Consistent direct-drive version of the NREL 5MW turbine

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Abstract. Access to relevant reference wind turbine models is important to the wind energy community to advance turbine technology and lower the cost of wind energy. Multiple reference turbines are available, which can be used to simulate their structural response using aero-elastic codes. A common feature of current reference turbines is the utilization of a gearbox, and at present no direct-drive reference model is publicly available. This does not reflect the trend in the industry with direct-drive turbines becoming increasingly popular.

In this work we develop an onshore direct-drive version of the geared 5MW reference wind turbine by NREL. The presented direct-drive model is a fully consistent conversion of the geared design, intended to analyse the differences in structural loads between the two concepts.

By simulating the developed direct-drive turbine model we show that fatigue loads on the drivetrain differ significantly for the gearless design, with approximately 10% lower loads for design class IIB from the IEC 61400-1 design standard. The developed direct-drive turbine model can be used in the wind energy community to improve the understanding of differences in structural loads between geared and direct-drive designs of modern multi-megawatt wind turbines.

1. Introduction

Multiple reference wind turbines are available for the scientific community to simulate the response of modern utility turbines. Some relevant examples are the 1.5MW windPACT turbine [1], the 5MW turbine by NREL [2], and the 10MW turbine by DTU [3]. Recently an 8MW reference turbine was also developed in the LEANWIND project to fill the gap between the 5MW turbine by NREL and the 10MW turbine by DTU [4]. A common feature for all currently available reference turbines is the utilization of a gearbox to increase the rotational speed of the rotor to match the demand of a high-speed electrical generator. However, for utility wind turbines in the megawatt range the concept of "direct-drive" design, where the generator is connected directly to the shaft of the turbine rotor, has become widely used.

As the direct-drive concept becomes increasingly popular, it is important to study how it differs from its geared counterpart. This is also reflected by the "IEA Wind Task 37 - Systems Engineering" [5] where a direct-drive version of the 10MW turbine by DTU for offshore application is under development. In [6] a 5MW direct-drive turbine was also developed for the aero-elastic code HAWC2 with focus on showing its application for floating spar-buoy wind turbines. However, although the model was described in detail, it was not made publicly available.

The aim of the present work is to develop a consistent direct-drive version of the 5MW reference turbine by NREL. The model is developed for onshore applications using the freely available aero-elastic code FAST [7]. The goal is to establish a one-to-one conversion of the existing reference turbine, which makes the developed model suitable for comparing structural loads for the two design concepts even though the 5MW reference turbine may not necessarily reflect the design of modern utility turbines. The developed direct-drive model is intended as an open access reference turbine for the wind energy community.

2. Direct-drive specifications and assumptions

The transition from gearbox to direct-drive is based on the following two key assumptions:

- The control strategy used for the geared design is applicable for the direct-drive design.
- The total mass of the entire nacelle is the same for both designs.

The former assumption implies that the baseline controller for the geared 5MW turbine can be redesigned by scaling the control parameters related to the speed of the high-speed shaft (HSS) and the torque. The latter assumption implies that the same structural properties of the tower may be used for both designs. It is noted though, that there will likely be a difference in the weight of the nacelle between the two concepts for real turbines but depending on the manufacturer it may be either lighter or heavier. A simple approach for a generic model is therefore to assume the same weight which in turn also makes it possible to compare loads in the tower without influence of changes in its design.

The drivetrain of the original 5MW reference turbine consists of a high-speed multiple-stage gearbox system with a ratio of 1:97. It is modelled as a single torsional degree of freedom system with a structural damping ratio of 5% relative to the critical damping. In the developed direct-drive design the gearbox is "removed" by changing the ratio to 1:1, while assuming that the drive-shaft torsional stiffness and damping constant is the same as for the geared design. Note that this approach does not actually remove the HSS in the structural model; However, this has no influence on the results as the "fictional" HSS can be considered equivalent to the low speed shaft (LSS) that is attached directly to the rotor when appropriate scaling is applied to the control parameters.

Another important difference between the geared and direct-drive design concepts is the size and type of generator. The generator inertia around the "fictional" HSS in the model must be specified in accordance to a direct-drive low speed generator, which is larger than traditional high-speed generators. Furthermore, the change of generator and removal of the gearbox may influence the location of the nacelle center of mass (NacCM). In the developed direct-drive design NacCM is assumed unchanged compared to the geared turbine (1.9m "downwind" compared to the yaw axis). The influence of this assumption on fatigue loads is analysed in a sensitivity study in section 3.

In the following the changes made to successfully convert the geared design to a direct-drive-design are quantified, first focusing on the controller specifications and next the drivetrain specifications.

2.1. Controller specifications

The baseline controller for the geared 5MW turbine consists of a generator-torque controller and a full-span rotor-collective blade-pitch controller both described in detail in [2]. The controller operates in five regions; 1, 1½, 2, 2½ and 3 which is shown schematically in Figure 1.

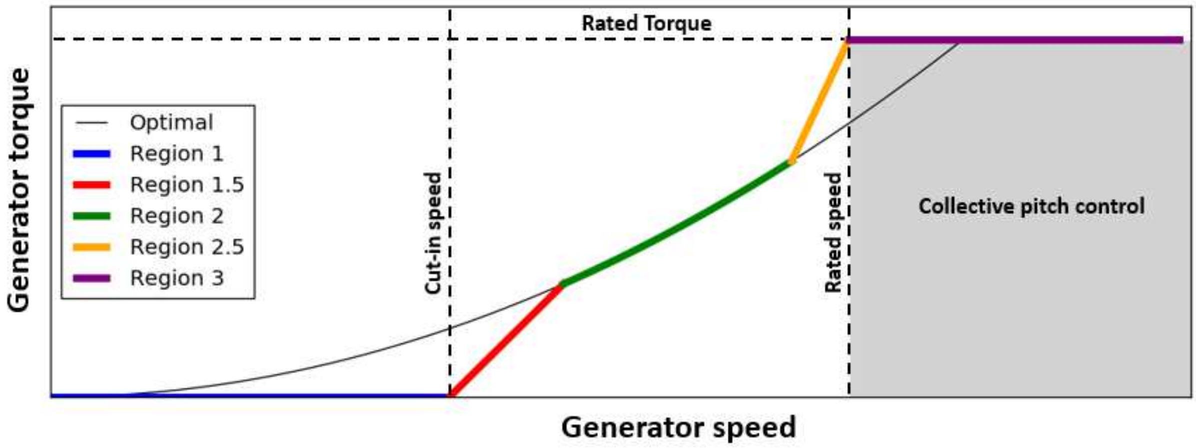

Figure 1: Schematic overview of the 5MW reference turbine baseline controller by NREL.

Region 1 is before cut-in windspeed where the torque is zero and the wind is used to accelerate the rotor for start-up. Region 2 is the control region for optimized power capture, where the torque is controlled to maintain an optimal tip speed ratio. In region 3 the rated generator power is reached, and the control system is designed to keep this constant by collective pitch of the blades. Region 1½ is a linear transition between regions 1 and 2 used for start-up and region 2½ is a linear transition between regions 2 and 3 used to limit tip speed and thus noise emissions near rated power [2].

To adapt the generator-torque controller to the direct-drive version all HSS speed parameters are scaled down with respect to the change in gearbox ratio (GBRatio) and all torque parameters are scaled up (factor of 97). All changes are listed in Table 1 using the same parameter descriptions as in the source code for the controller [2].

Table 1. Generator torque control parameters.

Parameter	**Description**	**Gearbox design**	**Direct-drive design**	**Scaling**
Rated rotor speed [RPM]	-	12.1	12.1	-
GBRatio [-]	Gearbox ratio	1:97	1:1	-
VS_CtInSp [rad/s]	Transitional generator speed (HSS side) between regions 1 and 1 1/2	70.16224	0.72332	GBRatio
VS_MaxRat [Nm/s]	Maximum torque rate (in absolute value) in torque controller	15,000.0	1,455,000.0	GBRatio
VS_MaxTq [Nm]	Maximum torque in region 3 (HSS side)	47,402.91	4,598,082.27	GBRatio
VS_Rgn2K [Nm/(rad/s)^2]	Generator torque constant in Region 2 (HSS side)	2.332287	2,128,615.373	GBRatio^3
VS_Rgn2Sp [rad/s]	Transitional generator speed (HSS side) between regions 1 1/2 and 2	91.21091	0.940319	GBRatio
VS_RtGnSp [rad/s]	Rated generator speed (HSS side)	121.6805	1.254438	GBRatio
VS_RtPwr [W]	Rated generator power in Region 3	5,296,610.0	5,296,610.0	-

The blade-pitch controller operates in region 3 using gain-scheduled proportional integral control on the speed error between the filtered generator speed and the desired generator speed. The pitch control is adapted to the direct-drive design by scaling the pitch gains and desired HSS speed according to the change in gearbox ratio as described in Table 2. The parameter descriptions are taken from the source code for the controller [2].

Table 2. Full-span rotor-collective pitch control parameters.

Parameter	Description	Gearbox design	Direct-drive design	Scaling
PC_KI [-]	Integral gain for pitch controller at rated pitch	0.008068634	0.782657498	GBRatio
PC_KP [s]	Proportional gain for pitch controller at rated pitch	0.01882681	1.82620057	GBRatio
PC_RefSpd [rad/s]	Desired (reference) HSS speed for pitch controller	122.9096	1.2671	GBRatio

2.2. Drivetrain specifications

The direct-drive generator inertia is set to 250,000kgm^2, assuming that the generator has a diameter of approximately 6m, with a mass of the generator yoke including magnets and a brake disc of approximately 25,000 kg. These parameters are based on engineering judgement and may deviate for real designs and therefore a sensitivity study of the influence of the generator inertia on fatigue loads is conducted in section 3. In Table 3 some selected structural properties related to the drivetrain of the direct-drive and geared design are compared. Note that the generator inertia is specified around the HSS which is artificial in the direct-drive design and equal to the LSS. For comparison, the reflected load inertia of the generator around the LSS in the gearbox design should be scaled with the gearbox ratio squared (~5,000,000 kgm^2), which results in a factor or ~20 between the two inertias.

Table 3. Drivetrain comparison.

Parameter	Description	Gearbox design	Direct-drive design	Scaling
DrTrDOF [-]	Drivetrain rotational degree of freedom	Enabled	Enabled	-
GenIner [kgm^2]	Generator inertia about HSS	534.12	250,000.0	Engineering judgement
DTTorSpr [Nm/rad]	Drivetrain torsional spring	867,637,000	867,637,000	-
DTTorDmp [Nm/(rad/s)]	Drivetrain torsional damper	6,215,000	6,215,000	-

3. Results

In this section the performance of the developed 5MW direct-drive turbine is compared to the original gearbox design. To verify the scaling of the controller, both turbines are simulated in FAST when exposed to a linearly increasing windspeed event and a turbulent wind field above rated windspeed, respectively.

The results of the simulations are shown in figures 2 and 3 in terms of wind speed, generator power and blade pitch. Coloured lines represent the direct-drive design (DD) and the black lines represent the original gearbox design (GB). Overall, the output from the two turbines is very similar indicating a successful conversion of the controller.

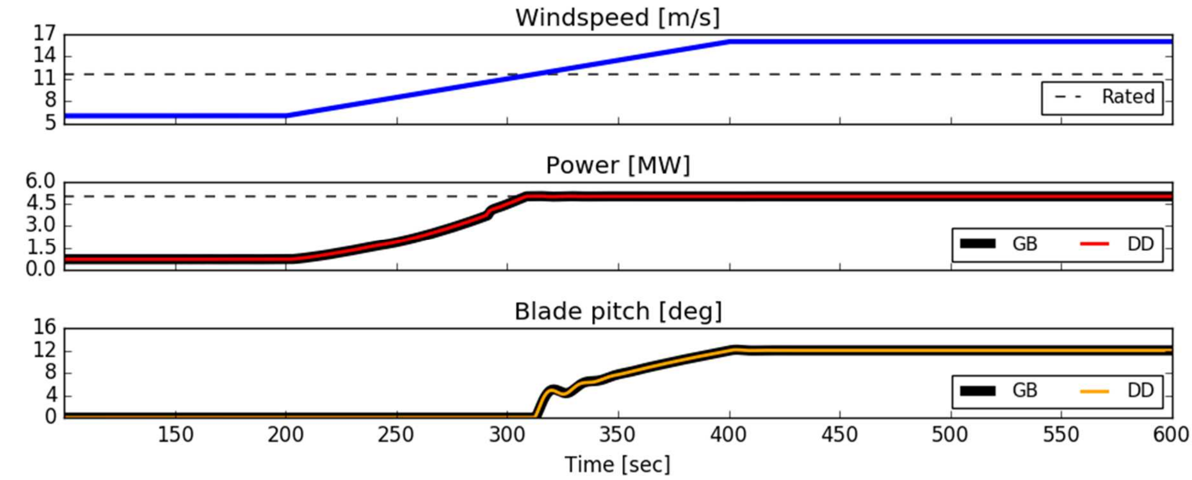

Figure 2: Comparison of the original and scaled controller during a linear increase in windspeed from 6m/s to 16m/s. GB is the original geared turbine and DD is the direct-drive version.

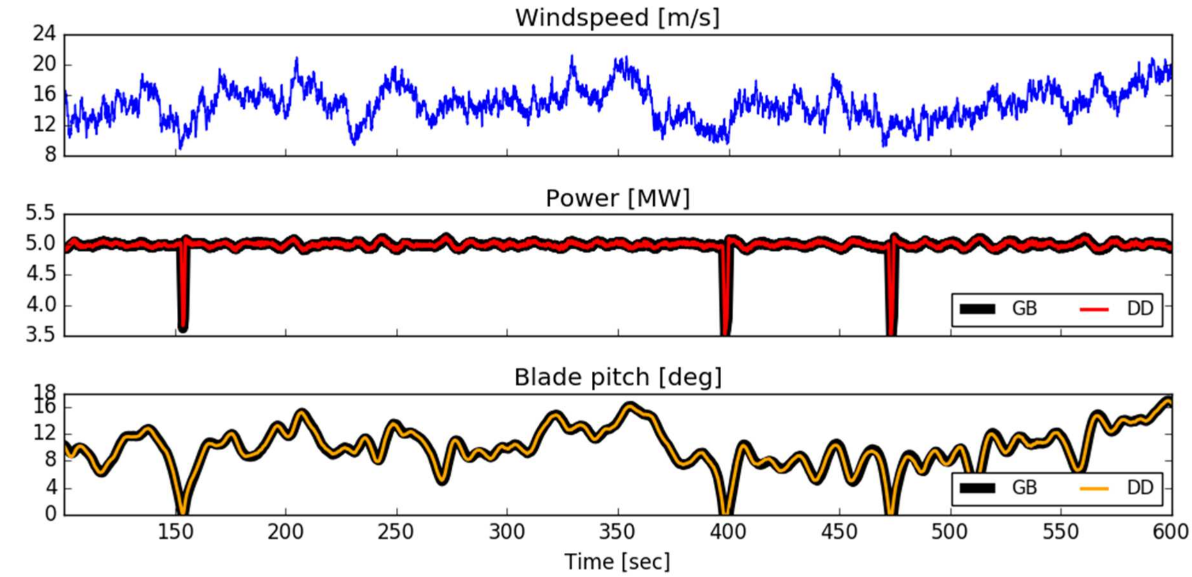

Figure 3: Comparison of the original and scaled controller at a mean windspeed of 17m/s and turbulence intensity of 0.15. GB is the original geared turbine and DD is the direct-drive version.

3.1. Fatigue loads

Based on wind turbine class IIB defined in the Design Standard IEC 61400-1 3rd ed. [8], fatigue loads during normal operation have been computed for both designs, assuming a lifetime of 20 years. The results are summarized in Table 4 in terms of "damage equivalent loads" (DEL) for four selected main components. For all components a slight reduction in fatigue loads is achieved by the direct-drive design concept; However, the only significant reduction is obtained for the LSS, with a reduction of approximately 10%.

Table 4. Design class IIB fatigue loads for both designs and the relative difference.

Component	DEL Gearbox [kNm]	DEL Direct-drive [kNm]	Relative Difference
Blade root flapwise moment	9,504	9,418	-0.9%
Yaw bearing tilt moment	7,848	7,837	-0.1%
Tower bottom for-aft moment	44,690	44,531	-0.4%
Low speed shaft torque	1,733	1,554	-10.3%

The reduction in the LSS torque fatigue load is directly related to the reduction in the reflected load inertia. This is shown in Figure 6 where the shaft torque and blade root flap moment timeseries are compared when both the geared and direct-drive turbine are exposed to a turbulent wind field. For the blades almost no difference is observed whereas the LSS torque is significantly "smoothed" by the lower inertia, thus leading to fewer load cycles.

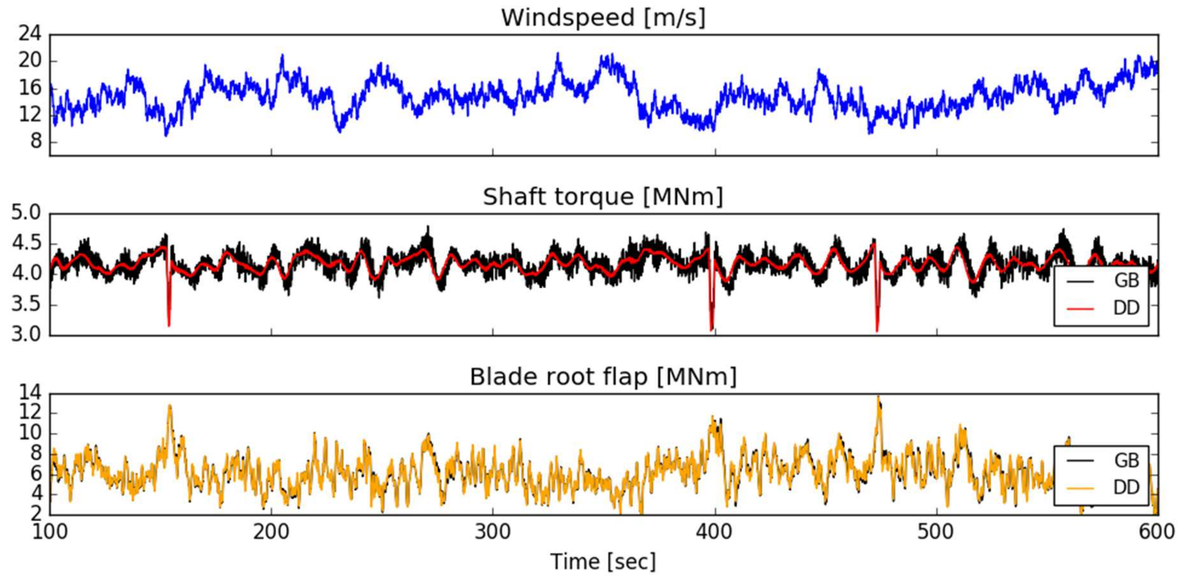

Figure 4: Response time series of LSS torque and blade root flap moment. GB is the original geared turbine and DD is the direct-drive version.

3.2. Sensitivity study, generator inertia

The chosen generator inertia (250,000kgm^2) is based on engineering judgement, hence it is subject to uncertainty. Therefore, a sensitivity study has been conducted where the generator inertia has been changed between 200,000kgm^2 and 500,000kgm^2 and the sensitivity of DELs for the selected main sensors has been evaluated. The turbine is simulated using a highly turbulent wind field with a mean wind speed of 15m/s. The results of the sensitivity analysis are shown in figure 5 normalized with the chosen design.

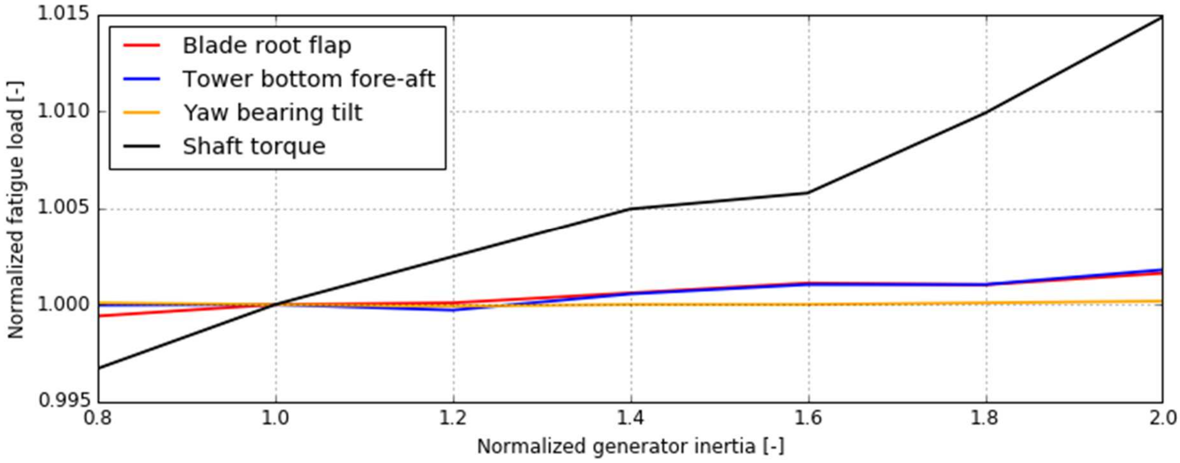

Figure 5: Fatigue load sensitivity to generator inertia normalized with respect to the default inertia of 250.000 kgm^2 for easy comparison.

In the range from 200,000kgm^2 to 500,000kgm^2 the relative difference is 0.2% for the blades and tower, 0.0% for the yaw bearing and 1.8% for the shaft. Therefore, the chosen inertia of 250,000kgm^2 seems appropriate and a specific generator should differ significantly from this to have a noticeable effect on the fatigue loads.

3.3. Sensitivity study, Nacelle center of mass

The NacCM is located 1.9m “downwind” compared to the yaw axis in the original geared design, and the same position is assumed for the direct-drive design. In this section it is investigated if the DELs on the main components are sensitive to moving the center of mass for the direct-drive design. Note that when the center of mass is moved the nacelle inertia (NacIner) around the yaw axis is changed using the parallel axis theorem where the mass of the nacelle is 240,000kg and its base inertia is 1,741,493kgm^2 [2]. The possible change in the eigen-frequency related to the torsion mode shape of the tower is not accounted for, as it is assumed that the mass and position of the rotor hub and blades are by far the most important contributions to this frequency. The result of the sensitivity study is shown in figure 6 normalized with the chosen NacCM position.

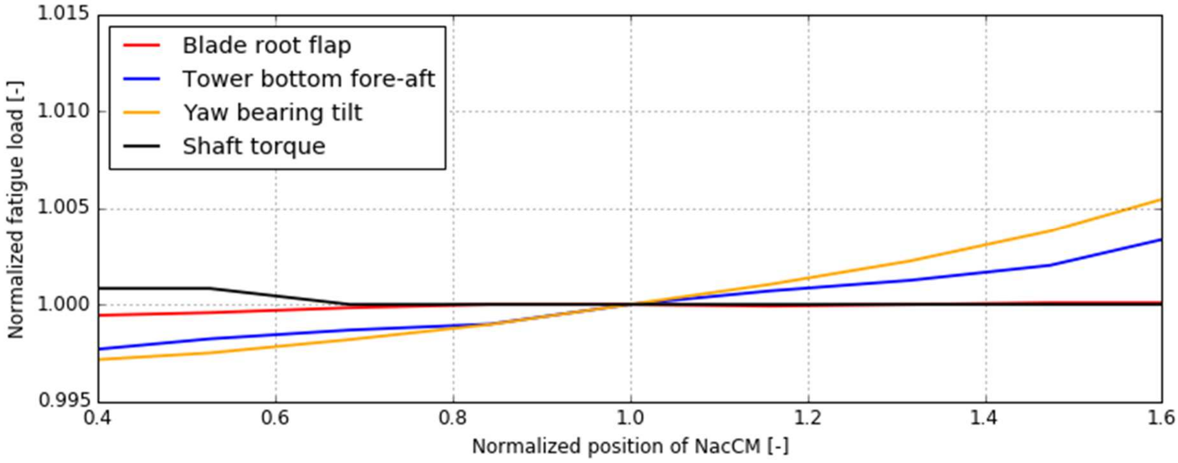

Figure 6: Fatigue load sensitivity towards the downwind position of NacCM normalized with respect to the default position of 1.9m downwind for easy comparison.

It is seen that in the investigated range between 0.7m downwind and 3.1m downwind the relative fatigue load difference is 0.1% for the blades, 0.6% for the tower, 0.9% for the yaw bearing tilt and 0.1% for the shaft. Results have also been computed (but not shown here) for the yaw bearing yaw and the tower torsion, as they are expected to see the highest sensitivity, but both are within 2%.

4. Conclusion

A fully consistent direct-drive version of the onshore 5MW reference wind turbine by NREL has been developed. By assuming the same control strategy for both designs, the baseline controller for the 5MW geared turbine has been scaled to apply to the direct-drive version. To achieve a consistent one-to-one conversion the weight of the nacelle is assumed the same both designs. Using typical values for the dimensions and mass of a low speed generator its inertia around the low speed shaft of the direct-drive turbine has been established. The position of the nacelle center of mass is assumed unchanged compared to the geared design.

By simulating design class IIB fatigue loads during normal operation for both the original geared and the developed direct turbine turbines, it is shown that only the fatigue loads on the low speed shaft change significantly between the two design concepts. Compared to the geared turbine, the direct-drive design obtained approximately a 10% lower DEL in the main shaft, while the blade root flapwise moment, tower base for-aft moment, and yaw bearing tilt moment were all within 1%.

Sensitivity studies with respect to fatigue loads were performed for the generator inertia and nacelle center of mass position. This showed that both design parameters should deviate significantly from the chosen values to have a significant impact on the results. By doubling the generator inertia none of the investigated components showed a relative difference in fatigue loads larger than 2%. Similarly, the position of the nacelle center of mass was moved more than 1m both upwind and downwind without any changes in fatigue loads greater than 2%.

The developed direct-drive turbine is intended as an open access reference turbine, which can be used by the wind energy community to analyse the difference in structural loads between a geared turbine and a fully consistent direct-drive version. It is noted that even though the 5MW reference turbine may not represent modern utility wind turbines perfectly, the developed direct-drive turbine together with the original geared turbine may still provide a solid basis for comparative analyses of the two design concepts.

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