Wind Turbine Load Mitigation based on Multivariable Robust Control and Blade Root Sensors

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Abstract. This paper presents two $H_\infty$ multivariable robust controllers based on blade root sensors’ information for individual pitch angle control. The wind turbine of 5 MW defined in the Upwind European project is the reference non-linear model used in this research work, which has been modelled in the GH Bladed 4.0 software package. The main objective of these controllers is load mitigation in different components of wind turbines during power production in the above rated control zone. The first proposed multi-input multi-output (MIMO) individual pitch $H_\infty$ controller mitigates the wind effect on the tower side-to-side acceleration and reduces the asymmetrical loads which appear in the rotor due to its misalignment. The second individual pitch $H_\infty$ multivariable controller mitigates the loads on the three blades reducing the wind effect on the bending flapwise and edgewise momentums in the blades. The designed $H_\infty$ controllers have been validated in GH Bladed and an exhaustive analysis has been carried out to calculate fatigue load reduction on wind turbine components, as well as to analyze load mitigation in some extreme cases.

1. Introduction
In recent years, the incessant increase of wind turbines size due to the demand of higher power production installations, has led to new challenges in the design of them. Moreover, new control strategies are being developed. Today’s strategies trend towards being multi-variable and multi-objective in order to fulfill the numerous control design specifications. One of the most important specifications is to mitigate loads in the turbine components to increase their life time. The aerodynamic non-linear constitution of the wind turbines demands a robust behavior in the closed loop systems. Over the recent years, modern techniques and new control loops are being developed to improve the classical control structure performance. One of these control loops is the Individual Pitch Controller (IPC). It consists of a controller which generates independent demanded pitch signals for each blade to mitigate loads in the wind turbine based on blade root sensors’ information. The main objective of the IPC is to reduce the asymmetrical loads which appear in the rotor due to its misalignment caused by phenomena like wind shear or tower shadow. In [1, 2], decentralized d-q axes controllers based on proportional-integral (PI) controllers are proposed to solve this main objective using the Coleman transformation. Due to the coupling existing in wind turbines, other articles [3, 4] propose multivariable modern control techniques like Linear Quadratic Gaussian (LQG) controllers to carry out the IPC. On the other hand, the loads in the tower are considerably mitigated in [5] using the IPC with other sensors in wind turbines. Field tests have been done using the Controls Advanced Research Turbine (CART3) wind turbine. Other different methods based on higher harmonics or cyclic pitch controllers are developed in [6] to include other control objectives in the independent
pitch control signal. In [7], $H_\infty$ robust controllers are also used to design multivariable IPC controllers in wind turbines in order to align the rotor plane. Field tests are published in [8] using the CART turbine and $H_\infty$ multivariable controllers, where the good response of this control technique are remarked.

Initially, in this paper two baseline control strategies, C1 and C2, explained and developed in [9], are briefly summarized to compare them to the new proposed control strategies. New control strategies proposed in this paper are based on the improvement of the C2 control strategy by using blade root sensors. These strategies include two new robust MIMO controllers based on the $H_\infty$ norm reduction for individual blade pitch angle. The first proposed MIMO controller mitigates the wind effect in the tower side-to-side first mode and reduces the asymmetrical loads in the rotor. The second proposed MIMO controller mitigates the loads in the three blades. The pitch angle demanded for each blade is calculated from the independent contributions of the two MIMO controllers and the collective pitch angle obtained in the $H_\infty$ MISO Pitch Controller of the C2 control strategy.

Finally, results using the new $H_\infty$ controllers are compared to the results of the baseline controllers in order to carry out a load mitigation analysis. In this load analysis, both fatigue damage cases (DLC1.2 in IEC61400-1 Second Edition) and some extreme load cases (DLC1.6 and DLC1.9 in IEC61400-1 Second Edition) are taken into account.

2. Linear models from GH Bladed

The Upwind wind turbine defined in the Upwind European project was modelled in GH Bladed 4.0 and it is the reference non-linear model used in this research work. The Upwind model consists of a 5 MW offshore wind turbine [10] with a monopile structure in the foundation. It has three blades and each blade has an individual pitch actuator. The rotor diameter is 126 m, the hub height is 90 m, it has a gear box ratio of 97, the rated wind speed is 11.3 m/s, the cut-out wind speed is 25 m/s and the rated rotor rotational speed is 12.1 rpm. The wind turbine linear models are obtained in different operational points from the GH Bladed (version 4.0) non-linear model using the linearization tool of this software. Twelve operational points are defined from 3 m/s to 25 m/s. An exhaustive modal analysis of the model is done in [9], where the Campbell diagram is represented showing the frequencies of the structural modes of the linear model family with respect to the operational points. In the operational point of 11 m/s wind speed, the modes used throughout this paper are represented in Table 1.

| Element       | Mode                      | Freq (Hz) | Abrev. |
|---------------|---------------------------|-----------|--------|
| Drive Train   | Drive Train               | 1.66      | $M_{DT}$ |
| Tower         | 1st tower side-to-side    | 0.28      | $M_{T1ss}$ |
|               | 1st tower fore-aft        | 0.28      | $M_{T1fa}$ |

Linear models (1) are expressed by the state-space matrices and have different inputs and outputs. The inputs $u(t)$ are the collective pitch angle $\beta(t)$, the individual pitch angle in each blade $\beta_1(t), \beta_2(t), \beta_3(t)$, the generator torque control $T(t)$ and the disturbance output $w(t)$ caused by the wind speed. The outputs $y(t)$ are the sensorized measurements used to design the controller. In this case, these outputs are the generator speed $\omega_g(t)$, the tower top fore-aft acceleration $a_{tfa}(t)$, the tower top side-to-side acceleration $a_{tss}(t)$ and the bending flapwise $M_{f}(t)$ and the bending edgewise $M_{e}(t)$ momentums in the blades. Due to the non-linear model complexity, and the number of modes taken into account, the order of the linear models is 55.

$$
\dot{x}(t) = A_x x(t) + B_u u(t) + B_w w(t) \\
y(t) = C_x x(t) + D_u u(t) + D_w w(t)
$$

(1)
3. Baseline control strategies (C1 and C2)

Initially, two baseline control strategies, explained and developed in [9], are presented to compare the new proposed control strategies with them. The first baseline control strategy C1 (see Figure 1) consists of the classical control strategy defined by Bossanyi in [1] and it is based on uncoupled SISO control loops and filters. In the above rated zone two uncoupled controllers exist: collective pitch controller and generator torque controller. The generator torque controller consists of a Drive Train Damping filter. Furthermore, the collective pitch controller is a gain scheduled PI controller with some series filters to guarantee the robust behavior in this non-linear control zone. Tower Fore Aft Damping filter is included to mitigate the wind effect in the tower fore-aft first $MT_{1fa}$ mode generating a pitch angle contribution to the collective pitch control signal. The second strategy C2 (see Figure 2) is based on two robust $H_{\infty}$ multi-input single output (MISO) controllers. In C2, the first MISO controller is a generator torque controller which reduces the wind effect in the drive train $MDT$ and tower first side-to-side $MT_{1ss}$ modes. The other MISO controller is the collective pitch angle controller which controls the generator speed at the nominal value and reduces the wind effect in the wind turbine tower fore-aft first $MT_{1fa}$ mode.
4. New control objectives
The new control objectives for the developed wind turbine control strategies working in the above rated power production zone are as follows:

- To reduce the asymmetrical loads which appear in the rotor due to its misalignment.
- To mitigate the loads in the tower reducing the wind effect in the tower side-to-side first mode.
- To mitigate the loads in the blades reducing their vibrations in specific frequencies.

5. Design process of the new control strategies (C3 and C4)
Two robust MIMO independent blade pitch controllers based on the $H_\infty$ norm reduction (see Figure 3) are proposed to solve the new control objectives. The proposed $H_\infty$ IPC 1 MIMO controller mitigates the wind effect in the tower side-to-side first mode (operation removed from the torque controller in C2) and reduces the asymmetrical loads in the rotor. The second proposed $H_\infty$ IPC 2 MIMO controller mitigates the loads in the three blades. The C3 control strategy consists of the C2 control strategy with the tower side-to-side damping torque loop removed and with the $H_\infty$ IPC 1 activated. The C4 control strategy consists of the C3 control strategy and the $H_\infty$ IPC 2 controller activated. The MIMO controllers need the sensorized signals from the bending flapwise $M_{flap}$ and edgewise $M_{edge}$ momentums in the blades and the side-to-side tower top acceleration $a_{tss}$.

5.1. $H_\infty$ IPC 1 individual pitch MIMO controller with tower side-to-side damping and rotor alignment
The first step in the design of the $H_\infty$ IPC 1 is to create the nominal model which will be included in the mixed sensitivity problem to make the $H_\infty$ controller synthesis reducing the $H_\infty$ norm. To create this plant, firstly the flapwise and edgewise momentums extracted from the strain gauges in the blades are transformed [11] to the out-of-plane momentum $M_{oop}$ using the transformation $T$ (2), where $\theta_T$ and $\beta$ are the twist and pitch angle at the blade root section. The $M_{tilt}$ and $M_{yaw}$ rotor tilt and yaw momentums are obtained using the transformation (3) where $\psi$ is the azimuth angle in each blade. The tilt and yaw momentums show how the blade loads developed in a rotating reference frame are transferred to a fixed reference frame. In this case, the Coleman transformation [1] is used, and it is a change from a rotating to a fixed reference frame, so to $M_{tilt}$ and $M_{yaw}$ are proportional to the Coleman transformation outputs and the controller can be easily scaled.

The inverse of the Coleman transformation [1] $C^{-1}$ is used to transform the fixed frame to the frame in blades.

\[
M_{oop} = M_{flap} \cos(\theta_T + \beta) - M_{edge} \sin(\theta_T + \beta)
\]

(2)

\[
\begin{pmatrix} M_{tilt} \\ M_{yaw} \end{pmatrix} = \begin{pmatrix} \cos \psi_1 & \cos \psi_2 & \cos \psi_3 \\ \sin \psi_1 & \sin \psi_2 & \sin \psi_3 \end{pmatrix} \begin{pmatrix} M_{oop1} \\ M_{oop2} \\ M_{oop3} \end{pmatrix}
\]

(3)

After carrying out these transformations, the created nominal plant $G_i(s)$ is composed of the wind turbine plant linearized at the operational point of 19 m/s, the $T$ transformation and the $C$ and $C^{-1}$ transformations and it has three outputs ($a_{tss}$, $M_{tilt}$ and $M_{yaw}$) and two inputs ($\beta_{tilt}$ and $\beta_{yaw}$). The nominal plant is scaled to delimit all signals in the same range, obtaining as a result the scaled nominal plant $G_i(s)$. The $H_\infty$ mixed sensitivity synthesis method is proposed to design the controller stabilizing the plant $G_{i}(s)$ and minimizing a $H_\infty$ norm cost. The uncertainties of the family of linear models are not considered in the robust control design because the nominal plant represents all operational points in the above rated zone. For this controller synthesis, the $W_i$ matrix of weight functions is a diagonal 3x3 matrix with three weight functions $W_i=\text{diag}(W_{i1},W_{i2},W_{i3})$. $W_{i1}$ is an inverted notch filter centred on the $M_{flap}$ frequency, $W_{i2}$ and $W_{i3}$ are inverted high pass filters to guarantee the integral control activity. The $W_j$ matrix is a diagonal 2x2 matrix $W_j=\text{diag}(W_{j1},W_{j2})$. $W_{j1}$ and $W_{j2}$ are inverted low pass filters to reduce the controller activity in high frequencies. The $W_j$ matrix is an unitary 3x3 diagonal matrix. Finally, the controller designed using the Robust Control Toolbox in MATLAB is re-scaled and discretized with a sample time of 0.01s. The $H_\infty$ IPC 1 (4)
controller, represented in the state space, has three inputs \((a_{\text{Tss}}, M_{\text{tilt}}, M_{\text{yaw}})\) and two outputs \((\beta_{\text{tilt}}, \beta_{\text{yaw}})\) and its order is 54.

\[
x(k + 1) = A_{\text{ipc1}}x(k) + B_{\text{ipc1}} \begin{pmatrix} a_{\text{Tss}}(k) \\ M_{\text{tilt}}(k) \\ M_{\text{yaw}}(k) \end{pmatrix} \\
\begin{pmatrix} \beta_{\text{tilt}}(k) \\ \beta_{\text{yaw}}(k) \end{pmatrix} = C_{\text{ipc1}}x(k) + D_{\text{ipc1}} \begin{pmatrix} a_{\text{Tss}}(k) \\ M_{\text{tilt}}(k) \\ M_{\text{yaw}}(k) \end{pmatrix}
\] (4)

The \(H_{\infty}\) IPC 1 controller is analyzed in MATLAB to check the fulfilment of the control objectives (to mitigate the wind effect in the tower side-to-side first mode and to reduce the asymmetrical loads in the rotor). As Figure 4 shows, the wind effect in the tower side-to-side acceleration is mitigated at the \(M_{\text{Tss}}\) mode. This reduction is important in terms of gain analyzing the wind speed unit step response of the tower top side-to-side acceleration. The integral part of the \(H_{\infty}\) IPC 1 controller is used to control \(M_{\text{tilt}}\) and \(M_{\text{yaw}}\). Figure 4 shows the rotor tilt momentum response for a wind speed input in the frequency domain. This reduction of gain at low frequencies and the wind speed unit step response of the rotor tilt momentum confirm the integral control of the \(M_{\text{tilt}}\) with an output disturbance bandwidth near to 0.1 Hz. The results of the control of the \(M_{\text{yaw}}\) are similar to the results of the \(M_{\text{tilt}}\) channel.

5.2. \(H_{\infty}\) IPC 2 individual pitch MIMO controller to mitigate loads in the blades

Due to the coupling in the blades, a multivariable controller is needed to solve the control objectives imposed to the \(H_{\infty}\) IPC 2 control strategy (to mitigate the loads in the blades reducing their activity in specify frequencies). In this new mixed sensitivity problem, the nominal plant \(G_2(s)\) has six outputs directly from the blade sensors \((M_{\text{flap1}}, M_{\text{edge1}}, M_{\text{flap2}}, M_{\text{edge2}}, M_{\text{flap3}}, M_{\text{edge3}})\) and three individual pitch inputs \((\beta_1, \beta_2, \beta_3)\) and it corresponds to the linearized plant at the operational point of 19 m/s. The nominal plant is scaled and a new \(H_{\infty}\) mixed sensitivity synthesis method is proposed to design the controller stabilizing the plant \(G_2(s)\) and minimizing a defined \(H_{\infty}\) norm cost function. The uncertainties of the family of linear models are not considered in the robust control design because the nominal plant represents all operational points in the above rated zone. For this controller synthesis, in this case, the \(W_1\) matrix of weight functions is a diagonal 6x6 matrix with six weight functions \(W_{11}, W_{12}, W_{13}, W_{14}, W_{15}, W_{16}\) in the diagonal. These weight functions are inverted notch filters centred on the frequency of 0.146 Hz to mitigate the load activity in this frequency value. The \(W_2\) matrix is a unitary 3x3 diagonal matrix and the \(W_3\) matrix also is a unitary 6x6 diagonal matrix. Finally, the controller

![Figure 4: Analysis of the C3 control strategy](image-url)
designed using the Robust Control Toolbox in MATLAB is re-scaled and discretized with a sample time of 0.01s. The $H_\infty$ IPC 2 controller, represented in the state space, has six inputs ($M_{flap1}$, $M_{edge1}$, $M_{flap2}$, $M_{edge2}$, $M_{flap3}$, $M_{edge3}$), three independent pitch contribution outputs ($\beta_{bl1}$, $\beta_{bl2}$, $\beta_{bl3}$) and its order is 73. In Figure 5, how the wind effect in the $M_{flap}$ and $M_{edge}$ modes is mitigated around 0.146 Hz it is shown, which improves the time domain response.

6. Results in GH Bladed

The C3 and C4 control strategies are included in the External Controller in GH Bladed and different time domain simulations are carried out with the Upwind non-linear wind turbine model. The input of one of these simulations is a turbulent production wind of 19 m/s mean wind speed. In the first graph of Figure 6, the independent pitch control signals of the C4 control strategy are compared with the collective pitch signals of the baseline strategies. Figure 6 shows also the time domain response of control signals and controlled variables. In C3 and C4 control strategies the frequency activity of the electrical power is smaller because the tower side-to-side damping is performed using the independent pitch signal instead of using the generator torque. The quality of the electrical power is better using the C3 and C4 control strategies, and it is not very fluctuating near the nominal value.

The PSD (Power Spectral Density) of momentums in different parts of the wind turbine are represented in Figure 7. The C3 control strategy reduces the activity at the $IP$ frequency in the blade out-of-plane momentum $M_{oop}$ and mitigates the activity of the $M_{flap}$ momentum around $IP$. However, the $M_{flap}$ momentum hardly depends on the $IP$ frequency and it is very difficult to mitigate loads in this variable. If the pitch actuator bandwidth is bigger, the activity of the blade first in-plane momentum at 1.1 Hz in $M_{edge}$ would be reduced, but the pitch actuator bandwidth of the Upwind model.

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**Figure 5**: Analysis of the C4 control strategy

**Figure 6**: Time domain analysis with turbulent production wind of 19 m/s
is 1 Hz. The Tower Base $Mx$ momentum activity is reduced using the C3 control strategy at the $M_{TSS}$ frequency, and the Stationary Hub momentum activity is mitigated at small frequencies due to the correct alignment of the rotor plane. The C4 control strategy’s benefits can be clearly seen in the blade out-of-plane momentum $Moop$ and in other variables. In $M_{Moop}$ the activity is reduced near the frequency of 0.146 Hz considered in the controller design process. Finally, a fatigue load equivalent analysis (DLC1.2 in IEC61400-1 Second Edition) is carried out and some extreme cases are analyzed (DLC1.6 and DLC1.9 in IEC61400-1 Second Edition).

Table 2. Comparison of the load analysis

|                | Load equivalent analysis | Extreme load analysis DLC 1.6 | Extreme load analysis DLC 1.9 |
|----------------|--------------------------|-------------------------------|------------------------------|
|                | C1  m  C2  C3  C4 | C2  C3  C4 | C2  C3  C4 | C2  C3  C4 | C2  C3  C4 |
| Gen. Speed     |                          | 91.62  92.34  92.37 | 100.59  100.7  100.74 |
| Blade1MFlap    | 100  12  100  98.61 | 97.11  92.75  93.68 | 100.18  95.59  96.30 |
| Blade1MEdge    | 100  12  100.1  99.5 | 76.29  77.49  77.66 | 101.66  99.39  98.32 |
| BladeRootMx    | 100  12  100.1  101.0 | 94.98  108.97  109.01 | 99.14  97.14  98.14 |
| BladeRootMy    | 100  12  98.71  91.34 | 96.89  93.45  93.5 | 99.81  95.00  95.74 |
| BladeRootMz    | 100  12  98.69  99.09 | 89.63  90.12  89.64 | 100.45  112.41  112.00 |
| Stac Hub Mx    | 100  9  99.35  99.02 | 85.52  85.14  85.16 | 99.05  98.98  99.52 |
| Stac Hub My    | 100  9  99.2  92.84  88.56 | 95.02  66.35  67.14 | 99.31  56.06  53.87 |
| Stac Hub Mz    | 100  9  99.4  94.06  88.83 | 103.36  123.85  124.47 | 90.95  98.15  98.66 |
| TowerBaseMx    | 100  3  88.1  85.26  86.46 | 87.92  65.17  65.48 | 98.29  73.17  72.15 |
| TowerBaseMy    | 100  3  95.05  97.03  96.37 | 98.60  98.80  97.84 | 98.89  98.52  97.05 |
| TowerBaseMz    | 100  3  99.9  108.8  104.2 | 106.34  130.49  131.24 | 93.31  101.14  101.82 |

Table 2 shows the comparison of the load equivalent analysis between the four control strategies. The load percentage in the axis z using the C3 and C4 control strategies increases, but it is not important because the absolute value of the momentums in this axis is extremely low compared to the momentums in the other axes. In this Table the material m values are 3 for the tower, 9 for the hub and 12 for the blades. The BladeRootMy is reduced in 7.37% using the C3 control strategy instead of using C2. Also, StacHubMy is reduced in 6.36% and TowerBaseMx in 2.84%. Using the C4 control strategy the Blade1Mflap and StacHubMy are slightly reduced (1.5% and 4.28% respectively). Furthermore,
Table 2 shows the comparison of the extreme load analysis (DLC 1.6 and DLC 1.9). The most important improvements of the C3 and C4 control strategies appear in the StacHubMy, TowerBaseMx and BladeRootMy compared to the baseline control strategies. The StacHubMy has a reduction of 28.67% in DLC1.6 and 43.25% in DLC1.9 analysis respect to the C2 control strategy. The loads in the TowerBaseMx also have a reduction of 22.75% in DLC1.6 and 22.15% in DLC1.9.

7. Conclusions
Some conclusions can be extracted from the work carried out and presented in this paper:

• The C4 control strategy satisfies the proposed control objectives: to reduce the asymmetrical loads which appear in the rotor due to its misalignment, to mitigate the load in the tower reducing the wind effect in the tower side-to-side first mode and to mitigate the loads in the blades reducing their activity in specific frequencies.

• The load mitigation in the tower reducing the wind effect in the tower side-to-side first mode using the C3 control strategy improves the load reduction results comparing to the C2 and C1 baseline control strategies. Furthermore, the quality of the electrical power using the C3 control strategy is better than using the C2 control strategy.

• If the pitch actuator bandwidth increases, the performance of the H∞ IPC 2 controller would be better.

• The proposed control strategies are validated in GH Bladed for production and some extreme cases.

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