

Combined wind turbine fatigue and ultimate load reduction by individual blade control

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Abstract. If each blade of the wind turbine has individual pitch actuator, there is possibility of employing the pitch system to mitigate structural loads through advanced control methods. Previously, considerable reduction of blade lifetime equivalent fatigue loads has been achieved by Individual Blade Control (IBC) and in addition, it has also been shown the potential in blade ultimate loads reduction. However, both fatigue and ultimate loads impact on the design and life of wind turbine blades. In this paper, the design and application of IBC that concurrently reduce both blade fatigue and ultimate loads is investigated. The contributions of blade load spectral components, which are $1P$, $2P$ and edgewise mode from blade in-plane and/or out-of-plane bending moments, are firstly explored. Four different control options for reducing various combinations of these load components are compared. In response to the different spectral peaks of both fatigue and ultimate loads, the controller has been designed so that it can act on different frequency components which vary with wind speed. The performance of the IBC controller on fatigue and ultimate load reduction is assessed by simulating a 5MW exemplar wind turbine. Simulation results show that with a proper selection of controlling inputs at different wind speed, the use of a single combined IBC can achieve satisfactory reduction on both fatigue and ultimate loads.

Keywords: wind turbine control; individual blade control; fatigue loads; ultimate loads.

1. Introduction

Large multi-MW wind turbines experience large unbalanced loads on the blades and rotor induced by the time and spatial variation of the wind field. Rotational sampling induces large spectral peaks on the blade loads at multiples of the rotor rotational speed, P , i.e. $1P$, $2P$, $3P$ etc.. Both blade in-plane (M_x) and out-of-plane (M_y) bending moments are dominated by the $1P$ component. With a three-bladed wind turbine, the hub loads and other structural loads are dominated by $3P$, $6P$, etc., due to the 120 degrees of phase between the contributions from each blade. Additional significant components in the loads arise from structural modes, e.g. blade flapwise and edgewise modes. The flapwise mode is normally aerodynamically well damped but the edgewise mode is not [1]. All these components contribute to the lifetime equivalent fatigue loads and ultimate loads of wind turbine structural elements.

Individual blade pitching has been proposed to reduce these loads. As many wind turbine blades use independent pitch actuators, the existing pitch system makes this approach feasible. The fundamental idea is to adjust pitch angle of the blades individually in response to load measurements using advanced strain gauges, or even on load estimation [2], to reduce significantly the continuous load variations on each blade. It is the purpose of this paper to apply independent blade pitching to reduce both the lifetime fatigue loads and ultimate loads.



Since the dynamics of the wind turbine, including those for each blade, are rather complex due to the rotation of the rotor and the aerodynamic nonlinearities, the design of full envelope controllers that can reduce both the lifetime equivalent fatigue loads and the ultimate loads on each blade, is demanding. Instead, practical approaches using a controller structure, that removes those aspects of the dynamics due to the rotation of the rotor, have been proposed. One such approach is Individual Pitch Control (IPC) [3] whereby the Coleman transformation is employed to transform the blade bending moments from the frame of reference rotating with the rotor to a non-rotating frame of reference. It has been demonstrated that IPC [4] can directly reduce the lifetime equivalent fatigue loads on the rotor, specifically, the rotor yawing and nodding moments, and indirectly the lifetime equivalent fatigue loads on the blades, specifically, the blade out-of-plane bending moments. However, much information about the loads on an individual blade is lost through applying the Coleman Transformation and it is not possible to apply IPC to directly reduce the loads experienced by a single blade and so to reduce its ultimate loads.

An alternative approach is Individual Blade Control (IBC) [5]. To remove those aspects of the dynamics due to the rotation of the rotor, the dynamics of a blade in the non-inertial reference plane rotating with the rotor are transformed to those in an inertial stationary reference frame. A controller is designed using a measurement of the blade root bending moments to reduce some target load. Since no information about the blade loads is lost in this approach, it has more flexibility over the choice of target loads. The application of IBC (IBC_iss1) to directly reduce the lifetime equivalent blade loads and to indirectly reduce the lifetime equivalent loads has been investigated [5]. Furthermore, the application of IBC (IBC_iss2) to reduce ultimate loads has, also, been investigated [6]. The load reductions achieved by both these designs are compared with the baseline full envelope controller and performance are briefly summarised in Table 1.

For brevity, only the lifetime fatigue loads for blade root out-of-plane, hub tilting and tower base fore-aft bending moment are tabulated. Only the ultimate blade loads L1 and L2 at one blade station, as discussed in Section 4, are included. Clearly IBC_iss1, which is designed to reduce the lifetime equivalent fatigue loads, can obtain satisfactory reductions of order 3%~27% on the blade, hub and tower but it does not reduce significantly the blade ultimate loads. In contrast, IBC_iss2, which is designed to reduce the blade ultimate loads, can achieve a reduction greater than 20% on both load L1 and L2 but does not reduce the lifetime equivalent fatigue loads significantly.

Table 1 Load reductions achieved by previous controllers

Controller designs	IBC_iss1		IBC_iss2	
Blade fatigue load	-26.87%		0.60%	
Hub fatigue load	-19.53%		1.65%	
Tower fatigue load	-3.52%		-1.07%	
Blade ultimate load	L1	L2	L1	L2
	-0.35%	-13.82%	-23.02%	-22.79%

In this paper, the application of IBC to reduce both blade fatigue and ultimate loads concurrently is investigated. The contributions of spectral load components, $1P$, $2P$ and edgewise mode, is explored and different control options for reducing various combinations of these load components are compared. Because IPC cannot be used to directly reduce blade ultimate loads it is not considered further. The paper is divided into 5 sections: in section 2, a description of individual blade load control is presented. Then a general overview of blade fatigue and ultimate loads is given in section 3. Section 4 discusses the simulation results for an exemplar 5MW wind turbine based on four different controller designs. Finally, in section 5, discussions and conclusions are outlined.

2. Individual blade control for load reduction

In IBC, each blade has its own actuator, sensor and importantly, its own controller, see Figure 1. The central controller determines the collective pitch angle demand required for normal rotor speed regulation and sometimes, also, for tower fore-aft mode damping. An incremental adjustment to the collective pitch demand is made by each blade controller in response to a blade load measurement. Note, the measured bending moment M_i ($i = 1,2,3$) could be both in-plane (M_x) and out-of-plane (M_y)

and are not communicated to the central controller. The tuning of the controller for each blade depends solely on the dynamics of the blade and actuator. There is also no need of communication between these localised blade control systems.

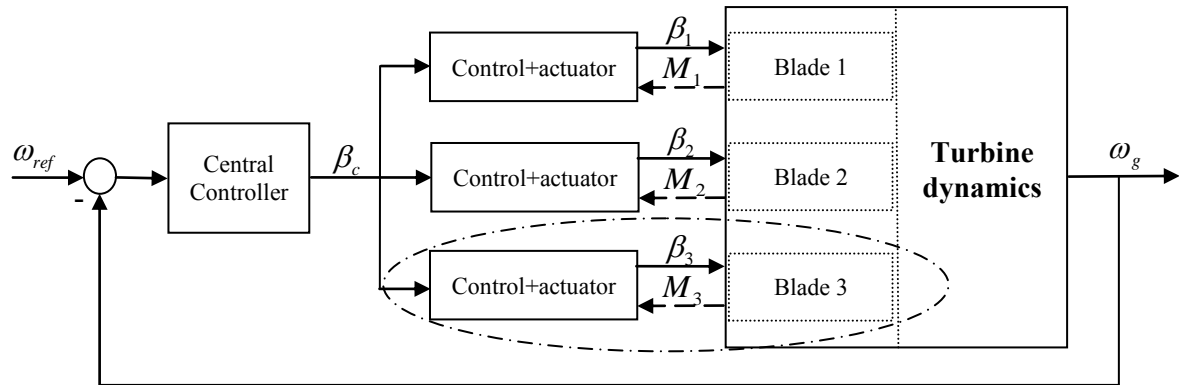


Figure 1: Schematic illustration of Individual Blade Control

Obviously, the force upon on the blade will be transmitted to the rest of wind turbine via the hub. There are strong dynamic linkages between blade and the wind turbine which means the blade is situated in a non-inertial reference frame that moves linearly with tower head, rotationally with the nacelle and rotates with the rotor. The difference between the dynamics in a non-inertial reference frame and in an inertial reference frame is described by the fictitious forces. By subtracting these fictitious forces from the measured root bending moments, the dynamics remained are essentially just the actuator and blade dynamics. The blade control system including fictitious forces for one blade is depicted in Figure 2.

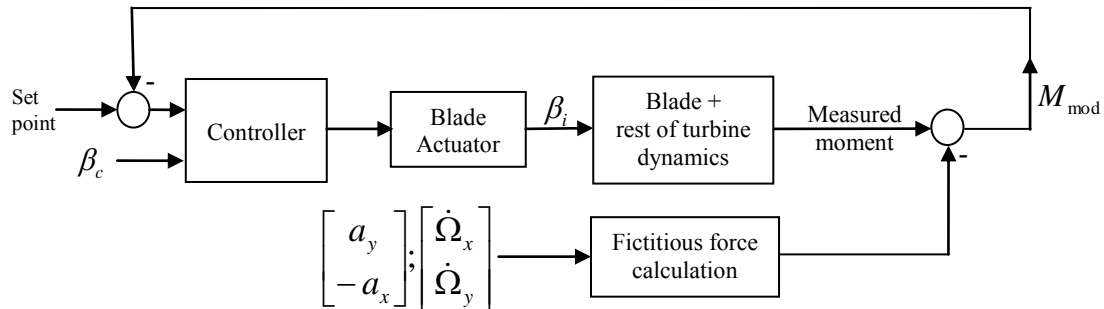


Figure 2: Individual blade control with fictitious forces

These fictitious forces are the linear and angular accelerations of the non-inertial reference frame relative to the inertial reference frame scaled by masses and inertias, respectively. For the blade, the fictitious forces are,

$$\begin{bmatrix} M_{Fx} \\ M_{Fy} \end{bmatrix} = m_b \ell \begin{bmatrix} a_y \\ -a_x \end{bmatrix} + J \begin{bmatrix} \dot{\Omega}_x \\ \dot{\Omega}_y \end{bmatrix} \quad (1)$$

where all the variables are defined in [6]. It is important to point out that the final contribution of the fictitious forces to the modified bending moment M_{mod} can be a combination of M_{Fx} and M_{Fy} , depending on the selected bending moment inputted to the controller.

Under such structure, the controller tuning is based on the linearised dynamic model linking pitch demand to blade bending moment including the pitch servo model. The implementation of IBC needs no modification of central controller and the dynamic linkage can be largely decoupled from one individual blade to the others.

3. Blade fatigue and ultimate loads

With regard to lifetime fatigue loads, the aggregative effect, that the forces would have on the structure over the whole lifetime, matters. Hence, a general reduction in load transients on the blades can achieve an improvement and performance can be assessed from some typical 10 minute

simulation runs. Controller design can have the straightforward objective of reducing transient loads. With regards to ultimate loads, it is a specific single event that matters, when all the components conspire to contribute to the load without any cancellation. Hence, controller design must be effective on those specific rare combinations of load components that result in ultimate loads. This requires precise information on those specific circumstances to directly guide controller design.

The major contributions to the blade lifetime equivalent fatigue load and so the rotor lifetime equivalent fatigue load are the $1P$ and to a lesser extent $2P$ components of M_y . In contrast, the major contributions to the blade ultimate loads are the $1P$ components of M_x and M_y and the blade edgewise mode component. The precise combination of these components depends on wind speed; that is, a different combination applies in high wind speed as opposed to low wind speed. It should, also, be noted that, at each blade station, different blade loads may reach their extremes at different wind speeds. Hence, the design of controllers to reduce ultimate loads needs to act on a combination of measured M_x and M_y that changes with wind speed. Furthermore, the choice of components, $1P$ etc., on which the controller acts, also, change with wind speed. These changes in the controller must be done in a smooth manner to avoid introducing extra transients. In addition, gain-scheduling of the controller is required to counteract nonlinear aerodynamic effects. Although only blade root bending moments are assumed to be available, measurements further out from the root would probably be more appropriate since the most important ultimate loads are located at stations near the middle of the blade [7].

The choice of components of $1P$, $2P$ and edgewise mode, that the controller acts on, is guided strongly by an understanding of how the ultimate loads arise. For the wind turbine in this paper, when the wind speed is near 12 m/s, the controller acts on both the $1P$ and $2P$ peaks of M_y plus the edgewise mode peak of M_x . When the wind speed is above 20m/s, the controller acts on both the $1P$ and $2P$ peaks of M_{xy} , where $M_{xy} = \sin(\gamma)M_x + \cos(\gamma)M_y$. As discussed in [6], for ultimate load control, the wind speed dependent selection of the targeted peaks and combination of M_x and M_y , including γ , is the key to the controller design. The remaining task, other than for gain scheduling, is to design the local linear controllers, acting on the selected combinations. A series of band-pass filters centred on the frequency of the targeted peaks suffices. When the controller acts on the $1P$ of M_x , the gain of the associated band-pass filter is limited since it is dominated by gravity. For the wind turbine considered here, the most appropriate choice of γ is 15 degrees.

The trade-off between load reduction and pitch activity is always an important consideration for pitching individual blades. Due to lack of space this trade-off is not investigated here. Nevertheless, for the turbine considered here with the pitch rate limited to ± 8 degrees/sec, the limits are rarely reached.

4. Simulation and performance evaluation

The performance of the fatigue and ultimate load reduction by the IBC controller is assessed using a 5MW exemplar wind turbine model and simulated using the DNV GL Bladed software. According to IEC standard [8], two design load cases, i.e. normal turbulence model (NTM) and extreme turbulence model (ETM) are simulated across full range of wind speeds. Both wind turbulence model are simulated with three seeds at each mean wind speed. All the relevant results are compared with the baseline controller which includes the rotor speed control action and drive-train resonant damper. The calculated assessments are compared as a percentage relative to the results when the baseline central controller is operating on its own. The comparisons, related to blade lifetime fatigue load (20 years) and rotor lifetime fatigue load, are examined under NTM to evaluate the total equivalent damage, considering all the simulations and the wind distribution/times per year/hours per year over the whole life of the wind turbine; while the comparison related to blade ultimate load is examined under ETM to determine the worst load case where it is identified as the maximum from all the evaluations.

It is worth stressing that when assessing the ultimate blade loads, the most pertinent results are the projections onto particular directions in the $M_y - M_x$ plane of the loads contained in related sectors of the $M_y - M_x$ plane. For example, a sector might be between 22.5 degrees and 67.5 degrees with the projection onto the middle line at 45 degrees. For a particular blade, the most important loads are those projections onto specific directions for different blade stations. For the blades of this particular wind turbine, two projected loadings: $L1$ and $L2$, are of particular importance as they are most likely

to exceed its design limits [7]. The analysis of ultimate load reduction is made at blade root [0m], as well as the reductions at other blade stations from 4m to 30m away from the root.

In order to investigate how the different controller designs corresponding to different load measurements at different wind speeds would affect the reduction of fatigue and ultimate loads, four different IBC controllers have been designed and simulated for comparisons. Table 2 presents the different targeted spectral peaks and in what wind speed regions they operate. In the table, “AR” refers to the operation in above rated wind speeds, “FULL” refers to the operation in both below and above rated wind speeds and “N/A” refers to no controlling action at all.

Table 2 Operating region of four different IBC controllers

Controller No.	1P	2P	Edgewise
Controller 1 (IBC1)	AR	N/A	AR
Controller 2 (IBC2)	AR	AR	AR
Controller 3 (IBC3)	AR	AR	FULL
Controller 4 (IBC4)	FULL	FULL	FULL

4.1. Fatigue and ultimate load reduction by IBC1 and IBC2

4.1.1. Blade fatigue load reduction and rotor balancing. The effectiveness of IBC1 on lifetime fatigue load reduction is mainly assessed on blade root out-of-plane bending moment (M_y) and hub tilting bending moment (Fixed hub M_y). The results presented in Figure 3 for illustration are from one 10 min simulation at a mean wind speed of 18 m/s. In respect to IBC1 1P (about 1.24 rad/s) control (green line), it is clear that the reduction of 1P spectral peak from blade M_y results in the reduction of 0P (mean value) on fixed hub M_y and the reduction of 1P on the rotating hub M_y . The 2P (about 2.28 rad/s) peaks of these are almost unchanged. On the fixed components this indicates that only the low frequencies are mitigated, leaving the fatigue dominating 3P (about 3.72 rad/s) peak almost unchanged. In contrast, the IBC2 controller, which includes the additional controlling actions on 2P frequency (red line), not only reduces the 2P peak (with basic 1P still the same) on blade M_y and rotating hub M_y but also reduces the 3P peak on the fixed hub M_y in a more modest way. From the cumulative spectra, the changes at significant frequencies are also obvious. The price is paid by extra pitch activity as shown in the spectra of pitch rate. Note that the increased pitch activity above 3P is not useful and could be reduced by further adjusting the high-frequency response of the controller.

The calculated fatigue load reductions with respect to the baseline controller without IBC are summarised in Table 3. It shows the lifetime fatigue load reductions on blade M_y obtained by IBC1 control are around 12% for the blades with also slight reductions on blade M_x . However, there is just a negligible reduction (0.06%) on the hub tilting fatigue load (Fixed Hub M_y) but it can be improved to 7.60% by the additional 2P control (IBC2), with supplementary benefits of 1% and 6%, respectively, on the blade M_y and hub yawing fatigue load (Fixed Hub M_z). However, improvements on the rotating hub M_y is marginal with the reduction reaching to 16%. In addition, the fatigue load on the tower base fore-aft bending moment (Tower base M_y) is slightly enhanced by both controllers while the reduction of torsional bending moment (Tower base M_z) can be improved to 8% by IBC2, around 7% more than IBC1.

4.1.2. Blade ultimate load reduction. Due to the fact that the largest contribution of blade ultimate load is the 1P component of the combined M_x and M_y , there is little difference between IBC1 and IBC2 control. The extra benefits for ultimate loads $L1$ and $L2$ brought by the 2P component control is generally less than 1%, see Table 4. Hence, no comparison between two cases will be presented and all the discussions are for the IBC2 case only as it delivers the best performance on fatigue load reduction. It worth mentioning that both IBC controllers are designed to increase the damping of blade edgewise dynamic mode in response to a measurement of M_x in low wind speed (where the ultimate load $L1$ is critical) and to diminish the spectral peaks of combined M_x and M_y (where the ultimate load $L2$ is critical) in high wind speed.

In Figure 4, the ultimate load reduction of load $L1$ responding to M_x at blade station 14m in low wind speed is demonstrated (upper row). From the subfigure on left side, time trace of a fraction of 10

min run clearly manifest that the M_x vibration at blade edgewise frequency $w_e = 8.13 \text{ rad/s}$ is greatly removed. Note that these severe blade vibrations are not due to under damping but just in these specific circumstances the blade edgewise mode are excited. Consequently, the projection of the maximum load point on $L1$ is reduced, as shown in M_y - M_x plane on the right hand side, indicating a rise of damping in the blade edgewise dynamic mode; as for the ultimate load reduction of load $L2$ (lower row), a reduction of $1P$ component on the time trace of M_y in a 10 min run in high wind speed is obvious to see from the subfigure in left hand side. The bending moments in M_y - M_x plane showing in the right hand side plot supports the conclusion that the loads are squeezed along the 'L2' line, indicating load reduction on the targeted load $L2$.

The reduction of lifetime ultimate blade loads for loads $L1$ and $L2$, at the different blade stations are tabulated in Table 4. The improvement in performance is shown as a percentage relative to the baseline ultimate loads without IBC. The IBC2 M_x control achieves a reduction of 10% ~ 15% of $L1$ while M_{xy} control obtains a reduction of 20% ~ 30% of $L2$ at central blade stations, although there are fewer benefits at the stations towards further to the blade tip. The lost of performance might be explained that the extremes at these blade stations could differ from the extremes measured at blade root. Different blade specification, e.g. mass and stiffness distribution may have an effect on how the performance is deteriorated with the distance away from blade root.

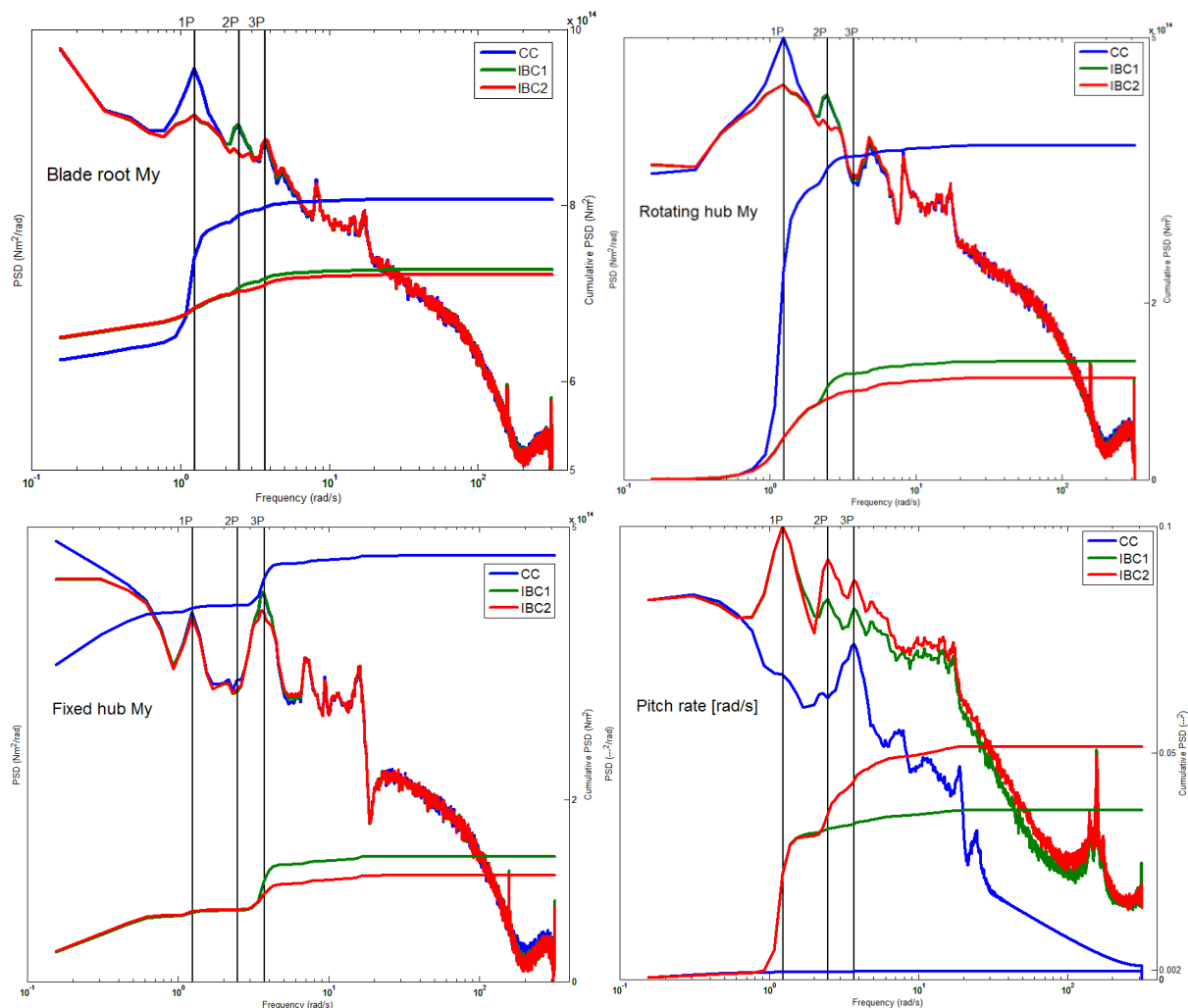


Figure 3: Power spectra of Blade root M_y , Fixed hub M_y , Rotating hub M_y and Pitch Rate from 10 min simulation at mean wind speed 18m/s between central controller (CC), IBC1 and IBC2

Table 3 Lifetime (20 years) equivalent damage load comparison between baseline controller and four IBC designs

Lifetime equivalent damage load (Nm)	IBC1	IBC2	IBC3	IBC4
Blade1 root M_{x_s} SN10	-2.51%	-2.39%	-7.39%	-8.60%
Blade1 root M_{y_s} SN10	-12.60%	-13.46%	-13.38%	-26.71%
Blade2 root M_{x_s} SN10	-2.48%	-2.37%	-7.76%	-8.86%
Blade2 root M_{y_s} SN10	-11.20%	-12.01%	-12.48%	-25.27%
Blade3 root M_{x_s} SN10	-2.51%	-2.50%	-7.15%	-8.27%
Blade3 root M_{y_s} SN10	-12.89%	-13.81%	-13.90%	-25.44%
Rotating Hub M_{y_s} SN4	-13.90%	-15.35%	-15.39%	-43.87%
Rotating Hub M_{z_s} SN4	-14.45%	-15.98%	-16.02%	-44.62%
Fixed Hub M_{y_s} SN4	-0.06%	-7.60%	-7.57%	-19.82%
Fixed Hub M_{z_s} SN4	-1.78%	-8.45%	-8.45%	-22.56%
Tower base M_{y_s} SN4	+1.60%	+1.47%	+1.59%	-3.44%
Tower base M_{z_s} SN4	-1.51%	-8.06%	-8.19%	-22.44%

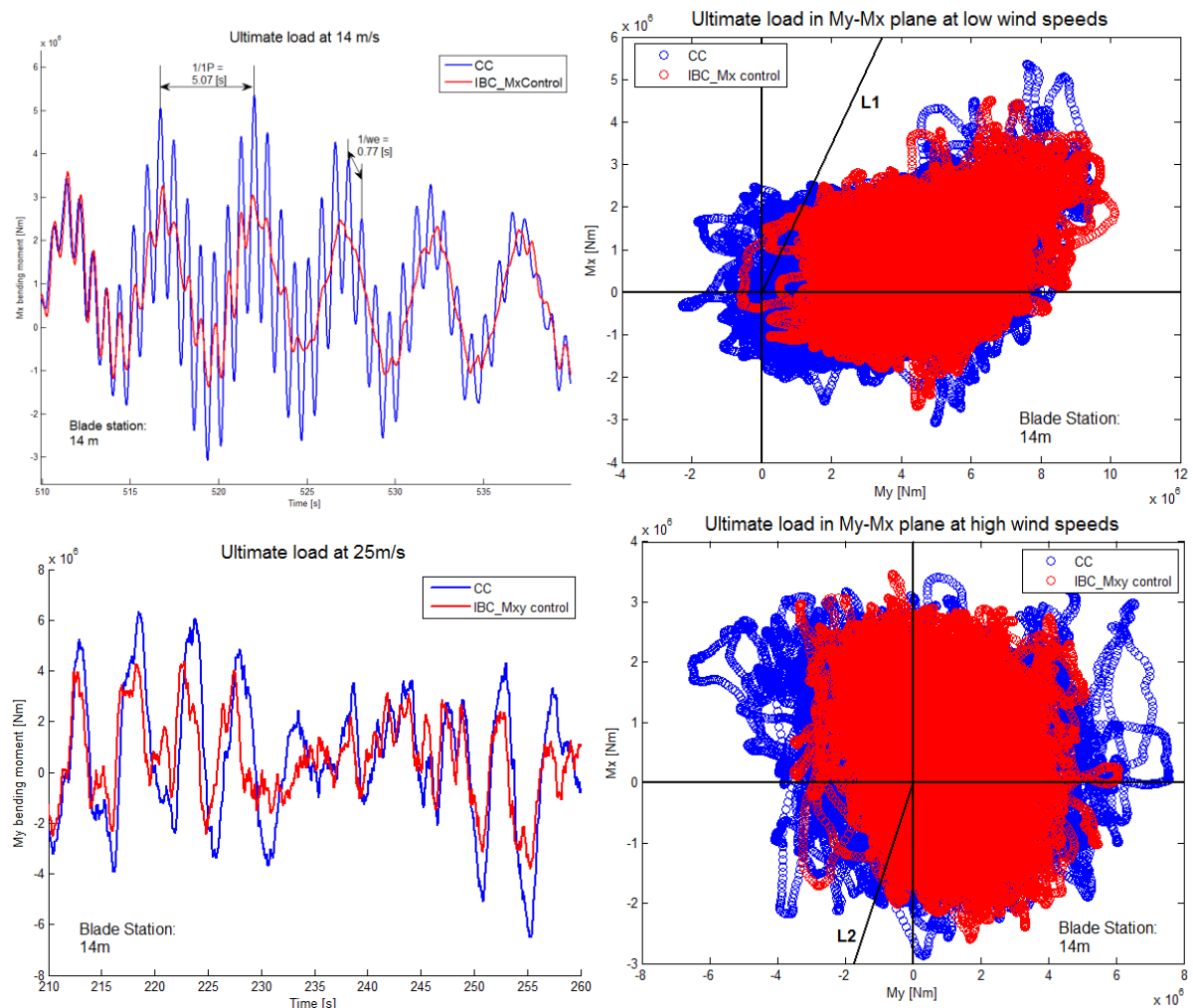
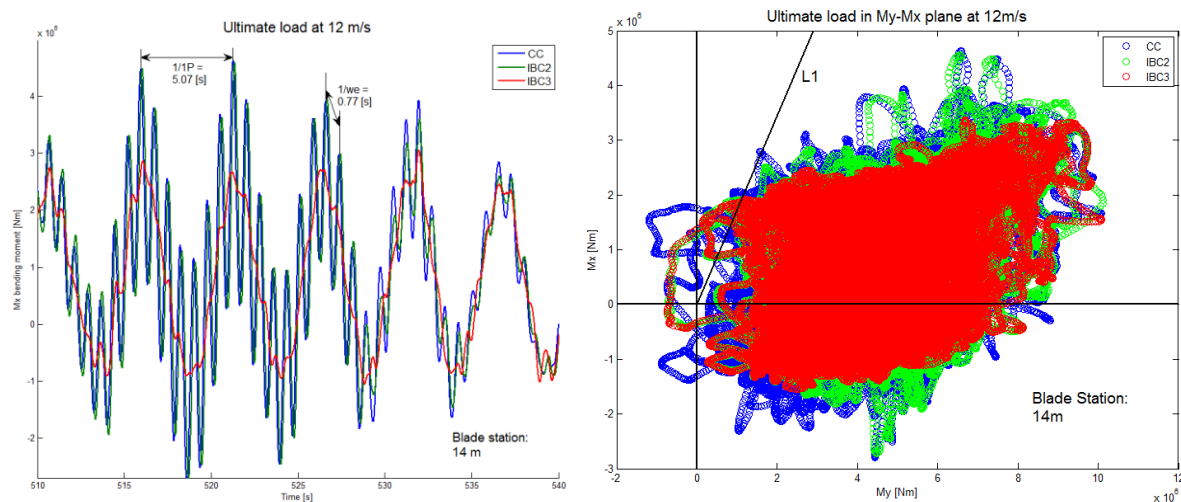


Figure 4: Ultimate load comparison at blade station 14m for load L1 and L2; the blue ones are for central controller (CC) only and the red ones are for IBC2

Table 4 Blade ultimate load reduction for four controllers

Blade Stations [m]	IBC1		IBC2		IBC3		IBC4	
	L1	L2	L1	L2	L1	L2	L1	L2
0	-11.09%	-23.71%	-11.09%	-23.24%	-28.19%	-23.24%	-28.19%	-23.27%
4	-13.51%	-24.09%	-13.28%	-25.56%	-29.64%	-25.56%	-29.64%	-25.59%
10	10.57%	-24.12%	-10.69%	-25.27%	-30.20%	-25.27%	-30.20%	-25.28%
14	-13.01%	-25.11%	-13.10%	-23.86%	-33.06%	-23.86%	-33.06%	-23.83%
18	-10.19%	-29.49%	-10.24%	-30.33%	-33.11%	-30.33%	-33.11%	-30.32%
22	-14.42%	-22.62%	-13.90%	-22.87%	-45.18%	-22.87%	-45.18%	-22.89%
26	-14.76%	-18.66%	-15.29%	-20.32%	-46.24%	-20.32%	-46.24%	-20.34%
30	-14.76%	-8.72%	-15.27%	-11.88%	-47.41%	-11.88%	-47.41%	-11.90%

**Figure 5:** Time series of Blade root M_x and ultimate load of L1 from a 10 min simulation at mean wind speed 12m/s; the blue one is for central controller (CC), the green one for IBC2 and the red one for IBC3

4.2. Fatigue and ultimate load reduction by IBC3 and IBC4

4.2.1. Ultimate load reduction improved by IBC3. The extension of edgewise damping control into below rated wind speeds is with major consideration of further ultimate load reduction of L1 which is determined in around rated wind speeds (both below and above). On the other hand, L2 is determined from high wind speeds (above 24m/s) and the reduction on it will remain the same. It could also be found in Table 3 that the fatigue load for both the blade and hub are almost unchanged as they are mainly contributed by 1P and 2P of blade M_y in low wind speeds. Figure 5 shows a fraction of 10 minutes time trace of M_x loads and the bending moments in M_y - M_x plane at mean wind speed 12 m/s. The load comparison between central controller and two IBC controllers indicates that the blade M_x edgewise vibration can be further eliminated by IBC3 (red line) controller over other wind speeds in below rated region. The remaining component in blade in-plane bending moment is basically just the gravitational 1P. Hence, the projection of load onto load L1 can be reduced significantly.

4.2.2. Fatigue load reduction improved by IBC4. After the improvement of ultimate load reduction on L1, the improvements on blade fatigue load reduction have also been investigated, leading to the design of IBC4. In this design, both edgewise damping and 1P + 2P control are extended to below rated wind speed region and hence the benefits for ultimate load reduction achieved by IBC3 can be inherited while it can also further improve the performance on fatigue load reduction.

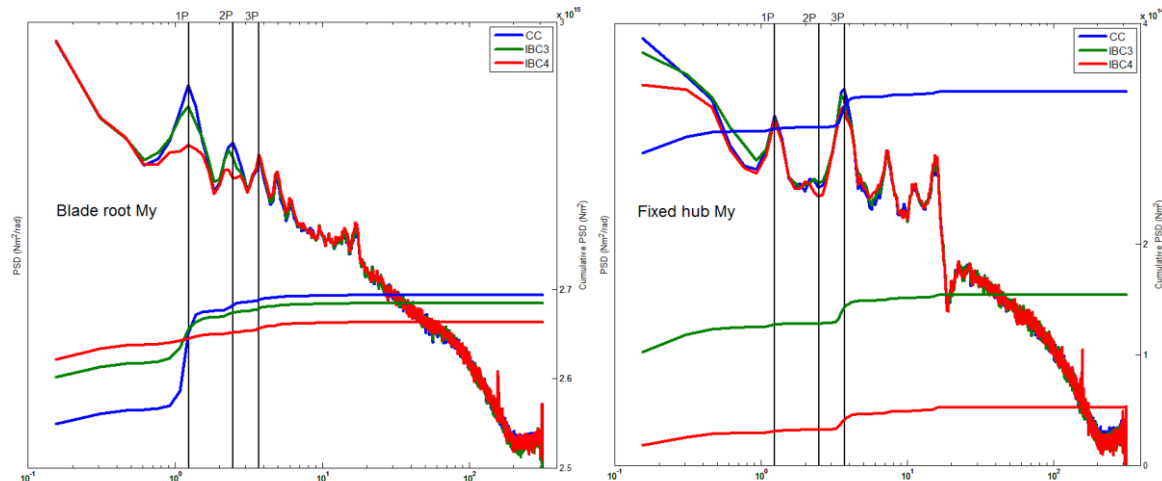


Figure 6: Power spectral density of blade root M_y and fixed hub M_y from a 10 min simulation at mean wind speed 12m/s; the blue one is for central controller (CC), the green one for IBC3 and the red one for IBC4

The lifetime fatigue load reduction on blade and hub can be found in the Table 3 under column “IBC4”. Apart from the slight improvement on blade M_x , it is more obvious that the mitigation of blade root M_y by IBC4 is almost double from what was achieved by IBC3, raising to around 25% for all the blades. Meanwhile, it also reduces the rotating and fixed hub M_y (tilting fatigue load) about 30% and 12% more, reaching to 43.87% and 19.82%, respectively. The hub yawing fatigue load (Fixed Hub M_z) is reduced by an order of 22%. Figure 6 compares the power spectral density of blade root M_y and fixed hub M_y at mean wind speed 12 m/s. It is clear that IBC4 (red one) can further compress the spectral peaks of 1P and 2P on blade M_y and consequently, leading to more mitigation at 0P, and more importantly 3P, on the fixed hub M_y , as shown in the right hand side plot. These indicate that, by using the IBC4, there are more lifetime fatigue load reduction on both blade and hub.

To summarise, with a combination of 1P and 2P control on blade M_y or both M_x and M_y , together with the suppression of edgewise vibration on M_x , including the operation over the full envelope of wind speeds, a single combined IBC controller design (IBC4) can achieve significant reduction of fatigue load on the blade and hub by an order of around 25% and 20%, respectively, in comparison with the baseline central controller. There are also improvements on the tower loads. Meanwhile, with the same IBC controller, the ultimate load is proved to be reduced by an order of above 30% for load L1 and above 20% for load L2 at many different stations along the blade. The load reduction on blade fatigue and ultimate load (L1) could be nearly halved of those benefits if below rated wind speed operation is precluded but, the regulation on ultimate load (L2) remained almost unchanged as it is determined in high wind speeds.

5. Conclusion and discussion

To meet the growing requirements of dynamical load regulation on large wind turbines, the role of the controller has been extending with the growth of the turbine size. Rather than redesigning the blade, there is considerable potential for employing the pitch system to reduce the load on the blade, and thus the rest of wind turbine structure, via an advanced control method. One approach to reduce the blade loads and the rotor unbalances is Individual Blade Control (IBC). Since no information of load measurements on the blade root is lost, there is significant flexibility over the choice of blade bending moment and load components to regulate.

This work demonstrates the further exploration of the merits of IBC to enable a single combined controller to alleviate both fatigue and ultimate load concurrently. To do so, IBC is designed to respond to different load measurements at varying operational points; that is, to target the correct components of blade load at different wind speeds. The load components of major concerns are spectral peaks at blade in-plane and out-of-plane bending moment or a combination of both. Different functions are applied separately with purpose of load reduction for each of the load components.

Generally, by comparing the performance obtained by the four different IBC controller designs, it can be found that both fatigue and ultimate load on the blade can be reduced with a proper selection of load measurements for the controller. With some augmented designs, fatigue load reduction on the

hub is also achievable. There are great flexibilities of choosing the different control targets when implementing the IBC controller. The choice of the controller input could be a combination of blade in-plane and out-of-plane bending moments at varying wind speeds. To select which spectral peaks to be regulated from blade loads is mainly dependent on whether fatigue or ultimate load dominates in that wind speed region. Any unnecessary pitch demand from the control loops for different spectral peaks should be properly phased out to avoid excessive pitch activities. It is worth mentioning that the weighting given to each control loop could change for other wind turbines with different configuration, i.e. the IBC load control requirements may need to adjust to cater for the various fatigue and ultimate load characteristics that each turbine may have. It has been found that the aerodynamic conditions and the blade designs can have significant effects on the ultimate load pattern, which to some extent, would require the IBC controller to be designed on a per-turbine basis.

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