



## WIND TURBINE IPC BASED ON ROBUST ADAPTIVE CONTROLLER

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### ABSTRACT

This paper presents an IPC system based on RMRAC controller to reduce the asymmetric mechanical loading of the large wind turbines, mainly caused by some known reasons, like wind shear, tower shadow and wind turbulence. It was used the blade root loads measurement and the Coleman transformation to obtain the Hub mechanical loads. Simulations were performed to show the feasibility of the proposed controller.

**Keywords:** *Wind Turbine, Adaptive Control, RMRAC, IPC, FAST.*

### 1. INTRODUCTION

The use of wind power for generating electricity has been increasing in the last decades. The incentives for the development of wind energy has varied over the time, for example, the increase the cost of oil during 1970s, the low CO<sub>2</sub> emissions in 1990s, and around 2006s the new increase of the oil price with concerns over security of energy supplies. All these factors have led to increase the interest in wind energy [1], resulting in new wind turbines with larger size and increased rated power. Larger wind turbines exhibits different aerodynamic behavior, as their structures have more flexibility and are subjected to more local



variations of the wind in its rotor swept area. As the modern wind turbines operates in a wide range of wind speeds and the power available in the wind is proportional to the third power of wind speed [1], they are subject to a variety of operating conditions. Concerning the wind turbine control systems, there are different goals according to the point in which the turbine is operating. When the wind speed is below the rated power, the main target is to extract more energy, what means that efficiency is at premium. For wind speeds above the rated power, the control system has the function of limiting the power capture from the wind. In this operating mode, tower oscillations and structural loads should not be neglected. The structural loads on the blades and the rotor are consequence mainly of the gravity, inertia, wind shear and tower shadow [3]. Wind shear is a result of wind speed variations according to the vertical position whilst tower shadow introduces wind speed variations in each blade when it is parallel to the tower. These effects appears mainly in 1p (once per revolution) frequency [7] and can be significantly reduced by means of the Individual Pitch Control (IPC) of the blades [2]. In this technique, each blade pitch angle is individually controlled, with the aim of reducing asymmetric loads, since each blade experience different wind speeds and should have its pitch angle adjusted according to it. This task can be accomplished by measuring the resulting loads in the wind turbine hub by means of strain gauges located in the blade roots or by another technology that can measure the blade loading. In this paper, the blade root loads are measured by means of strain gauges and are converted to the Hub Moments using Coleman transformation.

To realize the IPC, the use of PI controllers is the straightforward option. Some authors have shown the feasibility of LQG controllers in IPC systems for load reductions [2][8]. In this paper, we have chosen the RMRAC controller instead. The main reason for this choice was the ability of RMRAC to overcome some issues, namely nonlinearities and parametrization problems [5]. Once the two moment's axis exhibits some coupling it was chosen the decentralized RMRAC [6].

This paper is organized as follows. Section 2 presents the IPC system, section 3 introduces the RMRAC controller and section 4 bring the simulation conditions. The results are discussed in section 5 and the paper is ended with the conclusions in the section 6.

## 2. INDIVIDUAL PITCH CONTROL

When the wind turbine is operating with wind speeds above the rated speed, the collective pitch control system has the responsibility of regulating the rotor speed at the rated speed, which corresponds to nominal power generation. This task is done by pitching the three blades simultaneously and so modifying the

aerodynamic efficiency. But with this control scheme, asymmetric structural loads are not alleviated. To achieve this goal, the IPC scheme is added to the Collective system. The IPC is based on load measurements or calculations, depending on the instrumentation technology used [9]. In this paper, we consider the use of strain gauges located at the blade roots. When the IPC is active, each blade is commanded with the Collective pitch plus the individual pitch demand, what means that the aerodynamic efficiency is unique for each blade according to its loads. For the measurements of the blade loads with strain gauges, it is necessary to establish the coordinate systems of the mechanical subsystems of the wind turbine. Once the loads measurements are from the blades, they should be represented in the nacelle coordinate system, where they will result in the Tilt and Yaw moments ( $M_{tilt}$  and  $M_{yaw}$ ) [4]. The transformations are made using the Coleman Transformation, also known as Park Transformation [2]. For more information about the coordinate system, refer to [3]. Once the Coordinate system was established, it is straightforward to make the mechanical transformations to convert the Blade Root Moments in  $M_{tilt}$  and  $M_{yaw}$ . These correspond to the direct and quadrature axis in the Coleman transformation, which can also be reversed. The direct and inverse transformations are given by:

$$\begin{bmatrix} M_{tilt} \\ M_{yaw} \end{bmatrix} = \mathbf{T1} \begin{bmatrix} M_{y,1} \\ M_{y,2} \\ M_{y,3} \end{bmatrix}, \quad \begin{bmatrix} M_{y,1} \\ M_{y,2} \\ M_{y,3} \end{bmatrix} = \mathbf{T2} \begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix}. \quad (1)$$

Where  $\mathbf{T1}$  and  $\mathbf{T2}$  are the matrices for the direct and inverse transformation:

$$\mathbf{T1} = \frac{2}{3} \begin{bmatrix} \cos(\varphi) & \cos(\varphi + \frac{2\pi}{3}) & \cos(\varphi + \frac{4\pi}{3}) \\ \sin(\varphi) & \sin(\varphi + \frac{2\pi}{3}) & \sin(\varphi + \frac{4\pi}{3}) \end{bmatrix}, \quad \mathbf{T2} = \begin{bmatrix} \cos(\varphi) & \sin(\varphi) \\ \cos(\varphi + \frac{2\pi}{3}) & \sin(\varphi + \frac{2\pi}{3}) \\ \cos(\varphi + \frac{4\pi}{3}) & \sin(\varphi + \frac{4\pi}{3}) \end{bmatrix}. \quad (2)$$

In these equations,  $M_{y,i}$  is the flatwise moment for blade  $i$  and  $\varphi$  is the azimuth angle of the reference blade. The rotor azimuth angle corresponds to the angle range between the blades positions during a rotor revolution counted from a fixed position. The azimuth  $0^\circ$  is defined when the blade is pointing up and an azimuth of  $360^\circ$  is reached once the rotor performs a complete revolution. Although there are moments in other

directions, the most dominant in terms of loadings is the  $M_{y,i}$  [3]. It is known that there are some couplings between  $M_{tilt}$  and  $M_{yaw}$ , as a result of the use of the Coleman transformation [10].

### 3. THE DECENTRALIZED RMRAC CONTROLLER

In this paper, a Robust Model Reference Adaptive Controller (RMRAC) is employed to IPC of wind turbine with the aim to reduce asymmetric loads. As the result of the Coleman transformation is a DC signal in the frequency of interest, the controller will deal essentially with DC signals, and the plant is considered as a first order system with coupling and unmodeled dynamics:

$$y_1 = G_{11}(s)(1 + \Delta_m(s))(u_1 + du_1) + \mu G_{12}(s)y_2, \quad y_2 = G_{22}(s)(1 + \Delta_m(s))(u_2 + du_2) + \mu G_{21}(s)y_1. \quad (3)$$

Where  $\Delta_m(s)$  are the multiplicative uncertainties,  $\mu$  is a small constant,  $G_{12}(s)$  and  $G_{21}(s)$  are the system dynamics interconnections (which are known to be of a small value) and  $du_i$  are disturbances. The stable modeled parts of the plant are given by  $G_{11}(s)$  and  $G_{22}(s)$ . The goal is to use a controller that find the best solution to the unknown parameters and at the same time guarantees stability and good performance despite the presence of  $\Delta_m(s)$  as stated in [10]. Therefore, a first order RMRAC was employed. The control laws to the Tilt and Yaw axis are:

$$u_1 = -\theta_1 y_1, \text{ and } u_2 = -\theta_2 y_2. \quad (4)$$

The Gradient parameter adapter, for a first order proposed controller:

$$\begin{aligned} \dot{\theta}_i &= \gamma_i \varepsilon_i \phi_i - \sigma_{s,i} \gamma_i \theta_i, \quad \varepsilon_i = \frac{z_i - \theta_i \phi_i}{m_{s,i}^2}, \quad \phi_i = \frac{b_m}{s + a_m} y_i, \quad z_i = y_i - \frac{b_m}{s + a_m} u_i, \\ m_{s,i}^2 &= 1 + n_{d,i}, \quad \dot{n}_{d,i} = -\delta_0 n_{d,i} + u_i^2 + \frac{1}{2}(y_1^2 + y_2^2), \quad n_{d,i}(0) = 0. \end{aligned} \quad (5)$$

Where  $\theta_i$  is the identified parameter,  $\gamma$  and  $\sigma_s$  are scalars positive constants,  $y_1$  and  $y_2$  are plant output, in this case the moments  $M_{tilt}$  and  $M_{yaw}$  after the low-pass filtering. The controllers outputs,  $u_1$  and  $u_2$

correspond to the signals  $\beta_d$  and  $\beta_q$ . The Model Reference transfer function is,  $W_{mi}(s) = b_{mi} / (s + a_{mi})$ . The robustness of the controller is ensured by means of the sigma-modification in the parameter adapter [10]:

$$\sigma_{s,i} = \begin{cases} 0 & \text{if } |\theta_i| < MO_i \\ \left(\frac{|\theta_i|}{MO_i} - 1\right)\sigma_0 & \text{if } MO_i < |\theta_i| \leq 2MO_i \\ \sigma_0 & \text{if } |\theta_i| > 2MO_i \end{cases} \quad (6)$$

If the parameter vector  $\theta_i$  deviates from the limits given by  $MO_i$ , the switching function inserts a dynamic system instead of the pure integral action of the parameter adapter. To use this RMRAC we need to define the reference model parameters, the Gradient gain  $\gamma$  and  $MO_i$ . The Model Reference gives the controller dynamics, so we need some knowledge about the desirable plant behavior to choose it properly. This task can be accomplished with the aid of the FAST code simulation [14].

#### 4. SIMULATION

To perform the simulation, the load measurement and the control system were designed as shown in Figure 1. The IPC controller output manipulates the  $\beta_i$  blade pitch angles individually and the plant output are the resulting moments. The individual pitch demands  $\beta_i$  are added to the collective demand  $\beta_c$ . After the Coleman transformation, the measured Moments signals pass through the Low-Pass Filters (LPF)  $F_d^i$ ,  $F_q^i$  and are scaled by the gains  $k_d$  and  $k_q$ . The inputs  $M_{y,i}^B$  are the blade root moments from wind turbine instrumentation, where the superscript “B” means the number of blades, in this case three. The pitch actuators are modeled as a first order dynamic system by some authors [10] while others represent it by a second order system [12][13]. Regarding to the controller project, the main consideration about the pitch actuator system is its phase delay. This is due to the limited speed of the mechanical system. Beside this, if the pitch actuator has a fast response, it will produce oscillations and undesirable loadings. The pitch actuator dynamics are represented, as in [13]:

$$\frac{\beta_i}{\beta_{i,r}} = \frac{\omega_\beta^2}{s^2 + 2\zeta\omega_\beta s + \omega_\beta^2} \quad (7)$$

Where  $\omega_\beta = 6,28$  and  $\zeta = \sqrt{2} / 2$ .  $\beta_i$  is the measured blade pitch angle and  $\beta_{i,r}$  is the commanded blade pitch angle by the IPC controller output. The system was simulated using the FAST software by NREL [14] by means of Matlab Simulink® interface. The FAST software is able to simulate the aerodynamics of wind turbines, allowing a realistic evaluation of the controller performance. The wind time series were generated with NREL TurbSim [15] software. A FAST validated 1.5 MW wind turbine model was chosen to perform the simulations.

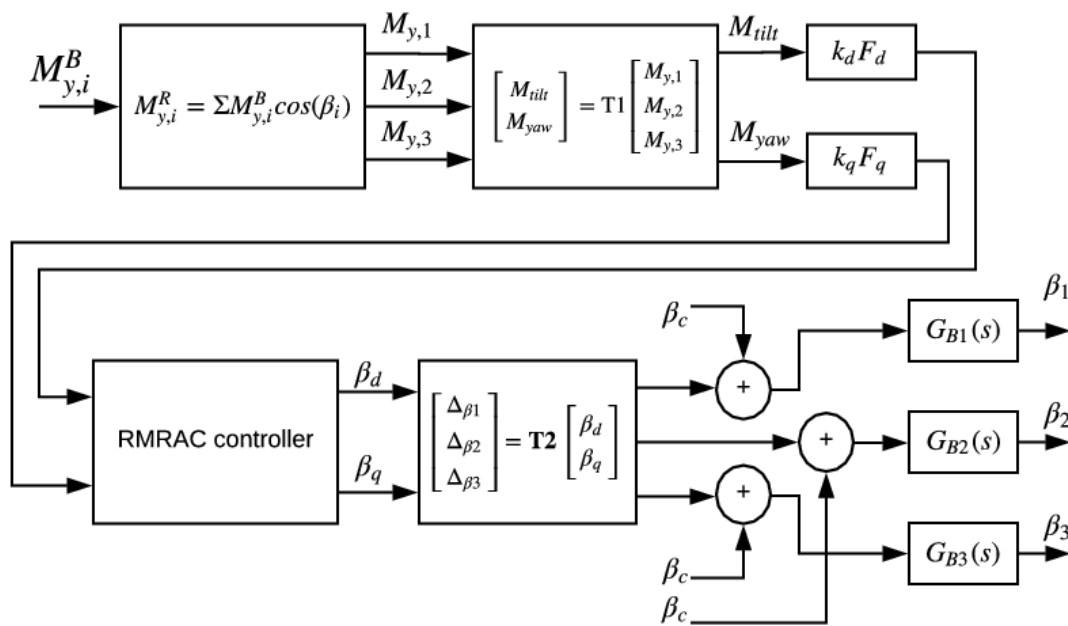


Figure 1- Proposed IPC.

Other simulated wind turbine data are: Rotor diameter: 70 m; Rotor speed: 2.1 rad/s; Nominal torque: 736.79 kN; n° of blades: 3; Hub height: 84 m; Gear box: 1:87.9.

## 5. RESULTS AND DISCUSSION

To evaluate the performance of the proposed control system, simulations were performed with collective pitch controller and IPC to compare the results, for a 10 minutes time, using turbulent wind time series generated by TurbSim [15], with an 18 m/s mean speed. The simulations were made in the power limiting operating point (constant generator torque). Figure 2 shows the spectrum analysis of for blade 1,

where we can observe a significant reduction of the intensity of  $M_{y,1}$  at 1p frequency with the proposed IPC controller when compared to the collective approach.

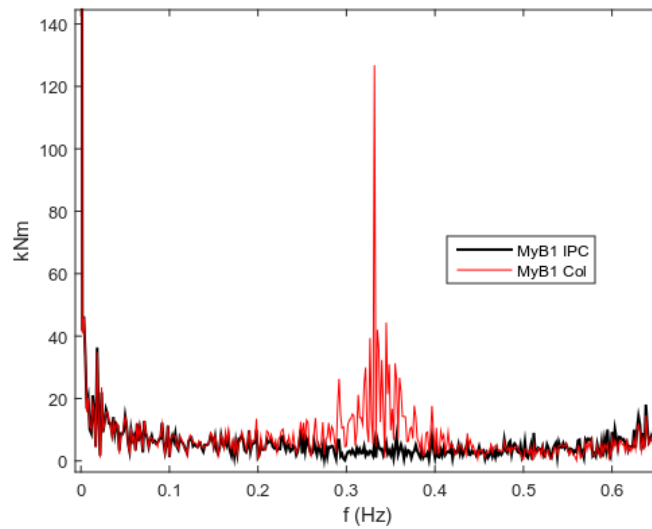


Figure 2 - Blade 1 My axis moment FFT.

The  $M_{tilt}$  and  $M_{yaw}$  comparative between Collective and IPC controllers are shown in Figure 3.

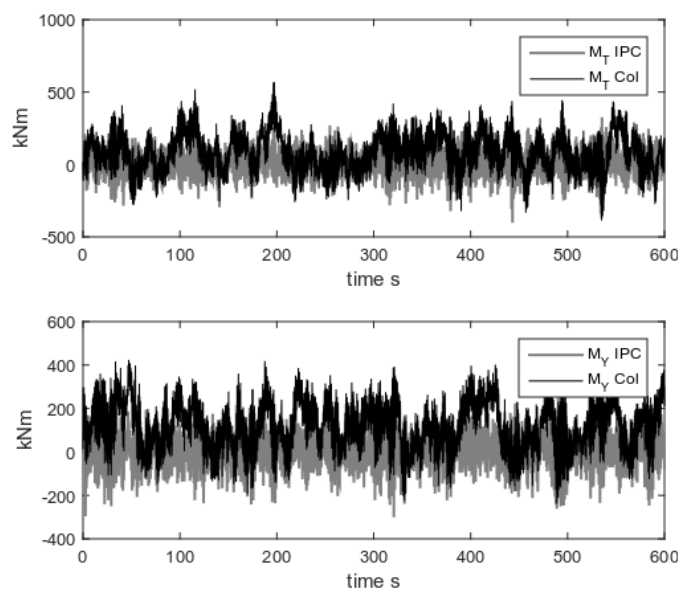


Figure 3 - Tilt and Yaw moments.

The Power Spectrum Density (PSD) FFT analysis in terms of Tilt and Yaw moments are shown in Figure 4, where is remarkable the  $0p$  (in the hub coordinate system) loads reduction. It is worth to note that after Coleman transformation the  $1p$  rotating moments will appear as  $0p$  in the Hub fixed coordinate system.

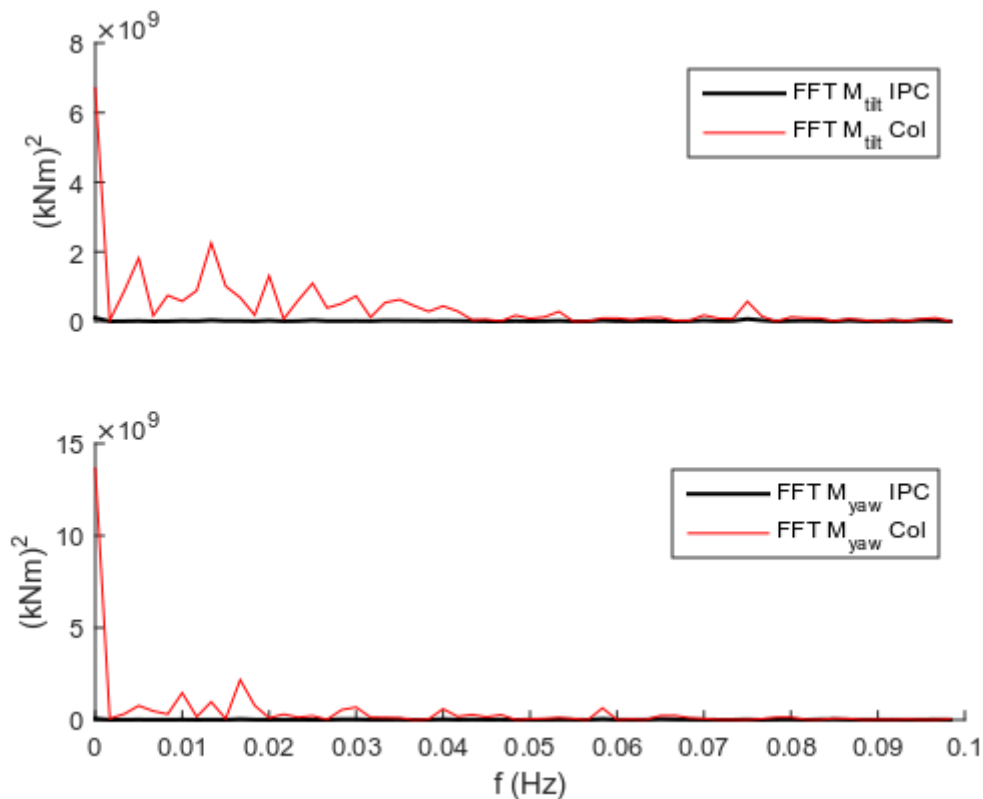


Figure 4 - Power density spectrum of  $M_{tilt}$  and  $M_{yaw}$ .

We verified in the simulations that the derivative of the pitch angles were limited to about  $6^\circ/s$ . That means the proposed controller agree with the practical limitations of the blade pitching systems.

## 6. CONCLUSION

This paper presented an IPC controller based on Adaptive Control theory for  $1p$  asymmetric mechanical load reductions in large Wind turbines. The loads were measured by means of the strain gauges located at the blade roots and converted in two axis coordinates using the Coleman transformation. The results of simulation showed good performance, indicating that the proposed controller is feasible. As it was verified, the main mechanical loads were reduced and the pitch activity was not significantly increased.





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