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F.D. Bianchi, R.S. Sánchez Peña and M. Guadayol

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Gain scheduled control based on high fidelity local wind turbine models

F.D. Bianchi[a,*], R.S. Sánchez-Peña[b], M. Guadayol[c]

[a] *IREC Catalonia Institute for Energy Research*
Josep Pla, B2, Pl. Baixa, 08019 Barcelona, Spain.
[b] *CONICET and Instituto Tecnológico de Buenos Aires*
Av. E. Madero 399, (C1106ACD) Buenos Aires - Argentina
[c] *ALSTOM Wind*
Roc Boronat 78, 08005 Barcelona, Spain.

Abstract

A new design methodology of gain scheduled controllers for wind turbines is presented. The proposed methodology is intended to deal with multi-variable and high order models as those produced by high fidelity aeroelastic simulators. The methodology consists in interpolating the local controller outputs and does not require a uniform state definition either of the local controllers or of the linear models. This allows the design of each controller independently, an essential point in cases of high order models. An aeroelastic model of a typical commercial wind turbine is used to illustrate the methodology.

Keywords: Wind energy, wind turbine control, gain-scheduling, high fidelity models.

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1. Introduction

In the last years, wind power has exhibited the highest growth rates among the renewable energy sources. It can be considered as the most promising option for replacing a significant part of the electricity produced by conventional sources [1, 2]. This is a consequence of the development of new constructions capable of increasing the efficiency and extending turbine life, which has led to a reduction of the energy costs. Control systems have had an important role in this success. In a wind turbine, the control system must provide good regulation of the captured energy and of the rotational speed, but also it must ensure that the mechanical loads do not compromise the lifetime of the components [3, 4]. Today, this last objective is becoming

*Corresponding author. Phone: +34 93 3562615 / Fax: +34 93 3563802.
Email addresses: `fbianchi@irec.cat` (F.D. Bianchi), `rsanchez@itba.edu.ar` (R.S. Sánchez-Peña)

more and more important due to the current trend towards building larger turbines with lighter and more flexible components [5].

A large number of control schemes for wind turbines has been proposed in the literature (see *e.g.* [4, 6, 7]). The control tools range from multiple PIDs with nonlinear gains to complex nonlinear strategies. Probably, the most extended tools are the gain scheduling techniques. In general, these techniques result attractive to designers due to the possibility of using the well developed linear tools, especially when the designers must deal with high order models. Many of the other techniques rely on simple descriptions of the system and are difficult to apply in complex models. Nevertheless, the complex phenomena related with mechanical loads and fatigue damages need complex models to design controllers capable of mitigating their undesired effects.

The main idea on gain scheduling control consists in designing a set of linear controllers based on the local dynamics at a set of representative operating points. Then, the global strategy is constructed by interpolating or by switching these local controllers. In general, the interpolation is preferred to the switched schemes since it provides smooth transitions among controllers. However, the implementation is more complex, especially if the controller is multi-input multi-output (MIMO). A typical solution is the interpolation of the state-space realisations but this alternative is possible only if a uniform state definition of all local controllers can be ensured [8, 9]. In addition, the interpolation of multiple controllers independently designed is a non trivial problem in the case stability and performance of the intermediate closed loop systems need to be guaranteed [10]. In a similar line, the linear parameter varying (LPV) system theory provides a formal framework with stability and performance guarantees [11, 12]. However, the design algorithms limit their use from low to medium order systems. In this case, for the same reasons, model order and MIMO, the design and implementation of these controllers would suffer important numerical problems.

This work presents a gain scheduling strategy for wind turbines based on the output interpolation of a set of local controllers designed independently. The methodology is intended to deal with high order models as those produced by high fidelity aeroelastic simulators. In these cases, the design of the local controllers relies on a set of linear models obtained in several operating points by linearisation, in which is not possible to ensure a uniform state definition. The local controllers are designed with $\mathcal{H}_\infty$ optimal control tools due to the high order and the MIMO nature of the models. This methodology also allows to consider the modelling errors produced by linearisation and model order reduction procedures.

The paper is organised as follows. In the next section, a brief description of the control of wind turbines is presented. Section 3 contains the main contributions. Firstly, the modelling of turbines from aeroelastic codes is discussed. Then, the gain scheduling scheme and the local controller designs are introduced. The section ends with the discussion of an anti-windup strategy in order to avoid the performance degradation caused by the actuator saturation. In Section 4, the control strategy is illustrated by nonlinear simulations corresponding to a typical commercial wind turbine described by a high-fidelity aeroelastic model. Finally, Section 5 summarises our conclusions.

2. Control of variable-speed variable-pitch wind turbines

The power P_r captured by a wind rotor of radius R facing an airflow of speed V and density ρ is

$$P_r = \frac{1}{2}\pi R^2 \rho C_P(\lambda, \beta) V^3, \tag{1}$$

where C_P describes the turbine aerodynamics. This power coefficient is a nonlinear function of the pitch angle β and the tip-speed-ratio $\lambda = R\Omega_r/V$, with Ω_r being the rotational speed. This equation reveals that the pitch angle and the rotational speed permit to control the energy captured by the wind turbine. The pitch actuator rotates the blades around their longitudinal axes modifying the aerodynamic characteristics of the wind rotor. The rotational speed is influenced by the pitch angle but also by the resistant torque produced by the electric generator. This last torque is controlled by a power converter acting on the power flow between the generator and electrical grid. The transmission system connects the rotational speed Ω_r with the generator speed Ω_g.

The purpose of the control system is to regulate the electrical power P_e and the generator speed Ω_g. Figure 1 shows the stationary values of the pitch angle β, the generator speed Ω_g and the electrical power P_e corresponding to a common control strategy. In the operating range defined by the cut-in speed V_{in} and the cut-off speed V_{out}, two operating modes can be observed. In the partial load mode ($V < V_{\text{N}}$), the kinetic energy in the wind is not sufficient to reach the rated power production P_{N}. Usually, in this circumstance, the control aims to maximise the wind power extraction, which implies to maintain $C_P(\beta, \lambda)$ at its maximum value $C_{P_{\max}} = C_P(\beta_{\max}, \lambda_{\max})$. To achieve this objective, the reference power P_{ref} is modified in order to track the predefined rotational speed curve $\Omega_{\text{ref}} = \lambda_{\max}\hat{V}/R$, where $\hat{V}$ denotes an estimation of the wind speed. The optimal power curve tracking is employed until the rotational speed arrives at its nominal value Ω_{N}. From this point, the rotational speed is maintained close to Ω_{N}. On the other hand, the full load mode ($V > V_{\text{N}}$) is characterised by the need of regulating the electrical power and the rotational speed around their rated values. In high wind speeds, the wind power exceeds the nominal electrical power and both pitch and power references must be used to avoid overloading the system.

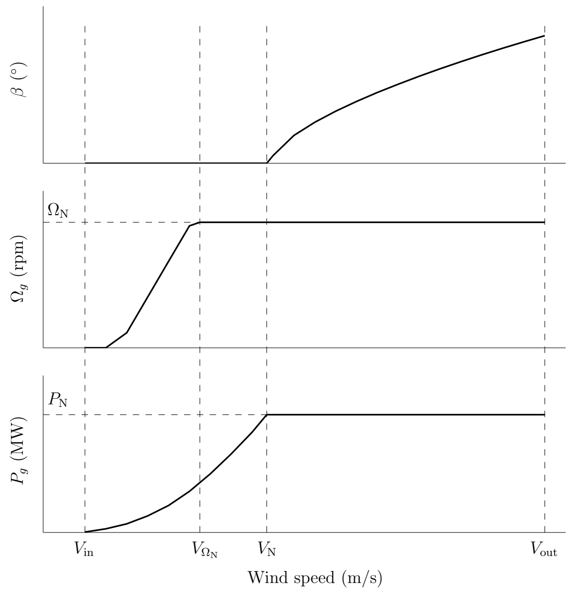

Figure 1: Operating points corresponding to a common control strategy

In addition to the aforementioned specifications, the control must also fulfil the following requirements [3]:

- To minimise the mechanical loads and accelerations, especially in drive train and the fore-aft movements, in order to reduce the fatigue damages. The effect of the loads is estimated with a performance index based on the equivalent load calculation [13]. In fact, this requirement may become the most important one since the useful life and the cost per kW depend mainly on the mechanical loads and vibrations.
- The control variables must be kept under their limits, special attention must be paid to the pitch angle which can operate near the saturation limits. Also, the first and second derivatives of the pitch angle must be bounded. As a general rule, the actuator activity must be as low as possible.

These last specifications are more important in full load mode due to the magnitude of the involved variables.

3. Gain scheduling control based on high fidelity models

In this section, a gain scheduling approach for high order models obtained under a "black box" concept is proposed. The aim of this methodology is to enable an independent design of each local controller without demanding a uniform state definition in each of them. This is essential to deal with high order models as those produced by high fidelity simulators.

3.1. Wind turbine model for control design

Wind turbines are complex mechanical systems with several flexible structures moving and interacting among them. This makes the modelling of wind turbines a very challenging task. For the control design purpose, turbines are usually described by simple parametric models fitted by identification or validation procedures. These models are useful to describe electrical aspects of the wind turbine and fairly simple phenomena associated with mechanical loads. However, the full complexity of the wind turbine movements including the vibrations causing fatigue damages can only be accurately captured by aeroelastic codes. Unfortunately, these models are too complex to be employed in the controller design without any previous manipulations.

The appeal of gain scheduling techniques is that the control can be obtained from linearisations of the system. That is, to design the gain scheduled controller, it is sufficient to have a set of linear models describing the local dynamic behaviour at a set of representative operating points $\{\varphi_i,\ i = 1, 2, \ldots, n\}$. These models can be obtained by identification or by linearisation modules usually provided with the aeroelastic codes. Each element of the set of systems

$$\mathcal{G} = \{G_i(s), \quad i = 1, 2, \ldots, n\},$$

is associated to an operating point φ_i indexed by the scheduling variable θ. An estimation of the wind speed can be chosen as a scheduling variable.

Typically, the model inputs are the wind speed V, the pitch angle reference β_{ref} and the power reference P_{ref}. The first one is a disturbance whose effect on the output must be attenuated and the others are used as control variables. The outputs to be controlled are the generator speed Ω_g and the electrical power P_e. Additionally, variables associated with fatigue phenomena such as the fore-aft acceleration η_x can be also included in the output vector. Therefore, at each operating point $\varphi_i = \varphi(\theta_i)$ the input-output relation is given by

$$y = \begin{bmatrix} \eta_x \\ \Omega_g \\ P_e \end{bmatrix} = G_{1,i}(s)V + G_{2,i}(s) \begin{bmatrix} \beta_{\text{ref}} \\ P_{\text{ref}} \end{bmatrix}.$$

In general, the order of the linear models produced by the aeroelastic codes is too high to be used in the controller design. With the aim of making the controller designs more tractable, it is recommended to apply a model order reduction procedure. This algorithm eliminates the less controllable or less observable states, *i.e.*, those states less visible from the input-output behaviour viewpoint [14]. In Figure 5, examples of maximum singular values[1] of $G_{2,i}(s)$ and its reduced order version for several wind speeds can be observed.

The modelling errors caused by the order reduction and also by the linearisation can be included in the controller design in the form of model uncertainty. The difference between the model and the real system must be taken into account because these errors may affect the stability and the performance. To this end, each linear system is represented as a family of models in the form

$$\tilde{G}_i(s) = G_i(s) + W_{\Delta,i}(s)\Delta_i(s), \quad i = 1, 2, \dots, n$$

where Δ_i is any LTI[2] system such that $\|\Delta_i\|_\infty \leq 1$ and $W_{\Delta,i}(s)$ reflects the frequency distribution of the errors[3]. Commonly, this weighting function is given by

$$W_{\Delta,i}(s) = \frac{k_{\Delta,i}(1 + s/2\pi f_{\Delta,i})}{(1 + s/2\pi c_{\Delta,i} f_{\Delta,i})} I, \quad c_{\Delta,i} > 1 \tag{2}$$

which indicates that the error is smaller in low frequencies and larger in high frequencies, as in most of the electro-mechanical systems. In order for a controller $K_i(s)$ to guarantee stability for any plant in $\tilde{G}_i(s)$, the condition $\|K_i(I + G_i K_i)^{-1} W_\Delta\|_\infty < 1$ must be held (see *e.g.* [15, 16]).

3.2. Gain scheduled controller

As mentioned, it is assumed that the only available information about the nonlinear system is a set of linear models $\mathcal{G}$ describing its local behaviour at a set of operating points $\{\varphi(\theta_i),\ i = 1, 2, \dots, n\}$. Furthermore, it can not be ensured that the $G_i(s)$'s share the same state definitions since they are obtained by numerical linearisation. In this circumstance, each controller needs to be designed independently and then interpolated in some way in order to construct the gain scheduled controller.

In general, interpolation is a fairly simple solution in the cases of single-input single-output problems or fixed structure controllers, due to the fact that only certain fixed parameters are interpolated, *e.g.* gains, poles, numerator/denominator coefficients. However, in more general cases where the set of controllers have been designed independently and they are MIMO, the implementation of the parameter interpolation is not as simple [10]. The option of interpolating the controller state-space realisations is not available since the non-uniform definition of the controller states may cause unexpected results. A possible solution in this case is the interpolation of the outputs or the inputs of the controllers.

[1]The maximum singular value is defined as $\bar{\sigma}(A) = \max_i \sqrt{\lambda_i(A^T A)}$, and represents a norm of a matrix.

[2]Linear, time-invariant.

[3]Where $\|G\|_\infty$ denotes the infinity norm of $G(s)$, *i.e.*, $\|G\|_\infty = \max_{u \neq 0} \frac{\|y\|_2}{\|u\|_2}$, with $\|y\|_2^2 = \int_0^\infty y^T y \, dt$.

Assuming that the local controller is governed by

$$K_i : \begin{cases} \dot{x}_{k,i} = A_{k,i} x_{k,i} + B_{k,i} e, \\ u = C_{k,i} x_{k,i} + D_{k,i} e, \end{cases} \quad i = 1, 2, \ldots, n, \tag{3}$$

in a output interpolation scheme, the gain scheduled controller is constructed in the form

$$K(\theta) : \begin{cases} \dot{x}_k = \begin{bmatrix} A_{k,1} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & \cdots & A_{k,n} \end{bmatrix} x_k + \begin{bmatrix} B_{k,1} \\ \vdots \\ B_{k,n} \end{bmatrix} e, \\ u = \sum_{i=1}^{n} \alpha_i(\theta) C_{k,i} x_{k,i} + \sum_{i=1}^{n} \alpha_i(\theta) D_{k,i} e, \end{cases} \tag{4}$$

where the parameters α_i's are functions of the scheduling variable θ defined as

$$\alpha_i(\theta) = \begin{cases} 0, & \theta < \theta_{i-1} \text{ or } \theta \geq \theta_i; \\ \dfrac{\theta - \theta_{i-1}}{\theta_i - \theta_{i-1}}, & \text{otherwise} \end{cases}$$

and the set of linear controllers $\{K_i(s), \quad i = 1, 2, \ldots, n\}$ is associated to a grid of values of the scheduling variable $\Theta = \{\theta_i, \quad i = 1, 2, \ldots, n\}$, with $\theta_i < \theta_{i+1}$.

Thus, given the real-time value of the scheduling variable θ, the control variable is computed as a linear combination of the outputs of the two controllers corresponding to the pair of the closest points in the grid Θ to the value θ. For instance, if $\theta_j \leq \theta < \theta_{j+1}$, $\alpha_i \neq 0$ only for $i = j, j+1$, then from an input-output viewpoint the controller results as follows

$$K(\theta) : \begin{cases} \begin{bmatrix} \dot{x}_{k,j} \\ \dot{x}_{k,j+1} \end{bmatrix} = \begin{bmatrix} A_{k,j} & 0 \\ 0 & A_{k,j+1} \end{bmatrix} \begin{bmatrix} x_{k,j} \\ x_{k,j+1} \end{bmatrix} + \begin{bmatrix} B_{k,j} \\ B_{k,j+s} \end{bmatrix} e, \\ u = (\alpha_j(\theta) C_{k,j} x_{k,j} + \alpha_{j+1}(\theta) C_{k,j+1} x_{k,j+1}) + \\ \qquad + (\alpha_j(\theta) D_{k,j} + \alpha_{j+1}(\theta) D_{k,j+1}) e. \end{cases}$$

Notice that the other controllers are still present but their effect on the input-output behaviour is not visible. The accuracy of this method therefore depends on the accuracy of the local controller designs, presented in the following subsection.

In the case of wind turbines, the operating conditions are determined by the effective wind speed V and thus this variable is commonly used as a scheduling parameter. However, this variable is actually a fictitious signal that represents the effect of a three-dimensional field distributed in the whole wind rotor and the rest of the turbine structure. Therefore, the effective wind speed must be computed in real-time from other signals such as generator torque and generator speed.

3.3. Local controller design

In the previously described gain scheduling scheme, the local controllers can be designed with any linear tool. However, the high order of the plants and the need for considering the modelling error caused by the model order reduction and the linearisation errors recommend the use of robust techniques such as $\mathcal{H}_\infty$ optimal control or μ-synthesis [15, 16].

In $\mathcal{H}_\infty$ optimal control, the design problem is stated in terms of the minimisation of the relation between the energy of an input w and the energy of an output z representing the control specifications. Therefore, the first step in the controller design consists in identifying the so-called disturbance w and the performance variable or error z. Afterwards, functions weighting these inputs and outputs are selected. In general, these weights are dynamic systems, represented as linear fractional functions of the complex variable s, that help to put more emphasis on certain frequency ranges where the relation $w \to z$ must be minimised. The open loop interconnection of the plant with these weighting functions is denoted as the augmented plant.

In Figure 2, the particular augmented plant for the design of wind turbine local controllers can be seen. The input is $u = \begin{bmatrix}\beta_{\mathrm{ref}} & P_{\mathrm{ref}}\end{bmatrix}^T$ and the measured output is $y = \begin{bmatrix}\eta_x & \Omega_g & P_e\end{bmatrix}^T$. The wind speed V is regarded as the disturbance w. The performance specifications are translated into this format by selecting as performance output $z = \begin{bmatrix}\tilde{e} & \tilde{u}\end{bmatrix}^T$. These variables are obtained after weighting with

$$
\begin{aligned}
W_e(s) &= \begin{bmatrix} k_{e1}\dfrac{1+s/2\pi f_{e1}}{1+s/2\pi c_{e1} f_{e1}} & 0 & 0 \\ 0 & \dfrac{k_{e2}}{s} & 0 \\ 0 & 0 & \dfrac{k_{e3}}{s} \end{bmatrix} && (5) \\
W_u(s) &= \begin{bmatrix} k_{u1}\dfrac{1+s/2\pi f_{u1}}{1+s/2\pi c_{u1} f_{u1}} & 0 \\ 0 & k_{u2}\dfrac{1+s/2\pi f_{u2}}{1+s/2\pi c_{u2} f_{u2}} \end{bmatrix} && (6)
\end{aligned}
$$

where $c_{e1} < 1$, $c_{u1} > 1$, $c_{u2} > 1$.

The elements $(2, 2)$ and $(3, 3)$ of $W_e(s)$ aim to reduce the low frequency errors in the rotational speed and in the electrical power, respectively. On the other hand, the element $(1, 1)$ stresses the fore-aft acceleration η_x in order to minimise the mechanical loads. The purpose of the other weighting function W_u is to limit the control variables, especially the pitch actuator activity. This function also covers the uncertainty weight with the purpose of limiting the controller bandwidth and preventing unstable behaviours due to high frequency modelling errors. Typical frequency responses for these weights can be observed in Figure 3. The parameters of these functions are

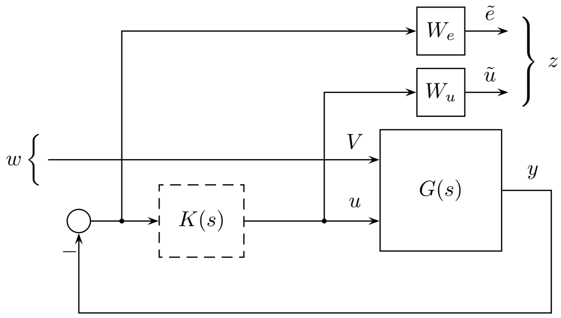

Figure 2: Plant augmented with weighting functions

fixed at each operating point to achieve the desirable performance. The order of each controller is given by the order of the augmented plant. Nevertheless, it is possible to apply an order reduction procedure to simplify the controller implementation.

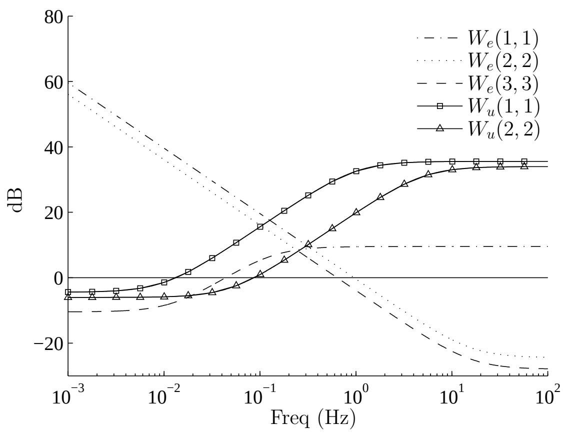

Figure 3: Typical frequency responses for weights $W_e(s)$ and $W_u(s)$.

This control setup needs just simple modifications in order to design the controller in partial load mode. In this case, the control variable is P_{ref} and the controlled output is $y = \begin{bmatrix} n_x & \Omega_g \end{bmatrix}^T$. The objective is to control only the rotational speed and fore-aft acceleration. The pitch angle is close to its minimum and does not provide additional control action. Therefore, the weights reduce to

$$
\begin{aligned}
W_e(s) &= \begin{bmatrix} k_{e1}\dfrac{1+s/2\pi f_{e1}}{1+s/2\pi c_{e1} f_{e1}} & 0 \\ 0 & \dfrac{k_{e2}}{s} \end{bmatrix} \\
W_u(s) &= k_{u1}\frac{1+s/2\pi f_{u1}}{1+s/2\pi c_{u1} f_{u1}}
\end{aligned}
$$

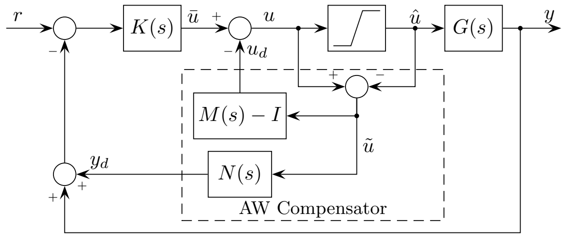

Figure 4: Anti-windup compensation scheme

with $c_{e1} < 1$, $c_{u1} > 1$ and the variables to minimise are

$$z_1 = W_e(s) \begin{bmatrix} n_x \\ \Omega_g \end{bmatrix} \qquad\qquad z_2 = W_u(s) P_{\text{ref}}.$$

3.4. Anti-windup compensation

Both control variables can reach their saturation limits, especially the pitch angle. Therefore, it is important to include an anti-windup (AW) compensation strategy in each controller in order to avoid the subsequent performance degradation. The AW compensation employed is sketched in Figure 4 and it was proposed by Weston and Postlethwaite [17]. This strategy provides a systematic design procedure suitable for high order MIMO systems.

In this AW compensation, it is assumed that the plant $G(s)$ is stable and the controller $K(s)$ is stabilising. It is also assumed that the controller achieves the desirable performance when the actuator works in the linear zone ($\tilde{u} = 0$). The AW compensator adds a signal at the input and another at the output when the saturation occurs. It can be proved that the saturation effect depends only on the response of the filter $N(s)$ and the nonlinear loop formed by $M(s) - I$ and the dead zone nonlinearity. Then, to reduce the negative effects on the performance caused by the windup, the AW compensator must ensure the stability of the nonlinear loop and minimise the signal y_d when $\tilde{u} \neq 0$. From the small gain theorem, it can be concluded that the stability of the nonlinear loop is guaranteed if $||M(s) - I||_\infty < 1$ [15, 16]. On the other hand, the attenuation of the signal y_d can be achieved by imposing a bound γ on the relationship between the energy of $\tilde{u}$ and the energy of y_d, *i.e.*, $||N(s)||_\infty < \gamma$.

In the work by Weston and Postlethwaite [17], it is recommended to take $M(s)$ and $N(s)$ as the coprime factors of $G(s)$, which implies that

$$G(s) = M(s)^{-1} N(s).$$

These coprime factors can be obtained by solving a simple state feedback problem (see *e.g.* [15, 16]), with which the AW compensator can be found by solving an optimisation problem with LMI constraints [18].

4. Simulation results

The previous ideas have been applied to a 3 MW wind turbine, modelled with a high fidelity aeroelastic code including the most significant flexible modes for blades, tower and drive train. Three-dimensional turbulent wind fields have been used in order to take into account the temporal and spatial distribution of the wind.

The nonlinear model was linearised at 23 equally spaced operating points from 3 to 25 m/s. The order of the linear model was reduced four times down to order 12 by applying the Hankel model order approximation method. The maximum singular values of the $G_{2,i}(s)$ and its reduced order version corresponding to wind speeds from 3 m/s to 25 m/s can be observed in Figure 5. The differences between the full order model and the reduced one were covered by the additive uncertainty representation discussed in Section 3.1. Note that the largest differences are produced at high frequencies, in accordance with the usual practice for electromechanical devices. These reduced models were used to compute the corresponding controllers with $\mathcal{H}_\infty$ optimal control tools. Hence, this approach produces lower order controllers which are easier to simulate and implement. In addition, the high frequency uncertainty coverage induces controllers with lower frequency dynamics which in turn produces a smoother actuator response. This is specially important for the pitch angle control.

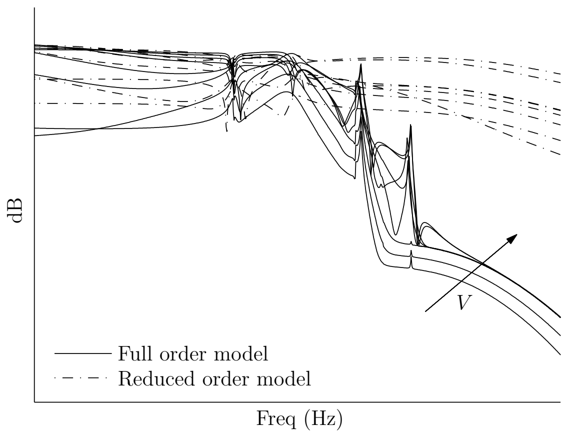

Figure 5: Maximum singular values of the $G_{2,i}(s)$ and its reduced order version at several wind speeds.

The augmented plant is depicted in Figure 2 and the weighting functions are given in (5)-(6). The parameters in the weighting functions were adjusted in order to achieve similar responses at each operating point. In Figure 6, the local closed loop responses corresponding to $\mathcal{H}_\infty$ controllers at three different wind speeds are shown. The wind profiles in this case have been selected to ensure that only the local dynamics are excited. It can be observed that

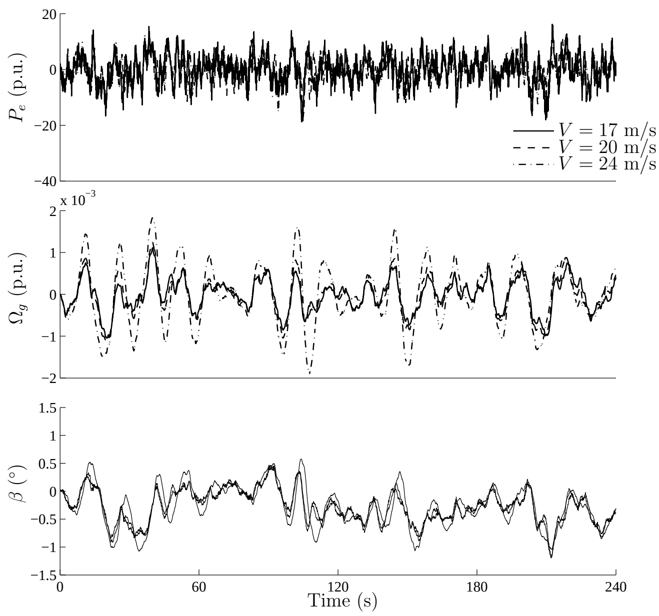

Figure 6: Local closed loop responses at several wind speeds.

a suitable control of the electrical power and the rotational speed in all cases with a reasonable activity of the pitch angle has been achieved. These results are in accordance with the industrial requirements.

The simulation results of the local controller designed for the 9 m/s model have revealed that in partial load this controller is able to provide a reasonable performance in the rest of the points, ranging from 3 to 12 m/s. The other local controllers are designed one for each wind speed ranging from 13 to 25 m/s, providing a total of 14 LTI controllers. Next, the gain scheduled controller was assembled according to the output interpolation scheme presented previously. This controller was tested by nonlinear simulations with a high-fidelity commercial aeroelastic model which represents a standard in these applications. Figure 7 shows the response of the system to a simple increasing wind profile. The solid lines correspond to the proposed control strategy and the dashed lines to an available and fully functional classical controller, which has been applied to the actual wind turbine. In this circumstance, the new strategy presents a better regulation of the electrical power and of the generator speed with a fairly similar pitch activity.

On the other hand, in Figure 8 the response of the closed loop system to a more realistic wind profile suggested in the certification standards can be observed. The response of the classical controller can be also observed in this figure. In the range from 50 to 100 seconds, it can be noted that the AW-compensator is capable of dealing with the saturation of the pitch

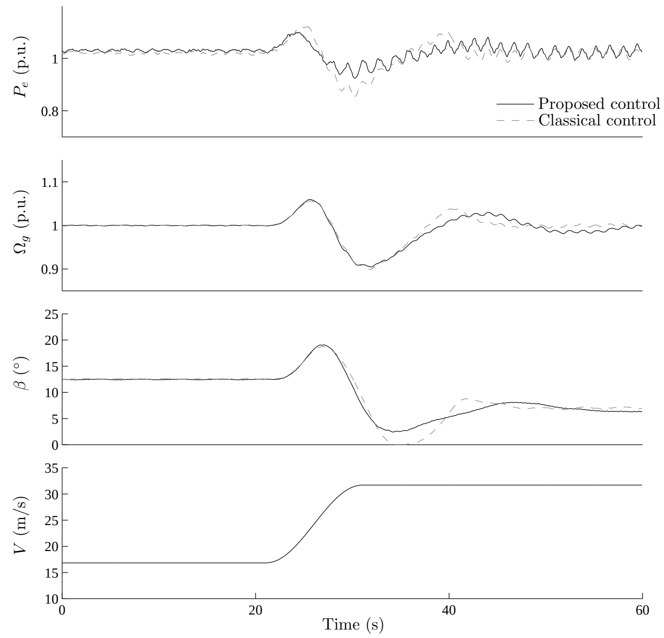

Figure 7: Nonlinear simulations of the proposed gain scheduled controller corresponding to an increasing wind profile.

actuator when the wind speed falls under 12 m/s. On the other hand, the regulation of the generator speed and the electrical power results similar to those predicted with the local models and a certain improvement with respect to the previous control can be noticed. The evaluation of the performance indexes based on the equivalent load calculation [13] reveals a slight improvement with the new controller, a 7.5% reduction in the fore-aft load and a 2.7% in the blade root load. The computation of these indexes, used to measure the fatigue loads, is described in [13] and the simulations lasted 600 s in accordance with certification standards.

As a result, the new controller provides similar or even better results than a classical one. Nevertheless, the main point here is that this gain scheduled controller has been designed with powerful up-to-date tools in a systematic way. There was no predefined structure for the controllers which may already fix their model order, and the resulting performance can be maximised. Our approach aims to reduce the number of iterations demanded in the case of classical designs. In addition, this method does not require a designer with an extensive knowledge in wind turbine dynamics.

5. Conclusions

A new gain scheduling strategy for wind turbines has been proposed. The design philosophy is based on the use of up-to-date high order aeroelas-

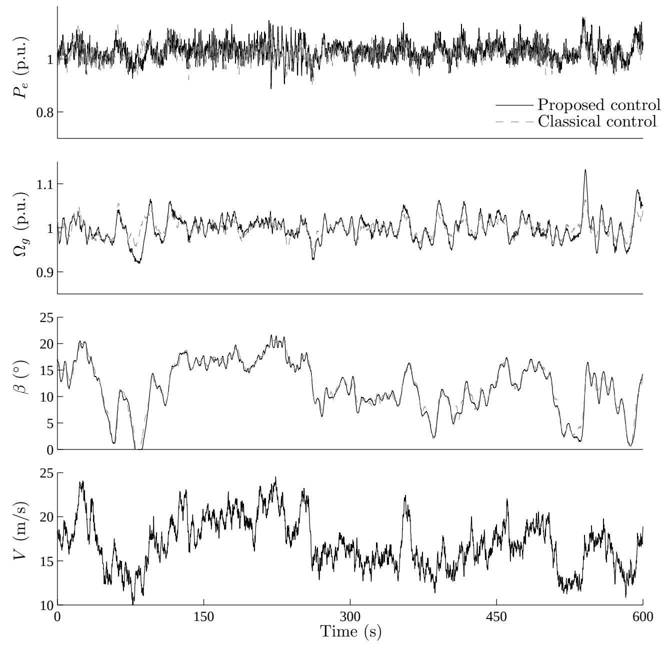

Figure 8: Nonlinear simulations of the proposed gain scheduled controller corresponding to a standard 17 m/s wind profile.

tic models, MIMO robust control design, model order reduction tools, and output controller interpolation to produce a systematic means of controlling wind turbines. The controllers are designed only with the information provided by a set of local linear models and it does not require a uniform definition of the states neither of the plant nor local controllers. Therefore, these can be computed independently with any linear design tool. The proposed procedure permits a certain simplification on the modelling stage by avoiding complex and tedious nonlinear identification procedures. In addition, the use of robust linear tools includes the modelling errors as a part of the controller designs.

A further study needs to be carried out in order to improve the performance on the proposed model-based control scheme. This is due to the fact that the high fidelity codes are aimed to simulate and include dynamics that are not directly related to the control objectives. Therefore, extracting a better control-oriented model from these codes would increase the overall performance. However, this is not a simple task.

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