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PERFORMANCE STUDY OF WIND TURBINES WITH BEND-TWIST COUPLED BLADES AT UNDERRATED WIND SPEEDS

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ABSTRACT

Use of bend-twist coupled blades is one of the ways to alleviate fatigue loads in wind turbine systems. Load reduction is achieved by placing off-axis layers in the spar caps of composite wind turbine blades. Off-axis layers provide twisting of the blade in the feathering direction thereby decreasing the aerodynamic loads due to the reduced effective angle of attack. Reduction of fatigue loads in the wind turbine system is generally measured by the damage equivalent load. In the present study, performance of bend-twist coupled blades designed for a 5 MW wind turbine is investigated for the wind speeds ranging from the cut-in speed to the overrated wind speeds. The initial analysis of the wind turbine is done at the overrated speed of 15 m/s and it is shown that reduction in damage equivalent loads is achieved at almost no loss in the rated power compared to the reference wind turbine with the baseline blade. However, it is also demonstrated that at the underrated speeds; although reduction in damage equivalent loads can still be achieved with the bend-twist coupled blade, power loss occurs compared to the reference turbine. This study aims to make a performance study of wind turbine systems with bend-twist coupled blades in terms of load reduction achieved and power production and to propose modifications to simultaneously reduce the generator power losses and damage equivalent loads. As a preliminary design modification, it is shown that by reducing the pre-twist angle of the bend-twist coupled sections of the blades, it has been possible to eliminate the power loss disadvantage of wind turbines at the underrated wind speeds, while still achieving reduction in damage equivalent loads.

INTRODUCTION

Wind turbines of the next generation will be bigger with long blades because the power demand from the wind turbines increases every day and to get the highest power from a single turbine is the most efficient way. However, when the turbine gets bigger, loads which occur due to the bending and twisting of the blades get higher and should be alleviated to improve the fatigue life and the reliability of the wind turbine system. The fatigue loads should be alleviated because fatigue loads decrease the operational life of the wind turbine and its subsystems. The operational life is the very important for the customer of a wind turbine due to the operational cost.

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Load alleviation in wind turbines can be performed by two main control mechanisms which are active and passive. Passive control is achieved utilizing the anisotropic behavior of the composite material used in the wind turbine blade. Active control mechanisms are commonly the pitch angle control of the blade or the trailing edge flap control. Passive control depends on the bending-twisting coupling potential of the wind turbine blade. Bend-twist coupling occurs due to the anisotropy of the composite material. When a bending load is applied to the bend-twist coupled blade, twisting occurs due to bending and vice versa. For symmetric composite laminates, Equation 1 gives the relation between the moment resultants and the curvatures for a mid-plane symmetric composite laminate [Jones, 1999]. Coupling stiffness coefficients D_{16} and D_{26} terms account for the bending-twisting coupling in composite laminates. For isotropic materials, coupling coefficients D_{16} and D_{26} are zero.

$$\begin{Bmatrix} M_{edgewise} \\ M_{flapwise} \\ M_{torsion} \end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} K_{edgewise} \\ K_{flapwise} \\ K_{torsion} \end{Bmatrix} \tag{1}$$

In wind turbine blades, off-axis layers provide twisting of the blade in the feathering direction thereby decreasing the aerodynamic loads due to reduced effective angle of attack. Thus, damage equivalent loads in the wind turbine system also decrease. However, at the underrated speeds; although reduction in damage equivalent loads can still be achieved with the bend-twist coupled blade, power loss occurs compared to the reference turbine. Hence, the generated power in wind turbines with the bend-twist coupled blade is less than the one in the reference wind turbine at underrated wind speeds.

In the literature, there have been studies on the load alleviation in wind turbine blades using bend-twist coupled blades. Gözcü et al. [Gözcü, 2014] demonstrated the use of super element model of the turbine blade in the wind turbine system and obtained reductions in damage equivalent loads in the whole wind turbine system at the overrated wind speed of 15 m/s for a 5 MW wind turbine. Gözcü et al. [Gözcü, 2015] investigated the effect of hybrid usage of GFRP-CFRP in wind turbine blades on the reduction of fatigue damage equivalent loads in the wind turbine system, again at the overrated wind speed of 15 m/s for the 5 MW wind turbine system. Hayat and Ha [Hayat, 2015] studied load mitigation in wind turbine blade by aeroelastic tailoring via unbalanced laminates composites. Şener et al. [Şener, 2017] investigated the damage equivalent loads at several crucial monitor points and examined maximum stresses in the bend-twist coupled wind turbine blades.

The main objective of the present study is to investigate the effect of bend-twist coupled blades on the reduction of damage equivalent loads and power generation for a 5 MW wind turbine system across the turbulent wind profiles with mean velocities ranging from the cut-in speed to the overrated wind speeds. For this purpose, in the first phase of the study, a reference wind turbine blade and a reference 5 MW wind turbine system is established and the effect of off-axis fiber angle of the bend-twist coupled blades on the load reduction and power generation is studied in detail. In the second phase of the study, modifications are proposed in the pre-twist schedule of the wind turbine blade to simultaneously reduce damage equivalent loads and power loss across the wide range of wind speeds.

METHOD

Wind Turbine Modeling

In this study, NREL's 5 MW [Jonkman, 2009] wind turbine is used as the reference wind turbine and full glass fiber reinforced plastic (GFRP) blade has been used as the reference blade. Most of the properties of the NREL's 5 MW wind turbine are used directly but some of the properties are modified such as the rotor speed, generator torque curve, due to the change in the gear ratio from 97 to 105. Table 1 presents the main properties of the 5 MW reference wind turbine system with flexible blade and tower models.

Table 1: Main properties of the reference wind turbine

Nominal power	5 MW
Number of blades	3
Blade prebent at the tip	4 m
Rated rotor speed	12 RPM
Rated wind speed	12 m/s
Demanded rated generator torque	37880 Nm
Gearbox ratio	105
Rotor/Hub diameter	126 m / 4 m
Hub length	4 m
Blade length	61.5 m
Rotor conicity	0°
Rotor tilt angle	5°
Tower centerline elevation	98.2 m
Hub height	100 m
Hub mass	50,000 kg
Hub inertia	100000 kgm^2

The full GFRP reference blade design is based on the previous study of Gözcü et al. [Gözcü, 2014]. Bend-twist coupled blades are designed by modifying the fiber angle in the outboard blade section towards the leading edge. Figure 1 describes the bend-twist coupled blade design. In this study, bend-twist coupled blades are composed of full GFRP material. In the bend-twist sections of the blade, unidirectional GFRP plies between the shear webs in the pressure and suction side of the blades are rotated towards the leading edge by the off-axis ply angle θ. In the present study, performance study of the wind turbine having GFRP bend-twist coupled blade with 5° off-axis ply angle has been performed. For higher fiber angles, similar study can be performed and such a study is planned as the future work. Thus, three different bend-twist coupled blade configurations are generated. As shown in Figure 1, bend-twist sections of the blade are in the 30 m of the blade measured from the tip of the blade.

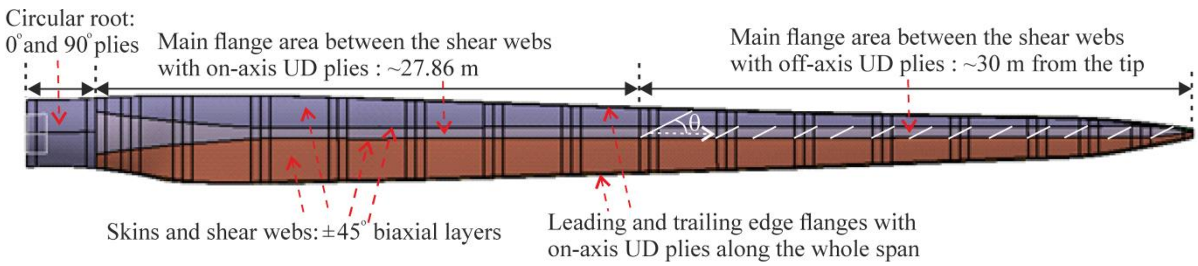

Figure 1: Description of the bend-twist coupled blade design

Multibody simulations of the wind turbine system

Multibody simulations of the wind turbine system are performed in the multibody wind turbine simulation code PHATAS [Lindenburg, 2012]. Firstly, reference wind turbine model is set up in PHATAS. Figure 2 shows the standard drive train model of the wind turbine system used in PHATAS.

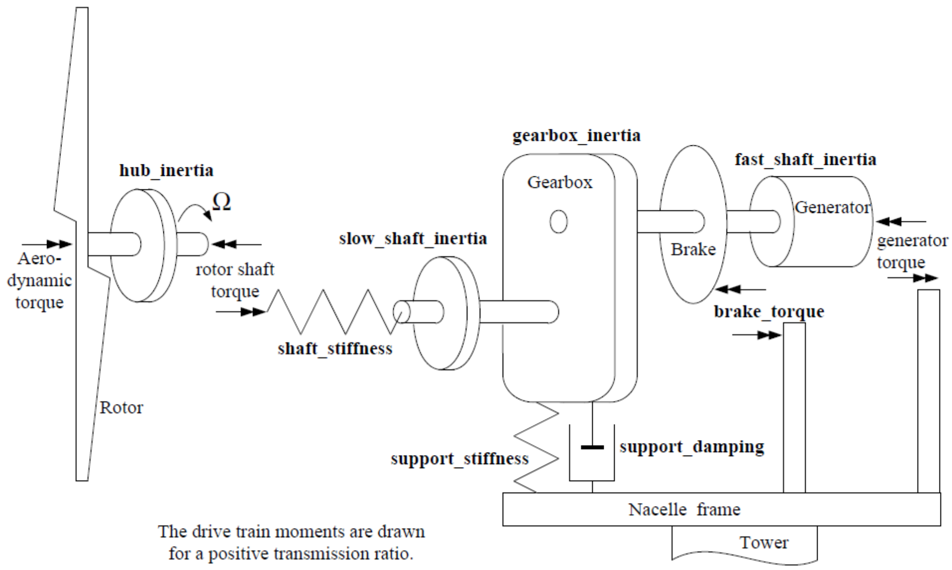

Figure 2: Drive train model in PHATAS

In the PHATAS model, blades are modeled as geometrically non-linear beams. The blade is divided into 17 elements and in the present study, sectional properties of the beam blade are calculated by VABS [Hodges, 2012]. For the stiffness properties of the beam model, Timoshenko stiffness matrix, which is calculated by the variational asymptotic beam section analysis method, is used. Thus, for the bend-twist coupled blades, coupling stiffness coefficients are taken into account properly.

The turbulence generator of PHATAS is the SWIFT code [Winkelaar, 1992]. Important settings used in PHATAS simulations are given in Table 2.

Table 2: PHATAS simulation settings

Number of blade elements	17
Turbulent wind generator	SWIFT15
Control	PD pitch speed control
Control increment	0.01 s

Wind turbine simulations are performed for the reference wind turbine with the baseline GFRP blade and for wind turbines with bend-twist coupled blades. For damage equivalent load calculations, random turbulent wind profiles are generated for mean wind speeds ranging from the cut-in speed to the overrated wind speed of 20 m/s. On the other hand, power curve calculations of the reference wind turbine and the wind turbine with bend-twist coupled blades are performed at uniform wind speeds ranging from the cut-in speed to the overrated wind speed of 20 m/s.

Damage equivalent loads are calculated using Equation 2 which is derived based on the assumption that fatigue loads (F) are related with number of load cycles (N) such that the product F^mN is constant and in the Miner's rule, damage term is taken as 1 which indicates the occurrence of the fatigue failure. In Equation 2, N_{ref} is the reference number of cycles (10^8), m is the fatigue exponent with typical values in the range 3-10 depending on the material system, and F_i is the internal load corresponding to i^{th} bin with n_i being the number of fatigue load cycles corresponding to i^{th} bin.

$$F_{ref} = \sum_{i=1}(F_i^m n_i)/N_{ref} \quad (2)$$

RESULTS

Effect of bend-twist coupling on the power curves

For the reference wind turbine with the baseline blade with glass fiber oriented at 0° with respect to the blade axis and for the wind turbine with the bend-twist coupled blade with glass fiber oriented at 5° with respect to the blade axis, power curves are compared in Figure 3.

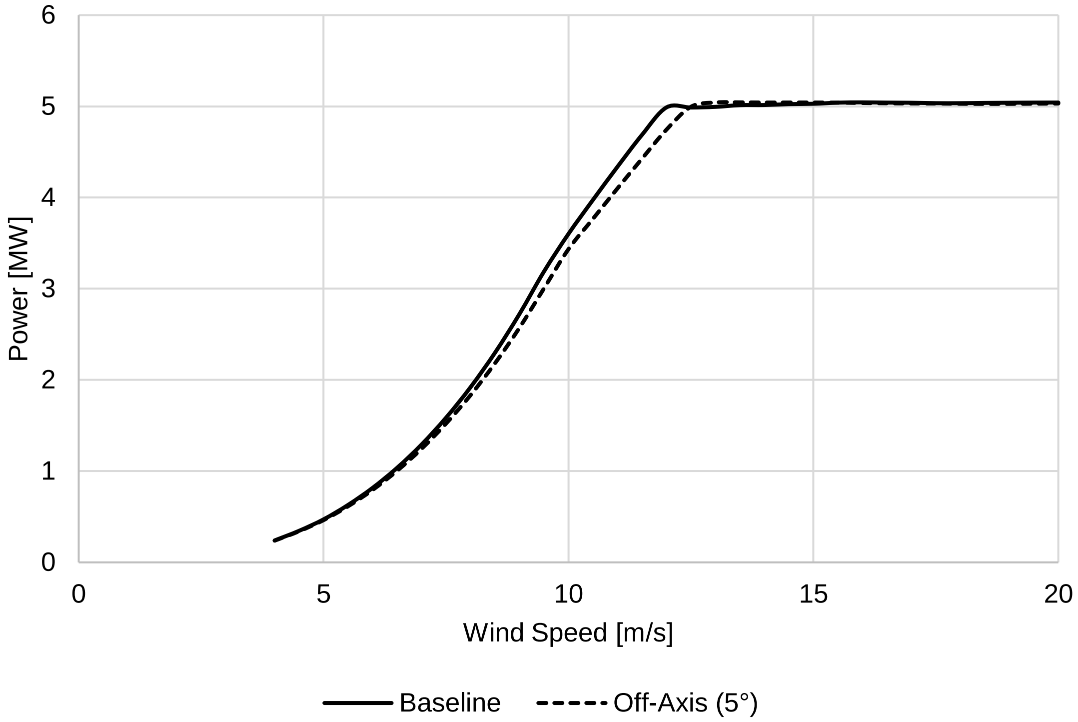

Figure 3: Power curves of the reference wind turbine and wind turbine with bend-twist coupled blade

As seen in Figure 3, wind turbine with the bend-twist coupled blade gives lower power than the reference wind turbine with the baseline blade at underrated wind speeds. On the other hand, both turbines produce the rated power of 5 MW at the overrated wind speeds. Moreover, wind turbine with the bend-twist coupled blade has a slightly higher rated wind speed than the reference wind turbine.

To compensate for the loss of power at the underrated wind speeds, it is decided to change twist schedule of all blades of wind turbine until the desired power increase is achieved at underrated wind speeds with no increase or small acceptable increase in damage equivalent loads. To compensate for the power loss, the pre-twist angles of the bend-twist sections of the GFRP bend-twist coupled blade with 5° off-axis ply angle are reduced. Reduction of the pre-twist angle increases the effective angle of attack of the blade sections which in turn increases the lift on the blades; therefore, the aerodynamic torque is also increased resulting in increase of the power at underrated wind speeds. The original and the modified twist schedules used in the GFRP bend-twist blade with 5° ply angle are given in Figure 4. Besides the original pre-twist of the blade, four different modified pre-twist configurations are implemented in the bend-twist coupled blade.

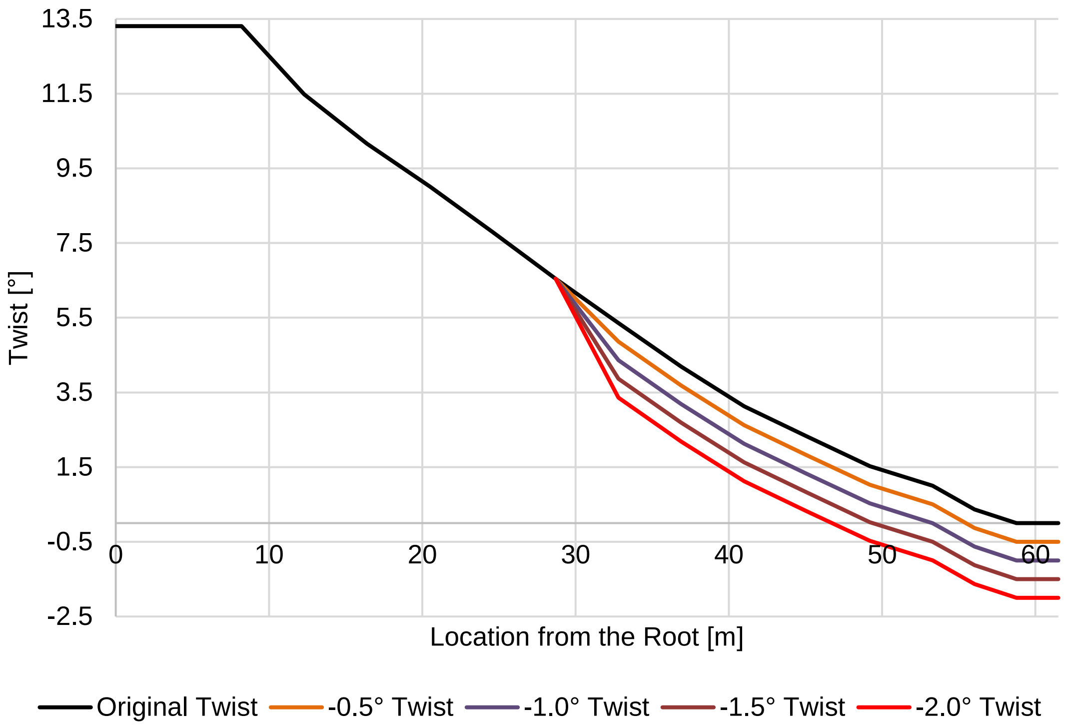

Figure 4: Twist schedules of the reference blade and GFRP bend-twist coupled blade with 5° off-axis ply angle

As seen in Figure 4, only the twist after the specific location of the blade span is modified. This location is the beginning of the off-axis plies and it is at approximately 32.8 meters from the root of the blade. In other words, for all blades, the GFRP plies in the spar flange area are oriented at 0° along the blade axis between the root and 32.8 meters from the root with the original twist schedule. On the other hand, for the bend-twist coupled blade spar cap plies are oriented at 5° between 32.8 meters from the root to the tip of the blade with modified twist schedule. In Figure 4, the legend -n° Twist implies that in the bend-twist coupled sections of the bend-twist coupled blade, pre-twist angle of the blade sections is reduced by n degrees. In this respect, for the four different bend-twist coupled blades with the modified pre-twist schedule, pre-twist angle of the bend-twist coupled sections of the blade is reduced by 0.5°, 1.0°, 1.5° and 2°, respectively.

By decreasing the pre-twist in the bend-twist coupled sections of the blade, increase in power is expected, as mentioned before. Using the stationary analysis of the PHATAS code, power curves are obtained for the wind turbines having blades with different twist schedules. Power curves of the wind turbines with the baseline blade and bend-twist coupled blades with different twist schedules are given in Figure 5. In Figure 4 and Figure 5 same color codes are used for the wind turbines with different blades.

It can be easily seen in Figure 5 that the power generations of the wind turbines having bend-twist coupled blades with modified twist schedule are higher than the power generation of the wind turbine with the bend-twist coupled blade having original pre-twist schedule. In order to distinguish the power curves better, a zoomed view is presented in Figure 6.

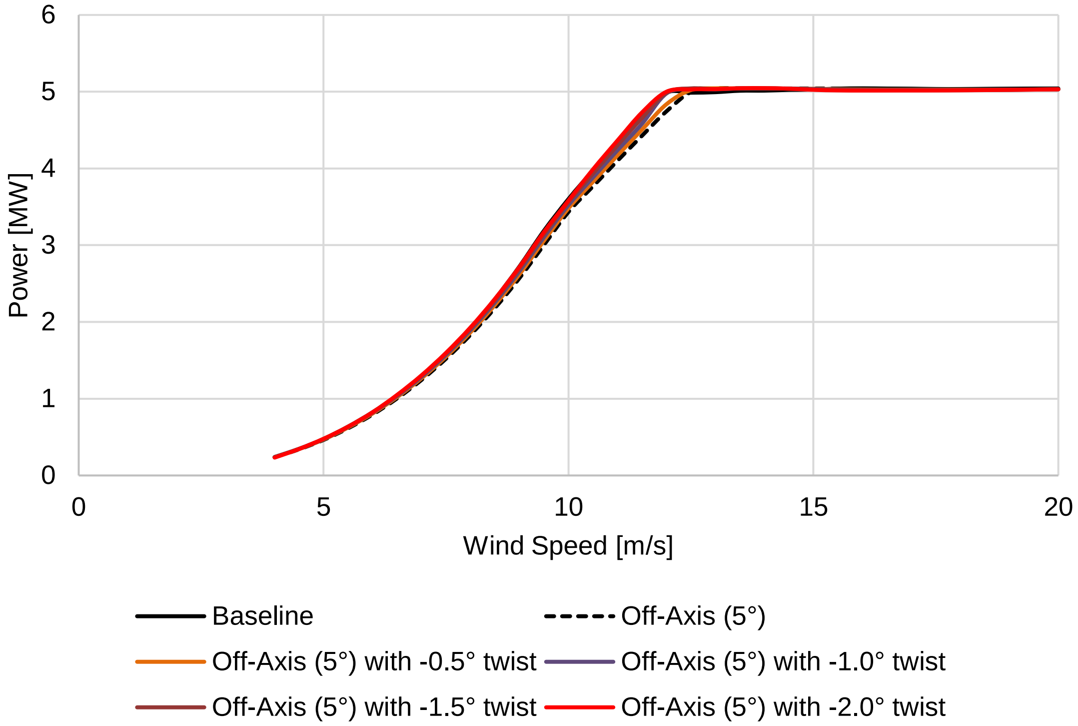

Figure 5: Power curves of the wind turbines having different twist schedules on their blades

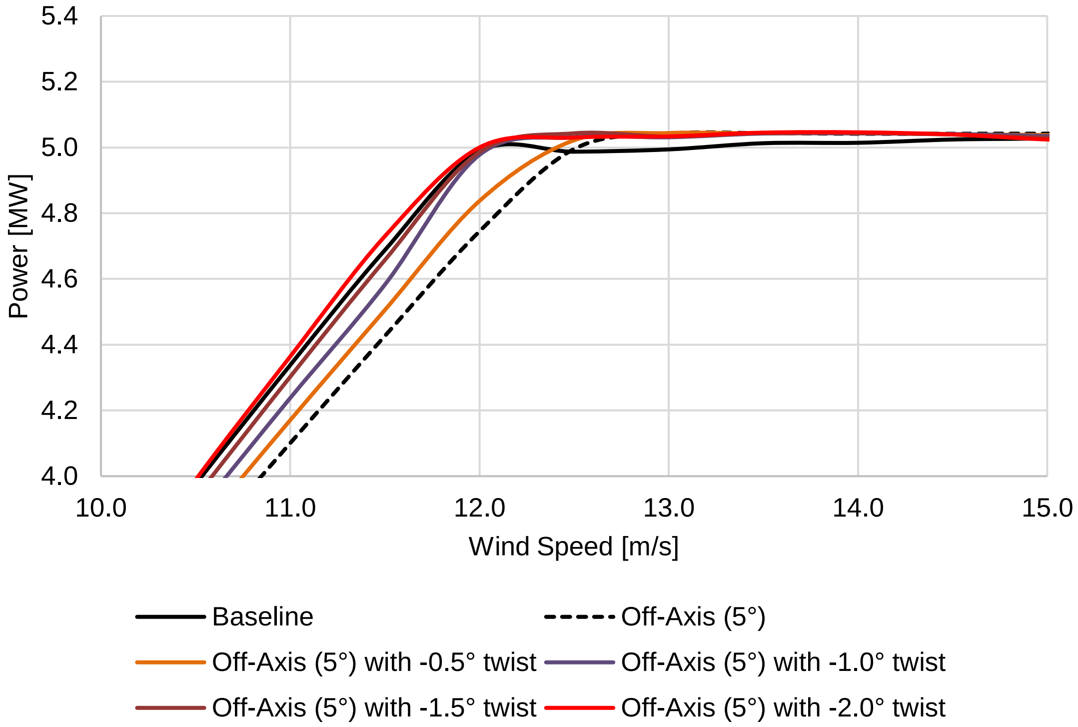

Figure 6: Power Curves of the wind turbines having different twist schedules on their blades at wind speeds from 10 m/s to 15 m/s

It can be deduced from the Figure 6 that by decreasing twist of the bend-twist coupled sections of the blade from 32.8 m to the tip of the blade leads to increase in power generation at underrated wind speeds. As the twist angle in the bend-twist coupled sections of the blade is reduced, power curve of the wind turbine with bend-twist coupled blade approaches to the power curve of the wind turbine with the baseline blade. It is also seen that the wind turbine having blades with modified twist schedule reaches rated power of 5 MW faster at the rated speed of 12 m/s. Whereas, the wind turbine having the bend-twist coupled blade with the original twist schedule reaches the rated power of 5 MW at a slightly higher wind speed than the rated wind speed of 12 m/s. From Figure 6, it is seen that the wind turbine with the bend-twist coupled blade with the original twist schedule reaches the rated power at about 12.5 m/s. As it is mentioned before, in this study, the twist in the bend-twist coupled sections of the blade is decreased by 0.5°, 1.0°, 1.5°, and 2.0° and for different twist schedules, power curve and time response analysis for the determination of damage equivalent loads are all done. It should be noted that, the pre-twist in the bend-twist coupled sections of the blade may be decreased even more than 2° to increase the power at underrated wind speeds. However, in this case due to the associated lift and torque increases, higher twist reduction may lead to higher increase in damage equivalent loads, and shortens the operation life of the wind turbine system due to the fatigue loads. Therefore, there should be a balance between the maximum reductions in the pre-twist angle in the bend-twist coupled sections of the blade and the resulting damage equivalent loads. According to the damage equivalent load analysis performed by the PHATAS code, it is seen that 0.5°, 1.0°, 1.5°, and 2.0° change in the twist angle in the bend-twist coupled blade give very close damage equivalent loads. Therefore, maximum 2.0° change in the pre-twist is considered to be enough to get a balanced power curve and damage equivalent load output from the wind turbine with bend-twist coupled blades. Figure 5 and Figure 6 show that in term of power production, wind turbine with bend-twist coupled blade with 2° reduction in the pre-twist angle in the bend-twist coupled sections of the blade is even better than the wind turbine with the baseline blade.

Effect of bend-twist coupling on the damage equivalent loads

For the power calculations, the main deal is to increase power generation at underrated wind speeds. However, a wind turbine not always operates at underrated wind speeds but also operates at rated and overrated wind speeds. For wind turbines with bend-twist coupled blades, besides maintaining the same or higher power production as the reference wind turbine between the cut-in and cut-out wind speeds, reduction in damage equivalent loads should also be achieved for the critical load components. Therefore, in the present study, time response analyses have been performed for the underrated, rated and overrated wind speeds to calculate the damage equivalent loads for the critical load components. Time response analyses have been performed for the reference wind turbine, wind turbine with GFRP bend-twist coupled blade having original twist schedule and 5° off-axis ply angle in the spar cap of the bend-twist sections of the blade, and for the wind turbine with the same bend-twist coupled blade but with modified twist schedule in the bend-twist coupled sections of the blade

Damage equivalent loads are calculated for turbulent wind conditions. Ten minute random wind profiles generated by the SWIFT code are used in wind turbine simulations performed by PHATAS. For the rated mean wind speed of 12 m/s, Figure 7 shows the 10-minute turbulent wind profile used in the wind turbine simulations for load calculations. For the underrated mean wind speed of 8 m/s and overrated mean wind speed of 15 m/s, same random variation of the wind profile is used. For the rated 10-minute random wind profile given in Figure 7, Figure 8 compares the time responses of the flapwise and edgewise bending and torsional moments at the blade root for the reference wind turbine with the baseline blade. As seen in Figure 8, torsional moment is almost negligible compared to the flapwise and edgewise bending moments. Therefore, in the following, damage equivalent torsional moment is not calculated, because damage equivalent flapwise and edgewise blade root bending moments are much more significant compared to the damage equivalent blade root torsional moment.

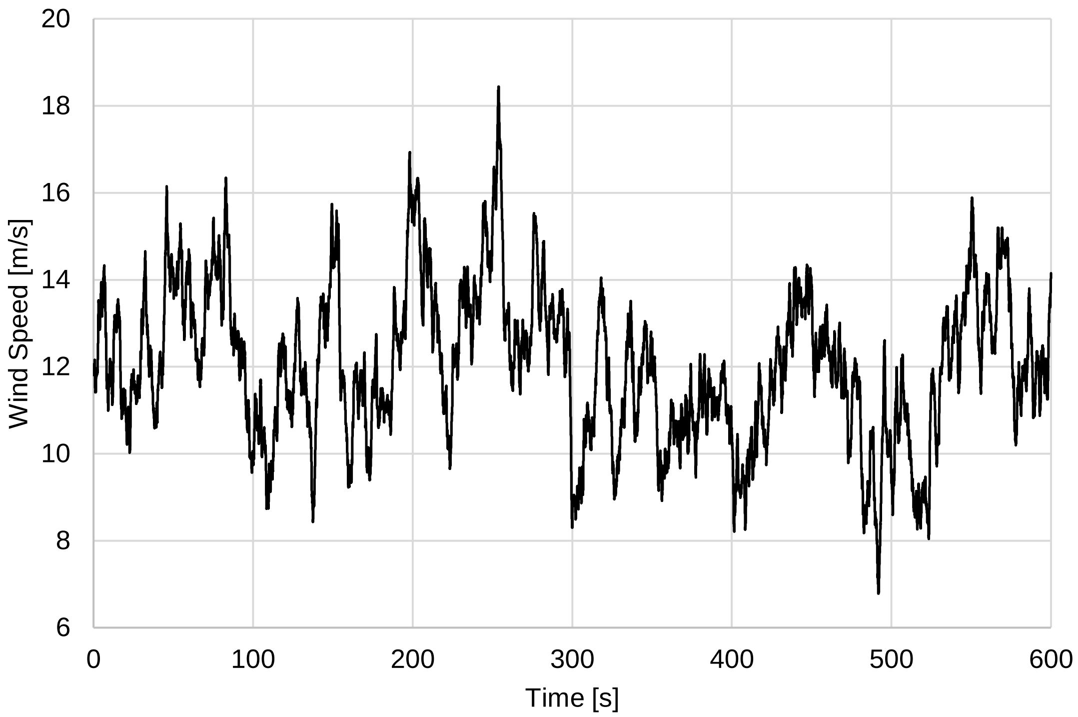

Figure 7: 10-minute turbulent wind profile for the mean wind speed of 12 m/s

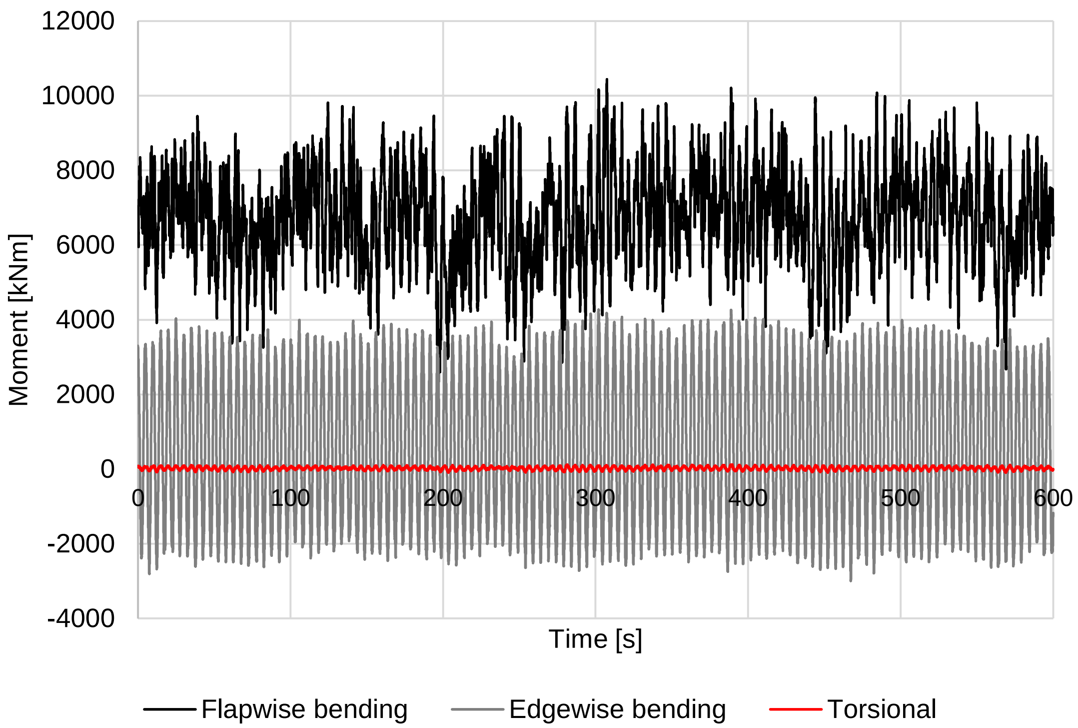

Figure 8: Comparison of the time responses of the flapwise and edgewise bending and torsional moments

As a result of 10-minute multibody simulations of the reference wind turbine and the turbine with bend-twist coupled blade with 5° off-axis fiber angle in the bend-twist sections of the blade, damage equivalent loads are calculated for the selected load components in the blade and in the drive train of the wind turbine systems. Selected load components are given in Table 3 together with the code numbers used in PHATAS. For each load component, damage equivalent load is calculated for the reference wind turbine and for the wind turbine with bend-twist coupled blades having original twist schedule and modified twist schedule. The effect of bending twisting coupling on the damage equivalent loads is assessed by the "damage equivalent load ratio" which is calculated by dividing the damage equivalent load for the particular load component in the reference wind turbine with the corresponding damage equivalent load in the wind turbine having bend-twist coupled blades with original and modified twist schedules.

Table 3: Selected load components from damage equivalent loads

	Code Number	Load Component
Blades	-133	Flapwise bending moment in the blade.
	171	Edgewise bending moment in the blade.
	144	Flapwise shear force in the blade.
	-176	Edgewise shear force in the blade.
Drive Train	61	Torque on the rotor shaft.
	50	Resultant bending moment in the rotor shaft.
	52	Tilting moment on the drive train.
	64	Axial (compressive) force on shaft.

The comparison of the damage equivalent load ratios for the reference wind turbine and wind turbines with bend-twist coupled blades with original and modified twist schedules are given in Figure 9, Figure 10, and Figure 11 for the underrated, rated, and overrated wind speeds, respectively.

It should be noted that in Figure 9 - Figure 11, code numbers of the damage equivalent loads introduced in Table 3 are used to also indicate the damage equivalent load ratios.

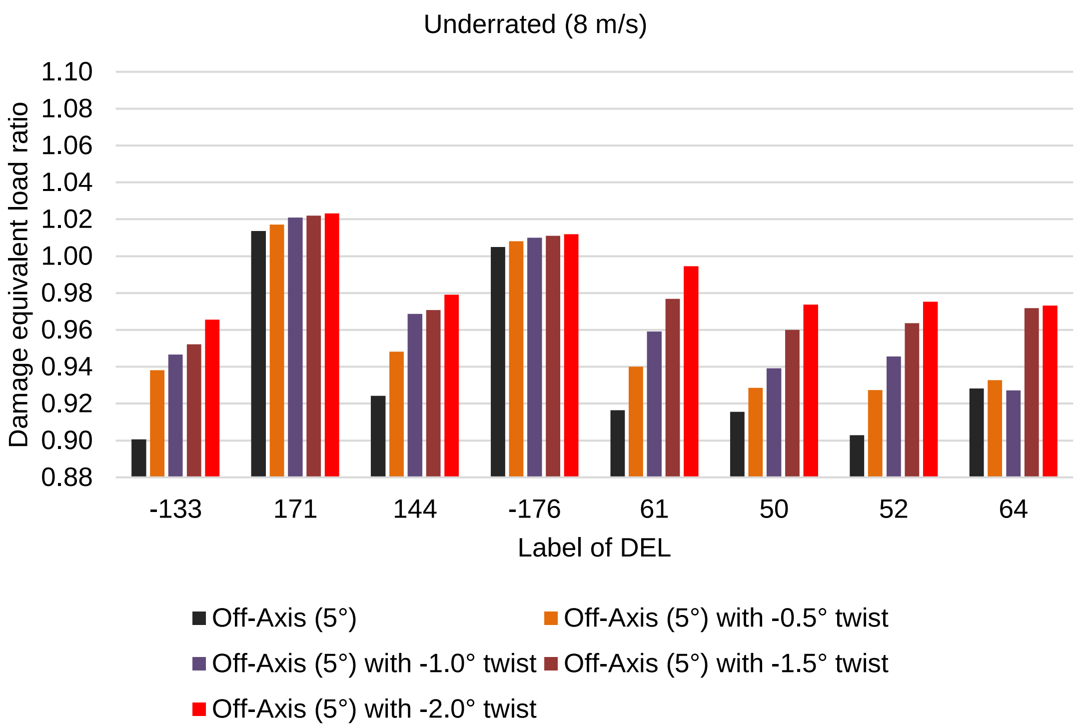

Figure 9: Comparison of damage equivalent load ratios at the underrated mean wind speed (8 m/s)

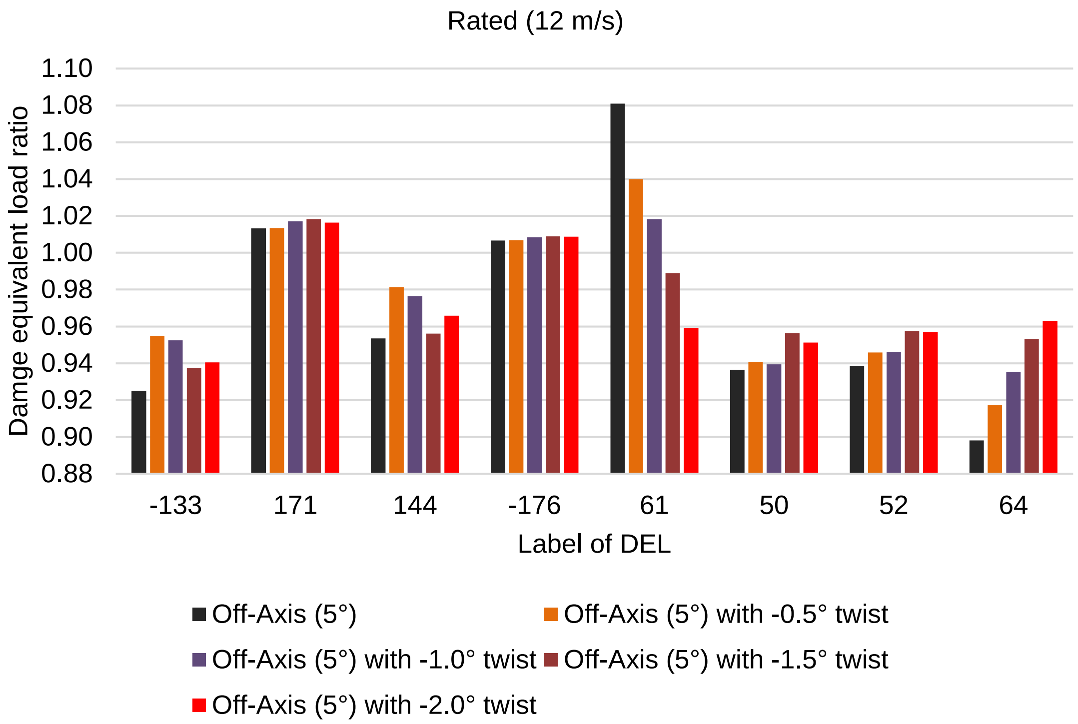

Figure 10: Comparison of damage equivalent load ratios at the rated mean wind speed (12 m/s)

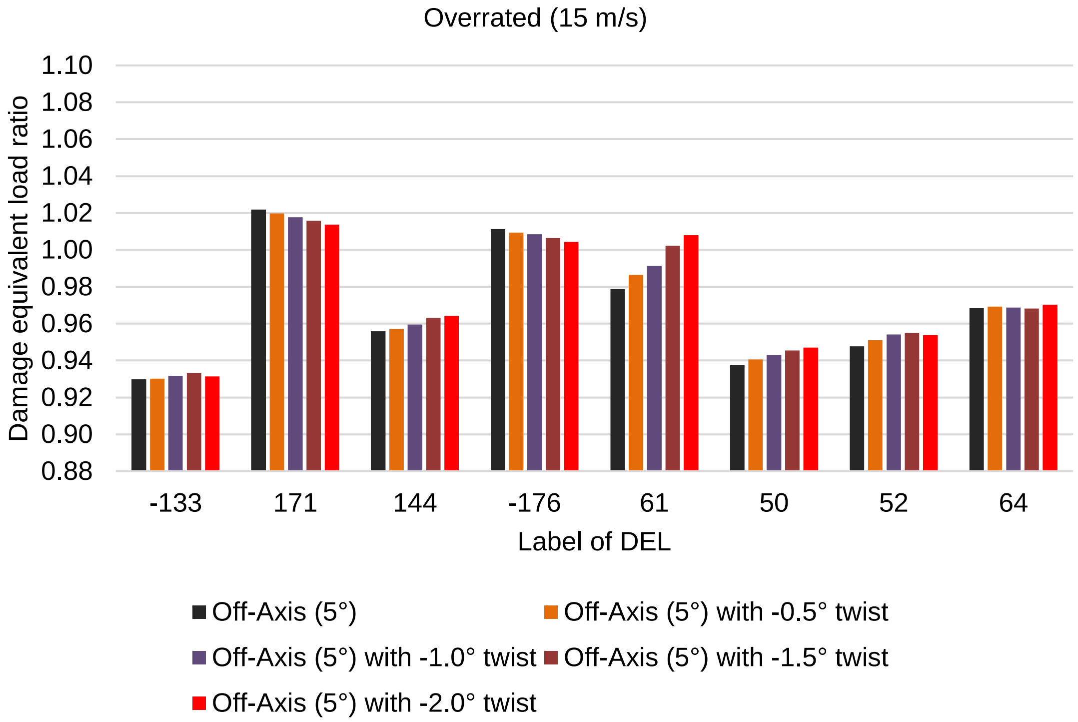

Figure 11: Comparison of damage equivalent load ratios at the overrated mean wind speed (15 m/s)

The following observations are made based on the power curve and damage equivalent load ratio results.

- It should be noted that the wind turbines with bend-twist coupled blades which have 1.5° or 2° lower twist angles in the bend-twist sections of the blades have satisfactory power output, which is almost same or better than the reference wind turbine, over the whole wind speed range from the cut-in wind speed to the cut-out wind speed. Therefore, in assessing the damage equivalent loads, wind turbines with bend-twist coupled blades which have 1.5° or 2° lower twist angles in the bend-twist sections of the blades are selected for further evaluation.

- Figure 9 - Figure 11 show that except for the edgewise bending moment and the shear force, wind turbines with bend-twist coupled blades which have modified twist schedules have either lower damage equivalent loads than the reference wind turbine system or have almost the same damage equivalent loads as the reference wind turbine. Slight increases (1%-2%) in the damage equivalent edgewise bending moment and edgewise shear force are obtained but for the rest of the selected blade root and drive train load components, damage equivalent loads either decrease or remain same as the reference turbine.

- For the wind turbines with bend-twist coupled blades having 5° off-axis spar cap plies in the bend-twist sections, by reducing the pre-twist angle by 2° in the bend-twist coupled sections, wind turbine produces same or higher power than the reference wind turbine and at the same time reduction in damage equivalent loads can be obtained. Higher reductions in damage equivalent loads could be obtained by using higher off-axis fiber angle in the bend-twist coupled sections of the blade, but in this case pre-twist schedule has to be optimized again for maximum power production across the whole wind speed range achieving higher reductions in damage equivalent loads compared to the 5° off-axis ply angle case. The use of higher off-axis ply angles in the bend-twist coupled sections is planned as the follow-up study.

- Rotor shaft torque is a critical load component, because rotor shaft torque is transmitted to the generator via the gearbox and reduction in damage equivalent rotor shaft torque also implies that fatigue failures associated with the gearbox are also reduced. Results of the present study show that for the three mean wind speeds at which damage equivalent loads are calculated, in the wind turbines with bend-twist coupled blades, which have pre-twist angles reduced by 1.5° or 2° in the bend-twist sections of the blades, damage equivalent rotor shaft torque is either reduced, as in mean rated wind speed, or remains almost same as the reference wind turbine, as in underrated or overrated mean speeds of 8 m/s and 15 m/s, respectively.

- For most of the load components, damage equivalent loads increase with the decrease in the pre-twist schedule, as expected. Exception to this is the rotor shaft torque at the rated mean wind speed of 12 m/s. At the rated mean wind speed, damage equivalent shaft torque decreases by reducing the twist angle in the bend-twist sections of the blade. It should be noted that damage equivalent loads depend on both magnitude of the load component and fluctuation of the load as shown in Equation 2. Table 4 presents the 10-minute average of the rotor shaft torques and damage equivalent shaft torques for all wind turbines at the rated mean wind speed of 12 m/s. Table 4 clearly shows that for the wind turbine with bend-twist coupled blades having spar cap plies oriented at 5° with respect to the blade axis in the bend-twist coupled sections of the blades, the average shaft torque reduces due to the reduction in the lift caused by the bending-twisting coupling. However, for the same wind turbine damage equivalent shaft torque is higher than the damage equivalent shaft torque for the reference wind turbine. With the decrease in the pre-twist angle in the bend-twist sections of the blades, it is seen that average shaft torque increases due to the increase in the effective angle attack of bend-twist sections of the blades. With the increase in the average shaft torque, power loss in the wind turbine with bend-twist coupled blades is compensated, as shown graphically in Figure 5 and Figure 6. Thus, for the mean rated wind speed of 12 m/s, power generation goal is achieved. For the mean rated wind speed of 12 m/s, damage equivalent shaft torque decreases when the pre-twist angle is decreased. The reason for the decrease of the damage equivalent shaft torque when the pre-twist angle is decreased could be due to the change in the fluctuation frequency of the shaft torque. As Table 4 shows, when the pre-twist angle is decreased, average shaft torque increases and one would normally expect that damage equivalent shaft torque would also increase. Since damage equivalent load depends also on the fluctuation of the load, it is concluded that at the mean rated wind speed, the change in the fluctuation of the shaft torque must have caused reduction in damage equivalent shaft torque as the pre-twist angle of the bend-twist coupled sections of the blades is decreased.

- Figure 10 and Table 4 also show that for the rated mean wind speed of 12 m/s, in the wind turbine with bend-twist coupled blades, which have original twist schedule, damage equivalent shaft torque increases by 8% compared to the reference wind turbine. However, when the pre-twist schedule of the bend-twist coupled blades is modified such that the pre-twist angle is reduced in the bend-twist sections of the blade, damage equivalent shaft torque decreases to levels lower than the damage equivalent shaft torque of the reference wind turbine. Considering that rotor shaft torque is a critical load component directly related to the fatigue life of the gearbox, 8% increase in the damage equivalent rotor shaft torque is not acceptable. Therefore, bend-twist coupled blade should be used in the wind turbine system only after the modification of the pre-twist schedule in the bend-twist section of the blades.

Table 4: 10-minute average of the shaft torques and damage equivalent shaft torques at the rated mean wind speed of 12 m/s

	Reference Turbine	Wind turbine with bend-twist coupled GFRP blades with off-axis fiber angle of 5°				
		Original Pre-twist	Pre-twist reduction in the bend-twist sections			
			0.5°	1°	1.5°	2°
Average shaft torque [Nm]	3782208	3705086	3731771	3755679	3773953	3790074
Damage equivalent shaft torque [Nm]	27916	30175	29032	28424	27609	26777

- In this study, the torque demand curve on the generator side and the rated rotor speed are not changed for the wind turbines which have bend-twist coupled blades with modified twist schedules. Torque demand curve and rated rotor speed of the wind turbines with bend-twist coupled blades which have modified twist schedules could also be modified to come up with optimum torque demand curve and rated rotor speed to maximize the reduction of damage equivalent loads while still maintaining the same or better power output as the reference wind turbine.

CONCLUSION

In this study, the effect of bend-twist coupled blades on the damage equivalent loads and the power generation performance of the wind turbine system is investigated. It is demonstrated that with the bend-twist coupled blades, although reduction of damage equivalent loads could be achieved at the underrated wind speeds, power production of the wind turbine with the bend-twist coupled blade is less than the reference wind turbine.

The performance of wind turbines with full GFRP bend-twist coupled blades is presented in terms of damage equivalent loads and power generation. Bend-twist coupled blade is designed by rotating the spar cap plies in the last 30 m of the blade towards the leading edge by 5°. Power curves are obtained for wind speeds ranging from the cut-in speed to the overrated speed of 20 m/s. Damage equivalent loads are calculated at three mean wind speeds; underrated wind speed of 8 m/s, rated wind speed of 12 m/s and overrated wind speed of 15 m/s.

Power curve analyses showed that wind turbines with bend-twist coupled blades can provide the rated power at the overrated wind speeds but power loss occurs at the underrated wind speeds. On the other hand, damage equivalent load calculations show that for most of the load components, reduction of damage equivalent loads can be obtained at the underrated, rated and overrated mean wind speeds. Since the main goal of this study is to achieve the same or better power generation performance of the wind turbine with the bend-twist coupled blade as the reference wind turbine, while still achieving reduction in damage equivalent loads in main load components for wind speeds ranging from the cut-in speed to the overrated wind speed, a design modification is proposed. In this respect, pre-twist angles of the bend-twist sections of the blades are reduced by 0.5°, 1.0°, 1.5° and 2.0° with goal of increasing the effective angle of attack of bend-twist coupled sections of the blades to compensate for the power loss at the underrated wind speeds. Results show that the best power generation performance is obtained when the pre-twist angles of the bend-twist coupled sections of the blade are lowered by 2°. For the wind turbines with bend-twist coupled blades with the modified twist schedule, it is observed that slight increases (1%-2%) in the damage equivalent edgewise bending moment and edgewise shear force are obtained but for the rest of the selected blade root and drive train load components, damage equivalent loads either decrease or remain same as the reference turbine for the three mean wind speeds at which time response and accompanying damage equivalent load analyses have been performed. Thus, with 2° reduction in the pre-twist angles of the bend-twist coupled sections of the blades, simultaneously reduction of the generator power losses at the underrated wind speeds, and damage equivalent loads for the selected underrated, rated and overrated wind speeds has been achieved.

This study shows that modification of the pre-twist schedule is a valid design change to be applied to the bend-twist coupled blades in order to eliminate the power loss disadvantage of wind turbines at the underrated wind speeds, while still achieving reduction in damage equivalent loads in the wind turbine system.

For the future studies, other parameters of the wind turbine such as generator demand curve or rated rotor speed may be changed while changing the pre-twist to decrease damage equivalent loads with better power generation in the underrated wind speeds. Moreover, modifying the twist schedule over the whole wind turbine and performing an optimization study to determine the optimum pre-twist schedule and application region over the span of the blade are other future studies that can be performed.

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