Field tests of Individual Blade Control and its impact on the wind turbine components lifetime

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Summary

This papers describes the work carried out to demonstrate and validate Individual Blade Control (IBC) on a wind turbine and evaluate its benefits. IBC is SgurrControl's patented solution to reduce loads and extend life of key components on a wind turbine. IBC modifies the pitch angle of each individual blade in response to measured blade loads to account for the varying wind filed across the rotor and hence reducing rotor aerodynamic imbalances.

IBC was commissioned and tested on a Clipper C96 2.5 MW owned by the University of Minnesota. The data gathered proved the effectiveness of IBC on reducing blade and drive-train loads. The results were compared against the simulation outputs from the corresponding aero-elastic model of the turbine under same conditions resulting in a very good match between the model results and the field data. This validation process is key since it confirms the lifetime predictions using the simulation outputs and conclusions can be extrapolated to other wind conditions and other wind turbines.

Romax Technology independently assessed the benefits of IBC on the drive train (namely on the gearbox and main bearing) confirming that IBC extends the life of these components and can prevent many failures observed in the field. Romax also evaluated the impact on the pitch bearings and confirmed no significant difference in lifetimes when using the collective and IBC control methods. Additionally, Romax evaluated the reductions of CAPEX and OPEX costs that IBC would bring on a wind turbine.

1 Introduction

In recent years the size of offshore wind turbines has undergone a considerable step change with many commercial wind turbines now rated at above 6 MW. This increase in rated power comes with an associated increment in loads on the whole wind turbine. Furthermore, the bigger rotors, that are required in these turbines, experience a greater uneven distribution of the wind field over the rotor which, therefore, experiences more unbalanced loads. In addition, onshore wind turbines can experience similar unbalanced rotor loads in extreme wind conditions due to, for example, complex terrain, high shear, high veer or low level jets.

These imbalanced loads which concentrates at the rotor speed (1P) and other multiples of the rotor speed are transmitted to the drive train as off-axis loads that augment misalignments of the gears and shafts and shorten the life of these components.

SgurrControlôs solution to counteract rotor imbalances is achieved by adjusting the pitch of each blade individually in response to measurements of the loads at the root of the blade. Unlike other individual pitch methods that transform the blade loads into hub loads, IBC works locally on each blade. Having a control loop for each blade gives more versatility to tackle specific loads on the wind turbine.

Figure 1 depicts the schematic diagram of IBC. Inside IBC there are three individual controllers, one for each blade which outputs an individual pitch angle (β_1, β_2 *and* β_3). The inputs to each controller is the collective pitch demand and a blade bending moment measurement (M_1, M_2, *and* M_3) (any combination of flap and edgewise bending moment can be used as the input to the controller).

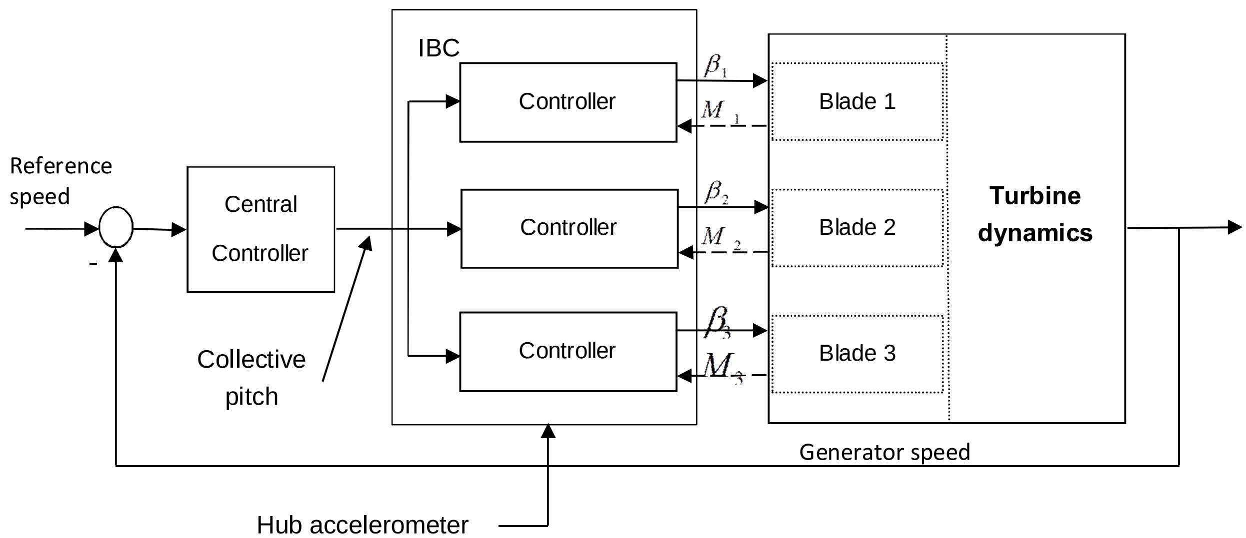


Figure 1: IBC scheme

Fictitious forces are used to decouple the blade dynamics from the dynamics of the rest of the wind turbine [1]. This is achieved by using an accelerometer mounted in the hub. By decoupling the dynamics (blade and turbine), the control model gets simplified in a substantial manner. The simplicity of the model brings benefits in the design by having a direct correspondence between the output sensitivity function and the resulting loads on the blade and also the simpler model ensures the robustness of the design.

IBC is a solution that can be integrated with the OEMsô controller. In this case, IBC will help to reduce the CAPEX costs or it can allow the rotor size to be increased while maintaining the same level of loads and hence decreasing the levelised cost of energy by increasing the energy capture.

It can also be retrofitted on existing wind turbines, since it works independently from the turbine controller. This is the approach followed with the implementation on the Clipper C96 wind turbine.

2 Implementation

Following an extensive research and demonstration of IBC using simulations on different wind turbines in a variety of circumstances [2][3], IBC was implemented and tested on a Clipper C96 wind turbine owned by the University of Minnesota.

2.1 IBC tuning for the C96 wind turbine

IBC can be tuned to target the various nP (n=1,2,3..., P is the rotor rotational speed) spectral peaks on the blade loads. By reducing the 1P out of plane load on the blade, the mean value (0P) of the hub off-axis loads (nodding and the yawing moment on the hub) is reduced. The out of plane fatigue load is dominated by the 1P component and by targeting 1P on the blade the off-axis loads on the drive train are targeted at the same time.

It is worth pointing out that the performance of IBC is also significantly affected by pitch activity. In order to maintain the pitch duty within reasonable values, a trade-off is necessary among various factors, e.g. weighting of control efforts in different wind speed regions and weighting between 1P and 2P control etc. Considering all these factors, the IBC was tuned to focus on 1P control with operation in above rated wind speeds only (see Figure 2)

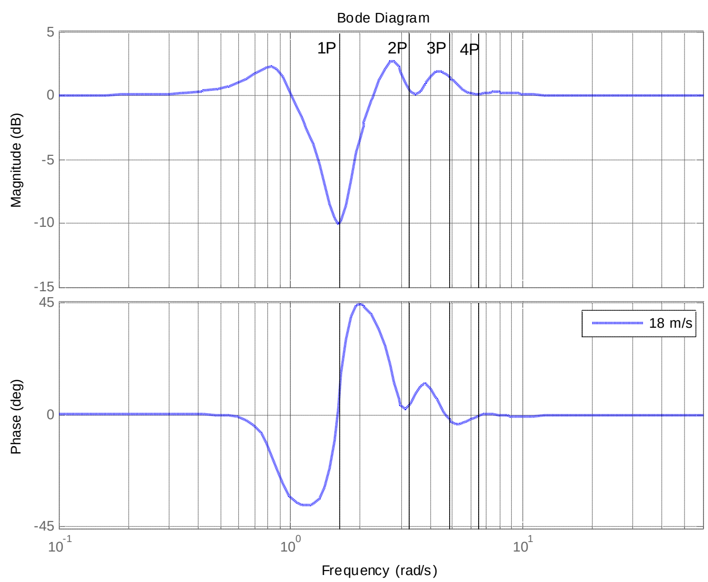


Figure 2 Bode diagram of output sensitivity function

2.2 Implementation

ATLAS™ (the commercial name of IBC) consists of a PLC (Programmable Logic Controller) installed in the hub which intercepts the communication between the turbine controller unit (TCU) and the pitch controller unit (PCU). The PLC receives the measurements from the fibre optic strain gauge system installed on the three blades and the measurements from the accelerometer in the hub. Each control cycle, a new pitch command to the PCU is issued that consists of the collective pitch demand coming from the TCU modified by the IBC algorithm. All the alarms and safety system features of the turbine are kept in place.

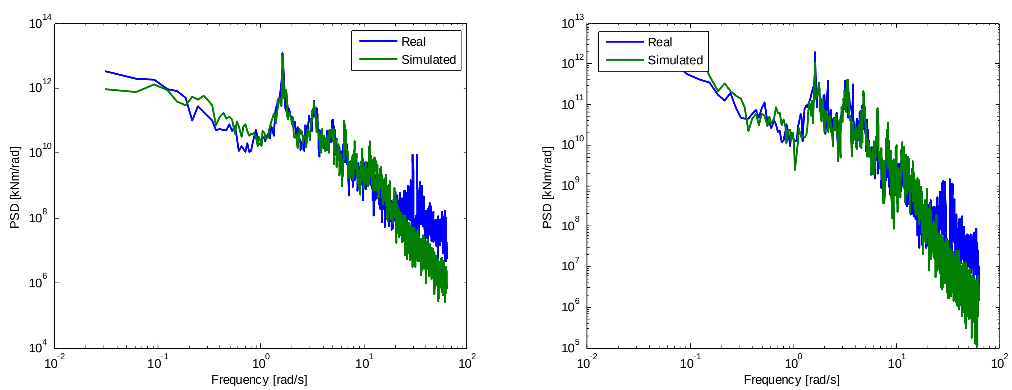
3 Analysis

In order to perform a fair analysis, data were collected in similar wind conditions for both normal collective control (CC) and IBC. To do so, IBC was switched on and off automatically every 11 minutes in order to have 10 minutes of pure collective or IBC data. The data collected was analysed with two main purposes:

1. Validation of the model and the predictions made from it
2. Demonstration of the value of IBC in reducing loads

3.1 Validation

For the first objective, the data collected is compared to the simulated data for similar wind conditions. The data from a met mast near the wind turbine is used to determine the wind speed, turbulence intensity, wind shear and air density to be used in the simulation. Figure 3 shows the spectra of the blade root flapwise bending moment under collective and IBC control. It is clear that there is a good match between the measured and simulated data especially at the frequencies around 1P, 2P and 3P where the IBC is focused.



(a) (b)

Figure 3: Spectra of the blade root flapwise bending moment. a) Collective b) IBC

A good match is also observed in other variables (i.e. generator speed, pitch angle, generated power). A good correlation between the data from the model and the field-test is an important outcome because, under this premise, the data from the full set of simulations, for conditions far beyond those for the data collected, can be used to evaluate the lifetime of the components. To that end, Romax, with the simulated lifetime loads and by using an accurate model of the C96 drive train, assessed the impact of IBC in key components (main bearing and gearbox) over lifetime wind conditions. The conclusions of that analysis are detailed in Section 3.4.

3.2 Blade loads reduction

The comparison of the out-of-plane blade load (the input load to IBC) spectrum of two 10-minute consecutive data with collective pitch and IBC is shown in Figure 4. It can be seen that the 1P component of the bending moment is decreased by IBC without much alteration of other components (2P, 3P, etc.). This can more clearly be observed from the cumulative spectra (dashed lines). This indicates that the variations of the bending moment at the 1P frequency are being effectively reduced which will translate to fatigue load reduction.

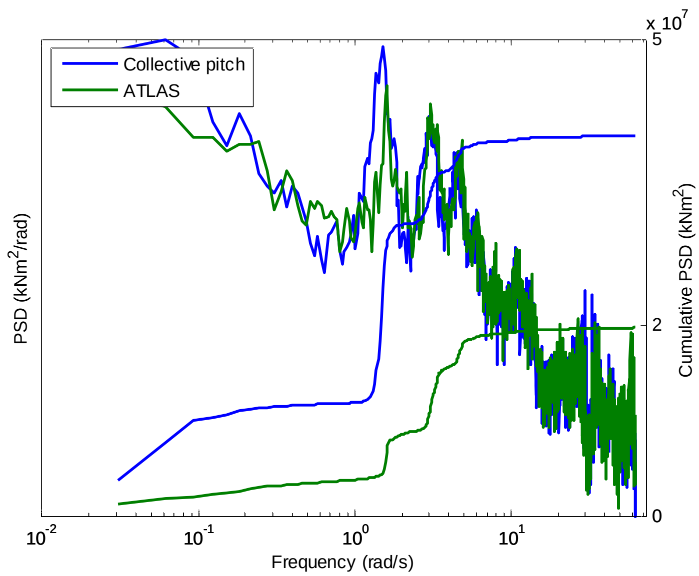


Figure 4: Out-plane blade root bending moment

In addition to the spectral investigation, an analysis aggregating the data in order to eliminate the difference in turbulence intensity, wind shear, yaw error etc. or data that was not collected at the same time is presented in Figure 5. The dots in the graphs represent the damage equivalent fatigue load (DEL) for a set of 10-minute data and the lines represent the average binned by wind speed. The effectiveness of IBC in reducing the DEL in a wide range of wind speeds is clear.

The simulations carried out following the IEC-61400 standard yields a reduction in the out of plane lifetime DEL by 10 %. This percentage depends on the size of the wind turbine and the wind conditions. Previous analysis by SgurrControl [2] demonstrate that for a larger 5 MW offshore wind turbine the blade load reduction will exceed 20 %. A further study has also proven significant benefits on the loads when IBC is applied to wind turbines in adverse wind conditions such as low level jets or extreme wind shear [3].

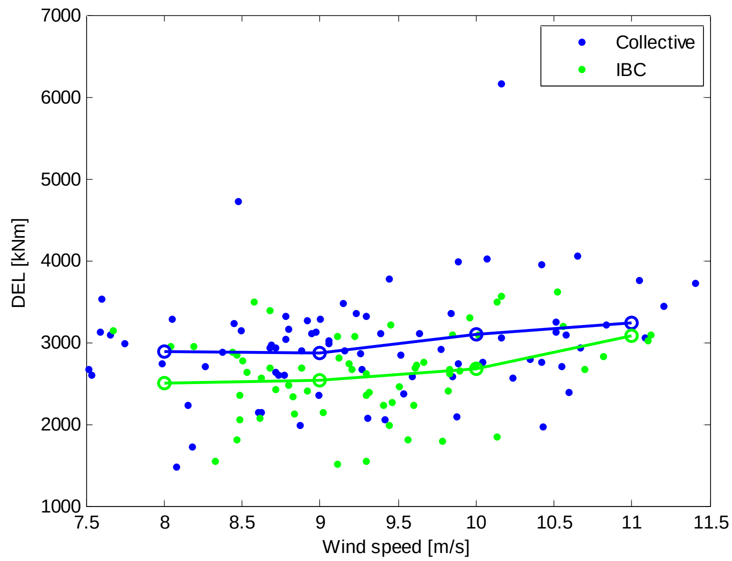


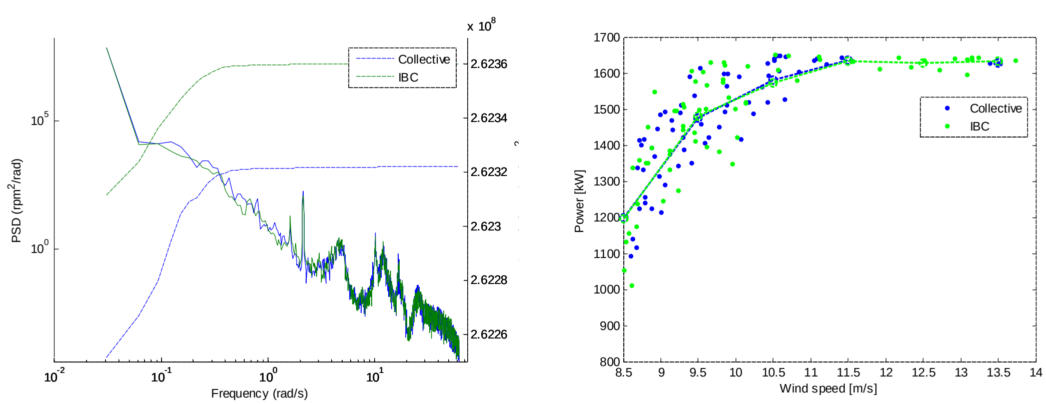
Figure 5: Damage equivalent load for blade out-of-plane bending moment.

3.3 Impact on the wind turbine controller

IBC is designed as an addition to the turbine controller, which is in charge of regulating the speed and power and as such IBC should not interfere with it. It is important to validate this aspect as well.

a) shows the PSD of the generator speed with the data collected with collective pitch and IBC under similar wind conditions. Both spectra match up well which shows that IBC does not interfere with the speed control.

The other key point regarding how IBC could influence the performance of the main controller is the energy capture. The main objective of IBC is reducing loads and therefore the energy capture should not be altered. b) depicts the power curve obtained with collective pitch and IBC. The variation in the power curves with the two methods is negligible.



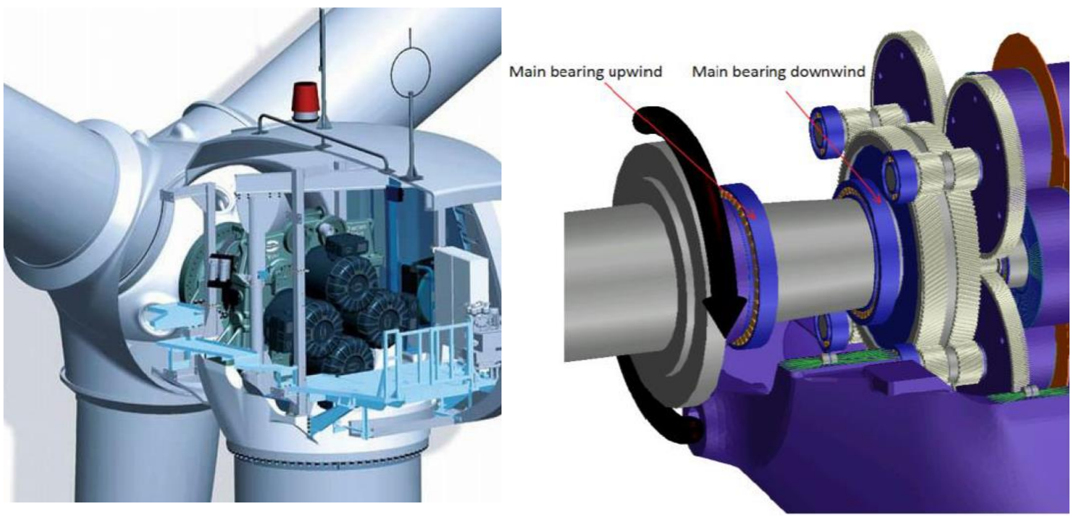
(a) (b)

Figure 6: Comparison Collective vs IBC: a) Generator speed PSD b) Power curve

3.4 Influence on the lifetime of key components

The analysis of the impact of key components on the wind turbine was carried independently by Romax. They developed in their RomaxWIND software [4], a comprehensive model of the drive train which includes the gearbox and the main bearing (Figure 7 b). The assessment was carried out following the implementation of the ISO standards for gears and bearings [5][6] in RomaxWIND.

Additionally Romax developed a model of the pitch bearing to evaluate the influence of IBC on the pitch bearings.



(a) (b)

Figure 7: a) View of the C96 drive train b) RomaxWIND model of drive train

3.4.1 Drive train analysis

The C96 has an unusual gearbox (Figure 7a). The input torque is divided into four outputs that feed four independent generators. Because of this configuration, the gearbox is very sensitive to the input driving torque which produces large misalignments that dominates the life of the gearbox and prevents the gearbox meeting safety factors that warranty a life of 20 years. Therefore, in order to exploit the full capability of IBC a mild derating to 2.3 MW was implemented to allow the IBC system to have a much greater benefit to the life of the gearbox. Table 1 gathers, for the different configurations, the improvement in the minimum safety factors for the gears in the gearbox with respect to the original configuration. It is quite clear that IBC manages to significantly increase the life of the gearbox and conversely derating on its own does not significantly reduce the damage on this component.

Table 1: Power generating gear flank improvement in lowest safety factors (%)

Control strategy	2.5 MW	2.3 MW
Collective	-	3
IBC	6	13

3.4.2 Main Bearing

The analysis on the main bearing is summarised in Table 2. It shows the damage predicted by using directionally standardised binning. It is confirmed that the addition of IBC decreases the damage and thus extends the life of the main bearing, and in turbines where the raceway fatigue life is an issue, IBC is a way of significantly improving a turbine's lifetime.

Table 2: Main bearing damage relative to the original configuration (%) assessed by ISO281:16281

Control strategy	Upwind bearing		Downwind bearing	
	2.5 MW	2.3 MW	2.5 MW	2.3 MW
Collective	-	91	-	83
IBC	87	73	99	69

A key fact to point out is that the bearing raceway is assessed in detail but its failure is rarely observed in the field and actually the key potential of IBC is avoiding other failure modes seen in the field, for example edge load failure, cage failure and cage debris related failures. These field failure modes have some circumstantial evidence of common causality, in relation to operation with high levels of misalignment experienced during high instantaneous conditions during normal operation of the turbine. SgurrControl also implemented a specific strategy to counteract these highest peak loads. This strategy was found to give significant reductions in the instantaneous stress arising in the main bearings, and Romax confirmed that these will be beneficial for these failures which are observed in the field.

3.4.3 Pitch bearings impact

One key aspect that has previously casted doubts on any kind of Individual Pitch Control (IPC) strategy is the impact on the pitch bearings. Blade loads reduction and increase in pitch activity are intimately related although the relationship between these two opposite objectives is not linear and, as usually happens in control, a trade-off has to be found between both. Unlike other IPC methods, IBC has much more flexibility to shape the controller to balance the blade load reduction and the increase pitch activity. In that respect, the IBC tuning has limited the increase in lifetime pitch activity (Figure 8).

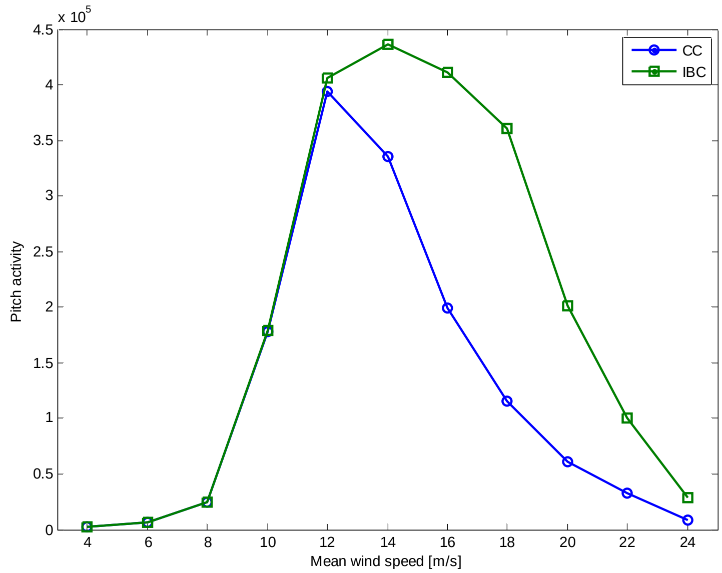


Figure 8: Pitch activity distribution

The analysis Romax performed following the NREL DG03 method suggested that there was little difference between the IBC and collective control schemes with regards to pitch bearing life and that both methods result in approximately the same damage and life.

In both cases the majority of the oscillations are below the dither amplitude (0.17°) and are not accounted for in the NREL DG03 methodology. Only a slight increase in the overall number of oscillations is observed between IBC and collective pitch.

The magnitude of the results predicted by the NREL method appear to be unrealistically low. Therefore, in addition to the NREL method calculation, a study into the load cycle was also made by Romax. The mean loads per oscillation on the blades were shown to be similar under both control strategies. However, the peak force and moment loading could be seen to be lower for the IBC case. This should provide fatigue benefits but will not show up in a fatigue rating. The results of this additional analysis also implied that the pitch bearing is not adversely affected by the IBC strategy.

3.4.4 CAPEX and OPEX Reduction

Romax also explored how much a turbine would benefit if IBC was incorporated in a standard 3MW turbine design in terms of CAPEX reduction. The NREL turbine design and cost scaling model was employed to comparatively assess the turbine CAPEX. This method was used in its standard form for the turbine with collective control and a modified model derived taking into account the loads reductions when IBC control is used. The comparative CAPEX assessment highlighted potential component cost reductions up to 5% if IBC was employed at the beginning of turbine design.

To assess the potential OPEX benefits a scenario based methodology was employed. In this scenario it is explored from an operational perspective, in terms of turbine downtime, weather windows, and lost energy capture if there is main bearing failure during the winter months that IBC could prevent. During winter months the loads and energy capture are normally the highest and also is the highest capacity factor (between 0.4 and 0.6). In the worst case scenario, with the failure at the beginning of the winter and without being able to replace the damaged component, the economic loss could reach up to £500k. In turn, IBC could protect the main bearing and allow it to operate through winter until a replacement could be installed saving that amount of money

4 Conclusions

Individual Blade Control, SgurrControlôs solution to reduce loads and extend life of wind turbines was demonstrated in a Clipper C96 2.5 MW. The analysis of the data collected on site confirms the expected reduction in blade loads. The model and methods were validated using the data from the wind turbine and a near met mast and the aero-elastic model.

Romax, as an independent third party, assessed how the reduction in loads would affect key components in the wind turbine. In that respect, it can be confirmed that IBC will extend the life of the gearbox that otherwise will not reach the 20 years expected life in this case. IBC will also reduce the damage in the raceway of the main bearing caused by fatigue loads, but more importantly it will help to prevent other main bearing failures modes that are more likely to occur in the field.

The main outcome from the analysis on the pitch bearing is that the use of IBC will not have a negative impact on this component. It is worth pointing out that special care was taken when tuning IBC to have a moderate increase of pitch activity and this is more difficult to achieve with other IPC methods.

The investigation on how the integration of IBC in the design of a new wind turbine reveals that up to 5 % reduction of the CAPEX costs can be achieved. For multi-MW offshore wind turbines it is expected a higher value since bigger loads reductions will be reached with the use of IBC.

IBC has also the potential to reduce OPEX costs by preventing damage and failures of certain components which would entail a downtime period and loss of energy capture.

5 References

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