

Individual blade pitch for yaw control

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Abstract. Individual pitch control (IPC) for reducing blade loads has been investigated and proven successful in recent literature. For IPC, the multi-blade co-ordinate (MBC) transformation is used to process the blade load signals from the rotating to a stationary frame of reference. In the stationary frame of reference, the yaw error of a turbine can be appended to generate IPC actions that are able to achieve turbine yaw control for a turbine in free yaw. In this paper, IPC for yaw control is tested on a high-fidelity numerical model of a commercially produced wind turbine in free yaw. The tests show that yaw control using IPC has the distinct advantage that the yaw system loads and support structure loading are substantially reduced. However, IPC for yaw control also shows a reduction in IPC blade load reduction potential and causes a slight increase in pitch activity. Thus, the key contribution of this paper is the concept demonstration of IPC for yaw control. Further, using IPC for yaw as a tuning parameter, it is shown how the best trade-off between blade loading, pitch activity and support structure loading can be achieved for wind turbine design.

1. Introduction

Modern multi-megawatt wind turbines are designed to be in an upwind configuration to minimise power loss and blade loading induced by tower shadow. A downwind turbine can be stable in free yaw, as shown in [1], however a typical modern upwind turbine requires active yaw control to ensure that the wind turbine rotor is aligned with the wind direction in normal operation. Yaw control is conventionally achieved by a yaw actuation mechanism that is located between the base of the nacelle and the top of the tower. This mechanism forms one of the most highly stressed subsystems of the turbine and is critical for power production and turbine reliability, estimated to account for around 10-15% of breakdowns in operating turbines [2]. Further, it has been shown in [3] that the yaw behaviour of a turbine has a significant impact on its overall structural loading, and this effect is more dominant for turbines with highly flexible support structures.

Studies have been done on optimising the dynamic behaviour of the yaw system during the wind turbine design phase by tuning turbine structural parameters [4], for instance by reducing the stiffness of the yaw drive [5]. The principle of achieving active yaw control by extending recent blade load reduction techniques such as Individual Pitch Control (IPC) has recently been described in [6]. However the effect of active yaw control on structural loads and actuator duty cycle has not been investigated.

For rotating structures of the scale of modern wind turbines, it has become the norm to implement IPC, as described in [7] as an active blade load control methodology to withstand the increased dynamic loads occurring over the turbine lifetime. IPC is one of the most directly implementable and successful methods for reducing periodic loads on the blades. IPC also reduces periodic loads to some extent in the turbine support structure. However, as explained in [8], reduction of blade loads and support structure



loads involves a trade-off; with the use of conventional IPC, optimal blade load reduction results in sub-optimal support structure load reduction.

It is shown in [9] that the yaw degree of freedom of a wind turbine plays a crucial rôle in blade load control and is one of the major factors introducing load periodicity in the wind turbine system. However, in conventional IPC implementations, the load controller is designed independently of the yaw controller. This paper considers the extension of IPC [6] by incorporating yaw control such that support structure load reduction can be enhanced with a minor effect on blade load reduction and yaw regulation.

This paper presents for the first time an investigation of the effect of the recently proposed methodology for yaw control using Individual Pitch Control (IPC) on the loading at the yaw bearing and the rest of the support structure. The trade-off entailing increased pitch activity and reduced blade load alleviation is also explored. Further, the paper posits the option of virtually eliminating the entire yaw actuation subsystem. While safety considerations and low wind speed yaw actuation requirements may necessitate the existence of a conventional yaw actuation system, its activity can be reduced to negligible amounts using IPC for yaw control, eliminating yaw actuator-related maintenance issues almost entirely.

The rest of the paper is structured as follows: in section 2, the simulation environment and the model used for validating the concept is described. The methodology used for implementing the IPC controller is described in section 3. In section 4, the results obtained from the implementation of the controller are described, and the conclusions drawn therefrom are discussed in section 5.

2. Simulation model and environment

The control strategy proposed in the subsequent sections is tested in the simulation environment GH BladedTM from Garrad Hassan & Partners Ltd. This software has been certified for use in the commercial development of wind turbines and has also been used in recent literature for comparing load control strategies like IPC [10].

GH Bladed represents a wind turbine using multi-body simulations, typically with flexible blades and tower. It is also capable of simulating a three-dimensional turbulent wind field, incorporating wind shear and gusts. The interaction between the wind field and the turbine is defined using the Blade Element Momentum (BEM) theory, augmented to include dynamic stall and wake corrections. The desired controller can be compiled into a dynamic link library (DLL) and interfaced with GH Bladed.

The model used for simulation purposes is that of a commercial wind turbine, the XEMC-Darwind XD115, 5MW. The general characteristics of this turbine are given in table 1. A baseline controller is used in closed-loop with the turbine, and it includes the following major components:

- Torque controller for speed control in the below-rated region
- Collective pitch controller for speed control in the above-rated region
- Tower fore-aft damping using collective pitch action.

The option for free yaw is switched on in the Bladed model. Thus, the baseline-controlled turbine has no yaw control, is inherently unstable and will attempt to move into a downwind position. The augmented IPC controller, which includes yaw control, is connected in closed-loop with this baseline-controlled wind turbine system. The methodology of implementation of this augmented IPC controller is described in the next section.

3. Methodology of IPC for yaw control

Typically, as described in [7] and [11], IPC for load control is implemented via the so-called Multi-Blade Co-ordinate (MBC) transformation or Coleman transformation. In this method, the three measured blade

Table 1. XEMC-Darwind XD115 wind turbine specifications [12].

Description	value
rated power	5000 kW
rotor diameter	115 m
cut-in wind speed	4 m/s
rated wind speed	12 m/s
cut-out wind speed	25 m/s
rated rotational speed	18 rpm
gearbox ratio	1.0 [direct drive]
pitch rate limit	6 °/s

loads M_i , $i = 1, 2, 3$ are first transformed to two signals in the stationary frame, M_t and M_y :

$$\begin{bmatrix} M_t \\ M_y \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\psi) & \cos(\psi + \frac{2\pi}{3}) & \cos(\psi + \frac{4\pi}{3}) \\ \sin(\psi) & \sin(\psi + \frac{2\pi}{3}) & \sin(\psi + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}. \quad (1)$$

Here, ψ is the azimuth angle of blade 1, measured clockwise-positive from the vertical position of this blade. Now, based on the load signals M_t and M_y , pitch command inputs θ_t and θ_y are synthesised (using for instance, a simple integral controller per channel) in the stationary frame of reference, to minimise the loading. The angles θ_t and θ_y are reconverted into the rotating frame by using the inverse MBC transformation, in order to obtain the three individual blade pitch commands θ_i , $i = 1, 2, 3$:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \cos(\psi) & \sin \psi \\ \cos(\psi + \frac{2\pi}{3}) & \sin(\psi + \frac{2\pi}{3}) \\ \cos(\psi + \frac{4\pi}{3}) & \sin(\psi + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} \theta_t \\ \theta_y \end{bmatrix}. \quad (2)$$

The conventional implementation of IPC as described by the formulation above is shown in figure 1. The wind turbine system with baseline speed control is shown within the blue box. The IPC controller is encapsulated within the red box, and will be modified in order to include yaw control. It can be directly seen that, as according to the equations above, the forward MBC transformation generates two signals in the stationary frame of reference, M_t and M_y , from the three blade root load signals, M_1 , M_2 , M_3 and the rotor azimuth angle ψ . The stationary frame of reference is denoted by the area outside the dashed box. Conversely, the inverse MBC transform takes two control input signals θ_t and θ_y from the stationary frame of reference generated by the IPC controller, and synthesises the three individual blade pitch control inputs θ_1 , θ_2 and θ_3 that are then applied to the wind turbine system.

It has been shown in [13], that the two loads in the stationary frame of reference M_t and M_y are direct measures of the tilt and yaw moment respectively. As such, using IPC with the MBC transformation, when the turbine is fixed in yaw, the yaw moment at the yaw bearing can be reduced. Conversely, if the turbine were in free yaw, IPC could be used to reject yaw error and stabilise the turbine such that the rotor is aligned with the wind direction. Thus, IPC can be used for turbine yaw control. If the measured yaw error is χ , then a pitch command input in the stationary frame of reference θ_y^χ can be synthesised using a simple Proportional-Integral (PI) controller to reject this yaw error and stabilise the turbine in yaw:

$$\theta_y^\chi = K_p \chi + K_i \int d\chi, \quad (3)$$

where K_p and K_i are tunable parameters of the PI controller. The individual pitch command signals will

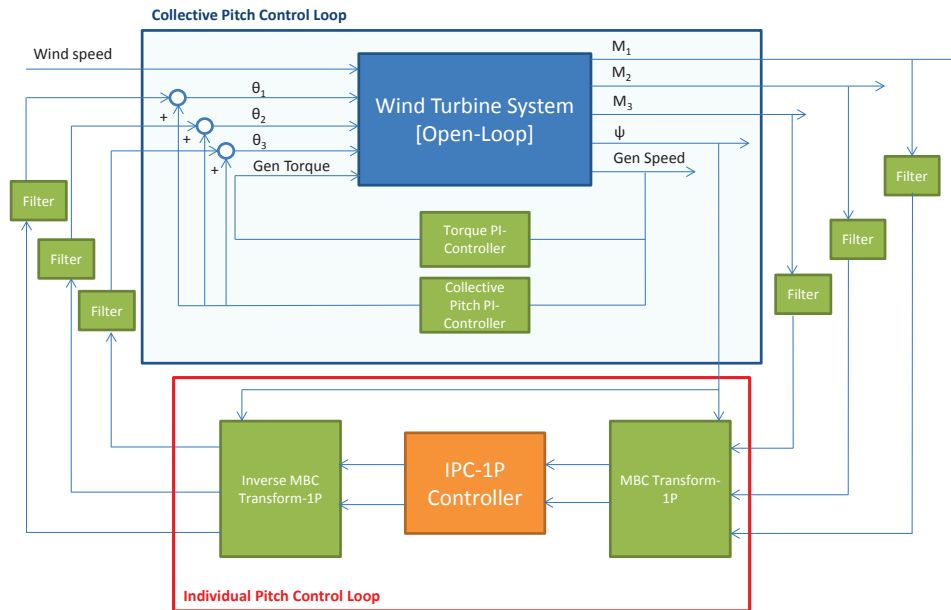


Figure 1. Conventional implementation of IPC

now be given by:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \cos(\psi) & \sin \psi \\ \cos(\psi + \frac{2\pi}{3}) & \sin(\psi + \frac{2\pi}{3}) \\ \cos(\psi + \frac{4\pi}{3}) & \sin(\psi + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} \theta_t \\ \theta_y + \theta_y^x \end{bmatrix}. \quad (4)$$

The implementation of this control strategy is shown in block diagram format in figure 2. As can be seen, the pitch control input connected with yaw in the stationary frame of reference, θ_y , is augmented by a term that is synthesised by an IPC yaw controller, θ_y^x . This implementation replaces the conventional implementation of IPC within the red box in Fig. 1.

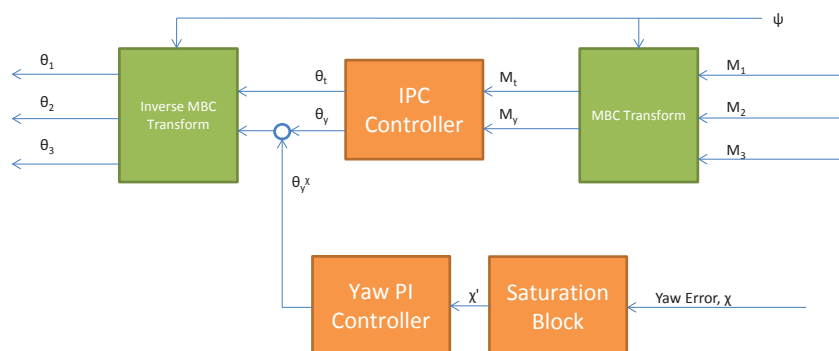


Figure 2. Implementation of yaw control using IPC

Due to the effect of yaw bearing friction, small IPC actions for yaw correction will not have any effect and are hence required to be eliminated. For this, the yaw error is preconditioned with a saturation block before using it as input to the PI controller. This saturation cut-off ensures that the IPC controller does not react to very small yaw misalignments. The saturated yaw error χ' is related to the actual yaw error

in the following way:

$$\chi' = \begin{cases} \chi \frac{\tanh(\chi+\mu)-1}{2} & \text{if } \chi \leq 0 \\ \chi \frac{\tanh(\chi-\mu)+1}{2} & \text{if } \chi > 0. \end{cases} \quad (5)$$

Here, μ is the user-defined amount of yaw misalignment that may be tolerated, and depends on the effect on power production and the reliability of the yaw error measurement. The action of the saturation block is depicted in figure 3. The PI controller now acts on the saturated yaw error signal χ' to generate the pitch action in the stationary frame θ_y^χ , thus:

$$\theta_y^\chi = K_p \chi' + K_i \int d\chi', \quad (6)$$

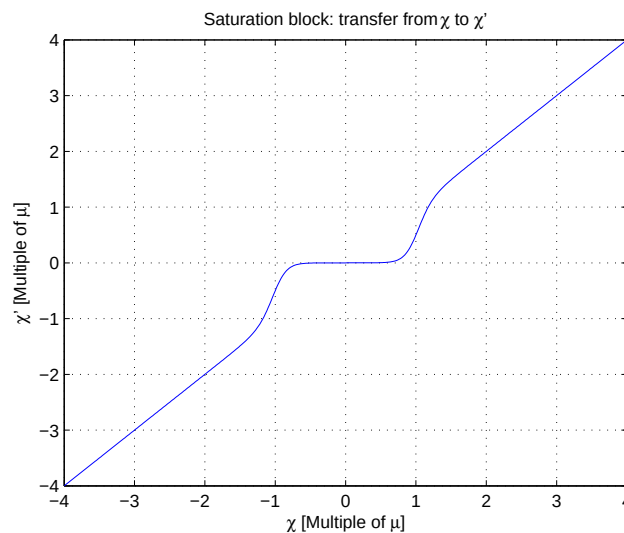


Figure 3. Saturation block to avoid small yaw corrections.

This controller is simulated for the turbine model described in Section 2. The results of the simulation study are given in the next section.

4. Simulation study

In this section, the IPC-yaw controller is designed for a model of a turbine in free yaw, which has been described in Section 2 and the results of the simulations done with this controller are presented in order to study the modifications in the turbine behaviour.

The controller block that generates an additional input θ_y^χ in response to the yaw error χ in figure 2 is implemented using a simple PI controller, as described by equation (6). An integral controller is chosen to ensure that the steady-state error asymptotes to zero.

The operation of the three following controllers is compared in the simulation environment:

- Turbine in free yaw with IPC for combined blade load reduction and yaw control and CPC for speed control
- Turbine with constant yaw stiffness of 1×10^8 N-m/rad and IPC only for blade load reduction and CPC for speed control
- Turbine with constant yaw stiffness of 1×10^8 N-m/rad without IPC but with CPC for speed regulation.

For the turbine in free yaw, a constant value of yaw friction is assumed and taken to be equal to 10% of the average yawing moment for the turbine with stiff yaw. While a conservative estimate, simulations with yaw friction enable a more realistic investigation of the yaw control methodology.

It is seen that, under all ordinary operating conditions, it is possible to stabilise the turbine in free yaw using IPC. Further, it is seen that by tuning the aggressiveness of the controller, it is possible to tune the trade-off between load reduction and yaw error rejection. The aggressiveness of the controller is measured in terms of its bandwidth, or the frequency at which its dynamic gain falls below -3 dB [14]. The bandwidth of the controller can be increased by increasing the value of K_i and K_p in equation (3), and reduced by reducing the value of K_i and K_p .

Selected results are presented to demonstrate the behaviour of the IPC yaw control algorithm. The wind speed for the case presented is 18 m/s, with a low turbulence intensity of 3.75%, where turbulence intensity is defined as the ratio of the standard deviation of the wind speed signal to its mean. To be noted is that all results have been presented with normalised units; this is to preserve the confidentiality of the data.

For ordinary IPC, the mean of the yaw loading is reduced. However since the controller has been tuned for maximum blade load reduction, optimal yaw load reductions are not achieved, and there is in fact a small increase in the yaw loading. With IPC for yaw control, since the only load being transferred arises out of yaw friction, the yawing moment at the yaw bearing is reduced by a factor of 15. This can be seen in figure 4. At the same time, the use of IPC for yaw control reduces the yaw error rejection capability of the turbine, this can be observed in Fig. 5. While yaw error increases with IPC for yaw control by a factor of 14, as shown in table 2, it is to be noted that the standard deviation of the yaw error remains bounded within a few degrees for this case. Yaw error standard deviation is also not significantly high for high turbulence cases.

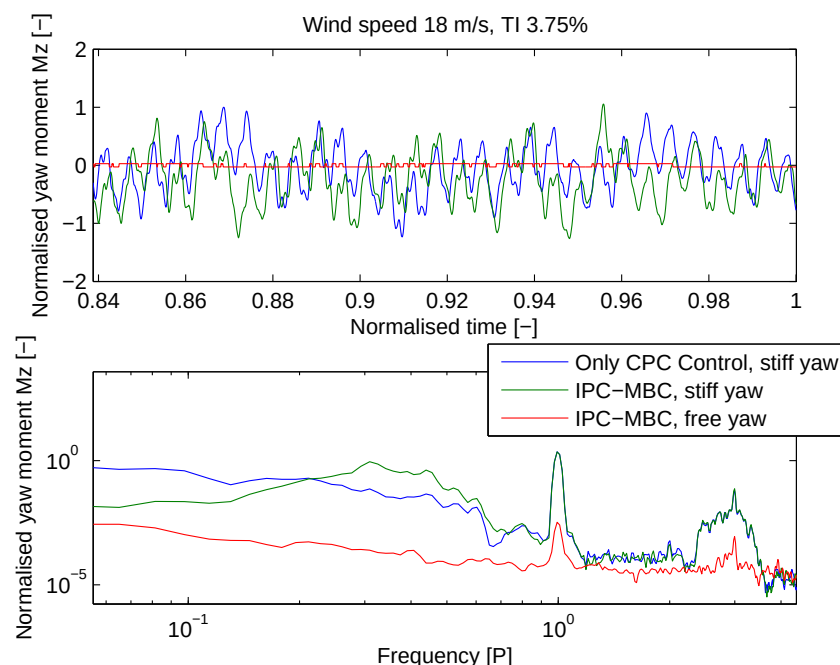


Figure 4. Yaw moment at yaw bearing for wind speed 18 m/s, TI 3.75%.

The decoupling of the blade loads from the support structure also reduces tower loads to a large extent, as can be seen in figure 6, which depicts the side-side loading of the tower. Ordinary IPC and the CPC cases have very similar loads and show dominant peaks at 1P (imbalance) and 3P (blade-passing).

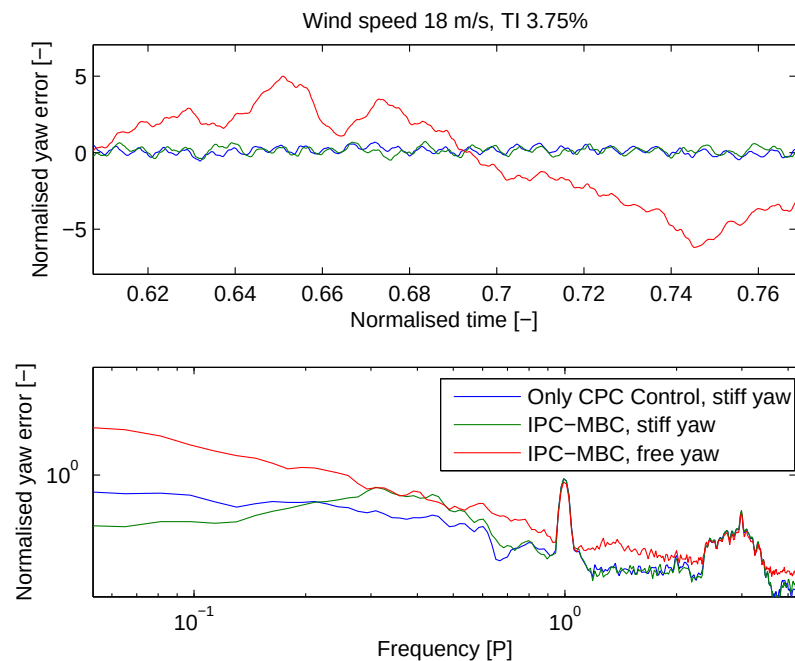


Figure 5. Yaw error for wind speed 18 m/s, TI 3.75%.

With ordinary IPC, the mean load is reduced, however since the controller is tuned for maximal blade load reduction, the tower load reduction is sub-optimal. The use of IPC for yaw control implies that a large part of the load is not transferred to the tower and the support structure through the yaw bearing, and the 1P component of the loading is reduced significantly. On account of yaw friction, there is a small increase in the low frequency energy content of tower loading. Overall, the standard deviation of the tower side-side loading is reduced by 52.64% for this low turbulence case, as shown in table 2.

The use of IPC for yaw control reduces the blade load alleviation potential of IPC, as can be seen in Fig. 7. Ordinary IPC can reduce blade load standard deviation to an extent of 45% as compared to the no-control case. However, with yaw control, the blade load standard deviation reduction is 43% as compared to the no-control case.

Finally, as can be seen in figure 8, the demanded pitch rate of IPC for yaw control is not very different from that of ordinary IPC, in both cases it is about 5 times that of the baseline CPC controller. The pitch command for both IPC algorithms is dominated by the 1P peak, which is to be expected since the 1P MBC transform is used to generate the IPC pitch signals. There is a slight difference in the phase of the signals for the turbine in free and stiff yaw, which accounts for the yaw error rejection capability of the IPC algorithm for yaw control.

With a higher bandwidth, larger reductions in support structure loads can be achieved, at the expense of increased blade loads. On the other hand, a less aggressive yaw controller with a lower bandwidth will lead to increased yaw error, while blade loads can be reduced to a larger extent, as in table 2. The effect of increasing turbulence is shown in table 3. While the yaw performance remains the same, the load reduction potential for both blade and tower loads reduces with increasing turbulence.

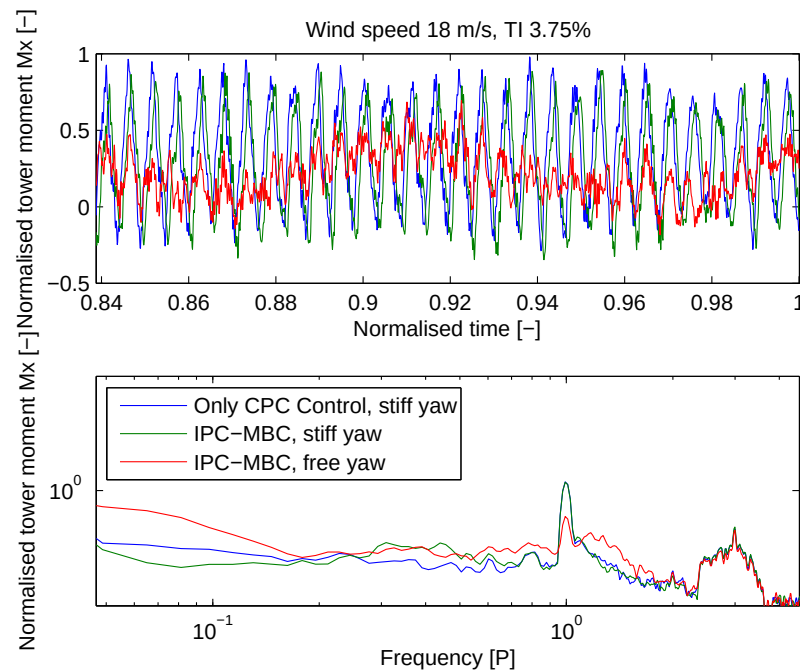


Figure 6. Tower side-side loading for wind speed 18 m/s, TI 3.75%.

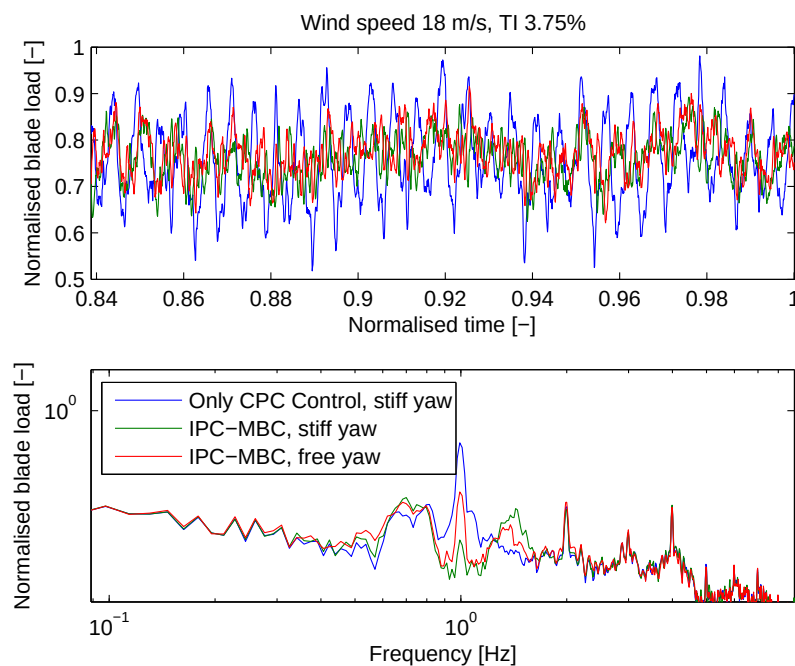


Figure 7. Blade 1 out-of-plane load reduction for wind speed 18 m/s, TI 3.75%.

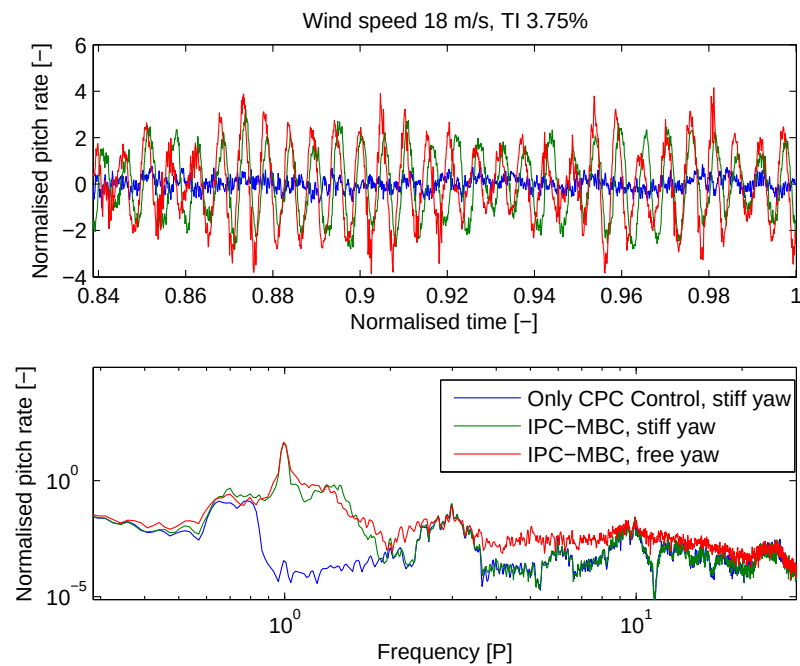


Figure 8. Pitch rate command for wind speed 18 m/s, TI 3.75%.

Table 2. Effect of changing yaw controller bandwidth, turbulence intensity 3.75%

Normalised quantity	No IPC	IPC	IPC	IPC	IPC
Yaw mode	stiff	stiff	free	free	free
Yaw controller bandwidth			0.0048P	0.0063P	0.0077P
Yaw bearing moment std dev	1	1.076	0.065	0.065	0.065
Yaw error std dev	1	1.076	14.30	13.37	12.20
Tower side-side moment std dev	1	0.990	0.474	0.470	0.463
Blade out-of-plane moment std dev	1	0.553	0.564	0.567	0.574
Pitch rate std dev	1	5.122	5.566	5.613	5.675

Table 3. Effect of changing turbulence intensity, yaw controller bandwidth 0.0077P

Normalised quantity	No IPC	IPC	IPC	IPC	IPC	IPC	IPC
Yaw mode	stiff	stiff	free	stiff	free	stiff	free
Turbulence intensity [%]	All	3.75	3.75	6	6	14	14
Yaw bearing moment std dev	1	1.076	0.065	1.019	0.047	0.972	0.029
Yaw error std dev	1	1.076	12.20	1.020	12.41	0.972	13.97
Tower side-side moment std dev	1	0.990	0.463	1.007	0.637	1.012	0.936
Blade out-of-plane moment std dev	1	0.553	0.574	0.657	0.697	0.884	0.904
Pitch rate std dev	1	5.122	5.675	4.613	5.319	3.402	4.477

5. Conclusion

The key contribution of this paper is the demonstration of Individual Pitch Control (IPC) for yaw control. A state-of-the-art large upwind wind turbine can be stabilised in free yaw purely by using IPC, without requiring a separate yaw actuation mechanism. This concept can prove useful in eliminating the yaw motors or reducing the yaw motor duty cycle drastically. Further, it would be possible to use IPC as a redundant yaw actuator in case of failure of the primary yaw actuation mechanism.

When IPC is used for yaw control, yawing moments on the nacelle are transferred to a very small extent to the tower through yaw bearing friction, significantly reducing support structure loads. This comes at the expense of an increased yaw error. However, in absolute terms, the increase in yaw error remains within a few degrees, which may still be acceptable from a power production perspective. The effect of active yaw control using IPC on the power production has not been explored in this document, and shall be investigated in the future. IPC for yaw control reduces its blade load reduction potential and increases pitch activity. However, this degradation in IPC performance is very limited. By tuning the bandwidth of the IPC yaw controller, it is possible to reach the desired trade-off between the yaw control and load reduction capabilities of IPC.

Further, IPC for yaw control can broaden the design parameter space of a turbine by (partially) eliminating the present yaw actuators. It can also offer possibilities for the online tuning of turbine behaviour and advanced control techniques for performance optimisation qua yaw error rejection, blade load reduction and support structure load reduction.

The capability of using IPC for yaw control has been demonstrated in high-fidelity numerical simulations; this controller should further be validated on physical wind turbine prototypes to establish its practical viability.

Acknowledgments

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