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# Cyclic pitch control for the reduction of ultimate loads on wind turbines

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## Abstract.

In this paper we study the use of individual blade pitch control as a way to reduce ultimate loads. This load alleviation strategy exploits the fact that cyclic pitching of the blades induces in general a reduction of the average loading of a wind turbine, at least for some components as the main bearing, the yaw bearing, or the tower.

When ultimate loads are generated during shutdowns, the effect of the use of cyclic pitch results in reduced peak loads. In fact, as the machine starts from a less stressed condition, the response to an extreme gust or other event will result in reduced loading on its components. This form of load mitigation can be seen as a preventative load mitigation strategy: the effect on load reduction is obtained without the need to detect and react to an extreme event, but by simply unloading the machine so that, in case an extreme event happens, the result will be less severe.

The effect of peak load mitigation by preventative cyclic pitch is investigated with reference to a multi-MW wind turbine, by using high-fidelity aeroelastic simulations in a variety of operating conditions.

## 1. Introduction

In the last decade, the ability of cyclic pitch control systems to lower fatigue loading on wind turbines has been thoroughly investigated and quantified, as witnessed by a significant body of literature devoted to this subject (cf. Refs. [1] to [11], and references therein). Notwithstanding the several different possible implementations of such controllers, the majority of the results obtained by simulation or in the field show that the use of cyclic pitch is typically quite beneficial in the reduction of fatigue loading. Unfortunately, this advantage comes at the price of an increased pitch activity, as for example quantified by the actuator duty cycle (ADC) or other similar metrics. As the additional wear and effort increases manufacturing, maintenance and operational costs, cyclic pitch is still considered with caution by industry, and it is not always economically beneficial.

Less can be found in the existing literature about the effects that cyclic pitch can bear on the ultimate loads affecting a wind turbine. This is unfortunate, as ultimate loads rather than fatigue may drive the design of some wind turbine sub-systems. To address this gap, this work investigates the ability of a cyclic pitch controller to mitigate ultimate loads on some key components of a wind turbine.



The point of departure of the present analysis is the observation that cyclic pitch, in addition to the already mentioned reduction in fatigue loading, has also the effect of reducing the average loading on the machine. For example, by cyclic pitch one can easily very significantly reduce the average nodding and yawing moments due to wind misalignment and shears. As peak loads are typically generated by strong wind gusts or violent emergency maneuvers, it is rather clear that, all the rest being equal, the same event will lead to a smaller peak load when starting from a less loaded condition than from a more heavily stressed one. In this sense, cyclic pitch control can be used as a *preventative* measure that unloads the machine so that, if an extreme event happens, the machine will end up with smaller ultimate loads. Notice that this does not require any particular detection of the causing extreme event. This is important, because systems that rely on detection of some special condition may suffer from fragility, unless the detection can be proven to be bullet proof.

A second key observation of the present work is that extreme events do not always lead to ultimate loads. In fact, the extreme gusts or emergency shutdowns that define the load envelope of a machine are typically clustered around the rated and cut-out wind speeds. This means that, if one wants to use a cyclic pitch controller for the mitigation of extreme loads, then cyclic pitch does not need to be used at all times. On the contrary, it can be used in a *selective* manner only when the machine is operating in proximity of “dangerous” wind speeds, and be switched off otherwise. Therefore, in this case the increase in pitch activity due to the use of cyclic pitch may be not as pronounced as in the case when cyclic pitch is used for fatigue alleviation, thereby mitigating some of its perceived drawbacks.

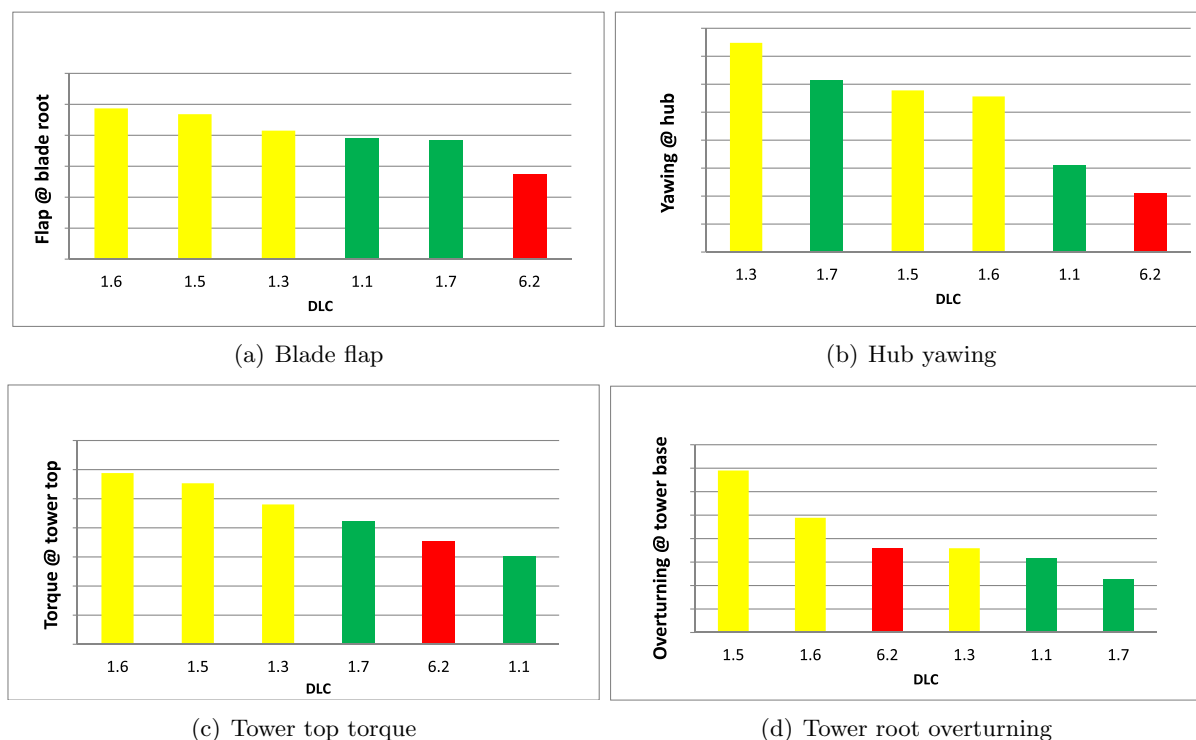
To investigate the role of cyclic pitch control on the reduction of peak loads, the present work starts by analyzing the ranking of the most demanding design load cases (DLCs) on a wind turbine. The analysis considers loads at the root of the blades, on the shaft and on the tower. The ranking analysis readily illustrates which loads can be affected by the use of cyclic pitch, and which can be not. For example, if the top ranking load was due to a storm DLC where the rotor is idling, then clearly it could only be reduced by a redesign of the blade and not by a modification to the control laws of the machine. The same analysis also yields the wind speed ranges where ultimate loads are generated, a piece of information that can be readily used to define those wind speeds where pitch control should be active and those where it should be not.

In a second stage of the analysis, a cyclic pitch controller is synthesized and used selectively on board a wind turbine. A strategy is also devised for conducting a pitch-to-feather maneuver during an emergency shutdown when cyclic pitch is active. Simulations conducted in a high-fidelity aeroservoelastic environment illustrate the main features of the proposed approach, and allow to draw some conclusions on the effectiveness of the present idea.

## 2. DLC Ranking

The analysis of the DLC ranking on wind turbine components is rather instructive, and it can be profitably used to gain a better understanding on what improvements are possible and how such improvements can be gained. Figure 1 shows the ranking of the DLCs for a multi-MW wind turbine, considering some key loads at the root of the blades, at the main bearing and at the top of the tower. These results, although specific to the considered wind turbine and not necessarily of general validity, are quite typical of similar existing machines.

The wind turbine, simulated with the help of a high-fidelity aeroservoelastic code [12, 13], operates in closed-loop with a collective pitch and torque controller. The wind turbine model was subjected to a complete set of DLCs, including those prescribed by certification guidelines [14], and complemented by other additional verification conditions at wind speeds between the rated and cut-out. The figure reports the rankings of four bending moments: blade flap (where the worst case on all blades was considered), hub yawing, torque at tower top and tower base overturning. In the figure, DLCs where the machine is operated by the closed-loop controller



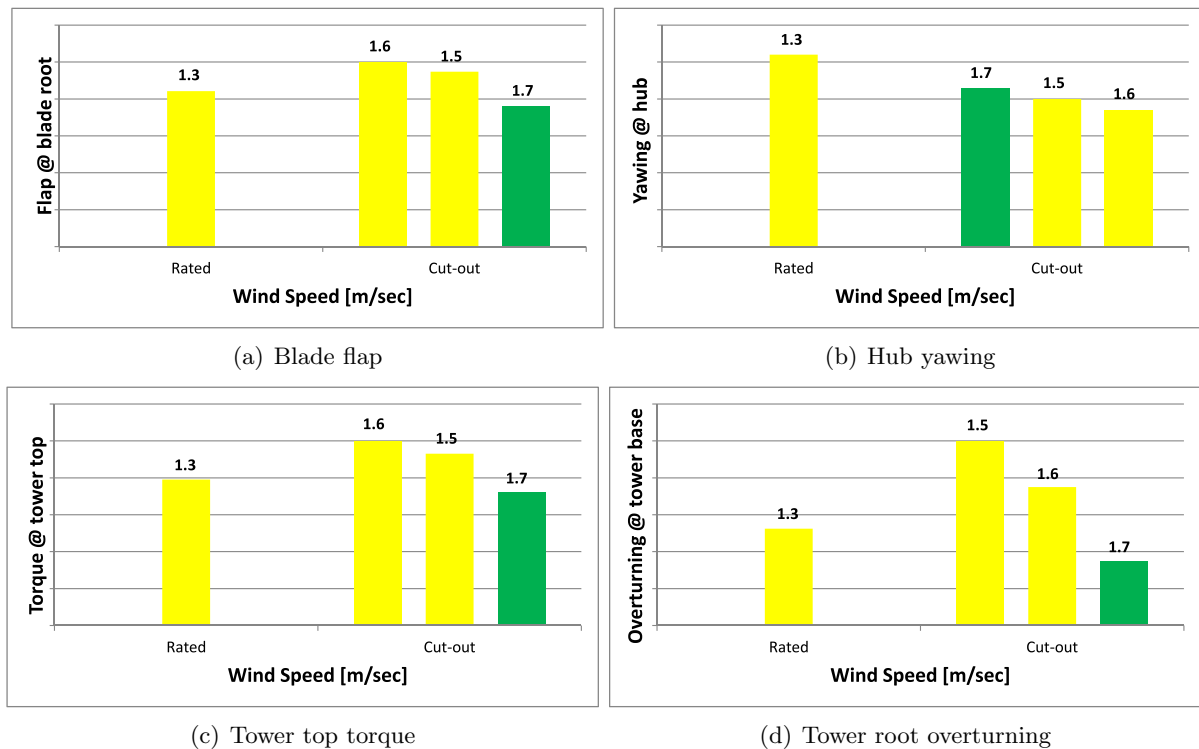
**Figure 1.** DLC ranking for blade flap (worst of three blades), shaft yawing, tower top torque and tower base overturning moments.

are colored in green (DLC 1.1 and 1.7). Clearly, such loads can benefit from a well performing control system, including therefore the use of cyclic pitch. Those conditions where the machine undergoes a shutdown, in concomitance with faults (DLC 1.5) or not (DLC 1.3 and 1.6), are colored in yellow. As illustrated later on, it is one of the contributions of this work to show that cyclic pitch can be very effective even in these conditions, as it allows the machine to enter into a shutdown from a less loaded state. Finally, DLCs for which the control system is not operative (DLC 6.2), because the machine is parked with the blades in the full-feather position, are marked red. No change to the control system will affect the response of the turbine in such DLCs.

It appears that all four loads considered in Figure 1 have very significant margins for reduction by the use of improved controls, as the red (uncontrolled) cases feature quite down in the rankings.

As previously stated in this work, probably the most relevant drawback of the application of a cyclic pitch controller is the increased actuator activity. For this reason, specific attention was dedicated here to the reduction of the usage of cyclic control to a minimum, without losing the ability to effectively lower ultimate loads. The ranking of DLCs can be profitably used to identify those wind speeds where ultimate loads are generated. To this end, DLCs were simulated at several reference wind speeds, with a closer spacing between wind values than commonly done for certification [14]. The results of the analysis show that most high-ranking DLCs are recorded for wind speeds in proximity of the rated and in a relatively wide region ending with the cut-out wind speed (Figure 2).

Using cyclic control in any other operative region may bring advantages in terms of fatigue reduction, but it will not affect the ultimate loads and hence it will have no impact on the structural design, while at the same time it will certainly increase ADC.



**Figure 2.** Top ranking DLCs with respect to the wind speed for blade flap (worst of three blades), shaft yawing, tower top torque and tower base overturning moments.

### 3. Cyclic pitch control for the mitigation of ultimate loads

The top ranking DLCs colored in red in Figure 1 constitute a limit to the improvement that is potentially attainable by modifications to the control laws, and altering the results of such DLCs requires a redesign of the wind turbine. For the particular wind turbine considered in this work, the only load for which DLC 6.2 ranks significantly high is the tower base overturning moment, and this result is quite typical of contemporary multi-MW wind turbines.

To reduce peak loads, possibly up to the level of DLC 6.2, in this section we consider the use of cyclic pitch control. A multi-layer approach is used for this purpose [11]. A collective pitch and torque controller is used for regulating the machine around a given set point during power curve tracking, and for gust load alleviation. This control layer is implemented using the speed-scheduled linear quadratic regulator (LQR) described in [15], augmented with an integral term. The cyclic pitch loop is implemented using the formulation of Ref. [3], where two independent single-input/single-output (SISO) proportional-integral (PI) controllers are used for reducing the d-q axis [3] loads, i.e. the fixed system yawing and nodding moment components  $\mathbf{m}_{dq}$ . These can be measured directly by sensors in the fixed reference frame, are computed from blade load measurements as

$$\mathbf{m}_{dq}(t) = \mathbf{C}(t)\mathbf{m}_b(t), \quad (1)$$

where  $\mathbf{C}(t)$  is the partial Coleman transformation matrix at time  $t$ , which writes

$$\mathbf{C}(t) = \begin{bmatrix} \cos \psi_1(t) & \cos \psi_2(t) & \cos \psi_3(t) \\ \sin \psi_1(t) & \sin \psi_2(t) & \sin \psi_3(t) \end{bmatrix}, \quad (2)$$

where  $\psi_i$  is the azimuthal angle of the  $i$ th blade and  $\mathbf{m}_b$  the vector of blade bending loads. The

fixed system pitch inputs are defined as

$$\beta_{dq}(t) = -K_P \mathbf{m}_{dq}(t) - K_I \int_{t_0}^t \mathbf{m}_{dq}(\tau) d\tau, \quad (3)$$

where  $K_P$  and  $K_I$  are the proportional and integral gains, respectively. The corresponding blade pitch inputs are then computed using the partial inverse Coleman transform  $\tilde{\mathbf{C}}(t)$  as

$$\beta_{cycl}(t) = \tilde{\mathbf{C}}(t) \beta_{dq}(t), \quad (4)$$

where  $\tilde{\mathbf{C}} = \mathbf{C}^T$ . These additional pitch inputs are combined with the ones provided by the collective layer and sent to the blade actuators.

### 3.1. Cyclic pitch during shutdowns

Among the DLCs where the machine is undergoing a shutdown, colored in yellow in the rankings of Figure 1, two different situations can be distinguished. DLC 1.3, 1.6 and 1.7 correspond to scenarios where there are no faults, and the turbine is pushed into an overspeed condition because of an extreme wind event. On the contrary, DLC 1.5 considers a grid disconnection, resulting in the loss of the sensor signals and of torque control. Furthermore, the pitch actuators have a limited operability, as they can only operate at a reduced pitch rate due to the fact that they are powered by batteries. In such a scenario, the control system can operate only in open loop, as no feedback signals are assumed to be available.

In the no fault scenarios, after entering the overspeed region, the supervisory system will trigger a shutdown maneuver by a pitch-to-feather of the blades, while using torque for supporting the deceleration of the rotor. The breaking maneuver is performed by a collective pitch of the three blades at a high rate, in order to counteract the effects of the gust and to quickly bring to rotor speed down. When cyclic pitch is used, it is beneficial to keep it operational for a short period of time after fault, as this helps reducing loads and results in a smooth slowing down of the rotor. After this initial phase, chosen as long enough so that the time of peak load has passed, all blades are lead towards a common final collective pitch motion until the idling position is reached.

In the scenarios with concomitant faults, torque cannot be used to help in the deceleration of the rotor, and no feedback control is possible. The design of a collective open-loop pitch-to-feather maneuver can be performed manually, or by using optimal control theory as suggested in [16]. In this work, the following simple open-loop time history for the cyclic pitch of the  $i$ th blade was used

$$\beta_{i,cycl \text{ open-loop}}(t) = \beta_{i,cycl}(t_{\text{fault}}) \cos \left( \Omega(t_{\text{fault}})(t - t_{\text{fault}}) + (i - 1) \frac{2\pi}{3} \right), \quad (5)$$

where  $t_{\text{fault}}$  is the fault time and  $\Omega$  the rotor speed. Similarly to the no fault scenario, this cyclic pitch action is used for a short period of time following a fault until passed the time when peak loads are generated, after which all blades are realigned and collectively pitched towards the idle position.

### 3.2. Wind speed cyclic pitch scheduling

As previously mentioned, the analysis of the DLC ranking highlights the ranges of wind speeds where ultimate loads are generated. When cyclic pitch is used for the mitigation of extreme loads, as done here, its usage should be restricted to these regions of the speed range, and elsewhere it could be switched off to avoid unnecessary increases in the ADC.

To implement this preventative use of cyclic pitch, here a simple weighting was used, where the total blade pitch is computed as

$$\beta(t) = \beta_{\text{coll}}(t) + w(\hat{V})\beta_{\text{cycl}}(t), \quad (6)$$

where  $w(\hat{V}) \in [0, 1]$  is a weighting factor, scheduled as a function of the wind speed  $\hat{V}$  around which the machine is operating. Ramps can be used in the definition of  $w(\hat{V})$ , as shown later on, to smoothly switch the cyclic controller on or off.

When  $w = 1$ , cyclic pitch is active. The 1P harmonic components of the blade loads are transformed into 0P harmonics in the fixed d-q axis. In turn, these are canceled out by the integral terms in the control (3), resulting into a 1P harmonic pitching of the blades. The very significant reduction of the 0P harmonics that is obtained in this way, implies that the machine is much less loaded than in the collective case; for example, the nodding moment, depurated from the effects of gravity, is virtually null in the case of cyclic control, while it is not in the case of collective control. This less loaded condition then results in smaller peak loads, in case an extreme event takes place. Hence, cyclic pitch acts in such a way as to safeguard the machine.

On the other hand, when  $w = 0$ , cyclic pitch is not active. Its unloading effects are not present, but nonetheless the machine is safe, because even if an extreme event takes place, then it would still generate loads that are smaller than in other wind conditions.

An alternative way of managing a cyclic controller for the reduction of ultimate loads would appear to be that of monitoring the appearance of extreme wind condition, and activating the cyclic controller only once such an event is detected. This would provide the advantage of a further reduced ADC, for the cyclic controller would be activated only sporadically. Apart from the difficult problem of guaranteeing a reliable detection of all such events, this strategy would still not work, as the machine needs to be in an unloaded condition before the event takes place. This reinforces the importance of the proposed control strategy, which shows that preventing is often better than curing.

#### 4. Results

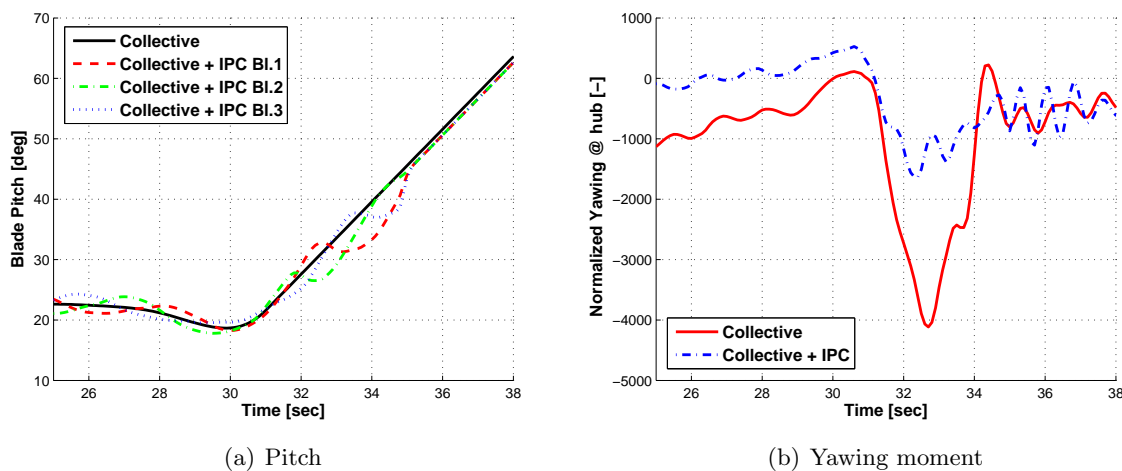
The proposed extreme load mitigation method was tested using a 3.0 MW three-bladed wind turbine, with a rotor diameter of approximately 100 m. The virtual model was simulated using the Cp-Lambda aeroservoelastic code [12, 13], which implements a geometrically exact finite-element/multibody formulation based on a scaled index-3 approach, coupled to a BEM lifting line model. The wind turbine model operates in closed-loop with the controllers described above. The cyclic loop uses fixed-frame nodding and yawing moments at the main shaft bearing for feedback. The controller gains were tuned to achieve satisfactory performance on loads, while contemporarily avoiding an excessive increase in ADC, under both deterministic and turbulent (DLC 1.1) wind conditions. The maximum pitch rate attainable by the actuators, modeled as second order systems, is of 6 deg/sec.

The ranking of DLCs for this turbine using collective pitch control was shown earlier in Figure 1 and, as previously noted, there is ample margin for improvements of all considered ultimate loads. As shown later on, the same holds true also for other loads, as the main bearing shaft nodding moment or the blade root edge one.

All DLCs were run at rated wind speed  $V_{\text{rated}}$ ,  $V_{\text{rated}} - 2$  m/sec,  $V_{\text{rated}} + 2$  m/sec, and the cut-out  $V_{\text{cut-out}}$  as prescribed by international standards [14]. In order to better assess the usefulness of cyclic control over the entire region III span (i.e. in the above-rated region), all DLCs were also run between  $V_{\text{rated}} + 2$  m/sec and  $V_{\text{cut-out}}$  every 2 m/sec. Furthermore, the same DLCs were run considering a null, positive (+8 deg) and negative (-8 deg) vertical inclination of the wind field, and three initial azimuthal positions of the rotor, where the initial azimuth of the first blade was set to 0, 30 and 90 deg, respectively. The effect of cyclic control in the partial

power region II (i.e. below rated wind speed) was not investigated, because of limits on pitch excursion there. Furthermore, no DLCs at low wind speeds appear among the top-ranking ones.

Figure 3 shows, on the left, the pitch time history during a shutdown triggered by a 50-year gust (DCL 1.6) at a reference speed of 25 m/sec, which is the cut-out speed for this wind turbine. The same figure shows on the right the corresponding time history of the hub yawing moment.



**Figure 3.** Effects of a 50-year gust at cut-out wind speed, using collective or cyclic pitch control. Left: pitch time histories. Right: yawing moment.

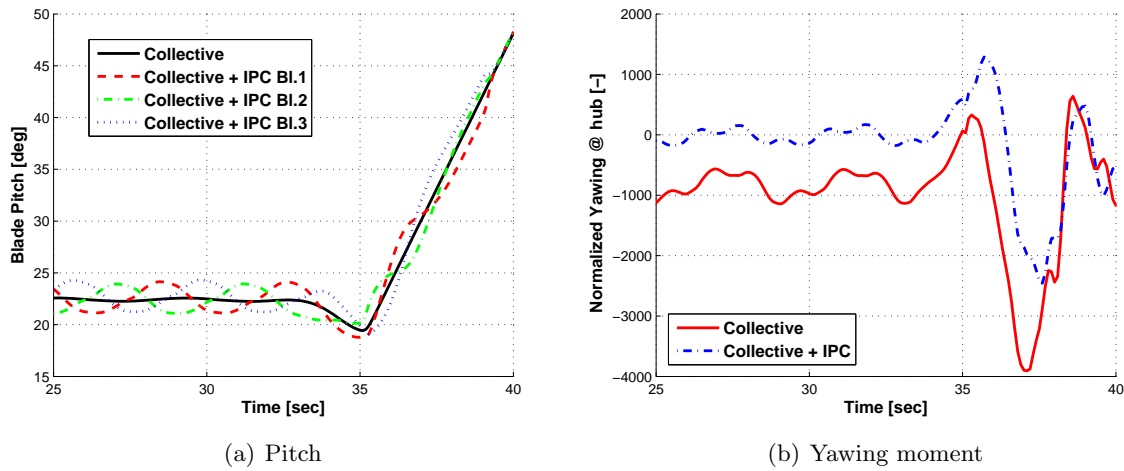
In this example, the rotor reaches the overspeed limit close to  $t=31$  sec throughout the simulation. As shown in Figure 3 at left, cyclic control is kept active for a window of 4 sec after the machine has initiated the shutdown procedure. On the right of the same figure, the effects of cyclic control is clearly noticeable: the average load in the constant wind phase preceding the gust is markedly reduced when cyclic pitch is used. This initial less loaded state, together with the action of cyclic control during the gust, results in a very significant reduction of the peak load.

Figure 4 shows similar effects of cyclic pitch and similar results in terms of load reduction, in this case when the machine encounters a 1-year gust with a concurrent grid loss (DLC 1.5). Differently from the previous case, open (instead of closed) loop control is used after the fault instant  $t_{\text{fault}}=35$  sec. The load is nonetheless very effectively reduced even in this case, as shown on the right part of the figure.

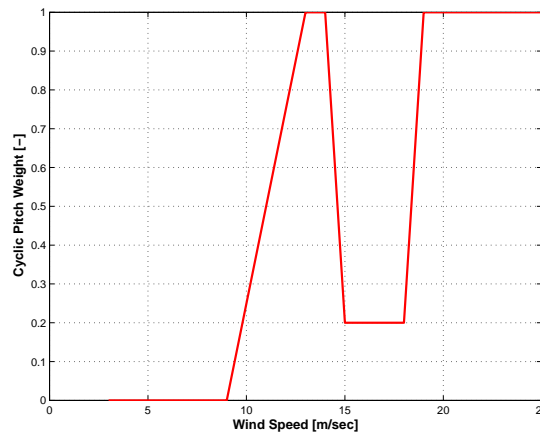
By looking at the results of all DLCs, it was realized that the use of cyclic pitch control on the section of the full power region between  $V_{\text{rated}} + 2$  m/sec and  $V_{\text{cut-out}} - 4$  m/sec was not necessary as far as ultimate loads are concerned, as these are not generated in that wind speed range. This analysis lead to the definition of the weight function  $w(\hat{V})$  of Eq. (6). The function, shown in Figure 5, enforces the use of cyclic control to the portions of region III around rated and close to the cut-out wind speeds, with ramps that are used for smooth transitioning between ranges when the controller is on or off.

The ADC was computed using DLC 1.1 and weighted with a Weibull centered at 8.5 m/sec, which corresponds to class IIA. While the ADC remains 2.4 times greater than in the collective pitch case, this metric quantity is reduced by 36% when the weighting of Figure 5 is used, compared to the case where cyclic pitch is used for the entire region III. On the other hand, fatigue, measured in terms of damage equivalent loads (DEL), saw a decrease of -4.7% on the combined bending moment at the root of the blade with respect to the collective case, which should be compared with a reduction of -6.8% obtained with the continuous use of cyclic control





**Figure 4.** Effects of a 1-year gust at cut-out wind speed, with a grid loss at 35 sec, using open-loop collective and cyclic pitch control. Left: pitch profiles in the presence of cyclic pitch control. Right: yawing moment.



**Figure 5.** Weight function  $w(V_h)$  of cyclic pitch control.

in the full power region. Similarly, the reduction in the DEL measured on the combined bending moment on the shaft passed from -5.0% for continuous IPC operation to -2.5% when applying the gain of Figure 5. Finally, AEP was reduced by -2.3% with respect to the collective control case when cyclic pitch is active for all wind speeds, and of only -0.4% when used selectively.

Table 1 illustrates the effect of the use of the preventative cyclic control strategy in terms of ultimate loads. The table reports changes in the top ranking DLC with respect to the collective control case.

The loads on the blade show a negligible change. In fact, the effects of cyclic pitch on the loads measured in the rotating system is more apparent in terms of fatigue than in terms of ultimate loads. This is to be expected, as cyclic pitch does not significantly alter the average loading of the blades, while it lowers the loads in the fixed system, thereby resulting in lower peak loads during extreme transients.

On the contrary, it appears that cyclic pitch is very effective in reducing peak loads on the hub, both in the yawing and nodding components. This result is according to intuition, as lower average loading leads to reduced peaks in transients, as argued earlier on. The observed

Load	$\Delta$	Top DLC (Collective)	Top DLC (Cyclic)
<i>Blade</i>			
Flapwise (positive)	+3.7%	1.6	1.5
Flapwise (negative)	+7.5%	1.3	1.5
Edgewise (positive)	+1.9%	1.5	1.5
Edgewise (negative)	+0.6%	1.5	1.5
<i>Hub</i>			
Nodding (absolute)	-19.5%	1.3	1.3
Yawing (absolute)	-20.4%	1.3	1.5
<i>Tower</i>			
Base overturning (absolute)	-0.1%	1.5	1.5
Top torque (absolute)	-30.9%	1.5	1.5

**Table 1.** Effects of preventative cyclic pitch control on top ranking DLCs for blade, shaft and tower loads. First column: percent load change. Second and third columns: top ranking DLC for collective and cyclic control, respectively.

load reductions might be possibly translated into weight and cost savings in the nacelle system, although this analysis was not conducted in the present study.

Finally, the effects on the tower are more varied, and need some interpretation. In fact, the base overturning moment is basically unchanged, whereas the effect on the tower top torsional moment is good, with a substantial reduction. The latter effect can be explained using arguments similar to the ones used above. On the other hand, the former is due to the large negative thrust that is produced during an emergency shutdown. In fact, in such a maneuver, the blades are pitched forward at a fast rate with the goal of creating an aerodynamic breaking effect. As the aerodynamic torque is initially decreased and then rendered negative, which is responsible for the slowing down of the rotor and the reduction of its very large kinetic energy, the aerodynamic thrust becomes large and negative, propelling the machine forward. This creates a rapid swinging fore-aft motion of the wind turbine, and the peak loads in the tower are generated during the first cycle, when the machine reaches its maximum fore deflection, before starting to spring back. As this load is generated by the breaking maneuver of the rotor, the effect of cyclic pitch is negligible, and the reduction of this load can be achieved by a better management of the pitch to feather maneuver, as shown in [16].

It should be noticed that the top ranking DLCs are largely the same in the collective and cyclic pitch cases. This is mostly due to the fact that the cyclic pitch gains and its weighting function were here tuned in order to balance load reductions with ADC increases. It was found that further load reductions would be possible in the case of the present machine, but at the cost of a significant increase in the ADC.

It should also be stressed that one might pursue strategies other than the preventative one discussed here. For example, one might be willing to accept increases in ADC, by using a more aggressive cyclic control throughout the entire operating range of wind speeds between the high end of region II to the end of region III, as already done by some wind turbine manufacturers. This way one would obtain reductions in fatigue but would also, as shown here, obtain as a byproduct interesting reductions in ultimate loads.

## 5. Conclusions

The paper has presented a load mitigation strategy based on the preventative use of cyclic pitching of the blades. The reduced loading of the machine by cyclic pitch was shown to yield less severe peak loads during extreme events for the main bearing, yaw bearing and tower.

In addition, the paper exploited the fact that peak loads are generated only for some specific ranges of wind speeds, typically around the rated and the cut-out speeds. By using this fact, it was suggested that cyclic pitch could be turned on only in those potentially dangerous speed regimes, and turned off elsewhere. This might be used to reduce ADC, clearly at the cost of a reduced effectiveness on fatigue loading.

In conclusion, the numerical simulations conducted in this work show that cyclic pitching, in addition or in alternative to its more common use for fatigue alleviation, can also be profitably used for the mitigation of ultimate loads. This result can be achieved without excessive complexities and does not necessitate of additional sensors or of specific logics for the detection of extreme events. This makes this strategy of particular interest for the practical application on existing wind turbines. The possible benefits of this idea should be more fully assessed by a complete design exercise, where one could evaluate the effects on loads, fatigue and ADC in terms of their overall impact on the cost of energy.

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## References

- [1] Stol K A 2003 Disturbance tracking control and blade load mitigation for variable-speed wind turbines *ASME J. of Sol. Energy Eng.* **125** 396-401.
- [2] Bossanyi E 2003 Wind turbine control for load reduction *Wind Energy*. **6** 229-244.
- [3] Bossanyi E 2003 Individual blade pitch control for load reduction *Wind Energy*. **6** 119-128.
- [4] Bossanyi E 2004 Developments in individual blade pitch control *Proc. The Science of Making Torque from Wind Conf. (Delft)*.
- [5] Bossanyi E 2005 Further load reductions with individual pitch control *Wind Energy*. **8** 481-485.
- [6] Geyler M and Caselitz P 2008 Robust multivariable pitch control design for load reduction on large wind turbines *ASME J. of Sol. Energy Eng.* **130** 031014/1-031014/12.
- [7] van Engelen T G 2006 Design model and load reduction assessment for multi-rotational mode individual pitch control (Higher Harmonics Control) *Proc. European Wind Energy Conf. (Athens)*.
- [8] van Engelen T G and Kanev S 2009 Exploring the limits in individual pitch control *Proc. European Wind Energy Conf. (Marseille)*.
- [9] Geyler M and Caselitz P 2007 Individual blade pitch control design for load reduction on large wind turbines *Proc. European Wind Energy Conf. (Milano)*.
- [10] Leithead W E, Neilson V and Dominguez S 2009 Alleviation of unbalanced rotor loads by single blade controllers *Proc. European Wind Energy Conf. (Marseille)*.
- [11] Bottasso C L, Croce A, Riboldi C E D and Nam Y 2013 Multi-layer control architecture for the reduction of deterministic and non-deterministic loads on wind turbines *Renew. Energ.* **51** 159-169.
- [12] Bauchau O A, Bottasso C L and Trainelli L 2003 Robust integration schemes for flexible multibody systems *Computer Methods Appl. Mech. Eng.* **192** 395-420.
- [13] Bottasso C L and Croce A 2014 *Cp-Lambda: user's manual Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano*
- [14] *Guideline for the Certification of Wind Turbines* 2010 (Hamburg: Germanischer Lloyd Industrial Services GmbH)
- [15] Bottasso C L, Croce A, Nam Y and Riboldi C E D 2012 Power curve tracking in the presence of a tip speed constraint *Renew. Energ.* **40** 1-12.
- [16] Bottasso C L, Croce A and Riboldi C E D 2014 Optimization of the open-loop pitch profile during an emergency shutdown *Preprint*