Robust Gain Scheduling Controller for Pitch Regulated Variable Speed Wind Turbine

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Abstract: The paper deals with the design of a control system for a variable-speed pitch-regulated wind turbine. The control objectives of such system are mostly to ensure a good energy conversion performances and to reduce the mechanical stresses of the plant components. For the different operating areas of the plant, the non linear behavior of the system is described by a polytopic model and a robust linear parameter varying (LPV) controller is designed in order to minimize the multiobjective H_2 / H_∞ performance of the closed loop system from a linear matrix inequality (LMI) formulation of the problem. For each operating area, the designed controller is robust to the evolution of the plant parameters with changing operating conditions. The controller performances are then compared in simulation with those of a gain scheduling linear quadratic gaussian (LQG) controller, and is seen to be much more efficient especially for alleviation of mechanical stresses on the plant drive train.

Keywords: Wind Turbine, LPV control design, LMI optimization, mechanical stresses.

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1. INTRODUCTION

Wind energy has widely grown during the last decades and nowadays is the most competitive form of renewable energy. Nonetheless, wind energy is not yet cost effective. In consequence, the development of new technology will be crucial that the wind energy penetrates into electricity market successfully. Implementation of advanced control systems is considered as a promising way to improve wind turbine conversion system and to decrease wind energy cost [18][22]. Wind turbine control objectives are mainly to optimize wind energy conversion, and to reduce dynamic loads experienced by the plant mechanical structure [7][15]. Dynamic loads hardly affect the lifetime of wind turbines and mainly determine mechanic components design [3][18].

Wind energy conversion systems are receiving considerable interest from control community, especially concerning pitch regulated, variable speed wind turbines, which have the highest potential to reach effective cost [22]. Control system of this kind of plant is then multivariable because it can act on both electromagnetic generator torque and blades pitch angle. Designing this control system presents several issues: the system behavior is both highly non linear and quite uncertain, especially because of blades aerodynamic properties which are sensitive to climatic conditions [13]. Moreover, the control purpose is a multiobjective task, because the control system has to optimize a trade off between energy conversion maximization and alleviation of mechanical dynamic loads due to very lightly damped resonant modes of the system [14][21]. The wind turbine operation is also decomposed into several operating zones, depending on the wind speed through the rotor: for low wind speed, wind energy system has to maximize produced power, whereas for high wind speed, electric power has to be maintained to the generator nominal power. Another issue of this wind turbine control problem is the uncontrollable and stochastic nature of the main component acting on the plant: the wind speed. Moreover, effective wind speed acting on the whole turbine rotor is a fictitious quantity and is thus not measurable nor available for control operation [11][15].

Various control synthesis options have been applied in response to wind turbine control problem, such as PI controllers [10], LQG controllers [11], fuzzy logic controllers [24] or optimal robust control [6][8]. Most of time, provided controllers are designed around an operating point and are valid only for a narrow range of operation which does not cover the whole operating range. Few works treat wind turbine non linear control problem by using gain scheduled controller. Proposed gain scheduled controllers are based on interpolation of several linear controllers designed for specific operating points [4][12][17]. Therefore, using linear controllers interpolation, closed loop stability is guaranteed only for sufficient slow system parameters variations, whereas wind speed is a highly stochastic component which can vary very quickly. However, stability guarantees are to be provided in order to prevent system from destabilizing and thus from experiencing large load fluctuations [13]. In [5], a Linear Parameter Varying (LPV) controller is proposed for a stall regulated wind turbine, minimizing H_∞ norm between wind speed disturbance and controlled outputs, and provides good results in simulation. Therefore, stall regulated wind turbines operate at a fixed pitch angle and are thus less effective than pitch regulated ones [22].

In this paper a robust gain scheduled controller synthesis for pitch regulated, variable speed wind turbines is presented for the two main areas of operation of the system and takes into account main issues of the referent control problem. For each operating range, the wind turbine behavior is described by a polytopic model with parametric uncertainties, and optimal LPV control techniques are employed for controller synthesis, via a Linear Matrix Inequalities (LMI) formulation of closed loop system constraints. Hence, a multichannel H_2 / H_∞ controller is synthesized in order to optimize a trade off between different control objectives.

The paper is organized as follows. Firstly the wind energy conversion system is described and modelled in view to control synthesis. Then, the control task and the control objectives are defined. Theoretical concepts and tools are then presented before being applied to the studied system. Finally, the performances of the proposed controller are compared, at the sight of simulation results, with a gain scheduling optimal Linear Quadratic Gaussian (LQG) controller for the two studied operating regions.

2. Modelling of the System

2.1. System Description

The structure of a variable speed, pitch regulated wind energy conversion system is presented in Figure 1. The system is formed by the wind turbine, the drive train, and by a generator unit, composed by the generator and the static converter connected to the electrical grid. The control system acts on generator in order to apply the reference electromagnetic torque $T_{G,ref}$ and on the pitch actuator in order to control the pitch angle of the blades.

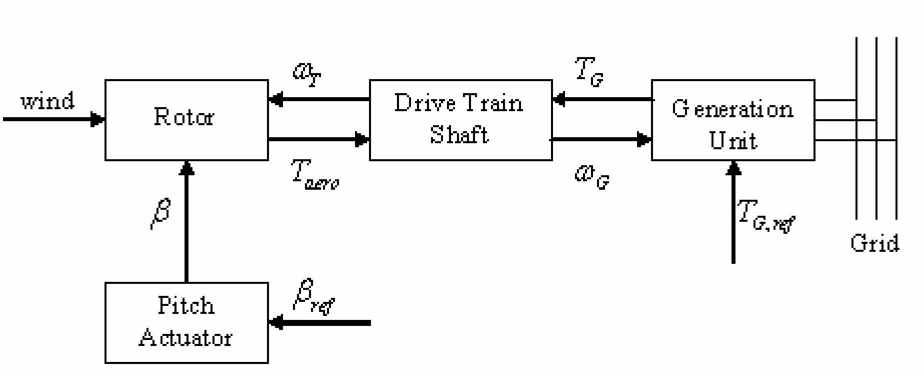

Figure 1. Wind Energy Conversion System Structure.

The aerodynamic torque T_{aero} extracted by the turbine from the wind is a function of the air mass density ρ, the wind velocity v, the rotational speed of the turbine ω_T and the power coefficient C_p:

$$T_{aero} = \frac{1}{2}\rho\pi R^2 \frac{v^3}{\omega_T} C_p \tag{1}$$

with R the length of the rotor blades. The power coefficient C_p is a non linear function depending on blades pitch angle β and tip speed ratio λ defined by the relation:

$$\lambda = \frac{\omega_T R}{v} \tag{2}$$

Figure 2 represents typical curves of $C_p(\lambda, \beta)$ for a commercial variable speed, pitch regulated wind turbine.

The mechanical subsystem connecting the wind rotor to the generator is described by a flexible shaft with one resonant mode. Thus, this subsystem is modelled by a two inertia model connected by a spring and a damper. Drive train torsional torque T_D experienced by the flexible shaft is then expressed by:

$$T_D = d\left(\omega_T - \omega_G\right) + k\left(\theta_T - \theta_G\right) \tag{3}$$

where d is the damping coefficient, k the stiffness coefficient, ω_G the generator rotational speed, θ_T and θ_G the angular positions of the shaft at the rotor and generator sides.

The electrical subsystem, corresponding to the generation unit, composed by the generator and the power electronic components, has very fast dynamics compared with dynamics of the other subsystem. Consequently, and considering the objectives of the study, electrical dynamics are neglected. Hence, electromagnetic torque T_G is supposed equal to its reference $T_{G,ref}$.

The pitch actuator subsystem represents the hydraulic or electric system which makes the blades revolve around their lengthwise axis. This system is described by a first order transfer function with a time constant T_β.

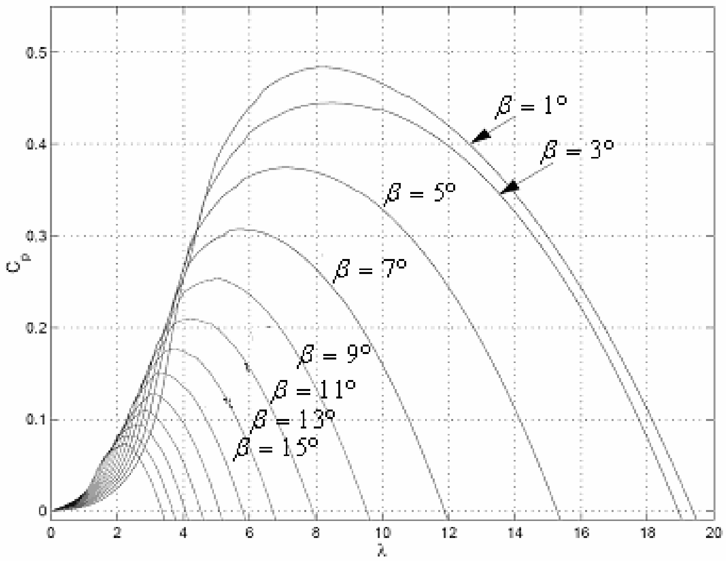

Figure 2. Power Coefficient $C_p(\lambda, \beta)$ Curves.

2.2. Wind Model

In addition to the plant model, a wind model is established for the control design model. Wind velocity in a fixed point of space has known properties in the frequency range, represented by the Van der Hoven spectrum (Figure 3). Two main components appear in this spectrum: a slow time varying component, representing seasonal value $v_m(t)$ of wind speed, and a turbulent one $v_t(t)$. A model of the power spectrum of the turbulent part $\Phi_v(\omega)$ is proposed by von Karman [11][19]:

$$\Phi_v(\omega) = \frac{K}{\left(1 + (T_v\omega)^2\right)^{\frac{5}{6}}} \quad (4)$$

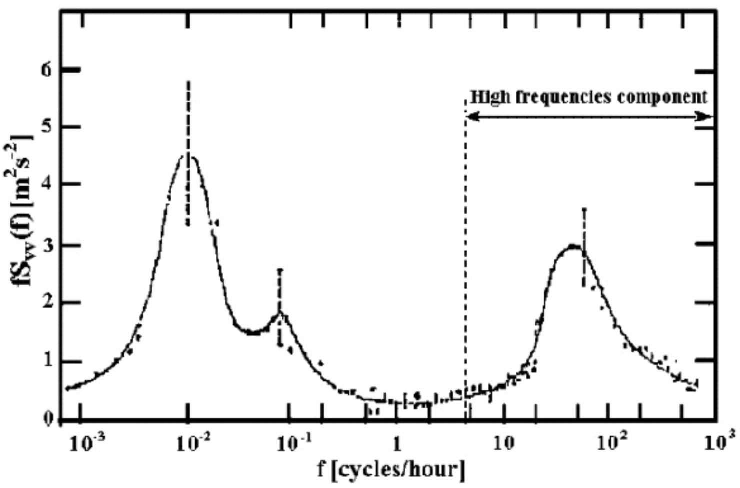

Figure 3. Spectrum of Horizontal Wind Speed

For the control synthesis purpose, a linear model of turbulent part $v_t(t)$ is employed, composed by a first order filter disturbed by a Gaussian white noise $m_v(t)$ [11]:

$$\dot{v}_t = -\frac{1}{T_v} v_t(t) + m_v(t) \tag{5}$$

The power spectrum corresponding to this linear model is:

$$\Phi_v(\omega) = \frac{K}{\left(1 + \left(T_v \omega\right)^2\right)} \tag{6}$$

and represents an acceptable approximation of (4). Time constant T_v of (5) and standard deviation of $m_v(t)$ are depending on the mean wind speed $v_m(t)$:

$$T_v = \frac{L}{v_m}$$

$$\sigma_m = k_{\sigma,v} v_m$$

where the turbulence length scale L and the parameter $k_{\sigma,v}$ are proper to plant installation site and have to be determined experimentally [19].

2. 3. The Linear Model

The interconnection of the models of the different plant subsystems leads to a global highly non linear system, due to the expression of the aerodynamic torque T_{aero} in (1). For control design purpose, the global model can be linearized around an operating point $S_{op} = \left\{x_{op}, u_{op}\right\}$, by linearizing the expression of aerodynamic torque:

$$\Delta T_{aero} = \gamma_{w,op} \Delta\omega_T + \gamma_{v,op} \Delta v + \gamma_{\beta,op} \Delta\beta \tag{7}$$

The operator Δ corresponds to the deviation of values around the linearization point S_{op}, and the coefficients $\gamma_{\omega,op}$, $\gamma_{v,op}$ and $\gamma_{\beta,op}$ are defined by:

$$\gamma_{\omega,op} = \left(\frac{\partial T_{aero}}{\partial \omega_T}\right)_{S_{op}}, \quad \gamma_{v,op} = \left(\frac{\partial T_{aero}}{\partial v}\right)_{S_{op}}, \quad \gamma_{\beta,op} = \left(\frac{\partial T_{aero}}{\partial \beta}\right)_{S_{op}} \tag{8}$$

Hence the linearized model of the global system, locally valid around a operating point, results

$$\dot{x} = \begin{pmatrix} \frac{1}{J_T}\left(\gamma_{\omega,op} - f_T\right) & 0 & -\frac{1}{J_T} & \frac{1}{J_T}\gamma_{\beta,op} & \frac{1}{J_T}\gamma_{v,op} \\ 0 & \frac{1}{J_G} f_G & \frac{1}{J_G} & 0 & 0 \\ d + \frac{k}{J_T}\left(\gamma_{\omega,op} - f_T\right) & -d - \frac{k}{J_G} f_G & \frac{k}{J_T} - \frac{k}{J_G} & \frac{k}{J_T}\gamma_{\beta,op} & \frac{k}{J_T}\gamma_{v,op} \\ 0 & 0 & 0 & -\frac{1}{T_\beta} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_v} \end{pmatrix} x$$

$$
+\begin{pmatrix} 0 & 0 \\ -\frac{1}{J_G} & 0 \\ \frac{k}{J_G} & 0 \\ 0 & \frac{1}{T_\beta} \\ 0 & 0 \end{pmatrix}\begin{pmatrix} T_G \\ \beta_{ref} \end{pmatrix}+\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} m_v(t) \qquad (9)
$$

setting $x = \left(\Delta\omega_T \quad \Delta\omega_G \quad \Delta T_D \quad \Delta\beta \quad \Delta v_t\right)^T$. J_T and J_G are the moments of inertia of the turbine and the generator, f_T and f_G are the friction coefficients of the shaft at the rotor and generator sides.

3. Control Task

3. 1. System Operating Regions

The wind turbine operation area can be divided into three zones, depending on wind speed acting on blades. Energy conversion objectives, and thus control objectives, are different for each zone.

For low wind speed, i.e. for wind speeds less than a specific value ($v < v_1$), the main objective is to maximize the system energy conversion yield. In this Partial Load 1 zone, the system has to operate at $C_p(\lambda, \beta) = C_{p,\max}$. Pitch angle β is then maintained constant at β_{opt} and rotational speed ω_T is controlled to operate at $\lambda = \lambda_{opt}$, by acting only on the electromagnetic generator torque T_G.

For higher wind speed, corresponding to $v_1 < v < v_2$, the rotational speed attained by the turbine by applying the previous control strategy would be over the nominal generator speed. In this Partial Load 2 zone, the turbine rotational speed ω_T is maintained at the nominal generator speed by acting on electromagnetic torque T_G. Pitch angle β is also maintained at β_{opt} to maximize energy conversion efficiency.

For high wind speed, i.e. $v > v_2$, wind turbine operates in Full Load and the electric power produced by the system has to be regulated at the nominal generator power. The turbine rotational speed is maintained around the nominal generator speed and pitch angle β is controlled in order to reduce the power coefficient $C_p(\lambda, \beta)$. Control system is then multivariable in this zone, because it acts on both generator torque and pitch angle.

Other constraints than those related to generator specifications explain speed and power limitations, such as blades noise emission limitation or limitation of mechanical loads supported by the mechanical structure [7][9].

Evolution of main values in function of wind speed are presented on Figure 4.

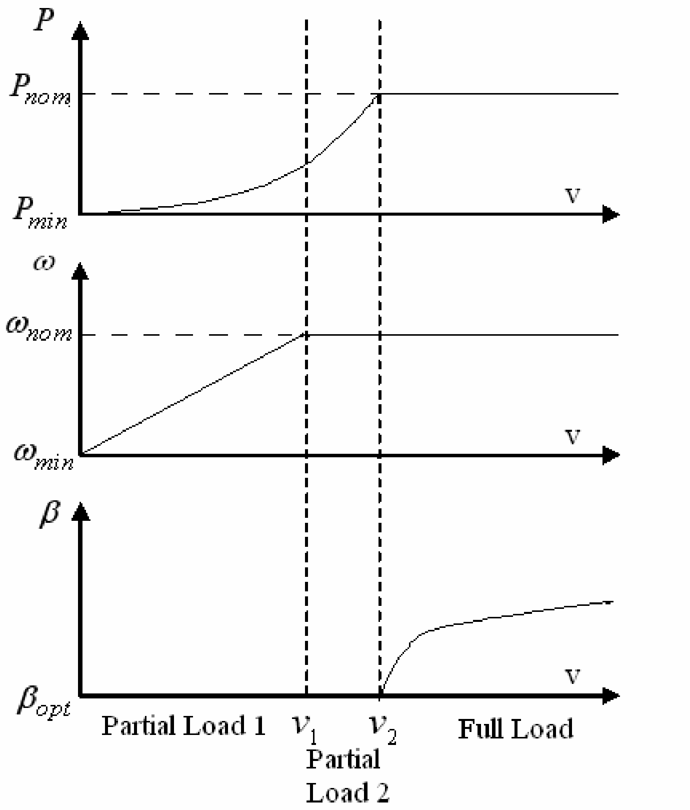

Figure 4. Main Temporal Series Evolution Function of Wind Speed.

In this paper, control design of Partial Load 1 and Full Load are considered.

3. 2. Control Objectives

The two main objectives of the wind turbine control problem are to ensure an optimal energy conversion, i.e. tracking the curves of Figure 4, and to reduce dynamic loads experienced by the mechanical components of the plant. The mechanical fatigue experienced by flexible shaft is particularly of interest, because drive train structural dynamics are very lightly damped and give rise to oscillating phenomena on drive train torque that induce an increase of the mechanical loads [9] [20].

Besides, the aerodynamic representation used is very basic and subject to considerable uncertainty [9]. Indeed, the aerodynamic parameters of the blades can seriously vary with turbine operating conditions such as moisture or ice accretion. These parametric uncertainties can give rise to undesirable system behavior which can induce an increase of mechanical fatigue [13]. Even if it is not possible to quantify the uncertainty in the aerodynamic model, because of the complexity of the interaction between wind and rotor, the controller has to guarantee system stability and suitable behavior in a wide range of aerodynamic parameters.

Hence the designed control system has to satisfy the following properties:

- to optimize the energy conversion, by tracking the curves presented in Figure 4,
- to minimize the mechanical loads experienced by the flexible drive train,
- to ensure a suitable behavior of the system for a wide range of aerodynamic properties of blades.

4. Control Design

The control problem formulated in the last section results in a optimal control problem between several objectives of a non-linear system with parametric uncertainties.

In the context of multiobjective optimization design of a linear system with parametric uncertainties, the synthesis problem can be formulated as a convex optimization problem with linear matrix inequalities (LMI). In response to the non linear property of the system, gain scheduling can be used to adapt the controller parameters to actual operating points. In the case of linear parameter-varying (LPV) systems, which are linear time-varying systems whose state matrices are fixed functions of some parameters which are in-real-time available, synthesis technics have been developed to guarantee quite same specifications of the closed loop system in the whole operating range as in the linear context.

4. 1. Dynamic Output Feedback Synthesis of LPV Systems

Suppose that we have the following linear parameter-varying system $S(\theta(t))$ depending on some varying parameter vector $\theta(t) \in \mathbb{R}^p$ with state-space representation:

$$S(\theta(t)) \begin{cases} \dot{x}(t) = A(\theta(t))x(t) + B_1(\theta(t))u(t) + B_2(\theta(t))w(t) \\ z(t) = C_1(\theta(t))x(t) + D_1(\theta(t))u(t) \\ y(t) = C_2 x(t) \end{cases}$$

where $x \in \mathbb{R}^n$ is the state, u is the control input, w the exogenous input, z the performance output and y the measured output. The time varying parameter $\theta(t)$ is assumed to be measured and bounded in a known polytopic set Θ such as $\Theta_i = \left[\underline{\theta_i}; \overline{\theta_i}\right], i = 1..p$.

The dynamic output feedback synthesis $\Omega(\theta(t))$ of the LPV system (10) consists in finding a controller

$$\Omega(\theta(t)) \begin{cases} \dot{x}_K(t) = A_K(\theta(t))x_K(t) + B_K(\theta(t))y(t) \\ u(t) = C_K(\theta(t))x_K(t) + D_K(\theta(t))y(t) \end{cases}$$

which ensures stability and such time domain or disturbance rejection performances for the closed loop system, as pole placement, H_2 or H_∞ performance. Such synthesis constraints have been expressed by [1][2]. For instance, assume that the closed loop system performance is evaluated from several different objectives with two different specifications of disturbance rejection, i.e. constraints on H_2 or H_∞ norms of transfer functions between disturbance w and performance z. Performance vector and state space matrices C_1 and D_1 can then be divided into two parts $z = \begin{pmatrix} z_2 & z_\infty \end{pmatrix}^T$, $C_1 = \begin{pmatrix} C_{1,2}^T & C_{1,\infty}^T \end{pmatrix}^T$ and $D_1 = \begin{pmatrix} D_{1,2}^T & D_{1,\infty}^T \end{pmatrix}^T$.

Moreover, assume that the state space matrices of the system (10) have an affine dependance of the parameter vector $\theta(t)$:

$$S(\theta(t)) = S_0 + \sum_{i=1}^{r} S_i \theta(t) \tag{10}$$

with S_i corresponding to the system on the extremal points of the polytope. Hence, the system (10) can be represented by:

$$S(\theta(t)) = \sum_{i=1}^{r} \alpha_i S_i,\ \alpha_i > 0,\ \sum_{i=1}^{r} \alpha_i = 1 \tag{11}$$

In the same way, the controller is represented in the analogous form:

$$\Omega(\theta(t)) = \sum_{i=1}^{r} \alpha_i \Omega_i \tag{12}$$

The problem of the synthesis of a dynamic output feedback with respect to the multiobjective H_2 and H_∞ constraints can be expressed with a LMI formulation.

Theorem 1:[2][23]

If there exist two symmetric positive matrices X and Y, matrices $\hat{A}_i, \hat{B}_i, \hat{C}_i, \hat{D}_i, i = 1..r$ and a symmetric matrix Q such as:

$$\begin{pmatrix} A_i X + B_{1,i}\hat{C}_i + * & * & * & * \\ \hat{A}_i + \left(A_i + B_{1,i}\hat{D}_i C_2\right)^T & YA_i + \hat{B}_i C_2 + * & * & * \\ B_{2,i} & B_{2,i}^T Y & -\gamma I & * \\ C_{1,\infty} X + D_{1,\infty}\hat{C}_i & C_{1,\infty} + D_{1,\infty}\hat{D}_i C_2 & 0 & -\gamma I \end{pmatrix} < 0$$

$$\begin{pmatrix} A_i X + B_{1,i}\hat{C}_i + * & * & * \\ \hat{A}_i + \left(A_i + B_{1,i}\hat{D}_i C_2\right)^T & YA_i + \hat{B}_i C_2 + * & * \\ B_{2,i} & B_{2,i}^T Y & -I \end{pmatrix} < 0$$

$$\begin{pmatrix} X & * & * \\ I & Y & * \\ C_{1,2} X + D_{1,2}\hat{C}_i & C_{1,\infty} + D_{1,2}\hat{D}_i C_2 & Q \end{pmatrix} > 0$$

$$Tr(Q) < \nu$$

then the closed loop system composed by the system (10) and the polytopic controller expressed by

$$\Omega\left(\theta(t)\right) = \sum_{i=1}^{r} \alpha_i \begin{pmatrix} A_{K,i} & B_{K,i} \\ C_{K,i} & D_{K,i} \end{pmatrix}$$

with

$$D_{K,i} = \hat{D}_i$$

$$C_{K,i} = \left(\hat{C}_i - D_{K,i} C_{2,i} X\right) M^{-T}$$

$$B_{K,i} = N^{-1}\left(\hat{B}_i - YB_{1,i} D_{K,i}\right)$$

$$A_{K,i} = N^{-1}\left(\hat{A}_i - NB_{K,i} C_{2,i} X - YB_{1,i} C_{K,i} M^T - Y\left(A_i + B_{1,i} D_{K,i} C_{2,i}\right) X\right) M^{-T}$$

where M and N satisfy $MN^T = I - XY$, is exponentially stable for any trajectory $\theta(t)$ and have a H_∞ performance between w and z_∞ less than γ, and a H_2 performance between w and z_2 less than ν.

4. 2. Parametric Robustness

Assume that matrices A_i defined in (10) are subject to bounded parametric uncertainties, i.e. that are described by $A_{i,\Delta} = A_i + \Delta_i A_i$, with $\Delta_i = \left[-\delta_i ; \delta_i\right]$. Hence matrix A_i can also be expressed by the polytopic representation:

$$A_i = \sum_{j=1}^{s} \beta_{ij} A_{ij} : \ \beta_{ij} > 0, \ \sum_{j=1}^{s} \beta_{ij} = 1$$

A placement of the poles of the closed loop system in a region ***D*** of the state space can be guaranteed satisfying the following LMI constraints:

$$l_{pq}\begin{pmatrix} X & I \\ I & Y \end{pmatrix} + m_{pq}\begin{pmatrix} A_{ij} X + B_{1,i}\hat{C}_i & A_{ij} + B_{1,i}\hat{D}_i C_{2,i} \\ \hat{A}_i & YA_{ij} + \hat{B}_i C_{2,i} \end{pmatrix}^T + m_{qp}\begin{pmatrix} A_{ij} X + B_{1,i}\hat{C}_i & A_{ij} + B_{1,i}\hat{D}_i C_{2,i} \\ \hat{A}_i & YA_{ij} + \hat{B}_i C_{2,i} \end{pmatrix} < 0$$

where l_{pq} and m_{pq} define the geometry of the region ***D***, in order to guarantee stability and minimal closed loop damping of the uncertain system.

4.3. Wind Turbine LPV Controller

4.3.1. Partial Load 1

In the operating area corresponding to low wind speeds, the main turbine objective is to operate at the maximum power production, and thus aerodynamic power coefficient is reached to be maintained at its maximal value $C_{p,opt}$ by operating at $\lambda = \lambda_{opt}$ and $\beta = \beta_{opt}$. Linearizing the aerodynamic torque on the reference trajectory, the aerodynamic coefficients of the system defined by (7) can be rewritten as:

$$\gamma_{\omega} = \frac{\partial T_{aero}}{\partial \omega_T} = -\frac{1}{2}\rho\pi R^5 \frac{C_{p,opt}}{\lambda_{opt}^3}\omega_T = k_{\omega}\omega_T$$

$$\gamma_{\omega} = \frac{\partial T_{aero}}{\partial v} = \frac{3}{2}\rho\pi R^4 \frac{C_{p,opt}}{\lambda_{opt}^2}\omega_T = k_v\omega_T$$

$$\gamma_{\beta} = \frac{\partial T_{aero}}{\partial \beta} = 0$$

Then the aerodynamics coefficients are affine functions of ω_T along the reference trajectory, and system (9) can then be written as:

$$\dot{x} = \left(A_0 + \omega_T A_1\right)x + Bu + Gw \tag{13}$$

Considering that the torsional deflection of the drive train is weak, ω_T can be approximated by ω_G, which is in real time measured and the system described by (13) is then a LPV system as defined in the last section. Moreover, in order to guarantee robustness to uncertainties concerning the aerodynamic properties of the blades, the coefficients γ_{ω} and γ_v are considered bounded in the intervals $\left[\gamma_{\omega}\left(1-\delta_{\omega}\right);\gamma_{\omega}\left(1+\delta_{\omega}\right)\right]$ and $\left[\gamma_v\left(1-\delta_v\right);\gamma_v\left(1+\delta_v\right)\right]$. Hence system (13) can be rewritten as:

$$\dot{x} = \left(A_0 + \omega_G\left[k_{\omega}A_{\omega}\left(1+\Delta_{\omega}\right) + k_v A_v\left(1+\Delta_v\right)\right]\right)x + Bu + Gw \tag{14}$$

with Δ_{ω} and Δ_v respectively in $\left[-\delta_{\omega};\delta_{\omega}\right]$ and $\left[-\delta_v;\delta_v\right]$, and the jacobian matrices $A_{\omega} = \frac{1}{k_{\omega}}\frac{\partial A}{\partial \omega_T}$ and $A_v = \frac{1}{k_v}\frac{\partial A}{\partial v}$. The system (14) is then an uncertain LPV system as described in the last section.

In order to consider the properties of the control objectives in the frequency range, the system (9) is augmented with weighting functions as shown in the block diagram in Fig 5. The weighting function W_{λ} is a low pass filter that tends the tip speed ratio λ to ensure a good tracking at low frequency. At high frequency, a good tracking of λ_{opt} is not reached because it would induce an increase of dynamical loads on the drive train. The high pass filter W_{T_D} ensures weak variations of the drive train torque at high frequency, in order to increase damping around the resonance frequency. Indeed, following Miner's rules, the estimation of the mechanical fatigue is based on the number of load cycles at different stress levels [16]. Thus, decreasing mechanical loads on the drive train at high frequency would induce an increase of its life time.

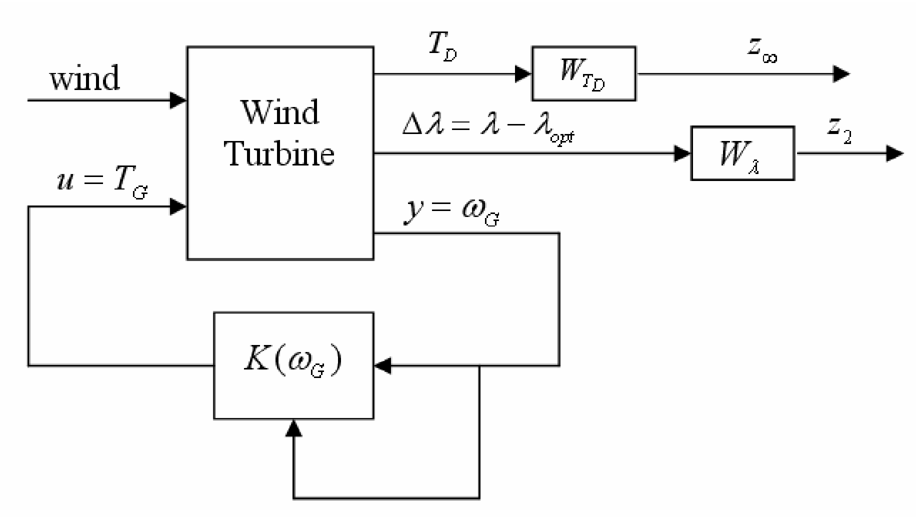

Figure 5. Partial Load: Block Diagram of the Augmented System

H_∞ norm minimization between the augmented drive train torque $\tilde{T}_D$ and the external disturbance m_v is chosen in order to vanish the resonance peak of the drive train torque response. On the other hand, H_2 norm optimization is chosen for rotational speed tracking because of the large bandwidth of the stochastic and external disturbance m_v. The robust to parametric uncertainties and gain scheduling controller is then obtained by applying the set of LMIs of Theorem 1 with the following objectives to the nominal system, i.e. without considering uncertainties:

$$\min \ \nu \quad \text{subject to: } \left\| Tr\left(\frac{z_\infty}{w}\right) \right\|_\infty < \gamma \text{ and } \left\| Tr\left(\frac{z_2}{w}\right) \right\|_2 < \nu$$

with $Tr\left(\frac{z}{w}\right)$ representing the transfer function from w to z, and with γ fixed to be small enough to vanish the resonance peak; and to ensure pole placement into a state space region ***D*** in order to ensure both stability and minimum damping for the uncertain system. This controller can then be easily set in the implementable form:

$$\Omega(t) = \Omega_0 + \omega_G(t)\Omega_1$$

4.3.2. Full Load

In the operating area corresponding to high wind speeds, electric power produced by the plant has to be regulated at the nominal power of the generator. The plant is then reached to operate at the nominal rotational speed of the generator and acts on both the electromagnetic torque of the generator and the pitch angle of blades. In order to follow the same control design procedure as in the last section, the linearized system, and then the aerodynamic coefficients γ_ω , γ_v and γ_β have to be expressed as an affine function of a measured parameter of the plant along the reference trajectory corresponding to Full Load operation. In Figure 6, and for the Power coefficients curves presented in Figure 2, considering the aerodynamic coefficients as affine functions of β^2 is seen to be an acceptable approximation. Moreover, because of the consideration of parametric uncertainties on these coefficients during control design, the errors of approximation can be seen as additional uncertainties and is thus taken into account during the control synthesis. Then, for Full Load operation, the system (9) can be expressed as:

$$\dot{x} = \left(A_0 + \beta^2\left[k_\omega A_\omega\left(1+\Delta_\omega\right) + k_v A_v\left(1+\Delta_v\right) + k_\beta A_\beta\left(1+\Delta_\beta\right)\right]\right)x + Bu + Gw \tag{15}$$

with $k_\omega = \frac{1}{\beta^2}\frac{\partial T_{aero}}{\partial \omega_T}$, $k_v = \frac{1}{\beta^2}\frac{\partial T_{aero}}{\partial v}$ and $k_\beta = \frac{1}{\beta^2}\frac{\partial T_{aero}}{\partial \beta}$.

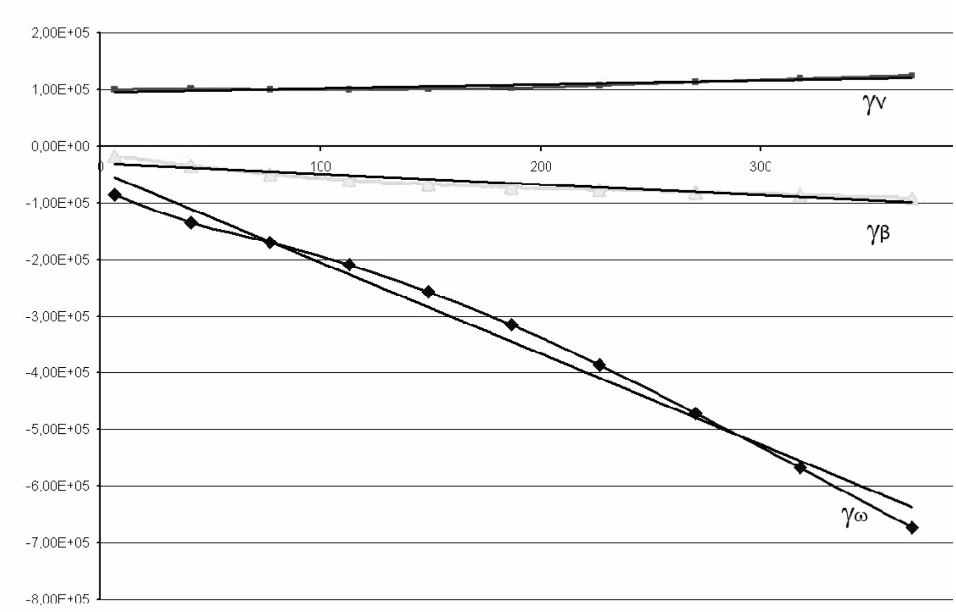

Figure 6. Aerodynamic Coefficients γ_ω , γ_v and γ_β , and Their Linear Approximations in Function of β^2 Along the Full Load Reference Trajectory.

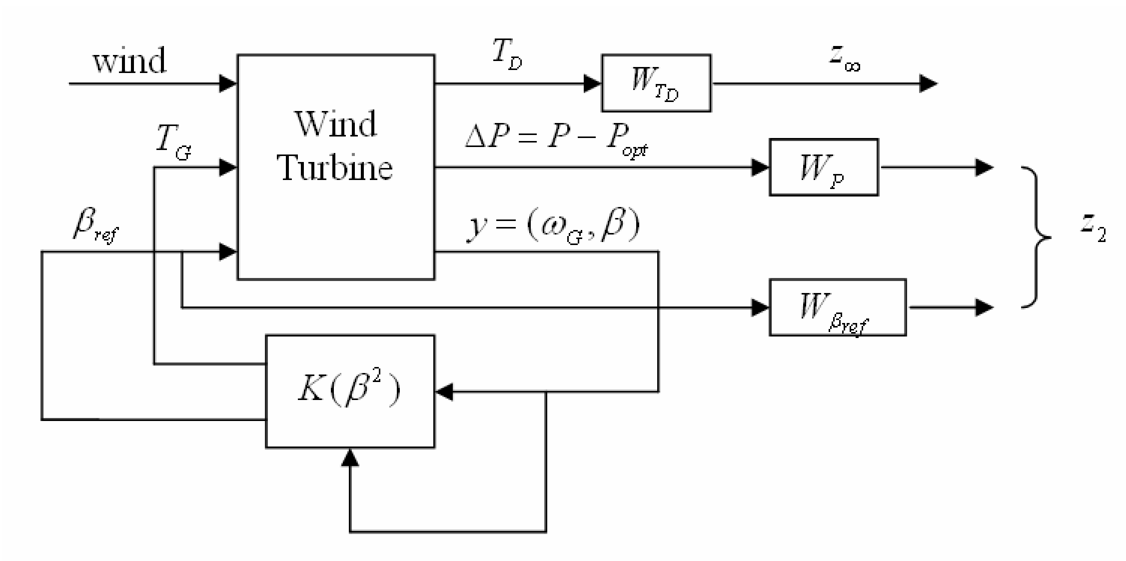

Figure 7. Full Load: Block Diagram of the Augmented System

In the same way as in Partial Load 1 operation, the plant is augmented with weighting functions (Figure 7). The same high pass filter W_{T_D} is used for limiting drive train torque variations at high frequency. $W_{\beta_{ref}}$ is a high pass filter which limits variations of the pitch angle demand at high frequency in order to limit the pitch actuator fatigue. The low pass filter $W_{P_{ref}}$ ensures a good regulation of the produced electric power at low frequency. In the same way as in Partial Load 1, a good tracking at high frequency is not reached in order to prevent from high mechanical damage.

Similarly to Partial Load 1 operation, the minimization of the H_∞ norm between the augmented drive train torque $\tilde{T}_D$ and the external disturbance w is chosen in order to vanish the resonance peak. H_2 norm optimization is then chosen in order to ensure an optimal regulation of the produced power and to limit the variations of the pitch angle.

The controller is then calculated by applying the set of LMIs of Theorem 1 with the same objectives than in Partial Load 1, and is thus implanted as:

$$\Omega(t) = \Omega_0 + \beta^2(t)\Omega_1 .$$

5. Simulation Results

The presented control design procedure is applied to a model of a 1.2 MW commercial variable speed, pitch regulated wind turbine. The non linear model of wind turbine includes the non linearities of the power coefficients curves, and the pitch actuator saturations on pitch amplitude and pitch rate. The simulated wind speed is generated from a white noise generator and by a filter block as explained in [19] in order to fulfill the stochastic requirements described in Section 2. The performances of the proposed controller are compared for the two operating areas corresponding to Partial and Full Load with those of a gain scheduling LQG controller described in [17]. This LQG controller is designed for each operating region to optimize a trade off between the same criteria as the proposed LPV controller. The parameters of the LQG controller are calculated on several points on the reference trajectory and are interpolated following the Takagi-Sugeno's concept. Hence, unlike the proposed controller, the LQG controller does not ensure stability along the reference trajectory but only locally around the points selected for controller synthesis, and moreover, it does not provide any robustness to the uncertainties concerning the aerodynamic properties of the blades.

In Partial Load 1, the Bode responses of drive train torque T_D and deviation of tip speed ratio λ around λ_{opt} to the external disturbance w are presented in Figure 8. The resonance peak on the drive train torque response is efficiently vanished by the proposed controller, unlike the LQG controller. Moreover, the proposed LPV controller induces a very weakly higher yield than the LQG one in this phase (Table 1). The Power Spectral Density of the drive train torque shows in Figure 10 that the resonance peak, which is greatly responsible for the mechanical fatigue of the shaft, is completely vanished by the proposed controller. Hence, the equivalent load cycles corresponding to this frequency would be highly reduced and an increase of the lifetime of this component is then expected [16].

Table 1: Partial Load: Energy yield

	LQG Controller	LPV Controller
Energy yield	92.69%	92.71%

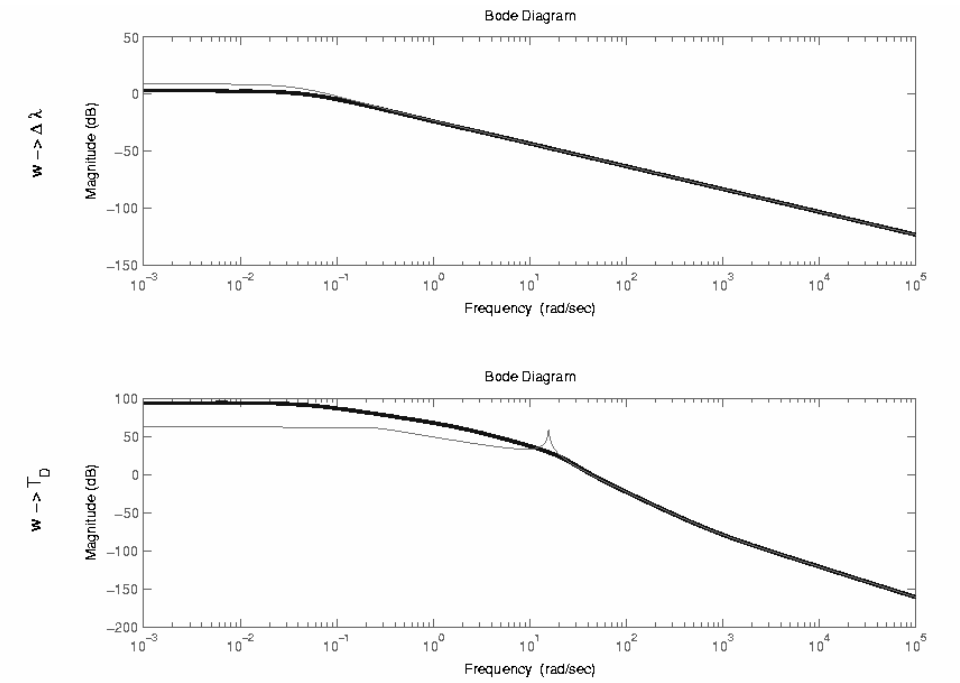

Figure 8. Partial Load: Bode Responses to External Disturbances; thin: LQG Controller, Thick: Proposed Controller

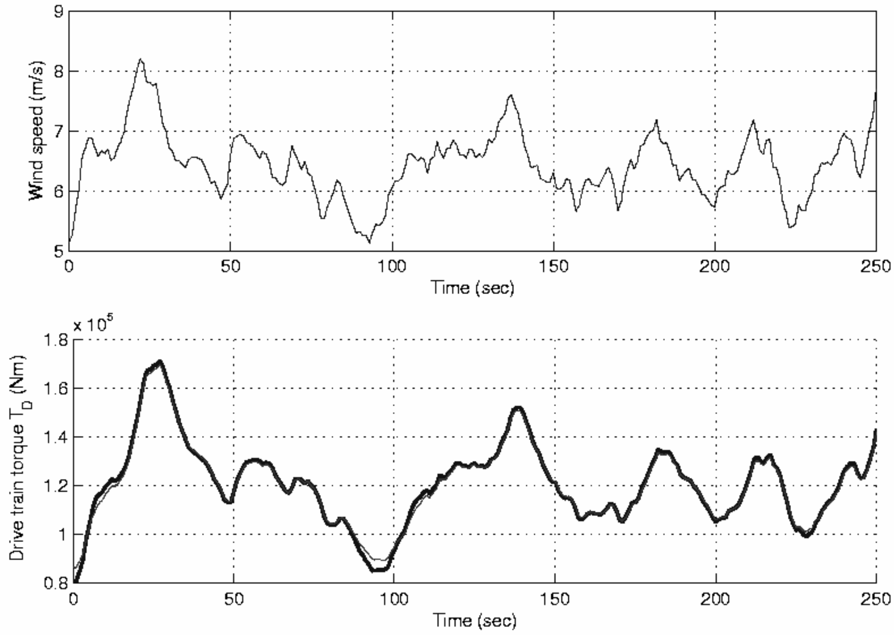

Figure 9. Partial Load: Main Temporal series; thin: LQG Controller, Thick: Proposed Controller

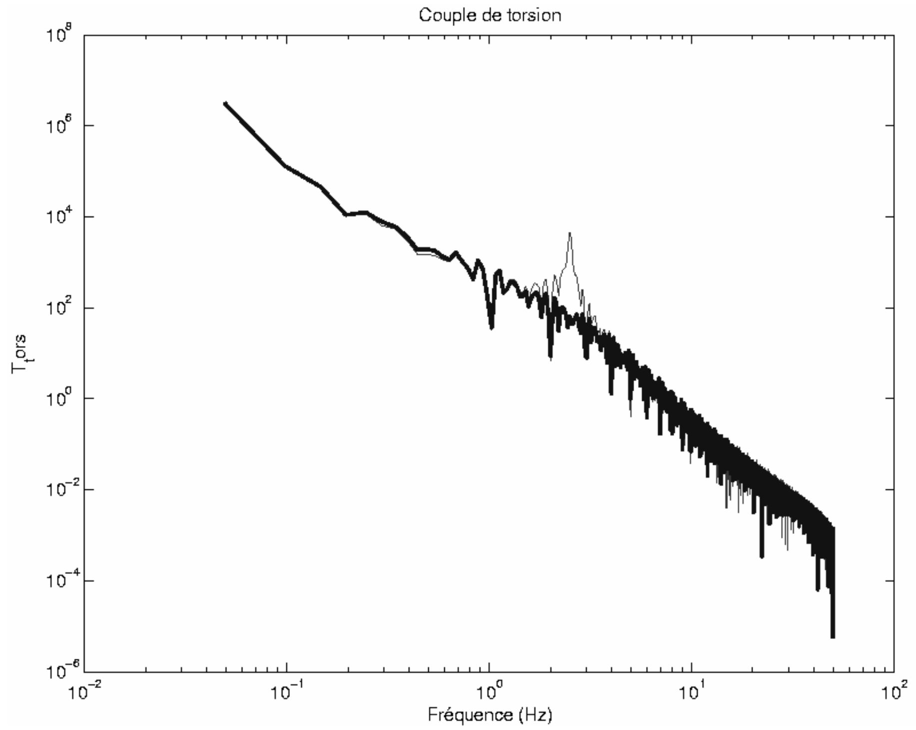

Figure 10. Partial Load: Power Spectral Density of the Drive Train Torque; thin: LQG Controller, Thick: Proposed Controller

In Full Load, the proposed LPV controller presents a better tracking of the nominal power, especially at low frequency, and a better damping of the resonant mode corresponding to the drive train torque, as described in the Bode responses between the deviation of the electric power and of the drive train torque to the external disturbances in Figure 11 and in the temporal series presented in Figure 12. Moreover, the Power Spectral Density shows that as in Partial Load 1, the resonant peak due to drive train torsion is completely vanished with the proposed controller.

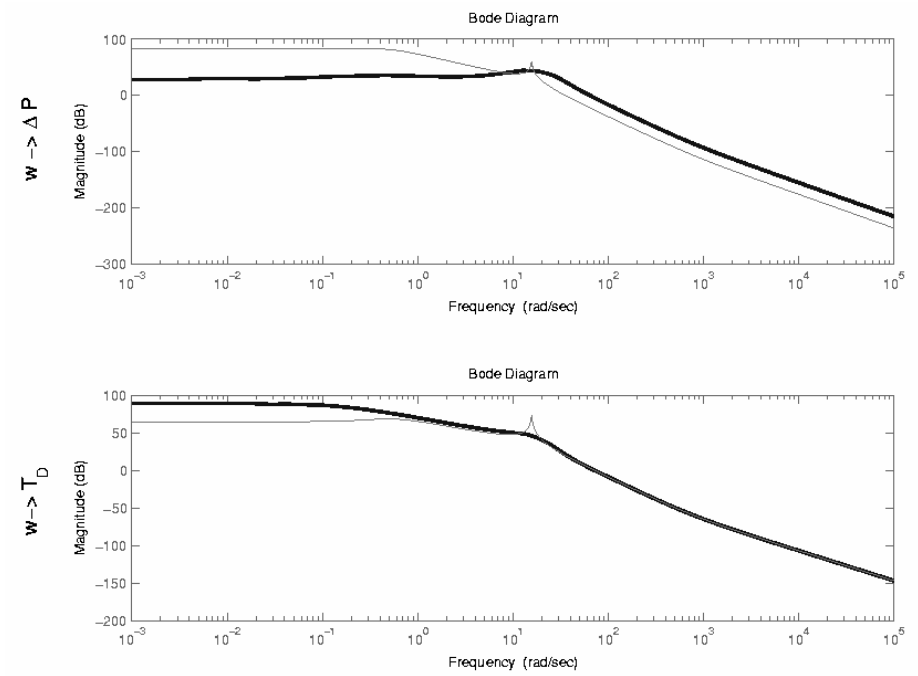

Figure 11. Full Load: Bode Responses to External Disturbances; thin: LQG Controller, Thick: Proposed Controller

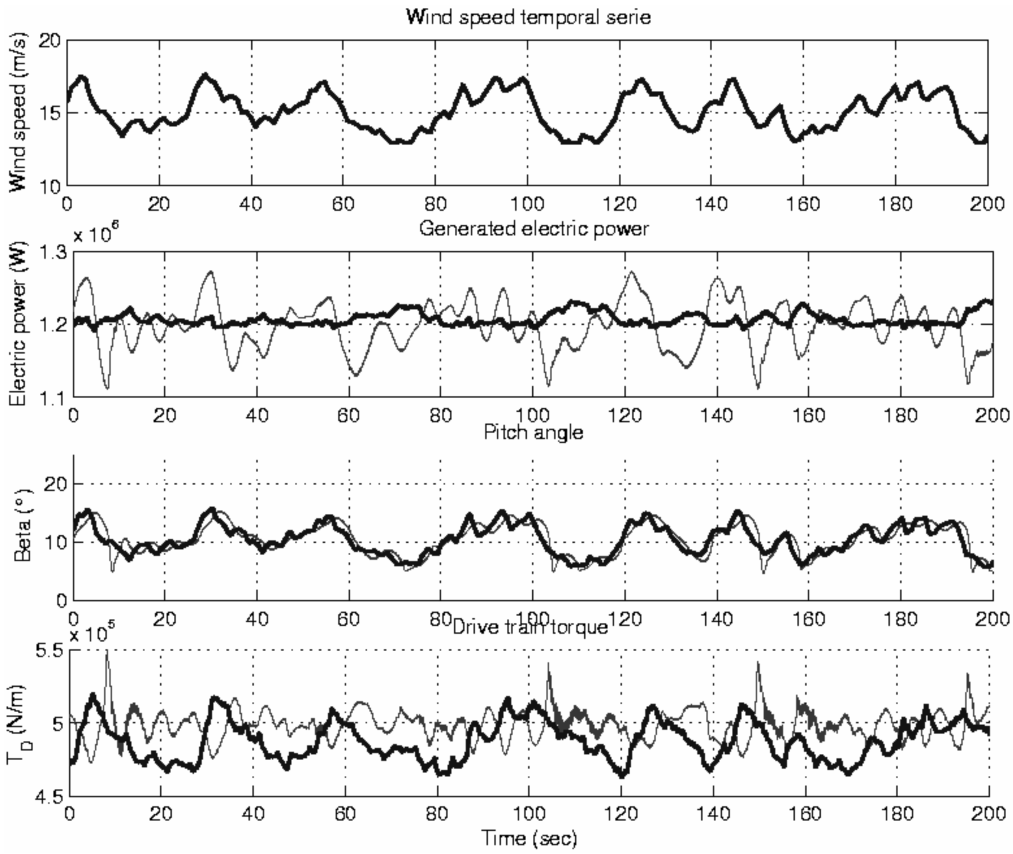

Figure 12. Full Load: Main Temporal Series; thin: LQG Controller, Thick: Proposed Controller

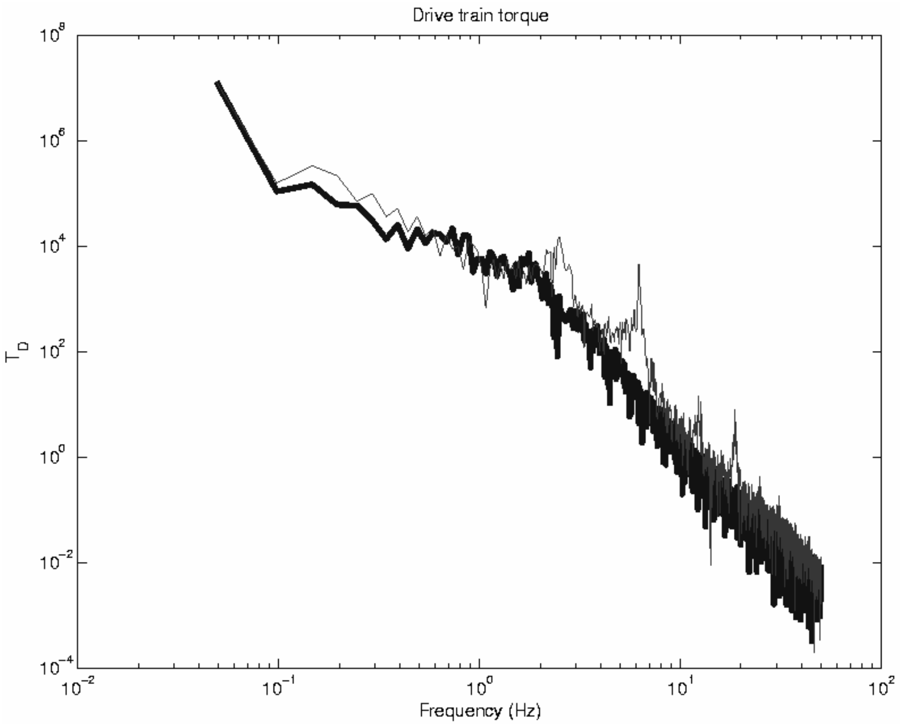

Figure 13. Full Load: Power Spectral Density of the Drive Train Torque; thin: LQG Controller, Thick: Proposed Controller

6. Conclusion

In this paper, the synthesis of a robust gain scheduling controller for a variable speed, pitch regulated wind turbine has been proposed for the two more important operation modes of the plant, the Partial Load 1 and the Full Load operations. For these two operating regions, the controller achieves good performances for energy production, energy maximization for Partial Load case and power regulation for Full Load case, and the controller provides very good damping of the resonant mode due to the flexibility of the drive train. This increase of damping would induce lighter material stress and then an increase of the lifetime of the plant. Moreover, in addition to optimize the trade off between energy optimization and reduction of material stress, the proposed controller guarantees stability in spite of changings of the aerodynamics properties of the blades.

Nevertheless, transitions between the different operating modes of the plant has yet to be studied in order to make the global controller provide an optimal behavior for the whole operating zone of the wind energy conversion system. Moreover, the wind turbine controller could be tuned in order to ensure a good damping of not only the resonant mode corresponding to the drive train flexibility, but also of the resonant modes of all plant components. This controller would increase the lifetime of the whole plant.

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