Tailoring the Employment of Offshore Wind Turbine Support Structure Load Mitigation Controllers

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Abstract. The currently available control concepts to mitigate aerodynamic and hydrodynamic induced support structure loads reduce either fore-aft or side-to-side damage under certain operational conditions. The load reduction is achieved together with an increase in loads in other components of the turbine e.g. pitch actuators or drive train, increasing the risk of unscheduled maintenance. The main objective of this paper is to demonstrate a methodology for reduction of support structure damage equivalent loads (DEL) in fore-aft and side-to-side directions using already available control concepts. A multi-objective optimization problem is formulated to minimize the DELs, while limiting the collateral effects of the control algorithms for load reduction. The optimization gives trigger values of sea state condition for the activation or deactivation of certain control concepts. As a result, by accepting the consumption of a small fraction of the load reserve in the design load envelope of other turbine components, a considerable reduction of the support structure loads is facilitated.

1. Introduction
The offshore wind turbine support structures are subjected to both aerodynamic and hydrodynamic induced load resulting in fatigue loads, in both fore-aft and side-to-side direction. Moreover, the support structures account approximately one fifth of the total wind farm capital cost without considering installation cost [1]. Various operational wind turbine control concepts [2][3][4][5][6] are capable of effectively reducing aerodynamic or hydrodynamic induced support structure fatigue loads, and are operating well in certain operational ranges. Although such control concepts are capable of load reduction, they often lead to higher loads in some other wind turbine components. This could result in reduced wind turbine lifetime and increased unscheduled maintenance. Fischer [7] analysed, at least qualitatively, the relation of loads reduced at the tower fore-aft and side-to-side directions and the collateral effects in the other turbine components using different operational controls. He also proposed to employ certain control concepts at particular loading and operational conditions.

So far only a limited number of papers consider control algorithms for load reduction while limiting the collateral effects in a more rational manner, for example [8]. The objective of this paper is to present a methodology to define a trade-off among different available operational control concepts, in order to reduce the support structure fatigue loads while limiting the increase in load in other turbine parts. A multi-objective optimization introduced in [9] is performed for a selection of the ‘most effective controller’ for each possible sea state conditions. The selection of a controller will depend on trigger values of environmental conditions, and the demonstration of the implementation of the control concepts is presented with simple on and off switching. The implementation of the concept in the real turbine will require smooth transition between the activation and deactivation of a controller. Also, the event trigger
control approach is already being used for wind turbine control sector e.g. [10] and [11]. However, this paper highlights the trade-off methodology showing how the proposed concept could be used to achieve the maximum possible support structure load reduction conditional on a prescribed level of additional collateral effects.

2. Methodology
The objective of this paper is to present the methodology for tailoring the employment of different operational control concepts demonstrated in Fig. 1. For a given sea state, an 'optimal control concept' is selected and it is activated as long as the control concept is effective. Both ambient conditions and turbine load responses are continuously monitored to decide if the implemented control concept is still the most effective one. The selection of the control concept depends on the result from a multi-objective optimization performed to minimize the support structure loads with a constraint in collateral effects. These collateral effects are the negative side effects, i.e. increase in load in the other components of the turbine, when activating the control concepts. Depending on the design load envelope, an acceptable increase in loads in the other parts of the turbine as a trade-off for the support structure load reduction is selected. The optimization uses a database of the simulated loads and the collateral effects caused by the control algorithms.

This section further explains the steps followed for the selection of the 'most effective' control concept shown in Fig. 2. For the current research, NREL 5 MW offshore reference turbine [12] is used which is mounted atop of a monopile foundation in 25 m water depth (MSL). The research turbine is a three-bladed, variable-speed and pitch controlled design with 126 m rotor diameter.

2.1. Operational control concepts and collateral effects
To demonstrate the tailoring methodology, two different support structure load reduction control concepts are selected: tower fore-aft controller (TFA) for fore-aft load reduction and active generator torque controller (AGT) for side-to-side load reduction. A selection of either none, one or both of these control concepts in addition to the baseline controller (BLC) is possible as shown in Fig. 3.

The BLC is based on [12] with the correction of gain scheduling according to [13]. The power
production operation employs the generator-torque controller to maximize the power in the below-rated region and the blade-pitch controller to regulate generator speed in the rated power region. With TFA, based on the UpWind controller [14], the aerodynamic damping is enhanced to reduce the tower fore-aft response with an additional pitch angle superimposed to the value provided by BLC. This additional pitch angle is proportional to the tower fore-aft velocity, which is derived by integrating the acceleration measurement. The reduction in the tower load comes with side effects such as increase in pitch activity and power fluctuation [7]. Similarly, AGT uses the tower side-to-side acceleration to determine an additional tower side-to-side damping torque and is superimposed to the generator torque provided by the BLC. The side effect of implementing AGT are higher load fluctuations in drive train and power electronics [7]. Quantifying the load reduction at a particular hot spot is straight forward but the evaluation and the judgement of the various collateral effects inside the whole turbine system is a complex task. The collateral effects of each concept could be quite different, both in magnitude and the place where they occur within the turbine system, even when different control concepts are used to reduce the same load [7]. Hence, in the scope of this paper, one collateral effect is considered for each operational control concept. The pitch control and generator torque are used as cost parameters when selecting controllers for tower fore-aft load damping and active drive train damping, respectively [7][11]. The pitch activity is represented by the pitch Actuator Duty Cycle (ADC) [15] given by:

\[
ADC_n = \sum_{n} \left( \int_{0}^{T} \frac{\dot{\beta}(t,n)}{\dot{\beta}_{norm}} \, dt \right) ; \quad \dot{\beta}_{norm} = \begin{cases} \dot{\beta}_{max}, & \dot{\beta}(t,n) \geq 0 \\ \dot{\beta}_{min}, & \dot{\beta}(t,n) < 0 \end{cases}
\]

where,
- \( n \) : sea state of duration \( T \)
- \( \dot{\beta} \) : time series of the blade pitch rate [deg/s]
- \( \dot{\beta}_{norm} \) : the maximum or the minimum allowable pitch rate [deg/s]

The increased drive train activity is represented by the standard deviation of generator torque (std GT).

2.2. Simplified model for load and collateral effect

In order to perform the optimization, it is important to quantify the load reduced and the collateral effect induced by the implementation of each control concept for each possible sea state. But performing
simulation for all possible sea states would highly increase the computational time. Therefore, for the 
current research, hydro-servo-aeroelastic simulation is performed for a lower number of lumped sea 
states. With the quantification of the damage equivalent load (DEL) and the collateral effects, ADC and 
std GT, for all the possible combination of control concepts, a simplified model for load and collateral 
effects is generated, from which specific values for any possible sea state could be interpolated.

2.2.1. Environmental conditions:

The database with 3 hour average sea state conditions for the period of 22 years from K13 met-mast 
located in the Dutch North Sea at 25 m water depth (MSL) [16] is used. The aerodynamic damping during 
the power production mode is acting only in the fore-aft direction, resulting in high side-to-side loading 
due to high hydrodynamic excitation when the wind and wave are misaligned. This could be sensitive 
for the relatively soft monopile support structure at deep water locations. According to [7][17], the 
loading on the monopile at the seabed can be maximal in the fore-aft direction for up to 30° wind-wave 
misalignment, while higher loads can occur in the sideways direction for larger misalignments. Because 
of this effect, sea states with different wind-wave misalignment are considered with the direction bin 
of 45°. Further, the misalignment groups from opposite directions are merged together. For the load 
simulations, wind is considered to be always coming from the North. Fig. 4 shows the considered wind-
wave misalignment groups (δ): 0°, 45°, 90° and 135°.

The load simulations are performed for each wind speed (V) bin of 2 m/s and wind wave-
misalignment (δ) bin of 45° with three to four different wave heights (Hs) and wave periods (Tp), 
calculated by sea state lumping [17]. The criteria selected for lumping was to have similar probability 
of occurrence for each lumped Hs case and also similar damage where, \( damage \propto (H_s)^m \), where \( m = 4 \) is the inverse slope of S-N curve. The Tp values could have been further lumped in a similar manner. 
However to reduce the complexity and number of sea states, only one Tp is lumped for each Hs group. 
Hence the long-term environmental conditions are modelled by lumped sea states each with certain V, δ 
and Hs values.

2.2.2. Load simulation and derivation of a simplified load model:

The hydro-servo-aeroelastic simulations are performed using GH Bladed v4.4 [18] with 3D turbulent 
wind field with a Kaimal model and irregular sea states according to the Pierson-Moskowitz spectrum. 
Design Load Case 1.2 according to IEC 64100-3 [19] is selected to analyse fatigue loads during the 
power production i.e. wind speed ranging from 4 m/s to 24 m/s with 2 m/s bins. The damage equivalent 
loads of the bending moment in fore-aft direction (DEL(TM_y)), side-to-side direction (DEL(TM_x)) and 
the resultant load (DEL(TM_xy)) at the mudline location are calculated using the rainflow cycle counting 
method, considering a reference cycle number of 2E7 for 20 years lifetime and an inverse S-N-slope of 
4, typical for steel.

From the three to four simulated lumped sea states for each combination of V, δ and controller 
concept c, one simplified model is derived. It provides the DEL and collateral effects as a continuous 
function of Hs with stepwise constant slope (see Fig. 5). These simplified models are later utilized 
during the optimization run in order to determine the range of Hs where a certain control concept will be 
activated.

2.3. Multi-objective optimization

The selection of the ‘most effective’ control concept for the given sea state condition is a result of 
a multi-objective optimization. The methodology is introduced in [9], demonstrating the possibility 
to significantly reduce the target load, while limiting the collateral effects. It is also shown that the 
optimization performed considering actual sea states yields higher load reduction with significantly lower 
increase of the collateral effects, compared to the load reduced when the control concept is activated for 
a certain percentage of time irrespective of the actual sea states.
Therefore, for the current research, optimization is performed with a time series of three hours averaged values of the operational wind speed $V$ in the range of 4 - 24 m/s with 2 m/s bin, wind-wave misalignment $\delta$ with 45° bin and wave height $H_s$ bin of 0.1 m. Let us now consider $n$ as the total number of subsequent sea states during a time series of e.g. one or 20 years duration. The probability of occurrence, $p$, of a sea state is calculated from the probability distribution for $H_s$ and each pair of $V$ and $\delta$. The corresponding DELs and collateral effects (ADC and std GT) for each available control concept for the given $n$ sea states are calculated from the simplified model (Section 2.2).

In order to consider both tower fore-aft and side-to-side loads simultaneously, the optimization is performed to reduce the resultant DEL($TM_{xy}$) given by:

$$DEL(TM_{xy}) = \sqrt{\sum_c \sum_n p_n \cdot q_{c,n} \cdot DEL(TM_{xy})_{c,n}^m}$$

where, $m$: inverse slope of S-N curve (here 4, typical for steel)
$\sum_c \sum_n$: probability of occurrence of a particular sea state $n$
$q_{c,n}$: the flag for selection of control concept $c$ and sea state $n$

As presented in Section 2.1, there are four possible controller options to select: 1) BLC only, 2) BLC with TFA, 3) BLC with AGT or 4) all three controllers (TFA1AGT1). Therefore, the variables for optimization, $q_{c,n}$, are the flags for activating any of the given four controller options. They are given as the four vectors of size [1 x n] (example: $q_{BLC} = [q_{BLC,1} \ q_{BLC,2} \ ... \ q_{BLC,n}]$, for $n$ sea states). A constraint condition of the four $q_c$ vectors is introduced to ensure that for each sea state $n$ only one and exactly one controller concept is selected i.e. $\sum_c q_{c,n} = 1$ for each sea state $n$ where $q_{c,n} \in \{0, 1\}$.

The objective of the multi-objective optimization is to minimize the DEL while accepting certain level of collateral effect. Thus, the maximum allowable ADC and std GT values are defined with a constraint factor, $C_{ADC}$ and $C_{std \ GT}$ respectively, expressed as percentage of the possible increase of collateral effect when both tower dampers are fully active all time with respect to the situation when only BLC is used. For instance, a value of $C_{ADC} = 0.5$ means that the maximum load reduction is search made with the constraint that ADC should not exceed 50 % of the additional ADC when all three controllers (TFA1AGT1) would be operating continuously. During the optimization and also as the result of it, the
actual ADC, denoted as $ADC_{\text{final}}$ can be lower than the maximum allowed value $ADC_{\text{max}}$. Such as:

$$ADC_{BLC} \leq ADC_{\text{final}} \leq ADC_{\text{max}}$$

$$\text{std } GT_{BLC} \leq \text{std } GT_{\text{final}} \leq \text{std } GT_{\text{max}}$$

Therefore the final and the maximum ADC and std GT respectively are calculated as follows:

$$ADC_{\text{final}} = \sum_{c}^{n}(p_{n} \cdot q_{c,n} \cdot ADC_{c,n}); \text{ std } GT_{\text{final}} = \sum_{c}^{n}(p_{n} \cdot q_{c,n} \cdot \text{std } GT_{c,n})$$

$$ADC_{\text{max}} = \sum(ADC_{BLC,n} + C_{ADC} (ADC_{TFA1AGT1,n} - ADC_{BLC,n}))$$

$$\text{std } GT_{\text{max}} = \sum(\text{std } GT_{BLC,n} + C_{STD} \text{ GT} (\text{std } GT_{TFA1AGT1,n} - \text{std } GT_{BLC,n}))$$

where, $p_{n}$ : probability of occurrence of a particular sea state $n$

$C_{ADC}$ and $C_{\text{std } GT}$ : constraint factors, $0 \leq C_{ADC} \leq 1$ and $0 \leq C_{\text{std } GT} \leq 1$

$ADC_{c,n}$ and $\text{std } GT_{c,n}$: ADC and std GT when controller $c$ is activated for the sea state $n$

Therefore, the optimization equation is formulated as: for the given $C_{ADC}$ and $C_{\text{std } GT}$, find the four vectors $q_{c}$ which minimize $\text{DEL}(TM_{xy})$ subject to the constraints $ADC_{BLC} \leq ADC_{\text{final}} \leq ADC_{\text{max}}$ and $\text{std } GT_{BLC} \leq \text{std } GT_{\text{final}} \leq \text{std } GT_{\text{max}}$, $q_{c}$ is either 0 or 1 and $\sum q_{c,n} = 1$.

The optimization will select the control concept that result in a minimum load and that satisfy the constraint in maximum allowable values for ADC and std GT. The optimization results in trigger values of wave height $H_{s\text{ trigger},V,\delta}$ corresponding to the activation of one control concept or the other for a certain wind speed $V$ and wind-wave misalignment $\delta$.

In order to demonstrate this, the optimization result for $C_{ADC}$ and $C_{\text{std } GT} = 50 \%$ filtered for $V = 4$ m/s and $\delta = 45^\circ$ is plotted in Fig. 5. The plain coloured lines in Fig. 5a illustrate the simplified load model for $\text{DEL}(TM_{xy})$ against the $H_{s}$ on the x-axis with different colour representing different controller options. The resultant values of $\text{DEL}(TM_{xy})$ from the optimization is presented with a marked line. The dotted vertical lines are inserted to mark the trigger values of $H_{s\text{ trigger},V,\delta}$ where the selection of the control option from the optimization is changed. Fig. 5b and 5c illustrate the same information for ADC and std GT.

For smaller values of $H_{s}$, only BLC is operating until the first $H_{s\text{ trigger},4m/s,45^\circ} = 1.3$ m is reached. In this region, no reduction in DEL is performed which means that the constraint on the collateral effect is being considered. For higher $H_{s}$ values, TFA is activated. The DEL is reduced along with the increase in ADC (Fig. 5b) whereas the std GT is even reduced (Fig. 5c). This also highlights that the activation of an operational controller has an effect in more than one part of the turbine. Finally, beyond $H_{s\text{ trigger},4m/s,45^\circ} = 5.2$ m, the TFA controller is switched off and AGT is activated. The resulting load in this section (see Fig. 5a) is minimum and there is penalty only on std GT and not on ADC.

Therefore, the optimization minimizes the $\text{DEL}(TM_{xy})$ by using such a combination of control algorithms that satisfy the given overall limit on the collateral effects.

3. Results

Next we are presenting the optimization results and the demonstration of the optimized control concept for the time series of the environmental condition from the K13 data, minimizing the $\text{DEL}(TM_{xy})$ while constraining the collateral effects.

The cost function $\text{DEL}(TM_{xy})$ and the collateral effects for different values of constraint factors is presented in Fig. 6, with values of $C_{ADC}$ in x-axis and $C_{\text{std } GT}$ in y-axis. Each of the contour plots demonstrate the relative change for the variables when considering BLC as the lower reference and TFA1AGT1 as the higher reference. The contour lines represent the relative change resulting from the optimizations with different constraint factors. For example, in Fig. 6a, for $C_{ADC} = 0.1$ and $C_{\text{std } GT} = 0.25$,
the optimization finds a certain combination of controller activation for the seas states that keeps the collateral effects within the desired limits. However, this results in a lower load reduction than the maximally achievable with all the controllers active (TFA1AGT1), i.e. 80% of maximum achievable load reduction is obtained. Note that load reduction is expressed as percentage of the load reduction when all the controllers are active (TFA1AGT1) with respect to the baseline (BLC) case. The objective of this paper is to demonstrate the trade-off analysis using different controllers rather than optimizing the controllers itself. Therefore, the magnitude of actual load reduction achieved by certain controllers in this paper is only indicative.

The corresponding relative decrease in the fore-aft and side-to-side load is presented in Fig. 6b and 6c, respectively. The final two plots, Fig. 6d and 6e, show the increase in the ADC and std GT, respectively for different constraint factors.

The proposed operational control as a function of time is demonstrated in Fig. 7. The first three plots from the top include the environmental conditions, namely wind speed ($V$), wind-wave misalignment ($\delta$) and wave height ($H_s$) taken from 18 subsequent sea state situations of K13 measurement data [16] from the year 2000. The next sub-plot marks the control concepts selected from the optimization for the corresponding sea states. The coloured lines in the plot of DEL(TM$_{xy}$) are the loads for the corresponding sea states with different colour representing different control concepts. The last two plots represent the penalty on ADC and std GT when activating different controllers. The dotted points in the last three plots are the resultant DEL(TM$_{xy}$) and the collateral effects due to the tailored controller selection. The controller selection is result from the optimization performed to minimize DEL(TM$_{xy}$) with $C_{ADC}$ and

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**Figure 6.** Effect of different $C_{ADC}$ and $C_{std \ GT}$ in optimization presented as the relative change in a) DEL(TM$_{xy}$), b) DEL(TM$_y$), c) DEL(TM$_x$), d) ADC and e) std GT compared to the possible reduction when implementing TFA1AGT1 with respect to the reference control concept, BLC.
Figure 7. Optimization result to minimize DEL(TM_{xy}) with constraint factors C_{ADC} and C_{std GT} of 10% for the sea states represented by a) wind speed, b) wind-wave misalignment, c) significant wave height. d) The control options selected by optimization. The corresponding e) DEL(TM_{xy}), f) ADC and g) std GT for different control options are plotted in coloured lines with the tailored values as the dotted lines.

C_{std GT} of 10%. While the absolute reduction of DEL(TM_{xy}) in this plot is only moderate, the plots demonstrate the successful tailoring of the control concept when being applied in measured time series events.

4. Discussion

The result of the methodology presented in the paper is discussed in this section. A multi-objective optimization is performed to tailor the implementation of different control concepts for support structure load reduction while limiting the collateral effects in other wind turbine components.

The optimization result in Fig. 5 for V = 4 m/s and δ = 45° with C_{ADC} and C_{std GT} = 50%, illustrates how different sea state trigger values could be derived for different control options.

With relatively small collateral effects, a significant load reduction is achievable. For example, in the contour plot in Fig. 6a, the relative decrease in DEL(TM_{xy}) is presented with tailoring performed for different constraint factors. For small collateral effects, say C_{ADC} and C_{std GT} = 0.25, the relative decrease in DEL(TM_{xy}) reaches approx. 85% of the maximal achievable load reduction.

However, the highest load reduction is achieved only with a combination of all controllers. For instance, if the constraint for AGT is kept constant for C_{std GT} < 1, relaxing the constraint for TFA (i.e. increasing C_{ADC} from 0 to 1) will achieve load reduction only up to a certain level. After reaching this level, additional TFA control actions will not lead to significant further load reduction. As an example, we take C_{std GT} = 0.25 as fixed. As seen in Fig. 6a, increasing TFA activity leads to load reduction only up to C_{ADC}=0.4, and further load reduction is not possible without enabling more activity from AGT. Similar behaviour occurs when C_{ADC} is fixed. AGT can achieve load reduction only up to a certain level, and no further load reduction is possible without increasing TFA activity.

The corresponding relative decrease in DEL(TM_{x}), in Fig. 6b, has a similar pattern to that of the DEL(TM_{xy}) (Fig. 6a). The DEL(TM_{x}) is normally higher compared to the DEL(TM_{xy}) which also means that there is more room to reduce the load by the optimization. Therefore, we can say that DEL(TM_{x}) is the main driver during the optimization for this particular design and site.
The effect of optimization for different constraint factors on the side-to-side tower load, DEL(TM\(x\)), is presented in Fig. 6c. The bending moment DEL(TM\(x\)) is mainly influenced by AGT, therefore, significant reduction of DEL(TM\(x\)) can be achieved even with a moderate increase in ADC, i.e. for a small \(C_{ADC}\). However, load reduction does not always increase with the increase in constraint factors. For example, if \(C_{ADC} = 0.2\) and \(C_{std\ GT} = 0.3\), the reduction in DEL(TM\(x\)) is approx. 20 %. If both constraint factors are increased to 0.4, hardly any additional load reduction is achieved. But due to this increase in the constraint factors, the reduction of DEL(TM\(y\)) (in Fig. 6b) improves from approx. 85 % to more than 90 %. Here, the tailoring of the controller is performed by optimization to find the combinations where the minimum load is achieved for the given constraint.

The constraints for the optimization is limiting the ADC and std GT values as presented in Fig. 6d and Fig. 6e, respectively. However, the maximum allowable value for a constraint parameter will not be reached by relaxing the constraint factor for that parameter only unless a certain value of constraint factor is provided for the other constraint parameter. For example, if we consider \(C_{ADC} = 0.4\), the ADC value is not saturated to 40 % until the \(C_{std\ GT}\) is 0.25. But after reaching this level, the ADC will remain the same even when the \(C_{std\ GT}\) relaxed. Meanwhile, for the same scenario in Fig. 6e, when \(C_{ADC}\) is fixed to 0.4, the increase in \(C_{std\ GT}\) will increase the std GT. But now, if we check the corresponding fore-aft and side-to-side load reduction in Fig. 6b and 6c, the DEL(TM\(x\)) reduction is almost saturated while further decrease in DEL(TM\(y\)) is achieved when \(C_{std\ GT}\) is increased above 0.25.

Moreover, the large darker area in Fig. 6a illustrates that for high constraint factors, the relative decrease in DEL(TM\(y\)) is insignificant i.e. there is negligible decrease in load for higher collateral effects while still a significant load reduction is possible for lower penalties. For the considered control concepts, if there is enough reserve in the design load envelope giving freedom to increase both constraint factors, one can select the operating point for the optimization. Relatively high decrease in DEL(TM\(x\)) and DEL(TM\(y\)), for example 90 %, could be achieved by around 30 % increase in \(C_{ADC}\) and \(C_{std\ GT}\). However, the corresponding decrease in side-to-side load reduction would be only 20 %. In case lower sideways load is necessary and if higher torque activity (i.e. higher \(C_{std\ GT}\)) is possible, then relatively small \(C_{ADC}\) with high value of \(C_{std\ GT}\) can be selected.

This means that there are two factors that need to be considered to effectively reduce the load. One is to find the acceptable increase in loads in other wind turbine components which will depend on the design load envelope of the considered parameters. The other factor is to find out the optimal combination of the constraint factors.

In Fig. 7, the implementation of this operational control concept is demonstrated for a continuous sea state history taken from measurement data. Depending on the sea state, and with the trigger values, \(H_t\, trigger\, V, \delta\) - selection of the controllers can be performed. For example, in the region between the two vertical lines in the figure, wind is changing between 6 m/s and 12 m/s, with varying wind-wave misalignment and the wave height decreasing from approx. 2.5 m to 1 m. For the sea state index 8 (\(V = 12\; m/s, \delta = 0^\circ\) and \(H_t = 2.3\; m\)), all controllers are active. But from the sea state index 9 (\(V = 10\; m/s, \delta = 45^\circ\) and \(H_t = 2\; m\)), the TFA and AGT controllers are deactivated resulting in the operation of only BLC. In case of activating TFA1AGT1 option for both index 8 and 9, the ADC value would be doubled. This shows how the controller selection changes depending on the sea state and the corresponding load and collateral effects.

The transition among different control concepts is not considered in this paper. When applying this tailoring control concepts in the real turbine, smooth transition between activation and deactivation of a controller has to be performed such that the phase in and out of the controllers is performed. One example to perform the smooth transition could be to replace the control concept activation flag (in Fig. 3) by a variable, acting as a gain, that gradually increases or decreases between 0 and 1 for activation or deactivation of the control concept, respectively.
5. Conclusion
The methodology presented for tailoring the implementation of different operational control concepts can make the most out of different controllers, reducing considerable DEL for relatively small increase in the collateral effects. The smart selection of the constraint factors is essential to achieve an effective load reduction with the minimum possible penalties. With spending a small penalty from the load reserve in the other components of a turbine, considerable decrease in the support structure load is possible.

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