H_∞ Based Gain Scheduled Robust Control for Load Mitigation in a Commercial 3 MW Wind Turbine

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INTRODUCTION

The design and analysis of different robust control strategies applied to a commercial 3 MW wind turbine is presented in this paper. An exhaustive simulation analysis is developed with the proposed robust control strategies and it is compared to the baseline control strategy installed in the commercial wind turbine in terms of Key Performance Indicators (KPI). The family of linear models extracted from a high-fidelity aeroelastic code is used to design the robust control strategies and this software package is also used to perform a full set of calculations including both extreme and fatigue load cases.

APPROACH

In the last years, the incessant increase of size of wind turbines, inherent to the electric power production capacity, has introduced new challenges in the control systems. These control systems have to be more complex to match tight design specifications in terms of loads and performance. Such design targets have often opposite trends and the best trade-off must be found. In this way, the number of control objectives has become higher and, due to coupling of variables and components of wind turbines, the actual tendency of the control strategy design is to be multi-objective and multivariable schemes. Several applications of advanced multivariable control techniques are found in the literature, and some of them have also been field-tested in wind turbine prototypes [2].

In previous work of the authors [1][4][5] gain-scheduled (GS) robust controllers were designed for the public 5 MW 'upwind' model. The adaptability of the controllers obtained, which varies their behaviour according to the different operating points in wind turbine non-linear systems, improves the closed loop performance compared to Linear Time Invariant control techniques. Furthermore, the presented controllers are designed by using high ordered (55^{th} order) family of linear plants extracted from the high reliability wind turbine non-linear model. The high order of these plants involves high order of the designed H_∞ norm based controllers, so the interpolation of these high ordered controllers implicates an important contribution in the LTI control interpolation field due to the mathematical calculation convergence problems. Recently, in a new approach, the robust control techniques have been applied to a commercial multi-megawatt wind turbine. The different controllers obtained were integrated in the control code and in the control hardware. As a previous step before field-testing, the control algorithms have been tested by Hardware in the Loop (HIL). To consolidate the results presented in this paper with field data, an experimental test campaign will be carried-out at the real wind turbine in the coming months.

Fig 1. *ALSTOM's wind turbine*

MAIN BODY

The objective of the present work is to compare different control structures based on robust control algorithms and designed for a multi-megawatt commercial wind turbine against its baseline controller. The comparison of these control structures has been developed by means of simulations in a high-fidelity aeroelastic code. Four control structures are analyzed, named BCS, RC*S1*, *RCS2* and *RCS3*, which are described as it follows.

BCS (*Baseline Control Structure):* Control structure based on the classical control design proposed by Bossanyi in [3]. This control design considers uncoupled monovariable pitch angle and generator torque control loops and the controllers are based on gain-scheduled Proportional-Integral (PI) controllers and filters.

The control objectives for the novel proposed robust control algorithms are improving the regulation of the generator speed, mitigating the wind effect in the tower fore-aft and side-to-side first modes and damping the drive train mode with the main objectives of mitigating the loads in the wind turbine and improving the generation of electric power. Fig. 2 shows a general view of the proposed robust control structure in this work, which is based on two multivariable collective pitch and generator torque controllers.

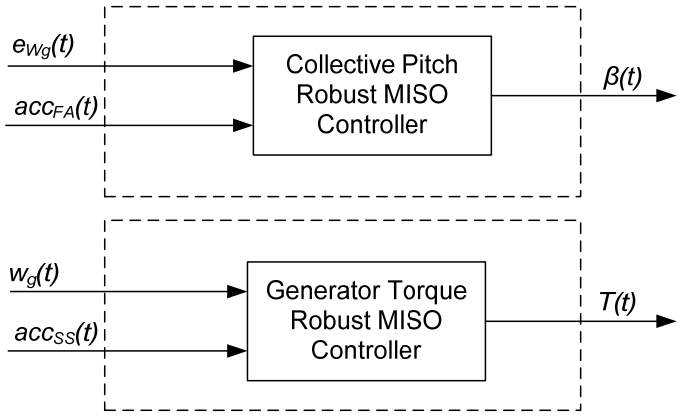

Fig 2. *General view of the robust control structure in the above rated control zone*

RCS1 (*Robust Control Structure 1*): The design process of this control structure is comprehensively explained in [4]. The first MISO (Multi-Input Single-Output) controller is a generator torque controller which reduces the wind effect in the drive train and tower side-to-side first modes. The collective pitch angle MISO controller is designed for the operating point with a mean speed of 15 m/s and regulates the generator speed at the nominal value while the wind effect in the wind turbine tower fore-aft first mode is mitigated.

Then, three collective pitch H_∞ controllers are designed in three operating points in the above rated zone for wind speeds of 13 m/s, 19 m/s and 25 m/s to improve the regulation of the generator speed achieved with the LTI (Linear Time Invariant) pitch control designed in RCS1. The interpolation of these three controllers has been developed with a gain-scheduling [5] of the controller's state space matrices by polynomials approximations, where the controller is represented by Linear Fractional Transformation (LFT), or with a more sophisticated interpolation method solving a complex a Linear Matrix Inequalities (LMI) system, which guarantees the closed loop stability during the transitions.

RCS2 (*Robust Control Structure 2*): The generator torque control is the same than the MISO generator torque controller used in RCS1. The interpolation of the LTI H_∞ controllers is based on the gain-scheduling of the coefficients of the three LTI controller's state-space matrices. The stability in all trajectories of the above rated zone is not guaranteed in the control design with this LFT represented gain-scheduled controller. Fig. 3 shows the upper LFT representation of the gain-scheduled robust pitch controller, where the varying parameter is named *p(t)* and it varies according to the present pitch angle.

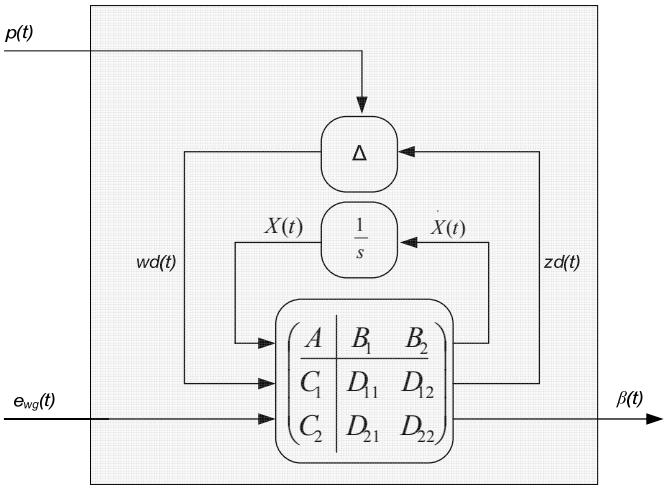

Fig 3. *Upper LFT representation of the gain-scheduled robust pitch controller*

RCS3 (*Robust Control Structure 3)*: The generator torque is not changed from RCS2 to this control structure. However, the interpolation of the three collective H_∞ pitch controllers is based on solving a Linear Matrix Inequalities (LMI) system to represent it in a new gain scheduled scenario (see Fig.4), where the LTI controllers are interpolated according to a gain matrix and guaranteeing the stability in all points of the parameter trajectory considered in the design process.

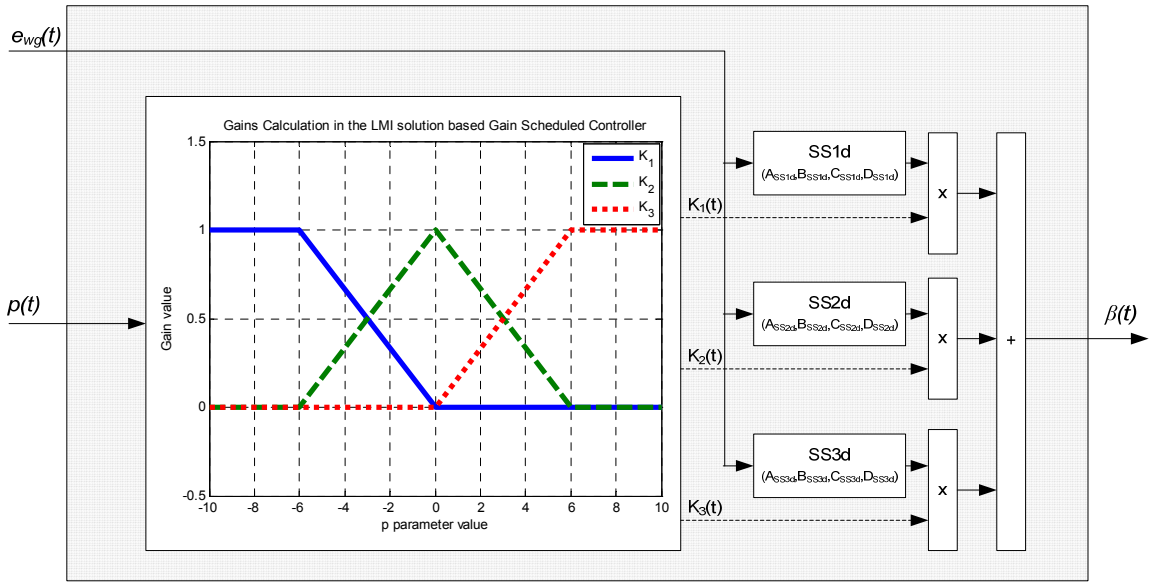

Fig 4. *Structure of the LMI solution based gain-scheduled pitch control*

Regarding to the simulation results, the regulation of the generator speed with the gain-scheduled controllers *RCS2* and *RCS3* is improved compared to the *BSC* and *RCS1* in the above rated zone. As an example, Fig. 5 shows the generator speed, generator torque, blade pitch angle and electric power signals for a power production wind with a mean speed of 18 m/s by using the four analyzed control strategies.

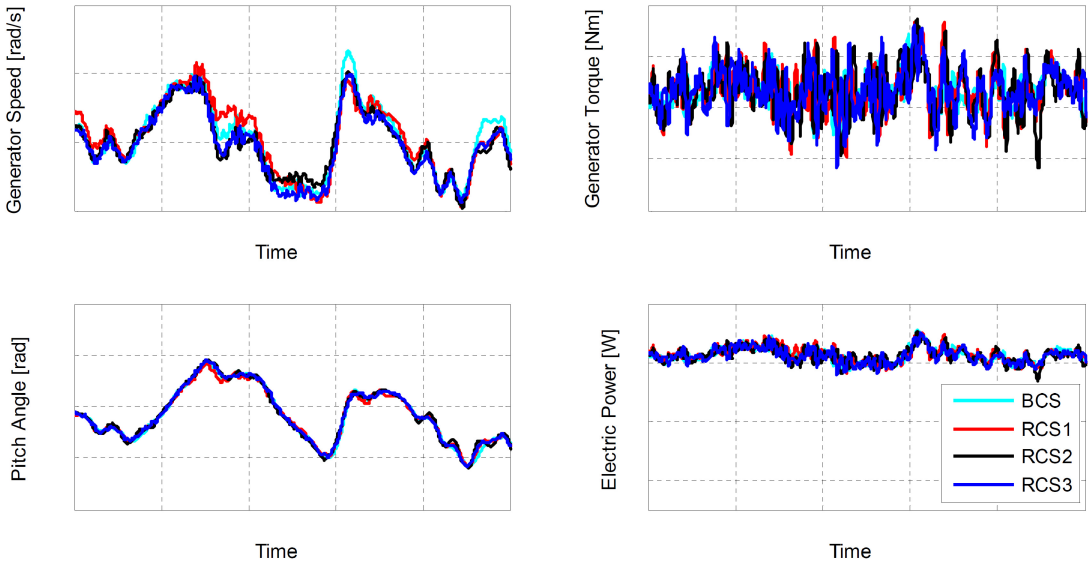

Fig 5. *Controlled and set-point signals for a power production wind (mean speed of 19 m/s)*

An exhaustive analysis will be presented in the full-text version of this work, where the designed robust control strategies for a commercial wind turbine will be compared to the baseline control strategy of that wind turbine in terms of Key Performance Indicators (KPI). As an example, Fig. 6 shows the comparison table for the fatigue of Tower Base My variable. As well, Fig. 7 shows the comparison table for the Annual Energy Yield.

Tower Base My (m = 4)				
Mean Wind	BCS (%)	RCS1	RCS2	RCS3
4	100	-1.4%	-0.4%	-0.4%
6	100	-0.3%	-0.1%	-0.1%
8	100	-2.4%	1.9%	1.9%
10	100	0.1%	-1.0%	-3.1%
12	100	-2.4%	-3.3%	-3.3%
14	100	2.0%	-2.3%	1.7%
16	100	-9.5%	3.1%	-3.4%
18	100	-9.9%	5.4%	-6.8%
20	100	0.5%	6.4%	-5.1%
22	100	2.0%	2.7%	-1.8%
24	100	7.7%	0.2%	-9.2%
TOTAL	100	-1.2%	1.2%	-1.7%

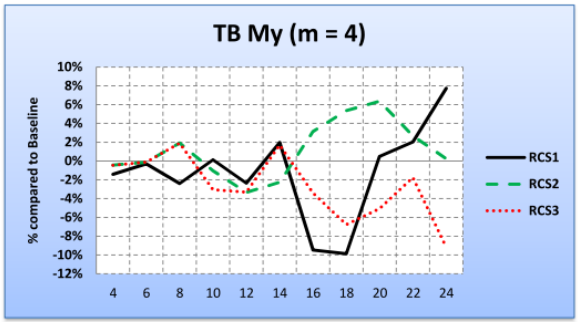

Fig 6. *KPI Table for fatigue comparison with relation to BCS controller*

Power Curve [kW]				
Mean Wind	BCS (%)	RCS1	RCS2	RCS3
4	100	0.0%	-0.1%	-0.1%
6	100	0.0%	0.1%	0.1%
8	100	-0.3%	0.2%	0.2%
10	100	-0.5%	0.6%	0.4%
12	100	-0.3%	0.5%	0.3%
14	100	-0.2%	0.1%	-0.3%
16	100	0.0%	0.1%	-0.2%
18	100	0.2%	0.2%	-0.1%
20	100	-0.1%	-0.3%	-0.3%
22	100	-0.2%	-0.5%	-0.2%
24	100	-1.5%	-0.8%	-0.8%
AEY [kWh/year]	100	-0.3%	0.3%	0.2%

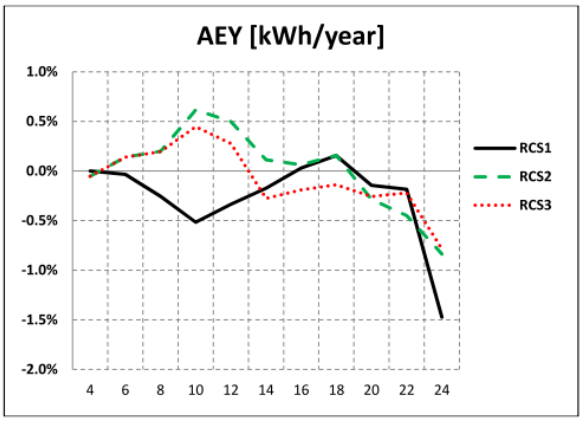

Fig 7. *KPI Table for comparison of Annual Energy Yield with relation to BCS controller*

CONCLUSIONS

This paper presents a comparison of different robust controllers, designed for a commercial Alstom's 3 MW wind turbine, to its baseline control strategy. The family of linear models extracted from a linearization process in a high-fidelity aeroelastic code is used to design the proposed collective pitch and generator torque robust controllers. Also, this software package is used to develop the battery of simulations for the calculations of the extreme and fatigue load cases and to determine the values of the KPI, whose some summary results are presented in Fig. 8.

KPI analysis		Control strategy			
		BCS [%]	RCS1 [%]	RCS2 [%]	RCS3 [%]
Fatigue Loads	Tower Base Mx (m=4)	100	-15.6	-15.6	-15.5
	Tower Base My (m=4)	100	-1.2	1.2	-1.7
	Blade Root Mflap (m=9)	100	0.5	1.5	1.6
	BladeRootMedge (m=9)	100	0.3	0.1	0.1
	Stat. Hub Mx (m=3)	100	4.4	2.9	3.0
	Stat. Hub My (m=3)	100	-0.5	0.2	0.0
	Stat. Hub Mz (m=3)	100	-0.6	-0.2	-0.5
Extreme Loads	Tower Base Mxy	100	-4.9	-0.3	-0.6
	Blade Root Mflap (max)	100	-1.1	-1.3	-2.4
	Blade Root Mflap (min)	100	-2.8	0.2	-0.3
	BladeRootMedge (max)	100	1.0	-1.3	-1.6
	BladeRootMedge (min)	100	1.0	-0.3	-0.9
	Stat. Hub Mx	100	-3.0	0.0	-1.0
	Stat. Hub Myz	100	-0.9	3.2	-0.3
Anual Energy Yield		100	-0.3	0.3	0.2
OverSpeed		100	-0.2	0.0	0.6
Tower Clearance		100	-1.3	0.8	0.0
Pitch Duty		100	59.8	13.6	17.8

Fig 8. *Summary KPI Table*

Furthermore, the use of gain-scheduled collective pitch control based on the interpolation of three H_∞ controllers improves the response of the loop in this control zone due to the controller adaptability to the wind turbine operating points. The two methods analyzed to develop the interpolation are based on the gain-scheduling of the controller's state space matrices by polynomials approximations or solving Linear Matrix Inequalities (LMI) systems. In the first one, the stability is not guaranteed in the control design and it has to be demonstrated with simulations in the non-linear closed loop. However, the stability in the second method is guaranteed because it is considered in the formulation of the LMI system.

The generator speed regulation is improved with the gain-scheduled controllers in the above rated zone and, inherently, the electric power production is regulated in the above rated control zone with more accuracy near the nominal value of 3 MW. Also, a generator torque control loop to mitigate the wind effect in the tower side-to-side first mode is proposed and analyzed for this commercial Alstom's wind turbine.

Overall, the results obtained from this study are very promising in terms of loads and performance. Load levels are generally aligned with the baseline controller, and even allowing some extra load reduction, which is a good result considering that the baseline is a mature turbine product. In addition, it is expected that the robust control approach, being intrinsically multi-objective and multi-variable, is particularly suitable for complex systems such as offshore floating wind turbine.

The work presented in this paper is the first fundamental step for the implementation of advanced robust controllers in real commercial wind turbines. Moreover, the robust control strategy has been integrated into the whole control software package and validated through HIL, confirming the capability of the current control hardware to work with such high ordered state-space represented robust controllers. The following step consists in performing a comprehensive field test campaign, in order to complete the validation cycle and make this solution available for industrial applications,

LEARNING OBJECTIVES

The Alstom's control code is now prepared to work with these multivariable robust controllers in LTI or GS based control scenarios. A simulation validation is shown in this work to see the real performance levels of different robust controllers in a commercial Alstom's 3 MW wind turbine compared to the baseline control strategy. This is an important first step in the process to field-test these controllers in the commercial wind turbine.

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