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Design of Individual Blade Control modified to reduce the 1P disturbance on blade flap

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Abstract. In large wind turbines, the ability to pitch each blade individually is exploited to reduce blade and rotor loads. A second generation control strategy is IBC, independent blade control, whereby the dynamics of the blade are completely decoupled from the rest of the wind turbine as is the design of the individual blade controller from the design of the turbine full envelope controller. In this paper, the development and implementation of the structure of a modified version of the IBC is presented, with the aim of reducing the 1P disturbance on the spectrum of the out-of-plane blade root bending moment (blade flap). As the modified IBC also allows the blade dynamics and the design of the individual blade controller to be isolated from the rest of the turbine, a linearized single blade model is developed and a controller is designed, in a simple feedback with this model, to achieve closed-loop stability and a sensitivity function to suppress the 1P disturbance. The results from the implementation of the modified IBC structure in the provided Simulink model of a 5MW Supergen Wind Turbine demonstrated the success of the individual blade controller design, as a significant reduction in the 1P disturbance is found.

Keywords: Independent blade control, disturbance, fatigue load, sensitivity function, spectral analysis.

1 Introduction

As of recently, in their new report for the government, the Committee on Climate Change (CCC) have stated that in order to help UK obtain zero net carbon emissions in 31 years' time, around 7,500 turbines will be required to go from the current total offshore wind capacity in the UK of around 8GW to a capacity of 75 GW [1]. One of the interpretations from this 'target' is the requirement of not only a substantial number of turbines but also bigger turbines (over 10 MW). One of the major implications of such rapid increase in turbine size is the increased impact of the tower and rotor fatigue loads. Besides making the components of the turbine more load tolerant, active regulation can be utilised to reduce these loads. In large multimegawatt wind turbines, the blade and rotor load reduction is achieved through exploiting the ability to pitch each blade independently. Two types of well-established control strategies exist to achieve this, which are: IPC, independent pitch control, and IBC, independent blade control.

IBC transforms the dynamics of a single blade from an inertial reference frame, fixed with respect to the hub, to a non-inertial reference frame, fixed with respect to the hub, by means of amending the measured blade bending moments by addition of fictitious forces. This results in the decoupling of the blade dynamics (and actuator dynamics) and the design of the individual blade controller from the rest of the turbine and the central/speed controller. This is the main feature of the IBC, as each blade has its own pitch control system (i.e. sensor and controller) operating in isolation from the central/speed controller. This makes IBC structurally simple, easy to implement and tune. [2]

IPC, on the other hand, uses Coleman transformation, (1), to transform the out-of-plane bending moments, M_1, M_2 and M_3, from a stationary coordinate system to a rotating coordinate system of 2 orthogonal phases, d and q [2]. This can be thought of as the projection of the dynamic loading from each of the 3 blades on to axes related to the nodding and yawing loads.

$$\begin{bmatrix} M_d \\ M_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta_R) & \cos(\theta_R + \frac{2\pi}{3}) & \cos(\theta_R + \frac{4\pi}{3}) \\ \sin(\theta_R) & \sin(\theta_R + \frac{2\pi}{3}) & \sin(\theta_R + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \tag{1}$$

One of the major problem with this kind transformation is that it is a function of the azimuth angle, θ, which introduces a non-linear action. The other problem is that there is loss of information (i.e. a degree of freedom) when going from 3 loads to 2 loads. Instead, the full IBC can be modified by using a slightly different transformation. This transformation for one coordinate, d, is:

$$M_d = M_1 + M_2 cos\left(\frac{2\pi}{3}\right) + M_3 cos\left(\frac{4\pi}{3}\right) \tag{2}$$

In addition to this, the modified IBC also incorporates the transformation of the reference frame from inertial to non-inertial (main feature of the original IBC), as aforementioned, through addition of fictitious torques to the measured bending moments:

$$M_d = (M_1 + FT_1) + (M_2 + FT_2) cos\left(\frac{2\pi}{3}\right) + (M_3 + FT_3) cos\left(\frac{4\pi}{3}\right) \tag{3}$$

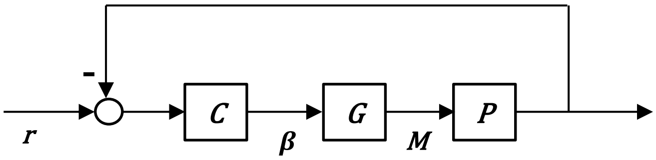
Since the fictitious torques are the sum of the linear and angular fictitious torques, it can be proved by (3) that the linear accelerations, which is just the hub acceleration, cancel out and since the angular acceleration is not significant in comparison to the linear acceleration, these terms are also dropped. Hence, the resulting expression is the one that was originally defined by (2).

Therefore, the major advantages of the modified IBC over IPC and the full IBC are: (a) the blade dynamics and the design of the blade controller are decoupled from the rest of the wind turbine, which is not the case with IPC, and (b) structurally simpler to implement than the full IBC because the fictitious torques do not have any contribution towards the transformation of the bending moments and therefore, need not to be determined. In addition, many turbine manufacturers prioritise ease of implementation over optimal performance of the active regulation control strategy.

This paper presents the development of the complete structure of the modified version of the IBC, explained in section 2, with the overall aim of implementing the designed individual blade controller in the provided Simulink/Matlab model of a 5MW Supergen Wind Turbine and assessing the effectiveness of the designed individual blade controller, within the modified IBC structure, upon the reduction of the 1P disturbance present on the spectrum of the out-of-plane blade root bending moment.

2 Structure of the modified IBC

The basic structure of the modified IBC applied to the whole wind turbine is demonstrated by figure 1 [3]. **G** describes the plant dynamics and, in this configuration, it is representative of the wind turbine. The central/speed controller is omitted from the following diagram for simplicity.



$$\boldsymbol{M} = \boldsymbol{G\beta} \quad ; \quad \boldsymbol{\beta} = \boldsymbol{C}(\boldsymbol{r} - \boldsymbol{PM})$$

Figure 1 Modified IBC Control System

where,

$$\boldsymbol{M} = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}; \boldsymbol{G} = \begin{bmatrix} G & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & G \end{bmatrix}; \boldsymbol{C} = \begin{bmatrix} C & 0 & 0 \\ 0 & C & 0 \\ 0 & 0 & C \end{bmatrix}; \boldsymbol{\beta} = \begin{bmatrix} \Delta\beta_1 \\ \Delta\beta_2 \\ \Delta\beta_3 \end{bmatrix}; \boldsymbol{r} = 0; \boldsymbol{P} = \left\{ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \frac{1}{3} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \right\}$$

It can be seen from figure 1 that the measurements of the out-of-plane blade root bending moments from each of the three blades, contained within vector **M** as outputs from **G**, are adjusted/amended by a matrix **P**. This adjusted **M**, **PM**, is then fed back and subtracted from a reference/set-point **r**. The difference, **r**-**PM**, is the input to **C**, which represents a matrix containing the three individual blade controllers. As a result, $\boldsymbol{\beta}$, the output from **C**, contains the increment in pitch angle for each blade. These pitch angle increments are then added to the collective pitch angle, the value of pitch angle that is demanded by the central/speed controller, before feeding into each blade's own pitch actuator.

As aforementioned, **G**, in the structure/configuration shown by figure 1, represents the whole of the wind turbine. However, due to the decoupling of the blade and pitch actuator dynamics from the rest of the turbine dynamics, in order to design a controller, C, for a single blade, G, which is a component of **G**, is simply a function of the single blade dynamics, $G_1(s)$, and the pitch actuator dynamics, $G_2(s)$, only:

$$G(s) = G_1(s) * G_2(s) \tag{4}$$

where,

$$G_1(s) = \frac{k}{s^2 + a\,s + {\omega_B}^2}\,; \tag{5}$$

$$G_2(s) = \frac{{\omega_a}^2}{s^2 + b\,s + {\omega_a}^2}\,; \tag{6}$$

s is the Laplace variable, and ω_a and b are parameters of the actuator dynamics, which are 8 rad/s and 11.2, respectively, provided explicitly within the 5MW Simulink model. The values of k and a, however, are dependant on the aerodynamics of a single blade and is to be determined algebraically through linearizing the non-linear single blade model (see section 3). The resulting linearized expression, in the Laplace domain, can then be represented as a 2nd order transfer function from change in pitch angle ($\Delta\beta$) to change in out-of-plane root bending moment (ΔM_{OP}).

Once all of the parameters of G are known, the individual blade controller, C, can then be designed with respect to G in a simple feedback configuration shown in figure 2.

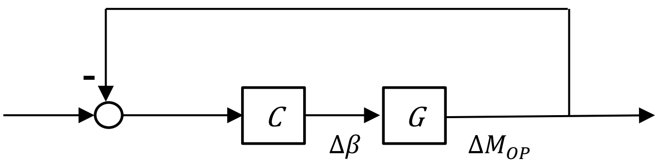


Figure 2 Single blade feedback loop

3 Linearization of single blade model

Considering a single non-rigid blade defined within an inertial reference frame fixed with respect to the hub (i.e. non-rotating rotor, rigid nacelle and tower), (7) represents a simple Newtonian dynamics lumped parameter blade model [2]:

$$\begin{bmatrix} \ddot{\theta_B} \\ \ddot{\phi_B} \end{bmatrix} = -\frac{1}{J}\begin{bmatrix} M_{IP} \\ M_{OP} \end{bmatrix} + \frac{1}{J}\begin{bmatrix} M_{A\theta_B} \\ M_{A\phi_B} \end{bmatrix} \tag{7}$$

where J is the blade inertia relative to the root of the blade, θ_B and ϕ_B represent the in-plane and out-of-plane angular displacements of the blade, respectively, M_{IP} and M_{OP} are the in-plane and out-of-plane blade root bending moments, respectively. $M_{A\theta_B}$ and $M_{A\phi_B}$ are the in-plane and out-of-plane external torques relative to the root of the blade, respectively. In (7), the external torques are the aerodynamic torques. The root bending moments, in-plane and out-of-plane, are defined as:

$$\begin{bmatrix} M_{IP} \\ M_{OP} \end{bmatrix} = J\, A(\beta) \begin{bmatrix} \theta_B \\ \phi_B \end{bmatrix} \tag{8}$$

where,

$$A(\beta) = \begin{bmatrix} \omega_E{}^2 cos^2(\beta) + \omega_F{}^2 sin^2(\beta) & -(\omega_E{}^2 - \omega_F{}^2) sin(\beta) cos(\beta) \\ -(\omega_E{}^2 - \omega_F{}^2) sin(\beta) cos(\beta) & \omega_E{}^2 sin^2(\beta) + \omega_F{}^2 cos^2(\beta) \end{bmatrix};$$

$\boldsymbol{\omega_E}$ and $\boldsymbol{\omega_F}$ are the blade's edge and flap frequency, respectively.

In reality, the rotor is rotating and the tower and nacelle are not rigid, which is why the reference frame, fixed with respect to the hub, is in actual fact non-inertial. In order to transform the blade dynamics from an inertial reference frame to a non-inertial reference frame, fictitious torques (in-plane and out-of-plane) should be added to the measured bending moments, as it represents the difference between the two reference frames. However, as aforementioned, the fictitious torques/forces of each of the three blades cancel out in the transformation of the bending moments used by the modified IBC. Therefore, the fictitious torques are not required and it suffices to linearize (7).

In order to linearize any non-linear system, equilibrium operating points are required. The dynamics of that system can be linearized locally around these points. Considering a general non-linear dynamic system [4]:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u})\,;\, \boldsymbol{y} = \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u}) \tag{9}$$

where, **x** is a vector containing the system's states, **u** is the vector containing the inputs to the system and **y** contains the system outputs. With respect to the non-linear single blade model, **x**, therefore, contains the in-plane and out-of-plane angular displacements, **u** is the aerodynamic torques and **y** is the root bending moments. Then, equilibrium operating points are just the values of **u**, **x** and **y** ($\mathbf{u_0}$, $\mathbf{x_0}$, $\mathbf{y_0}$) at which the system is at rest (i.e. zero velocity/acceleration trim condition) and it is these points around which the system is linearized. In the case of wind turbines, the equilibrium operating points are the steady state values of pitch angle, wind speed and rotor speed:

$$\beta = \beta_0; v = v_0;\ \Omega = \Omega_0;\ \begin{bmatrix} M_{A\theta_B} \\ M_{A\phi_B} \end{bmatrix} = \begin{bmatrix} M_{A\theta_B 0} \\ M_{A\phi_B 0} \end{bmatrix}$$

Taylor series expansion is utilised to linearize (7) and (8) locally around these equilibrium operating points. Ignoring any terms higher than 1st order, the linearized expression are as follows:

$$\begin{bmatrix}\Delta\ddot{\theta_B}\\ \Delta\ddot{\phi_B}\end{bmatrix} = -A'(\beta_0)\begin{bmatrix}\theta_{B0}\\ \phi_{B0}\end{bmatrix}\Delta\beta - A(\beta_0)\begin{bmatrix}\Delta\theta_B\\ \Delta\phi_B\end{bmatrix} + \frac{1}{J}\begin{bmatrix}\frac{\partial M_{A\theta_B}}{\partial\beta}\Delta\beta + \frac{\partial M_{A\theta_B}}{\partial\Omega}\Delta\dot{\theta}_B - L\frac{\partial M_{A\theta_B}}{\partial v}\Delta\dot{\phi}_B + \frac{\partial M_{A\theta_B}}{\partial v}\Delta v\\ \frac{\partial M_{A\phi_B}}{\partial\beta}\Delta\beta + \frac{\partial M_{A\phi_B}}{\partial\Omega}\Delta\dot{\theta}_B - L\frac{\partial M_{A\phi_B}}{\partial v}\Delta\dot{\phi}_B + \frac{\partial M_{A\phi_B}}{\partial v}\Delta v\end{bmatrix} \quad (10)$$

$$\begin{bmatrix}\Delta M_{IP}\\ \Delta M_{OP}\end{bmatrix} = J\,A'(\beta_0)\begin{bmatrix}\theta_{B0}\\ \phi_{B0}\end{bmatrix}\Delta\beta + J\,A(\beta_0)\begin{bmatrix}\Delta\theta_B\\ \Delta\phi_B\end{bmatrix} \quad (11)$$

where, θ_{B0} and ϕ_{B0} are the steady state values of the system's states and L is the effective blade length, which is defined as the distance from the root of the blade to a point on the blade that gives the total out-of-plane bending moment on the rotor. L appears in (10) as result of the wind experienced by the rotor being damped by the out-of-plane and fore-aft motions of the blade and tower. Therefore, the actual wind speed $\boldsymbol{v}$ is given by:

$$v = v_3 - L\dot{\phi}_B - h\dot{\phi}_T \quad (12)$$

where, v_3 is the effective wind speed and h is the hub height.

Then, by taking the Laplace transform of (10), the expression for $[\Delta\theta_B \quad \Delta\phi_B]^T$ is found to be:

$$\begin{bmatrix}\Delta\theta_B\\ \Delta\phi_B\end{bmatrix} = \begin{bmatrix}s^2 + B_{11}\,s + A_{11} & B_{12}\,s + A_{12}\\ B_{21}\,s + A_{21} & s^2 + B_{22}\,s + A_{22}\end{bmatrix}^{-1}\begin{bmatrix}-A'_{11}\theta_{B0} - A'_{12}\,\phi_{B0} + B_{13}\\ -A'_{21}\theta_{B0} - A'_{22}\,\phi_{B0} + B_{23}\end{bmatrix}\Delta\beta \quad (13)$$

where,

$$B = \frac{1}{J}\begin{bmatrix}-\frac{\partial M_{A\theta_B}}{\partial\Omega} & L\frac{\partial M_{A\theta_B}}{\partial v} & \frac{\partial M_{A\theta_B}}{\partial\beta}\\ -\frac{\partial M_{A\phi_B}}{\partial\Omega} & L\frac{\partial M_{A\phi_B}}{\partial v} & \frac{\partial M_{A\phi_B}}{\partial\beta}\end{bmatrix};\ A'(\beta) = ({\omega_E}^2 - {\omega_F}^2)\begin{bmatrix}-sin2\beta & -cos2\beta\\ -cos2\beta & sin2\beta\end{bmatrix}$$

The partial derivatives of the aerodynamic torques in (13) need to be evaluated at the equilibrium operating points. The values of operating points is determined by running the provided Simulink model of the 5MW Supergen Wind turbine at a constant wind speed (v_0) and obtaining the final (i.e. steady state) values of pitch angle (β_0) and rotor speed (Ω_0). These values are found to be β_0=0.2082 rads and Ω_0=1.2371 rad/s, when the simulation is run at v_0=16 m/s. Also, the steady state values of the system's states are θ_{B0} = 0.0199 rads and ϕ_{B0}=0.0367 rads.

The in-plane aerodynamic torque/loading (i.e. external torque relative to the blade root) on the whole rotor is given by:

$$M_{A\theta_B} = \frac{\rho\,\pi\,R^2\,v^3\,C_P(\beta,\lambda)}{2\,\Omega} \quad (14)$$

where, ρ is the air density (1.225kg/m^3), R is the rotor radius (63m) and $C_P(\beta,\lambda)$ is the power coefficient (in-plane aerodynamic coefficient), which is a function of pitch angle and tip-speed ratio. The values of partial derivatives of $M_{A\theta_B}$ with respect to pitch angle, rotor speed and wind speed, evaluated at the operating points (β_0, v_0, Ω_0) , are determined to be as the following:

$$\frac{\partial M_{A\theta_B}}{\partial\beta} = -1.333\times10^7\frac{Nm}{rad};\ \frac{\partial M_{A\theta_B}}{\partial v} = 3.772\times10^5\,Ns;\ \frac{\partial M_{A\theta_B}}{\partial\Omega} = -2.45\times10^6\,Nms/rad$$

The out-of-plane aerodynamic torque, on the whole rotor, is defined using an equivalent performance coefficient to that of the power coefficient, which is the out-of-plane aerodynamic coefficient C_o:

$$M_{A\phi_B} = \frac{1}{2}\,\rho\,\pi\,R^3\,v^2\,C_o(\beta,\lambda) \qquad (15)$$

C_o is also a function pitch angle and rotor speed, therefore, the look-up table in the provided wind turbine model was utilised to obtain the value of this coefficient and it's gradient (w.r.t pitch angle and tip-speed ratio). The resulting values of partial derivatives of $M_{A\phi_B}$ are found to be:

$$\frac{\partial M_{A\phi_B}}{\partial \beta} = -5.14\times 10^7\,\frac{Nm}{rad};\ \frac{\partial M_{A\phi_B}}{\partial \text{v}} = 9.57\times 10^5\ Ns;\ \frac{\partial M_{A\phi_B}}{\partial \Omega} = -4.3\times 10^6\,\frac{Nms}{rad}$$

With all the parameters of the expression for $[\Delta\theta_B \ \ \Delta\phi_B]^T$ defined, (13) is then substituted into (11). This results in a 4th order transfer function from change in pitch angle ($\Delta\beta$) to the change in out-of-plane root bending moment (ΔM_{OP}). However, as shown by figure 3, this transfer function is approximated well by a second order transfer function, where, from (5), $k = -9.07\times 10^8$; $a = 6.075$; ω_B= 4.257rads, which is the blade flap frequency.

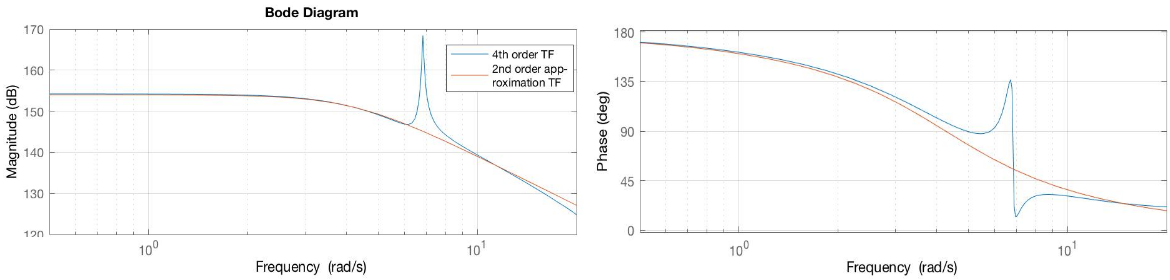


Figure 3 4th order transfer function from pitch angle to out-of-plane blade root bending moment and its 2nd order approximation

Controller design

As aforementioned, the preliminary aim of the individual blade controller, within the modified IBC structure, is to aid in the reduction of the nP disturbances. As the area under the spectrum, is the strength of that signal (in this case, the time series of out-of-plane blade bending moment), it is clear from figure 4(a), for the conditions of 16 m/s uniform wind speed and no turbulence, that the most powerful and therefore the most damaging disturbance is the 1P disturbance, where P is the rotor speed (Ω_0). With this in mind, this paper investigates the reduction of the 1P disturbance. The controller should also make the closed-loop system of figure 2 stable, which is a fundamental control objective.

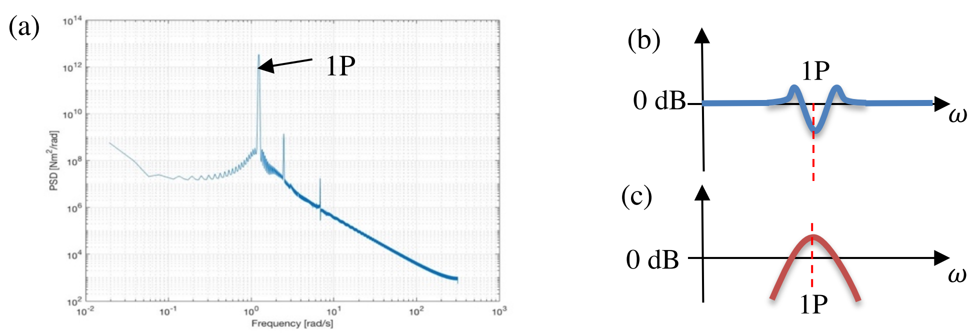


Figure 4 (a) Spectrum of the out-of-plane blade root bending moment. (b) Desired gain of sensitivity function. (c) Desired open-loop gain

In order to reduce the spectral disturbance at a specific frequency, the magnitude/gain of the sensitivity function of the simple feedback loop (i.e. 1/1+CG) shown in figure 2 has to look something like the shape shown in figure 4(b). It is the 'dip/hole' shape of the sensitivity function – the area below the 0dB line (low gain) and centred at the 1P disturbance frequency – that is responsible for reducing the power of the spectral disturbance of interest. The reason for this can be realised by considering the relationship between the spectrum of the input (disturbance, S_{dd}) and the spectrum of the output (out-of-plane blade root bending moment, S_{yy}):

$$S_{yy}(\omega) = \frac{1}{|1 + L(j\omega)|^2} S_{dd}(\omega) \tag{16}$$

where, $1/|1 + L(j\omega)|^2$ is the magnitude of the sensitivity function squared. Therefore, it is clear from (16) that whenever the sensitivity function is below 0 dB (i.e. low gain), the strength of output at those frequencies is much less than the input. Since the sensitivity function is defined as 1/(1+CG), where CG is the open-loop gain, in order to achieve sensitivity function as shown in figure 4(b), the individual blade controller C is to be designed in a way to obtain a shape of the open-loop gain with the same characteristics as shown in figure 4(c). One of the key characteristics of the desired open-loop gain is key feature is that for frequencies up to around the 1P frequency, the gain should be of a differentiator (s) and for higher frequencies, the bode plot should look like an integrator (1/s). This is achieved by designing the controller in the form of a second order transfer function multiplied by s, similar to a bandpass filter:

$$C = \frac{p\,s}{s^2 + 2\zeta\omega_n s + {\omega_n}^2}$$

where, p and ζ represent, respectively, a constant and damping ratio, which are also the tuning parameters of the controller to obtain the desired open-loop gain and closed-loop stability. The parameter ω_n represents the frequency around which the gain of the controller is to be centred, which, in this case, is fixed at the 1P frequency.

Figure 5 shows the final shape of the open-loop gain, which achieves the desired shape of the sensitivity function (also shown in figure 7) and the decay in the step response of the closed-loop system (CG/1+CG) confirms closed-loop stability.

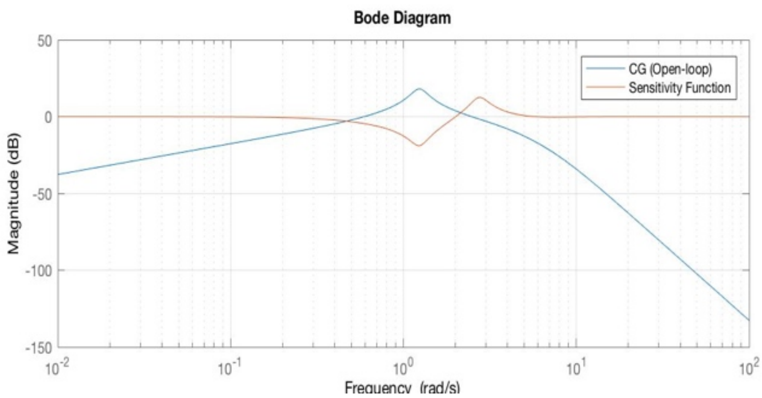


Figure 5 Open-loop gain and corresponding sensitivity function

Also, The corresponding transfer function of the individual blade controller is given by (17), where the final/tuned values of p and ζ are, respectively, 4×10^{-8} and 0.1.

$$C = \frac{-4 \times 10^{-8}\,s}{s^2 + 0.247\,s + 1.53} \tag{17}$$

4 Implementation of controller

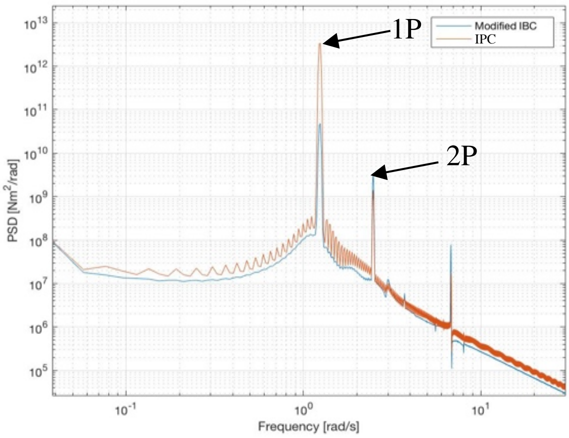


Figure 6 Comparison between the generated blade flap spectra using collective pitch and modified IBC

By implementing the structure of the modified IBC (shown in figure 1) into the Simulink model wind turbine, with the designed individual controller, the simulation is run at an uniform speed of 16 m/s (with no turbulence) and the out-of-plane blade root bending moment time series is used to generate it's PSD. This is to compare the modified IBC with the case of individual pitch control (utilised originally by the Simulink model). It is clear from figure 6 that there is a significant reduction in the 1P load (98.6% decrease). This highlights the effectiveness of the controller and success of its design.

However, there is an enhancement of the 2P disturbance observed. The change is not as significant as the change in magnitude of the 1P disturbance. This enhancement is the manifestation of the positive dB area of the sensitivity function, which has a prominent peak located in the vicinity of 2P frequency (see figure 5). This is an inevitability of controllers that as well as diminishing specific disturbances, they enhance others. The peak, above the 0dB line, in the sensitivity function can be reduced by adding filters, in the form of second order transfer function as well, in addition to the blade controllers. This is will be the foundation of future work.

5 Conclusion

In this paper, the development and implementation of the structure of the modified IBC control strategy, using a Simulink/Matlab model of a 5MW Supergen Wind Turbine, is presented. A linearized single blade model is developed algebraically and the individual blade controller is designed, with respect to this model in a simple feedback loop, successfully to achieve the necessary conditions of closed-loop stability and reducing the 1P disturbance on the spectrum of out-of-plane blade root bending moment. A significant reduction in the 1P disturbance is found, with slight enhancement of the 2P disturbance. It is shown that these enhancements are a manifestation of the prominent peak, above the 0 dB line, in the sensitivity function and the reduction of which is the source of future works through design of additional filters (i.e. second order transfer functions).

Bibliography

[1] Imeche.org. (2019). *Offshore wind power capacity 'could get 10 times bigger' to help stop UK emissions*. [online] Available at: https://www.imeche.org/news/news-article/offshore-wind-power-capacity-'could-get-10-times-bigger'-to-meet-uk-net-zero-emissions [Accessed 24 Jul. 2019].

[2] Leithead, W. (n.d.). Control of turbines. In: W. Leithead, ed.

[3] Leithead, W. (n.d.). *Modified IBC*.

[4] Leithead, W. (n.d.). *Gain-scheduling*. pp.1-7.