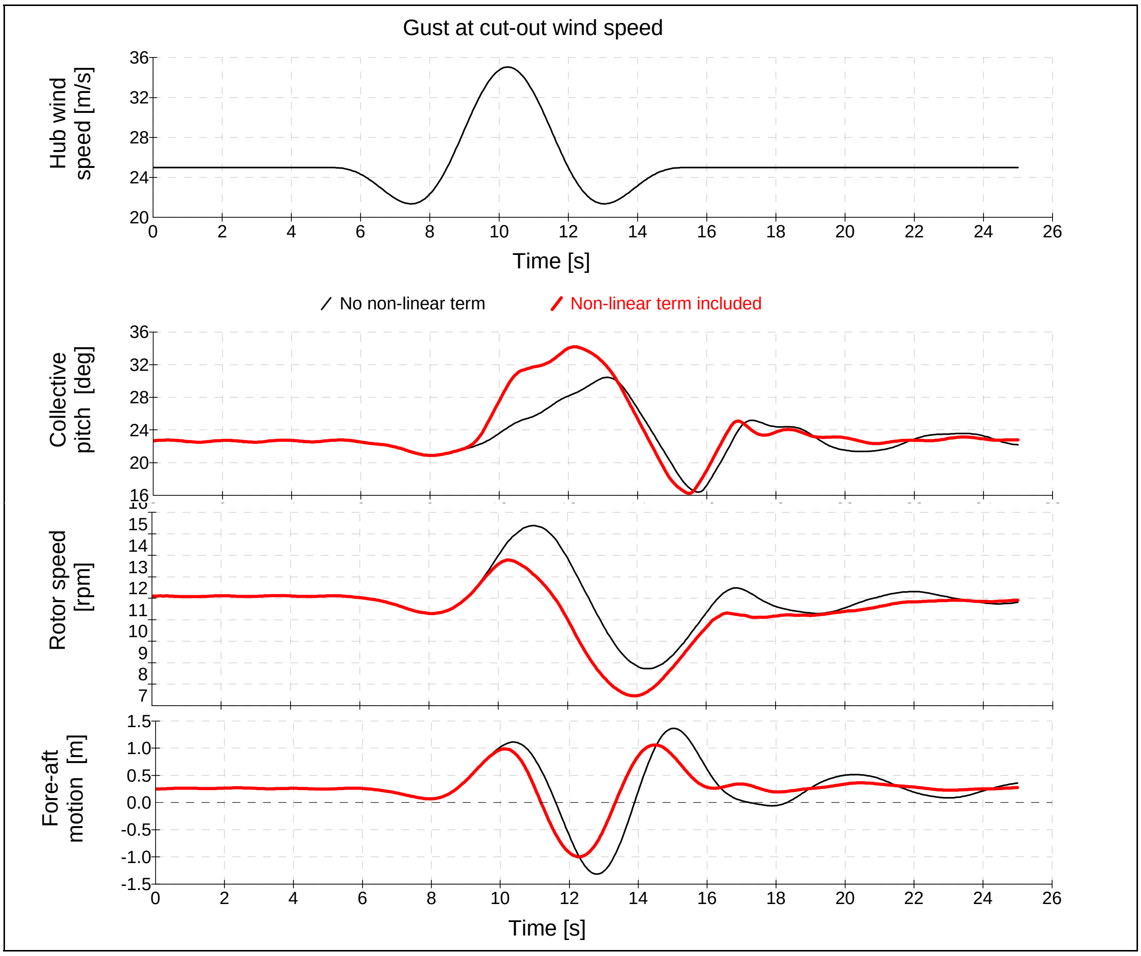

Figure 3.2: Effect of non-linear term on extreme gust at cut-out wind speed

The effect of the individual pitch control is best illustrated by examining the effect on the blade root out of plane (My) loading, the rotating hub moment My or Mz (the effect is very similar on these two loads) and the non-rotating My (nodding) or Mz (yawing) moment at the yaw bearing (again the effect on these two loads is very similar). A turbulent wind simulation at 19m/s mean wind speed has been selected to demonstrate the effect. The turbulence intensities are 16.7% (longitudinal), 13.1% (lateral) and 9.3% (vertical). The results are very similar at other wind speeds across the above-rated range. Obviously the effect decreases below rated as the individual pitch control is phased out.

Spectra of the principally-affected loads are shown in Figure 3.3. The upper two plots are for loads on rotating components, where the large fatigue-dominating peak at 1P (0.2 Hz) is completely removed by the 1P (first harmonic) individual pitch control. That leaves a smaller peak at 2P, which is removed by the 2P (second harmonic) individual pitch control.

The lower graph represents the non-rotating loads, where the 1P individual pitch loop removes the 0P (low-frequency) variations (it would also remove any 2P component if it were present), while the 2P loop attenuates the fatigue-dominating 3P peak (it would also remove any 1P component if it were present).

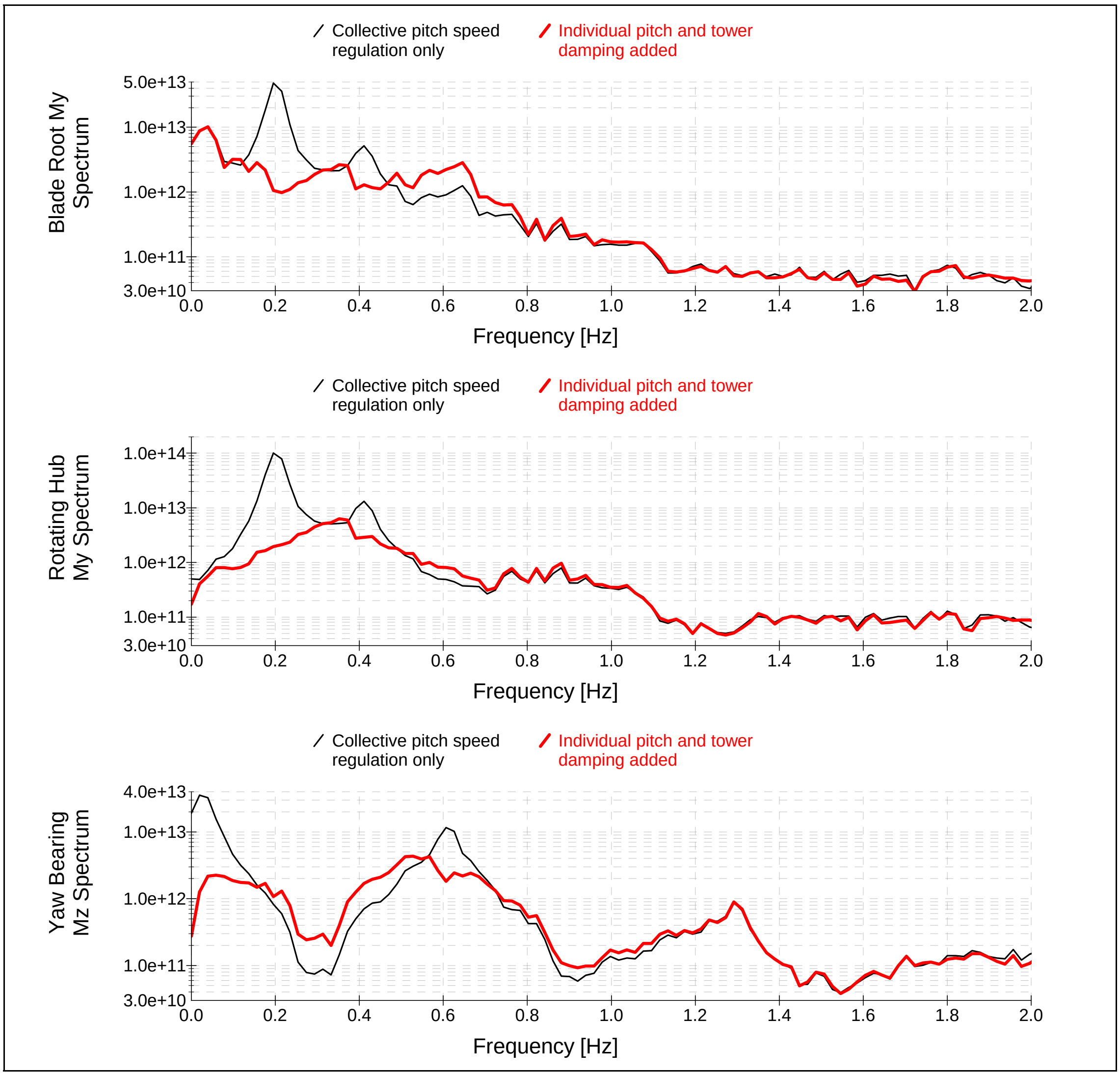

Figure 3.3: Load spectra: effect of individual pitch control

Sample time histories of these loads are shown in Figure 3.4, clearly demonstrating the same features.

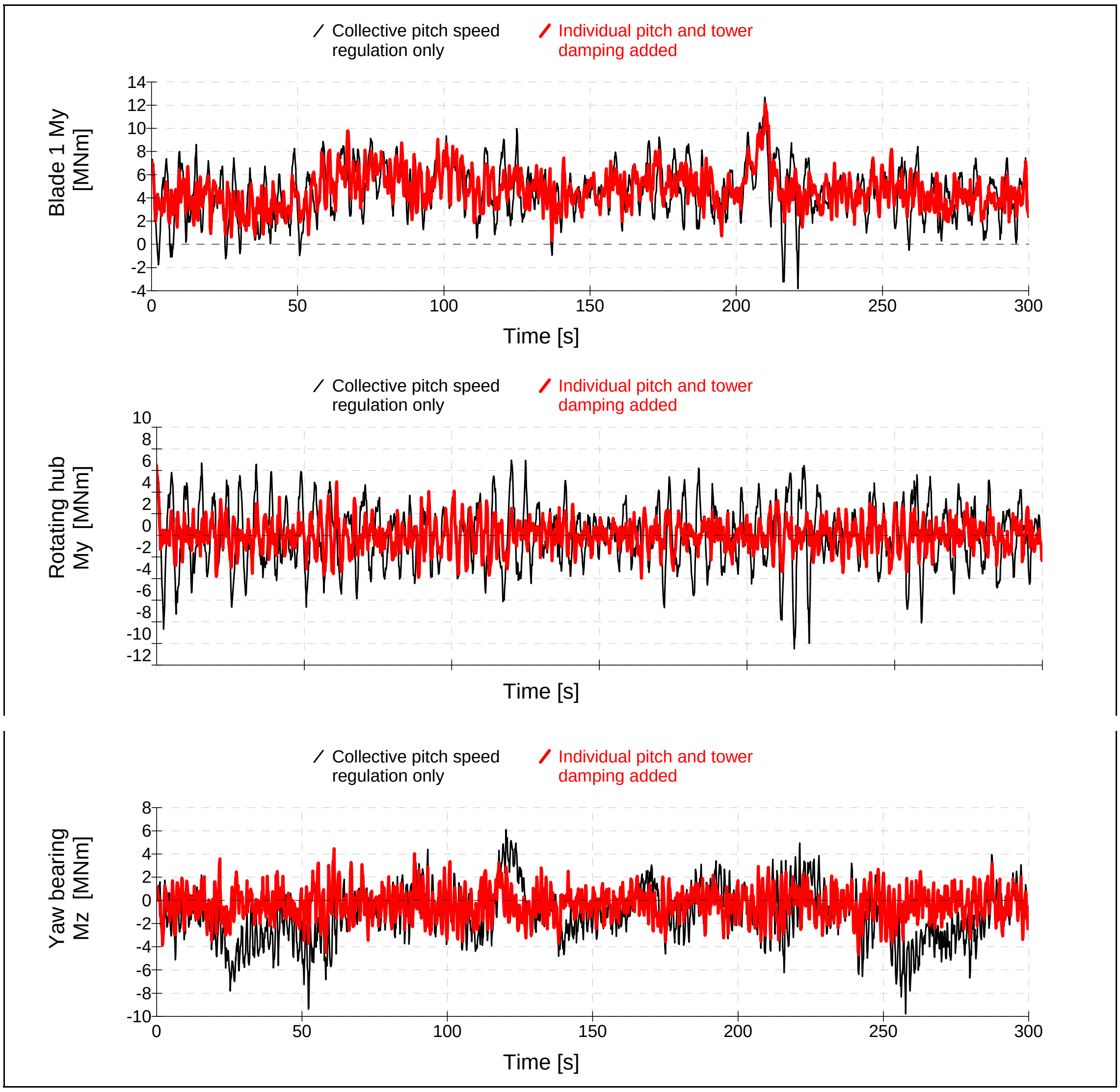

Figure 3.4: Sample time histories: effect of individual pitch control

Figure 3.5 shows a sample of the increased pitch duty caused mainly by IPC (there is very little contribution from the fore-aft tower damper in this case).

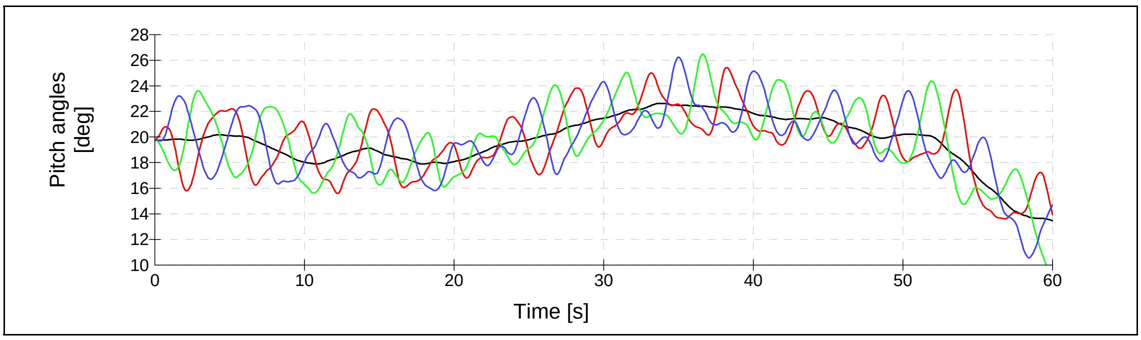

Figure 3.5: Individual pitch control: pitch angles compared to collective pitch

4. Controller parameters

The complete turbine model including this controller is available to UPWIND partners in the form of a *GH Bladed* project file, together with a separate external controller DLL containing the dynamic control algorithm.

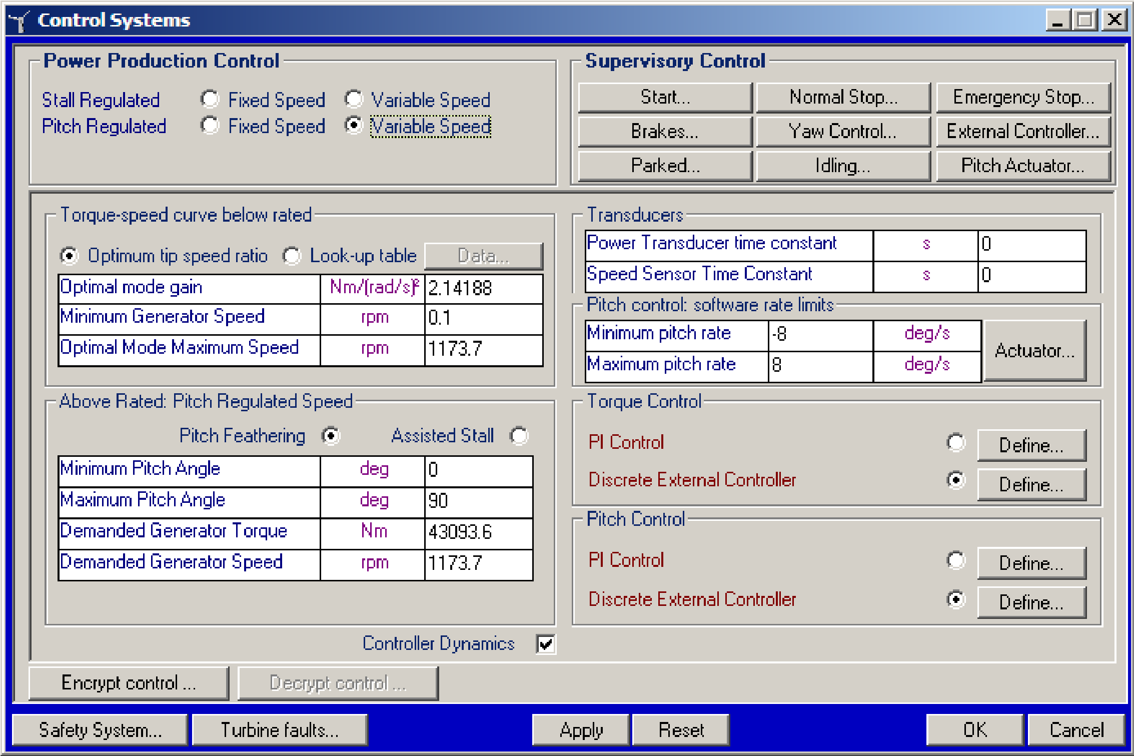

Figure 4.1: Steady-state controller parameters in the *GH Bladed* model

The left-hand side of Figure 4.1 shows the steady-state parameters, which correspond to the operating curve of Figure 2.1. The generator speed range is from the 'Minimum generator speed' to the 'Optimal mode maximum speed'. The latter is the same as the 'Demanded generator speed', which is the speed set-point for the pitch control. The 'Optimal mode gain' is the constant which defines the quadratic part of the torque-speed curve of Figure 2.1. The 'Minimum pitch angle' is the fine pitch limit, at which the highest peak power coefficient (Cp) is obtained. The software pitch rate limits of $\pm 8^{\circ}$/s are shown on the right. All these parameters are passed through to the external controller DLL.

Additional parameters are used by the external controller DLL to define its dynamic behaviour as described above. These parameter values are defined within the project file, in the "External Controller Data" field. Comments are provided in this field so that the meanings of all the parameters can be identified, and related to the algorithm description in this report. The DLL is called with a controller timestep of 0.01s.

5. References

[1] Wind Turbine Control for Load Reduction, E Bossanyi, Wind Energy 2003 vol 6 pp 229-244.
[2] Developments in Individual Blade Pitch Control, E Bossanyi, "The Science of making Torque from Wind" Delft University of Technology, The Netherlands, April 19-21 2004.