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# Effect of Turbulence on Power for Bend-Twist Coupled Blades

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**Abstract.** Bend-twist coupling of wind turbine blades reduces the structural loads of the turbine but it also results in a decrease of the annual energy production. The main part of the power loss can be mitigated by pretwisting the blade, but some power loss remains and previous studies indicate that it might be related to the dynamic response of bend-twist coupled blades in turbulent flow. This paper contains estimations of the power curve from nonlinear time simulations, a linear frequency domain based method and a normal distribution weighted average method. It is shown that the frequency domain based estimation is highly dependant on the validity of the linearized model, thus estimations are poor for operational points close to rated wind speed. The weighted average method gives good results if an appropriate standard deviation is known a priori. The nonlinear time simulations show that changes in power due to turbulence are similar for coupled and uncoupled blades. Power gains at low wind speeds are related to the curvature of the steady state power curve. Losses around rated wind speed are caused by the effects of controller switching between partial and full power operation.

## 1. Introduction

Bend-twist coupling intends to reduce ultimate and fatigue loads of wind turbine blades by coupling the aerodynamic forces, which induce bending in the blade, with the twist of the blade. The twist of the blade in turn changes the angle of attack and thereby the aerodynamic forces. This feedback loop, when twisting towards a lower angle of attack, enables the blade to self-alleviate sudden inflow changes, as in gusty or turbulent conditions. Bend-twist coupling can be achieved either by sweeping the planform of the blade (geometric coupling) or by utilising the anisotropic properties of the blade material (material coupling). Previous studies report a fatigue load reduction of 10-20% in coupled blades [1, 2]. While the load reduction is desirable, bend-twist coupling also leads to a slight decrease in the annual energy production (AEP) of the turbine [2, 3, 4]. The reduction is mainly related to a no longer optimal twist distribution along the blade due to the coupling induced twist [2]. Lobitz and Veers [1] compensate for the power loss by determining the linear elastic twist and applying it as pretwist to the blade. A similar procedure for non-linear blade deflections is proposed by Ståblein et al. [5] who show that pretwisting reduces the AEP loss of coupled blades significantly while having little effect on fatigue load reduction. In addition to the twist related power loss, the results of Lobitz and Veers [1] indicate that power loss increases with turbulence for coupled blades.

This paper contains estimations of the power curve from nonlinear time simulations, a linear frequency domain based method and a normal distribution weighted average method. For



the frequency domain based method the difference between steady state power and power in turbulent flow is estimated by integrating the product of shaft torque and generator speed variations. The variations are obtained from wind inputs along the blade and the transfer functions of a linearised aero-servo-elastic turbine model. The weighted average method integrates the product of a normal distribution and the steady state power curve over the operational range.

The effect of turbulence on power is investigated for the DTU 10 MW Reference Wind Turbine (10 MW RWT) [6] with uncoupled and bend-twist coupled blades that have been pretwisted. It is shown that the frequency domain based estimation is highly dependant on the validity of the linearized model, thus estimations are poor for operational points close to rated wind speed. The weighted average method gives good results if an appropriate standard deviation is chosen. The nonlinear time simulations show that changes in power due to turbulence are similar for coupled and uncoupled blades. Power gains at low wind speed are related to the curvature of the steady state power curve. Losses around rated wind speed are caused by the effects of controller switching between partial and full power operation.

## 2. Methods

### 2.1. Coupling & Pretwist

Bend-twist coupling of wind turbine blades can be achieved by changing the fibre direction of the anisotropic blade material. This change leads to coupling terms in the  $6 \times 6$  cross-sectional stiffness matrix of the blade. For this study, the cross-sectional stiffness matrices of the 10 MW RWT were obtained. Coupling was introduced by setting entries  $K_{46}$  of the stiffness matrices, which couple flapwise bending with torsion, to  $K_{46} = \gamma\sqrt{K_{44}K_{66}}$  where  $\gamma$  is a coupling coefficient as proposed by Lobitz and Veers [7] and  $K_{44}$  and  $K_{66}$  are the flapwise bending and torsional stiffness of the cross-section. To mitigate some of the bend-twist related power loss, the blade was pretwisted with the iterative procedure presented in [5] to provide the same angle of attack along the blade as the uncoupled blade at a reference wind speed.

### 2.2. Frequency Domain Power Estimation

The average power  $P_{av}$  in turbulent flow over a period of  $T = 10$  min can be calculated by

$$P_{av} = \frac{1}{T} \int_{t=0}^T (Q_0 + Q_1)(\Omega_0 + \Omega_1) dt \quad (1)$$

where  $Q_0, \Omega_0$  are the steady state values and  $Q_1(t), \Omega_1(t)$  are the variations of the shaft torque and generator speed. Assuming a zero average of  $Q_1$  and  $\Omega_1$ , Equation (1) can be simplified to

$$P_{av} = P_{ss} + \frac{1}{T} \int_{t=0}^T Q_1 \Omega_1 dt \quad (2)$$

where  $P_{ss} = Q_0 \Omega_0$  is the steady state power. The variations in frequency domain

$$\mathbf{Y}(\omega) = \int_{t=-\infty}^{\infty} \begin{Bmatrix} Q_1(t) \\ \Omega_1(t) \end{Bmatrix} e^{-i\omega t} dt \quad (3)$$

were obtained from wind inputs  $\mathbf{U}(\omega)$  along the blade and the transfer functions  $\mathbf{H}(\omega)$  of a linearised aero-servo-elastic turbine model. The wind inputs were calculated by:

- (i) Obtaining the wind speeds at 28 stations along the blade from non-linear time domain simulations in HAWC2 [8, 9].
- (ii) Transforming the wind speeds into multi-blade coordinates.

(iii) Fourier transformation of the wind speeds.

The transfer functions  $\mathbf{H}(\omega)$ , which include dynamic inflow, unsteady aerofoil aerodynamics, structural elasticity and the turbine controller, were obtained from a linearisation around a steady state equilibrium using the aeroservoelastic analysis tool HAWCStab2 [10, 11, 12]. The variations are calculated as  $\mathbf{Y}(\omega) = \mathbf{H}(\omega)\mathbf{U}(\omega)$ .

### 2.3. Normal Distribution Weighted Average Power Estimation

The weighted average method estimates the power at wind speed  $v_0$  by integrating the product of a normal distribution  $f(v|v_0, \sigma)$  with a mean of  $v_0$  and a standard deviation  $\sigma$ , and the steady state power curve  $P_{ss}(v)$  over the operational range of the turbine:

$$P_{av}(v_0) = \int_{v=4}^{25} P_{ss}(v) f(v|v_0, \sigma) dv \quad (4)$$

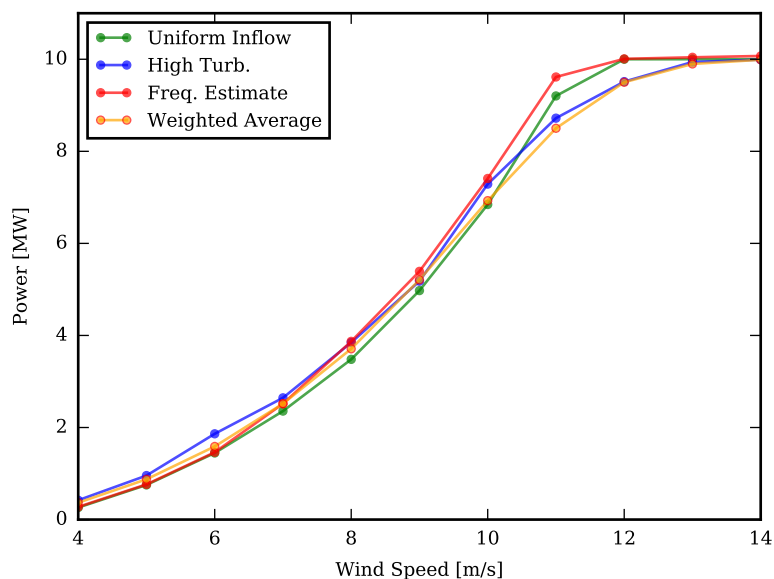
An appropriate standard deviation of the normal distribution has to be assumed a priori for this method.

## 3. Results

For this study the original 10 MW RWT turbine and a coupled version with a constant coupling coefficient of  $\gamma = 0.2$  twisting towards feather for flapwise bending downwind were analysed. The coupled blades were pretwisted at 8 m/s to reduce the coupling related power loss. Both turbines were simulated in uniform inflow (no turbulence, wind shear or tower shadow) and in IEC 61400-1 Class A ( $I_{ref} = 0.16$ ) and Class C ( $I_{ref} = 0.12$ ) turbulent flow (including wind shear and tower shadow) using HAWC2. At each wind speed the turbines were simulated with eighteen 10 min turbulence seeds at yaw angles of  $-10^\circ/0^\circ/+10^\circ$  (6 seeds each). The same set of turbulence seeds at each wind speed was used for both turbines. The power at each wind speed was obtained by taking the average of the eighteen 10 min seeds. Blade root flapwise damage equivalent load was calculated using the rainflow counting method recommended in IEC 61400-13 with load cycles of 1 Hz and a Wöhler exponent of  $m=10$ . The blade root flapwise moment was taken in a coordinate system pitching with the blade. The closed-loop state space model of the turbine was obtained using HAWCStab2.

First, the different methods to estimate the power curve in turbulent flow were investigated using the uncoupled reference blade. The wind input was obtained from the same time domain simulations that were used to obtain the high turbulence power curve used in the comparison. Figure 1 shows the power curves of the DTU 10 MW RWT in uniform inflow (green) and high (Class A) turbulence (blue), and the estimated power curves from the frequency domain (red) and weighted average (orange) methods. In the weighted average method, the normal distribution had a standard deviation of  $\sigma = 1.0$  m/s. The frequency method is not able to capture the effect of turbulence in the wind speed range between 4 and 7 m/s. Between 7 and 10 m/s the approximation of the power curve from non-linear time domain simulations is good. Between 10 and 12 m/s power is overestimated. The weighted average based method is quite close to the power curve over the full wind speed range.

To better understand the inaccuracies of the frequency method, the rotational speed (left), shaft torque (middle), and power (right) of the non-linear time domain simulation (blue) and the linear frequency approximation (red) for wind speeds of 8 (top), 11 (middle), and 12 m/s (bottom) have been plotted in Figure 2 (with steady state values indicated by a grey line). The graph shows that the linear approximation used in the frequency model cannot always match the behaviour seen in nonlinear time simulations. At 8 m/s the rotational speed of the time domain simulation has a lower limit of 6 rpm. The linear model with a steady state rotor speed of 6.4 rpm and a constant positive rotor-to-wind speed gradient is not able to represent this limit and the



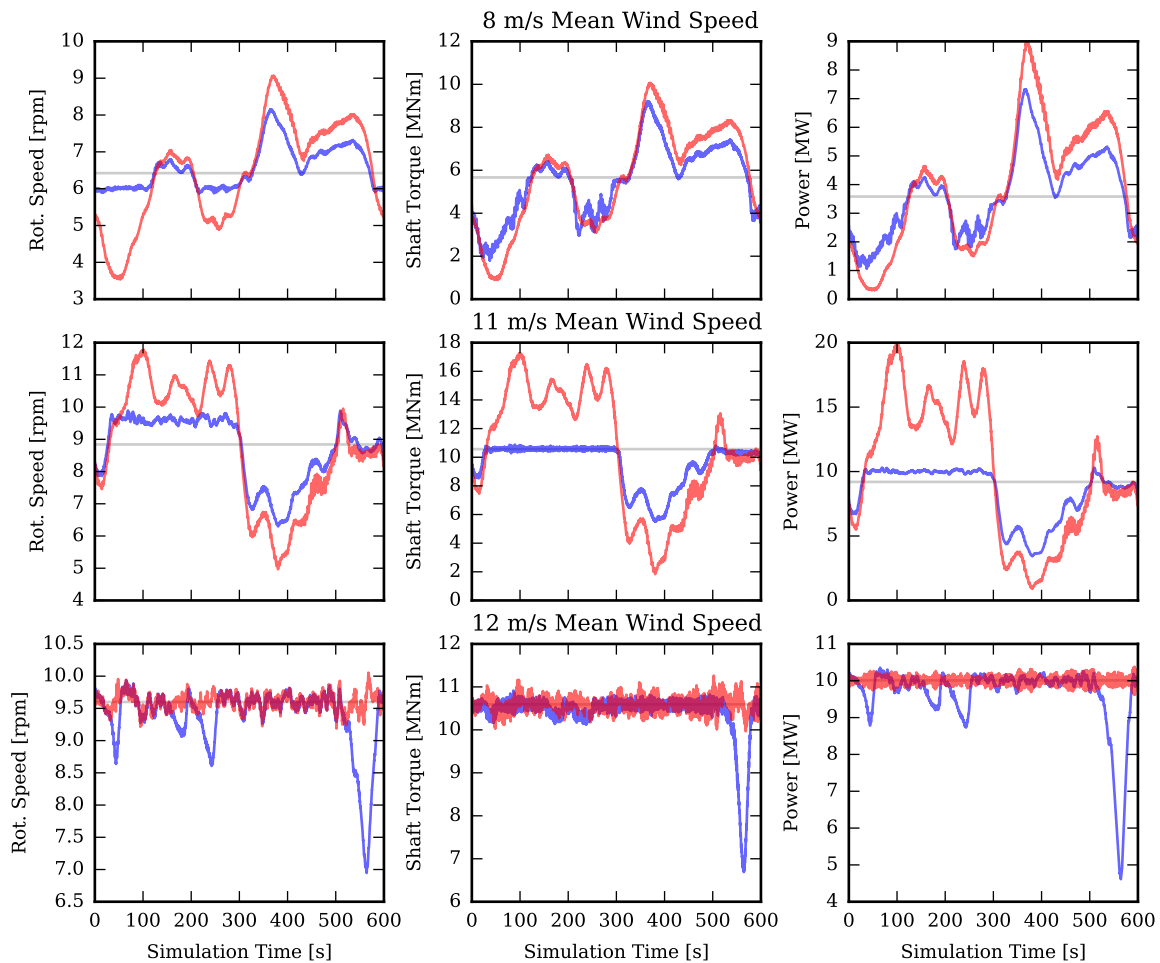
**Figure 1.** Power curves of the DTU 10 MW RWT in uniform inflow (green) and high (IEC Class A) turbulence (blue), and the frequency (red) and weighted average (orange) estimates of the power curve. The weighted average method has a normal distribution of  $\sigma = 1.0$  m/s.

rotational speed is underestimated if the wind speed drops. Nevertheless, the linear prediction of the mean power remains quite accurate. At 11 m/s the rotational speed of the time domain simulation has an upper limit of 9.6 rpm. Shaft torque is limited by 10.6 MNm. Hence, the linear model with its constant and positive gradients on both rotor speed and generator torque overestimates power. At 12 m/s the linear model remains at nominal rotational speed and shaft torque, and it cannot capture the power drops in the nonlinear simulation when the wind speed is below rated.

If the weighted average method can be improved by making the standard deviation  $\sigma$  in Equation (4) dependant on wind speed has also been investigated. The ‘optimal’ standard deviations  $\sigma$  that minimize the difference between the weighted average power and the actual power from HAWC2 simulations (red) have been computed and compared to the standard deviations of the actual wind speed at hub height (blue) and the rotor effective wind speed (instantaneous average over rotor area) (green) in Figure 3. The hub height deviations (blue) increase linear with wind speed as defined in IEC 61400-1 for the normal turbulence model. The rotor effective wind speed deviations (green) also increase linear, albeit with lower values and a lower slope due to averaging over the rotor area. The ‘optimal’ deviations do not follow a similar trend. The deviations are higher for low wind speeds. When the steady state curve crosses the unsteady curve at around 10 m/s wind speed little averaging is needed and the deviations drop and subsequently increase again. Above rated wind speeds ( $\geq 12$  m/s) power is kept constant, less averaging is required and the deviations drop.

Figure 4 shows power and damage equivalent load and their differences for the reference turbine, the coupled blade without pretwist and the coupled blade with pretwist in IEC Class A turbulent flow. Below rated the coupling results in a significant power loss. The power loss reduces if the blade is pretwisted. The coupling results in reduced damage equivalent loads over the whole operational wind speed range. The pretwisting has only a small influence on the fatigue load reduction.

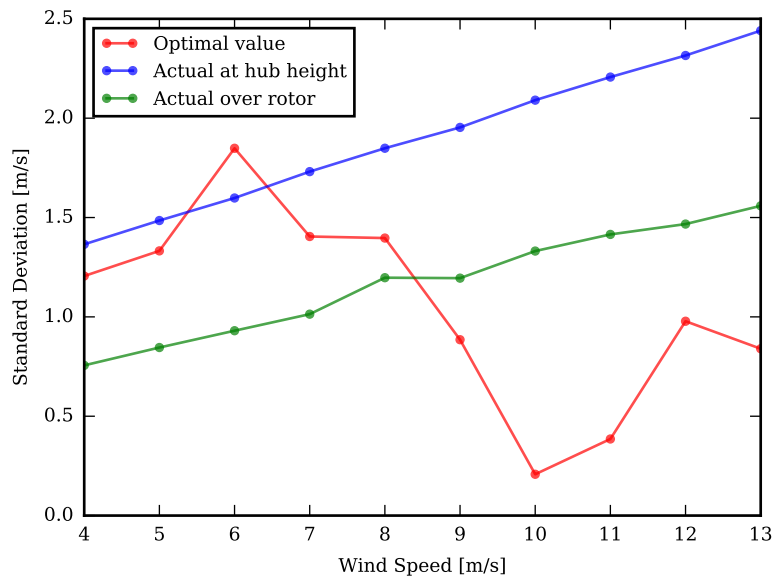
Figure 5 shows the power difference between the uncoupled and the coupled and pretwisted blade in uniform inflow and in different turbulent inflows over wind speed. The effect of



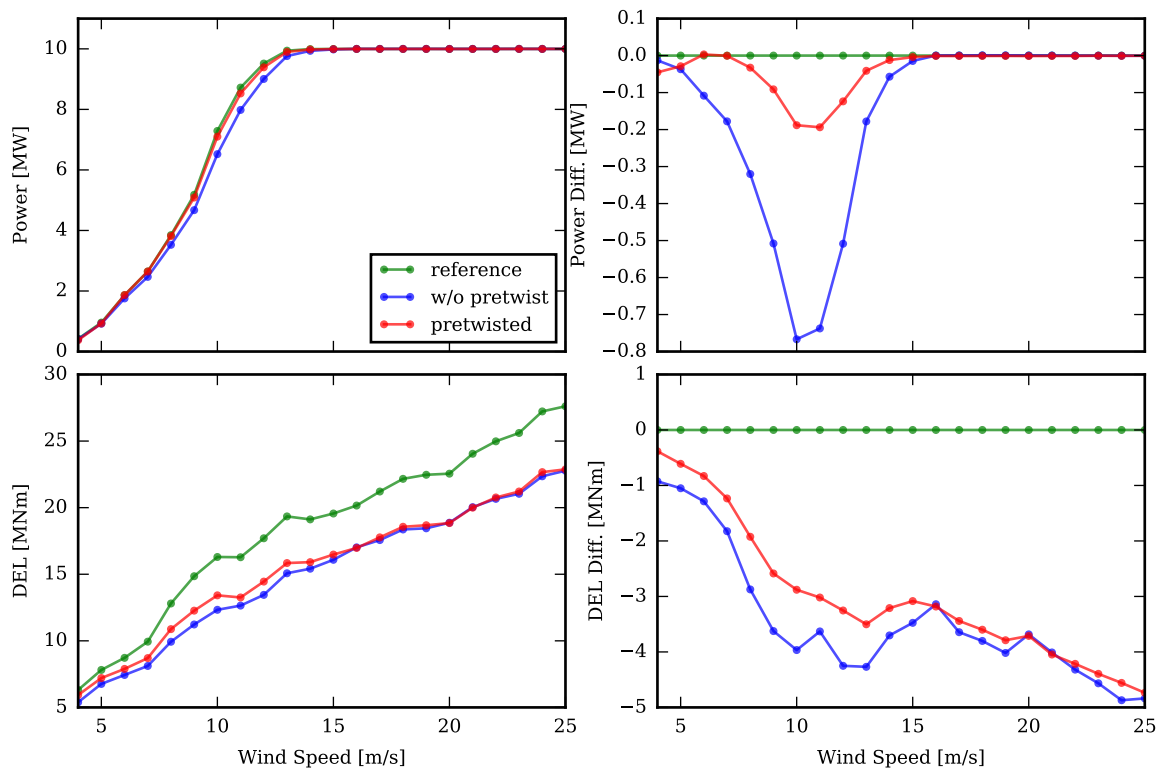
**Figure 2.** Rotational speed (left), shaft torque (middle), and power (right) for the non-linear time domain simulation (blue) and the linear frequency approximation (red) for wind speeds of 8 (top), 11 (middle), and 12 m/s (bottom). The steady state values are also indicated (grey).

turbulence varies with the wind speed. Between 4 and 10 m/s turbulence leads to a power loss for the coupled blade. At 11 m/s turbulence has a positive effect by reducing the power loss to about half the steady state value. Between 12 and 14 m/s turbulence has again a negative effect on the power but reduces with wind speed. Above 14 m/s the coupled blade provides the same power as the uncoupled blade.

Table 1 compares the annual energy production and the annual damage equivalent load of the reference and the coupled and pretwisted DTU 10 MW RWT in uniform and turbulent (IEC Class A) flow. The values were obtained with a Rayleigh distribution and a mean wind speed of 10 m/s. The coupling has a negative effect on the steady state power due to the coupling induced twist. Turbulence increases the annual energy production for both blades. The AEP of the reference blade increases by 0.68 GWh (1.40 %) while the coupled blade increases by 0.66 GWh (1.37 %) compared to their steady state AEP. The annual damage equivalent load of the blade root flapwise moment is reduced by 2.14 MNm (16 %) for the coupled and pretwisted blade.

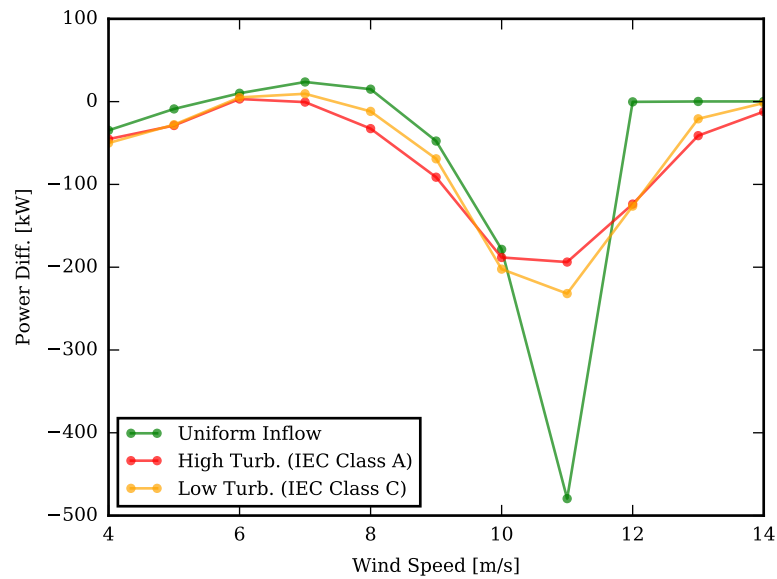


**Figure 3.** Standard deviations of the wind speed used in Equation (4) that minimize the difference between the weighted average power and the actual power from HAWC2 simulations (red), compared to the standard deviations of the actual wind speed at hub height (blue) and the rotor effective wind speed (green).



**Figure 4.** Power and damage equivalent load and their differences for the reference turbine, and the coupled blade ( $\gamma = 0.2$  twist to feather) with and without pretwist in IEC Class A turbulent flow.





**Figure 5.** Power difference between the uncoupled and the coupled and pretwisted blade in uniform inflow and in different turbulent (IEC Class A + C) inflows over wind speed.

Turbine	Inflow	AEP [GWh]	Annual DEL [MNm]
reference	uniform	48.54	-
	turbulent	49.22	13.40
coupled + pretwisted	uniform	48.14	-
	turbulent	48.80	11.26

**Table 1.** Comparison of annual energy production and annual damage equivalent load of the blade root flapwise moment for the reference and coupled and pretwisted DTU 10 MW RWT in uniform and turbulent (IEC Class A) flow.

#### 4. Discussion

The effect of turbulence on power for the DTU 10 MW RWT with uncoupled and bend-twist coupled blades has been investigated. Power estimations of the uncoupled DTU 10 MW RWT blade obtained from nonlinear time simulations, the linear frequency domain based method, and the normal distribution weighted average method are shown in Figure 1. The frequency method provides good results until a wind speed of about 10 m/s where the turbine is running in partial power operation. Between 10 and 13 m/s wind speed the results are not accurate. The inaccuracy is related to the switching of the control regime from partial to full power operation due to wind speed variations. For wind speeds above 13 m/s, when the turbine is running in full power operation, the results of the linear method are accurate again. The effects of the control regime change can also be observed in Figure 2. At 11 m/s mean wind speed the linear model is in partial power operation and power is overestimated if the wind speed increases. At 12 m/s mean wind speed the linear model is in full power operation and power is overestimated when the wind speed drops. The results show that the frequency domain method depends on the validity of the linearised model. In the region around rated, where the control regime changes, the gradients of rotor speed and generator torque are only valid close to the linearisation point and estimations of the linear model are poor.

The weighted average method gives good results if an appropriate standard deviation is assumed. The weighted average results show that the power curve in turbulent flow is mainly influenced by wind speed variations around the 10 min mean wind speed. The wind speed  $v$  enters the power equation  $P = \frac{1}{2}\rho AC_p v^3$  in the third order. The resulting curvature of the power curve leads to higher power gains for wind variations above the mean than is lost due to variations below the mean wind speed. For higher wind speeds the power is limited by the controller switching from partial to full power operation. Variations above the mean wind speed thus contribute less to mean power than variations below mean wind speed reduce it and the turbulent power curve drops below the steady state power curve. There seems to be little correlation between the standard deviations of the wind field and deviations required to minimize the error between predicted and actual power. Improving the weighted average method by changing the standard deviation with wind speed would require further research.

The effects of pretwisting on the power curve and the damage equivalent load are shown in Figure 4. As reported in a previous study [5] pretwisting reduces the coupling related power loss significantly while having little effect on the fatigue load alleviation. The annual damage equivalent load is reduced by 16 %. Similar values (10-20 %) have been reported in previous studies [1, 2].

The question if there is a turbulence related power loss for coupled blades is answered in Figure 5. The power difference for uniform inflow is related to the non optimal twist distribution along the blade. Turbulence increases the power loss in the region between 4 and 10 m/s. An increased power loss is also reported by Lobitz and Veers [1] at a wind speed of 8 m/s. In the region between 10 and 12 m/s, where the steady state power loss increases significantly, turbulence reduces the power loss. To provide a better overall picture of the turbine's performance, the annual energy production is compared in Table 1. Turbulence increases the annual energy production for both, the reference and the coupled turbine model. For the reference turbine turbulence increases the AEP by 1.40 % while it increases 1.37 % for coupled blades, relative to uniform inflow. The difference in AEP increase due to turbulence between the reference and the coupled blade is small. Thus changes in power due to turbulence are similar for coupled and uncoupled blades.

## 5. Conclusion

In this paper the effect of turbulent inflow on the power production for rotors with and without coupling of flapwise blade bending and blade torsion has been investigated by nonlinear time domain simulations. The results show that the changes in power due to turbulence are similar for coupled and uncoupled blades. Power gains at low wind speed are related to the curvature of the steady state power curve. Losses around rated wind speed are caused by the effects of controller switching between partial and full power operation. A linear frequency domain method to predict the power curve in turbulent flow cannot be used to capture the nonlinear controller effects around rated. Simple integrations of the steady state power curve weighted by normal distributions of wind speeds around each mean wind speed are close to the power obtained from the nonlinear simulations.

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