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A novel approach to structural load control using Intelligent Actuators

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Abstract— **The recent trend towards large multi-MW wind turbines resulted in the role of the control system becoming increasingly important. The extension of the role of the controller to alleviate structural loads has motivated the exploration of novel control strategies, which seek to maximise load reduction by exploiting the blade pitch system. The reduction of blade fatigue loads through individual blade pitch control is one of the examples. A novel approach to reduction of the unbalanced rotor loads by pitch control is presented in this paper. Each blade is equipped with its own actuator, sensors and controller. These local blade control loops operate in isolation without a need of communication with each other. The single blade control approach to regulation of unbalanced rotor loads presented in this paper has an important advantage of being relatively easy to design and tune. Furthermore, it does not affect the operation of the central controller and the latter need not be re-designed when used in conjunction with the single blade controllers. Their performance is assessed using BLADED simulations.**

Keywords-control;individual pitch;unbalanced rotor loads;

I. INTRODUCTION

Wind turbine technology has undergone a rapid development over the last three decades, largely driven by concerns over the environment. In the last decade, the power rating and size of wind turbines has increased rapidly, and turbines rated at 5MW with 120m rotor diameter are commercially available today. With the increased turbine size and structural flexibility, greater demands have been placed on the control system to alleviate asymmetric loads on the rotor.

As a wind turbine blade sweeps through the wind-field, it experiences loads caused by the rotational sampling of the wind-field. These $n\Omega_0$ loads are concentrated at integer multiples (n) of the rotor speed (Ω_0) and consist of both deterministic and stochastic components. The stochastic component largely arises from the turbulence of the wind. The deterministic loads largely arise from wind shear, tower shadow and blade imbalance [1]. In combination the rotationally sampled blade loads result in an unbalanced rotor loads which not only impact on the blades and rotor but on the rest of the wind turbine structure and the drive-train. The most significant components of these loads are typically those at $1\Omega_0$, $2\Omega_0$ and $3\Omega_0$.

Individual blade pitch control has demonstrated great potential to alleviate rotor loads in above rated wind speed operation [2, 3, 4]. While these reported algorithms may differ in structure or implementation details, all aim to reduce the asymmetric loads by varying the pitch angle of each blade individually in response to some suitable measurement such as blade bending moments. Improvements in sensor technology are now making these individual pitch control algorithm a practical possibility [2]. In Bell *et al* [2] significant reductions in fatigue equivalent loads on the blade, the main shaft and the yaw bearing are reported. In previously reported approaches to individual pitch control, individual pitch control is realised through the wind turbine central controller. The loads on each blade are measured, communicated to some controller which then determines the pitch angle demand for each blade using all the measurements. The direct-quadrature (d-q) axis transformation [3] is central to this procedure. In this paper a novel approach to reducing the unbalanced rotor loads by individual pitch control is presented. Each blade has its own pitch control system operating in isolation from the wind turbine central controller. The objective for this SISO feedback loop is chosen so that only the contribution to rotor imbalance is regulated. An incremental adjustment to the pitch demand from the collective pitch demand from the central controller is determined for the blade using only the measurement of the load on that blade. The instrumentation required for each blade is bending moment sensors, typically optical fibre sensors, and linear and angular acceleration sensors to determine the tower motion.

The paper is structured as follows. In section II, the conventional individual pitch control design based on the d-q axis transformation is discussed, followed by an introduction of the single blade controller in section III. In Section IV, the dynamic model for a single blade is presented. This includes the fact that the blade is coupled to the dynamics of the whole wind turbine. Also, the required modification to the dynamics of the blade in terms of fictitious forces dependent on measured accelerations is introduced. The single blade model is validated in section V. The design issues associated with Individual Pitch Control system based on single blade control is discussed in Section VI and conclusions drawn in Section VII.

II. CONVETIONAL INDIVIDUAL PITCH CONTROL

The reasons behind a drive towards individual pitch control have its origins in blade loads being dependent on the azimuth and wind conditions as seen by the blade. Rotating blades sample the uneven wind-field resulting in significant load variation. These include deterministic components such as tower shadow and wind sheer, and stochastic components that result from the turbulence. Most of these loads are concentrated around multiples of rotor speed. The most significant blade loads are concentrated at 1Ω0 frequency, as seen in Figure 1.

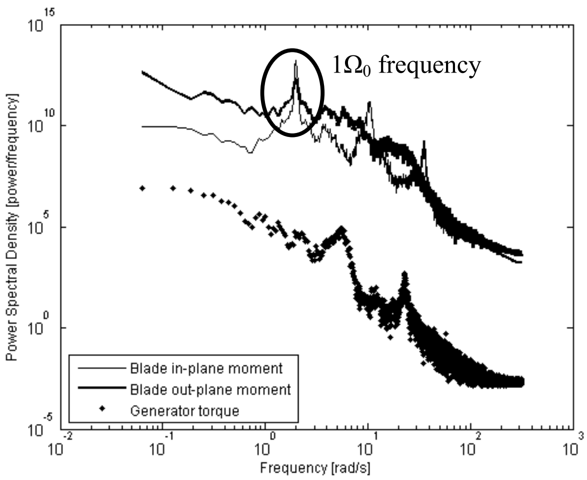

Figure 1: Rotor load imbalance spectrum

The rotor load imbalance may be tackled through the individual pitch control. It is intended to be used during above rated operation, where loads are the highest. The results reported so far demonstrate great potential to reduce asymmetric loading on the rotor. The individual pitch control algorithms have previously been embedded in the central controller, which necessitate careful tuning to the specific turbine. These control methods employ d-q transformation that has its origins in three-phase electrical machine theory [3]. It is the co-ordinate system transformation from the three-vector, $[X_a \quad X_b \quad X_c]^T$, to the two-vector, $[X_d \quad X_q]^T$, such that

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{4\pi}{3}) \\ \sin(\theta) & \sin(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{4\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (1)$$

The inverse transformation is

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{4\pi}{3}) & \sin(\theta + \frac{4\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} X_d \\ X_q \end{bmatrix} \quad (2)$$

The d-q transformation enables a degree of separation of the design of two controllers that apply to orthogonal directions of imbalance on the rotor. The tuning of the controller depends on full wind turbine dynamics including the interaction between the blade and the rest of the flexible structure. The central controller shown in the Figure 2 contains the d-q transformation and outputs three blade position setpoints.

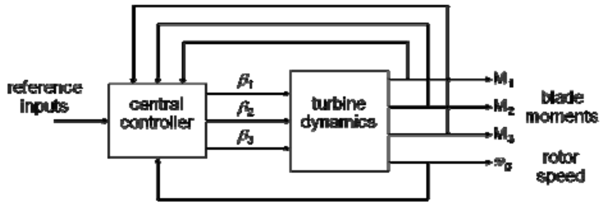

Figure 2: Individual Pitch Control concept

III. SINGLE BLADE CONTROLLER: THE INTELLIGENT ACTUATOR

The individual pitch control approach taken in this paper requires each blade to have its own local pitch controller. The central controller sets the average demand for the pitch angles as required to control the speed; the blade controllers make incremental adjustments to this average. The overall concept is illustrated in Figure 3. Note that bending moments M1-3 are not sent to the central controller, but are utilised by the local controllers. This results in the central controller providing only collective control for the pitch that is aimed at regulating the rotor speed. Local controllers for each blade will act upon variation of the bending moments and regulate these loads at a desired level.

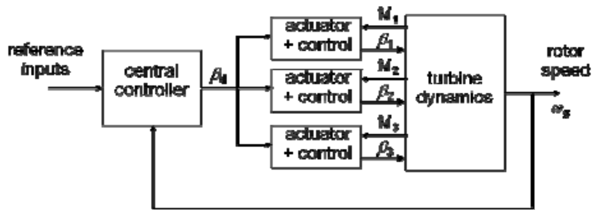

Figure 3: Single Blade Control concept

The conventional actuator has task of driving the blade pitch angle β_a, to demanded pitch, β_b. The central controller contains integral action that drives the difference between the demanded generator speed ω_d and actual ω_a to zero. The requirement for, what is called a cascade control loop is that the inner loop is markedly faster than the outer loop. However, this requirement is not always sufficiently fulfilled with the bandwidth of the outer loop in the region of 1 rad/s and the pitch actuator of the bandwidth of a region between 4 rad/s to 9 rad/s. That may sometimes result in an undesirable coupling between loops and special care should be taken during the design of both loops.

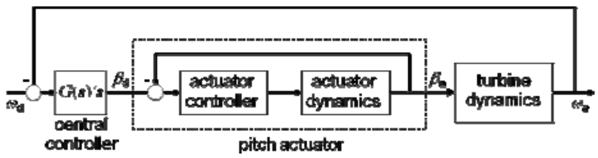

Figure 4: Single Blade Controller – conventional actuator

The controller structure used by the Intelligent Actuator is shown in Figure 5. The feedback loop in the actuator acts on blade root bending moment with the central controller enclosed in an outer feedback loop. The moment actuator sets the actual moment M_a to the demanded moment M_d.

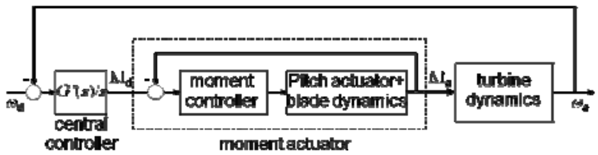

Figure 5: Single Blade Controller – Intelligent Actuator

The moment disturbances shown in Figure 6 are rejected by the inner loop controller through pitch manipulation. The pitch actuator plus blade feedback loop can be considered to be a modified actuator. The rotor speed disturbances are attenuated by the central controller that forms the outer loop.

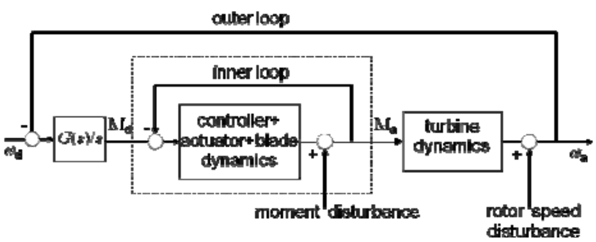

Figure 6: Single Blade Controller, disturbance rejection loops

The design of the two loops may be carried out independently if there is a sufficient loop bandwidth separation and there is no interaction between controlled system dynamics in the inner and outer loop. This unfortunately is not the case here. Pitch actuator constraints pose a limitation for the inner loop bandwidth that aims at achieving the bandwidth of roughly $2\Omega_0$, where Ω_0 is of about 2 rad/s. Outer loop aims to regulate rotor speed with a bandwidth around 1 rad/s and tower loads close to tower frequency, at about 2 rad/s. It is also clear that blade dynamics interact with the dynamics of the wind turbine, therefore inner and outer loop plant dynamics are not independent. In the next section a method of decoupling blade dynamics from the rest of the turbine will be outlined. With that the design of the single blade controller only depends on the dynamics of a single blade. This has the advantages of being structurally simple and easy to implement and tune.

IV. Full Blade Model

As was already mentioned, the blade motion will interact with the rest of the turbine. The coordinate system associated with the blade is not inertial. The dynamics in a non-inertial frame are the dynamics in an inertial reference frame plus fictitious forces proportional to the relative acceleration of the reference frames. The non-inertial reference frame moves linearly with tower head, rotationally with the nacelle and rotates with the rotor. To be able to compute fictitious forces acceleration measurement of the movement of non-inertial reference frame is required. Accelerometers will measure acceleration resulting from the movement of the turbine and the earth's gravity. Consequently, the contribution of the gravitational force is included in the fictitious forces.

The full non-linear model [5] of the blade including the coupling to the rest of the wind turbine dynamics is:

$$\begin{bmatrix}\ddot{\theta}_R\\ \ddot{\phi}_R\end{bmatrix} = -\begin{bmatrix}\omega_E^2 c_\alpha^2 + \omega_F^2 s_\alpha^2 & -\left(\omega_E^2 - \omega_F^2\right)s_\alpha c_\alpha\\ -\left(\omega_E^2 - \omega_F^2\right)s_\alpha c_\alpha & \omega_E^2 s_\alpha^2 + \omega_F^2 c_\alpha^2\end{bmatrix}\cdot\begin{bmatrix}\theta_R\\ \phi_R\end{bmatrix} + \frac{1}{J}\begin{bmatrix}M_{A\theta}\\ M_{A\phi}\end{bmatrix} + \frac{1}{J}\begin{bmatrix}M_{T\theta_R}\\ M_{T\phi_R}\end{bmatrix} \quad (3)$$

$$\begin{bmatrix}M_{I/P}\\ M_{O/P}\end{bmatrix} = J\cdot\begin{bmatrix}\omega_E^2 c_\alpha^2 + \omega_F^2 s_\alpha^2 & -\left(\omega_E^2 - \omega_F^2\right)s_\alpha c_\alpha\\ -\left(\omega_E^2 - \omega_F^2\right)s_\alpha c_\alpha & \omega_E^2 s_\alpha^2 + \omega_F^2 c_\alpha^2\end{bmatrix}\cdot\begin{bmatrix}\theta_R\\ \phi_R\end{bmatrix} \quad (4)$$

with the fictitious forces:

$$\begin{bmatrix}M_{T\theta_R}\\ M_{T\phi_R}\end{bmatrix} = m_b l\begin{bmatrix}a_{B2}\\ -a_{B3}\end{bmatrix} + J\begin{bmatrix}\dot{\Omega}_{zR}\\ \dot{\Omega}_{yR}\end{bmatrix} \quad (5)$$

The in-plane and out-plane angles of deflection of the blade are θ_R and ϕ_R and α is a pitch angle. J is blade inertia and ω_E and ω_F are blade and flap frequencies, respectively. The in-plane and out-of-plane blade root bending moments are denoted as $M_{I/P}$ and $M_{O/P}$. $M_{A\theta_R}$ and $M_{A\phi_R}$ are the in-plane and out-of-plane aerodynamics moments. a_{B2} is the acceleration of the centre of rotation of the blade perpendicular to the blade in the plane of rotation and a_{B3} is the acceleration of the centre of rotation of the blade perpendicular to the plane of rotation. $\dot{\Omega}_{zR}$ and $\dot{\Omega}_{yR}$ are rotational accelerations measured at the origin of the rotor plane (hub), m_B is the blade mass, l is the distance between the blade's centre of mass and the centre of rotation of the rotor.

More appropriately for the purpose intended here, this model can also be expressed in terms of the namely in-plane and out–of-plane moments:

$$\begin{bmatrix}\ddot{M}_{I/P}\\ \ddot{M}_{O/P}\end{bmatrix} = -A(\alpha)\begin{bmatrix}M_{I/P}\\ M_{O/P}\end{bmatrix} + A(\alpha)\begin{bmatrix}M_{A\theta_R} + M_{T\theta_R}\\ M_{A\phi_R} + M_{T\phi_R}\end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{\theta}_R \\ \dot{\phi}_R \end{bmatrix} = \frac{1}{J} A^{-1}(\alpha) \cdot \begin{bmatrix} \dot{M}_{I/P} \\ \dot{M}_{O/P} \end{bmatrix} \quad (7)$$

where

$$A(\alpha) = \begin{bmatrix} \omega_E^2 c_\alpha^2 + \omega_F^2 s_\alpha^2 & -(\omega_E^2 - \omega_F^2) s_\alpha c_\alpha \\ -(\omega_E^2 - \omega_F^2) s_\alpha c_\alpha & \omega_E^2 s_\alpha^2 + \omega_F^2 c_\alpha^2 \end{bmatrix} \quad (8)$$

$$A^{-1}(\alpha) = \frac{1}{\omega_E^2 \omega_F^2} \begin{bmatrix} \omega_E^2 s_\alpha^2 + \omega_F^2 c_\alpha^2 & (\omega_E^2 - \omega_F^2) s_\alpha c_\alpha \\ (\omega_E^2 - \omega_F^2) s_\alpha c_\alpha & \omega_E^2 c_\alpha^2 + \omega_F^2 s_\alpha^2 \end{bmatrix} \quad (9)$$

The derivation of this model is explained in [5].

Now, the control system should be modified by subtracting the contribution of the fictitious forces from the measured bending moment as shown in Figure 7. The fictitious forces are derived directly from measured accelerations.

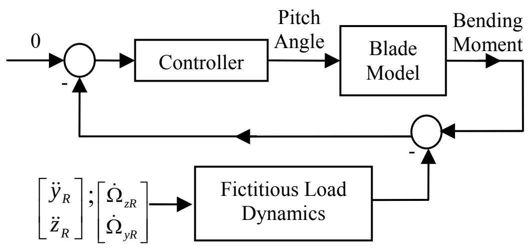

Figure 7: Feedback Control System for the Blade Model with Tower Dynamics Deducted

V. Blade Model Validation

To be able to validate the blade model a comparison between the simulation results obtained from Bladed and the response of a single blade model was carried out. The main problem associated with this comparison is inability of obtaining the magnitude of the aerodynamic moment that is seen by the blade. The procedure undertaken here is as follows. Fictitious forces are calculated using accelerations of the non-inertial reference frame extracted from Bladed. The hub wind speed is also extracted from Bladed and then fed into the single blade model and used to calculate the blade bending moments therein. The point wind speed is modified by the model shown in Figure 8 to generate the effective wind speed as seen by the blade.

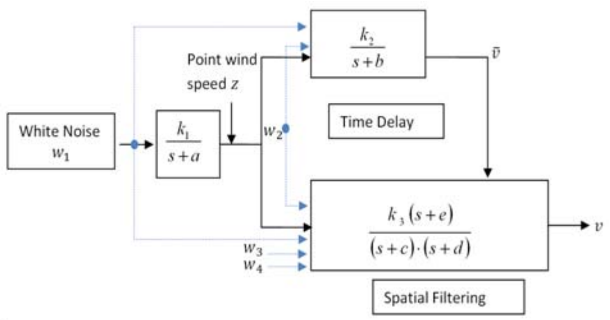

Figure 8: Wind model

The effective wind speed is augmented by 1 Ω_0 and 2 Ω_0 cyclic components prior to calculating the out-of-plane and in-plane aerodynamic moments in the usual manner. The blade model described in the previous section is implemented in Simulink along with the spatial filter and fictitious force models.

The simulation results obtained in Simulink are compared with Bladed results. Comparison of bending moment spectra is shown in Figure 9. A good match for frequencies range of interest is achieved, which confirms that the model may be used for the control design.

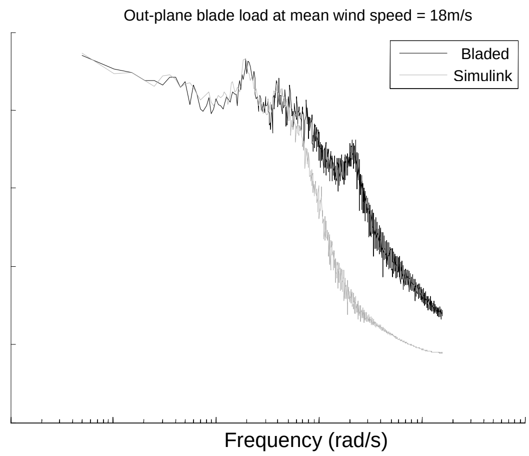

Figure 9: Blade model validation

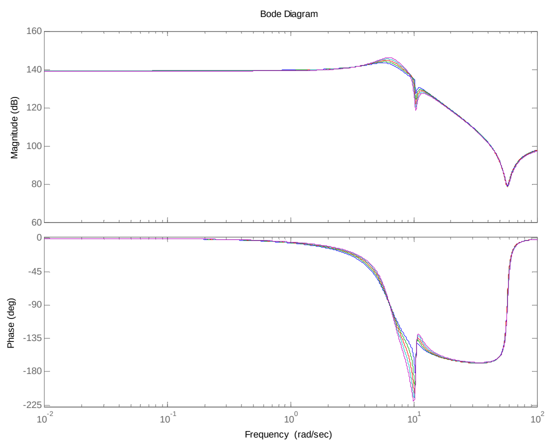

Figure 10: Bode plot of linearised blade model

The validated non-linear model needs to be linearised to extract the local characteristic that will be used for the linear control design. The Bode plot of the system is shown in Figure 10. The model exhibits dominant 2-nd order system behaviour.

VI. Control System Design

The controller for the blade is designed to achieve the following objectives:

- The blade out-of-plane bending moment is regulated to follow a set point derived from the central controller pitch demand. The pitch of the blade is adjusted to compensate for the disturbance to the out-of-plane bending moment at $1\Omega_0$ and $2\Omega_0$.
- The dynamics of the actuator must appear unchanged to the central controller.
- Aerodynamic non-linearity is counteracted by global non-linear control.
- Smooth switching between below-rated and above-rated must be achieved.

One possible controller structure is shown in Figure 11.

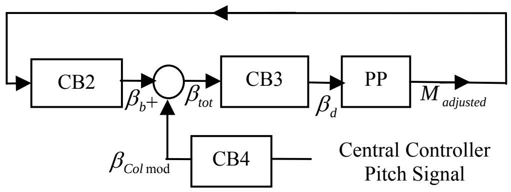

Figure 11: Overall Control Structure

PP represents the pitch actuator dynamics and the blade dynamics with the fictitious forces added to the measured out-of-plane bending moment to decouple their dynamics from the rest of the wind turbine dynamics.

CB2 is the pitch controller for the local feedback loop at the blade. If the sole objective of the blade controller is to reduce the unbalanced loads in the vicinity of $1\Omega_0$ then the pitch controller would be a form of band pass filter centred on $1\Omega_0$. Stability of the improved actuation system is ensured by the design of CB2 and the dynamics on which the CB2 is dependent upon is the dynamics of the associated blade, separated from the rest of the wind turbine. CB3 is the compensation for the aerodynamics non-linearity. Together with the switching position, velocity and acceleration of the actuator output are all constrained. Priority is given to the central controller demand. When the pitch position, velocity and the acceleration of the central controller demand approach their limits, the action of the local feedback loop is reduced accordingly. CB4 compensates the pitch demand from the central controller to counteract the change in the actuator dynamics caused by the local feedback loop. The local feedback loop is thereby made invisible to the central controller. Note that the non-linearity associated with the aerodynamic non-linearity is compensated by CB3. The overall results is that the controller CB2 controls the plant P (linearised blade model) in series with the pitch actuator model G. This forms a linear loop that may be tuned using linear control design methods. The non-linearity is re-instated in the CB2 block which also compensates for the modified actuator dynamics.

Bladed simulations were carried out and in the some of the results will now be presented. In Figure 12 the spectrum of the blade load is shown, where the individual pitch control reduces $1\Omega_0$ loads. The evidence of that may be examined in the time trace shown in Figure 13. The corresponding pitch action trace is presented in Figure 14.

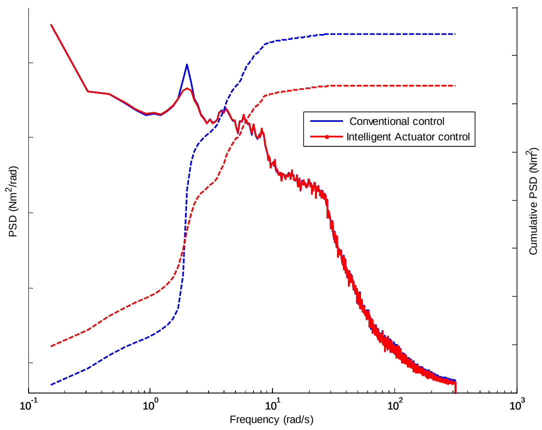

Figure 12: Blade bending moment spectra for conventional and IA control, turbulent wind

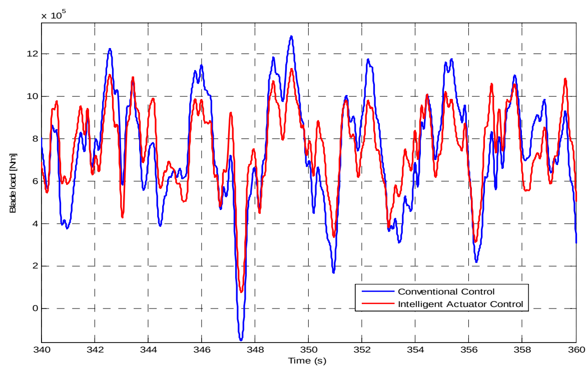

Figure 13: Example trace of Blade bending moment with conventional and IA control, turbulent wind

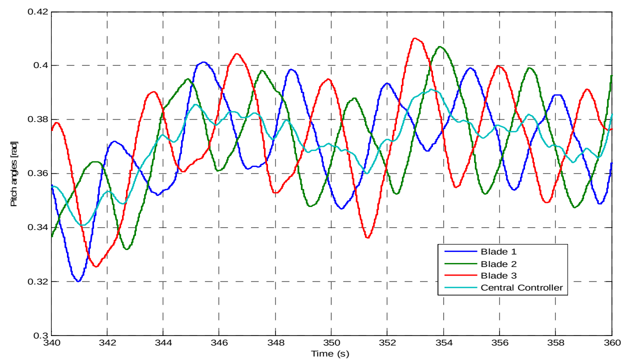

Figure 14: Example trace of individual and collective pitch control signals, turbulent wind

The actual correction commanded by Intelligent Actuators is shown in Figure 15. All results were generated with a turbulent wind file, with the turbulence intensity of 17% and average wind speed of 18m/s. The tower shadow and wind sheer were also enabled. The results demonstrate that the individual pitch control copes well with the combination of stochastic and deterministic components of the wind. Interesting observation can be made from the Figure 16. The results presented there gives the evidence that intelligent actuator subjected to a deterministic wind conditions behaves in a similar way to the cyclic control. Trace that demonstrates reduction of the blade load is shown in Figure 17.

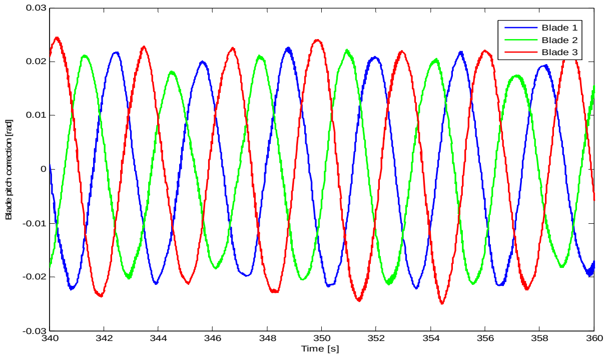

Figure 15: IA corrections over central controller command, turbulent wind

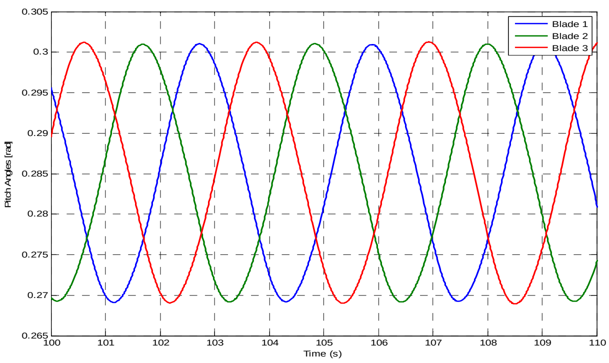

Figure 16: Example trace of individual pitch signals for steady laminar wind with wind sheer and tower shadow for IA control

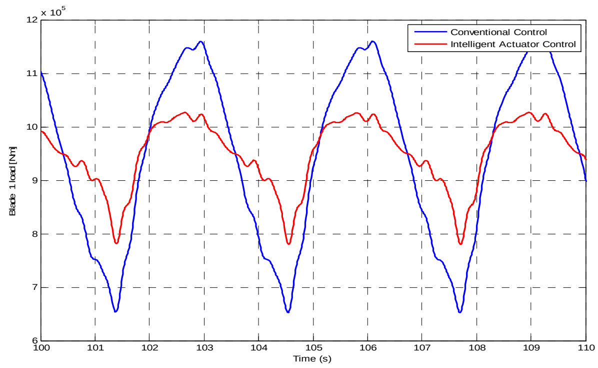

Figure 17: Example trace of blade load for steady laminar wind with wind sheer and tower shadow with conventional and IA control

Feedback loops as described above were applied to all three blades on a BLADED simulation of a large multi-MW wind turbine. To focus the assessment on the stochastic components rather than the deterministic components which can also be reduced by cyclic pitch control, the results are obtained with both tower shadow and wind shear turned off. With controller is active over a frequency range including $1\Omega_0$ and $2\Omega_0$ but with wash-out at low frequency and roll-off at high frequency. For a mean wind speed of 18m/s and turbulence intensity at 17%, the out-of-plane root bending moment is reduced by 12%. The tower torsional moment is reduced by 17%. The main bearing tilt moment is reduced by 23% and the main bearing yaw moment by 22%.

VII. Conclusions

The role of the wind turbine controller in modern designs is required to include the alleviation of structural loads. The alleviation of the rotor loads by pitch control has recently been investigated. By separately adjusting the angle of pitch of each blade, the unbalanced loads on the rotor could be reduced. A novel approach to reducing the unbalance rotor loads is presented in this paper. Each blade has its own actuator, sensors and controller. These localised blade control systems operate in isolation without need of communication with each other. The controller for a single blade is designed on the basis of the blade dynamics alone to determine the adjustment in pitch angle required to counteract the component of the blade bending moment contributing to unbalanced rotor loads. The following issues are discussed, the decoupling of the blade dynamics from the dynamics of the rest of the wind turbine, the dynamic model of the single blade, the nonlinear aspects of the controller design. This single blade control approach to regulation of unbalanced rotor loads has several advantages: there is no need to communicate with the central controller in the nacelle; the presence of the local blade controllers is invisible to the central controller; the controller, being dependent on the blade dynamics alone, is straightforward to design and easy to tune (indeed, re-tuning is not required if applied to a different wind turbine with the same blade). The performance of the single blade controllers is assessed using BLADED simulations.

Acknowledgment

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