PAPER • OPEN ACCESS

Down-regulation and individual blade control as lifetime extension enablers

View the article online for updates and enhancements.

Down-regulation and individual blade control as lifetime extension enablers

Vasilis Pettas and Po Wen Cheng

Stuttgart Wind Energy at University of Stuttgart, Allmandring 5B, 70569 Stuttgart, Germany

E-mail: `pettas@ifb.uni-stuttgart.de`

Abstract.   As more and more wind turbines are coming close to the end of their design lifetime, evaluation of end of life strategies is becoming highly relevant. Moreover, as turbine technology matures and wind farms grow larger, lifetime extension becomes a financially attractive option compared to re-powering and decommissioning. Present work suggests control strategies, namely down-regulation and individual blade control, as lifetime extension enablers. The concept of using them as retrofit control implementations is explained. Their individual and combined potential in fatigue load reduction is evaluated, along with their effect on other performance and pitch system metrics. Finally, the possible period of extension, beyond the nominal 20 years, is evaluated in an example case where the retrofit control strategy is applied after 15 years of baseline operation. The aeroelastic simulations are performed with a 10 MW reference wind turbine, according to load certification standards. Results show that the two methods complement each other in load alleviation. The pitch actuator demands are also significantly decreased when the two methods are combined.

1. Introduction

Life time extension (LTE) for existing turbines is of high interest as installed capacity increases and more projects, equipped with modern technology MW size machines, are reaching the end of their design life [1]. Furthermore, new standards [2] and guidelines [3] for LTE certification are being published showing the industrial relevance. In this context, load mitigation control strategies can be applied as retrofit in order to increase the fatigue reserve of the components while reducing the 'consumption rate' of these reserves. For this purpose, both active and passive control strategies have been researched [4], while emerging concepts like lidar assisted control [5] are also being investigated. For the purpose of life time extension, a suitable control system should be applicable with the minimum amount of changes TO the turbine components while, ideally, not affecting negatively any of the turbine's sub-systems and energy production.

Individual pitch control (IPC) [6, 7] is such a suitable method, that has been widely investigated, since most turbines already include individual pitch actuators, while relevant sensors like strain gauges for the blade root loads are becoming cheaper and more reliable. With IPC, the blades react individually to some sensor signal by pitching. Different approaches have been suggested for implementing IPC. The fundamental difference lies on whether the controlled input is on the non-rotating frame, based on coordinate transformations [8]. Thus, leading to an azimuth based control which is commonly referred to as cyclic pitching. The other approach considers the rotating frame, where a feedback (or feedforward) control law is applied on each blade's signal directly on the rotating frame, referred to as Individual Blade Control

(IBC). Moreover, different control algorithms have been investigated from PID schemes [6,9] to more advanced or optimal controllers [10] and even feedforward approaches incorporating some preview signal [11]. The main drawback of all IPC approaches is the inevitably increased pitch actuation demand. In this work the IBC method is used and the control algorithm is based on [12].

Down-regulation of power output is a technique that has been investigated for different purposes including wind farm wake optimization [13,14], energy curtailment [15], ancillary services [16,17] and condition based control [18,19]. These strategies focus mainly on accurate power production control and wake reduction. Although important for the turbine lifetime, the impact of these approaches on fatigue and extreme loads and turbine performance metrics has been less thoroughly investigated [20–23]. Down-regulation leads to the reduction of loads-mainly related to aerodynamic torque and thrust- while no new actuators or sensors are required, since it is based solely on changing the pitch and/or torque set points. In this study down-regulation is seen and investigated, purely as a load mitigation strategy for a single wind turbine in free stream conditions, leading to a machine with altered, but fixed, operational characteristics. Moreover, this perspective to down-regulation can have other secondary benefits including wake reduction, which could increase the plant performance as a whole. The obvious disadvantage of down-regulation, as a load reduction method, is the reduction in Annual Energy Production (AEP).

These two strategies can be combined for a more effective load reduction. The baseline controller regulating the operating points, by setting the collective pitch angle and generator torque based on rotor speed input, is re-tuned according to the down regulation strategy. Then IBC is tuned based on and applied on top of the new Collective Pitch Controller (CPC). This is done aiming to combine the load reductions of the system, since in bibliography it is seen that the two strategies are able to focus on different components. Moreover, the combination of them is expected to effect positively the pitch and turbine metrics too, hence this study focuses on the evaluation of these two techniques comparatively and in a combined manner.

The rest of the paper is organized as follows: In section two the retrofit control concept is explained, identifying the key aspects and suggesting an example application case. In section three, the suggested controllers for IBC and down-regulation as well as their combination are explained. Section four shows and discusses the results of full design load simulations, on fatigue loads and other performance metrics, of the two methods individually and combined. Furthermore, the life time extension potential is shown with an example case considering combined operation for 20 years. The last section summarizes the key findings in the conclusions and suggests further research on the topic.

## 2. Retrofit control concept for LTE

The concept of applying retrofit control for LTE is illustrated in figure 1. The new strategy is implemented after an initial period of operation with the baseline controller. The optimal switching point has to be identified based on optimization and is case specific. The benefit of retrofitting is the reduced period of operation with the new control which for the case of IPC for example would translate to reduced actuator duty cycle which can lead to O&M cost reduction compared to using it as a baseline feature. Similarly, switching to a down-regulated regime after a point will lead to reduced AEP. There, a cost function is required in order to take into account the trade-off between reduced power production and load mitigation along with the possible period of lifetime extension and identify the optimal switching strategy.

In order to evaluate the technical and financial feasibility of such concepts, multidisciplinary knowledge is required. On one hand, the Remaining Useful Lifetime (RUL) of all systems and components during operation should be known along with the estimated load and energy reductions by applying the new methods. On the other hand, specific knowledge on factors
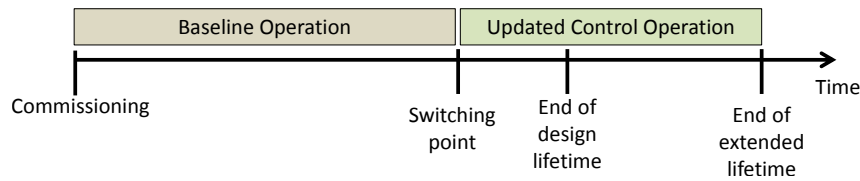
Figure 1. Concept of applying retrofit control for LTE

including local legislation, current and future electricity prices, current and updated O&M costs, and cost of implementing and certifying changes is equally important. The combination of these variables in an optimization problem, along with uncertainty quantification analysis ensuring the bankability of such a business case, can be used for a realistic assessment, as summarized in figure 2. The present study focuses only on the first part, the technical feasibility, evaluating expected fatigue load reductions and the influence on energy production and other turbine performance metrics.
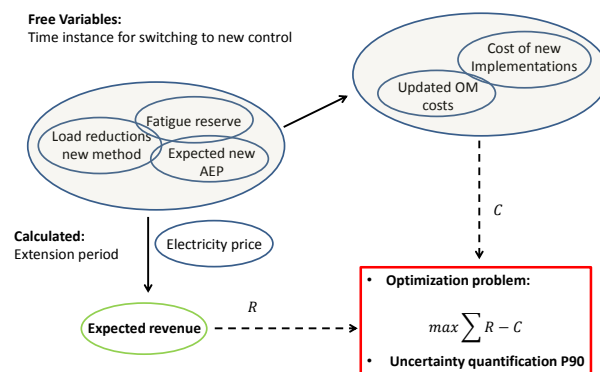
**Figure 2.** Evaluation of retrofit control strategies for LTE

In this context the two control methods suggested here, are implemented in an example case. The turbine operates for 15 years with the baseline controller and for the remaining 5 years of the design life time the new strategies are implemented. The resulting accumulated damage is calculated for the main turbine components and compared to the, assumed critical, damage from 20 year baseline operation. Based on these damage reserves, the possible life time extension period is calculated for each component taking into account the reduced fatigue consumption rate of the updated controller. Although this method requires a lot of assumptions and simplifications, it indicates the potential value of retrofit control in LTE applications.

3. Methodology
3.1. Individual blade control
The IPC method implemented here is referred to as individual blade control (IBC). Instead of using the traditional Coleman transformation for assigning an azimuth dependent pitch variation to the blades, with IBC three individual, decoupled controllers regulate each blade independently. The input signal is the blade root flapwise bending moment. IBC acts only in full load. This was chosen in order to avoid increasing pitch activity but also to avoid reducing energy production in partial load. Moreover, IBC is completely decoupled from the baseline PI collective pitch

controller (CPC), which is still responsible for regulating the low frequency bandwidth and hence the operating point (rotor speed). A combination of high pass (HP) filter for the input assuring the decoupling with the CPC, and bandstop (BS) notch filters for the output, limiting the control bandwidth up to 3P frequencies, are used. In order to achieve smooth switching between partial and full load the IBC output is weighted linearly with a factor between 0 and 1 varying linearly with the power output. The control scheme is a classical proportional feedback one. The gains are scheduled over mean pitch values in order to take into account the variation of the effect of pitch in aerodynamics in different wind speeds. A schematic representation is shown in figure 2, while more details on the controller synthesis can be found in [12].
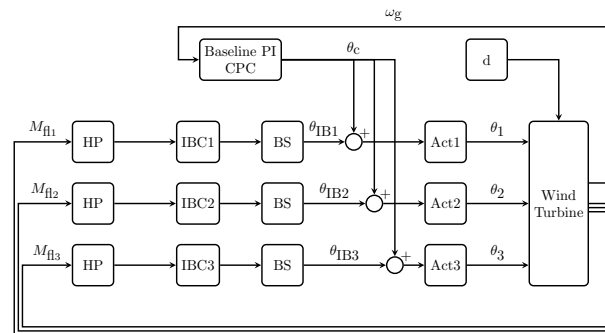

Figure 3. Schematic diagram of the individual blade controller system
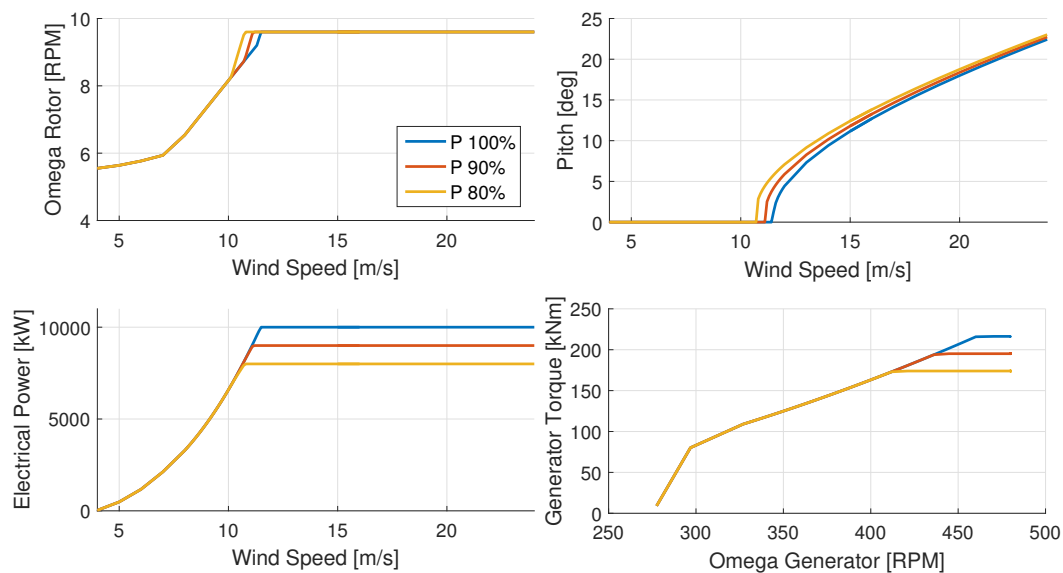
3.2. Down-regulation

In bibliography it is seen that depending on the application, e.g. ancillary services to the grid or wake reduction, different objectives like optimal set point tracking or minimization of C_T are to be considered. In choosing the optimal down regulation strategy for fatigue load alleviation purposes combined with IBC specific criteria have to be considered. These are the least possible pitch actuation and the absolute load reduction especially in the loads that are not highly affected by the IBC. Hence, it was decided to implement down-regulation only in the full load region by reducing the generator torque. The partial load region was not considered in order to avoid further AEP reduction but also avoid introducing pitch activity in this region. Moreover, the generator torque reduction was preferred compared to reduction of rated rotor speed in order to avoid reducing the dominant frequencies which in turn changes the aerodynamic damping and lead to increased tower loads and pitch activity as shown also in [18] and [22]. Especially for the DTU 10 MW turbine, the first tower frequency is at 0.25 Hz while the 3P baseline value is 0.45 Hz. This shows that reducing the rated speed by 20% or more can lead to structural resonance which counteracts the load reduction objective. The down-regulation strategy explained here is also referred to as derating.

With the chosen approach, the down-regulated turbine operates with the same rated rotor speed and hence the same Tip Speed Ratio (TSR) as the baseline. The collective pitch controller is responsible for regulating the rotor speed, which due to the decreased torque demand follows a lower C_P trajectory. Figure 4 shows the C_P and C_T trajectories of the baseline and down regulated cases over the TSR-pitch surfaces. The initial jump observed close to optimal C_P value is due to the particular region 2.5 of the DTU 10 MW where the rated generator torque is reached earlier than the rated rotor speed leading to a narrow region where TSR is increased beyond the optimal value. The trajectories show the reduced thrust and aerodynamic power for the same operating points where for the same TSR the increased pitch value offsets the trajectory horizontally to the right. This effect decreases as wind speeds increase.
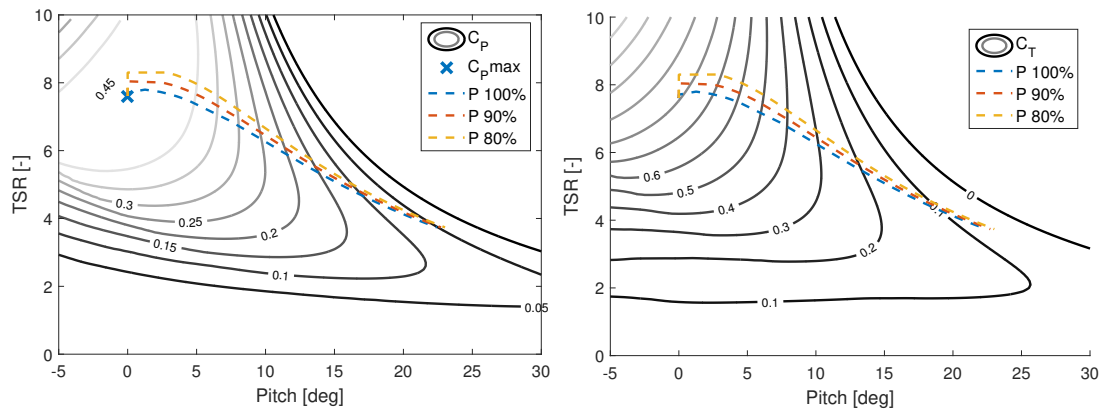
Figure 4. C_P and C_T trajectories over TSR and pitch. Wind speeds increase towards lower coefficient values

The steady state operational characteristics, as found by the non-linear simulations, are shown in figure 5. The rotor speed plot shows the reduction of rated speed from 11.4 m/s to 11.1 m/s and 10.7 m/s for 90% and 80% down-regulation. In addition, the increase of the aforementioned region 2.5 is shown here as well as in the generator torque versus generator speed plot. The pitch plot shows the increased pitch value per wind speed with the pitch value increase being lower as wind speed increases. This is also favorable for stability, since the blades operate in lower angles of attack and thus, further away from the stall region.

Figure 5. Steady state operational characteristics

3.3. Combining IBC and down-regulation

The baseline Variable Speed Pitch Regulated (VSPR) controller has a classical architecture. In region 1.5 the torque follows a ramp forcing the rotor speed to stay over a minimum value in order

5

to avoid tower resonance. In region 2 the optimal TSR for maximum Cp is tracked by applying a torque proportional to the square of the rotor speed. When the rated torque is reached, the turbine enters the transition region 2.5 where the rotor speeds up until the rated speed and power is reached. Then the turbine operates in full load. The collective pitch controller regulates the rotor speed based on a PI feedback scheme and the torque varies according to rotor speed in order to output constant, equal to rated, power. The gains are tuned with closed loop shaping using a simple 1DOF model and the partial derivatives of C_p in respect to pitch and TSR. These are derived from the steady state surface shown in figure 4.

For all the cases presented here, the tuning procedure followed the same steps. Firstly, the rated torque is changed to meet the down-regulation demand. Then, the new PI gains of the CPC were tuned using the closed loop shaping technique. This results to the altered operational characteristics shown in figure 5. The new IPC gain was tuned based on black-box identified linear blade models as shown in [12] for each wind speed.

4. Results and discussion

### 4.1. Controller performance

The control strategies investigated include the turbine operating with IBC only, down-regulation to 80% and 90% and their combination. Results of simulations are presented with the DTU 10 MW reference turbine [24] considering DLC1.2 class IA wind conditions as indicated by the IEC standard 61-400 ed. 3 [25] using the high fidelity aeroelastic code FAST v8 [26]. The Damage Equivalent Load (DEL) calculations are done according to the Palmgren-Miner rule [27] using the rainflow algorithm for counting the load cycles. The Wohler coefficient is considered equal to 4 for all the steel components, while for the blades a value of 10 is used. For the, Weibull distribution weighted, lifetime calculations the nominal design period is considered 20 years with a reference load cycle value of 10^7.

For an overview of the whole system's response, the following loads are considered: blade root flapwise and edgewise moments and torsion (BladeFW, BladeEW, BladeTor), tower base fore-aft and side to side moments and torsion (TwrBFA, TwrBSS, TwrBTOR), tower top/yaw bearing non-rotating pitch, yaw and roll moments (TTpitch, TTyaw, TTroll) and low speed shaft torsion (LSSTor). The metrics defined for the pitch actuator include: standard deviation of pitch rate and acceleration ($\dot{\theta},\ddot{\theta}$), and total pitch travel (θ). The metrics relevant to the turbine's performance are: produced electrical energy, standard deviation of generator speed (ω_g), generator torque (Gen Torque) and power (P). Initially, the results are discussed cumulatively for the total lifetime investigating the performance of the control strategies. This can also be seen as a 'per year' relative metric since same conditions and simulation cases are considered for every implementation. In the next section the possible contribution to lifetime extension as retrofit implementation is discussed.

The lifetime, or equivalently per year, relative to the baseline operation load reductions are shown in figure 6. Negative sign shows reduced loads. In general the load reductions achieved by applying only IBC are also achieved with the combined, while other loads that are out of the focus of IBC are reduced by the down-regulation. The main tradeoff is at the BladeFW load reduction. This comes from the transition region (2.5) where the lower the de-rating the larger the region becomes. This explains also why the largest reduction in BladeFW is seen when IBC is combined with P 90% where for all the other loads the combination with P 80% is more efficient. When the two methods are combined the BladeFW load reduction is less effective but still showing a reduction at a level of 10% which, as it will be shown also in the following sections, is satisfactory for LTE purposes. The blade edgewise loading, which is mainly driven by gravity and rotor speed, is practically not influenced. The blade torsional loads are decreased further with the down-regulation, since the aerodynamic pitching moment is decreased by operating in higher pitch, and the reduction is proportional to the level of the down regulation. Regarding

the tower bottom, the TwrBFA DEL is marginally decreased by IBC to a level of 3%. With the combined approach the expected thrust reduction from down-regulation leads to slightly higher reductions. The TwrBSS load is not influenced by the down regulation and the decrease in the level of 5% is attributed to IBC and is not affected by their combination. This is due to the fact that this mode presents low aerodynamic damping and is driven by the first tower frequency. The TwrBTOR load is decreased at a level of 8% with the IBC and slightly less with the down regulation. The same behavior is observed in the tower top TTpitch and TTyaw loads. This can be attributed to the reduced aerodynamic damping in higher wind speeds. The low speed shaft torque load is highly reduced due to the reduced rated torque from down regulation to a level of 14% and 11% with P90% and P80% respectively, while when IBC is implemented it is slightly increased. Moreover, the TTroll DEL is highly decreased, proportionally with the down regulation, due to reduced aerodynamic torque.

These two loads (TTroll and LSSTor) are the loads where down regulation contributes the most to, whereas when only IBC is considered they are not influenced. The same applies to a smaller extent for the blade root torsional loads which are also relevant for the damage of the pitch bearings. In general it was shown that the methods complement each other in load reduction and their combination leads to a significant load reduction for all the main system component with the exception of BladeEW loads. Further investigations are required on the switching regions which, although relatively small, was found to influence negatively the combined operation.
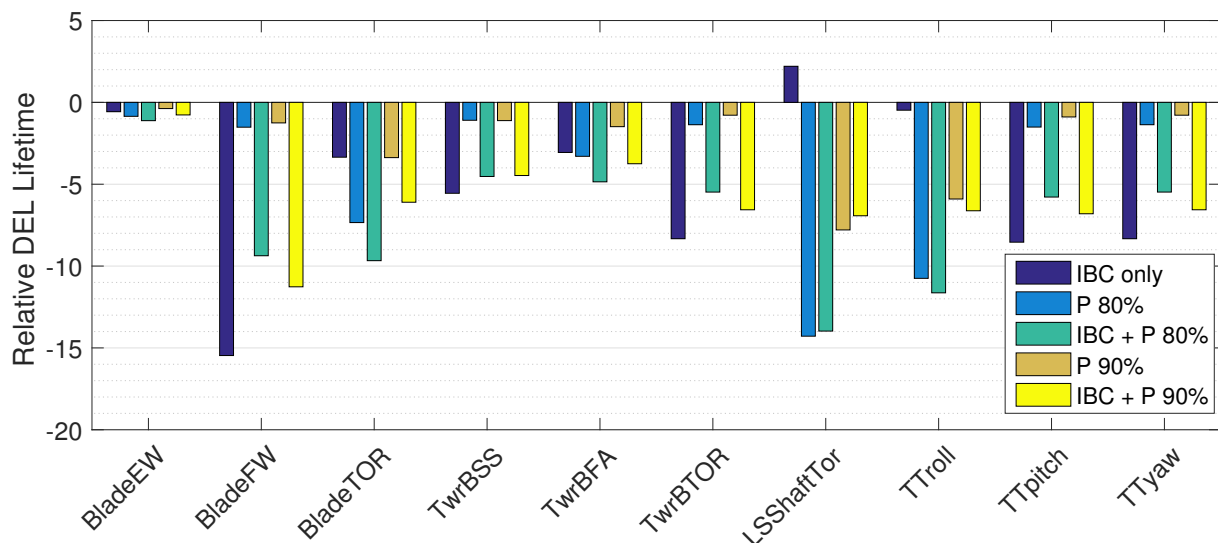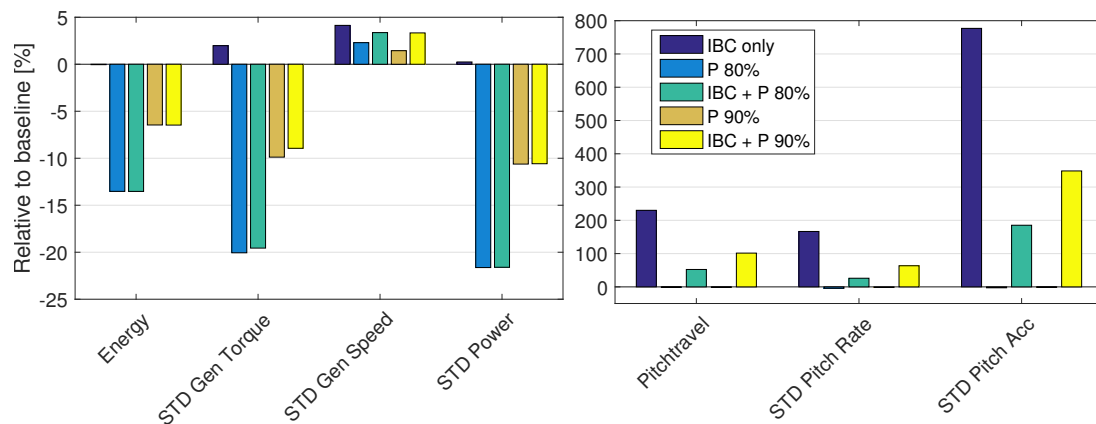

Figure 6. Lifetime (or equally per year) DEL reduction relative to baseline

Figure 7 shows the pitch and performance lifetime metrics. The AEP is not affected by the IBC in any case. Down-regulation of 90% leads to a 6.5 % decrease in AEP and 80% to a 13.5% decrease. The standard deviations of the generator torque and P are decreased proportionally to the down regulation levels showing improvement in the electrical power quality and generator damage. The standard deviation of ω_g is slightly increased to a level lower than 4% with all the methods. The pitch metrics show one of the main benefits in combining the two methods. On one hand, the de-rating approach has no impact on the pitch metrics. On the other hand, when combined with IBC, the pitch actuator demands are decreased substantially, compared to using only IBC. This can be explained by the different operating point compared to the baseline case (see fig. 4). For the updated trajectories the same change in pitch angle affects more the

aerodynamic forces.

Although there is no global pitch system damage metric, the results show clearly that the combination of IBC and down regulation reduce the demanded pitch activity from the actuator and the loads acting on the blade bearings. This shows the suitability of the suggested combination for LTE purposes since a wide load spectrum is decreased with reduced requirements from the pitch system. Then, more knowledge from the industry is required to evaluate whether this amount of increase is realistic and at what cost for a commercial pitch system. Of course, the reduction in AEP has to be also evaluated in a wider framework in order to evaluate the feasibility of such a business case.

**Figure 7.** Lifetime (or equally per year) metrics relative to baseline

4.2. Lifetime extension

For the LTE calculations with the retrofit controls some assumptions are required. Firstly, only fatigue is considered as the driver. Then, the total Damage is calculated based on the Linear Damage Hypothesis by Miner [27] considering the calculated lifetime DELs. Since more information is missing, it is assumed that the baseline damage is critical and hence equal to 1. This implies that there are no operational or design fatigue reserves which makes it a 'worst case' scenario. The combined Damage is then calculated taking into account only the updated controller load mitigation performance, in order to calculate the reserves. The key parameters are the application period of the update controller, the DEL reduction and the slope of the S-N curve (i.e. the Wohler exponent m) as seen in equation 1. Based on these reserves and assuming equal distribution of damage over time, the extension period can be calculated. More details on the calculations for life time extension can be found in [12].

$$D_{comb} = \frac{T_{base}}{T_{lifetime}} + \frac{T_{upd}}{T_{lifetime}} \left(\frac{DEL_{life,upd}}{DEL_{life,base}} \right)^m \tag{1}$$

For demonstration purposes, an example case is shown here for a combined 20 year lifetime where the turbine operates for 15 years with the baseline controller and 5 years with the updated. The cumulative damage per load channel is shown in figure 8.

Regarding the cumulative performance metrics for the combined life time, the first metric to be considered is the total energy produced. For the P 90% case the total reduction after 20 years is 1.6% compared to the baseline while for the P 80% case it is 3.4%. The cumulative pitch metrics are presented in figure 9, showing the benefit of applying IBC as retrofit for a limited
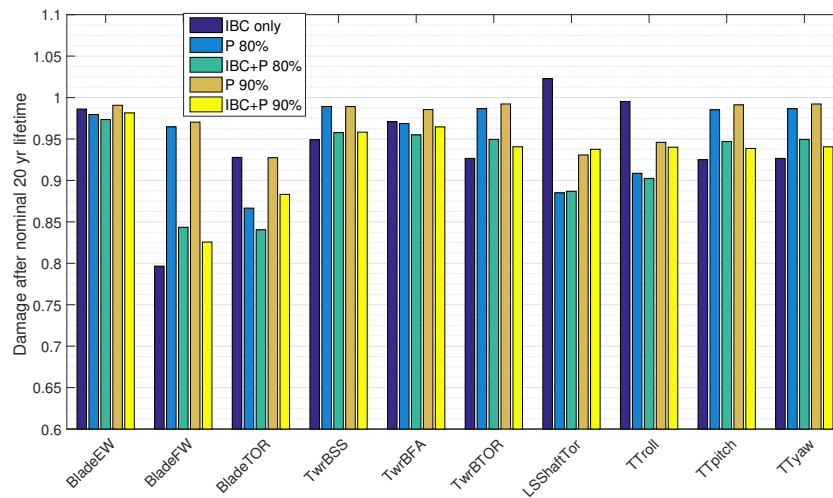
Figure 8. Damage after 20 years of combined operation (15 year baseline CPC)

period over applying it as a baseline feature. Even more, by combining it with down regulation the pitch demands increase to a level lower than 30% for total pitch travel and pitch rate while for the acceleration to a level lower than 100%.
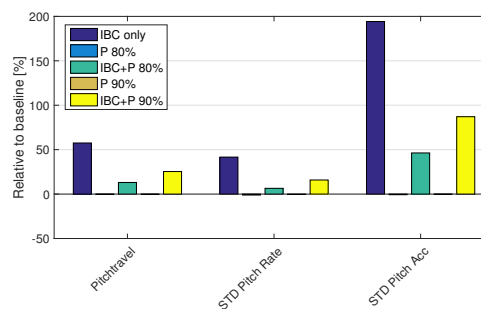
Figure 9. Pitch metrics after 20 years of combined operation (15 year baseline CPC)

The possible extension period in years based on the combined damage and the reduced 'consumption rate' with the new controller method is presented in figure 10. As stated earlier this is a worst case scenario since it is expected that there will be some operational and/or design fatigue reserves. The weight of the Wohler exponent, considered here for the blades, is shown; a damage reserve of 20% can lead to an extension period higher than double the life time. For the tower a period of 1-2 years is calculated. The tower top and shaft channels show a possible extension of 2-4 years. These results raise the question on whether a retrofit control strategy would even be necessary if in reality the operational damage reserves with the baseline controller are high enough. The answer is turbine- and site-specific and can only be answered having real data from operational condition monitoring and exact wind turbine models in order to evaluate each component individually. This discussion shows the limitations of such considerations without further insight.
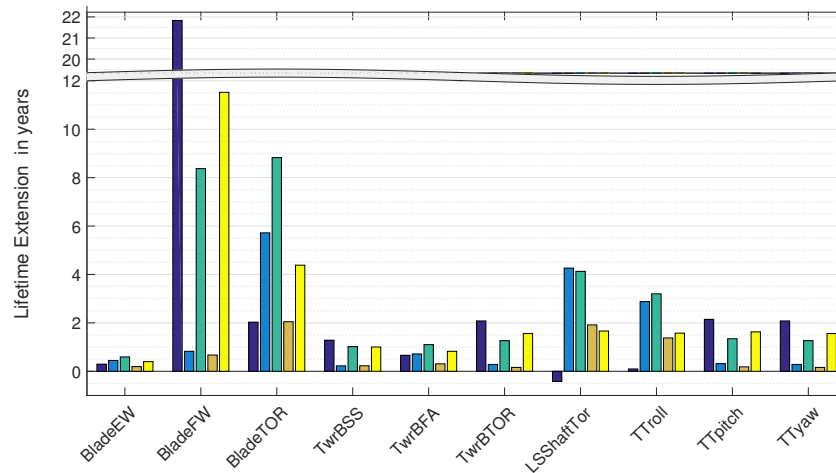
Figure 10. Period of life time extension

5. Conclusions and outlook

In the present work the concept of applying control strategies as retrofit for enhancing the life time extension was investigated. Two suitable control methods, down-regulation and IBC, are suggested, compared and combined. The control algorithms were presented and aeroelastic simulations according to the normal operation case DLC 1.2 were performed in order to evaluate their impact on loads, energy production, pitch and generator metrics. Moreover, a combined 20 year lifetime was considered, where the turbine operates for 15 years with the baseline control and 5 years with the updated scheme.

The results show that there is a benefit in combining down regulation and IBC in full load since they complement each other, in the sense that different loads are targeted with each method. The main focus of the combined scheme are the blade root loads, the low speed shaft torque and to a smaller extend the tower top loads. The tower bottom and blade root edgewise loads are not significantly reduced. Additionally, the actuator duty cycle is reduced when using combined IBC and down regulation compared to applying only IBC, although they are still increased compared to the baseline case. The switching region around rated showed to be a crucial region, dependent highly on the wind turbine and baseline controller design and it was seen that there is room for further optimization. The calculated reductions in AEP were found to be 6.5% and 13.5% for the 90% and 80% down-regulation cases respectively.

Further work on the topic would be to combine the information of Lidar preview in these control algorithms. Adding another, relatively cheap sensor, can give further load reductions combined with the strategies shown here, when a feedforward component can be added on top for both collective and individual pitch demands.

Finally, more information is required in order to have a realistic evaluation of the proposed retrofit control strategies. The need of condition monitoring insight and knowledge of fatigue reserve is prominent, while new methods to evaluate the damage and RUL for subsystems like the pitch system are required. To conclude, insight on the financial aspects of such implementations is critical for realistic feasibility and optimization studies and has to be also evaluated. Despite these, present work demonstrated the possible value of combining IBC and down regulation when applying retrofit control fro lifetime extension,

Acknowledgments

References

[1]   Ziegler L, Gonzalez E, Rubert T, Smolka U and Melero J J 2018 Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK *Renewable and Sustainable Energy Reviews* **82** 1261–1271 ISSN 18790690 URL http://dx.doi.org/10.1016/j.rser.2017.09.100
[2]   DNV GL 2016 ST-0262: Lifetime extension of wind turbines *Standard*
[3]   Megavind 2016 Strategy for Extending the Useful Lifetime of a Wind Turbine Tech. Rep. July
[4]   Barlas T K and van Kuik G A M 2010 Review of state of the art in smart rotor control research for wind turbines *Progress in Aerospace Sciences* **46** 1–27 ISSN 03760421
[5]   Schlipf D 2016 *Lidar-assisted control concepts for wind turbines* Phd thesis Stuttgart University URL https://doi.org/10.18419/OPUS-8796
[6]   Bossanyi E A 2003 Wind turbine control for load reduction *Wind Energy* **6** 229–244 ISSN 10954244
[7]   Lio W H 2017 *Blade-pitch Control for Wind Turbine Load Reductions* Phd thesis University of Sheffield
[8]   Bir G Multi-Blade Coordinate Transformation and its Application to Wind Turbine Analysis 2008 *46th AIAA Aerospace Sciences Meeting and Exhibit* (Reston, Virigina: American Institute of Aeronautics and Astronautics) ISBN 978-1-62410-128-1 URL http://arc.aiaa.org/doi/10.2514/6.2008-1300
[9]   Bossanyi E A 2005 Further load reductions with individual pitch control *Wind Energy* **8** 481–485
[10] Selvam K, Kanev S, van Wingerden J W, van Engelen T and Verhaegen M 2009 Feedback-feedforward individual pitch control for wind turbine load reduction *International Journal of Robust and Nonlinear Control* **19** 72–91 ISSN 10498923
[11] Laks J, Pao L and Wright A 2009 Combined Feed-forward/Feedback Control of Wind Turbines to Reduce Blade Flap Bending Moments *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition* 1–16 URL http://arc.aiaa.org/doi/abs/10.2514/6.2009-687
[12] Pettas V, Salari M, Schlipf D and Cheng P W 2018 Investigation on the potential of individual blade control for lifetime extension *Journal of Physics: Conference Series* **1037** 032006 ISSN 1742-6588
[13] Ma K, Zhu J, Soltani M, Hajizadeh A and Chen Z Wind turbine down-regulation strategy for minimum wake deficit 2017 *2017 11th Asian Control Conference (ASCC)* vol 2018-Janua (IEEE) pp 2652–2656 ISBN 978-1-5090-1573-3 URL http://ieeexplore.ieee.org/document/8287595/
[14] Astrain Juangarcia D, Eguinoa I and Knudsen T 2018 Derating a single wind farm turbine for reducing its wake and fatigue *Journal of Physics: Conference Series* **1037** 032039 ISSN 1742-6588
[15] Mirzaei M, Tuhfe G, Giebel G, Sørensen P E and Poulsen N K 2015 Turbine Control Strategies for Wind Farm Power Optimization *American Control Conference (ACC)* 1709–1714 ISSN 07431619
[16] Aho J, Buckspan A, Pao L Y and Fleming P A 2013 An Active Power Control System for Wind Turbines Capable of Primary and Secondary Frequency Control for Supporting Grid Reliability *AIAA/ASME Wind Symposium* 1–13
[17] Mirzaei M, Soltani M, Poulsen N K and Niemann H H 2014 Model based active power control of a wind turbine *2014 American Control Conference* 5037–5042 URL http://ieeexplore.ieee.org/document/6859055/
[18] Engels W P, Marina A, Kanev S and van der Hoek D 2017 Condition based control: Take the load off damaged components ECN-E–017-047 Tech. Rep. September ECN
[19] Richards P, Todd Griffth D and Hodges D 2015 Smart loads management for damaged offshore wind turbine blades *Wind Engineering* **39** 419–436 ISSN 0309524X
[20] Fleming P A, Aho J, Buckspan A, Ela E, Zhang Y, Gevorgian V, Scholbrock A, Pao L and Damiani R 2016 Effects of power reserve control on wind turbine structural loading *Wind Energy* **19** 453–469 ISSN 10954244
[21] DC van der Hoek; and Kanev S 2017 Reducing Wind Turbine Loads with Down-Regulation Tech. Rep. September ECN URL https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-E--17-032
[22] Aho J, Fleming P and Pao L Y Active power control of wind turbines for ancillary services: A comparison of pitch and torque control methodologies 2016 *2016 American Control Conference (ACC)* (IEEE) pp 1407–1412 ISBN 978-1-4673-8682-1 URL http://ieeexplore.ieee.org/document/7525114/
[23] Frost S A, Goebel K and Obrecht L 2013 Integrating Structural Health Management with Contingency Control for Wind Turbines *International Journal of Prognostics and Health Management* **4** 11–20 ISSN 21532648
[24] Bak C, Zahle F, Bitsche R, Yde A, Henriksen L C, Nata A and Hansen M H 2013 De-

scription of the DTU 10 MW Reference Wind Turbine Tech. Rep. July DTU Roskilde URL
https://dtu-10mw-rwt.vindenergi.dtu.dk

[25] International Electrotechnical Commision (IEC) 2005 Wind turbines Part 1: Design requirements 61400-1 ,
3rd edition Tech. rep. International Electrotechnical Commision (IEC) Switzerland

[26] Jonkman   J   and   Marshall   B   2005   FAST   User's   Guide   Tech.   Rep.   6   URL
http://www.ncbi.nlm.nih.gov/pubmed/21564034

[27] Miner M 1945 Cumulative Damage in Fatigue *Journal of Applied Mechanics* **3** 159–164