Nonlinear Dynamic Inversion Control for Wind Turbine Load Mitigation based on Wind Speed Measurement

Matthias J. Reiner[1] Dirk Zimmer[1]

[1]Institute of System Dynamics and Control, German Aerospace Center (DLR), Germany,
{Matthias.Reiner, Dirk.Zimmer}@DLR.de

Abstract

The design of an advanced controller for wind turbine load mitigation is presented. The controller is based on Nonlinear Dynamic Inversion control methods combined with Pseudo Control Hedging to account for the actuator limits and a two degree of freedom control system for the collective pitch control of the rotor blades. The controller uses wind speed measurement information to adjust to wind gust load. A newly developed wind turbine system dynamics library in the Modelica language is used to model an elastic wind turbine for a simulation study of the controller. The simulation results show a large reduction of the gust load on the wind turbine using the proposed controller.
Keywords: Elastic wind turbine modeling; nonlinear dynamic inversion; pseudo control hedging; optimization

1 Introduction

Wind energy has become an important energy source with worldwide growing capacities. Advanced control design can help to improve the energy generation and extend turbine lifetime.

While the nominal control of wind turbine is already well handled by the state of the art, and only minor improvements can be expected for the ideal case with smooth wind speed, there is still much potential in the field of load reduction. Especially under gust load conditions, the load on the flexible structure of the wind turbines can be reduced using advanced control methods.

One important aspect in this regard is the technological advance in wind speed measurement. Especially turbine-mounted light detection and ranging (LIDAR) based wind speed sensors have become much more affordable and accurate. The measurement of the wind speed opens a wide range of control methods. Gust load can be substantial and induce strong vibrations of the wind turbine tower, which can lead to a lifetime reduction.

In recent years, many different advanced control approaches have been proposed for the control of wind turbines that are based on wind speed measurements (Dunne et al., 2011). Especially methods based on Model Predictive Control (MPC) strategies and feed-forward disturbance compensation methods show promising results, e.g. (Schlipf et al., 2010; Wang and Johnson, 2011; Koerber and King, 2013). This simulation study focuses on an approach based on Nonlinear Dynamic Inversion (NDI) (Slotine and Li, 1991) combined with Pseudo Control Hedging (PCH) (Johnson and Calise, 2000). Similar controller structures are known from the field of aerospace control. Although not directly comparable, there are many similarities: in both cases, the main source for the nonlinearity results from the changing wind speed (e.g. airspeed) and resulting

Figure 1. Visualization of a Modelica Wind Turbine model using the DLR SimVis Library (Bellmann, 2009).

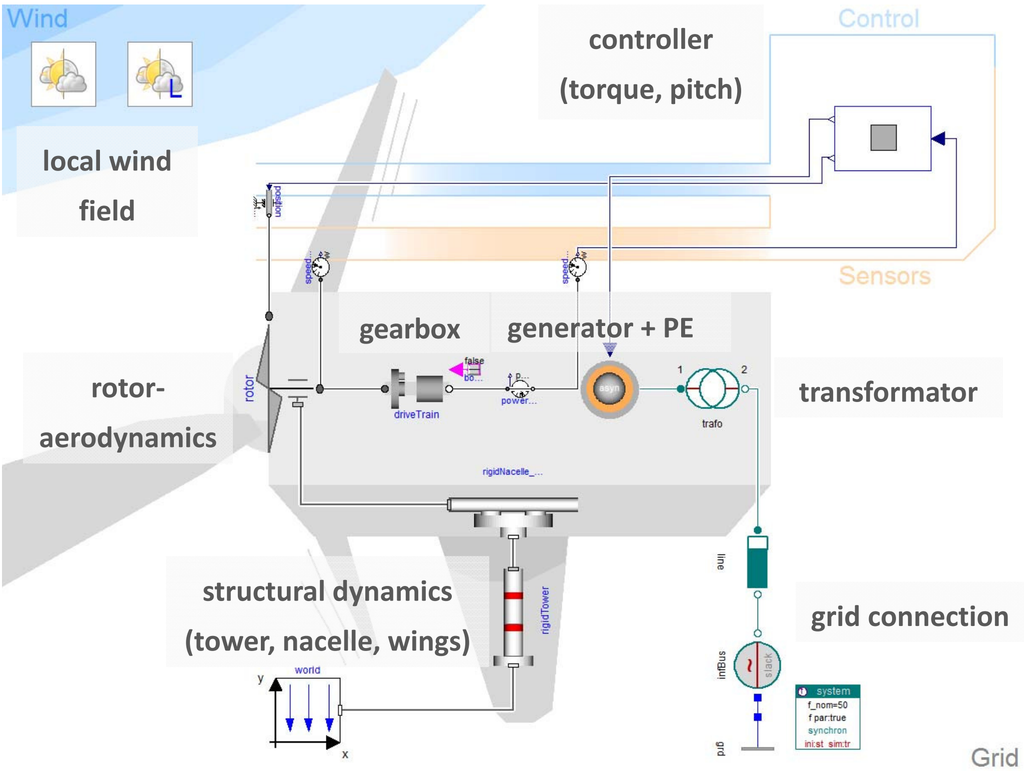

Figure 2. Top level Modelica model diagram of a typical wind turbine architecture.

aerodynamics. Actuator limits play a very important role (rates and absolute limits) and the excitation of the flexible structure has also to be considered in both cases during gust load situations.

Since good results have been achieved in the field of aerospace control using NDI with PCH, it is worthwhile to study its adaption and application for elastic wind turbines. One important aspect for the control of wind turbines are the dynamic ranges of the actuators. While the turbine generator can be controlled very fast to react to load changes, the pitch actuators of wind turbines are usually relatively slow. NDI has also recently been investigated for the pitch control of wind turbines (Geng et al., 2014) but we focus on the generator control, where a faster response can be achieved and use a two degree of freedom system for the pitch control. The actuator to turn the wind turbine into the wind direction (yaw axis) is usually the slowest actuator and therefore not relevant for load mitigation control and will not be considered here.

Section 2 describes the approach used for modeling the elastic wind turbine using the Modelica language (Modelica Association, 2010). Based on this nonlinear model the NDI & PCH based controller is described in section 3 using Modelica and the Functional Mock-up Interface technology (FMI) (development group, 2014). Simulation results and comparisons to a conventional scheduled controller are given in section 4. A conclusion and outlook is given in section 5.

2 Modeling of elastic wind turbines

Modern wind turbines represent multi-domain systems. Hence, to describe the dynamic behavior of a complete turbine, expertise from different areas is required: wind field analysis is needed to describe the environment; rotor-aerodynamics models the transformation of wind energy into kinetic energy; this kinetic energy is then turned into electric energy by the means of gears, electric machines and power system converters; also the flexibility of the tower structure and the blades needs to be taken into account.

Fig. 2 illustrates how all these components are ultimately assembled for a complete turbine model within Modelica. It represents one specific example of a wind turbine that is based on the 5MW reference turbine from NREL (Jonkman et al., 2009). The electric parts of the turbine (generator, converter, grid) have been adapted to the specifics of the European market.

Given any task, the modeler will need to adapt this turbine model to her or his specific needs. For instance, modeling the integration of a turbine into electric grid requires more detailed modelling of the generators and converters, whereas for the task of this paper, the generator can simply be represented as a controlled source of limited torque. It is thus necessary that each part of the turbine can be modeled with the appropriate level of complexity and detail. To ensure this flexibility, the modeling work is supported by a DLR library dedicated to

DOI 10.3384/ecp15118349

wind turbines. In this library, DLR offers its combined modeling know-how in the field of drive-train (Tobolar et al., 2007), aerodynamics (Looye, 2008), structural dynamics (Heckmann et al., 2006), and visualization (Bellmann, 2009) (see Fig. 1) in order to offer a complete system dynamics library for wind turbines. The following sections describe those parts of the library which are relevant for the control task at hand. These are: the modeling of the aerodynamics, the structural dynamics and the design of a standard controller.

2.1 Wind turbine aerodynamics

The evident key-component of a wind turbine is its rotor. The most-straight forward approach is to regard this component as one single entity that transforms wind energy into kinetic energy by a coefficient of efficiency C_P. This coefficient is typically defined as a function of the tip-speed ratio λ, expressing the relation between wind speed and the tip speed of the blades. If we take the collective pitch of the blades into account, we get a two-dimensional function, where both input parameters are subject to control laws: the pitch angle is controlled by the pitch actuators and the tip speed can be regulated by the power-off take of the generator. Hence this basic model of a rotor is well applicable for classic control tasks.

For more advanced tasks, the rotor is decomposed into its blades and the blades are decomposed into blade elements. Each such element then has its own airfoil polar that describes the aerodynamic forces for lift and drag dependent on the angle of attack within the induced wind field. The induced wind field is a superposition of the global wind in the vicinity of the rotor field and the wind that is induced by the rotor itself. For a certain induced wind, the momentum needed to change the wind velocity and the momentums emanated from the aerodynamic forces of the blade element are equal. This equilibrium can be described by a nonlinear system of equations and forms the basis of the well-established Blade-Element-Momentum (BEMT) Method (Hansen, 2008). It is suitable for wind turbines without strong cross-winds or significant local turbulences. It can be used to take the influence of wind shear into account and to design individual pitch control systems. In combination with flexible blades and towers, good estimation of the structural loads can be performed.

For the method's implementation in Modelica, a model of a local blade element has been created. In interaction with a global outer model for the rotor plane, this component determines the local aerodynamic forces. The individual blade elements can then be connected (rigidly or by a flexible body) to form a complete blade. Typically, three such blades then form the rotor.

2.2 Structural dynamics of tower and blade

Modern, large-scale wind turbines have rotors of more than 100 meters of diameter. The flexibility of such a large structure is an integral part of its design. Most important are the structural dynamics of those components which are most exposed to the wind: the tower and the blades. The flexibility of the nacelle, especially of the mounting of its devices and bearings, is currently not taken into account but the elasticity of the nacelle mounting on its tower is taken into account around the yaw angle.

For the modeling of these components, the DLR FlexibleBodies Library (Heckmann et al., 2006) is used. Using this library, the components can be modeled using standard connectors of the Modelica Standard library. The blade-elements of the rotor aerodynamics can hence be connected to a flexible blade as well as to a rigid blade.

The components of the FlexibleBodies library are based on a modal approach. Structural information of the blade and tower stiffness, as presented in (Jonkman et al., 2009) can be incorporated into the model by a SID file (Heckmann et al., 2006). Nonlinear effects such as the increased stiffness due to centrifugal stretching can be taken into account. The performance characteristics are comparable to the approach presented in (Thomas et al., 2014).

2.3 Complete turbine model

For the control task of this paper, the aerodynamics and structural elasticity are the key components of the wind turbine. Nevertheless, more components are needed to form a complete model. This is also shown in Fig. 2. Wind models are needed that prescribe the regional wind conditions but also model local effects like height dependent wind shear and the tower dam effect. Components for gearbox, emergency brake, generator and power electronics form the complete drive train of the turbine model. Many different designs for such drive trains exist in current wind turbines and the presented diagram just shows one possible setup.

Finally, the controller of the turbine model is depicted in Fig. 2 with its signals controlling motor torque and pitch angle. One possible and advanced design of such a controller is presented in the following chapters.

3 Controller design

The nonlinear characteristics of the wind turbine are considered in our control design by using an inverse model of the wind turbine as part of the controller. The approach used here is Nonlinear Dynamic Inversion (NDI) for the control of the generator torque together with Pseudo Control Hedging to handle actuator limits.

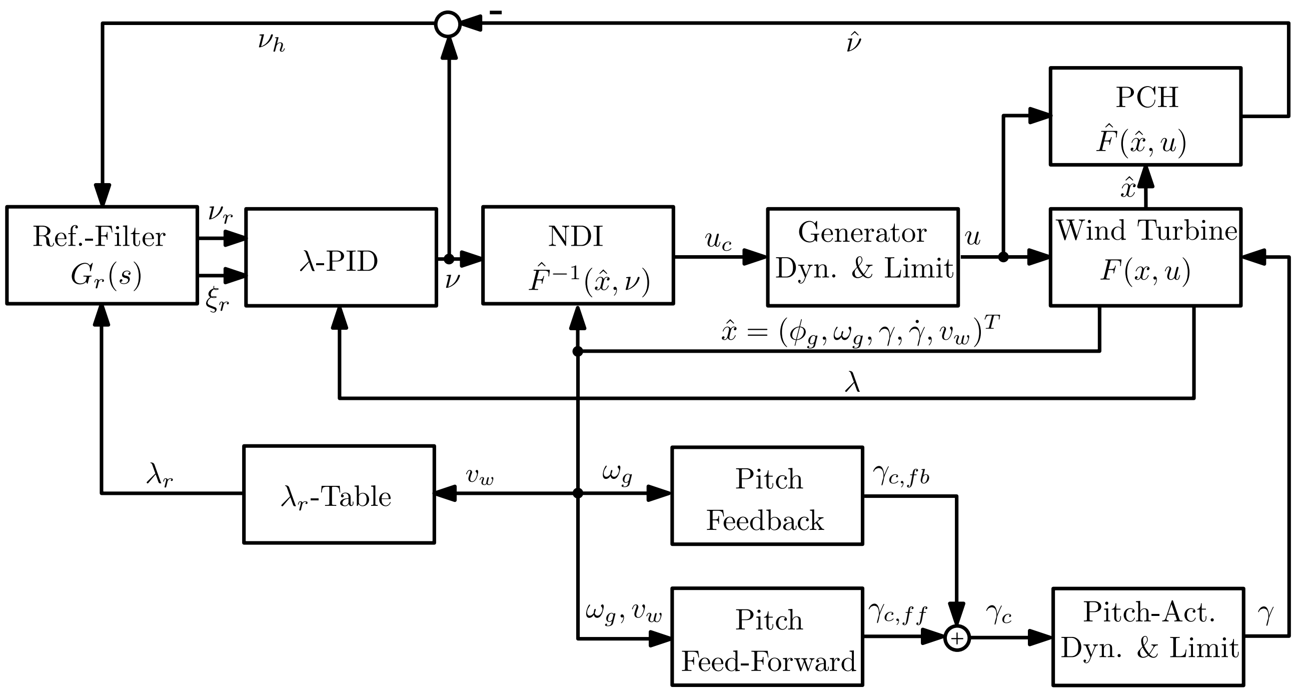

Figure 3. Overview of the combined NDI & PCH control system for the generator torque in addition to a two degree of freedom pitch controller. The connections show the data flow between the different components.

For our controller design, it is assumed that high accuracy measurement of the wind speed at the turbine is available. This could be based on LIDAR, e.g. (Simley et al., 2012) or similar measurement methods in combination with additional estimators or filters.

The notation and implementation used here is similar to (Looye, 2001; Holzapfel, 2004; Lombaerts et al., 2012) from the field of aerospace control.

As an extension for the NDI control of the generator torque, a feed-forward controller for the pitch control is used. The feedback controller design for the pitch control is based on the reference controller from (Jonkman et al., 2009) that will also be used for comparison of the controller performance in Sec. 4. The reference pitch controller from (Jonkman et al., 2009) is a scheduled (on the generator speed) PI controller. Under nominal conditions the controller already works very well, but can be improved by a wind speed feed-forward controller.

The feed-forward controller for the pitch actuator consists of different elements: the main part is a linear interpolated table which contains a function $\gamma_{tab}(v_w)$ of optimal pitch actuator angles γ depending on the measured wind speed. The optimal values are the steady-state results for a simulation using only the reference pitch controller and constant wind speed. Since the pitch actors are relatively slow, they should only be used when the generator is close to its limit. For this reason a switch is implemented in the feed-forward controller that only enables the controller close to the lower or upper limit of the generator speed ($\omega_{g,low}$ and $\omega_{g,high}$). A hysteresis loop is implemented to avoid jittering of the switch close to the limit. When active, the output of $\gamma_{tab}(v_w)$ is used as input for a low-pass Bessel filter $G_{bes}(s)$ (Laplace variable s) and a rate limiter (limit $\dot{\gamma}_{c,max}$) to ensure that the pitch actuators can follow the dynamics of the feed-forward controller.

$$\varkappa_{on} = \omega_g > \omega_{g,high} \vee \mathrm{pre}(\varkappa_{on}) \wedge \omega_g >= \omega_{g,low} \quad \text{(1a)}$$

$$\gamma_{c,uf} = \begin{cases} \gamma_{tab}(v_w), & \text{if } \varkappa_{on} = 1, \\ 0, & \text{if } \varkappa_{on} = 0\ . \end{cases} \quad \text{(1b)}$$

$$\gamma_{c,fi} = G_{bes}(s)\gamma_{c,uf} \quad \text{(1c)}$$

$$\dot{\gamma}_{c,ff} = \min\left(\max\left(\frac{\gamma_{c,fi} - \gamma_{c,ff}}{T_r}, -\dot{\gamma}_{c,max}\right), \dot{\gamma}_{c,max}\right) \quad \text{(1d)}$$

$$\gamma_{c,ff} = \int \dot{\gamma}_{c,ff} dt \quad \text{(1e)}$$

Eq. 1 shows the resulting equations and logic for the feed-forward controller. The feed-forward controller is combined with the scheduled PI pitch controller from (Jonkman et al., 2009) to form a two degree of freedom control system.

We assume the general nonlinear system description of the wind turbine in the form of Eq. (2) where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^k$ is the input vector, $y \in \mathbb{R}^l$ is the vector of outputs that are controlled, $p \in R^{n_p}$ are the parameters and known inputs of the system and $z \in \mathbb{R}^m$ contains any other outputs of the system. Any other control inputs are considered as known parameters ($\in p$). The nonlinear model is our implementation based on the 5-MW reference wind turbine from (Jonkman et al., 2009),

DOI 10.3384/ecp15118349

using the model library described in Sec. 2.

$$\dot{x} = f(x,p) + g(x,p)u \tag{2a}$$
$$y = h(x,p) \tag{2b}$$
$$z = h_0(x,p) \tag{2c}$$

The inverse system can be generated using Lie-derivatives of the output h along f and g.

$$\dot{y} = L_f h(x,p) + L_g h(x,p)u \tag{3}$$

Assuming that $L_g(x,p)$ is invertible and all outputs have the relative order 1 with respect to one of the inputs, the following control law can be constructed:

$$u_c = (L_g h(\hat{x},p))^{-1}\left(\dot{y}_d - L_f h(\hat{x},p)\right) \tag{4}$$

In Eq. (4) $y_d \in \mathbb{R}^l$ represents the demand rates and $\hat{x}$ represents a subset and estimation of the states x of the original system.

$$\hat{x} = (\phi_g, \omega_g, \gamma, \dot{\gamma}, v_w)^T \tag{5}$$

In the following, we will use a shortened notation where $F(x,u)$ is used for Eq. (2), $\hat{F}(\hat{x},u)$ for a differentiable approximation of $F(x,u)$ for which all assumptions are valid. For $\hat{F}(\hat{x},u)$, the flexible dynamics are neglected and the tables for the nonlinear aerodynamics are replaced by differentiable B-splines. For the modified system only a subset $\hat{x}$ of the states of the original system x are used. The subset of the states $\hat{x}$ in Eq. (5) consist of the generator angle ϕ_g and angular velocity ω_g, the pitch actuator angle γ and angular velocity $\dot{\gamma}$ as well as mean wind speed at the rotor blades v_w.

The inverse system based on $\hat{F}(\hat{x},u)$ and Eq. (4) is called $F^{-1}(\hat{x},\nu)$ using the virtual control input $\nu = \dot{y}$. Using $\hat{F}^{-1}(\hat{x},\nu)$ to generate the input u_c for $\hat{F}$ would lead in the ideal case (with $F = \hat{F}$ and all p perfectly known) to an input/output linearization such that the original nonlinear system is transformed to a closed loop system with decoupled linear dynamics:

$$\dot{\hat{x}} = \nu \tag{6}$$

But even in the case if only $F \approx \hat{F}$ the nonlinearity of the closed loop system can be greatly reduced, such that a linear controller is better able to achieve good performance.

The inverse control law of Eq. (4) can be generated automatically from a modified Modelica model of the wind turbine using the automatic differentiation and index reduction (Mattsson and Söderlind, 1993) features of Dymola (Otter et al., 1996). The inverse model is then converted to an FMI for which the states of the inverse system are transformed to additional inputs. An outer control loop is used in combination with $\hat{F}^{-1}(\hat{x},\nu)$ to control the resulting dynamic of Eq. (6) and to damp effects of modeling errors and parameter uncertainties.

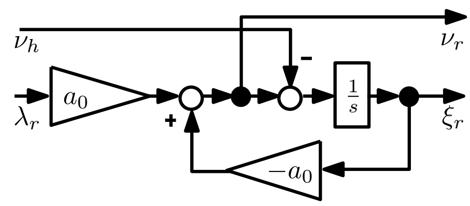

Figure 4. First order reference filter $G_r(s)$ for the PCH.

Since the actuators of wind turbines are limited and also have a dynamic behavior additional measures are necessary. An approach similar to (Holzapfel, 2004) and (Lombaerts et al., 2012), from the field of aerospace, is used here. It consists of a reference filter $G_r(s)$ (Fig. 4) and a model of the system $\hat{F}(\hat{x},u)$ in combination with a PID-feedback controller in the outer loop. An overview of the controller setup is shown in Fig. 3. The reference filter is used to modify the controller demand such that the actuator limits are maintained. To achieve this, a parallel model of the plant $\hat{F}(\hat{x},u)$ is used. The input for the parallel model are a subset of the measured states $\hat{x}$, defined in Eq. (5), of the wind turbine F. The outputs of the reference filter are the set point for the PID controller ξ_r and a term ν_r that is directly added to the output ν of the PID controller. The reference filter is parameterized as a critical damped filter with cut off frequency f_r (filter parameter $a_0 = 2\pi f_r$).

It is assumed that all these quantities are measurable or obtainable using an observer. For $\hat{F}$ the flexible dynamics of the wind turbine are neglected, i.e. no elasticity of the powertrain and tower is considered in $\hat{F}^{-1}(\hat{x},\nu)$. This means ϕ_g and ω_g can also be directly used to calculate the blade speed, except for a constant factor for the gear ratio I_{gen} and tip speed ratio $\lambda = \omega_g R / v_w$ (rotor radius R).

There a multiple reasons for approximation: If the elasticity of powertrain and especially the elasticity of the tower would be directly considered for $\hat{F}^{-1}$ the complexity would rise substantially. Although the inversion would still be possible, at least for a flexible powertrain using the automated possibilities of Dymola, higher order derivatives of the inputs and equations of motion for the inverse model would be required (e.g. of λ, v_w and γ). Since these are measurement values, it would make the inverse model very sensitive to noise and uncertainties in these quantities. For the NDI approach also additional measurements of the elastic deformations would then be necessary (since the whole state vector is required for the method) that are often not readily available. In addition the computational time for the control algorithm would rise considerably such that a real time implementation could be problematic. If elastic effects are considered, also the zero-dynamics of the system used for the inversion can be critical. A stable zero-dynamics is necessary for a stable inversion. The zero dynamics can be approximated by the (transmission-) zeros of a linearization of the nonlinear system since the full nonlinear analysis of the zero dynamics can usually not be solved analytically for complex systems. For the rigid system, all zeros have no positive real part, and therefore do not turn into unstable poles for the inverse system. The reasons mentioned here are likewise main factors why NDI control systems in the aerospace field are usually also based on rigid models, even though the aircraft can show significant elastic deformations.

For $\hat{F}^{-1}$ the inversion is done with respect to $\dot{\lambda}$, so that in Eq. (4) $u_c = \tau_g$ and $\dot{y} = \dot{\lambda}$. The tip speed ratio was chosen for the inversion since the optimal operation point can be found from C_p-λ curves. The model used for the inversion is modified such that the highest derivatives that are required for the inverse model are directly used as inputs and connected to integrator chains of the respective order.

The parallel model used for the PCH algorithm is the same forward model $\hat{F}^{-1}$ used to generate the inverse model $\hat{F}^{-1}$, but without the added integrator chains and re-defined inputs. The inversion is done using the Modelica/Dymola capabilities (see (Thümmel et al., 2005) for details).

The resulting inverse model of the rigid wind turbine is then exported as an FMI. In the FMI-code, the state of the inverse system is redefined as an input such that no integration of the derivatives is necessary. The resulting inverse system is therefore in the form of Eq. (4). The required Lie-derivatives are solved automatically by Modelica/Dymola. The modified FMI can then be used for a controller implementation directly on target hardware, or can be re-imported into the Modelica/Dymola to simulate the complete control system. To account for the actuator limits, the output of the inverse model u_c is modified by limiter for the absolute value and the rate, using the same limiter equation as in Eq. (1d) for the pitch rate $\dot{\gamma}$. The result is the generator torque u that is used as set point for the wind turbine torque generator and the PCH parallel model $\hat{F}$ (see Fig. 3).

To improve the numerical robustness of the control system and the numeric, the required derivatives of measurement values are calculated using filters. The Modelica approximated derivative blocks (DT1) are used. The time constants of the DT1 elements can be tuned to provide a good compromise between accuracy and robustness against noise as part of the controller synthesis. The DLR multi-case and multi-criteria optimization tool MOPS (Joos et al., 2002) was used to find suitable parameters for the controllers as well as the content of the table, which contains optimal set points λ_r depending on the wind speed v_w using a griding simulation optimization for different wind speed inputs of the control system. Since it is assumed that v_w is measurable the optimal λ_r can then be found using a linear interpolated table based on v_w (λ_r-Table in Fig. 3).

As will be seen in Sec. 4, the approximate inversion still helps considerably for the reduction of stress caused by elastic deflections because the controller reacts faster to quickly changing wind speed. This in turn reduces the acceleration peaks at the tower tip and therefore reduces the elastic vibrations.

4 Simulation results

For the simulation study, multiple scenarios of different wind speed trajectories have been analyzed. The nonlinear simulation plant model is based on the 5-MW reference wind turbine from (Jonkman et al., 2009) using modeling components form Sec. 2.

The model consists of a flexible tower (7 flexible modes, using the FlexibleBodies Library), flexible powertrain (modeled as spring damper system), flexible nacelle mounting (yaw axis) and simplified first order generator dynamics. The wind-rotor interaction dynamic is approximated using a tabled pitch correction factor together with a tabled rotor efficiency factor that is dependent on the tip speed ration and pitch correction factor. The controller from (Jonkman et al., 2009) is used as a reference to compare the results (will be referred to as reference controller in the following). The reference controller does not use wind measurement information, but works very well under nominal conditions and therefor provides a good benchmark for achievable performance without wind speed measurement. Since the main objective of wind turbines is to generate as much energy as possible, a controller needs to achieve a good compromise between generated energy and load reduction.

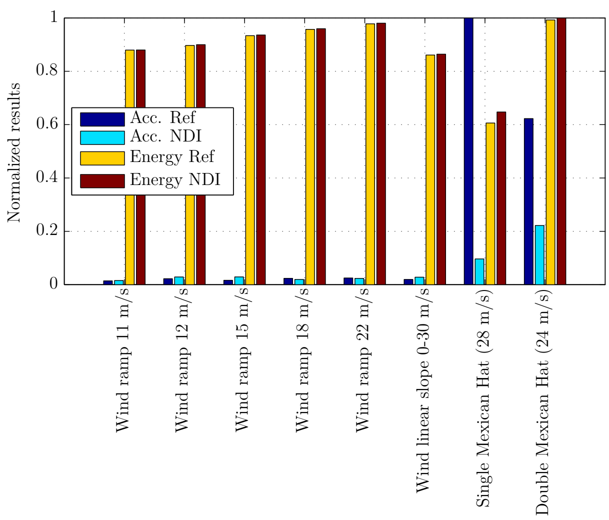

Figure 5. Normalized results of the generated energy of the wind turbine and acceleration at the tower tip for the different simulated scenarios.

It can be assumed that in the long term, load reduction on the tower can lead to an increase of the life time and less required service intervals. This can make the inclusion of a wind speed sensor cost-effective for future wind

DOI
10.3384/ecp15118349

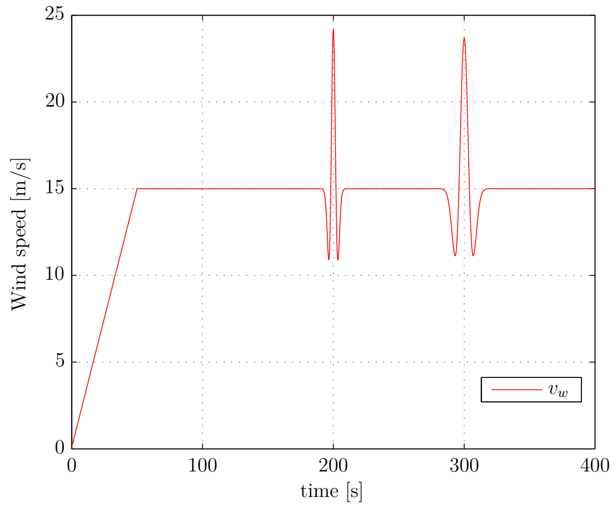

Figure 6. Wind speed for the scenario with a wind ramp and double wavelet disturbances.

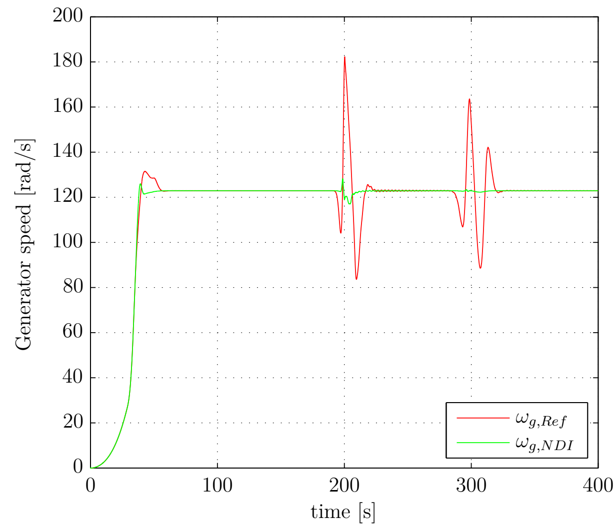

Figure 8. Comparison of the resulting generator speed for the scenario with a wind ramp and double wavelet disturbances.

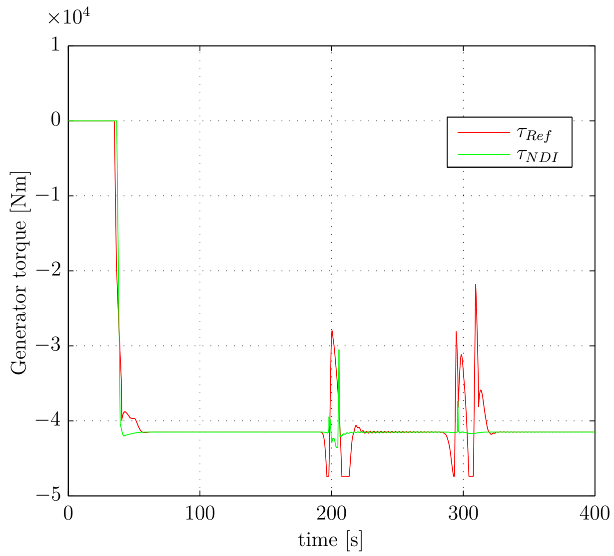

Figure 7. Comparison of the resulting generator torque for the scenario with a wind ramp and double wavelet disturbances.

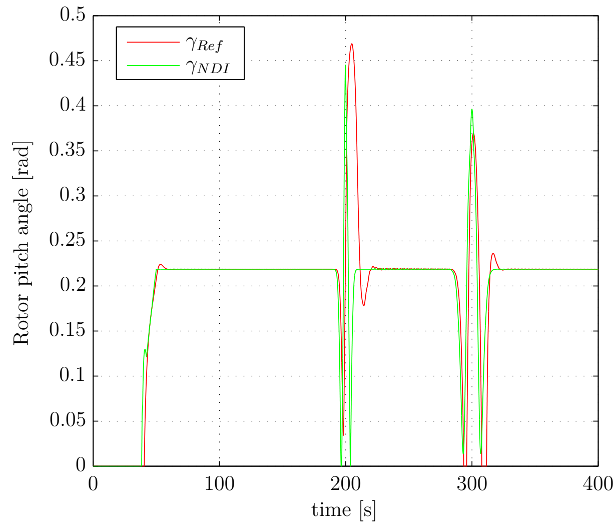

Figure 9. Rotor pitch angle comparison for the scenario with a wind ramp and double wavelet disturbances.

turbines. To verify the controller performance, eight different scenarios (cases) have been simulated for which the wind speed is varied:

- Wind ramps with different constant end wind speed $v_{w,max}$ (11,12,15,18 and 22 m/s).
- Linear wind speed slope from 0 m/s to 30 m/s.
- Wind ramp with single wavelet disturbance.
- Wind ramp with double wavelet disturbances.

The different cases are used to test different conditions for the control system of the wind turbine. The first five cases with the wind ramps are used to simulate the nominal conditions for the controller with constant wind speed after a startup phase. For these cases no big improvements can be expected compared to the reference controller. However the cases are important, since it has to be expected that an advanced control system should also be able to generate similar amounts of energy during nominal conditions, and not only focus on load reduction. The linear wind speed slope is used to verify the transition phases for the control law. For example the pitch control and pitch feed-forward control are only active if the generator speed is close to its allowed maximum $\omega_{g,high}$ and also the scheduled PI-Pitch controller has different gains depending on the current pitch angle γ. In addition the set point λ_r for the NDI control loop changes based on the current wind speed v_w. The last two cases are used to simulate the controller behavior under gust load conditions. To simulate the wind gust excitation of the elastic wind turbine tower, Ricker wavelets according to Eq. (7) are used. The wavelets are parameterized to simulate short wind gusts. Because of the form

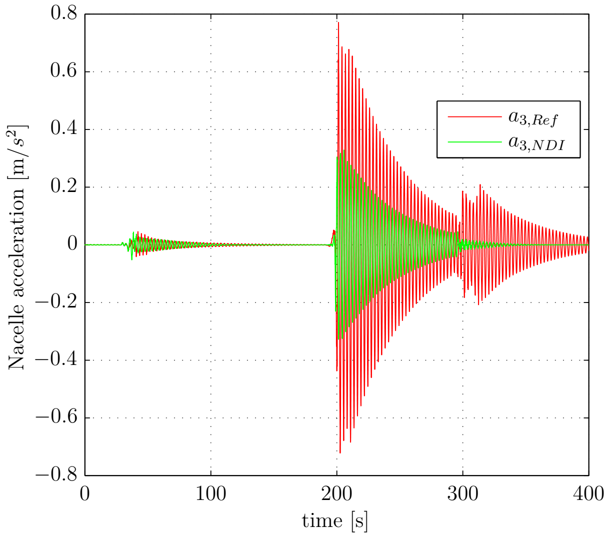

Figure 10. Acceleration vector component parallel to the wind direction at the top of the tower for the double wavelet scenario.

of the resulting shape they are often called Mexican Hat wavelet (see Fig. 6).

$$\psi(t) = \frac{2}{\sqrt{3\sigma}\pi^{\frac{1}{4}}}\left(1-\frac{t^2}{\sigma^2}\right)e^{\frac{-t^2}{2\sigma^2}} \tag{7}$$

Two criteria have been defined for the simulated scenarios to quantify the generated energy of the turbine and the load of the wind turbine tower in Eq. (8).

$$C_a = \int_0^{400} |a_t|_1 dt \tag{8a}$$

$$C_p = \int_0^{400} \tau_g \omega_g dt \tag{8b}$$

The criteria C_a is a measure for the load and is computed form the integral over the simulation time of 400s of the L1 norm of the acceleration at the tip of the tower a_t. A reduction of a_t is desirable to prolong the turbine's lifetime. The second criteria C_p is the generated energy of the wind wind turbine during the simulation. An increase in C_p leads to a more efficient turbine. Fig. 5 gives an overview of the results that have been normalized to the maximum values of all cases. As can be seen from the plot, the generated energy is very similar for all cases for the reference controller and the NDI based control system. The NDI controller acts faster what leads to a slight increase in generated energy. However the added benefit from the advanced control law based on the wind measurement can be seen for the resulting acceleration at the tower tip.

The wind gust, simulated by the wavelet, leads to very strong acceleration at the tower tip that can be reduced substantially using the new proposed control system, as can be seen from Fig. 5. In particular, for the case with only one wind peak, the wind gust load can be absorbed directly by the generator using the NDI control law.

Fig. 7 shows the resulting generator torque for this scenario, Fig. 8 the corresponding generator speed, Fig. 6 the wind speed and Fig. 9 the rotor pitch angle. As can be seen from the plots, the controller is able to use the additional information from the measured wind speed to react faster to changes in the wind speed, which results in a much smoother generator speed and generator torque for the NDI controller and additionally reduces the acceleration at the tower tip, as can be seen from Fig. 10. The feed-forward controller for the rotor pitch angle leads to a faster response. The reduced acceleration also lessens the load on the tower structure.

5 Conclusion and future work

The current design of controllers for wind turbines is rather conservative. The results of the last chapters indicate that using advanced control methods such as NDI, significant performance gains can be achieved especially in the field of load mitigation. LIDAR systems, however, are a key technology to enable the described control method. We expect LIDAR systems to become more widespread among new or retrofitted wind turbines due to upcoming reductions in production cost, especially in wind farms where one LIDAR system can be used for multiple turbines.

Modern control methods such as NDI represent model-based approaches. A multi-domain Modelica library for wind turbines with non-causal and hence invertible models forms an optimal basis for the development of suitable NDI controllers.

The simulation results for the NDI & PCH based controller, using advanced capabilities of Modelica and FMI, shows promising results. However in the future it would be necessary to verify the control systems on real wind turbines to analyze the robustness and performance under realistic conditions.

We hope that the simulation-based analysis can help to motivate the use of advanced control systems and sensors in the future.

6 Acknowledgment

The development of Modelica models for wind turbines is supported by DLR Technology Marketing.

References

T. Bellmann. Interactive simulations and advanced visualization with modelica. *Proceedings of the 7th Modelica Conference*, pages 541–550, 2009.

FMI development group. Functional mock-up interface for model exchange and co-simulation. Technical report, MODELISAR consortium, 2014.

F. Dunne, E. Simley, and L. Pao. Lidar wind speed measurement analysis and feed-forward blade pitch control for load mitigation in wind turbines. Technical report, National Renewable Energy Laboratory, 2011.

H. Geng, S. Xiao, W. Yang, and G. Yang. Nonlinear dynamic inversion approach applied to pitch control of wind turbines. In *Proceeding of the 11th World Congress on Intelligent Control and Automation*, 2014.

Martin Hansen. *Aerodynamics of Wind Turbines*. Earthscan, 2008. ISBN 978-1-84407-438-9.

A. Heckmann, M. Otter, S. Dietz, and J. Lopez. The DLR flexible bodies library to model large motions of beams and of flexible bodies exported from finite element programs. *The Modelica Association*, 2006.

F. Holzapfel. *Nichtlineare adaptive Regelung eines unbemannten Fluggerätes*. Verlag Dr. Hut, 2004. ISBN 9783899631128.

E. Johnson and A. Calise. Pseudo-control hedging: A new method for adaptive control, 2000.

J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-mw reference wind turbine for offshore system development. Technical report, National Renewable Energy Laboratory, 2009.

H. Joos, J. Bals, G. Looye, K. Schnepper, and A. Varga. A multi-objective optimisation based software environment for control systems design. *Proc. of 2002 IEEE International Conference on Control Applications and International Symposium on Computer Aided Control Systems Design, CCA/CACSD*, 2002.

A. Koerber and R. King. Combined feedback-feedforward control of wind turbines using state-constrained model predictive control. In *IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 21, NO. 4*, 2013.

T. Lombaerts, G. Looye, Q. Chu, and J. Mulder. Design and simulation of fault tolerant flight control based on a physical approach. *Aerospace Science and Technology*, 23(1): 151 – 171, 2012. ISSN 1270-9638. 35th ERF: Progress in Rotorcraft Research.

G. Looye. Design of robust autopilot control laws with nonlinear dynamic inversion. *at Automatisierungstechnik*, 49: 523–531, 2001.

G. Looye. The new DLR flight dynamics library. *Proceedings of the 6th Modelica Conference*, pages 193–202, 2008.

S. Mattsson and G. Söderlind. Index reduction in differential-algebraic equations using dummy derivatives. *SIAM Journal of Scientific and Statistical Computing*, 14:677–692, 1993.

Modelica Association, editor. *Modelica - A Unified Object-Oriented Language for Physical Systems Modeling Language Specification Version 3.2*. 2010.

M. Otter, H. Elmqvist, and F. Cellier. Modeling of multibody systems with the object-oriented modeling language dymola. Technical report, 1996.

David Schlipf, Tim Fischer, Carlo Carcangiu, Michele Rossetti, and Ervin Bossanyi. Load analysis of look-ahead collective pitch control using lidar. In *Proceedings of the 10th German Wind Energy Conference DEWEK*. Universitaet Stuttgart, 2010.

Eric Simley, Lucy Y. Pao, Neil Kelley, Bonnie Jonkman, and Rod Frehlich. Lidar wind speed measurements of evolving wind fields. In *Proc. ASME Wind Energy Symposium*, 2012.

Jean-Jacques E Slotine and Weiping Li. *Applied nonlinear control*. Pearson, Upper Saddle River, NJ, 1991.

P. Thomas, X. Gu, R. Samlaus, C. Hillmann, and U. Wihlfahrt. The onewind modelica library for wind turbine simulation with flexible structure - modal reduction method in modelica. *Proceedings of the 10th International Modelica Conference*, 2014.

M. Thümmel, G. Looye, M. Kurze, M. Otter, and J. Bals. Nonlinear inverse models for control. *Proceedings of the 4th International Modelica Conference,Hamburg, March 7-8*, 2005.

J. Tobolar, M. Otter, and T. Bünte. Modelling of vehicle powertrains with the modelica powertrain library. *Systemanalyse in der Kfz-Antriebstechnik IV*, 2007.

N. Wang and K. Johnson. Lidar-based fx-rls feedforward control for wind turbine load mitigation. In *Proceedings of the 2011 American Control Conference*, 2011.