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"Integrated Wind Turbine Design"

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Abstract: This document presents a state-of-the-art supervisory controller and load calculation for the UPWIND 5MW reference turbine with Individual Pitch Controller.

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PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

This report presents a state-of-the-art supervisory control design for the UPWIND 5MW reference turbine. A detailed description of the wind turbine model and power production controller can be found in [1]. The main principles of the controller are based on previous work [2], [3].

Individual pitch control (IPC) is very effective in reducing fatigue loads thanks to the different movement of the blades. Especially in turbulent wind conditions blades can assume quite different pitch angles and a drawback of this might come when shutdowns are triggered because if the shutdown is carried out with the blades set to different pitch angles rotor asymmetric loads might be higher than with a collective pitch controller. A particularly demanding case is for example the emergency shutdown, when the safety system is triggered and blades are pitched towards feather at the same rate starting from different angles.

Pitch faults might be difficult to detect as well. The present document assesses the supervisory control design for IPC and load analysis is carried out to compare the results with a collective pitch controller (CPC).

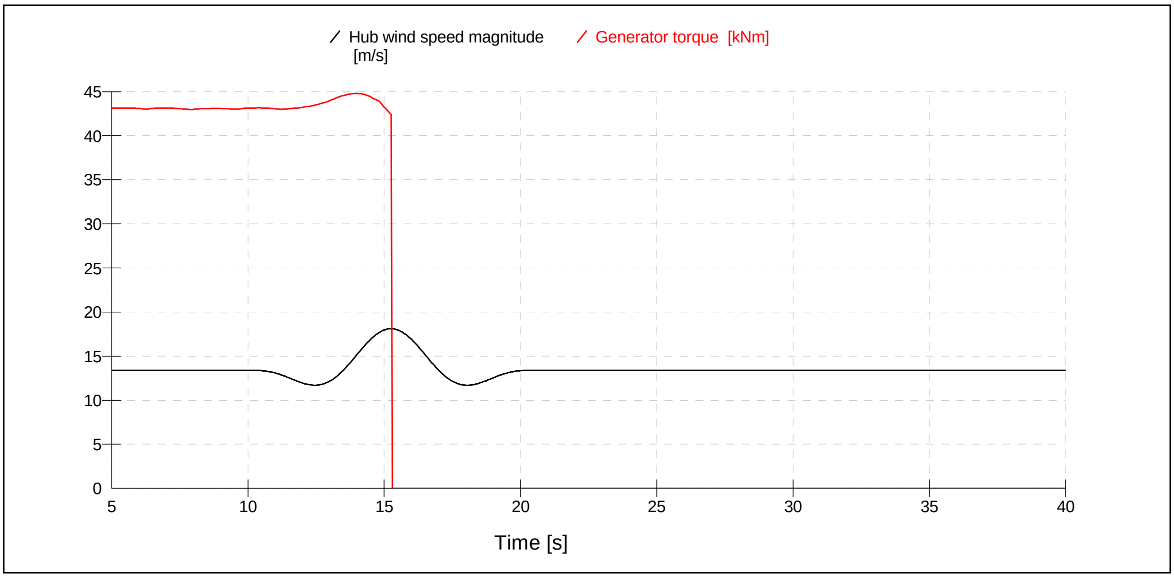
The load calculation is performed according to IEC61400-1 edition 3, wind class IA. Edition 3 seems particularly appropriate for the purpose of CPC-IPC comparison as turbulent wind is used for failure cases. Since in case of IPC the blades might be pitched at different angles depending on the wind condition, and the difference can be large or small thus leading to possible high loads when a safety system shutdown occurs, it is important to have a statistical representation of this event.

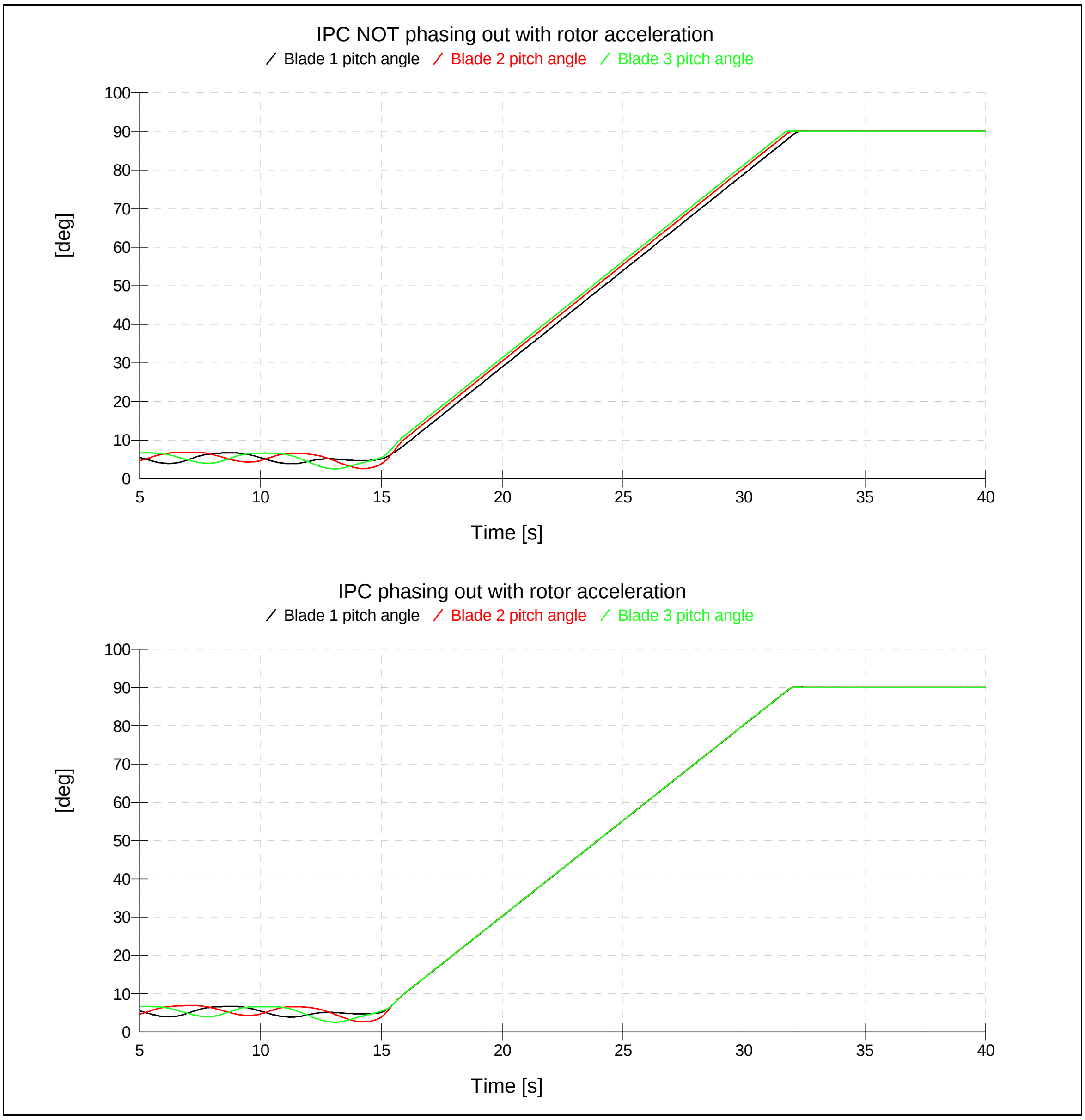
Load sensor failures have not been considered in the load calculations failure scenarios as they prove not to drive any extreme loads. A separate analysis has been carried out and reported in the document.

2. Power production controller

As mentioned earlier the IPC power production controller is fully described in [1]. However, an additional feature has been included to reduce extreme loads in shutdown cases due to overspeed. This feature phases out the individual pitch contribution with rotor acceleration, so that when the rotor accelerates for example during a gust and a shutdown is likely to occur the blades will be almost aligned before the shutdown begins.

The main reason for this is that the blades start pitching from different pitch angles when the shutdown begins. To improve loads the blades should be as much as possible aligned during the shutdown. An example of the benefits of this feature is reported in Figure 2-1. The figure reports the case dlc2.3 h_4_4 (refer to section 5.3 for a full description), where a grid loss occurs 5.25 seconds after the beginning of an annual extreme operating gust at 13.4m/s steady wind condition. When the fault occurs a grid loss shutdown procedure is initiated, after a few seconds the software overspeed limit is reached and a Fast shutdown is triggered immediately followed by a safety system shutdown when the safety system overspeed condition is reached. As shown in the figure, if the contribution of IPC is not reduced when the rotor starts accelerating the blades will not be aligned during the safety system shutdown. As a consequence some of the asymmetric loads will be much higher than those obtained with a CPC controller. For example the rotating hub My will be 45% higher and the tower base Mz will be 34% higher. If the IPC contribution is suitably reduced as the rotor accelerates, the blades are aligned before the shutdown begins and loads are restored to CPC levels. This feature is also beneficial in reducing overspeed in normal power production when speed regulation and IPC may be ‘competing’ to use the available pitch rates.




IPC NOT phasing out with rotor acceleration
Blade 1 pitch angle
Blade 2 pitch angle
Blade 3 pitch angle
[deg]
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
Time [s]
IPC phasing out with rotor acceleration
Blade 1 pitch angle
Blade 2 pitch angle
Blade 3 pitch angle
[deg]
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
Time [s]

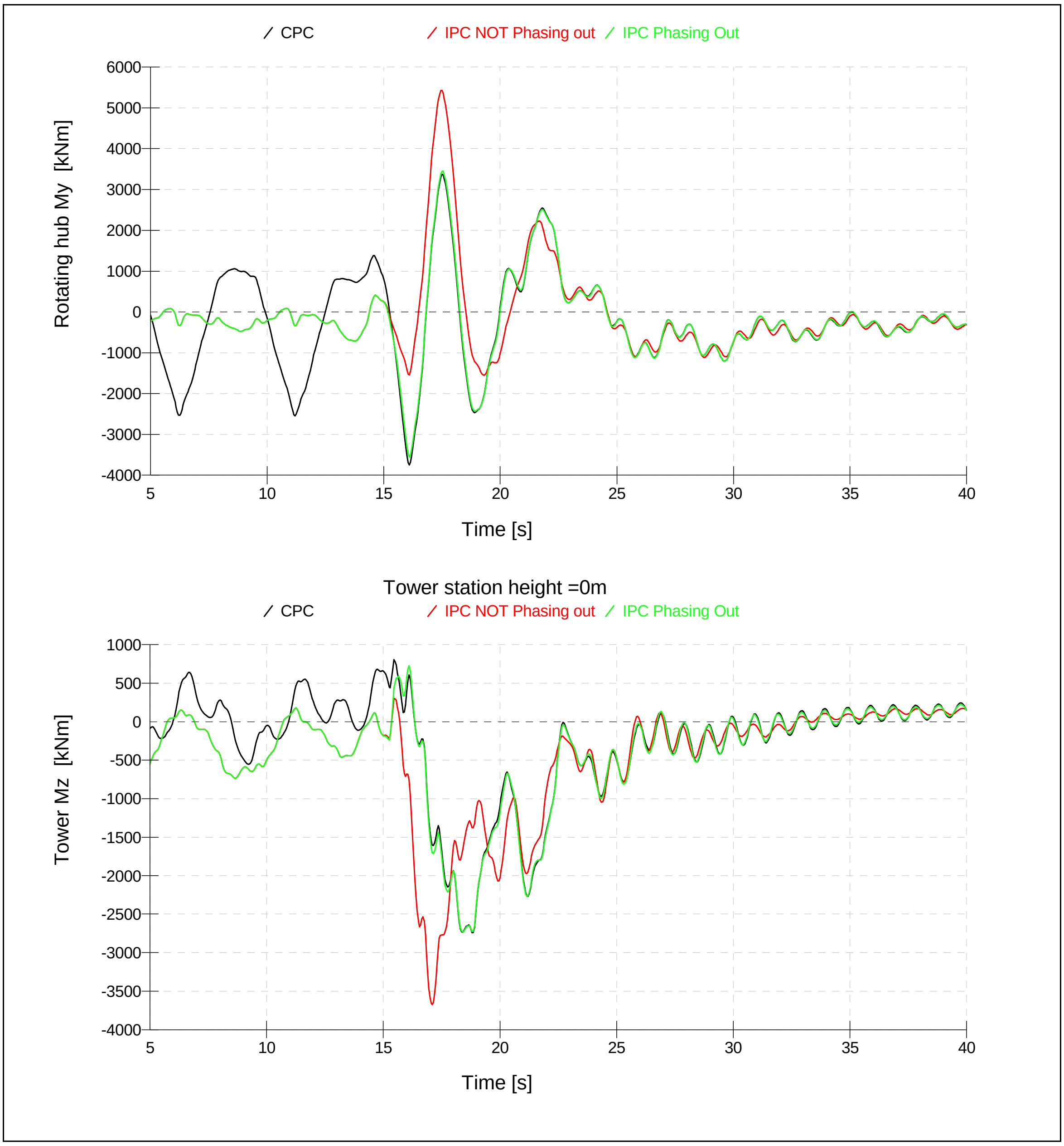


Figure 2-1 Effect of IPC phasing out with rotor acceleration

3. Supervisory control design

The supervisory control algorithm includes the procedure for normal turbine start up and shutdown as well as overspeed and overpower trips and the logic for determining failures of either the pitch or yaw subsystems. The supervisory skeleton for a collective and an individual pitch controller is the same with some differences in pitch failure detection logics. Moreover a suitable phasing out of individual pitch contribution should be used during turbine controller shutdowns. For the purpose of this document only shutdown procedures will be addressed in order to compare extreme loads

3.1 Shut down procedures

Shutdowns can be initiated by the wind turbine controller or by the safety system depending on the particular event.

Table 3.1 and Table 3.2 report the different shutdown procedures which have been modelled for the load calculation exercise implemented by the wind turbine controller and by the safety system respectively.

Wind turbine controller shutdown program	**Pitch system action**	**Generator action**	**Shaft brake applied?**
Normal Shut Down	Torque setpoint reduced to zero. Speed setpoint reduced to the minimum speed in order to shut down the turbine in 30seconds. When zero power is reached disconnect generator and feather blades at the collective Slow pitch rate, phase out individual pitch rate at Slow phase out rate		No
Fast Shut Down	Collective pitch at Fast pitch rate, individual pitch phasing out at Fast phase out rate	Torque demand ramped to zero. Disconnect on zero power.	No
Grid Loss Shut Down	Collective pitch at Grid Loss pitch rate, individual pitch phasing out at Grid Loss phase out rate	Disconnect immediately	No
Pitch Fault Shut Down	Autonomous pitch to feather	Torque demand ramped to zero. Disconnect on zero power	No

Table 3.1 Wind turbine controller shutdown programs

Safety system shutdown programs	Pitch system action	Generator action	Shaft brake applied?
Safety System Shut Down	Autonomous pitch to feather	Disconnect immediately	No
E-Stop Button Push Shut Down	Autonomous pitch to feather	Disconnect immediately	Yes

Table 3.2 Safety system shutdown programs

For the Normal, Fast and Grid Loss shutdown the blades are pitched towards feather by imposing a pitch rate for the collective pitch control and phasing out the individual pitch contribution so that the blades will be aligned as soon as possible during shutdown and in particular before the safety system is triggered. This phasing out might be unnecessary if the individual pitch contribution has been already erased by the feature described in section 2, but if it was not the case this solution will continue the phasing out to align the blades during the shutdown before the safety system is triggered.

	CPC [º/s]	IPC [º/s]
Collective Slow pitch rate	4	4
Collective Fast pitch rate	6	6
Collective Grid Loss pitch rate	6	6
Slow phase out individual pitch rate	-	1
Fast phase out individual pitch rate	-	6.6
Grid Loss phase out individual pitch rate	-	6.6
Safety system shutdown pitch rate	5	5

Table 3.3 Turbine shutdowns pitch rate

3.2 Speed ranges and trip levels

Simulations from the dlc1.2 cases have been used to estimate overspeed limits. Both collective and individual pitch control achieve a maximum overspeed of 110% of rated speed. The software overspeed level is set to 112% of rated speed and the safety system overspeed trip is set to 115% of rated speed.

	Rotor speed [rpm]	Generator speed [rpm]	Generator speed [%]
Minimum steady state speed	7	679	58
Maximum steady state speed	12.1	1173.7	100
Maximum expected operational speed with design turbulence	13.34	1298	110
Software overspeed trip	13.54	1314	112
Safety system overspeed trip	13.9	1349	115

Table 3.4 Speed range and trip levels

The software overspeed trip will result in a fast shut down procedure. The safety system overspeed trip will result in a safety system shut down procedure.

3.3 Yaw failure trip

If the turbine is operating and the 3s averaged yaw error exceeds a prescribed limit, the turbine will go into a Normal Shut Down procedure. Since the wind direction variability depends on the wind intensity and in particular at low wind speed is less likely to have a fixed specific direction, the yaw error limit has been scheduled with the 300s averaged wind speed as shown in the table below. The yaw error is not checked when the wind speed is below 2m/s.

Wind speed [m/s] averaged with a 300s time constant:	5	10	35
Yaw Error [°] :	60	45	30

3.4 Pitch failure modes

Different failure scenarios have been modelled in load calculations and Table 3.5 reports how the faults will be detected and which shutdown procedure will be activated. While the single blade seizure and runaway cases model a hardware pitch system failure, the all blades runaway scenario simulates a failure in the wind turbine controller algorithm.

Fault characteristic	**Fault detection**	**Shut down procedure**	**Consequent pitch motion**
All blades run away	Detected by pitch demand sanity check (details below).	Fast Shut Down	All blades feather at fast pitch rate
Single blade runaway	Difference between measured and demanded pitch of more than 3º for 1s. Following error trip OR Instantaneous difference between blades (see below)	Pitch Fault Shut Down.	All blades feather at the safety system pitch rate
Single blade seizure		Pitch Fault Shut Down.	Failed blade sticks. Operational blades feather at the safety system pitch rate

Table 3.5 Detection and consequences of pitch system failures

The pitch demand sanity check is intended to trap a condition where the Turbine Controller makes an erroneous pitch demand as a result of a failure in the power production pitch control algorithm. This type of Turbine Controller failure clearly does not register as a controller hardware failure and therefore does not trip any controller hardware alarms. The pitch demand sanity check is a simple set of rules which are implemented within the Turbine Controller and are capable of determining such erroneous pitch demands. The pitch demand sanity check is implemented as a test such that if the pitch rate demand computed as the mean values on the three blades is less than a certain rate whilst the generator speed is higher than a certain value and the generator is accelerating then the turbine enters a Fast Shut Down procedure.

Due to the different controller behaviour the trip levels for this failure detection are slightly different for IPC and CPC. For CPC the speed level has been set to 1256rpm (107% of rated generator speed) while the pitch rate threshold is -3º/s. IPC is using 1232rpm (105% of rated generator speed) while the pitch rate threshold is -4º/s.

The blade seizure fault can be detected either by a following error trip that compares the demanded and measured pitch angle on each blade, or by comparing the behaviour of two blades. If a collective pitch controller is used this fault can be detected by comparing the measured pitch angle of two blades and a Pitch Fault Shut Down is then triggered when the difference exceeds 1º. This trip can not be used with individual pitch control because, due to the nature of this algorithm, the instantaneous difference between blade angles can be large. As a consequence a high limit must be set and in case of failure the fault may only be detected after several seconds. For this reason another strategy has been designed to detect the failure as soon as possible. In particular if β_{id} and β_{im} are respectively the demanded and the measured pitch angle of blade i the following expression is monitored:

$$\left| (\beta_{id} - \beta_{jd}) - (\beta_{im} - \beta_{jm}) \right| \quad for\ i, j = 1, 2, \ldots N$$

where N is the number of blades. If this expression exceeds 5º a Pitch Fault shutdown is triggered.

All the fault limits described in this section have been set by analysing the results of different turbulent wind simulations and chosen to avoid unnecessary shutdowns during normal turbine operation.

4. Load sensor failure

IPC computes differential pitch actions based on load measurements (blade root or hub loads for example). This requires sensors, and any sensor is capable of failure. The potential impact of these failures on the controller performance and loads also has to be assessed and failure detection strategies should be implemented in the supervisory logic to detect fault events.

Different failure modes could be modelled depending on the measurement system employed (strain gauges or optical fibres) and some of them might be detected by the measurement system itself. Examples could be measurement outside a specific range or failed communication with a sensor. However some should be detected by the wind turbine controller in particular in case of sensor freezing or saturation to full scale or zero.

Possible ways of detecting these load sensor failures could be:

- Check the signal spectra to recognize anomalies in the signal energy content,
- Average the signal on a revolution to check the signal is consistent,
- If blade root loads are used, compare the signal on the three blades to check they are correlated.

This section describes an approach suitable if blade root sensors are used and is based on the load analysis on one revolution comparing the one-revolution loads mean (Dm) and peak-to-peak (Dr) maximum difference between blades to detect anomalies on one blade.

The quantity Dm is the maximum normalized absolute difference on the three blades of the average load value (where *k* is the generic controller timestep):

$$
\begin{aligned}
&Dm_{ij}(k) = (\overline{m}_i(k) - \overline{m}_j(k)) / M(k) \qquad i, j = 1,3 \\
&M(k) = \sum_i \overline{m}_i(k) \\
&Dm(k) = \max(|Dm_{ij}(k)|)
\end{aligned}
$$

where $\overline{m}_i$ is the flapwise (or edgewise) bending moment of blade i averaged over 1 revolution.

The quantity Dr is the maximum normalized absolute difference on the three blades of the peak-to-peak load value:

$$
\begin{aligned}
&Dr_{ij}(k) = (\overline{r}_i(k) - \overline{r}_j(k)) / R(k) \qquad i, j = 1,3 \\
&R(k) = \sum_i \overline{r}_i(k) \\
&Dr(k) = \max(|Dr_{ij}(k)|)
\end{aligned}
$$

where $\overline{r}_i$ is the peak-to-peak flapwise (or edgewise) bending moment of blade i averaged over 1 revolution.

The analysis below reports the failure detection approach for a simulation at 18m/s turbulent wind in case of sensor seizure and sensor saturating to zero. Figure 4-1 reports the measured blade root flapwise bending moment for the three blades with a failure occurring on blade 1. Figure 4-2 reports the values for indexes Dm and Dr. The two quantities described above are capable of detecting these types of failure by changing their value from a no fault condition (shown by the black line). Especially the index Dr, based on the peak-to-peak load value over a revolution, seems capable of capturing both the fault cases well.

These kinds of failures, although they reduce IPC performance, do not seem to be critical enough to compromise the wind turbine regulation, and the loads are still improved with respect to the collective pitch controller approach as reported in Figure 4-3. The figure shows the difference in terms of blade root out of plane bending moment and rotating hub My. By looking in particular at the hub load is possible to appreciate how the sensor failure affects the overall controller performance only slightly. For this reason load sensor failures are assumed not to drive any load and have not been included in the load calculation definition.

Other failures which need to be explored are

- bending moment sign reversal - after maintenance
- blade transposition - after maintenance
- rotor position sensor failure
- additional pitch system performance checks
- differential pitch algorithm failures

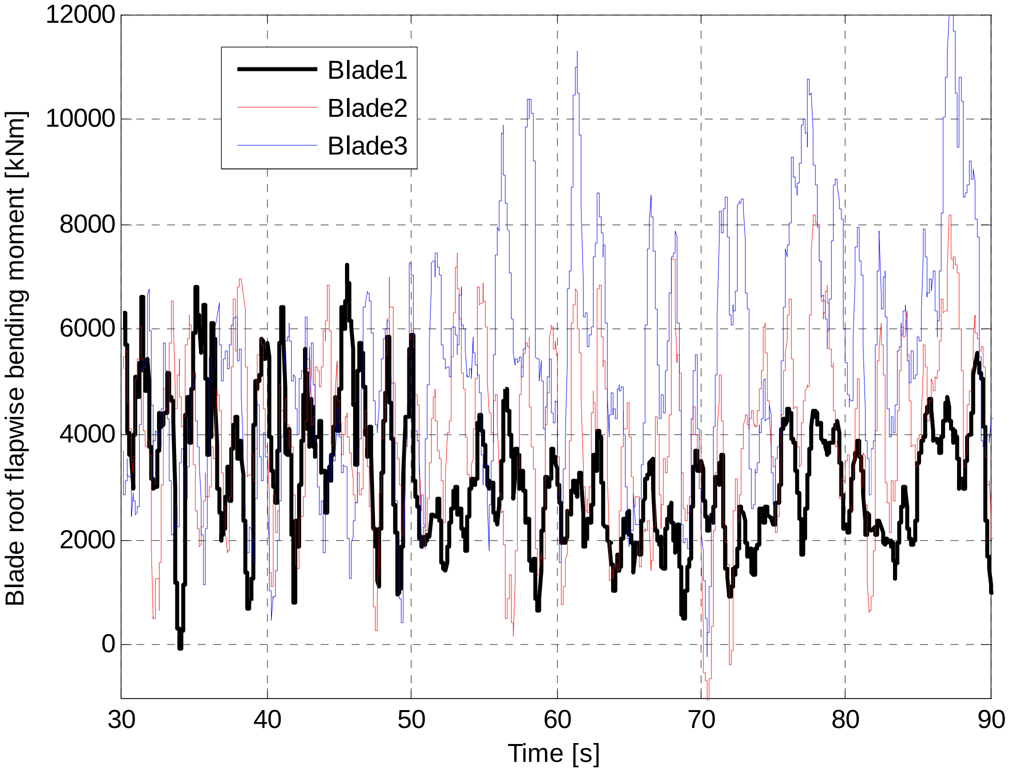


Figure 4-1 Blade root flapwise bending moment. One of the load sensors on blade 1 saturates to zero after 50 seconds.

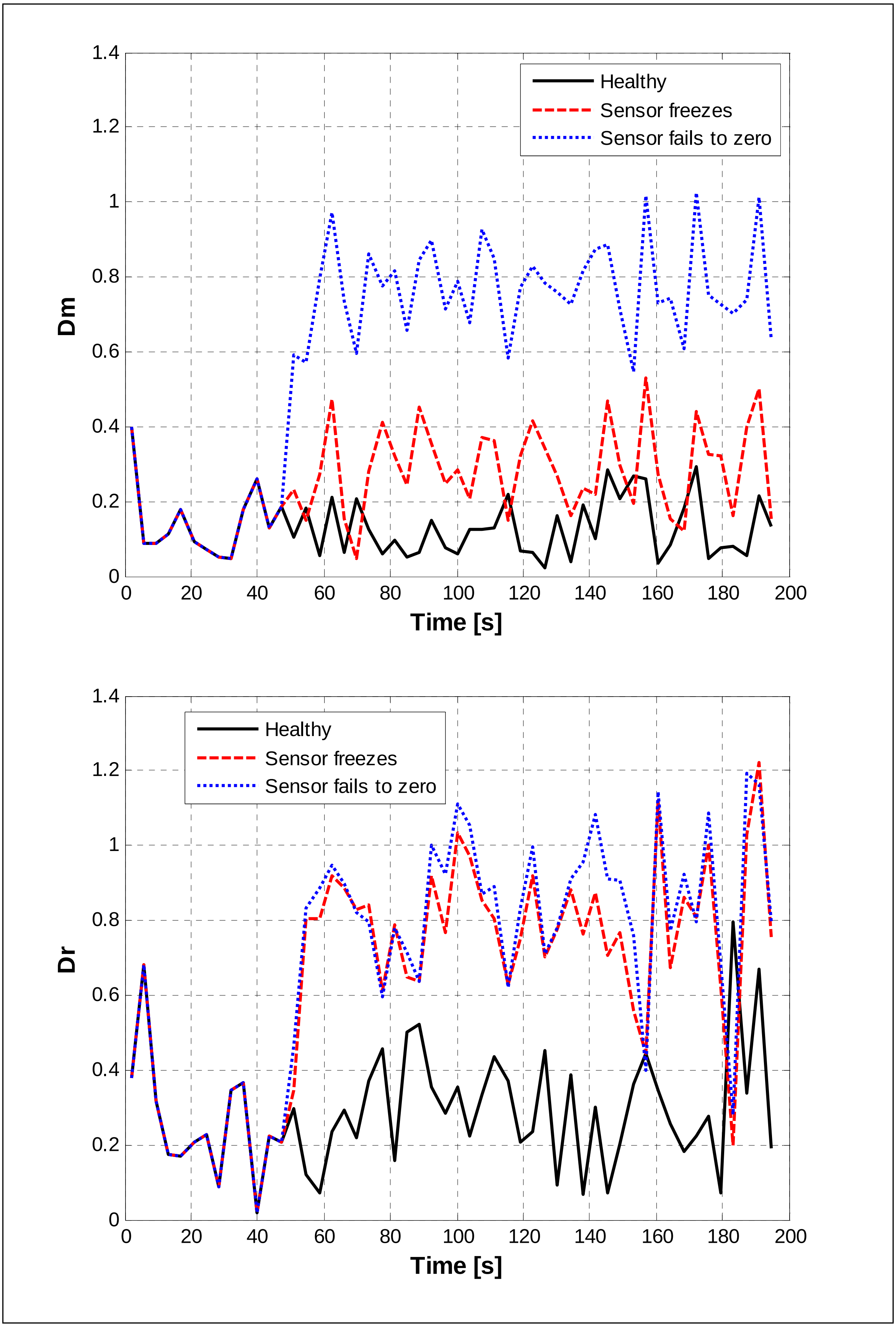


Figure 4-2 Indexes for blade load sensor failure

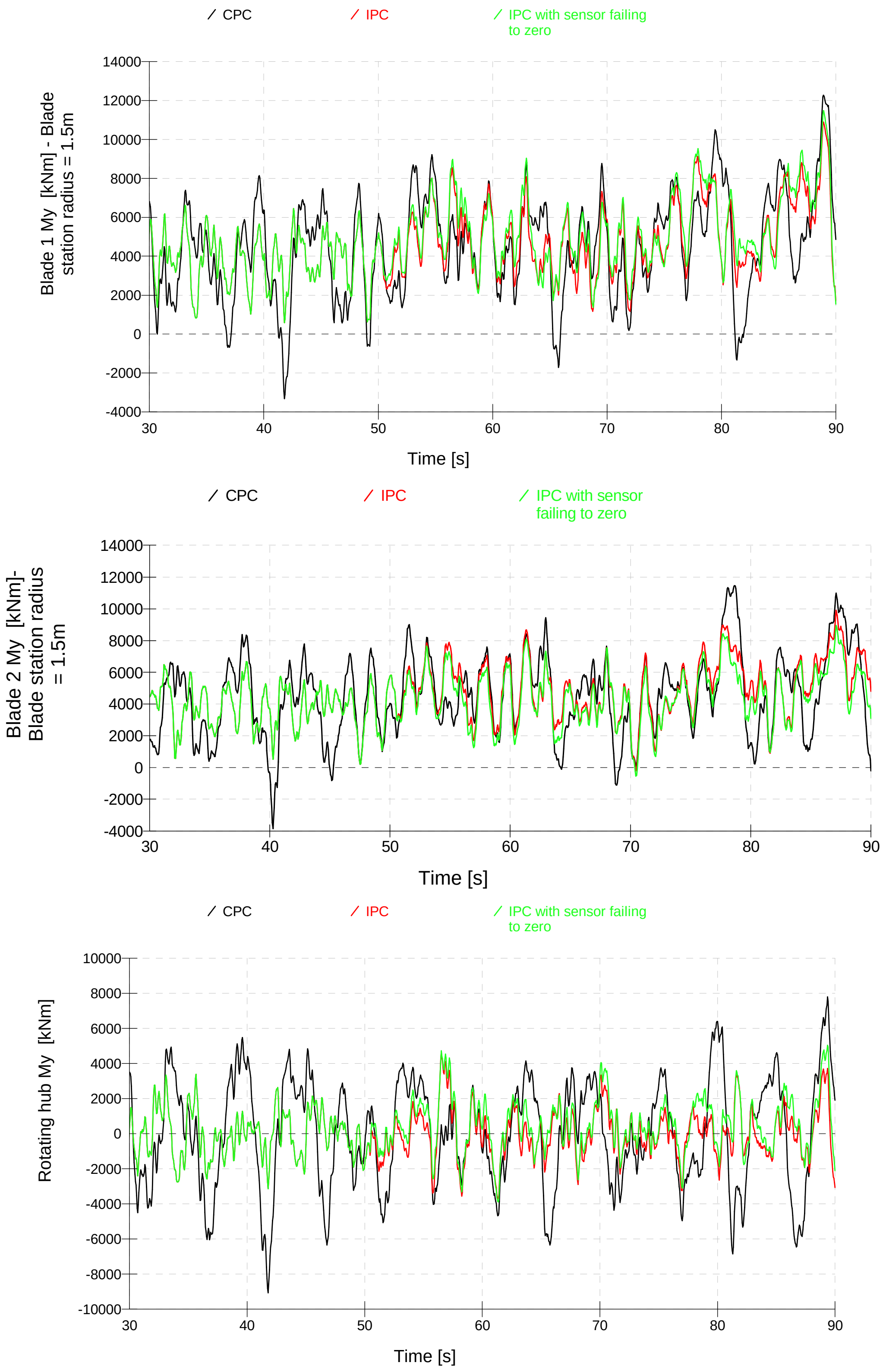


Figure 4-3 Loads comparison between CPC, IPC and IPC with load sensor failures to zero

5. Load case definition

This section describes the load cases which have been used to compare extreme loads between CPC and IPC. As well as load cases influenced by the control logic, idling cases have been included. This ensures any changes in loads due to the effects of the controller would be visible in practice, and not masked by higher, uncontrollable, idling loads.

The tables in this section give the case name, the initial turbine state, the initial conditions (wind speed, yaw error and pitch angle), and the details of any transient events or model of turbulence.

For these calculations a new version of *GH Bladed* which uses multibody dynamics has been used. The analytical methods are described in detail in [7]. A brief overview is given below in Table 5.1.

Wind shear	Standard power law model
Turbulence	Three-component Kaimal
Wake modelling	Dynamic wake
Stall modelling	Stall hysteresis starting at 25% radius
Bladed interface version	4.0
DTBLADED version	4.0
Load contributions, General	Aerodynamic Self weight Rotational inertial Modal inertial

Table 5.1 Summary of Bladed analytical basis

5.1 Input Parameters

The wind conditions for extreme load calculations are presented in Table 5.2.

Rated Power, P_{rated}	5,000	kW
Rated hub-height wind speed, V_r	11.4	m/s
Wind Class	I_A	
Air density	1.225	kg/m^3
Characteristic turbulence intensity at 15 m/s, I_{15}	16	%
Hub height	90	m
Hub-height 50-year extreme mean wind speed, V_{50}	50.0	m/s
Hub-height 1-year extreme mean wind speed, V_1	40.0	m/s
Hub-height 50-year extreme wind speed, V_{e50}	70.0	m/s
Hub-height 1-year extreme wind speed, V_{e1}	56.0	m/s
Annual average wind speed at hub height, V_{ave}	10	m/s
Hub-height operating wind speed range, V_{in} to V_{out}	4 to 25 (k=2.0)	m/s

Table 5.2 Design load case parameters

The turbulent variation in wind speed has been modelled using a three component Kaimal model with a characteristic turbulence intensity set according to the Normal Turbulence Model (as defined in IEC 61400-1 edition 3) [5].

The pitch failure and control system failure cases have been simulated with turbulent wind. 12 turbulent wind seeds are used and the characteristic load is taken to be the mean of the 6 seeds resulting in the largest maxima/minima.

Partial safety factors for loads have been applied externally to the results of the dynamic simulations. Table 5.3 summarises the safety factors that have been used in each load case.

Load case type	**Safety Factor**
Abnormal (DLCs 2.2, 2.3, 6.2)	1.10
Extreme and Normal (all other DLCs)	1.35

Table 5.3 Partial safety factors for all load cases

Unless otherwise stated, all simulations take account of:

- Rotor mass imbalance of 1820 kgm
- Rotor aerodynamic imbalance, set angles of +0.3, 0.0 and -0.3 deg on blades 1, 2 and 3 respectively
- Tower shadow
- Power law exponent α (characterising the wind gradient) = 0.20, except where otherwise stated.
- Vertical flow inclination 8 degrees

Simulations with turbulence also account for:

- Three component three dimensional Kaimal turbulent field

In this report loads are reported at:

- the blade root (at 1.5 m radius)
- the rotor centre (in rotating and stationary coordinates)
- the yaw bearing (coordinates fixed to the nacelle)
- tower heights of 0m and 87.6m.

The model of the turbine used for the load calculations includes four blade modes (two flapwise and two edgewise) and six tower modes (three fore-aft and three side-side).

5.2 Fatigue load case description

Load case number: DLC 1.2
Operating condition: Power production
Wind conditions: Normal Turbulence Model
Type of analysis: Fatigue
Description of simulations:

Load case identifier	Mean wind speed (m/s) (mid bin)	Longitudinal turbulence intensity (%)	Hours per year (for whole wind bin)	Yaw error (deg)
aa	5	29.9	1124	-8
ab				0
ac				8
ba	7	24.8	1304	-8
bb				0
bc				8
ca	9	22.0	1306	-8
cb				0
cc				8
da	11	20.1	1168	-8
db				0
dc				8
ea	13	18.9	949	-8
eb				0
ec				8
fa	15	18.0	707	-8
fb				0
fc				8
ga	17	17.3	486	-8
gb				0
gc				8
ha	19	16.7	309	-8
hb				0
hc				8
ia	21	16.3	183	-8
ib				0
ic				8
ja	23	15.9	101	-8
jb				0
jc				8
ka	25	15.6	30	-8
kb				0
kc				8

Comments: 10 minute simulations
Rayleigh wind distribution
Six turbulent wind fields used for each wind speed, each using a different random number seed (indexed 1-6).

Load case number:	DLC 2.4
Operating condition:	Power production
Wind conditions:	Normal Turbulence Model
Type of analysis:	Fatigue
Description of simulations:	

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw error (deg)	Occurrences per year	Comment
aa	11.4	19.86	0	10	Grid loss
ab	25	15.58	0	10	
ba	11.4	19.86	0	5	Transducer error, n4 trip
bb	25	15.58	0	3	

Comments:	Three dimensional three component Kaimal turbulent wind field (1 min sample). Wind gradient exponent (exponential model), α = 0.2 Fault occurs 10s into simulation Six turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-6).

Load case number:	DLC 4.1		
Operating condition:	Normal shut-down		
Wind conditions:	Normal wind profile, Vin < Vhub < Vout		
Type of analysis:	Fatigue		
Description of simulations:			
Load case identifier	Vhub (m/s)	Yaw error	Occurrences per year
a	4	0 deg	2000
b	11.4	0 deg	100
c	25	0 deg	100
Comments:	Steady wind One minute simulations Wind gradient exponent (exponential model), α = 0.2 The number of occurrences per year of normal shut-downs have been doubled to account for start-ups, which are not explicitly modelled. Normal stop occurs 10s into simulation		

Load case number: DLC 6.4
Operating condition: Parked (stand still or idling)
Wind conditions: Normal turbulence model, Vhub < 0.7 Vref
Type of analysis: Fatigue
Description of simulations:

Load case identifier	Mean wind speed (m/s) (upper bin)	Longitudinal turbulence intensity (%)	Yaw error	Hours / year
a	4	34.40	-8	1035
b			0	
c			8	
d	35	14.56	-8	65
e			0	
f			8	

Comments:

Three dimensional three component Kaimal turbulent wind field (10 min sample)

Six turbulent wind fields used for each wind speed bin, each using a different random number seed (indexed 1-6).

All blades at idling pitch angle of 90 deg

Wind gradient exponent (exponential model), α = 0.2

5.3 Extreme load case description

Design load case:	DLC 1.1
Operating condition:	Power production
Wind conditions:	Normal turbulence model
Type of analysis:	Extreme (extrapolation)
Partial safety factors:	Normal
Description of simulations:	
Comments:	Load extrapolation is omitted from this loadset

Design load case:	DLC 1.3
Operating condition:	Power production
Wind conditions:	Extreme turbulence model
Type of analysis:	Extreme
Partial safety factors:	Normal
Description of simulations:	

Load case identifier	Mean wind speed (m/s) (mid bin)	Longitudinal turbulence intensity (%)	Yaw error (deg)
aa	5	58.47	-8
ab			0
ac			8
ad	7	44.40	-8
ae			0
af			8
ba	9	36.58	-8
bb			0
bc			8
bd	11	31.60	-8
be			0
bf			8
ca	13	28.16	-8
cb			0
cc			8
cd	15	25.63	-8
ce			0
cf			8
da	17	23.70	-8
db			0
dc			8
dd	19	22.18	-8
de			0
df			8
ea	21	20.94	-8
eb			0
ec			8
ed	23	19.92	-8
ee			0
ef			8
fa	25	19.07	-8
fb			0
fc			8
Comments:	10 minute simulations Rayleigh wind distribution Turbulence scaling parameter, c=2 Six turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-6). The characteristic load for each wind speed is calculated as the mean of the maxima from each of the six seeds.		

Load case number:	DLC 1.4
Operating condition:	Power production
Wind conditions:	Extreme coherent gust with change of direction (ECD)
Type of analysis:	Ultimate
Partial safety factors:	Normal
Description of Simulations:	

Load case identifier	V0 (m/s)	ΔV (m/s)	Vend (m/s)	Direction change (deg)	Δt (s)	Yaw error (deg)
aa	9.4	15	24.4	76.6	10	-8
ab						0
ac						8
ad	11.4	15	26.4	63.2	10	-8
ae						0
af						8
ag	13.4	15	28.4	53.7	10	-8
ah						0
ai						8
aj	9.4	15	24.4	-76.6	10	-8
ak						0
al						8
am	11.4	15	26.4	-63.2	10	-8
an						0
ao						8
ap	13.4	15	28.4	-53.7	10	-8
aq						0
ar						8

Comments:	Steady wind with speed and direction transient (rise time = 10s) One minute simulations Transient occurs 10s into simulation Wind gradient exponent (exponential model), $\alpha = 0.2$ Starting azimuth angle varied from 0-90deg in 30deg intervals (indexed 1-4).

Load case number: DLC 1.5
Operating condition: Power production
Wind conditions: Extreme wind shear (EWS)
Type of analysis: Ultimate
Partial safety factors: Normal
Description of Simulations:

Load case identifier	Vhub (m/s)	Wind shear (m/s)	Yaw error (deg)
a_*x*_*y*	9.4	11.82	-8
b_*x*_*y*			0
c_*x*_*y*			8
d_*x*_*y*	11.4	12.63	-8
e_*x*_*y*			0
f_*x*_*y*			8
g_*x*_*y*	13.4	13.44	-8
h_*x*_*y*			0
i_*x*_*y*			8
j_*x*_*y*	20	16.10	-8
k_*x*_*y*			0
l_*x*_*y*			8
m_*x*_*y*	25	18.13	-8
n_*x*_*y*			0
o_*x*_*y*			8

Comments:

Steady wind with wind shear transient (period = 12s)
One minute simulations
Transient occurs 10s into simulation
Wind gradient exponent (exponential model), α = 0.2
Wind shear applied in 3 ways:

1) positive vertically (indexed *x*=1)
2) positive horizontally (indexed *x*=2)
3) negative horizontally (indexed *x*=3)

Starting azimuth angle varied from 0-90deg in 30deg intervals (indexed *y*=1-4).

Load case number: DLC 2.1
Operating condition: Power production plus occurrence of fault
Wind conditions: Normal turbulence model, Vin < Vhub < Vout
Type of analysis: Ultimate
Partial safety factors: Normal
Description of simulations:

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Fault
aa	9.4	21.53	Transducer failure, n4 tripped
ab	11.4	19.86	
ac	13.4	18.69	
ad	20	16.48	
ae	25	15.58	
af	9.4	21.53	All blades runaway to fine at -7.5deg/s
ag	11.4	19.86	
ah	13.4	18.69	
ai	20	16.48	
aj	25	15.58	

Comments:

Three dimensional three component Kaimal turbulent wind field (1 min sample).

Twelve turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-12)

Fault occurs 10s into simulation

Wind gradient exponent (exponential model), α = 0.2

Faults tested:

a) Transducer failure. Over speed n4 trip tested.

b) Collective pitch runaway. All blades pitch towards fine at –7.5 deg/s

The characteristic loads for each load case group are calculated as the mean of the upper half of the maxima from each of the twelve seeds.

Load case number: DLC 2.2
Operating condition: Power production plus occurrence of fault
Wind conditions: Normal turbulence model, Vin < Vhub < Vout
Type of analysis: Ultimate
Partial safety factors: Abnormal
Description of simulations:

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Fault
aa	9.4	21.53	Transducer failure, nA tripped
ab	11.4	19.86	
ac	13.4	18.69	
ad	20	16.48	
ae	25	15.58	
af	9.4	21.53	Pitch seized at instantaneous position
ag	11.4	19.86	
ah	13.4	18.69	
ai	20	16.48	
aj	25	15.58	
ak	9.4	21.53	Blade 1 runaway towards fine at -7.5deg/s
al	11.4	19.86	
am	13.4	18.69	
an	20	16.48	
ao	25	15.58	
ap	9.4	21.53	Blade 1 runaway towards feather at +7.5deg/s
aq	11.4	19.86	
ar	13.4	18.69	
as	20	16.48	
at	25	15.58	

Comments

Three dimensional three component Kaimal turbulent wind field (1 min sample).

Twelve turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-12)

Fault occurs 10s into simulation
Wind gradient exponent (exponential model), $\alpha = 0.2$
Faults tested:
a) Transducer failure. Over speed nA trip tested.
b) Pitch seizure. Single blade fails to pitch.
c) Pitch runaway. Blade 1 pitches towards fine or feather at 7.5 deg/s

The characteristic loads for each load case group are calculated as the mean of the upper half of the maxima from each of the twelve seeds.

Load case number:	DLC 2.3
Operating condition:	Power production plus loss of electrical grid connection
Wind conditions:	Extreme operating gust (EOG)
Type of analysis:	Ultimate
Partial safety factors:	Abnormal
Description of Simulations:	

Load case identifier	Vhub (m/s)	EOG gust (m/s)	Yaw error (deg)	Grid loss phasing
a *xy*	9.4	5.14	-8	tstart gust + 0 tstart gust + 2.45 tstart gust + 4 tstart gust + 5.25
b *xy*			0	
c *xy*			8	
d *xy*	11.4	5.75	-8	
e *xy*			0	
f *xy*			8	
g *xy*	13.4	6.36	-8	
h *xy*			0	
i *xy*			8	
j *xy*	20	8.37	-8	
k *xy*			0	
l *xy*			8	
m *xy*	25	9.89	-8	
n *xy*			0	
o *xy*			8	

Comments	Steady wind with transient gust (gust period = 10.5s) One minute simulations Gust occurs 10s into simulation Wind gradient exponent (exponential model), α = 0.2 Grid loss phasing indexed *x*=1 (t=10s), *x*=2 (t=12.45s), *x*=3 (t=14s), *x* =4 (t=15.25s) Starting azimuth angle varied from 0-90deg in 30deg intervals (indexed *y*=1-4).

Load case number:	DLC 3.1, 3.2 & 3.3
Operating condition:	Start-up
Wind conditions:	
Type of analysis:	
Partial safety factors:	
Description of Simulations:	
Startup simulations are not performed as they are more benign than shutdowns. The number of shutdowns considered in the fatigue postprocessing has been doubled to account for the absence of startup simulations.	

Load case number:	DLC 4.2
Operating condition:	Normal shut-down plus deterministic gust
Wind conditions:	Extreme operating gust (EOG)
Type of analysis:	Ultimate
Partial safety factors:	Normal
Description of Simulations:	

Load case identifier	Vhub (m/s)	EOG gust (m/s)	Yaw error (deg)
aa	9.4	5.14	-8
ab			0
ac			8
ba	11.4	5.75	-8
bb			0
bc			8
ca	13.4	6.36	-8
cb			0
cc			8
da	20	8.37	-8
db			0
dc			8
ea	25	9.89	-8
eb			0
ec			8

Comments:

Steady wind with transient gust (gust period = 10.5s)
One minute simulations
Gust occurs 10s into simulation
Wind gradient exponent (exponential model), α = 0.2
Shut down occurs at start of gust
Starting azimuth angle varied from 0-90deg in 30deg intervals (indexed 1-4).

Load case number: DLC 5.1
Operating condition: Emergency shut-down
Wind conditions: Normal turbulence model, Vin < Vhub < Vout
Type of analysis: Ultimate
Partial safety factors: Normal
Description of Simulations:

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw error (deg)
aa	9.4	21.53	-8
ab			0
ac			8
ba	11.4	19.86	-8
bb			0
bc			8
ca	13.4	18.69	-8
cb			0
cc			8
da	20	16.48	-8
db			0
dc			8
ea	25	15.58	-8
eb			0
ec			8
Comments	Three dimensional three component Kaimal turbulent wind field (1 min sample) Twelve turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-12) Shut down occurs 10s into simulation Wind gradient exponent (exponential model), $\alpha = 0.2$ The characteristic loads for each load case group are calculated as the mean of the upper half of the maxima from each of the twelve seeds.		

Design load case: DLC 6.1
Operating condition: Idling
Wind conditions: Extreme wind model (turbulent) (Vhub = V50)
Type of analysis: Ultimate
Partial safety factors: Normal
Description of simulations:

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw error (deg)
a	50	11.00	-8
b			0
c			8

Comments:

Three dimensional three component Kaimal turbulent wind field (10 min sample).

Six turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-6).

Wind gradient exponent (exponential model), $\alpha = 0.11$

The characteristic loads for each load case group are calculated as the mean of the maxima from each of the six seeds.

Design load case: DLC 6.2
Operating condition: Idling with loss of electrical network
Wind conditions: Extreme wind model (turbulent) (Vhub = V50)
Type of analysis: Ultimate
Partial safety factors: Abnormal
Description of simulations:

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw error (deg)
a	50	11.00	0
b			30
c			60
d			90
e			120
f			150
g			180
h			210
i			240
j			270
k			300
l			330

Comments:

Three dimensional three component Kaimal turbulent wind field (10 min sample).

Six turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-6).

Wind gradient exponent (exponential model), $\alpha = 0.11$

The characteristic loads for each load case group are calculated as the mean of the maxima from each of the six seeds.

Design load case: DLC 6.3
Operating condition: Idling with extreme yaw misalignment
Wind conditions: Extreme wind model (turbulent) (Vhub = V1)
Type of analysis: Ultimate
Partial safety factors: Normal
Description of Simulations

Load case identifier	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw error (deg)
aa	40	11.00	-20
ab			-10
ac			0
ad			10
ae			20

Comments:

Three dimensional three component Kaimal turbulent wind field (10 min sample).

Six turbulent wind fields used for each simulation, each using a different random number seed (indexed 1-6).

Wind gradient exponent (exponential model), $\alpha = 0.11$

The characteristic loads for each load case group are calculated as the mean of the maxima from each of the six seeds.

6. Individual pitch control loads

The *Bladed* software has been used to identify the maximum and minimum values of each load component and contemporaneous values of associated loads.

Unless specified in the load case description these loads data include aerodynamic, self weight, rotational inertial and dynamic inertial contributions. The dynamic contribution includes the effect of tower, blade, drive train, electrical and control system modes. The only functional loads are those due to the mechanical brake. All moments and forces in Section 6 are presented in kNm and kN respectively.

6.1 IEC Class I_A ultimate loads

The maximum and minimum values of each load, along with the contemporaneous value of associated loads, are presented. Safety factors have been applied. The loads are given with respect to GL axes and in metric units which are reported in Appendix A.

			Flap BM	**Edge BM**	**Mz**	**Flap SF**	**Edge SF**	**Fz**
		Load case	**kNm**	**kNm**	**kNm**	**kN**	**kN**	**kN**
Flap BM	**Max**	**dlc2.1ai+05**	25823.0	1137.8	1302.3	803.5	-185.6	1051.4
Flap BM	**Min**	**dlc1.4ao2**	-20122.0	12517.0	-661.3	-549.8	-344.4	239.1
Edge BM	**Max**	**dlc2.1aj+09**	-15437.0	15135.0	-646.1	-376.5	-562.5	1309.3
Edge BM	**Min**	**dlc2.1aj+08**	9925.2	-11189.0	629.3	307.5	365.8	1055.6
Mz	**Max**	**dlc2.1ai+05**	25823.0	1137.8	1302.3	803.5	-185.6	1051.4
Mz	**Min**	**dlc1.4ao3**	-17123.0	8788.8	-870.9	-512.4	-248.8	422.9
Flap SF	**Max**	**dlc2.1ai+09**	23846.0	1814.2	1194.6	752.4	-229.6	1161.9
Flap SF	**Min**	**dlc6.2c-1**	-16805.0	1761.3	-626.1	-623.1	-47.7	187.3
Edge SF	**Max**	**dlc2.1aj+08**	9925.2	-11189.0	629.3	307.5	365.8	1055.6
Edge SF	**Min**	**dlc2.1aj+04**	-10491.0	14542.0	-360.6	-171.3	-529.4	1314.8
Fz	**Max**	**dlc2.1ai+09**	3852.2	-4271.3	74.4	153.1	43.9	1968.5
Fz	**Min**	**dlc6.1b-4**	245.1	2238.5	-82.4	-67.9	-46.8	-247.5

Table 6.1 - Ultimate loads: blade root

			Mx	My	Mz	Myz	Fx	Fy	Fz	Fyz
		Load case	**kNm**	**kNm**	**kNm**	**kNm**	**kN**	**kN**	**kN**	**kN**
Mx	**Max**	**dlc1.3k-a2**	8411.6	-13111.0	883.4	13141.0	778.7	-1253.1	135.2	1260.3
Mx	**Min**	**dlc2.1aj+01**	-5393.3	10372.0	-684.5	10395.0	-675.3	678.8	-1096.9	1290.0
My	**Max**	**dlc2.2ag+05**	-2233.9	21377.0	3179.1	21612.0	-474.5	1011.7	344.0	1068.6
My	**Min**	**dlc1.4ao2**	220.3	-23889.0	671.6	23899.0	-630.8	-72.9	-1475.7	1477.5
Mz	**Max**	**dlc1.4ah1**	1177.7	5924.3	19807.0	20674.0	-664.7	1344.3	-385.7	1398.6
Mz	**Min**	**dlc1.4ar1**	1002.7	7257.9	-20158.0	21425.0	-508.9	1419.8	87.2	1422.5
Myz	**Max**	**dlc1.4ao2**	220.3	-23889.0	671.6	23899.0	-630.8	-72.9	-1475.7	1477.5
Myz	**Min**	**dlc4.2cc_3**	2628.5	-0.6	1.5	1.6	411.8	387.2	-1367.3	1421.0
Fx	**Max**	**dlc2.1ah+03**	6239.7	-1321.8	-733.2	1511.5	1735.8	596.1	1263.7	1397.2
Fx	**Min**	**dlc2.1ai+09**	-563.3	2340.2	-5308.4	5801.4	-1064.3	370.2	-1363.9	1413.3
Fy	**Max**	**dlc1.3i-b3**	5953.6	-4705.4	-3216.8	5699.9	658.4	1713.3	479.7	1779.2
Fy	**Min**	**dlc1.3k-a1**	5615.7	-55.3	4205.5	4205.9	573.7	-1697.3	-313.6	1726.1
Fz	**Max**	**dlc1.3k-b3**	6436.5	1111.0	185.6	1126.4	407.9	355.1	1679.4	1716.5
Fz	**Min**	**dlc1.3k-c5**	6649.7	-1796.8	3531.2	3962.1	800.1	-28.6	-1686.1	1686.3
Fyz	**Max**	**dlc1.3k-c6**	3462.6	3746.6	-3614.1	5205.6	335.1	1778.2	-73.4	1779.7
Fyz	**Min**	**dlc6.2a-6**	106.7	3432.1	1033.3	3584.2	56.6	-39.6	-368.9	371.0

Table 6.2 - Ultimate loads: hub (rotating coordinates)

			Mx	My	Mz	Myz	Fx	Fy	Fz	Fyz
		Load case	**kNm**	**kNm**	**kNm**	**kNm**	**kN**	**kN**	**kN**	**kN**
Mx	**Max**	**dlc1.3k-a2**	8411.6	431.5	-13134.0	13141.0	778.7	-9.3	-1260.3	1260.3
Mx	**Min**	**dlc2.1aj+01**	-5393.3	8669.9	-5734.2	10395.0	-675.3	46.1	-1289.1	1290.0
My	**Max**	**dlc1.4ah1**	1146.6	20596.0	-3690.3	20925.0	-647.4	-279.8	-1367.7	1396.1
My	**Min**	**dlc1.4ao2**	220.3	-23254.0	-5513.1	23899.0	-630.8	310.2	-1444.6	1477.5
Mz	**Max**	**dlc2.2ag+01**	2207.9	785.7	16910.0	16929.0	168.6	-40.8	-1240.5	1241.2
Mz	**Min**	**dlc2.2ag+08**	-1213.0	1374.3	-18673.0	18724.0	-114.2	61.2	-1101.7	1103.4
Myz	**Max**	**dlc1.4ao2**	220.3	-23254.0	-5513.1	23899.0	-630.8	310.2	-1444.6	1477.5
Myz	**Min**	**dlc4.2cc_3**	2628.5	-0.1	1.6	1.6	411.8	-14.7	-1421.0	1421.0
Fx	**Max**	**dlc2.1ah+03**	6239.7	898.2	1215.7	1511.5	1735.8	-17.8	-1397.1	1397.2
Fx	**Min**	**dlc2.1ai+09**	-563.3	1283.3	-5657.6	5801.4	-1064.3	102.9	-1409.5	1413.3
Fy	**Max**	**dlc6.1a-6**	615.4	6768.9	1262.7	6885.7	196.9	1066.7	-815.4	1342.7
Fy	**Min**	**dlc6.2c-6**	-145.4	-4727.9	1103.4	4855.0	-12.7	-1053.7	-1114.4	1533.6
Fz	**Max**	**dlc6.1c-5**	823.2	-1219.2	7832.7	7927.0	128.8	-292.4	-327.5	439.0
Fz	**Min**	**dlc1.3k-c6**	3462.6	-3362.0	-3974.4	5205.6	335.1	42.8	-1779.2	1779.7
Fyz	**Max**	**dlc1.3k-c6**	3462.6	-3362.0	-3974.4	5205.6	335.1	42.8	-1779.2	1779.7
Fyz	**Min**	**dlc6.2a-6**	106.7	3359.9	1248.1	3584.2	56.6	-16.2	-370.6	371.0

Table 6.3 - Ultimate loads: hub (stationary coordinates)

			Mx	My	Mxy	Mz	Fx	Fy	Fxy	Fz
		Load case	**kNm**	**kNm**	**kNm**	**kNm**	**kN**	**kN**	**kN**	**kN**
Mx	**Max**	**dlc1.3k-a2**	8701.3	-4981.4	10026.0	2817.3	565.5	-151.9	585.5	-4681.7
Mx	**Min**	**dlc2.1aj+01**	-5839.7	6032.8	8396.2	-5853.4	-1168.3	20.5	1168.5	-4460.1
My	**Max**	**dlc1.4ah1**	1773.8	17930.0	18017.0	-2399.1	-955.2	-378.5	1027.4	-4483.5
My	**Min**	**dlc1.4ao2**	-801.3	-26529.0	26541.0	-6704.7	-978.7	376.5	1048.6	-4568.8
Mxy	**Max**	**dlc1.4ao2**	-801.3	-26529.0	26541.0	-6704.7	-978.7	376.5	1048.6	-4568.8
Mxy	**Min**	**dlc2.3e_2_2**	1.8	-0.3	1.8	62.5	480.9	-46.0	483.1	-3756.5
Mz	**Max**	**dlc2.2ag+01**	3807.2	-1196.7	3990.8	17162.0	338.4	-170.5	379.0	-3865.4
Mz	**Min**	**dlc2.2ag+08**	-2826.4	-202.9	2833.7	-18910.0	-473.2	47.0	475.5	-3666.4
Fx	**Max**	**dlc2.1ai+05**	5823.1	2761.3	6444.6	1091.4	2022.3	-5.1	2022.3	-4782.8
Fx	**Min**	**dlc2.1aj+04**	-1922.9	-282.2	1943.5	-7682.7	-1651.8	-15.4	1651.8	-4457.7
Fy	**Max**	**dlc6.2k-2**	-3684.9	4255.6	5629.3	-2676.6	270.7	1522.9	1546.8	-3598.9
Fy	**Min**	**dlc6.2d-4**	3869.8	-3322.8	5100.7	4068.7	-1.1	-1596.4	1596.4	-3706.5
Fxy	**Max**	**dlc2.1ai+04**	-529.5	4025.3	4059.9	9787.1	2072.6	-22.2	2072.8	-4847.9
Fxy	**Min**	**dlc1.3a-b4**	68.3	-1806.1	1807.4	160.1	0.1	0.2	0.2	-4609.7
Fz	**Max**	**dlc6.2a-1**	747.3	6158.5	6203.7	104.2	-2.7	-229.2	229.2	-2971.3
Fz	**Min**	**dlc1.3k-b4**	4383.0	-7787.5	8936.2	1007.7	246.5	180.3	305.4	-4933.1

Table 6.4 - Ultimate loads: tower top

			Mx	My	Mxy	Mz	Fx	Fy	Fxy	Fz
		Load case	**kNm**	**kNm**	**kNm**	**kNm**	**kN**	**kN**	**kN**	**kN**
Mx	**Max**	**dlc6.2c-3**	215913	33635	218517	6854	445	-2142	2188	-9180
Mx	**Min**	**dlc6.2i-6**	-210583	-42378	214805	-3186	-498	2100	2158	-9273
My	**Max**	**dlc2.1ai+09**	-1587	254803	254807	-1775	2606	52	2606	-11672
My	**Min**	**dlc2.1aj+12**	18057	-185354	186231	-8746	-2031	-212	2042	-11352
Mxy	**Max**	**dlc2.1ai+09**	-1587	254803	254807	-1775	2606	52	2606	-11672
Mxy	**Min**	**dlc4.2cb_2**	47	-15	49	-119	28	-4	29	-11533
Mz	**Max**	**dlc2.2ag+01**	13006	42543	44487	17181	438	26	438	-9505
Mz	**Min**	**dlc2.2ag+08**	-8386	-58862	59456	-18891	-553	52	555	-9306
Fx	**Max**	**dlc2.1ai+04**	28233	260788	262312	10500	2474	-410	2508	-11794
Fx	**Min**	**dlc2.1aj+09**	41251	-166176	171219	-3805	-2133	-543	2201	-11365
Fy	**Max**	**dlc6.2j-2**	-209781	-5887	209863	-3832	-47	2122	2123	-9345
Fy	**Min**	**dlc6.2d-4**	215797	-5588	215869	4428	-25	-2194	2194	-9338
Fxy	**Max**	**dlc2.1ai+04**	28233	260788	262312	10500	2474	-410	2508	-11794
Fxy	**Min**	**dlc1.3a-c5**	118	-2230	2233	129	0	0	0	-11550
Fz	**Max**	**dlc6.2a-1**	32142	32138	45453	84	446	-312	545	-8612
Fz	**Min**	**dlc1.3k-b4**	-11509	19013	22225	1006	228	118	257	-11854

Table 6.5 - Ultimate loads: tower base

6.2 Fatigue Loads

Damage equivalent loads are used to equate the fatigue damage represented by RFCC data to that caused by a single stress range repeating at a single frequency. The method is based on the Miner's rule. The damage equivalent stress is given by the following formula:

$$L_N = \sqrt[m]{\frac{\sum L_i^m n_i}{N}}$$

where L_N is the equivalent stress for N cycles
L_i is the stress range bin i.
n_i is the number of rain flow cycles at stress range bin i.
m is the negative inverse of the slope on the material's Wöhler curve (m is also referred to as the S-N curve slope).
N is the number of cycle repetitions in the turbine lifetime.

The S-N curve slopes (m) used here are 4 representing steel for tower and hub loads and 10 representing glass reinforced plastic (GRP) for blade loads.

The stress, L_i, depends upon the geometry of the structure under consideration. It is assumed that stress is proportional to load, therefore it is quite acceptable to use load instead of stress in the above equation.

For simplicity, L_i and n_i have been derived from the one-dimensional table with no correction to account for the fatigue damage due to mean stresses.

The partial safety factor for fatigue loads required by the IEC 61400 edition 3 is 1.0 and a Rayleigh wind speed distribution with an annual mean wind speed of 10m/s is assumed.

Lifetime-integrated damage equivalent fatigue loads have been calculated for a reference frequency corresponding to 10^7 cycles in 20 years.

Inverse SN Slope	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]	Flapwise Bending Moment [kNm]	Edgewise Bending Moment [kNm]	Flapwise Shear Force [kN]	Edgewise Shear Force [kN]
3	16499.4	9797.8	229.6	298.1	792.4	742.6	11459.7	15639.0	415.9	748.8
4	13715.3	8538.4	197.4	253.5	657.6	623.5	10016.5	12986.1	359.7	620.9
5	12301.6	8167.3	182.7	238.8	588.6	566.6	9521.6	11636.2	337.5	555.3
6	11461.5	8118.5	174.9	234.7	547.1	537.4	9388.1	10830.6	328.2	515.7
7	10915.3	8208.6	170.5	235.2	519.7	523.9	9421.3	10303.9	325.0	489.3
8	10541.0	8364.0	168.0	237.9	500.3	520.7	9538.0	9940.0	325.0	470.6
9	10276.9	8552.3	166.8	241.8	486.0	524.4	9697.2	9680.6	326.9	456.6
10	10089.3	8759.9	166.2	246.3	475.2	532.7	9877.2	9493.7	329.8	445.8
11	9958.1	8982.0	166.2	251.3	466.8	543.8	10066.2	9360.3	333.4	437.3
12	9870.7	9218.0	166.6	256.7	460.2	556.5	10257.6	9268.8	337.4	430.5

Table 6.6 – Lifetime weighted equivalent loads: blade root

Tower Height [m]	**S-N Slope Value**									
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
-20.00	34936.1	36697.6	41208.5	46175.0	50961.7	55408.6	59498.4	63255.1	66711.8	69901.2
-10.00	29573.5	32141.5	36559.8	41180.6	45561.8	49606.7	53317.9	56724.1	59858.1	62750.3
0.00	25013.6	27967.1	32147.1	36368.2	40323.5	43959.3	47291.0	50348.8	53163.8	55763.7
8.00	21951.4	24931.4	28837.8	32714.4	36326.9	39643.4	42683.8	45477.4	48052.4	50433.3
17.76	18710.8	21521.3	25026.8	28456.7	31638.1	34555.9	37232.2	39694.1	41966.7	44071.2
33.28	14965.9	16930.7	19569.7	22207.3	24674.3	26945.8	29034.0	30958.3	32737.2	34386.9
48.80	11404.3	12493.4	14270.8	16120.5	17877.4	19506.9	21011.0	22400.7	23687.9	24883.2
56.56	9499.7	10224.3	11601.7	13071.4	14479.4	15789.7	17000.6	18119.6	19155.6	20117.0
64.32	7507.2	7936.0	8940.9	10045.7	11115.3	12115.7	13042.9	13901.3	14697.4	15436.9
72.08	5473.4	5667.1	6318.5	7068.8	7808.4	8506.1	9156.0	9759.6	10320.5	10842.4
79.84	3607.2	3552.0	3831.3	4213.1	4616.3	5009.4	5381.4	5729.4	6053.8	6355.8
87.60	2638.9	2299.8	2245.0	2291.1	2394.8	2552.4	2762.5	3008.3	3265.8	3518.0

Table 6.7 – Lifetime weighted equivalent loads: tower Mx [kNm]

Tower Height [m]	**S-N Slope Value**									
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
-20.00	65563.4	58273.5	56943.1	57455.0	58790.1	60705.3	63203.4	66323.5	70004.8	74060.4
-10.00	54415.4	49723.2	49173.6	49944.6	51360.1	53286.6	55760.4	58809.9	62344.3	66163.3
0.00	45044.9	42168.6	42112.6	43019.1	44450.8	46354.6	48790.7	51769.4	55163.4	58760.1
8.00	38995.5	37019.6	37194.4	38135.1	39519.6	41333.3	43647.1	46463.7	49645.3	52983.0
17.76	32778.9	31484.4	31814.3	32742.7	34041.2	35723.4	37861.2	40444.3	43329.8	46324.1
33.28	26239.8	25130.8	25357.7	26061.0	27046.8	28316.4	29927.5	31890.1	34110.4	36440.4
48.80	20766.4	19453.4	19487.4	19940.3	20600.1	21429.9	22450.3	23683.3	25107.4	26653.2
56.56	18104.4	16665.8	16582.2	16904.2	17409.3	18046.0	18817.4	19737.7	20802.0	21973.1
64.32	15502.7	13994.9	13801.4	13997.2	14350.5	14793.8	15311.6	15907.3	16586.8	17345.7
72.08	13113.2	11540.9	11219.8	11288.0	11508.2	11799.7	12130.8	12488.5	12867.3	13265.0
79.84	11398.6	9717.3	9237.7	9173.9	9285.9	9481.7	9720.5	9981.5	10253.0	10527.2
87.60	11000.1	9140.8	8495.7	8303.9	8322.7	8451.7	8642.4	8868.6	9114.4	9369.4

Table 6.8 – Lifetime weighted equivalent loads: tower My [kNm]

Tower Height [m]	S-N Slope Value									
	3	4	5	6	7	8	9	10	11	12
-20.00	11687.9	9588.4	8821.8	8543.7	8489.6	8552.7	8683.3	8856.3	9058.1	9280.7
-10.00	11687.9	9588.4	8821.8	8543.6	8489.6	8552.7	8683.3	8856.3	9058.1	9280.7
0.00	11687.9	9588.3	8821.8	8543.7	8489.6	8552.7	8683.3	8856.3	9058.1	9280.7
8.00	11687.8	9588.3	8821.7	8543.6	8489.6	8552.7	8683.3	8856.2	9058.1	9280.6
17.76	11687.5	9588.0	8821.5	8543.4	8489.4	8552.6	8683.2	8856.2	9058.1	9280.6
33.28	11686.8	9587.4	8820.8	8542.7	8488.5	8551.5	8681.8	8854.5	9056.2	9278.5
48.80	11685.9	9586.8	8820.3	8542.2	8488.1	8551.1	8681.4	8854.2	9055.8	9278.2
56.56	11685.0	9586.1	8819.8	8541.9	8487.8	8550.9	8681.3	8854.1	9055.8	9278.2
64.32	11683.9	9585.2	8819.1	8541.1	8487.2	8550.3	8680.7	8853.6	9055.4	9277.9
72.08	11682.7	9584.2	8818.3	8540.5	8486.7	8549.9	8680.5	8853.4	9055.2	9277.8
79.84	11681.7	9583.4	8817.5	8539.8	8486.1	8549.4	8680.1	8853.1	9055.0	9277.6
87.60	11680.2	9581.8	8815.6	8537.6	8483.4	8546.3	8676.7	8849.5	9051.4	9274.2

Table 6.9 – Lifetime weighted equivalent loads: tower Mz [kNm]

Tower Height [m]	S-N Slope Value									
	3	4	5	6	7	8	9	10	11	12
-20.00	1397.0	1075.8	954.6	904.2	885.3	882.5	888.6	900.0	914.6	931.3
-10.00	1349.3	1041.6	926.3	878.9	861.7	859.7	866.2	877.7	892.2	908.7
0.00	1060.5	838.6	761.0	733.6	727.7	732.4	742.9	757.3	774.6	794.4
8.00	941.9	757.1	695.8	676.8	675.4	682.8	695.3	711.5	731.1	753.9
17.76	824.5	678.2	633.5	622.5	625.5	635.5	650.1	668.9	691.9	719.0
33.28	644.3	560.5	540.4	540.7	549.7	564.1	583.5	608.2	638.2	672.2
48.80	524.8	481.5	476.0	483.3	497.2	516.5	541.5	572.4	608.0	646.1
56.56	514.1	472.9	468.4	476.2	490.3	510.0	535.9	568.2	605.5	645.1
64.32	527.3	479.6	473.2	480.1	493.5	512.2	536.7	567.5	603.5	642.3
72.08	542.9	486.7	478.2	484.3	497.1	515.0	538.6	568.4	603.5	641.8
79.84	553.5	490.3	480.0	485.6	498.2	515.7	538.6	567.5	601.7	639.2
87.60	550.7	486.2	475.8	481.5	494.0	511.4	533.9	562.4	596.4	633.7

Table 6.10 – Lifetime weighted equivalent loads: tower Fx [kN]

Tower Height [m]	**S-N Slope Value**									
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
-20.00	694.2	580.1	555.5	564.0	587.3	617.1	649.0	680.8	711.5	740.6
-10.00	669.8	562.3	541.2	552.1	577.1	608.1	640.7	672.9	703.8	733.0
0.00	524.3	461.0	464.3	491.5	527.1	564.3	600.5	634.7	666.4	695.9
8.00	465.2	422.4	436.9	470.5	509.5	548.3	585.2	619.6	651.4	680.8
17.76	407.2	386.3	411.8	450.8	491.9	531.6	568.6	602.9	634.5	663.6
33.28	321.7	336.0	376.0	420.5	463.5	503.4	540.2	574.0	605.1	633.8
48.80	270.0	302.3	347.8	393.5	436.3	475.5	511.5	544.5	575.0	603.2
56.56	269.5	298.2	341.9	386.5	428.4	467.1	502.6	535.3	565.5	593.5
64.32	278.6	299.0	339.2	381.9	422.7	460.6	495.4	527.5	557.2	584.8
72.08	289.2	299.9	335.8	376.4	415.9	452.7	486.8	518.3	547.4	574.4
79.84	296.4	298.5	330.4	368.8	406.8	442.5	475.6	506.3	534.6	560.9
87.60	294.3	292.2	321.6	358.4	395.2	430.1	462.4	492.4	520.1	545.9

Table 6.11 – Lifetime weighted equivalent loads: tower Fy [kN]

Tower Height [m]	**S-N Slope Value**									
	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
-20.00	285.4	236.8	223.2	221.8	225.6	231.9	239.3	247.3	255.4	263.3
-10.00	285.4	236.8	223.2	221.8	225.6	231.9	239.3	247.3	255.4	263.3
0.00	285.5	236.8	223.3	221.8	225.6	231.9	239.4	247.3	255.4	263.4
8.00	285.5	236.8	223.3	221.8	225.6	231.9	239.4	247.3	255.4	263.4
17.76	285.5	236.8	223.3	221.8	225.6	231.9	239.3	247.3	255.4	263.3
33.28	285.5	236.8	223.3	221.8	225.6	231.9	239.3	247.3	255.4	263.3
48.80	285.5	236.8	223.3	221.8	225.6	231.9	239.3	247.3	255.4	263.3
56.56	285.5	236.8	223.3	221.8	225.6	231.9	239.3	247.3	255.4	263.3
64.32	285.5	236.8	223.3	221.8	225.6	231.9	239.3	247.3	255.4	263.3
72.08	285.5	236.8	223.3	221.8	225.6	231.8	239.3	247.3	255.4	263.3
79.84	285.4	236.8	223.2	221.8	225.6	231.8	239.3	247.3	255.4	263.3
87.60	285.4	236.8	223.2	221.8	225.6	231.8	239.3	247.3	255.4	263.4

Table 6.12 – Lifetime weighted equivalent loads: tower Fz [kN]

Inverse SN Slope	**Mx** [kNm]	**My** [kNm]	**Mz** [kNm]	**Fx** [kN]	**Fy** [kN]	**Fz** [kN]
3	2511.8	11522.0	11539.8	487.7	4622.9	4621.9
4	2155.9	9781.7	9793.4	446.5	3831.9	3831.0
5	2090.4	9128.5	9135.6	443.7	3424.2	3423.3
6	2133.5	8881.2	8882.6	452.6	3177.0	3176.1
7	2240.4	8824.6	8817.4	466.3	3011.6	3010.7
8	2403.8	8871.7	8851.5	483.3	2893.4	2892.5
9	2616.3	8981.8	8942.7	504.0	2804.8	2803.9
10	2857.5	9134.6	9068.8	529.4	2736.0	2735.0
11	3105.2	9319.1	9217.3	559.8	2681.0	2680.1
12	3345.0	9529.3	9380.4	593.5	2636.2	2635.2

Table 6.13 – Lifetime weighted equivalent loads: hub (rotating coordinates)

Inverse SN Slope	**Mx** [kNm]	**My** [kNm]	**Mz** [kNm]	**Fx** [kN]	**Fy** [kN]	**Fz** [kN]
3	2511.8	10497.6	10531.9	487.7	346.7	398.3
4	2155.9	8746.1	8747.6	446.5	271.3	310.6
5	2090.4	8130.7	8104.6	443.7	251.0	280.5
6	2133.5	7944.5	7885.9	452.6	252.1	270.3
7	2240.4	7960.0	7861.9	466.3	264.5	268.8
8	2403.8	8082.9	7939.0	483.3	282.7	271.7
9	2616.3	8267.1	8074.0	504.0	303.0	276.8
10	2857.5	8487.7	8245.6	529.4	323.5	283.0
11	3105.2	8729.2	8442.3	559.8	342.9	289.6
12	3345.0	8981.5	8657.5	593.5	361.1	296.4

Table 6.14 – Lifetime weighted equivalent loads: hub (stationary coordinates)

Inverse SN Slope	**Mx** [kNm]	**My** [kNm]	**Mz** [kNm]	**Fx** [kN]	**Fy** [kN]	**Fz** [kN]
3	2612.7	10999.3	11688.2	569.2	305.2	285.1
4	2279.8	9139.7	9588.6	505.5	305.6	236.4
5	2228.1	8494.2	8821.9	496.1	337.7	222.8
6	2276.8	8301.8	8543.7	502.9	376.8	221.4
7	2383.9	8319.5	8489.7	516.5	415.8	225.2
8	2545.8	8446.8	8552.7	535.3	452.5	231.5
9	2760.1	8635.2	8683.3	559.6	486.7	239.0
10	3008.9	8858.5	8856.2	590.1	518.2	247.0
11	3267.9	9100.7	9058.1	626.2	547.4	255.1
12	3520.8	9351.8	9280.6	665.8	574.5	263.1

Table 6.15 – Lifetime weighted equivalent loads: yaw bearing

7. CPC and IPC load comparison

This section reports the load comparison between collective pitch controller and individual pitch controller both in terms of ultimate and fatigue loads.

7.1 Ultimate loads

Table 7.1 to Table 7.5 show that IPC ultimate loads are comparable with the ones achieved by CPC. The percentage change is computed relative to the CPC load.

The largest difference is a 10% reduction, with most components within 2%. Moreover, ultimate loads occur mostly in the same load cases for the two control strategies.

		CPC		IPC		%
Flap BM	[kNm]	dlc2.1ai+08	25719	dlc2.1ai+05	25823	**0.4**
Edge BM	[kNm]	dlc2.1aj+04	15392	dlc2.1aj+09	15135	**-1.7**
Mz	[kNm]	dlc2.1ai+05	1333	dlc2.1ai+05	1302	**-2.3**
Flap SF	[kN]	dlc2.1ai+08	782	dlc2.1ai+09	752	**-3.7**
Edge SF	[kN]	dlc2.1aj+07	556	dlc2.1aj+04	529	**-4.7**
Fz	[kN]	dlc2.1ai+09	1991	dlc2.1ai+09	1969	**-1.1**

Table 7.1 - Ultimate loads comparison: blade root

		CPC		IPC		%
Mx	[kNm]	dlc1.3k-c6	8675	dlc1.3k-a2	8412	**-3.0**
My	[kNm]	dlc1.4aq4	24683	dlc1.4ao2	23889	**-3.2**
Mz	[kNm]	dlc1.4ar1	20210	dlc1.4ar1	20158	**-0.3**
Myz	[kNm]	dlc1.4aq4	24741	dlc1.4ao2	23899	**-3.4**
Fx	[kN]	dlc2.1ai+12	1778	dlc2.1ah+03	1736	**-2.4**
Fy	[kN]	dlc1.3i-c6	1682	dlc1.3i-b3	1713	**1.9**
Fz	[kN]	dlc1.3k-c5	1676	dlc1.3k-c5	1686	**0.6**
Fyz	[kN]	dlc1.4aq1	1780	dlc1.3k-c6	1780	**0.0**

Table 7.2 - Ultimate loads comparison: hub (rotating coordinates)

		CPC		IPC		%
Mx	[kNm]	dlc1.3k-c6	8675	dlc1.3k-a2	8412	**-3.0**
My	[kNm]	dlc1.4ao2	23367	dlc1.4ao2	23254	**-0.5**
Mz	[kNm]	dlc2.2ag+06	20058	dlc2.2ag+08	18673	**-6.9**
Myz	[kNm]	dlc1.4aq4	24741	dlc1.4ao2	23899	**-3.4**
Fx	[kN]	dlc2.1ai+12	1778	dlc2.1ah+03	1736	**-2.4**
Fy	[kN]	dlc6.1a-6	1067	dlc6.1a-6	1067	**0.0**
Fz	[kN]	dlc1.4aq1	1751	dlc1.3k-c6	1779	**1.6**
Fyz	[kN]	dlc1.4aq1	1780	dlc1.3k-c6	1780	**0.0**

Table 7.3 - Ultimate loads comparison: hub (stationary coordinates)

		CPC		IPC		%
Mx	[kNm]	dlc6.2c-3	215913	dlc6.2c-3	215913	**0.0**
My	[kNm]	dlc2.1ai+12	257909	dlc2.1ai+09	254803	**-1.2**
Mxy	[kNm]	dlc2.1ai+09	260427	dlc2.1ai+09	254807	**-2.2**
Mz	[kNm]	dlc2.2ag+01	20946	dlc2.2ag+08	18891	**-9.8**
Fx	[kN]	dlc2.1ai+09	2525	dlc2.1ai+04	2474	**-2.0**
Fy	[kN]	dlc6.2d-4	2194	dlc6.2d-4	2194	**0.0**
Fxy	[kN]	dlc2.1ai+09	2544	dlc2.1ai+04	2508	**-1.4**
Fz	[kN]	dlc1.3k-c5	11844	dlc1.3k-b4	11854	**0.1**

Table 7.4 - Ultimate loads comparison: tower base

		CPC		IPC		%
Mx	[kNm]	dlc1.3k-a1	8905	dlc1.3k-a2	8701	**-2.3**
My	[kNm]	dlc1.4ao2	26576	dlc1.4ao2	26529	**-0.2**
Mxy	[kNm]	dlc1.4ao2	26610	dlc1.4ao2	26541	**-0.3**
Mz	[kNm]	dlc2.2ag+01	20981	dlc2.2ag+08	18910	**-9.9**
Fx	[kN]	dlc2.1ai+09	2136	dlc2.1ai+05	2022	**-5.3**
Fy	[kN]	dlc6.2d-4	1596	dlc6.2d-4	1596	**0.0**
Fxy	[kN]	dlc2.1ai+09	2137	dlc2.1ai+04	2073	**-3.0**
Fz	[kN]	dlc1.3k-c5	4923	dlc1.3k-b4	4933	**0.2**

Table 7.5 - Ultimate loads comparison: tower top

7.2 Fatigue loads

Tables 7-7, 7-11 show that IPC is capable of improving most of fatigue loads, especially the asymmetric ones as expected from the control design ([1], [2] and [3]). In particular blade root My, rotating hub My and Mz are reduced up to 30%. Reduction of 11% is achieved for the stationary hub and tower Mz.

	CPC	IPC	%
Mx [kNm]	10178.3	10089.3	**-0.9%**
My [kNm]	11385.1	8759.9	**-23.1%**
Mz [kNm]	314.7	246.3	**-21.7%**
Fx [kN]	475.2	475.2	**0.0%**
Fy [kN]	532.2	532.7	**0.1%**
Fz [kN]	9576.3	9493.7	**-0.9%**
Flap BM [kNm]	365.6	329.8	**-9.8%**
Edge BM [kNm]	446.7	445.8	**-0.2%**
Flap SF [kN]	10178.3	10089.3	**-0.9%**
Edge SF [kN]	11385.1	8759.9	**-23.1%**

Table 7.6 - Lifetime weighted equivalent loads comparison: blade root

	CPC	IPC	%
Mx [kNm]	2153.7	2155.9	**0.1%**
My [kNm]	14029.1	9781.7	**-30.3%**
Mz [kNm]	13974.0	9793.4	**-29.9%**
Fx [kN]	444.4	446.5	**0.5%**
Fy [kN]	3824.5	3831.9	**0.2%**
Fz [kN]	3821.2	3831.0	**0.3%**

Table 7.7 - Lifetime weighted equivalent loads comparison: hub (rotating coordinates)

	CPC	IPC	%
Mx [kNm]	2153.7	2155.9	**0.1%**
My [kNm]	9829.2	8746.1	**-11.0%**
Mz [kNm]	9869.3	8747.6	**-11.4%**
Fx [kN]	444.4	446.5	**0.5%**
Fy [kN]	272.3	271.3	**-0.4%**
Fz [kN]	312.6	310.6	**-0.6%**

Table 7.8 - Lifetime weighted equivalent loads comparison: hub (stationary coordinates)

	CPC	IPC	%
Mx [kNm]	2309.5	2279.8	**-1.3%**
My [kNm]	10168.0	9139.7	**-10.1%**
Mz [kNm]	10647.0	9588.6	**-9.9%**
Fx [kN]	503.5	505.5	**0.4%**
Fy [kN]	302.3	305.6	**1.1%**
Fz [kN]	238.9	236.4	**-1.0%**

Table 7.9 - Lifetime weighted equivalent loads comparison: yaw bearing

	CPC	IPC	%
Mx [kNm]	36258.1	36697.6	**1.2%**
My [kNm]	57595.7	58273.5	**1.2%**
Mz [kNm]	10647.1	9588.4	**-9.9%**
Fx [kN]	1080.0	1075.8	**-0.4%**
Fy [kN]	575.7	580.1	**0.8%**
Fz [kN]	239.4	236.8	**-1.1%**

Table 7.10 - Lifetime weighted equivalent loads comparison: tower base

7.3 Example simulation results

Some simulation results are reported in this section to show the behaviour of the controllers in different conditions.

Figure 7-1 shows the behaviour of the two controllers in turbulent wind condition at cut-out. In particular the blade pitch angle time history shows how the three blade pitch angles for the IPC case oscillate around the collective pitch angle dictated by the CPC. Rotating hub My is reported as an example to show load reduction achieved with IPC.

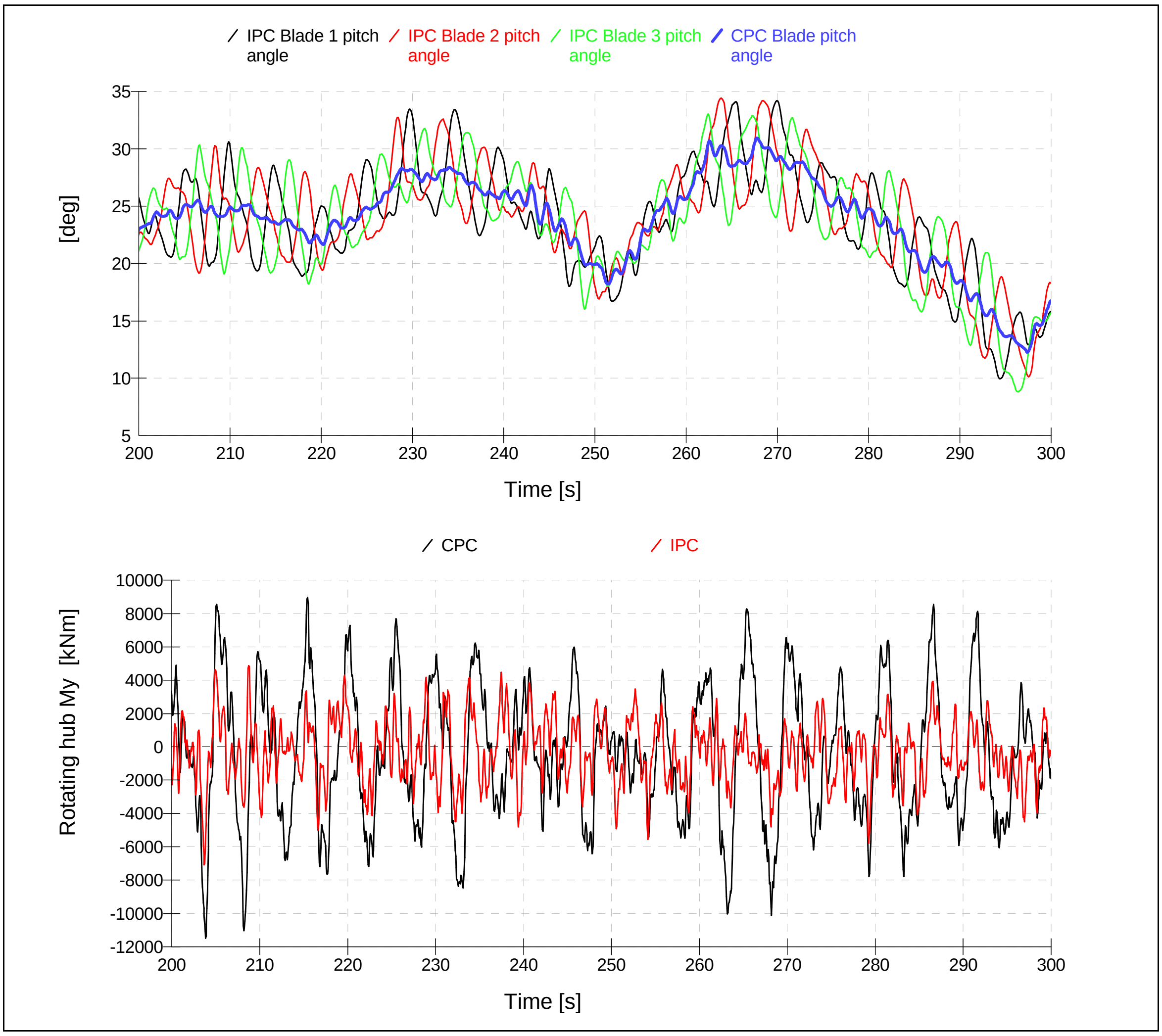


Figure 7-1 Turbulent wind condition

Load case 1.5 represents an extreme wind shear case. In this particular scenario the wind distribution on the rotor is highly asymmetric and this is one of the cases where an IPC approach could reduce asymmetric loads. As an example Figure 7-2 reports blade root out of plane bending moment and rotating hub Mz for dlc1.5 h_2_1 where horizontal extreme shear at 13.4m/s steady wind condition occurs. The figure shows the load reduction achieved by using IPC.

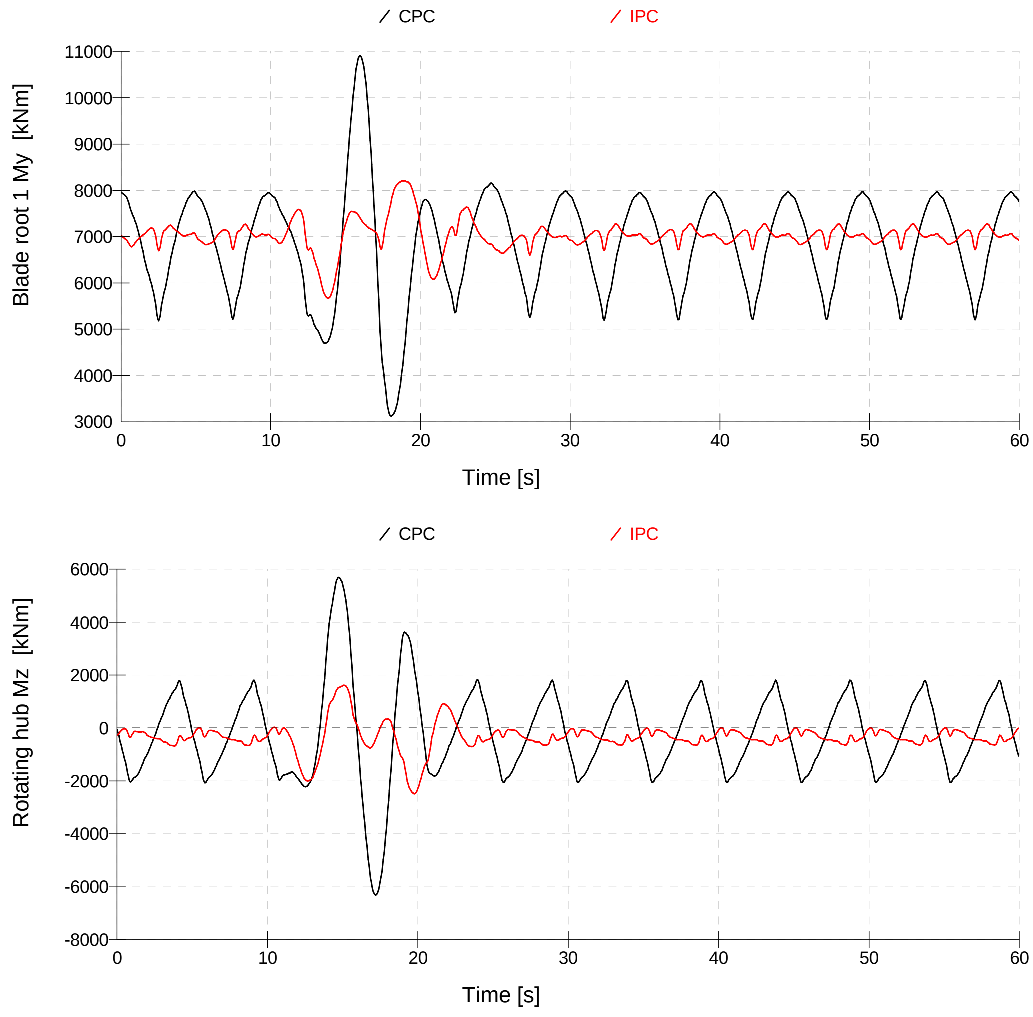


Figure 7-2 Extreme horizontal wind shear case

Load case 1.4 represents wind gust with extreme direction change. A normal shutdown is triggered when the yaw error exceeds a certain value and since normal shutdown is carried on with the controller in the loop the benefits of IPC reducing asymmetrical loads are still visible. As an example Figure 7-3 reports the case around rated and shows the reduction on rotating hub My and Mz load components.

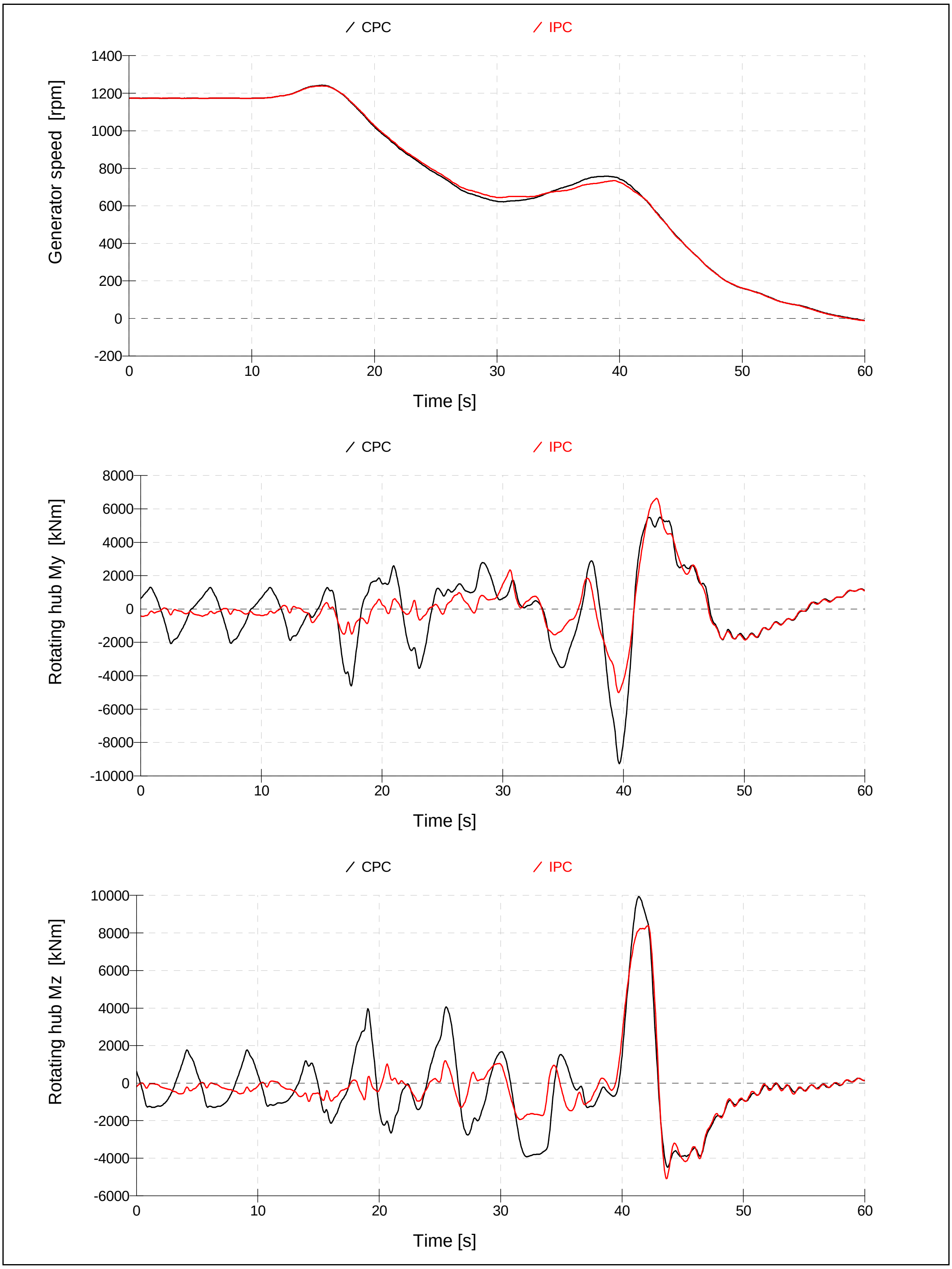


Figure 7-3 Extreme direction change case

8. Conclusions

A supervisory controller has been designed for the UPWIND 5MW reference turbine whose power production controller has been described in [1]. Shutdown conditions might be critical when an IPC controller is employed, as the blades might be pitched at different pitch angles during the shutdown thus increasing asymmetric loads and diminishing the benefits of using an IPC strategy. For this reason shutdown and fault detection logic has been designed to limit IPC extreme loads to the values obtained with a collective pitch controller. A load calculations analysis based on IEC 61400-1 edition 3 has been run to compare both fatigue and extreme loads against the ones achieved with a CPC.

The main conclusion from the design exercise is that the individual pitch action needs to be phased out when a shutdown is likely to occur (this can be done for example by monitoring rotor acceleration, or by limiting individual pitch activity in higher wind conditions) in order to align the blades as much as possible before the shutdown eventually occurs. Using this method, and suitable logic especially for pitch failure detection, the ultimate loads are comparable with the ones achieved using a collective pitch controller. It is important to note that, without increasing ultimate loads, IPC is capable of improving fatigue loads. The maximum improvement is a reduction of up to 30% on asymmetric loads.

Based on the load sensor failure modes modelled to date, the potential impact of load sensor failure is limited to reducing IPC controller performance, without leading to severe load conditions. However, strategies to detect load sensor failures should be implemented in supervisory logic.

Possible developments of this work could be to investigate other possible methods for a safe blade alignment during shutdowns and a more detailed investigation of possible failure modes and their implications on loads.

9. References

[1] Controller for 5MW reference turbine, E Bossanyi, Project UpWind Report 11593/BR/04/A

[2] Wind Turbine Control for Load Reduction, E Bossanyi, Wind Energy 2003 vol 6 pp 229-244.

[3] Developments in Individual Blade Pitch Control, E Bossanyi, “The Science of making Torque from Wind” Delft University of Technology, The Netherlands, April 19-21 2004.

[4] IEC 61400-1 International standard, Wind turbine generator systems – Part 1: Safety Requirements, 1998.

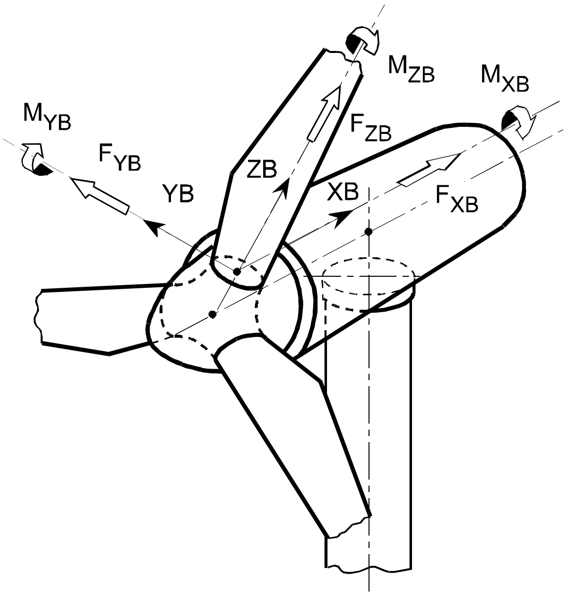
[5] IEC 61400-1 International Standard, Wind turbines – Part1: Design requirements, Third edition, 2005.

[6] CDV IEC 61400-1 A1 rev, International Standard, Wind turbines – Part1: Design requirements, Third edition, October 2008

[7] *Bladed* Theory Manual, October 2010.

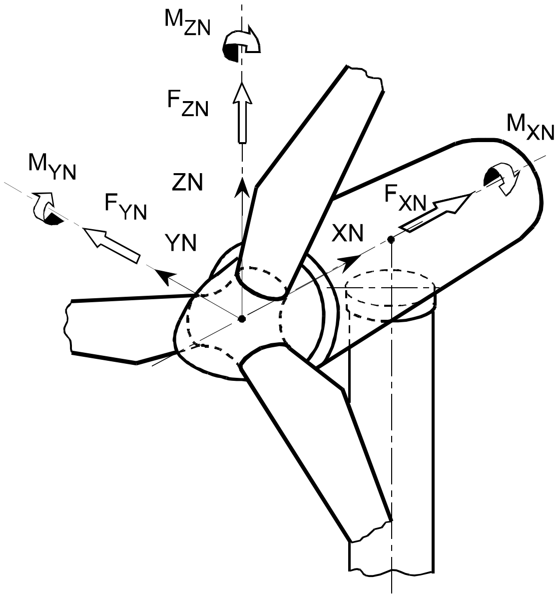
Appendix A

The co-ordinate systems used in this report are defined by the GL regulation [4] and are shown in Figures 3.1 to 3.3 below.



ZB	Radially along blade axis.
XB	Perpendicular to ZB, and pointing towards the tower for an upwind turbine, or away from the tower for a downwind turbine (the picture shows an upwind turbine).
YB	Perpendicular to blade axis and shaft axis, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.
Origin	At each blade station.

Figure 0-1 Co-ordinate system for blade loads and deflections



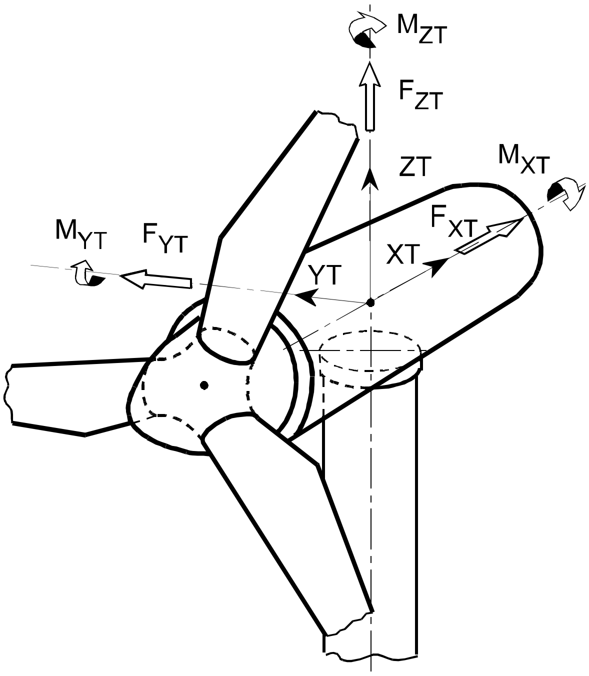
Hub loads in fixed frame of reference:

XN	Along shaft axis, and pointing towards the tower for an upwind turbine, or away from the tower for a downwind turbine (the picture shows an upwind turbine).
ZN	Perpendicular to XN, such that ZN would be vertically upwards if the tilt angle were zero.
YN	Horizontal, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.

Hub loads in rotating frame of reference:

XN	Along shaft axis, and pointing towards the tower for an upwind turbine, or away from the tower for a downwind turbine (the picture shows an upwind turbine).
ZN	Perpendicular to XN, such that ZN would be aligned with blade 1 axis if the cone angle were zero.
YN	Perpendicular to XN and ZN, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.
Origin	At hub centre (intersection of blade and shaft axes).

Figure 0-2 Co-ordinate system for hub loads



XT	Pointing South.
ZT	Vertically upwards.
YT	Pointing East.
Origin	At each tower station.

Figure 0-3 Co-ordinate system for tower loads and deflections