FRAUNHOFER-INSTITUTE FOR WIND ENERGY AND ENERGY SYSTEMS TECHNOLOGY

A SURVEY ON CONTROL METHODS FOR THE MITIGATION OF TOWER LOADS

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Abstract

This report gives an overview of the prospects of a wind turbine’s control system to mitigate loads on the support structure. Well-known strategies already applied in industry are being addressed as well as methods that are currently investigated in research. The survey has been compiled for Deliverable 4.1.1. of the project INNWIND.EU, founded by the European Commission (FP7-ENERGY.2012.2.3.1).

Content

1 Technologies used in industry

The primary objective of a wind turbine's control system is to ensure a safe and stable operation while maximising the overall energy output. Ensuring safety is achieved by keeping electrical and mechanical quantities within admissible ranges. Thus, the control system has a substantial impact on the loads experienced by the turbine during its lifetime. This, of course, also applies to the loads on the support structure. It is useful to distinguish between the operational and the dynamic control level.

The operational control deals with supervisory control tasks, e.g. triggering grid-connection when the conditions for power production are fulfilled. Its main inputs are averaged measurements of the wind field and the rotational speed. Based on these measurements it initiates transitions between the turbine's operational states: idling, start-up, power production, normal shutdown, and shutdown due to a fault.

Choosing operational control parameters like the cut-in and the cut-out wind speed does not only affect the annual energy yield. It has also a substantial influence on the loads. Mainly three dedicated load mitigation concepts are currently available on the operational control level: *speed exclusion zones*, *soft-cut out*, and *peak shaving*.

Dynamic control is related to several feedforward and feedback control strategies. Their primary objective is to ensure proper dynamic responses of the turbine, e.g. to changing mean wind speeds, to gusts, or to safety issues. For actuation, the typical basic controller structure uses the generator torque in the region below rated wind speed and the collective pitch angle in the region above rated wind speed. The rotational speed is used as the control input in both cases.

The basic feedback controllers have a tremendous impact especially on the fatigue loads of the tower. For example, most utility-scale wind turbines exhibit a bandwidth limitation for the closed loop system above rated wind speed due to the first tower mode [1, 2]. If this is not properly taken into account, the controller design might induce unwanted vibrations that emerge from interaction between controller and tower motion.

The basic control strategy can be enhanced by a large number of methods to actively mitigate loads, see e.g. [3]. Different methods are available for *active tower damping*. Furthermore, *active idling* is an interesting option for offshore turbines.

1.1 Speed exclusion zone

Speed exclusion zones, also called rotational speed windows or tower resonance bridging, can be useful when the rotor speed (1P) or blade passing frequency (3P) excites a structural resonance at a certain operating point, see e.g. [4, 5]. Such resonances can be avoided by choosing the turbine's natural frequencies outside the operational excitation ranges. However, sometimes this is not possible. This is shown in the Campell diagram in Fig. 1, where the frequency of the 1st tower mode lies within the 3p operational range of the turbine. At the red dot, the 3P-line cuts the dash-dotted line indicating the natural frequency. That is, when the system operates near this operating point, a vibration with the 1st tower frequency will be excited.

A speed exclusion zone can be employed in order to avoid this phenomenon. This means that the control system is modified such that the critical speed range includes no stable operating points. Thus, the rotor speed will rapidly drive though the critical speed range without severely exciting the natural frequency. Usually, this is implemented by modifying the speed-torque curve of the generator, see [4] and [6] for two implementation alternatives.

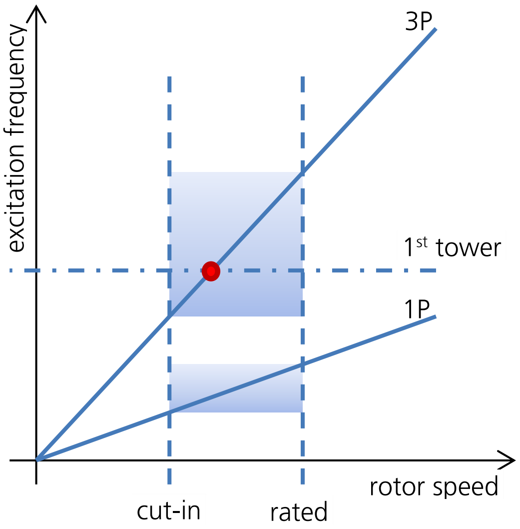


Fig. 1: Campell diagram. The red dot indicates an operating point where the 1st tower mode is excited by the blade passing frequency (3P).

1.2 Soft cut-out

Most turbines shut down at very high wind speeds. Typically, the cut-out wind speed lies around 25 m/s. E.g. when the average wind speed exceeds this limit, a shut-down-procedure is triggered to drive the turbine to the idling state. This straight-forward cut-out strategy is shown in Fig. 2a. Some sort of hysteresis should be involved before returning to power-production as to avoid heavy switching activities. Regarding the loads there is a trade-off between many factors: loads associated with shut-downs, operation/idling in high wind speeds, number of shut-downs, energy loss.

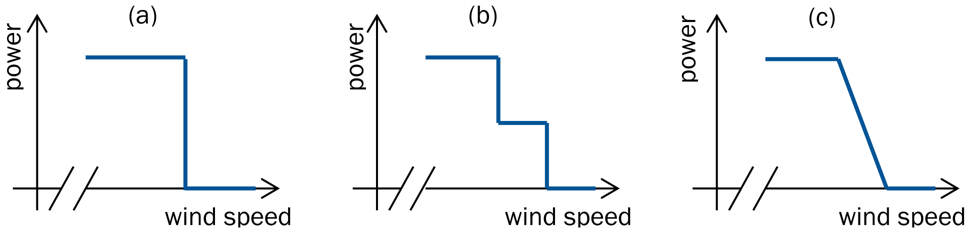


Fig. 2: Different cut-out strategies: straight forward (a), stepwise (b), continuously (c)

The operation above cut-out wind speed can been enhanced by soft cut-out strategies (also: "gradual" or "extended" cut-out) shown in Fig. 2b and Fig. 2c. The power output is gradually reduced either in stepwise (b) or continuously (c). The soft cut-out strategies have been originally intended to improve the behaviour of wind farms in storm conditions by avoiding too many turbines to shut down and disconnect from the grid at the same time [7]. However, they are also useful in terms of load mitigation.
The soft cut-out strategies are particularly interesting for offshore turbines [8]. Because the blades are not pitched to feather position, the aerodynamic damping is increased. This reduces especially wave induced fatigue loads.

1.3 Peak Shaving

Following the standard operating strategy (speed-torque curve below rated and speed regulation with collective pitch above rated), the steady state thrust force on the rotor plane peaks at rated wind speed, see the dashed line in the middle plot in Fig. 3. This usually causes high bending moments in the tower bottom and is critical both in terms of fatigue and extreme loads.

"Peak shaving" or "thrust clipping" is a strategy that reduces the maximum steady state thrust force. The basic idea is to begin pitching the blades slightly below rated wind speed, see the solid line in the left plot in Fig. 3, which reduces the thrust force in the critical range.

Simultaneously to shaving the thrust force peak the power capture in the transition region is reduced (right plot). Therefore, the design of a peak shaver is strongly subject to the trade-off between load mitigation and energy yield. Since its implementation is very simple it is often used as a last resort e.g. for meeting site-specific requirements. For offshore sites with considerable wave excitation, the reduction of aerodynamic damping must also be taken into account.

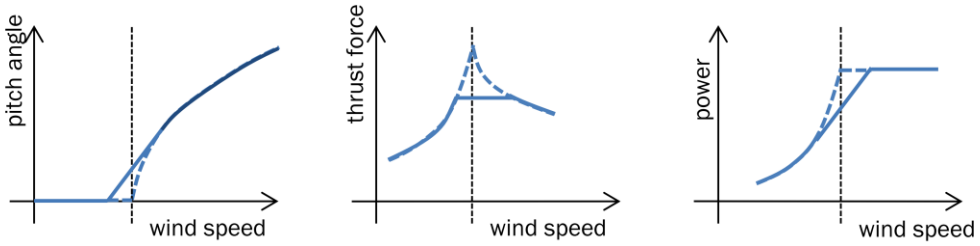


Fig. 3: Steady operating points with peak shaving (solid line) and without (dashed line).

1.4 Active tower damping

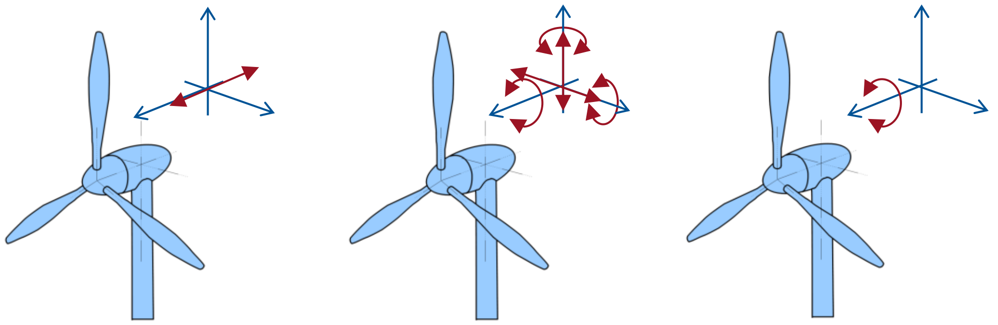
Controlling the pitch angles and generator torque allows for the active damping of vibrations of the support structure. This can be done in the fore-aft as well as in the side-side direction. The actuators are used in a feedback control loop to generate counter-acting forces and moments that reduce the motions of the structure. Usually, the motions are measured by accelerometers mounted on the tower top. To realize a damping effect it is necessary to generate a force that is inversely proportional to the velocity. Hence, the design of the closed loop system includes a filter design to assure an appropriate phasing.

Because the resulting control signals are added to those of the normal operating control loops, the coupling between the different control loops must be taken into account. This is not trivial especially when actuator amplitude and rate constraints are active. Furthermore, active load mitigation is in general subject to a "waterbed effect": When loads in a certain range in the frequency domain are reduced they will be increased in another range. And, more generally, when loads at a certain part on the turbine are reduced they will be increased on other parts. Consequently, different objectives must be balanced, and the application of mitigation strategies for the support structure requires a broad knowledge of the overall turbine design, see also the subsection on integrated design below.

A classification of different variants regarding actuator and motion direction is given in . These are discussed in detail in the following. Fig. 4 shows how the different actuators affect forces and moments on the tower top.

Table 1: Different variants for active tower damping.

Actuator	Tower fore-aft	Tower side-side
Collective pitch angle	✓	✗
Individual pitch angle	✓	✓
Generator torque	✗	✓



collective pitch

individual pitch

generator torque

Fig. 4: Different actuators for active tower damping and their effective force/moments on the tower top (red arrows).

The most widely spread variant is the damping of the 1st fore-aft tower mode for fatigue load reduction. For that purpose the fore-aft acceleration is fed back to the collective pitch angle using an appropriate filter. Consequently, a counter-acting thrust force on the rotor plane damps the tower vibration, see Fig. 4. Changing the collective pitch angle also has an influence on the normal rotor speed regulation. But, this is usually not a major issue because the frequency of pitch angle variations due to the active tower damping is in most cases greater than the bandwidth of the properly designed rotor speed control loops. More critical is the potential coupling with blade flap modes, see [9].

Depending on the specific turbine design, it might be beneficial to mitigate not only the vibrations related to the 1st tower mode. For example, in [10] it is shown that also tower loads related to 3P harmonic excitation can be reduced using the same feedback structure. Another variant is dedicated to the 2nd tower mode. This is especially interesting for offshore turbines because this mode is easily excited by the waves. However, controlling the pitch angles individually is sometimes superior in this case: Depending on the actual shape of the 2nd mode, the tilting of the nacelle might be dominant. Then, an individual pitch control strategy that generates a tilt moment is more effective.

The so called “Individual pitch control” (IPC) has been heavily discussed in literature for quite some time, see e.g. [11, 12]. It has been suggested for the reduction of loads on various components, which also includes the support structure. As shown in the middle of Fig. 4 it offers a wide range of forces and moments on the tower top. The measurements used for feedback include tower top acceleration in side-side direction, blade bending moments, or bending moments measured on the mainframe.

The most obvious idea for the support structure is the damping of the side-side motion [13–15]. This motion is being counteracted by a side-side force or a roll moment on the nacelle. For onshore turbines the tower side-side fatigue loads are usually less important as compared to those in fore-aft direction. In contrast, the support structure of offshore turbines can experience significant fatigue loads in the side-side direction. Especially wind-wave-misalignment induces side-side motion because of the low aerodynamic damping [8].

From the overall control system's point of view the coupling with the rotor speed control loop has to be considered. Furthermore, because the blades are actuated independently, either multivariable control design or a preliminary decoupling by a transformation must be carried out. The non-linear mapping, known under different names as "d-q axis-", "Coleman-", or "multiblade-" transformation, transforms rotating quantities into an non-rotating frame. In both cases significant amount is necessary for addressing issues like extreme loads induced by rotor asymmetry during shut-downs [16] and pitch system amplitude and rate constraints [17]. The latter can be an issue mainly in the operating regime around rated wind speed because large pitch angle variations are necessary.

The active side-side damping is also possible modifying the generator torque [18]. To this end, the side-side acceleration is fed back to the demanded generator torque using an appropriate filter. The generator torque is supported by the main frame and, thus, leads to a counter-acting roll moment on the tower top (Fig. 4). Due to the couplings between the various subsystems the interaction with the rotor speed control loop and the tower fore-aft loads has to be taken into account.

The enormous number of papers dealing with results from simulation studies contrasts with the little number of field-tests described in the literature. Some creditable exceptions include [16, 19–22]. These studies have been carried out on onshore turbines. Nevertheless, the reported results demonstrate the efficacy of the investigated load mitigation strategies by showing compliance with results obtained from simulations.

1.5 Active Idling

The term "active idling" refers to a control loop that is switched on during the idling state. Normally, when the turbine is in the idling state, the rotor almost stands still because the blades are in feather position. This also implicates low aerodynamic damping. The latter can be increased by reducing the pitch angle for a non-zero rotor speed. Consequently, tower vibrations stimulated e.g. by waves will be damped.

Measuring wind speed and/or rotor speed allows for adjusting a certain pitch angle, which, in turn, maintains the rotor idling with a certain, low rotor speed. [8] suggests defining the operating regime of this strategy up to slightly above rated wind speed. Thus, higher loads at higher wind speeds, e.g. due to extreme events, are being avoided. [23] proposes to start this procedure and to actively control the pitch angles depending on additional quantities such as the tower top acceleration. Active idling at higher wind speed is mentioned, although only for extraordinary conditions. The variant presented in [24] explicitly addresses high wind speeds. The main idea can be summarised in appling a "normal" active pitch angle regulation for load mitigation in wind speeds above cut-out wind speed – rather than just increasing the aerodynamic damping by a non-zero rotor speed.

1.6 Integrated design

As pointed out several times above, load mitigation strategies for the support structure should be carefully balanced by taking into account the overall turbine design. The numerous strategies can be beneficial for addressing site-specific characteristics. This is especially useful for retrofitting a type certified turbine in the engineering process for offshore project certification, see e.g. [25]. [26] demonstrates an integrated support structure optimisation by means of a reference study. However, integrating the load reduction capabilities of the control system from the start offers new possibilities for the whole turbine design [4, 27].

2 Technologies under research

This section provides a brief overview of several options that are currently discussed.

2.1 LiDAR

LiDAR (Light Detection And Ranging) enables the remote sensing of wind speed by measuring the speed of aerosols, see e.g. [28] for a comprehensive overview. It has become increasingly important not only for resource assessment. Mounted on the turbine and measuring the wind field that approaches the rotor, it also offers a wide range of opportunities for modifying the control system: To a certain extent, it means looking into the near future and renders possible e.g. the anticipation of extreme events.

The simplest integration of the knowledge of the future wind field is via a feedforward structure [29, 30], see Fig. 5. That is, a feedforward control signal is added on the "normal" feedback control signal. The feedforward algorithm uses the estimated future wind speed to compensate for varying wind conditions in good time. The estimation is subject to low pass filtering as i) the wind field measurement of the LiDAR system involves spatial averaging and ii) the high-frequency content in the wind field changes while it approaches the rotor [31].

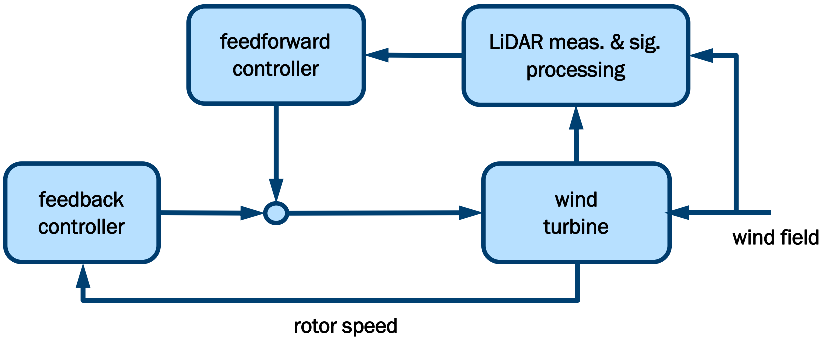


Fig. 5: Control system integrating turbine mounted LiDAR.

Although apparently appearing to be well suited for decreasing gust sensitivity, recently published results indicate that the most promising application is the reduction of tower fatigue loads [32, 33]. This is achieved by retuning the feedback controller. In short terms, a less "aggressive" feedback controller can be chosen because a part of the control burden is shifted to the feedforward path.

[34] presents preliminary field test results that show that implementation is possible in practice. However, the increased complexity of the overall control system must be carefully balanced with availability issues, and, the main obstacle at present remains the costliness of the LiDAR device.

2.2 Advanced control

Common practice in industry is to iteratively close several more or less decoupled single-input–single-output (SISO) control loops. Examples are the strategies for active tower damping discussed above, which are added to the normal controllers.

By considering all the controller inputs and outputs simultaneously, the wind turbine becomes a multiple-input-multiple-output (MIMO) system. "Advanced" control methods lend themselves nicely to addressing the nonlinear, multivariable nature of the control problem. Different approaches are applied in the wind turbine control literature, e.g. Linear Quadratic Gaussian (LQG) controllers [35, 36], controllers based on H_∞-theory [37], feedback linearization [38], or Model Predictive Control (MPC) [39–41], to mention only a few of them.

These methods intrinsically solve issues with nonlinearities, couplings between different physical pathways, and sensor fusion. In a mathematical systematic manner they find a control law that is optimal with respect to a certain cost function. Choosing this cost function however is not that straight-forward. The complexity of the overall turbine design makes it hard to reflect practical design objectives, which, ultimately, are driven by the reduction of cost of energy. Furthermore, the use of additional makeshift methods, e.g. for constraint handling, should be avoided, and the embedding in the supervisory operating system is challenging. See also the discussion on MIMO-controllers for wind turbines in [42].

2.3 Model predictive control

A special case is MPC. Assuming a rapid maturing of the nacelle-based LiDAR technology, this advanced control method becomes more attractive because it directly incorporates future values of the wind speed.

The basic principle is to calculate optimal values for the control signals over a certain time horizon in the future. To this end, it uses a dynamic model of the turbine, current measurements to update the state of this model, and the future course of external inputs; the latter being e.g. the rotor effective wind speed measured by the LiDAR system. Given that these elements are sufficiently representing the real system, its behaviour over the time horizon can be calculated depending on the control signals. This is used for determining an optimal trajectory of the control signals by solving a – possibly constrained – optimisation problem with a cost function that reflects the control objectives. The optimal control signals are applied to the system until new measurements and predictions are available. Then the whole procedure is repeated. This repetition makes the feedback controller out of subsequent actions that are individually feedforward.

On the one hand, MPC provides the simple incorporation of actuator constraints and wind speed predictions. On the other hand, solving the optimisation problem in real time is computationally demanding and some of the other obstacles for advanced control methods mentioned above still remain.

A comprehensive study of nonlinear MPC of a 5 MW benchmark turbine is reported in [43]. It considers uncertainty in the LiDAR measurement as well as the operation below and above rated wind speed including transitions between both regions. Promising load reductions were achieved without corrupting other aspects. However, the authors emphasise that, due to the immense computational effort for the online-solution of the optimisation problem, the chosen nonlinear approach should rather be considered as an upper benchmark for other controllers. To overcome issues with real time implementation they suggest investigating other variants of MPC.

[44] presents a real time feasible variant of MPC. A case study has been carried out, where the computational time of the MPC is increased by only 40% as compared to a conventional controller. Although future values of the wind speed are assumed to be constant, the controller achieved considerable extreme and fatigue load reductions on the tower bottom bending moment. The authors mention that, if available, wind speed predictions can easily be incorporated.

2.4 Integrated design

An approach for integrating the control design into the overall turbine design, which is very interesting from a theoretical point of view, is presented in [45]. Structural parameters and parameters of an advanced MIMO control strategy are directly optimised using an iterative algorithm. The cost function of the optimisation depends on both parameter sets. The structural design parameters are stiffness and damping coefficients of a lumped parameter model of the turbine.

From a practical point of view this choice is somewhat academic, but the authors point out that their work can be extended to more practical cases, e.g. by including the minimisation of structural mass. Even though the mathematical rigorousness of the approach is appealing – what has been mentioned in the advanced control section above also applies for this concept. In general, it is very hard to design a cost function that sufficiently reflects practical design objectives.

2.5 Smart blades

Recently there is a strong research focus on so called “smart blades”. The basic idea is to design additional aerodynamic actuators directly into the rotor blade. Many different types of actuators have been proposed in literature. A comprehensive overview on the status of development of “smart” rotor blades for wind turbines and helicopters is given in [50].

The main advantage of these new kinds of actuators is that aerodynamic forces can be influenced much faster than with conventional pitch control because only small masses have to be moved. The forces are influenced locally, preferably close to the blade tips where the effect is largest. If several actuators are placed along the span of the rotor blade, also the distribution of forces could be influenced.

So far, mainly simulation studies have been published. An exception is the work by Castaignet [51], which provides first field testing results for a modified 225 kW wind turbine, equipped with piezo-electrically actuated flaps and pitot tubes.

The main focus of “smart blades” research so far has been on rotor blade loads. However, also the loads of the support structure could be influenced in a favorable manner with faster, distributed aerodynamic actuators, see for instance [52]. As an example, higher harmonics control of blade bending moments could significantly reduce the 3p component of the tower bending moment. Also the active damping of higher tower bending modes might be feasible.

It must be stated, however, that a lot of research work is still to be done before this kind of technology can enter industrial application. Reliable actuators must be designed that can withstand a high number of actuation cycles. From the control design prospective, new kinds of models must be developed and validated that properly describe the fast aerodynamic effects and the aero-elastic interaction of actuators and rotor blade.

2.6 Situational controller adaptation

So far, the proposed additional methods for load mitigation have mostly been investigated as running continuously when the turbine is in a certain operating state. For example, virtually all works about IPC observe that the structural load reduction comes along with significantly increased pitch activity. When IPC is continuously active during power production, the pitch system requires considerable reinforcements, which might cancel out cost savings on other components. For a specific turbine, [16] suggests to select IPC only in the case of certain extreme operating conditions.

This idea is presented more generally in several publications [46–49]. The control system’s structure or parameters are adjusted according to certain operating situations. Thus, the controller is optimally adapted to the current operating conditions. This can result in two positive effects: i) loads experienced by different components are balanced, and ii) heavy duty cycles of the actuators are avoided.

3 References

[1] S. Dominguez and W. Leithead, “Size related performance limitations on wind turbine control performance,” in ICC 2006: International Control Conference, 2006.

[2] I. Sønderby and M. H. Hansen, “Open-loop frequency response analysis of a wind turbine using a high-order linear aeroelastic model,” Wind Energ, pp. n/a, 2013.

[3] E. A. Bossanyi, “Wind Turbine Control for Load Reduction,” Wind Energ, vol. 6, no. 3, pp. 229–244, 2003.

[4] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, Wind energy handbook, 2nd ed. Chichester: Wiley, 2011.

[5] S. Siegfriedsen, "Method for operating offshore wind turbine plants based on the frequency of their towers" US 6891280 B2. 2001.

[6] P. Schaak, G.P Corten, and E.L van der Hooft, “Crossing resonance rotor speeds of wind turbines,” in EWEC 2003, Madrid, 2003.

[7] E. Bossanyi, B. Savini, M. Rossetti, C.-E. Carcangiu, M. Iribas Latour, D. Wouters, T. van Engelen, P. Vyas, M. Geyler, M. Hau, B. Jasniewicz, S. Wortmann, H. Markou, and D. Schlipf, “Final report for WP5: Control systems,” 2011.

[8] T. Fischer and W. de Vries, “Final Report Taks 4.1: Integration of support structure and wind turbine design: Deliverable D 4.1.5 (WP4: Offshore Foundations and Support Structures),” 2011.

[9] W. E. Leithead, S. Dominguez, and C.J. Spruce, “Analysis of Tower/Blade interaction in the cancellation of the tower fore-aft mode via control,” in EWEC 2004, London, 2004.

[10] Weiwei Shan and Martin Shan, “Gain Scheduling Pitch Control Design for Active Tower Damping and 3p Harmonic Reduction,” in EWEA 2013, Proceedings, 2013.

[11] P. Caselitz, W. Kleinkauf, T. Krüger, J. Petschenka, M. Reichardt, and K. Störzel, “Reduction of fatigue loads on wind energy converters by advanced control methods,” in EWEC 1997: Proceedings of the European Wind Energy Conference, Dublin, 1997, pp. 555--558.

[12] E. A. Bossanyi, “Individual Blade Pitch Control for Load Reduction,” Wind Energ, vol. 6, no. 2, pp. 119–128, 2003.

[13] S. Wortmann and T. Krüger, "Method for operating a wind energy system" WO2009/083085 (A1). 2008.

[14] D. Duckwitz and M. Geyler, “Active damping of the side-to-side oscillation of the tower,” in DEWEK 2010: 10th German Wind Energy Conference, Bremen, 2010.

[15] Felix Hess and Boris Buchtala, "Method and Device for Preventing a Lateral Oscillation of a Wind Power Installation" US20130209254 A1. 2011.

[16] M. Shan, J. Jacobsen, and S. Adelt, “Field Testing and Practical Aspects of Load Reducing Pitch Control Systems for a 5 MW Offshore Wind Turbine,” in EWEA 2013, Scientific Proceedings, 2013, pp. 101–105.

[17] Stoyan Kanev and Tim van Engelen, “Exploring the Limits in Individual Pitch Control,” in EWEC 2009, 2009.

[18] T. van Engelen, E. van der Hooft, and P. Schaak, “Development of wind turbine control algorithms for industrial use,” in EWEC 2001, Copenhagen, 2001.

[19] M. Rossetti and E. Bossanyi, “Damping of tower motions via pitch control – theory and practice,” in EWEC 2004, London, 2004.

[20] M. Städler, “Controls for Load Reduction,” in DEWEK 2008: 9th German Wind Energy Conference, Bremen, 2008.

[21] Ervin Bossanyi, Alan Wright, and Paul Fleming, “Controller field tests on the NREL CART2 turbine: Upwind Project, Deliverable 5.6.1,” 2010.

[22] Svenja Wortmann and Henning Leweke, “REpower Field Test of Active Tower Damping: Upwind Project, Deliverable 5.6.3,” 2011.

[23] Marc Seidel, Dirk Steudel, and Martin Von Mutius, "Oscillation damping of a wind turbine" US8057158 B2. 2007.

[24] E. Gomez De Las Heras Carbonell, O. Hernandez Mascarell, and J. Suarez Aizpun, "Wind turbine having an active pitch angle control during idling situation" EP2447530(A2). 2011.

[25] M. Seidel, “Design of support structures for offshore wind turbines - Interfaces between project owner, turbine manufacturer, authorities and designer,” Stahlbau, vol. 79, no. 9, pp. 631–636, 2010.

[26] T. Fischer, W. Vries, P. Rainey, B. Schmidt, K. Argyriadis, and M. Kühn, “Offshore support structure optimization by means of integrated design and controls,” Wind Energy, vol. 15, no. 1, pp. 99–117, 2012.

[27] Various, “UpWind final publication: Design limits and solutions for very large wind turbines,” 2011.

[28] A. Pena, C. B. Hasager, J. Lange, J. Anger, M. Badger, F. Bingöl, O. Bischoff, J.-P. Cariou, F. Dunne, S. Emeis, M. Harris, M. Hofsäss, I. Karagali, J. Laks, S. E. Larsen, J. Mann, T. Mikkelsen, L. Y. Pao, M. Pitter, A. Rettenmeier, A. Sathe, F. Scanzani, D. Schlipf, E. Simley, C. Slinger, R. Wagner, and I. Würth, “Remote Sensing for Wind Energy,” DTU Wind Energy-E-Report-0029(EN), 2013.

[29] F. Dunne, L. Y. Pao, A. D. Wright, E. Simley, and B. Jonkman, “Adding Feedforward Blade Pitch Control for Load Mitigation in Wind Turbines: Non-Causal Series Expansion Preview Control and Optimized FIR Filter Methods ∗,” in 49th AIAA Aerospace Sciences Meeting, 2011, pp. 1–17.

[30] D. Schlipf, T. Fischer, C. E. Carcangiu, M. Rossetti, and E. Bossanyi, “Load analysis of look-ahead collective ptich control using LIDAR,” in DEWEK 2010: 10th German Wind Energy Conference, Bremen, 2010, pp. 4–7.

[31] David Schlipf, Jakob Mann, Andreas Rettenmeier, and Po Wen Cheng, “Model of the Correlation between Lidar Systems and Wind Turbines for Lidar Assisted Control,” Boulder, 2012.

[32] E. A. Bossanyi, A. Kumar, and O. Hugues-Salas, “Wind turbine control applications of turbine-mounted LIDAR,” Oldenburg, 2012.

[33] D. Schlipf and P. W. Cheng, “Adaptive Vorsteuerung für Windenergieanlagen,” at - Automatisierungstechnik, vol. 61, no. 5, pp. 329–338, 2013.

[34] D. Schlipf, P. Fleming, F. Haizmann, A. Scholbrock, M. Hofsäß, A. Wright, and P. W. Cheng, “Field Testing of Feedforward Collective Pitch Control on the CART2 Using a Nacelle-Based Lidar Scanner,” Oldenburg, 2012.

[35] Brad S. Liebst, “Pitch Control System for Large-Scale Wind Turbines,” J. Energy, vol. 7, no. 2, pp. 182–192, 1983.

[36] Alan D. Wright, “Modern Control Design for Flexible Wind Turbines,” NREL NREL/TP-500-35816, 2004.

[37] M. Geyler and P. Caselitz, “Robust Multivariable Pitch Control Design for Load Reduction on Large Wind Turbines,” Journal of Solar Energy Engineering, vol. 130, no. 3, p. 31014, 2008.

[38] Avishek Kumar and Karl Stol, “Simulating MIMO Feedback Linearization Control of Wind Turbines Using FAST,” in 46th AIAA Aerospace Sciences Meeting, 2008.

[39] R. A. Santos, “Damage mitigating control for wind turbines,” PhD Thesis, University of Colorado, 2007.

[40] C. L. Bottasso, A. Croce, and B. Savini, “Performance comparison of control schemes for variable-speed wind turbines,” J. Phys.: Conf. Ser, vol. 75, p. 12079, 2007.

[41] L. C. Henriksen, “Model Predictive Control of a Wind Turbine,” Master Thesis, Technical University of Denmark, 2007.

[42] E. A. Bossanyi, G. Ramtharan, and B. Savini, “The importance of control in wind turbine design and loading,” in Proceedings of 17th Mediterranean Conference on Control and Automation: IEEE, 2009, pp. 1269–1274.

[43] D. Schlipf, D. J. Schlipf, and M. Kühn, "Nonlinear model predictive control of wind turbines using LIDAR," Wind Energ, pp. n/a, 2012.

[44] J. Schuurmans, E. A. Nederkoom, S. Kanev, R. Rutteman, and E. Nguyen, "Optimised Aerodynamics and Control by Nonlinear Model based Predictive Control," in EWEA 2013, Scientific Proceedings, 2013, pp. 93--96.

[45] F. A. Shirazi, K. M. Grigoriadis, and D. Viassolo, "Wind turbine integrated structural and LPV control design for improved closed-loop performance," International Journal of Control, vol. 85, no. 8, pp. 1178–1196, 2012.

[46] P. Egedal and I. Frydendal, "Selecting a load reduction measure for operating a power generating machine" WO2011035976 (A1). 2010.

[47] R. A. Santos, "Control system for wind turbine" US7805205 (B2). 2006.

[48] Tim van Engelen, Stoyan Kanev, Jan Schuurmans, Xiukun Wei, Jianfei Dong, and Michel Verhaegen, "Suscon: New control concepts for exceptional conditions," 2010.

[49] Torsten Thomas, "Automated operation: The importance of communication," Sun & Wind Energy, no. 4, pp. 62–63, 2013.

[50] T. K. Barlas, G. A. M. van Kuik: Review of state of the art in smart rotor control research for wind turbines, - in: Progress in Aerospace Sciences, 46:1(1--27), 2010.

[51] D. Castaignet:, Model predictive control of trailing edge flaps on a wind turbine blade. PhD thesis, Technical University of Denmark, Nov. 2011.

[52] D.A. Griffin and T.J. McCoy, COE Reductions through Active Aerodynamic Control of Rotor Aerodynamics and Geometry, Global Energy Concepts, NREL Subcontract Report NREL/SR-500-43391, December 2008,