Variation of Extreme and Fatigue Design Loads on the Main Bearing of a Front Mounted Direct Drive System

Abrahamsen, Asger Bech; Natarajan, Anand

Published in:
Journal of Physics: Conference Series (Online)

Link to article, DOI:
10.1088/1742-6596/753/11/112006

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Abrahamsen, A. B., & Natarajan, A. (2016). Variation of Extreme and Fatigue Design Loads on the Main Bearing of a Front Mounted Direct Drive System. Journal of Physics: Conference Series (Online), 753, [112006]. DOI: 10.1088/1742-6596/753/11/112006

Variation of Extreme and Fatigue Design Loads on the Main Bearing of a Front Mounted Direct Drive System

2016 J. Phys.: Conf. Ser. 753 112006

(http://iopscience.iop.org/1742-6596/753/11/112006)

Variation of Extreme and Fatigue Design Loads on the Main Bearing of a Front Mounted Direct Drive System

Asger Bech Abrahamsen and Anand Natarajan

Technical University of Denmark, Department of Wind Energy,
Frederiksborgvej 399, 4000 Roskilde, Denmark

Abstract. The drivetrain of a 10 MW wind turbine has been designed as a direct drive transmission with a superconducting generator mounted in front of the hub and connected to the main frame through a King-pin stiff assembly by DNV-GL. The aeroelastic design loads of such an arrangement are evaluated based on the thrust and bending moments at the main bearing, both for ultimate design and in fatigue. It is found that the initial superconductor generator weight of 363 tons must be reduced by 25% in order not to result in higher extreme loads on main and yaw bearing than the reference10 MW geared reference drive train. A weight reduction of 50% is needed in order to maintain main bearing fatigue damage equivalent to the reference drive train. Thus a target mass of front mounted superconducting direct drive generators is found to be between 183-272 tons.

1. Introduction

Some manufacturers of large wind turbines prefer direct drive transmission configuration, implying no gearbox and unit transmission ratio. This may enable improved reliability of the transmission system due to lesser number of moving parts, but it also results in a large size generator, usually permanent magnet or other synchronous types. In order to develop a compact nacelle structure, some of the commercial designs such as for the Siemens 6 MW turbine [1] have the generator mounted direct to the hub with the entire nacelle in front of the tower. Thus the main bearing(s) supports a large amount of the bending moments resulting from asymmetric rotor loads. Another approach as followed in the INNWIND.EU project [2] develops the design of a 10 MW drivetrain and nacelle as a front mounted generator wherein the generator is again directly mounted to the hub, but in front of the rotor as given in Fig. 1. The main questions posed here are 1) Do these hub mounted generator concepts in front of the rotor provide any advantage in terms of the extreme loads and fatigue loads at the main bearing and yaw bearing and if so, 2) Quantify the sensitivity of the design loads on the mass of the generator.
Finally a reliability of the main bearing at the 10 MW turbine is investigated based on the drivetrain configuration with different overhang masses.

2. Design Configuration

Figure 1 is illustrating the King-Pin nacelle tailored for a 10 MW superconducting direct drive generator (SCDD) [3]. This configuration has been studied with different superconducting generator configurations in order to optimize the Cost of Energy (CoE) of the 10 MW INNWIND.EU turbine[4].

The major advantage of the SCDD is often stated to be the possibility of providing a light weight generator compared to traditional direct drive generators based on wound copper coils or permanent magnets[5]. However if the trade-off is a higher CAPEX that will drive up the cost of energy then the SCDD will lose its commercial potential. There are two distinct selection criteria to be followed in the design of SCDD: 1) The choice of the superconductor wires and the operation temperature, 2) The amount of silicon iron in the generator, which will reduce the needed amount of superconductor wire and thereby cost, but at the expense of a higher weight. The superconducting wires are categorized as Low- Medium and High Temperature superconductors with operation temperatures in the range of T > -268 ^{o}C (4 K), -262 to -252 ^{o}C (10-20 K) and -252 to -222 ^{o}C (20-50 K) being representative for the superconducting materials NbTi, MgB_2 and $RBa_2Cu_3O_{6+x}$. The cost per length of these wires scale roughly like 1:5:70, but the advantage of the expensive wire is much higher operation temperature and thereby a simpler and more efficient cryogenic cooling system to keep the superconductors cold [6]. In the INNWIND.EU project both the Medium (MgB_2) and High temperature superconductors(RBaCuO) have been investigated [7] and it is concluded that both wire types will currently benefit from putting as much iron into the generator as possible, but at the expense of a higher weight. This conclusion is in line with similar studies where it has been shown that such SCDD becomes similar to conventional direct drive, because the design is mainly driven by the properties of the silicon iron[8]. The INNWIND.EU front mounted 10 MW MgB_2 generator proposed for this study result in a diameter of D_{gen} = 6.6 m, a length of L_{gen} = 2.44 m and a weight of approximately m_{gen} ~ 363 tons [7].
The requirement to design SCDD with a reduced amount of silicon iron is that a lot of cheap and high performing superconductors are used to create the magnetic field in the generator. Such a design has been proposed GE Global Research for NbTi resulting in D_{gen} = 4.3 m, a length of L_{gen} = 1.88 m and a weight of approximately m_{gen} ~ 143 tons[9]. Due to the low cost of the NbTi wire then it was concluded that a cost of energy competing with the permanent magnet direct drive was possible [9], but it should be said that the concept is based on an rotating outer armature supplied with slip-rings, stationary superconducting field coils and a complicated cooling system, which will need de-risking for the offshore wind sector.

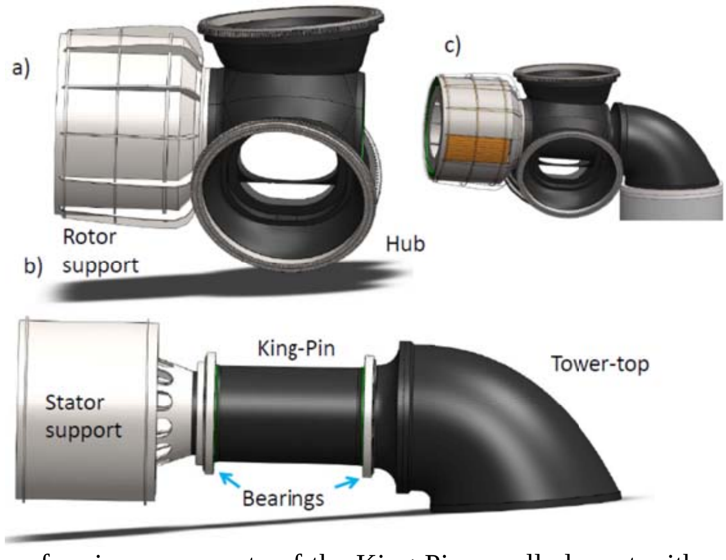

Figure 1. Illustration of main components of the King-Pin nacelle layout with a front mounted direct drive generator. **a**) Rotating part of the nacelle: The generator rotor support structure (left) is connected directly the hub (right) holding the pitch bearings for the blades. **b**) Static nacelle parts: The generator stator support (left) is connected to the King-pin (centre) supporting the hub with two main bearings and is connected to the tower-top (left). **c**) Combined king-pin nacelle layout.

The intention of this paper is to investigate the dynamic loads on the main- and yaw bearing of the turbine with the front mounted direct drive generator in comparison to the conventional geared configuration and thereby quantify the benefits thereof. Secondly it will be investigated how the turbine loads change as the mass of the front mounted generator is reduced towards the specifications of the NbTi machine as proposed by GE. This scaling is done by simple reducing the length of the machine and assuming the superconducting windings are replaced by better performing wires, which might also be operated at lower temperature to increase the magnetic flux density in the airgap of the generator. The advantage of this approach is that the moment of inertia is scaling linearly with the length.

3. Estimation of Loads using Aeroelastic Simulations

To perform aeroelastic simulations of the turbine with the front mounted generator, the mechanical characteristics of the nacelle are represented in terms of masses and moments of inertia with respect to the turbine tower axis as well as the rotation axis of the hub [10]. The nacelle mass is defined as being the tower-top and king-pin, the hub mass are all the rotating parts between the two main bearings (but excluding the blades) and the generator mass includes the rotor active materials (Si-steel and superconductors), rotor support (see fig 1), stator active materials (Si-steel and Cu) and the stator support (see fig 1). These parameters are listed in table A1 of appendix A and are combined with the INNWIND.EU 10 MW turbine having a hub height of h_{hub} = 119 m and a rotor diameter of D_{rotor} = 178 m [4].
Figure 2 is illustrating how the properties of the hub is conceptually combined with an outer rotor direct drive generator that is either placed in front of the rotor or behind the tower indicated by r_2 and r_3 respectively.

The center of mass of the generator and hub are found from the densities of the specific materials. The moment of inertia of the generator parts with respect to the y-axis are given by

$$I_{rotor} = \int r^2 dm = \int \rho(r) r^2 dv = \frac{\pi \rho L_{gen}}{2}(r_{rotor2}^4 - r_{rotor1}^4) \quad (1)$$

where r is the radius from the axis of evaluation, dm is a mass element, which can be related to a volume element dv using the mass density $\rho(r)$, $dm = \rho dv$. The length of the generator is denoted L_{gen}.

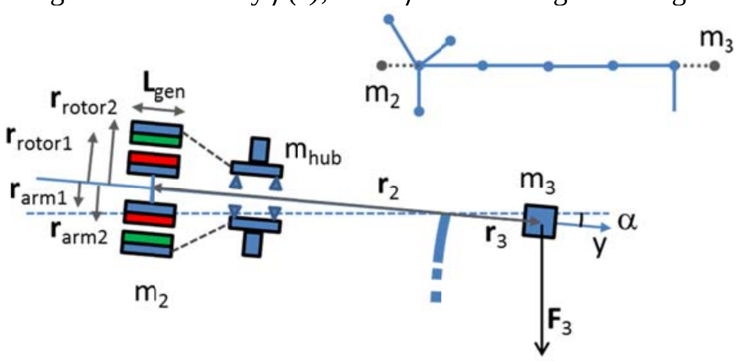

Figure 2. Illustration of the main dimensions of a front mounted direct drive generator with the rotor parts rotating with respect to the y-axis. The active materials being superconductor and silicon steel (green) are supported by the structural parts (blue), which are connected to the hub (dashed line). The active material (red) of the armature consisting of Cu and silicon steel are supported by structural material (blue) and fixed to the king-pin center line along the y-axis. The mass m_3 is illustrating the situation where the generator is mounted behind the tower (as in the conventional geared solution) and connected to the hub using a long flexible shaft (not shown). The inset illustrates the simplified beam element representation of the aeroelastic model.

From equation (1) it is possible to estimate the moment of inertia from an electromagnetic generator model and to combine that with an initial design of the generator support structure as shown in figure 1. Since they share the same rotation axis then the resulting moment of inertia for the generator $I_{rotor,gen}$ is the sum of moment of the active material $I_{rotor,active}$ and the structural parts $I_{rotor,structural}$.

$$I_{rotor,gen} = I_{rotor,active} + I_{rotor,structural} \qquad (2)$$

Table A2 is showing a series of generator specification in terms of component masses and moment of inertia I as found from eq. (2). The configuration denoted superconducting direct drive (SCDD) MgB_2 10 MW is the initial design of the front mounted generator, whereas the following design proposals are scaled with a shorter length to finally reach a generator mass that is similar the NbTi generator mass (last column). The properties of the 10 MW NbTi generator has been estimated from [9].

The key design load cases (DLC) that were determined to be design drivers for the 10 MW reference wind turbine tower top for ultimate design, that is DLC 1.3, normal operation under extreme turbulence and DLC 2.3, that is operating gust with grid loss were re-simulated with the new nacelle configuration. Further the fatigue on the main bearing will be quantified using DLC1.2 results; that is operation under normal wind turbulence [11]. Further along with the configuration in Fig. 1, three variations from table 2 are also simulated in HAWC2 with a decreasing weight corresponding to 75%, 50% and 40% of the initial direct drive king pin (DDK) generator length.

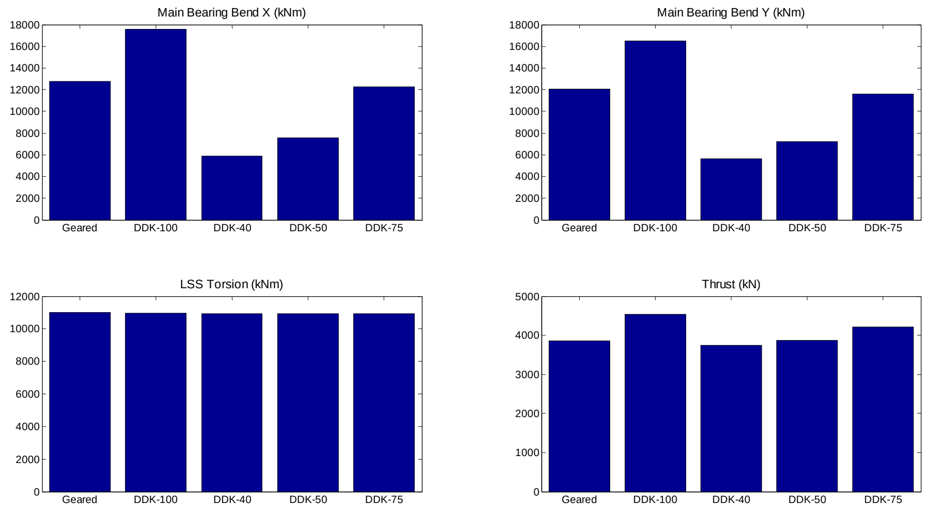

Figure 3. Variation in the extreme load under Design Load Case (DLC) 2.3 for different nacelle configurations: Geared – Conventional drivetrain with medium speed gearbox, Direct Drive King-pin (DDK)-100 overhanging generator concept with 100 % mass, DDK-40 - overhanging generator with 40% mass, DDK-50 - overhanging generator with 50% mass and DDK-75 - overhanging generator with 75% mass (as specified in table 2).

Figure 3 compares the extreme loads for all these 4 configurations compared with the baseline 10 MW nacelle configuration under DLC 2.3. As expected the conventional geared configuration has the least extreme loads on the main bearing compared to the initial 362 tons overhang generator. However if the overhanging generator mass can be reduced 75 %, then the extreme bending and thrust on the main bearing can be reduced to the geared configuration. Further reduction can be obtained for the lower weight configurations.

The extreme loads on the yaw bearings are signficantly higher with the front mounted generator concepts in comparison with the conventional nacelle arrangement as seen from Fig. 4. However for the 10 MW reference turbine design [4], the yaw bearing extreme loads were driven by DLC 1.3 (normal operation under extreme turbulence) and even the peak moment of 70 MNm expereinced by the heaviest of the king-pin cases in DLC 2.3 is within the design envelope of the reference yaw bearing. However it is possible that DLC 1.3 with the new configurations further amplify the extreme load magnitude and to mitigate this risk, an appropriate controller algorithm needs to be implemented to minimize tower top loads.

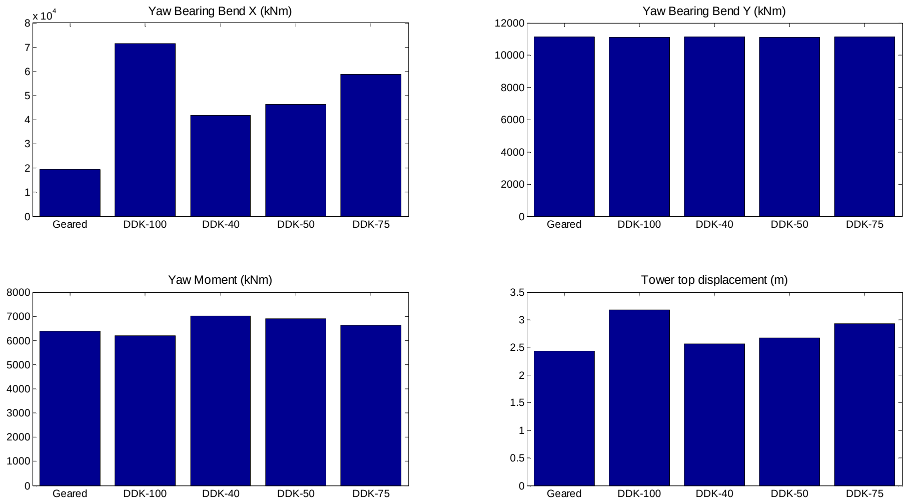

Figure 4: Extreme loads on the yaw bearing along with the peak tower top displacement

4. Fatigue Load Variation

The loads on the main bearing can be determined from the time series of the aero elastic simulation using simple beam theory as proposed in [12]. The axial load F_a on the main bearing is given by the rotor thrust, whereas the radial load F_r is given by

$$F_r = \frac{1}{y_g}\sqrt{{M_1}^2 + {M_2}^2} \qquad (3)$$

where y_g is the distance between the bearings, M_1 and M_2 are the resulting shaft bending moment due to the turbine rotor bending moments.

Eq. (3) is used to determine the rating life L_{nm} as specified by the bearing manufacture SKF[13]

$$L_{nm} = a_1 a_{1SKF}\left(\frac{C}{P}\right)^p \qquad (4)$$

where the constants a_1 is the life adjustment factor for reliability and a_{SKF} is the SKF life modification factor, C is the basic dynamic load rating, p is the exponent of the life equation and P is the equivalent dynamic bearing load. The latter is given related to axial and radial loads of equation (3) by determining the load spectrum.

Since the life of the bearing is directly linked to the dynamic bending moments, the corresponding damage equivalent bending moments at the main bearing and yaw bearing are compared between the different nacelle configurations in Fig. 5 using aeroelastic simulations results of the turbine in normal operation under normal turbulence (DLC1.2). It can be readily seen that there is no significant difference in the yaw bearing fatigue loads, but the main bearing fatigue is significantly higher for the case with the front mounted king-pin concept with the 100% mass. Therefore it can be concluded that at least a 50% reduction in the front mounted generator mass, that is the 50% DDK model is required.

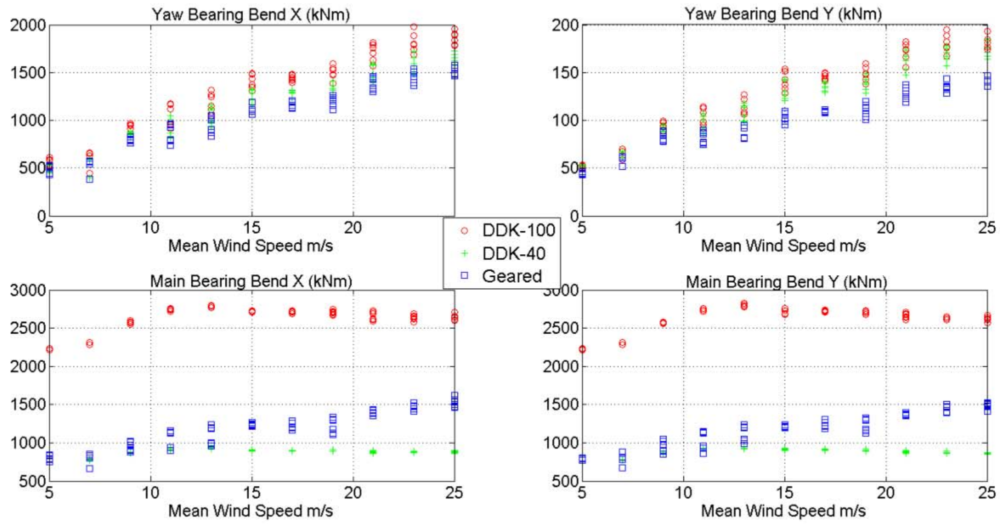

Figure 5: Variation of the damage equivalent moments over a 20 year lifetime for the direct drive king-pin 100% mass, 40% mass and conventional geared concept.

The main assumption behind the above conceptual analysis is that the failure mechanism of the large diameter bearings is Rolling Contact Fatigue (RCF) and that the greasing of the bearings is considered as ideal. This can easily be violated in practical applications and cause premature failures. The analysis of such cases will need a detailed description of the greasing systems, which is presently not available as the design is conceptual.

Finally the increased rotary inertia of the front mounted generator concepts can be beneficial also, as its effect is to reduce the fundamental support structure natural frequency. As described in [14], the reference 10 MW turbine is typically mounted on a jacket type structure for offshore applications, which due to its intrinsic stiff properties results in a net support structure frequency that is within the 3P excitation band. This implies that the rotor speed can excite the support structure at certain wind speeds leading to higher fatigue damage of the support structure.

5. Conclusions

An analysis of different direct drive nacelle configurations for a 10 MW wind turbine was presented, along with the corresponding extreme and fatigue loads on the main bearing. It was observed that an overhanging superconducting direct drive generator with a mass of 75% of the initial weight of 363 tons would result in main bearing extreme loads comparable to the a 10 MW gearbox reference drive train. Secondly the extreme loads on the yaw bearing were within the load envelope of the reference drive train, but the fatigue load on the main bearing is indicating that a mass reduction of 50 % is preferable. These findings will provide a valuable guidance on the target weight for further development of large front mounted superconducting generators.

Acknowledgments
This work was done as part of the INNWIND.EU project funded by European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No.308974. Valuable discussions with Ewoud Stehouwer, Ben Hendriks, Gerrit Jan van Zinderen, Ed Norton and James Dobbin at DNV-GL and Dong Liu at Delft University of Technology are highly acknowledged.

Appendix A

Table A1. Properties of INNWIND.EU 10 MW reference nacelle as represented in the aeroelastic model as well as the King-pin nacelle adapted to hold a 10 MW MgB_2 generator.

Nacelle properties	DTU 10 MW	SCDD 10 MW
Distance along Shaft from Hub Center to Yaw Axis (m)	7,07	6,09
Distance along Shaft from Hub Center to Main Bearing (m)	2,7	2,1
Hub Mass (kg)	105520	163669
Hub Inertia about Low-Speed Shaft (kg m^2)	3,26E+05	1,40E+06
Nacelle Mass (kg)	446036	140813
Nacelle Inertia about Yaw Axis (kg m^2)	7,33E+06	2,87E+06
Nacelle Inertia about rotation axis vertical (kg m^2)		3,60E+06
Nacelle Inertia about rotation axis horizontally (kg m^2)		1,14E+06
Nacelle CM Location Downwind of Yaw Axis (m)	2,68	3,31
Nacelle CM Location above Yaw Bearing (m)	2,45	2,34
Tilt of shaft, α (degrees)	5	5
DRIVE TRAIN		
Rated Rotor Speed (rpm)	9,6	9,6
Rated Generator Speed (rpm)	480	9,6
Gearbox Ratio	50:1	None
Electrical Generator Efficiency (%)	94	94
Generator Inertia About Medium-Speed Shaft (kg m^2)	1501	1,15E+06
Fully-Deployed Medium-Speed Shaft Brake Torque (N-m)	52254	None
Medium-Speed Shaft Brake Time Constant (sec)	0,74	None

Table A2. Mass and moment of inertia properties of 10 MW MgB_2 superconducting direct drive generator which is reduced in mass by reducing the length down to 40% of the initial design in order to approach the generator weigh proposed by the 10 MW NbTi machine of GE [9].

Generator rotor	SCDD MgB_2 10MW	SCDD 75 % Lgen	SCDD 50 % Lgen	SCDD 40%Lgen	GE NbTi 10 MW
Length [m]	2,44	1,83	1,22	0,98	1,88
$Radius_{outer}$ [m]	3,264	3,264	3,264	3,264	2,415
$Radius_{mid}$ [m]	3,146	3,146	3,146	3,146	2,291
$Radius_{inner}$ [m]	3,006	3,006	3,006	3,006	2,164
$Density_{outer}$ [kg/m^3]	7200	7200	7200	7200	7750
$Density_{inner}$ [kg/m^3]	7200	7200	7200	7200	6865
Fill $factor_{out}$	1,00	1,00	1,00	1,00	1,00
Fill $factor_{in}$	0,59	0,59	0,59	0,59	1,00
$Mass_{outer}$ [kg]	4,17E+04	3,13E+04	2,09E+04	1,67E+04	2,67E+04
$Mass_{inner}$ [kg]	2,80E+04	2,10E+04	1,40E+04	1,12E+04	2,29E+04
$Mass_{active\ total}$ [kg]	6,98E+04	5,23E+04	3,49E+04	2,79E+04	4,96E+04
$Mass_{suport}$ [kg]	7,00E+04	5,25E+04	3,50E+04	2,80E+04	
$Mass_{total}$ [kg]	1,40E+05	1,05E+05	6,99E+04	5,59E+04	4,96E+04
I_{outer} [kg m^2]	4,29E+05	3,22E+05	2,14E+05	1,71E+05	1,48E+05
I_{inner} [kg m^2]	2,65E+05	1,99E+05	1,33E+05	1,06E+05	1,14E+05
$I_{activetotal}$ [kg m^2]	6,94E+05	5,21E+05	3,47E+05	2,78E+05	2,62E+05

$I_{rotor\ support}$	[kg m^2]	4,58E+05	3,44E+05	2,29E+05	1,83E+05	
$I_{rotor\ total}$	[kg m^2]	1,15E+06	8,64E+05	5,76E+05	4,61E+05	2,62E+05
Generator stator						
$Mass_{stator\ active}$	[kg]	8,32E+04	6,24E+04	4,16E+04	3,33E+04	1,73E+04
$Mass_{stator\ support}$	[kg]	7,00E+04	5,25E+04	3,50E+04	2,80E+04	3,81E+04
$Mass_{stator\ total}$	[kg]	153284	114963	76642	61314	55319
Gen active mat						
$Mass_{rotor\ active}$	[kg]	6,98E+04	5,23E+04	3,49E+04	2,79E+04	4,96E+04
$Mass_{stator\ active}$	[kg]	8,32E+04	6,24E+04	4,16E+04	3,33E+04	1,73E+04
$Mass_{active\ total}$	[kg]	153000	114750	76500	61200	66886
Gen support mat						
$Mass_{rotor\ support}$	[kg]	1,40E+05	1,05E+05	6,99E+04	5,59E+04	3,81E+04
$Mass_{stator\ support}$	[kg]	7,00E+04	5,25E+04	3,50E+04	2,80E+04	3,81E+04
$Mass_{support\ total}$	[kg]	2,10E+05	1,57E+05	1,05E+05	8,39E+04	7,61E+04
$Mass_{generator\ total}$	[kg]	362836	272127	181418	145134	143000
Position[a]	[m]	10,74	10,44	10,13	10,01	10,46

[a]Generator center of mass position along y-axis with respect to yaw axis.

References

[1] P. Smith, "Turbine faults cost Siemens EUR 223m", Wind Power Monthly, 6 November 2014.
[2] INNWIND.EU project web site, www.innwind.eu (visited March 2016)
[3] Abrahamsen *et. al.*, "Design study of 10 MW MgB_2 superconductor direct drive wind turbine generator", EWEA 2014.
[4] Bak, C., Zahle, F., Bitsche, R., Kim, T., Yde, A., Henriksen, L.C., Andersen, P.B., Natarajan, A., Hansen, M.H., 2013. INNWIND.EU Deliverable 1.2.1 – Description of the DTU 10 MW Reference Wind Turbine. http://www.innwind.eu//media/Sites/innwind/Publications/Deliverables/DeliverableD1,-d-,21%20Aerodynamic_StructuralValidation_INNWIND,-d-,EU.ashx?la=da
[5] H. Polinder *et. al.*, "Trends in Wind Turbine Generator Systems", IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS,VOL.1,NO.3,174, (2013).
[6] B. B. Jensen, N. Mijatovic and A.B. Abrahamsen "Development of superconducting wind turbine generators", JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY 5, 023137 (2013).
[7] D. Liu, H. Polinder, A.B. Abrahamsen, J. Ferreira, "Comparison of 10 MW superconducting generator topologies for direct-drive wind turbines", Proceedings 2015 IEEE International Electric Machines & Drives Conference (IEMDC).
[8] I. Marino et. al., "Lightweight MgB2 superconducting 10MW wind generator", Supercond. Sci. Technol.29, 024005 (2016).
H. Karmaker, M. Ho and D. Kulkarni, "Comparison Between Different Design Topologies for Multi-Megawatt Direct Drive Wind Generators Using Improved Second Generation High Temperature Superconductors", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, 5201605 (2015).
[9] R. Fair et. al., "Superconductivity for Large Scale Wind Turbines", DOE report DE-EE0005143 (2012).
[10] Larsen T.J. and Hansen, A.M. (2012), "How to HAWC2, the user's manual. Tech", *Report Risø-R-1597(ver.4-3) (EN*), DTU Wind Energy. Roskilde, Denmark
[11] International standard IEC61400-1 "Wind Turbines" Edition 3, 2005
[12] DNV/Risø, "Guidelines for design of wind turbines", ISBN 87-550-2870-5 (2002)
[13] SKF web page, www.skf.com (visited March 2016)

[14] Von Borstel, T., 2013. INNWIND.EU Deliverable 4.3.1 – Design report – Reference Jacket. http://www.innwind.eu/-/media/Sites/innwind/Publications/Deliverables/DeliverableD4,-d-,31_20131030_INNWIND,-d-,EU.ashx?la=da (visited June 2016)