Optimal tuning for a classical wind turbine controller

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Optimal tuning for a classical wind turbine controller

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Abstract. Fine tuning of controllers for pitch-torque regulated wind turbines is an opportunity to improve the wind turbine performances and reduce the cost of energy without applying any changes to the design. For this purpose, a method for automatically tune a classical controller based on numerical optimization is developed and tested. To have a better understanding of the problem a parametric analysis of the wind turbine performances due to changes in the controller parameters is first performed. Thereafter results obtained with the automatic tuning show that is possible to identify a finer controller tuning that improves the wind turbine performances. For the case study selected in this work, a 2% cost of energy reduction is achieved with seven iterations.

1. Introduction

Most of the controllers that have been presented for pitch-torque controlled variable speed wind turbines require a set of gains or weights that have to be selected to obtain the desired behavior of wind turbine. With the continuous growth in the rotors sizes and the rated powers, the role of the controller is more central in the wind turbine design, where the abilities of active controllers to reduce the loads are essential in the pursuit of reducing the cost of energy.

Tuning of a controller is not a straightforward process because often the gains lead to contrasting performances. It is always necessary to identify a trade-off according to the requirements. Fine controller tuning requires several iterations and can also be very time consuming depending on the type of controller and the number of tuning parameters. To improve the selection of the controller parameters tuning by means of numerical optimization has been investigated in previous works. In the work by Hansen et al. [1] the gains of a classical PI controller are computed to minimize the standard deviation of the blade root flapwise bending moment. The load is evaluated with several simulations at different mean wind speeds above rated. In the investigation a reduction of the standard deviation of the blade root flapwise bending moment up to 2% is achieved. Bottasso and Croce [2] describe an approach to perform a goal-oriented optimization of the tuning parameters. In their work they describe a possible coupling between an optimization and an aero-servo-elastic software. They also focus on the multi-objective nature of the tuning problem showing two approaches, one based on a combined scalar objective function and one based on a multi-objective Pareto-front optimization.

In this paper, a study to identify a tuning of the controller with a parametric analysis and a numerical optimization is presented. The aim is to investigate a possible improvement in the wind turbine performances adjusting the controller parameters according with the loads computed during simulations. To identify the quality of the performances, a cost function is first proposed and then used both in the parametric analysis and in the optimization. The controller selected for this work is a classical regulator based on two proportional integral (PI) controllers, one for the constant speed-variable torque region, and one for the constant speed and constant power region. In the variable speed region a torque regulation proportional to the square of the measured rotational speed is used.

Results of the investigation here presented show that with an optimized controller tuning the cost of energy can be reduced.

A classical regulator framework is selected, because they are the most used to control variable-speed pitch-torque regulated wind turbines due to their easily implementation, reliability and robustness. The wind turbine used in this work is the NREL 5MW reference turbine [3]. The method developed in this paper is also valid for more advanced controllers, and most of the considerations and conclusions may apply also to different wind turbines.

In Section 2 the controller used for the investigation is described. The numerical optimization, the cost function and the constraints are introduced in Section 3. Section 4 contains a parametric analysis of the effect of each controller parameter on the wind turbine performances. In Section 5 the results of an optimization are shown and commented.

2. Controller description and classical tuning

The controller used here is inspired by Bossanyi [4]. It is divided into four different sub controllers, each for a different operational region. The four regions are:

- constant minimum rotor speed variable torque
- variable rotor speed, variable torque region;
- constant rated rotor speed, variable torque region;
- constant rated rotor speed, constant power region.

In the following each region controller is described to show the parameters of the optimization problem. The techniques of switching between regions are not described. It follows the ideas of Bossanyi [4] and is not part of the optimization problem.

2.1. Variable speed, variable torque region

The pitch is kept constant at the angle β^* and the generator torque is used to regulate the rotational speed Ω to track a constant tip-speed-ratio. The value of the torque is set to $Q_{ref} = k\Omega^2$ to balance the aerodynamic torque. The constant k can be computed as

$$k = \eta \frac{1}{2} \rho \pi \frac{R^5}{\lambda^{*3}} C_p(\beta^*, \lambda^*), \tag{1}$$

where ρ is the air density, R is the rotor radius, β^* and λ^* are the pitch angle and the tip-speed-ratio that maximize the power coefficient C_p, and $\eta \leq 1$ is an efficiency factor used to increase the tip-speed-ratio. Setting $\eta = 1$ the torque balance will ensure optimal tip-speed-ratio λ^* in steady state. However, due to turbulence and large rotor inertia, the controller actions is not quick enough to keep the tip-speed-ratio constant after a change in the wind speed. Variations in the tip-speed-ratio mean that, if λ and β are selected to maximize the power coefficient, the operating point will drop on one side of the $C_p(\lambda)$ curve creating a drop in power production. Moreover, if the tip-speed-ratio decreases for an increase in the wind speed while operating at the top of the C_p curve the flow on the blade will stall and the turbine may risk stall-induced vibrations. In the work by Johnson [5] he suggests to select η between 80% and 95% to increase the value of the tip-speed-ratio. This solution is a good guideline but it may not be the optimal for all wind turbines due to different wind conditions.

2.2. Constant speed, variable torque regions
When the wind turbine is operating at the minimum rotor speed (Ω_{min}) or rated Ω_R, the controller has to keep the rotational speed constant. In these regions, the regulation is performed with a PI controller on the generator torque while the blade pitch is kept constant. The reference torque is set as

$$Q_{ref} = k_p^Q(\Omega_f - \Omega_{set}) + k_i^Q \int_0^t (\Omega_f(\tau) - \Omega_{set})d\tau$$

where Ω_f is a low-pass second order filtered rotational speed, Ω_{set} is either the minimum rotor speed or the rated speed Ω_R, k_p^Q and k_i^Q are the proportional and the integral gains of the rotor speed error PI feedback.

2.3. Constant speed, constant power region
When the power reaches the rated value, the controller has to guarantee constant power and constant rotational speed. This regulation is obtained with a PI controller on the pitch angle

$$\beta_{ref} = k_{p,\Omega}^\beta \eta_k(\Omega_f - \Omega_R) + k_{p,P}^\beta \eta_k(P_{ref} - P_R) + \eta_k \int_0^t [k_{i,\Omega}^\beta(\Omega_f - \Omega_R) + k_{i,P}^\beta(P_{ref} - P_R)]d\tau$$

where β_{ref} is the reference pitch, $k_{p,\Omega}^\beta$ and $k_{i,\Omega}$ are the proportional and integral gains for the rotor speed error feedback, and η_k is a gain scheduling factor. In the pitch controller there are also a proportional and integral term depending on the error between the reference power and the rated power, P_{ref} and P_R. These terms are introduced to improve the transition between the different regions. The power reference is obtained multiplying the reference torque with the unfiltered rotor speed. The two integral terms share a saturated integrator ensuring minimum pitch in the variable speed region and a fast action when the power is increasing.

There are several techniques and methods to select the tuning parameters for PI controllers but they are based on simplified or linearized models and they do not take into account factors such as turbulence. This deficiency means that once the tuning is tested on a real machine or on an advanced model, it does not always show the desired behavior.

A possible strategy to tune the PI controllers is with a pole placement technique [1, 6, 7]. It may ensure that the frequency of the drivetrain rigid body mode is below the tower frequency to avoid a controller induced instability with the fore-aft tower mode, and sufficiently high to avoid large rotor speed variations. The main problems related with the pole placement approach for the constant rotational speed region are that this approach has the uncertainty to be based on a one degree of freedom model [7], and that the designer still have to identify the optimal position of the pole.

3. Optimization problem
The design variables for the given controller are the six gains of the PI controllers, the efficiency factor and the natural frequency and damping ratio of the second order low-pass filter on the measured generator speed.

Figure 1 shows a route diagram of the numerical optimization procedure. Simulations are performed with the multi-body aero-servo-elsastic code HAWC2 [8] according to the IEC standards [9] for a given set of controller parameters. When the simulations are terminated a post processing procedure extracts the equivalent fatigue loads, the ultimate loads and the power production performances. These values are used to compute a scalar cost function and evaluate the fulfillment of the constraints, which goes into the optimization routine that computes new design variables. A gradient based optimization algorithm implemented in the Matlab function

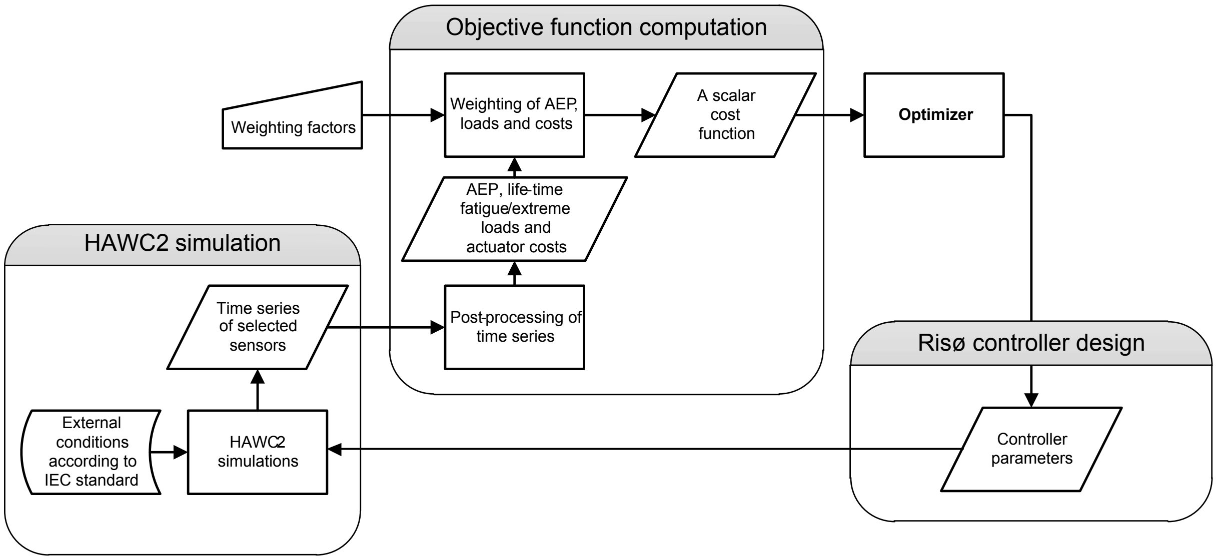

Figure 1. Route diagram of the numerical optimization procedure.

`fmincon` [10] has been used here. The procedure can be easily adapted to other algorithms and optimization platforms.

The cost function is based on loads l computed during simulations:

$$J = \sum_i w_i c_i(l) \tag{2}$$

were $c_i(l)$ are the costs of the wind turbine components and w_i are weights. The cost of the blade, the tower and the drivetrain are computed with an average between fatigue and ultimate loads divided by the annual energy production, while the cost of the pitch system (mechanism and bearings) is computed as the ratio between the normalized actuator duty cycle and the annual energy production.

$$c_i = \frac{1}{2}\frac{\hat{l}_{fatigue} + \hat{l}_{ultimate}}{\widehat{AEP}} \tag{3}$$

$$c_{pitch} = \frac{\widehat{ADC}}{\widehat{AEP}} \tag{4}$$

where $\hat{l}_{fatigue}$ is the normalized life-time damage equivalent load, $\hat{l}_{ultimate}$ is the normalized maximum load computed during the simulations, $\widehat{ADC}$ is the normalized actuator duty cycle and $\widehat{AEP}$ is the normalized annual energy production. The parameters $\hat{l}_{fatigue}$, $\hat{l}_{ultimate}$, $\widehat{ADC}$ and $\widehat{AEP}$ are normalized with respect to the corresponding value of a reference solution. The loads used for the tower and the blade are the resultant of the root section in-plane moments. The load used for the drivetrain is the torque on the shaft at the generator side. The ADC is defined as

$$ADC = \sum_j F(V_j)\frac{1}{T}\int_0^T \frac{\dot{\beta}(t, V_j)}{\dot{\beta}_{max}} dt \tag{5}$$

where $F(V_j)$ is the value of the life time Weibull probability function for the wind speed V_j, T is the length of a simulation, $\dot{\beta}$ is the pitch rate and $\dot{\beta}_{max}$ is the maximum allowable pitch rate.

The weights used in Equations (2) are shown in Table 1. These values are computed dividing an estimated cost of the component by an estimated cost of the wind turbine. The estimated costs are obtained using the method showed in [11].

To ensure tower-blade clearance and sufficient small variations of rotor speed to avoid emergency shutdowns in normal operations, two constraints are included. The first constrained parameter is the maximum blade tip deflection and the second is the maximum rotor speed. The constraints are defined in the optimization algorithm as inequality constraints:

$$m_i - m_{i,max} = \gamma_i \leq 0 \tag{6}$$

where m_i and $m_{i,max}$ are the normalized measured and the normalized maximum allowable value of the constrained parameter i and γ_i is the constraint feasibility. The parameters are normalized with respect to the reference solution. Table 2 shows the maximum allowable value of the two constraints.

The simulations used to compute the loads are in accordance with the DLC 1.2 [9]. Twelve different mean wind speeds are selected, and four different turbulent seeds are used for each of the mean wind speeds. To weight the effect of each wind speeds on the life time loads a Weibull distribution function is used.

All the results presented in the next sections are shown with respect to a reference solution for the 5MW NREL reference wind turbine. This solution is obtained tuning the controller with a classical approach. The controller parameters are

- Pitch angle and efficiency factor for the variable speed region: $\beta = 0°$ and $\eta = 1$;

- Proportional and integral gains of the pitch PI controller: $k^{\beta}_{p,\Omega} = 0.925\,\mathrm{rad/(rad/s)}$ and $k^{\beta}_{i,\Omega} = 0.207\,\mathrm{rad/rad}$ corresponding to a closed-loop pole of the rigid body drivetrain mode with frequency 0.05 Hz and damping 0.7;

- Proportional and integral gains of the torque PI controller: $k^{Q}_{p} = 2.022\,\mathrm{MNm/rpm}$ and $k^{Q}_{i} = 4.330$ MNm/rad corresponding to a closed-loop pole of the rigid body drivetrain mode with frequency 0.05 Hz and damping 0.7;

- Natural frequency and damping ratio of the second order low-pass filter on the measured generator speed: frequency 0.6 Hz and damping ratio 0.7. The free drivetrain frequency is about 1.65 Hz

Table 1. Cost function weights, w.

Component	c
Blade	0.311
Tower	0.122
Drivetrain	0.231
Pitching system	0.042

Table 2. Constraints.

Max tip deflection	5 m
Max rotor speed	$1.1\,\Omega_R$

4. Parametric analysis

The parametric analysis is performed to investigate how the tuning of the main controller parameters affects the behavior of the wind turbine. In the parametric analysis the four PI gains of the rotor speed error feedback, the efficiency factor of the torque controller and the natural frequency of the second order low pass filter are analyzed.

4.1. Proportional gain of the pitch PI controller

Figure 2 shows the variations of the normalized total cost and of the rotational speed constraint feasibility γ due to the proportional gain of the pitch controller. The total cost of the wind turbine decreases when the gain is decreased, while the maximum rotational speed increases. The damping of the drivetrain speed regulator mode is lower for reduced gains, hence the controller responds slower to the wind speed changes. A slower response leads to higher rotational speed variations and so to a higher maximum value. The solution becomes unfeasible ($\gamma > 1$) when the gain is 0.75 rad/(rad/s). In Figure 3, the costs variation of each wind turbine component are plotted for the same changes in the proportional gain. An aggressive pitch controller with high proportional gain leads to a higher pitch and tower cost. For faster control of the rotor speed the pitch action has to be higher leading to higher variations in the aerodynamic thrust and thereby larger tower oscillations. At low gain, the generator cost is higher because the torque has to counteract the large rotor speed variations to guarantee constant power.

4.2. Integral gain of the pitch PI controller

Figure 4 shows the variations of the normalized total cost and of the rotational speed constraint feasibility due to the integral gain of the pitch controller. The total cost is not significantly affected by changes in the integral gain of the pitch controller, whereas the variations of the maximum rotational speed are more significant. As for the proportional gain, a low gain leads to larger rotor speed variations. A lower frequency of the drivetrain speed regulator mode is equivalent to a reduction in the stiffness that keeps the rotor speed at its set-point, hence the larger rotor speed variations. Figure 5 shows the cost of the components. Larger integral feedback leads to larger cost variation for the pitch actuator, whereas low gains leads to lower blade cost. The cost variation is clearly not convex, hence the gradient-based optimization may fail identifying the global minimum.

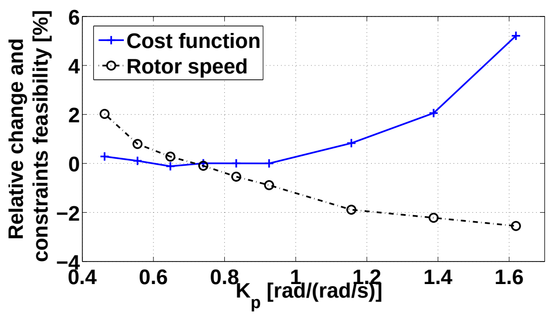

Figure 2. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the proportional gain of pitch controller.

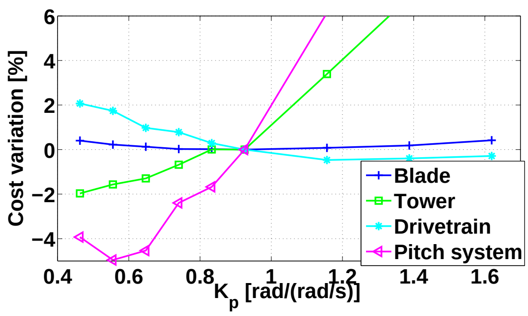

Figure 3. Variations of normalized component-cost due to changes in the proportional gain of pitch controller.

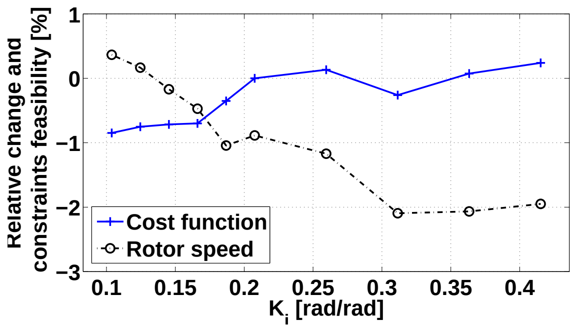

Figure 4. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the integral gain of pitch controller.

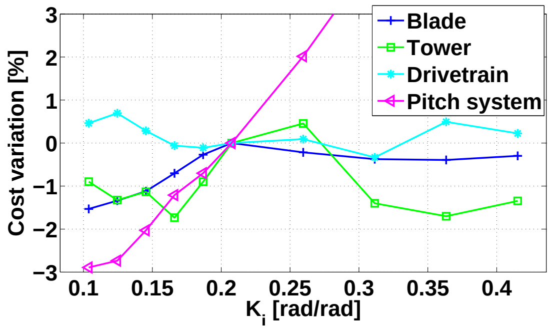

Figure 5. Variations of normalized component-cost due to changes in the integral gain of pitch controller.

4.3. Proportional gain of the torque PI controller

Variations of the normalized total cost and of the rotational speed constraint feasibility due the proportional gain of torque controller are plotted in Figure 6. Again, the cost decreases when reducing the proportional gain. The maximum value of the rotational speed is not significantly affected because overspeeds occur at a higher wind speed, where the pitch is used for the regulation. Figure 7 shows the components cost variations. The blade and the tower are subject to lower loads when the torque controller is less aggressive. Even if the torque controller is active in a small region, it significantly affects the cost function due to the wind speed probability distribution. Because the variable torque constant rotor speed region is small, in turbulent wind the loads might also depend on the switching conditions.

4.4. Integral gain of the torque PI controller

Figure 8 shows the total cost variation due to changes in the integral gain of the torque controller. The integral gain of the torque controller has a similar effect on the total cost as the proportional one. In Figure 9 the costs of the components are shown. When reducing the gain the tower cost decreases up to a value where it starts increasing again. The tower cost reduction is due to lower maximum loads, because a lower gain generates a slower controller and a less aggressive action after a switch between two regions.

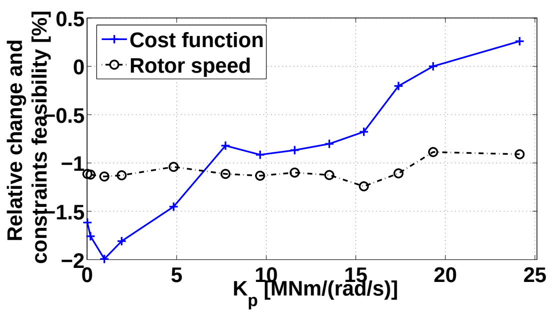

Figure 6. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the proportional gain of torque controller.

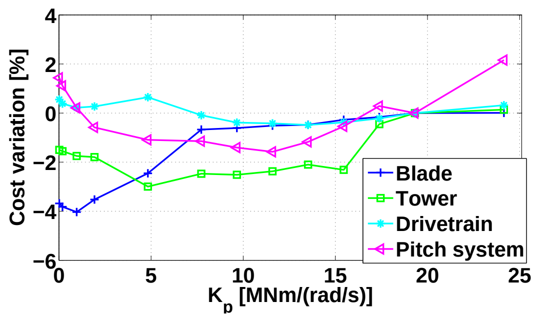

Figure 7. Variations of normalized component-cost due to changes in the proportional gain of torque controller.

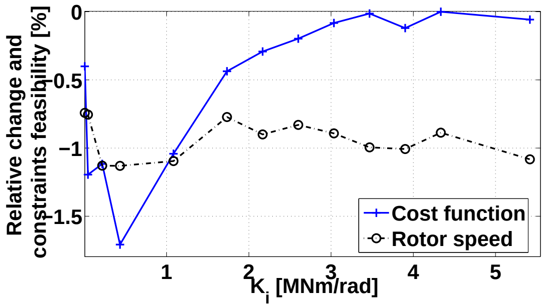

Figure 8. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the integral gain of torque controller.

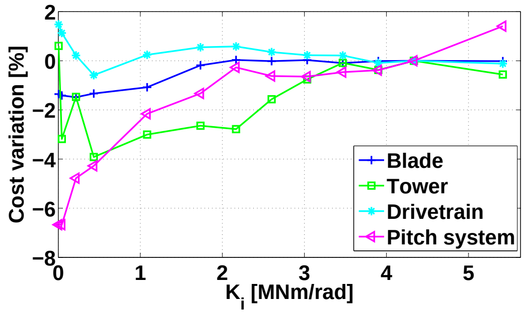

Figure 9. Variations of normalized component-cost due to changes in the integral gain of torque controller.

4.5. Efficiency factor for torque controller

Figure 10 shows the variations of the total costs and of the constraint feasibility due to the efficiency factor η of the $k\Omega^2$ controller, whereas Figure 11 shows the components costs variation. The plots show that there is a significant cost reduction for low values of η. The total cost reduction is mainly driven by the tower and the blade costs. Reducing the value of η the mean value of the rotational speed increases. A higher rotational speed increases the gap between the 3P frequency and the tower first natural frequency reducing the tower vibrations, hence the fatigue loads. For example, an efficiency factor of 80% increases the distance between the 3P and the first tower natural frequency of 7%. For very low efficiency factors the cost increases due to the reduction in the annual energy production.

4.6. Rotational speed low-pass filter natural frequency

Figure 12 shows the variations of the normalized total cost and of the rotational speed constraint feasibility due to changes in the natural frequency of the second order low-pass filter on the measured generator speed. If the frequency is low the control action is too soft, hence the performances are lower. For too high filter frequencies the response of the low-damped free-free drive train mode is not sufficiently attenuated in the feed-back measurement, therefore the loads on the drive train and the pitch actuator are higher. In Figure 13 the components cost variations

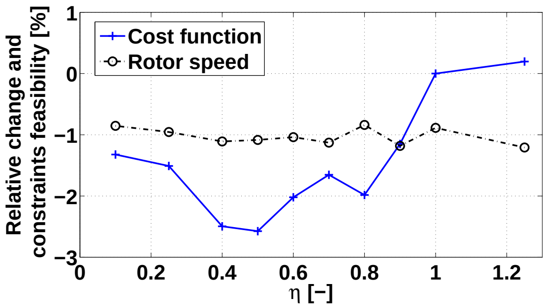

Figure 10. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the efficiency factor of the $k\Omega^2$ torque controller.

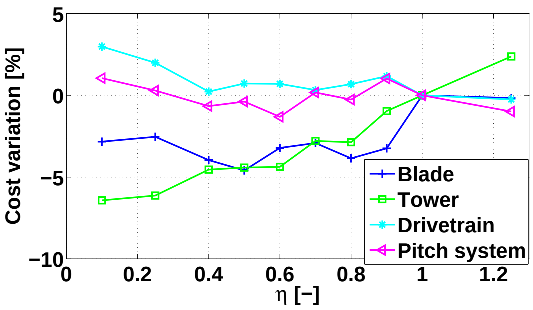

Figure 11. Variations of normalized component-cost due to changes in the efficiency factor of the $k\Omega^2$ torque controller

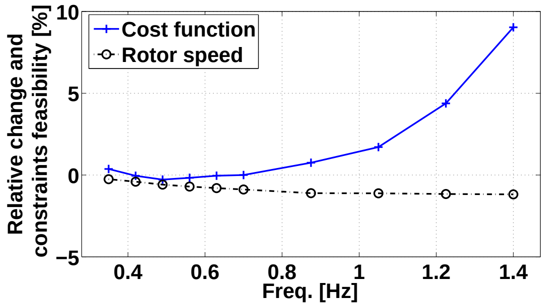

Figure 12. Variations of the normalized total cost and of the rotational speed constraint feasibility γ due to changes in the natural frequency of the second order low-pass filter on the measured generator speed.

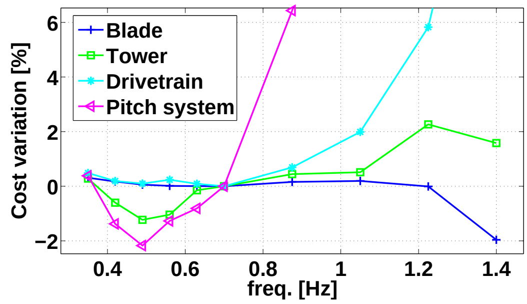

Figure 13. Variations of normalized component-cost due to changes in the natural frequency of the second order low-pass filter on the measured generator speed.

are shown. The plot shows that the components more influenced by the low-pass filter frequency are the drive train and the pitch system.

5. Automatic tuning

In this investigation only the four gains on the rotor speed feedback error are selected as optimization variables. The initial solution, required by the gradient based algorithm, is the reference solution described in Section 3. In Figure 14 the changes of the cost function in the first seven iterations are shown, where it is reduced by 2%. The cost reduction achieved with the optimization is close to the maximum reductions shown in the parametric analysis for the same parameters. This similarity in cost changes may mean that the optimization has stopped at a local minimum or that it is not possible to obtain a further reduction when optimizing with more variables at the same time. In Figure 14 also the changes in the feasibility of the constrains on the maximum tip deflection and the maximum rotational speed are plotted. The constraints are not significantly changed and they do not approach the feasibility limit. Only a small increase of the rotational speed constraint feasibility occurs, due to the reduction of integral gain of the pitch controller. Figure 15 shows the optimization variables variation with respect to the reference solution at the different iterations. During the optimization most of the parameters are reduced, in accordance with the results shown in the parametric analysis. Only the pitch

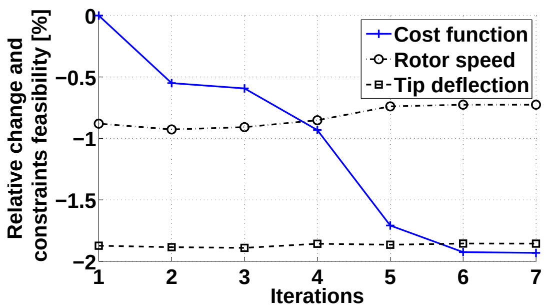

Figure 14. Automatic tuning: variations of the normalized total cost and of the rotational speed constraint feasibility γ.

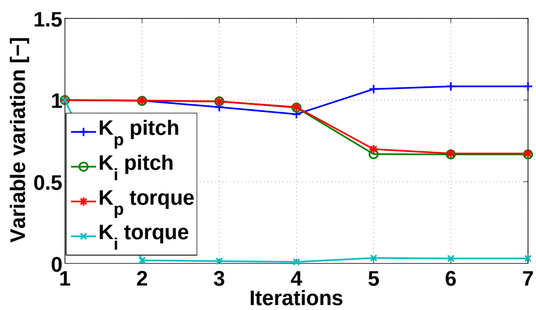

Figure 15. Automatic tuning: optimization variables variation with respect to the reference solution.

proportional gain increases leading to a more aggressive controller in the full load region. The variable that has the largest variation is the integral gain of the torque controller. Indeed, from the parametric analysis, it was evident that the gains of the torque controller allow larger cost reductions compared to the gains for the pitch controller. As in the parametric analysis the component that drives the reduction of the integral gain of the torque controller is the tower. The lower integral gain generates a less sharp corner in the mean wind speed versus mean rotor speed curve, making the switch less aggressive and reducing the loads on the tower. The CPU time needed for this optimization is approximately of 4000 hours.

6. Conclusions

In this work a method to tune a wind turbine controller using a numerical optimization has been presented. A parametric analysis of the main controller parameter has shown how the tuning affects the performances and the cost of the wind turbine. This study has highlighted the complexity of the tuning process showing the contrasting behavior of some parameters on the loads. The results from the numerical optimization have shown that is possible to achieve a fine tuning that can improve the wind turbine performances leading to a lower cost of energy. In seven iterations the cost of the energy has been reduced by 2%. The cost reduction has been achieved reducing the gains of the torque controller and the integral gain of the pitch controller. The integral gain of the torque controller has been reduced to a few percent of its original value to smooth the transition between the constant speed constant power region and the constant speed variable torque region.

Further investigations should focus on repeating the numerical optimization changing the initial guess. This study should identify if the gradient based algorithm has found a local minimum and if the cost can be further reduced. Future works may also focus on the improvement of the cost function and on the selection of a more suited optimization algorithm. A more realistic cost function could give more reliable and factual results while a more advanced algorithm, e.g. based on global optimization, could further improve the cost reduction identifying the global minimum.

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