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Load Reduction in Wind Turbines with Bend-Twist Coupled Blades without Power Loss at Underrated Wind Speeds

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Abstract. Usage of composite materials in wind turbine blades is a passive mechanism to alleviate fatigue loads besides the reduction in the mass of the wind turbine system. Off-axis plies in bend-twist coupled (BTC) blades account for the passive fatigue load reduction by reducing the effective angle of attack of blade sections. Reduction in fatigue loads is generally represented by damage equivalent load ratios. In the present study, multibody aeroelastic analyses are performed for wind turbine systems for the underrated, rated and the overrated turbulent wind speeds. It is shown that load reduction can be achieved for the whole range of wind speeds with the usage of bend-twist coupled blades at the cost of power loss at underrated wind speeds which is unacceptable. Thus, the main concern of the present study is first to make performance study of wind turbines with bend-twist coupled blades at underrated wind speeds and then to overcome the power loss while still achieving reduction in damage equivalent loads by the proper modification of the pre-twist variation of the bend-twist coupled blades together with the generator torque curve across whole range of wind speeds. This study has been performed utilizing the same pitch control settings in region 2 to examine the mere effect of pretwist modification on the power performance of the wind turbine and on the damage equivalent loads.

1. Introduction

Larger wind turbines with longer blades are needed in order to produce more energy from wind. However, for wind turbines with longer blades, mean and fatigue loads also increase due to the aeroelastic effects, and they should be alleviated by active, passive or hybrid active-passive means to keep the wind turbine operational for longer periods without any failure in its components.

Active control systems are commonly the pitch angle control of the blade, yaw angle control of the rotor and trailing edge flap control. Passive control utilizes the anisotropic behavior of composite materials through the bend-twist coupling concept [Jones, 1999]. When a uniform load is applied to the bend-twist coupled composite material, it does not only bend, but also twists and changes the effective angle of attack of blade sections. Thus, with bend-twist coupled blades, passive twist control can be achieved and this can be used to alleviate loads in wind turbine blades. One of the ways to generate bend-twist coupling is to use off-axis fiber angles in the main spar caps of the wind turbine blade. With the bend-twist concept, the increase in the angle of attack due to the twisting of the blade caused by the aerodynamic loading can be compensated by the proper placement of the off-axis layer through the wind turbine blade. Although damage equivalent loads in the wind turbine system reduce across the whole range of wind speeds with the use of bend-twist coupled blades, at the underrated wind speeds, power loss occurs due to the torque reduction which cannot be compensated by the pitch controller because of the minimum pitch limit. There has been several studies in the literature on the load reduction in wind turbine systems through the use of bend-twist coupled blades. Lobitz and Veers

[Lobitz, 2003] have demonstrated that bending-torsion coupling accounts for reduction in fatigue loads in wind turbines over a wide range of wind speeds, with no reduction in the mean power. In the study of Locke and Valencia [Locke, 2004], by rotating carbon plies in the spar caps in an experimental 9.2 m long blade, an overall weight advantage has been achieved compared to the reference E-Glass/Epoxy. A parametric study was conducted by varying the off-axis fiber angle from 5^o to 25^o in the all-carbon spar cap of a 37 m long blade [Wetzel, 2005]. The optimal angle of 7.5^o was found by minimizing the cost and satisfying the imposed constraints related to the blade stiffness and strength. Capellaro and Kühn have investigated BTC obtained by rotating the plies of the spar caps by 5° and 10° and have obtained reductions in damage equivalent loads as well as in maximum loads [Capellaro, 2010]. Bottasso et al. [Bottasso, 2013] have performed an optimization based study of bend-twist coupled rotor blades for passive and integrated passive/active load alleviation. Gözcü et al. have determined that fatigue loads in wind turbines could be reduced by means of hybrid GFRP and CFRP composite blades with induced bending-torsion coupling. Hayat and Ha [Hayat, 2015] have investigated the load alleviation in wind turbine blades using the unbalanced laminate composites.

In the example studies given, mainly load reduction in the wind turbine blades has been investigated through the use of bend-twist coupled blades rather than the loads in the drive train. In most of the studies performed in the literature, for the composite blades, fatigue exponent of 9 or 10 has been used and damage equivalent loads have been calculated in the composite blade. However, metallic parts of the wind turbine are more critical from fatigue failure point of view compared to the composite parts. In the present study, for the blades, damage equivalent loads at the blade root are calculated using a fatigue exponent of 4, which is applicable for steel. One of the main objectives of the study is to investigate the effect of bending twisting coupling on the damage equivalent loads at the metallic blade-hub connection and in the drive train where fatigue failures are more probable. Furthermore, comprehensive investigation of the energy production and damage equivalent loads in wind turbines with bend-twist coupled blades across a wide range of wind speeds from underrated to overrated has not been presented in most of the studies performed. In the present study, initially a comprehensive evaluation of power loss in the wind turbines with full GFRP and hybrid GFRP-CFRP bend-twist coupled blades at underrated wind speeds has been made. As a follow-up study, power loss at the underrated wind speeds is compensated by the proper modification of the pre-twist variation of the bend-twist coupled blades together with the generator torque curve, while still achieving reduction in fatigue damage equivalent loads across the whole range of wind speeds using an iterative procedure. For this purpose, multi-body model of a 5 MW wind turbine system is set up and power curve and transient analyses of the multi-body wind turbine system have been performed with the reference blade and with bend-twist coupled blades with original and modified pretwist variations and generator torque curves.

2. Method

2.1. Wind turbine modelling

NREL's 5 MW [Jonkman, 2009] wind turbine is selected as a reference wind turbine and modelled in PHATAS [Lindenburg, 2012] for this study. Reference blade is modified to have a prebent of 4 m at the blade tip. Rated rotor speed of the wind turbine is set at 12 rpm and for the rated conditions, wind speed is 12 m/s. Full GFRP reference blade has been designed by making the sectional mass and stiffness properties of the 3D blade as close to the sectional mass and stiffness properties of NREL's 5 MW turbine blade through an inverse design process, and original pretwist variation of NREL's turbine blade is kept as it is. Bend-twisting coupling is generated by rotating the spar cap plies towards the leading edge of the blades in the outboard 32.8 m of the 61.5 m long blade. Figure 1 describes the bend-twist coupled blade designs. For GFRP blades, 5° and 10° off-axis spar cap fiber angles are used in the bend-twist coupled blades, whereas for the hybrid GFRP-CFRP bend-twist coupled blade, off-axis spar cap fiber angle is taken as 5°. Hybrid GFRP and CFRP bend-twist coupled blade only has Carbon/Epoxy material in the main spar caps of the bend-twist coupled blade sections, and the number of off-axis Carbon/Epoxy layers has been adjusted to make the flatwise bending stiffness of the blade sections as close as possible to the flatwise bending stiffness of the bend-twist coupled GFRP blade.

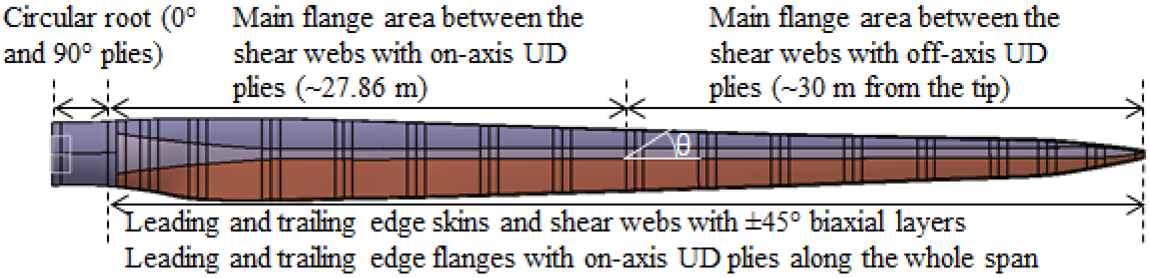

Figure 1. Bend-twist coupled blade design.

2.2. Multibody simulations of the wind turbine system

For the multibody aeroelastic simulations, PHATAS which uses the unsteady Blade Element Momentum (BEM) theory by taking the dynamic inflow, tip and hub losses and aerodynamic tower stagnation into account is used. PHATAS also has built-in sub-models, oblique inflow, vertical wind distribution, dynamic stall and effects of rotation on aerodynamic loads for accurate unsteady aerodynamics. Blade model used in PHATAS is a nonlinear coupled beam-blade model and in the beam formulation, warping has been neglected. In the constitutive equation, the axial force in the blade and the leadwise, flatwise and the torsional moments are related to the axial strain and to the respective curvatures through a fully populated 4×4 stiffness matrix. Strongly coupled aeroelastic multibody analyses of the wind turbine can be conducted in PHATAS by taking the aerodynamic, structural, control and multibody features into account [Lindenburg, 2012]. The geometric and elastic properties of the 17 sections of the reference and bend-twist coupled blades are calculated by Variational Asymptotic Beam Section (VABS) method [Yu et al., 2012], and bend-twist coupling effect is taken into account properly since VABS gives the coefficients of the fully populated sectional stiffness matrix along with the mass/inertia properties of the blade sections. Transient analyses of the wind turbine system are performed in turbulent wind conditions utilizing the SWIFT [Winkelaar, 1992] code which is the turbulence wind generator of PHATAS, and PD pitch speed control is used for the wind turbine control.

Initially, for the reference wind turbine, power curve analyses and transient multibody simulations for the calculation of damage equivalent loads are performed. Then, power curve and transient analyses of the wind turbines with GFRP and hybrid GFRP-CFRP BTC blades are performed to determine the power curves and to calculate the damage equivalent loads. Power calculations are performed from the cut-in wind speed of 4 m/s, to the overrated wind speed of 20 m/s. Ten minute transient multi-body simulations of the wind turbine system for the calculation of damage equivalent loads at turbulent wind conditions for the selected mean wind speeds are performed across the range of underrated to the overrated wind speeds. Design load case is taken as NTM power production and IEC turbulence category is taken as B and the wind turbine class is selected as 1. Transient analyses are performed using the Von Karman APSD. Based on the power curve and damage equivalent load results of the reference wind turbine and wind turbines with bend-twist coupled blades, pretwist variation of the bend-twist coupled blades is modified in an iterative fashion to decide on the best pretwist variations for the full GFRP and hybrid GFRP-CFRP bend-twist coupled blades to compensate for the power loss at the underrated wind speeds. For the wind turbines with bend-twist coupled blades with modified twist variations, it is seen that slight reductions in the generator torque demand accounts for slightly higher reductions in the damage equivalent loads. Hence, besides the pretwist modification, generator torque demand of the wind turbines with bend-twist coupled blades has been reduced to have slightly higher reduction in damage equivalent loads. Figure 2 shows the pretwist variation and the generator torque demand curve of the reference wind turbine.

The main objective of the study is to achieve no power loss at underrated wind speeds while still maintaining reduction in damage equivalent loads across the whole range of wind speeds for the wind turbines with bend-twist coupled blades. It should be noted that in the present study, the main aim is to use passive means to achieve reduction in damage equivalent loads in the wind turbine system. Moreover, since wind turbines usually operate at the rated or underrated wind speeds most of the time, achieving no power loss and reduction in damage equivalent loads at the rated and underrated wind speeds is the main consideration. It should be noted that in all wind turbine simulations, PD pitch speed control settings are kept the same and no attempt is made to optimize the controller settings for the wind turbines with bend-twist coupled blades. As a follow-up study, controller settings can be fine-tuned and optimized for each wind turbine system with bend-twist coupled blades which have modified pretwist variations.

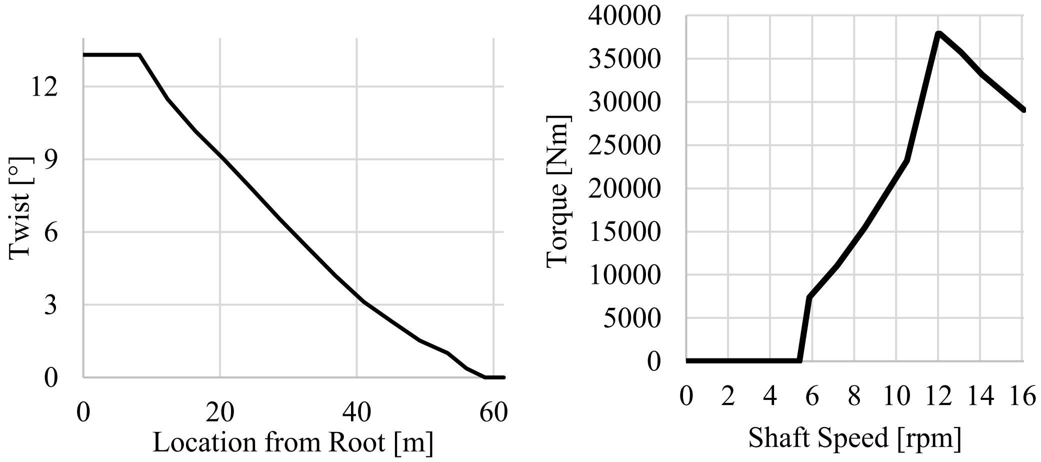

Figure 2. Pretwist variation and generator torque demand of the reference wind turbine.

3. Results

In Figure 3, power curves for the reference wind turbine and for the wind turbines with bend-twist coupled GFRP (GFRP-BTC) blade having 5° and 10° off-axis spar cap plies (GFRP-BTC (5°), GFRP-BTC (10°)) with respect to the blade axis and the wind turbine with bend-twist coupled hybrid GFRP-CFRP blade (Hybrid-BTC) having 5° off-axis spar cap plies (Hybrid-BTC (5°)) are given on the same plot.

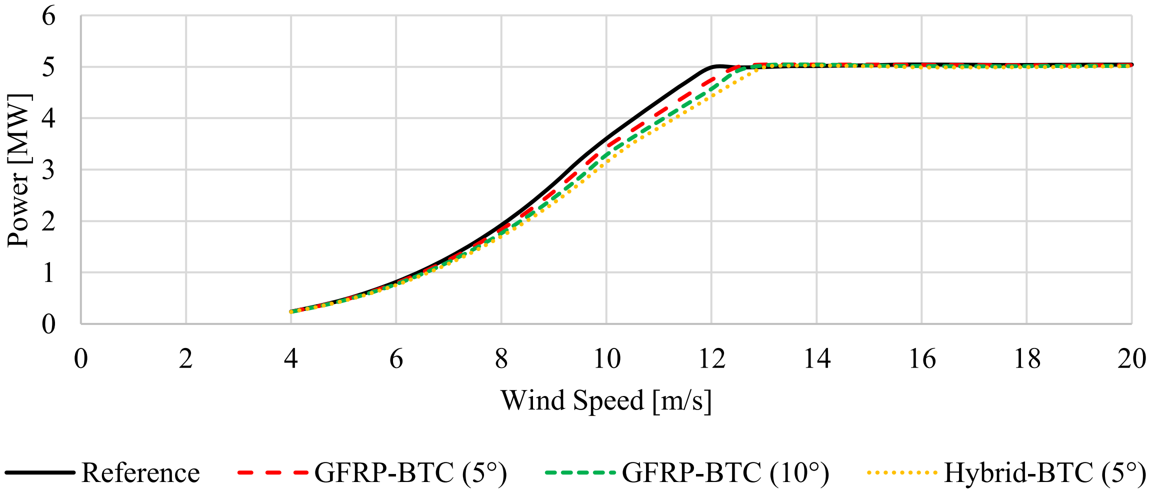

Figure 3. Power curves for the reference wind turbine and for wind turbines with bend-twist coupled full GFRP and hybrid GFRP-CFRP blades with original pretwist variations.

As seen in Figure 3, at the underrated wind speeds, wind turbines with bend-twist coupled blades produce less power compared to the reference wind turbine. Moreover, wind turbine with the bend-twist coupled hybrid GFRP-CFRP blade has the highest power loss compared to the wind turbines with bend-twist coupled full GFRP blades. Figure 3 clearly shows that wind turbines with bend-twist coupled blades reach the nominal power of 5 MW at a higher wind speed than the rated wind speed of 12 m/s of the reference wind turbine.

In the present study, power loss at the underrated wind speeds is compensated by modifying the pretwist variation of the reference blade in the outboard 32.8 m where bending twisting coupling is induced through the off-axis spar cap plies as described previously. Nineteen different pretwist variations are tried through an iterative trial and error process to get the desired power output at underrated wind speeds for the three wind turbines with the GFRP-BTC (5°) and GFRP-BTC (10°) and Hybrid-BTC (5°) blades. For the wind turbines with BTC blades, it is desired to keep the power difference at a minimum in region 2 with respect to the reference wind turbine. Table 1 shows the best pretwist modifications applied in the outboard 32.8 m of the bend-twist coupled blades. To increase the power production at the underrated wind speeds, pretwists of the blade sections in the outboard 32.8 m of the reference blade are decreased to increase the aerodynamic torque generation. Decisions on the best pretwist modifications are not made solely based on the compensation of the power loss at the underrated wind speeds, but also the damage equivalent loads in the wind turbine system have been monitored so that reductions in the damage equivalent loads could also be achieved. Hence, the criterion for the selection of the pretwist modification is to achieve the same power output as the reference wind turbine across the whole wind speed range, while still having reductions in some of the damage equivalent load components and no significant increases in the other damage equivalent load components. Moreover, damage equivalent load reduction at the rated and underrated wind speeds is considered to be more important and in selecting the pretwist modifications, this point is also taken into account.

Table 1. Best pretwist modifications applied in the outboard 32.8 m of the BTC blades.

Bend-twist coupled blade with modified pretwist	Pretwist modifications of the reference blade
GFRP-BTC-MT (5°)	Linear decrease of pretwist by 1.5° at 28.7 m from the blade root to 2.0° at the blade tip
GFRP-BTC-MT (10°)	Constant decrease of pretwist by 3.5° at 28.7 m from the blade root to the blade tip
Hybrid-BTC-MT (5°)	Constant decrease of pretwist by 4.5° at 28.7 m from the blade root to the blade tip

Figure 4 gives the power curve of the reference wind turbine and the wind turbines with BTC blades with modified pretwist variations.

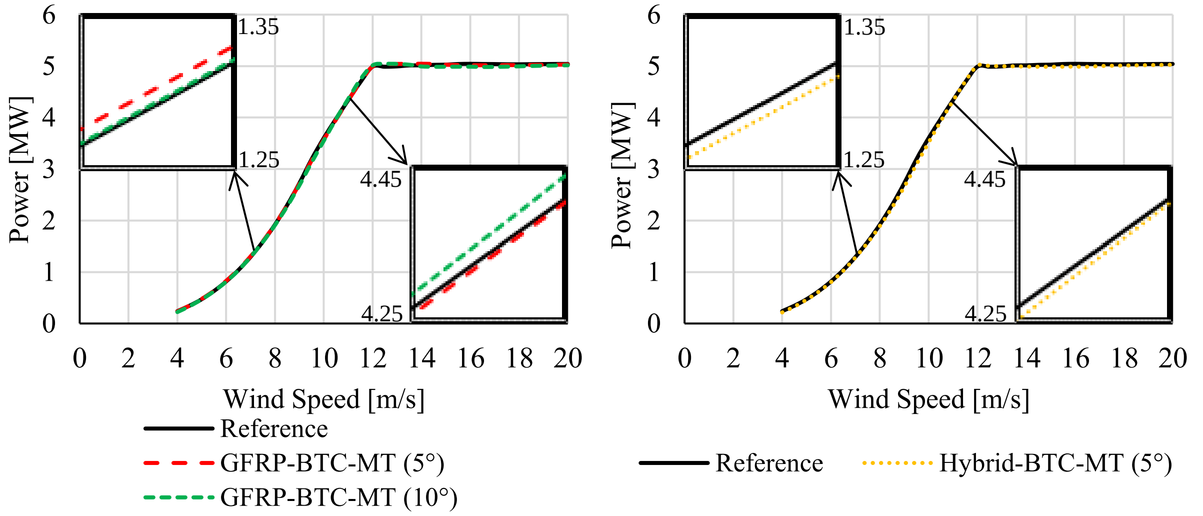

Figure 4. Power curves for the reference wind turbine and for wind turbines with bend-twist coupled full GFRP and hybrid GFRP-CFRP blades with modified pretwist variations.

Figure 4 shows that the suggested pretwist modifications in Table 1 are sufficient to achieve almost the same power output from the wind turbines with BTC blades across the whole wind speed range. It is seen that the wind turbine with the Hybrid-BTC-MT (5°) blade needs more reduction in the pretwist schedule to compensate for the power loss at the underrated wind speeds compared to the wind turbines with BTC GFRP blades because of the higher bend-twist coupling potential of the CFRP material. Careful examination of the power curves, which are obtained using the original generator torque demand curve given in

Figure 4, showed that for the wind turbine with the GFRP-BTC (5°) blade, power production at the overrated wind speeds is higher than the 5 MW rated power by a very small margin. However, for the wind turbines with the GFRP-BTC (10°) and the Hybrid-BTC (5°) blades, power productions at the overrated wind speeds are just about the same as the reference wind turbine. Therefore, in the present study, generator torque demand of the wind turbine with the GFRP-BTC (5°) blade has been decreased slightly so as to obtain slightly higher reductions in damage equivalent loads in the wind turbine system. According to the results of multibody simulations, it is observed that small changes in the generator torque demand does not affect the power generation at the underrated and the rated wind speeds, significantly. In light of this information, generator torque demand is decreased by 0.1% increments until the power generation remains more or less constant at the rated 5 MW power at the overrated wind speeds. This study showed that 0.5% reduction in the generator torque demand is acceptable for the wind turbine with the GFRP-BTC-MT (5°) blade. For the reference wind turbine, and for the wind turbines with the bend-twist coupled GFRP blades with the original pretwist variation (GFRP-BTC (5°)) and the modified pretwist variation (GFRP-BTC-MT (5°)), Figure 5 shows the variation of the generator power for the overrated wind speeds starting from the rated wind speed.

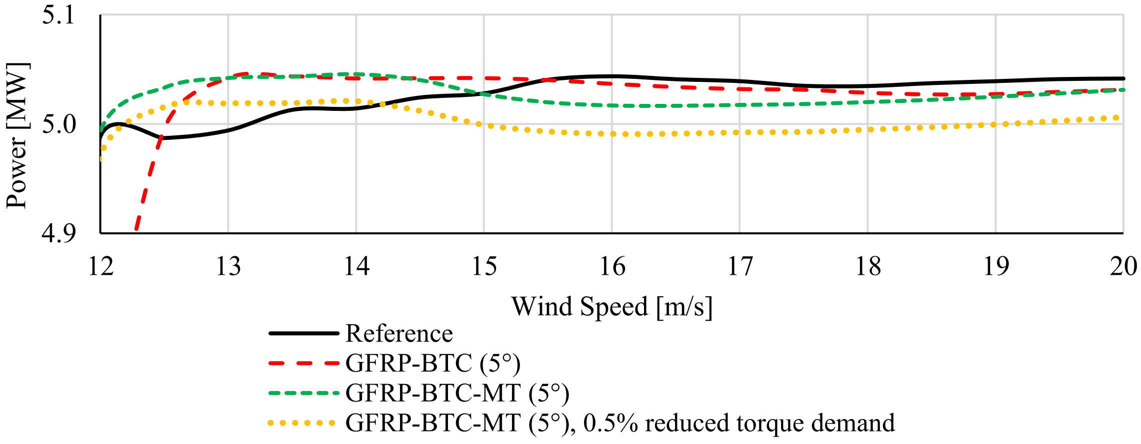

Figure 5. Effect of 0.5% reduction of the generator torque demand on the power production for the overrated wind speeds.

In Figure 5, it can be seen that for the wind turbine with the GFRP-BTC-MT (5°) blade, the overall power generation is still the rated value 5 MW for the overrated wind speeds when the generator torque demand is reduced by 0.5%. With this modification, rated power is still produced. Moreover, the reduction of the generator torque demand is expected to cause slight reductions in the damage equivalent loads in the wind turbine system. It should be noted that the results for the wind turbines with the GFRP-BTC-MT (10°) and the Hybrid-BTC-MT (5°) blades are not included, because reduction of the generator torque demand caused performance reductions, hence it is decided to use original generator torque demand curve in these wind turbines.

As mentioned before, the decision on the pretwist modifications in the bend-twist coupled blades is based on the requirement of producing the same power with the wind turbines with BTC blades as the reference wind turbine across the whole wind speed range, while still achieving reductions in some of the damage equivalent load components. Ten minute transient aeroelastic analyses of multibody wind turbine systems are performed under randomly generated turbulent wind profile, and time responses of the selected load components are processed to calculate the damage equivalent loads. For a load component, reduction in the damage equivalent loads is measured by calculating the damage equivalent load ratio which is defined as the ratio of the damage equivalent load in the wind turbine with BTC blades to the damage equivalent load in the reference wind turbine.

In Figure 6 - Figure 10, damage equivalent load ratios are presented as bar charts for the 6 m/s, 8 m/s, 10 m/s, 12 m/s and 15 m/s mean wind speeds. Based on the results presented in Figure 6 - Figure 10, the following conclusions are inferred.

- Reducing the pretwist in the bend-twist coupled sections of the blade, in general, causes the damage equivalent loads to increase in the wind turbines with BTC blades. But this increase has to be accepted since the wind turbines with BTC blades with the original pretwist variation produce less power than the reference wind turbine at the underrated wind speeds. The exception is the damage equivalent rotor shaft torque at the rated speed of 12 m/s. As Figure 9 shows, damage equivalent rotor shaft torque is lower in the wind turbines with BTC blades which have modified pretwist variation.
- Except for the slight increases in the damage equivalent blade root edgewise bending moment and shear force (1% - 3%), reductions have been obtained in the remaining damage equivalent load components at the blade root and in the drive train of wind turbines with BTC blades which have modified pretwist variations.
- In the wind turbines with BTC blades with original pretwist variation, high reductions occur in the damage equivalent blade root flapwise bending moment and the shear force. This is due to the use of off-axis plies, in the main spar caps of the BTC blades, which mainly cause flapwise bending and twisting coupling. In the wind turbines with the BTC blades with modified pretwist variations, damage equivalent blade root flapwise bending moment and shear force increase, but with respect to the reference wind turbine, damage equivalent blade root flapwise bending moment and the shear force reduce in the range between 3% - 13% across the 6 m/s - 15 m/s wind speed range.
- Except for the damage equivalent rotor shaft torque, damage equivalent drive train forces reduce across the 6 m/s - 15 m/s wind speed range in the wind turbines with BTC blades with modified pretwist variations.
- In the wind turbines with the BTC blades GFRP-BTC-MT (10°) and Hybrid-BTC-MT (5°), except for the damage equivalent rotor shaft torque, all other damage equivalent load components are lower than the corresponding damage equivalent load components in the wind turbine with the BTC blade GFRP-BTC-MT (5°). However, it is noted that in the wind turbines, most of the damage occurs in the gearbox bearings, and reduction of the damage equivalent rotor shaft torque in the wind turbines is very critical to reduce the fatigue failures in the gearbox as the torque of the rotor shaft that is transmitted to the gearbox is reduced in the gearbox stages. In this respect, GFRP-BTC-MT (5°) blade stands out as the best performing blade. In the wind turbine with the BTC blade GFRP-BTC-MT (5°), except of the edgewise bending moment and shear force, damage equivalent loads in the whole wind turbine either reduce or remain unchanged compared to the reference wind turbine across the 6 m/s - 15 m/s wind speed range.

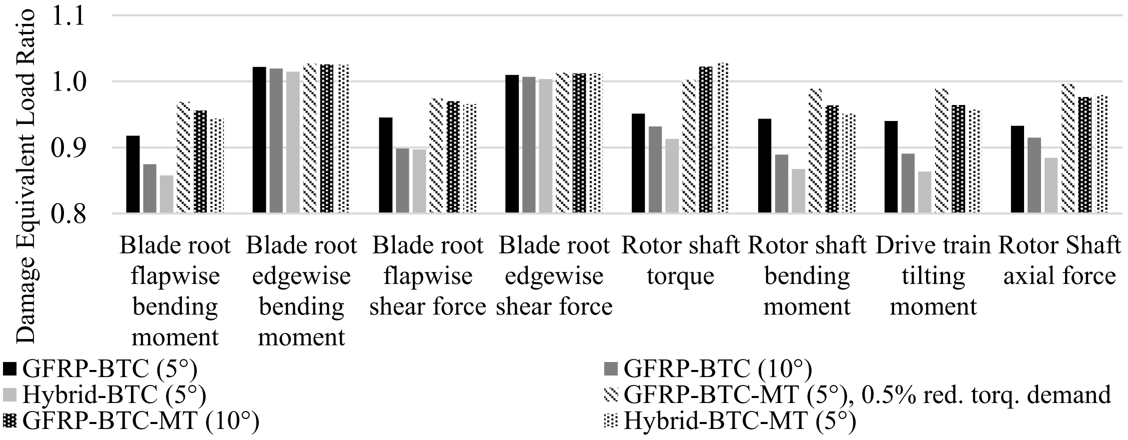

Figure 6. Damage equivalent load ratios in wind turbines with bend-twist coupled blades with the original and the modified pretwist variations at the underrated wind speed of 6 m/s.

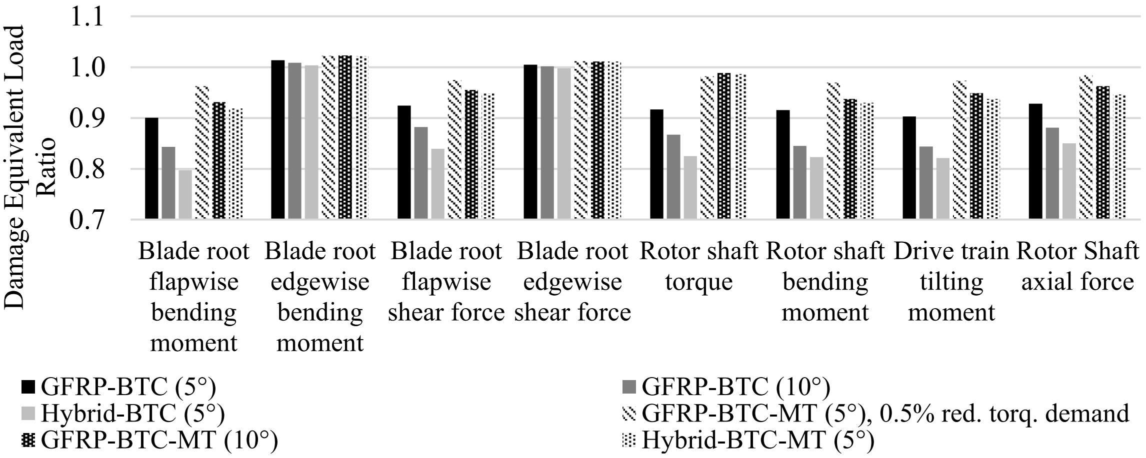

Figure 7. Damage equivalent load ratios in wind turbines with bend-twist coupled blades with the original and the modified pretwist variations at the underrated wind speed of 8 m/s.

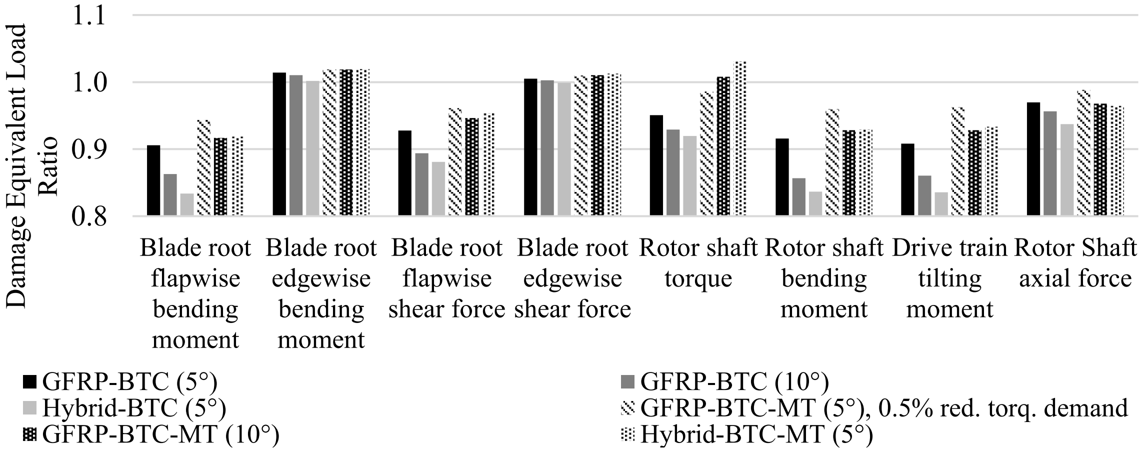

Figure 8. Damage equivalent load ratios in wind turbines with bend-twist coupled blades with the original and the modified pretwist variations at the underrated wind speed of 10 m/s.

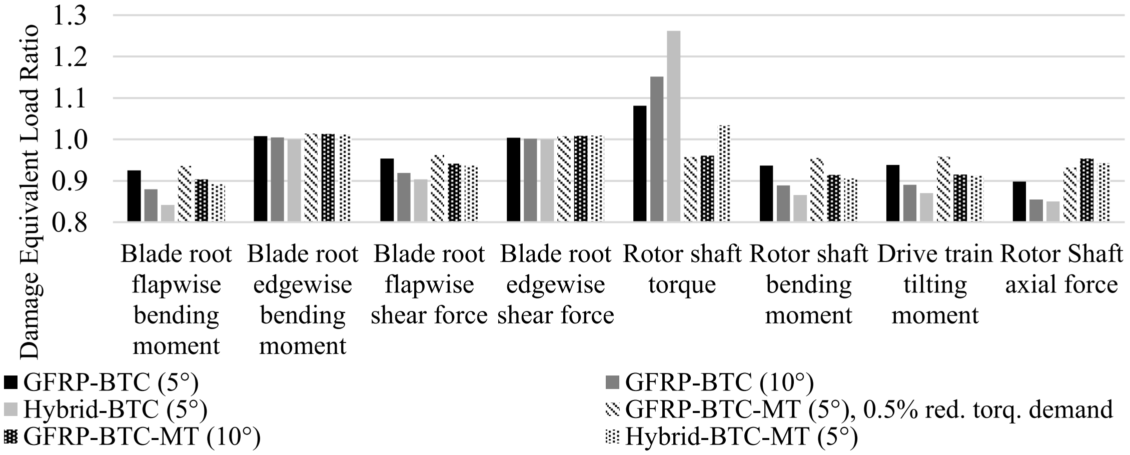

Figure 9. Damage equivalent load ratios in wind turbines with bend-twist coupled blades with the original and the modified pretwist variations at the underrated wind speed of 12 m/s.

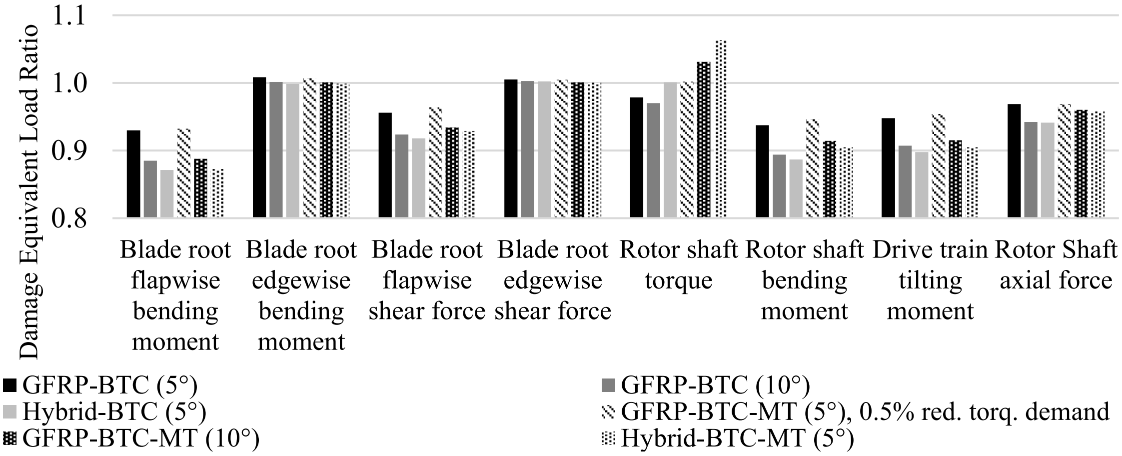

Figure 10. Damage equivalent load ratios in wind turbines with bend-twist coupled blades with the original and the modified pretwist variations at the underrated wind speed of 15 m/s.

4. Conclusion

In this study, the performances of the wind turbines with full GFRP and hybrid GFRP-CFRP bend-twist coupled blades are investigated by comparing the power curves and damage equivalent loads in the wind turbine system with corresponding data of the reference wind turbine. In this study, off-axis spar cap fiber angles 5° and 10° are used to induce bend-twist coupling. As a result of the wind turbine simulations performed in PHATAS, it is shown that the power productions of wind turbines with bend-twist coupled blades at the underrated wind speeds are less than the power generation of the reference wind turbine. To compensate for the power loss at the underrated wind speeds, pretwist variation in the bend-twist coupled sections of the bend-twist coupled full GFRP blades with 5° and 10° off-axis spar cap plies, and the hybrid GFRP-CFRP blade with 5° off-axis spar cap plies are modified. It is shown that with proper modification of the pretwist variation of the bend-twist coupled blades, power loss at the underrated wind speeds can be compensated. It should be noted that the present study has been performed utilizing the same pitch control settings in region 2 to examine the mere effect of pretwist modification on the power performance of the wind turbine and on the damage equivalent loads.

In the next phase of the study, 10 minute multibody simulations of the wind turbine system are performed in turbulent wind conditions for the calculation of damage equivalent loads mainly at the metallic parts at the blade root and in the drive train of the wind turbine. Damage equivalent loads in the wind turbine systems with the BTC blades, which have modified pretwist variations, are compared with the damage equivalent loads in the reference wind turbine and with the damage equivalent loads in the wind turbines with the BTC blades which have original pretwist variation. It is shown that with certain BTC blade configurations, reductions in damage equivalent loads in the wind turbine system can be achieved across the 6 m/s - 15 m/s wind speed range. Although higher reductions can be achieved in the damage equivalent loads with the use of hybrid GFRP-CFRP blade with the original pretwist distribution compared to the full GFRP blades, wind turbine with hybrid BTC GFRP-CFRP blade has the highest power loss at the underrated wind speeds. With pretwist modification, power loss at the underrated wind speeds can be compensated and the wind turbine with the hybrid BTC GFRP-CFRP blade has highest reduction in the damage equivalent loads except for the damage equivalent rotor shaft torque, because the damage equivalent shaft torque in the wind turbine with the hybrid BTC GFRP-CFRP blade with modified pretwist is higher than the damage equivalent shaft torque in the reference wind turbine. Since in wind turbines, most of the damage occurs in the gearbox, and reduction of the damage equivalent rotor shaft torque in the wind turbines is very critical to reduce the fatigue failures in the gearbox, GFRP-BTC-MT (5°) blade stands out as the best performing blade when the performance of the wind turbine and the damage equivalent load reduction across the underrated-overrated wind speeds are considered simultaneously. Similar argument can be made for the full GFRP BTC blade which has higher off-axis spar cap fiber angle (10°). Hence, it is concluded that the best performing BTC blade is the one which has the same material system as the reference blade and with small off-axis spar cap ply angle. However, this conclusion is valid when only the pretwist modification is applied without altering the pitch control setting in region 2. With this study, it is aimed to examine the sole effect of pretwist on the power generation of the wind turbine and on the damage equivalent loads without altering any of the wind turbine parameters. For small off-axis fiber angles, it has been possible to compensate for the power loss in region 2 merely by the pretwist modification. However, for higher off-axis fiber angles, which induce higher bend-twist coupling, proper adjustment of the pitch setting in region 2 is necessary to compensate for the power loss. Although not included in this study, it has not been possible to compensate the power loss in region 2 with the hybrid BTC GFRP-CFRP blade which has higher off-axis fiber angle. This is due to the fact that CFRP composite has higher bend-twist coupling potential and mere pretwist modification cannot compensate the power loss in region 2 without adjusting the pitch setting in region 2.

It should be noted that in the present study the main effort was to use passive means to alleviate loads while still achieving the same power production level of the reference wind turbine across the underrated-overrated wind speeds and pitch controller settings are not optimized with respect to the BTC blade configuration. As a future extension, pitch controller settings can be optimized for each wind turbine with different BTC blades to obtain better performance out of the wind turbines with BTC blades. With the proper adjustment of the pitch control settings in region 2, BTC blades with higher off-axis fiber angles can be used in wind turbine systems which may produce the same power across all wind speeds while still achieving reduction in damage equivalent loads.

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