Conceptual nacelle designs of 10-20 MW wind turbines

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1 INTRODUCTION

1.1 Background

The integration of a direct-drive type of generator has a large influence on the wind turbine Rotor and Nacelle (R&N) structural and mechanical design. It is therefore important to make proper motivated conceptual choices for a construction. The INNWIND.EU project investigates innovative wind turbine concepts and compares them using based on key performance indicators, of which the Cost of Energy is the most important one.

In the INNWIND.EU project, reference turbines of 10MW [1] and 20 MW [2] have been designed. For these reference turbines, the key performance indicators are evaluated.
In Section 3 of work package D3.42 "Proposed nacelle structures" [5] a first assessment of R&N assembly concepts using SCDD generators and Pseudo Direct Drive concepts was performed. The work in D3.42 forms the basis and starting point for the deeper conceptual investigations presented in this deliverable.

1.2 Objectives

The objectives of this report are the following.

- To describe the motivation for choosing a nacelle construction;
- To describe the chosen nacelle layout for the 10 and 20 MW superconducting generators and give estimations for the cost, size and weight of these nacelles;
- To describe the chosen nacelle layout for the 10 and 20 MW magnetic pseudo direct-drive generators and give indications for the cost, size and weight of these nacelles.

1.3 Report structure

To support the SCDD generator design of WP3.11 and to supply structural design data, it was agreed in the work package team that in this work package 3.41 high level conceptual design work would be conducted for the generator structure. This work is presented in 3.3.

In Section 3 the R&N layouts for the superconducting generators are presented and in Section 4 this is done for the pseudo direct-drive generators. The concept design nacelle structures are worked out in a good level of detail.

In Section 5 the estimated masses are presented for 10MW and 20MW concepts where for 3 concepts scaling has been performed from the baseline model which is the 10MW 198m rotor concept.

In Section 6 the Technology Readiness Level has been discussed briefly where focus has been kept on the important drivers.

In Section 7 the design integrity was discussed and finally in Section 8 some brief conclusions were drawn

1.4 General note on deliverable

In this current issue of the deliverable, many of the requirements are fulfilled but not all to the same level of detail or accurateness. This is the reason that this report should still be regarded as “in progress” with the aim to deliver the final before the end of 2016.

Main items that need more attention or intended to execute for the final deliverable:

- High level Finite Element Analysis for generator air gap analysis;
- Better scaling and TRL conclusions for the 10 and 20MW concepts;
- Expansion of conclusions.

2 PROPOSED NACELLE STRUCTURES

2.1 Introduction

The objective of this chapter is to discuss possible nacelle structures for the INNWIND.EU turbines and to motivate the choice of a nacelle structure for the project.

As agreed in the SMART deliverables document [1] of 3.42, 10 and 20 MW Rotor and Nacelle (R&A) assemblies will be conceptually designed. The main goal of the concept development is to provide insight and data for the key Performance Indicators (PI's) that will be used to evaluate and compare the different R&A concepts to identify what concept are most suitable. The main Performance Indicators (PI's) are; size, weight, cost, feasibility and maintenance, but other PI's may be used as well to evaluate the design concept.

For the following rating-rotor size machines an evaluation is performed:

Table 2-1: Rating and rotor configurations for evaluation

Rating	Rotor size	Comment
[MW]	[m]	[-]
10	178	Reference wind turbine, [1]
10	198	Additional size, based on work package meeting discussions
20	252	Reference wind turbine, [2]
20	278	Additional size, based on work package meeting discussions

DNVGL has experience in designing wind turbines with ratings in the range of 10MW-12MW with rotor sizes in the range of 200m-210m which is relatively close to the 10MW-198m configuration. For this reason first a good baseline 3D CAD concept is created for the 10MW-198m configuration and then to apply scale factors to create data for the other configurations. The advantage of this approach is that accurate PI data is generated for the 10MW configurations (10MW 178m is relatively close to the 10MW 198m) but also to create a good starting point for up scaling up to the 20MW configurations.

2.2 Description of proposed nacelle structures

In work package D3.42 [5] Section 3 a first assessment of R&N assembly concepts using SCDD generators and Pseudo Direct Drive concepts was performed. Based on this document and internal discussions in the workgroup the following concept designs are further investigated in this deliverable:

1. Concept 1-SCDD, Rotor king pin design with generator mounted upwind from the rotor;
2. Concept 2-SCDD, Rotor king pin design with generator mounted downwind and behind the rotor;
3. Concept 1-PDD, Rotor king pin design with generator mounted upwind from the rotor;
4. Concept 1-PDD, 2 Bearing design with generator mounted on the end of a mainshaft.

The main reasons to use a king pin design (concepts 1,2,3) is the balanced bearing loading with the main bearings more or less in line with the rotor and little effect from rotor mass overhang. For other main bearing solution with the bearings positioned downwind from the rotor the rotor overhang mass increases and has a large impact on the life of the bearing.

In Concept 4 the bearings are downwind from the rotor but was decided to still consider this a viable option for the 10MW sub 200m rotor class.

2.3 Load level for concept development

The main dimensions of the concepts in this deliverable are based on DNVGL experience on similar size machine projects which cannot be disclosed.

In order to check if these main dimensions can be applied validly for the Innwind project structural design concept investigations, a high level load comparison is performed.
In the torque paper from the University of Denmark [6] load levels are presented for a 178m rotor 10MW machine with a kingpin configuration. In Table 2-2 the yaw bearing Mxy_max load levels of both load sets is compared.

Table 2-2: Yaw bearing load level comparison

		DNVGL load set 200+m rotor	Torque paper load level 178m rotor
Mxy_max_yaw bearing	[MNm]	92	110
Mz_max_yaw bearing	[MNm]	67	70

The comparison shows that the $M_{xy\_yawbearing}$ load levels are at the same order of magnitude but the torque paper is higher. The reasons for the differences can be various (blade design, controller-operating settings etc) and will not be further discussed in this deliverable.
It is assumed that the DNVGL load levels that were used to establish the main dimensions for the 10MW-198m concept are plausible and applicable.

2.4 Cost prices for concept evaluation

Important part of the evaluation and comparing of the different concepts is the cost evaluation.
The cost evaluation will be performed on a high level using unit cost prices. Based on industry feedback the unit cost prices presented in Table 2-3 have been used in concept cost evaluation. The cost is based on a fully machined and finished component.

Table 2-3: Cost prices for concept evaluation

		Unit cost price [€/kg]
Fabricated component	Standard	2
Fabricated component	Complex	3
Cast component	Standard	3.5
Cast component	Complex	5

The high level cost analysis is sensitive to the unit cost used. It should be noted that the raw steel prices are mostly world prices but can change a lot over time. The cost of manufacturing the component has been taken into account in the unit cost prices. It is important to realise that the location of manufacturing has a large impact on the unit cost price. In the cost price above it is assumed that the components will be manufactured in Europe.

2.5 Scaling factors

For the 10MW-178m size rotor a 3D CAD design is generated from which geometric data can be derived directly. To generate geometric data for the other size configurations, scaling is applied.

The increase in load based for a larger rotor diameter approximately scales with the power law of 2.3 over the rotor diameter. This means that for a rotor diameter increase from 198m to 278m the expected load increase is roughly ($278^{2.3}/198^{2.3}$)=2.2, slightly more than double. Knowing that bending moments are generally the driving type of loading, the required scaling factor for a tubular type shape structure is $2.21^{(1/3)} = 1.3$. This factor is applied to the 10MW-198m configuration 3D CAD model components to generate mass estimations for the other configurations.

Table 2-4: Applied scaling factors

Drotor1 (base concept)	Drotor2	Power law	Load increase	3D CAD scale factor
[m]	[m]	[-]	[-]	[-]
198	178	2.3	0.78	0.92
198	252	2.3	1.74	1.20
198	278	2.3	2.18	1.30

3 NACELLE CONSTRUCTIONS FOR THE SUPERCONDUCTING DIRECT DRIVE GENERATORS

3.1 Introduction

In WP 3.11 work is performed on the concept design of a superconducting direct drive (SCDD) and a Magnetic Pseudo direct Drive (PDD) generator for a 10 MW and 20MW concept.

The Electromagnetic design report [4] was created as part of WP3.11 and in this report data is presented such as geometry, mass and other information of the SCDD generator concept.

The important geometric data used for the development of the different concept designs is presented in the Table 3-1.

Table 3-1: SCDD generator concept data for reference turbine 10MW 178m rotor

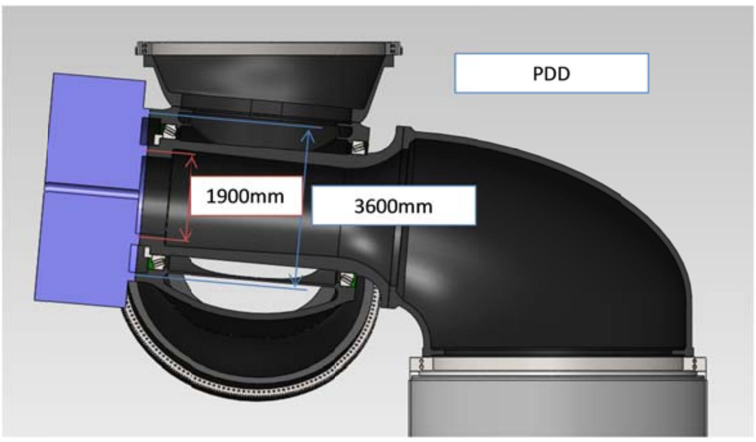
		SCDD 1	SCDD 2	SCDD 3
Stator outer Diameter	[m]	6.0	8.4	10.8
Diameter outer boundary of the rotor	[m]	6.528	8.9328	11.3376
Axial stack length	[m]	2.44	1.31	0.80
Total rotor mass	[ton]	75.00	55.46	44.04
Total stator mass	[ton]	77.92	62.43	51.88
Total mass	[ton]	152.92	117.89	95.92

The values for the diameter outer boundary of the rotor clearly show that for all the SCDD generator configurations the diameter is much larger than for a standard medium or high speed type of windturbine generator. Solutions for R&N assemblies with the SCDD generator are therefore found in direct drive type of concepts or novel concepts.

3.2 Rotor hub design change

The concept for the rotor hub described in work package D3.42 [5] Section 3, contained the combination of a relative small hub and the use of extenders to bridge the large difference between hub and blade root interface.

Figure 3-1: Figure 3.5 from [3]: Main PDD interface dimensions



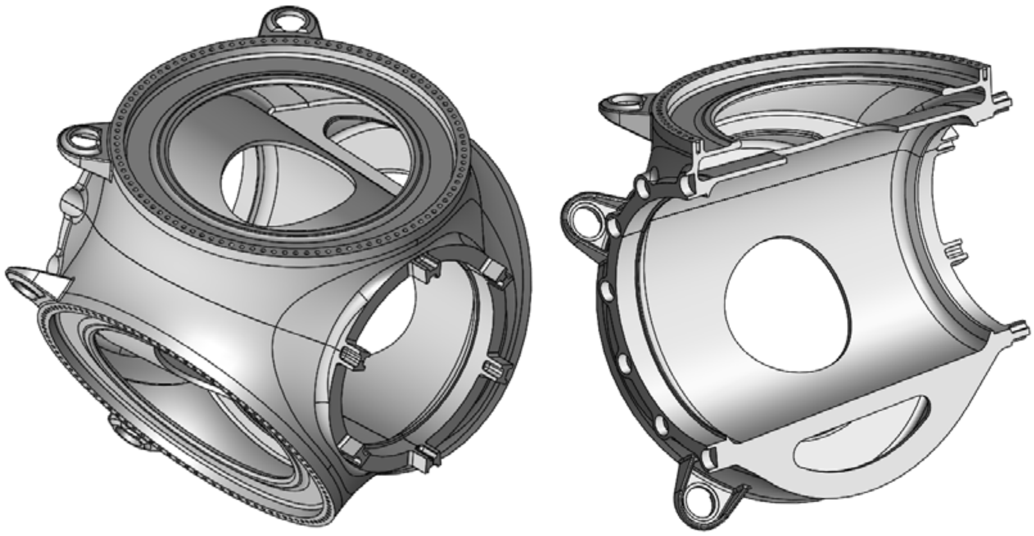
Based on experience gained after the issue of work package D3.42 it was decided to chance this concept into a hub design not requiring the large extenders. The reasons for this decision are:

- The size of the blade root largely dictates required size of the hub for strength reasons. Design and analysis experience shows that strength wise the hub size cannot be much smaller than the blade root size and that the all component shapes need to be smooth in order to avoid large stress concentration. In the hub with extenders design, the angle between the extender and hub highly likely results in strength problems.

- The 3 large extenders are relatively expensive due to the size and might be difficult to cast;

This decision has a large impact on the individual mass of the hub becoming much higher than stated in [5].

Figure 3-2: Hub design used for Concept 1-SCDD, Concept 2-SCDD and Concept 1-PDD



3.3 SCDD generator structural design

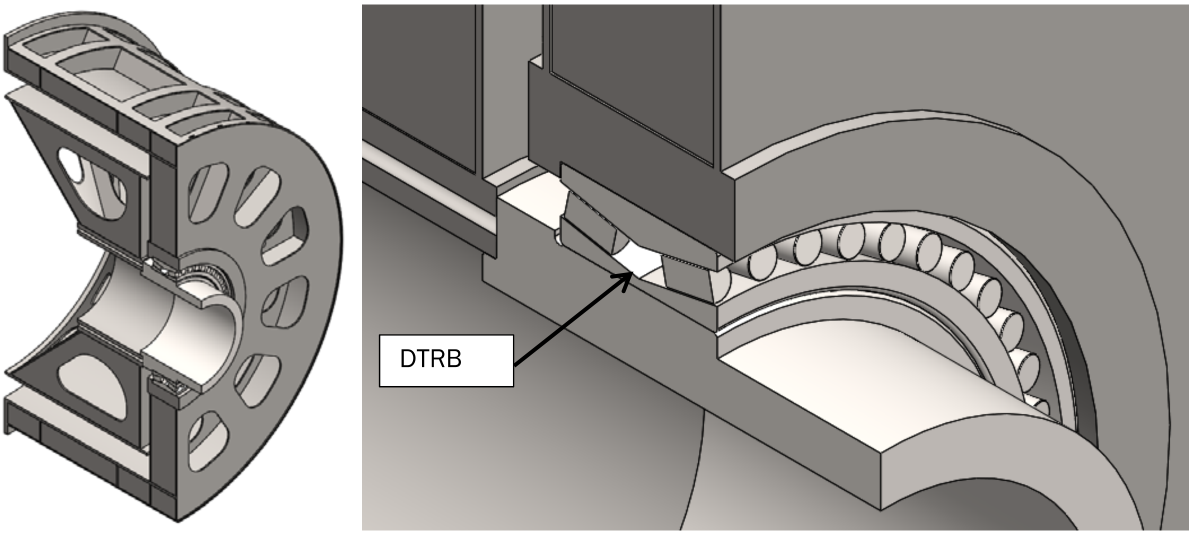
Generator bearing

To reduce the risk of large generator air gap deviations introduced by deflections of the main load carrying components a generator bearing solution was introduced. Using a generator bearing solution the generator can isolated from these deflections.

In Figure 3-3 a generator bearing is illustrated for SCDD1. In the concept a Double Taper Roller Bearing (DTRB) solution is applied using the “O” configuration (moment taking solution).The DTRB solution was selected as it geometrically fits well in the assembly.

The bearing stiffness behaviour has a substantial influence on the behaviour of the air gap, especially the rotational stiffness. Air gap requirement might well lead to a stiffer bearing solution like a Widely Spaced Tapered Roller Bearing (WSTRB) which would require a slightly different bearing housing and shaft solution.

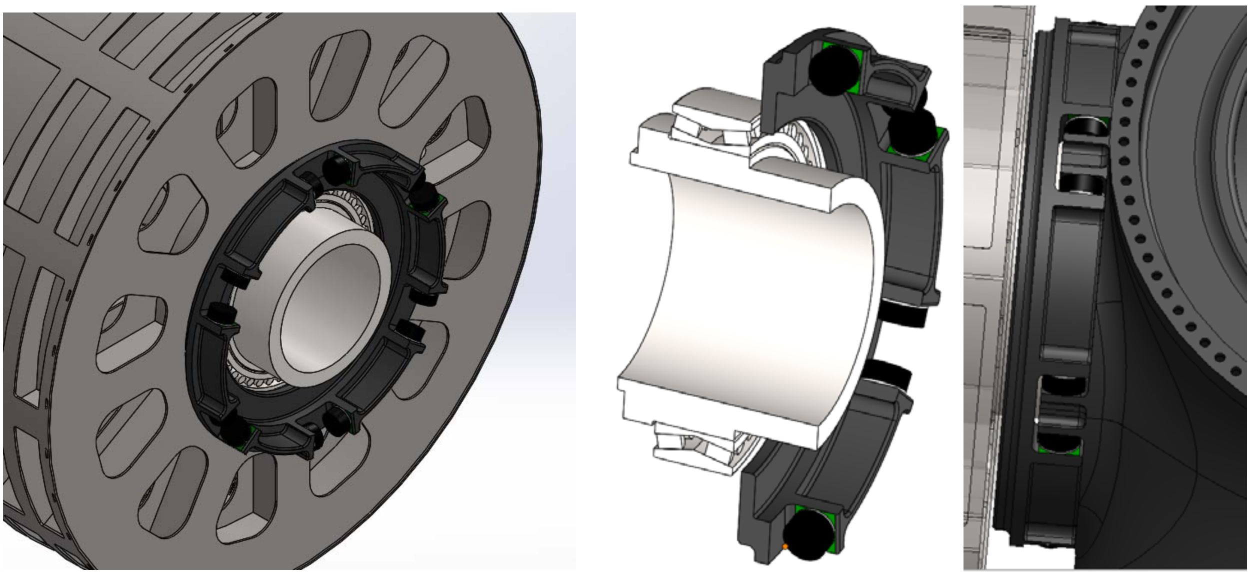
Figure 3-3: SCDD generator DTRB concept, SCDD1 example



Torque-only connection rotor hub to generator rotor

The choice for a generator bearing leads to the requirement of a torque-only connection between the rotor hub and the generator rotor. This can be established with the use of hydraulic rubber pads integrated I the torque path, illustrated in Figure 3-4.

Figure 3-4: SCDD generator torque only compliant connection, SCDD1 example



The hydraulic pads transmit the torque by the stiff behaviour in the pad normal direction but the pads are compliant in the other directions isolating the generator from the relative deflections between the rotor hub and kingpin.

In the installation process these pads can be positioned and then individually pressurized. This type of torque-only solution is currently used in the Alstom 6MW Haliade machine for the torque transmission to the direct drive generator, so there is a level of industry use and proof of system.

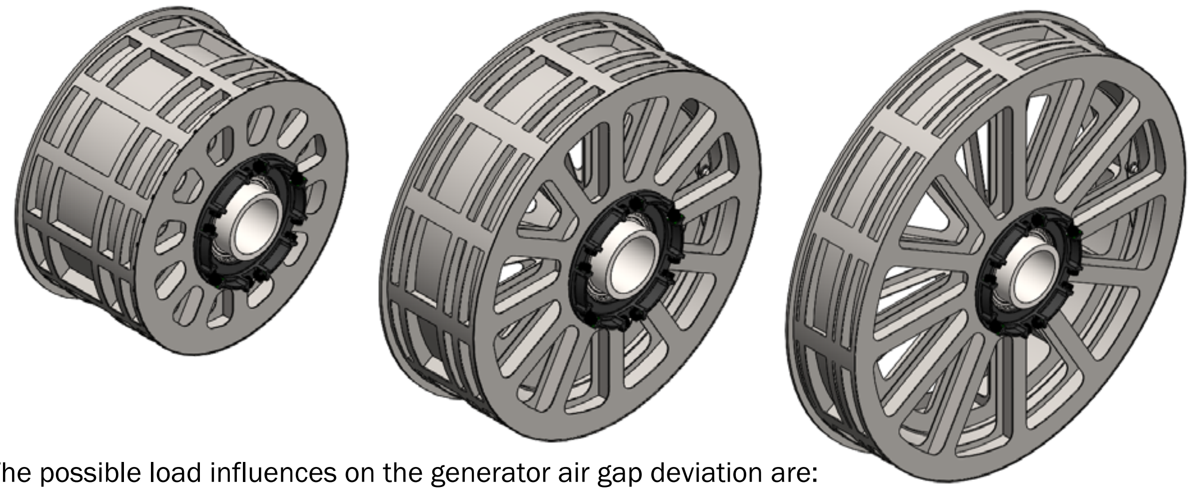
There are other types of torque-only transmission solutions but in this work package no further investigations are performed.

Generator structural design

For the SCDD generator concept design work it is assumed that the generator structure will be fabricated. Due to the large size it would make a casting difficult, very expensive and possibly impossible.

Figure 3-7 shows the three different sizes SCDD for the reference windturbine using the active generator component sizes of Table 3-1.

Figure 3-5: SCDD1, SCDD2 and SCDD3 generator structure concepts



The possible load influences on the generator air gap deviation are:

- Generator rotor and stator structural stiffness behaviour;
- Generator bearing stiffness behaviour;
- Main generator magnetic forces:
- Normal force: magnetic attraction perpendicular to the rotor and stator mounting surfaces;
- Torque force: action and reaction tangentially to the rotor and stator mounting surfaces;
- Gravity force;
- Additional eccentric generator magnetic force resulting from rotor-stator eccentricity from the combination of the above mentioned influences;
- Centrifugal force (rotor);

The main forces on the stator and rotor structure are the generator normal forces and are therefore the design driven loads for the generator structural design.

In Figure 3-6 and Figure 3-7 the structural design of the generator and rotor and stator structural components are presented.

The stator structure has a wheel like structure with two rim plates and a thicker outer cylinder to which the generator stator part can be mounted on. The two rim stator structure is a natural stiff shape and will deflect little to the magnetic forces.

The generator rotor the structure goes around the stator and is open on one side (up wind side). The structure is therefore less stiff than the rotor structure will be more influenced by the generator magnetic forces. To withstand the bending moments I-beam like structures are applied at 30 degree intervals around the structure.

The smaller diameter inner parts of the stator and rotor structures are thick forged rings (weld-able). Both structures need to have sufficient openness for the fabrication process and maintenance access and cooling.

At this moment a plate thickness of 25mm is used for most of structural plates. Only the cylindrical plates to which the generator active parts are mounted are 50mm.

To make a better judgement on the main structural design and plate thickness high level Finite Element Analysis (FEA) can be applied. The main FEA focus is on the generator air gap and general stress levels in the structure.

{At this stage the FEA is not yet performed, but will be later and added to this report}

Figure 3-6: SCDD generator structure concept, SCDD2 example

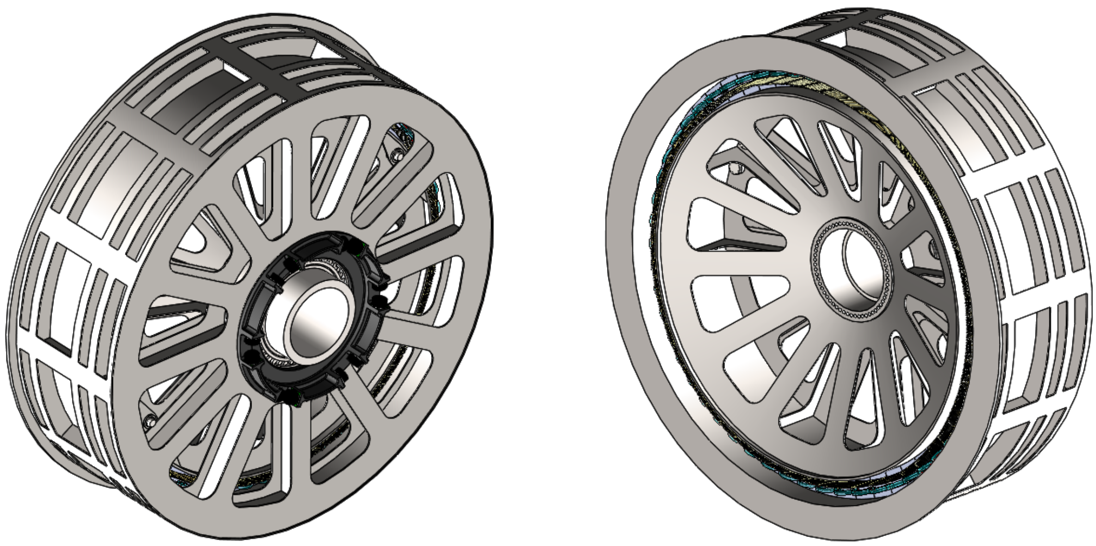
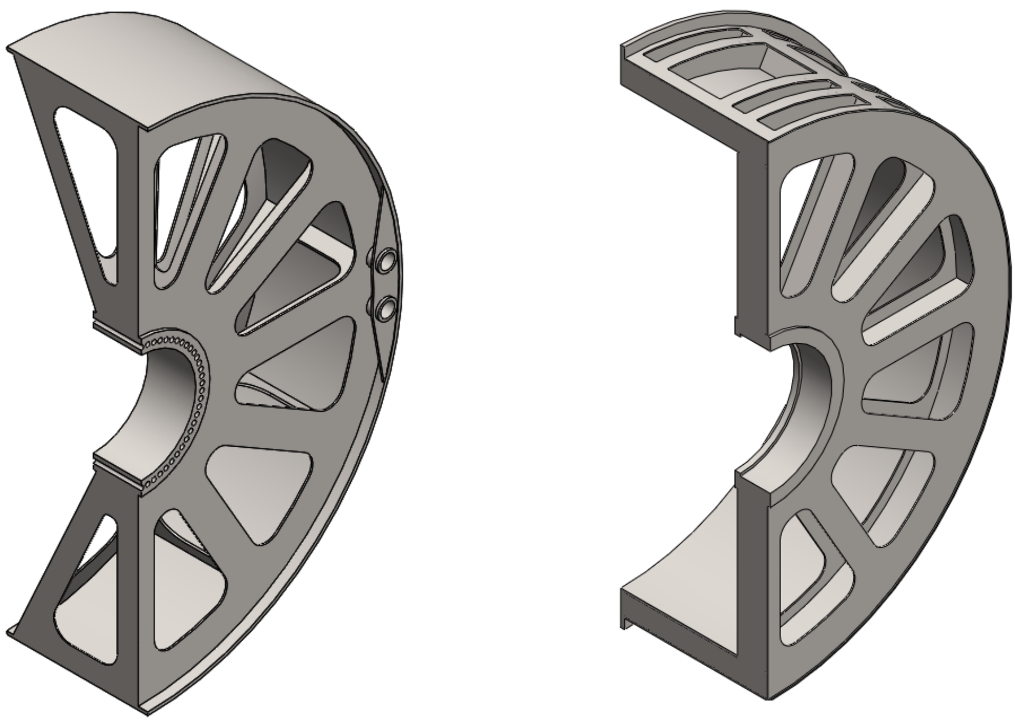


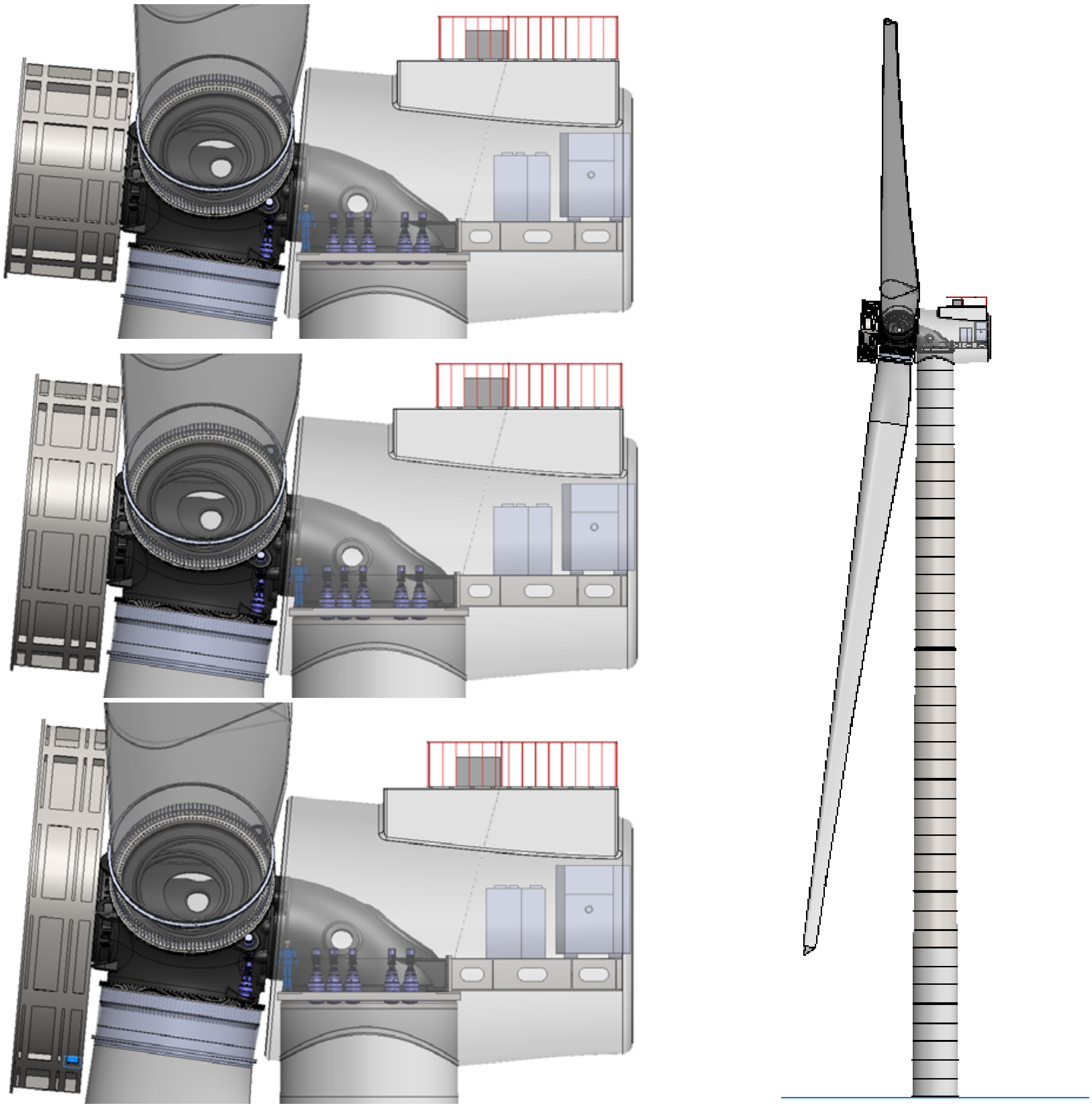
Figure 3-7: SCDD generator stator (left), rotor (middle) structural concepts and generator kingpin + torque transmission (right), SCDD2 example



3.4 Concept 1-SCDD

In Figure 3-8 the R&N concept of the upwind rotor mounted SCDD generator is presented for the different 3 generator configurations

Figure 3-8: Concept 1-SCDD, with SCDD1, SCDD2 and SCDD3

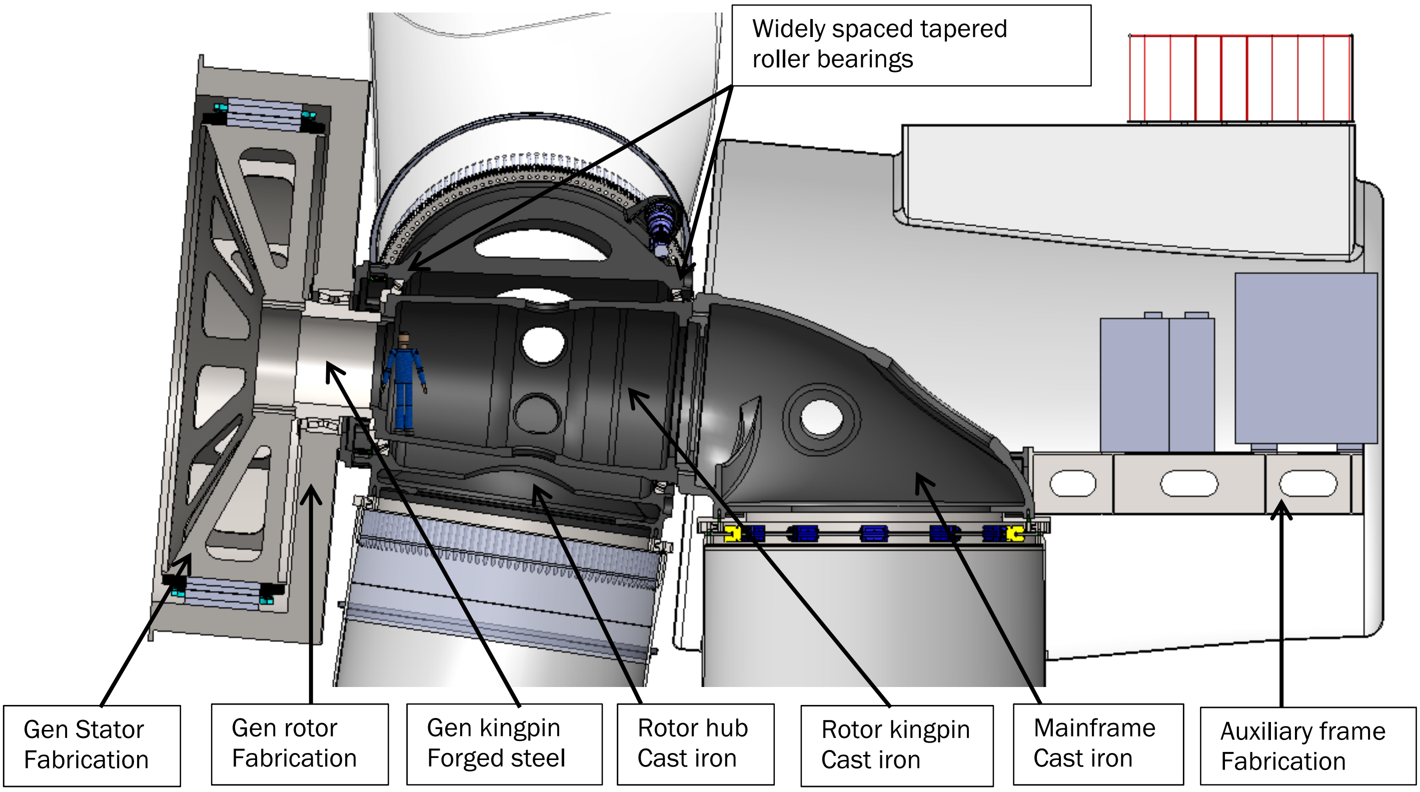


For all three generator configurations there is clearance between the generator structure and blade although for SCDD3 the clearance is small.

Upwind from the windturbine rotor, the large generator structure can be positioned freely from other structural components of the R&N assembly.
The upwind location of the generator makes it possible to lift off the generator without the need of taking the rotor off in the event of a generator exchange.

For the SCDD1 it will be easy to fit the generator within a spinner cover. For SCDD3 it might be necessary to have a separate generator cover which could be a disadvantage for normal maintenance but could be an advantage in the event of removal of the generator. In that event the generator could benefit from the cover protecting keeping it protected from weather conditions.

Figure 3-9: Cross section Concept 1-SCDD, SCDD2 example



The shape of the rotor king pin is deliberately chosen as large as possible maximising components strength and resulting in an efficient loaded bolted connection to the mainframe.
The upwind diameter of the rotor kingpin should be sufficient to design a strong enough bolted connection to the generator.
The access to the generator is easy due to the large inner diameter kingpin. The access to the blade root is a bit more difficult because first the hole through the kingpin and then also a hole in the hub need to be passed.

Table 3-2: General dimensions of the main load carrying components

		Dimension[m]
Hub	Pitch bearing interface outer diameter	5.2
	DW main bearing housing diameter	3.6
	UW main bearing housing diameter	3.1
	General casting thickness outer shell	0.11
King pin	UW bearing seat diameter	3.17
	DW bearing seat diameter	2.55
	Total length	5.39
	General casting thickness outside bearing region	0.12
Mainframe	King pin interface outer diameter	3.2
	Yaw bearing interface outer diameter	5.65

For the different SCDD generator concepts the following evaluation of mass and cost has been made in Table 3-3.

Table 3-3: Concept 1 SCDD generator concept mass and cost price estimation (reference wind turbine 10MW 178m rotor)

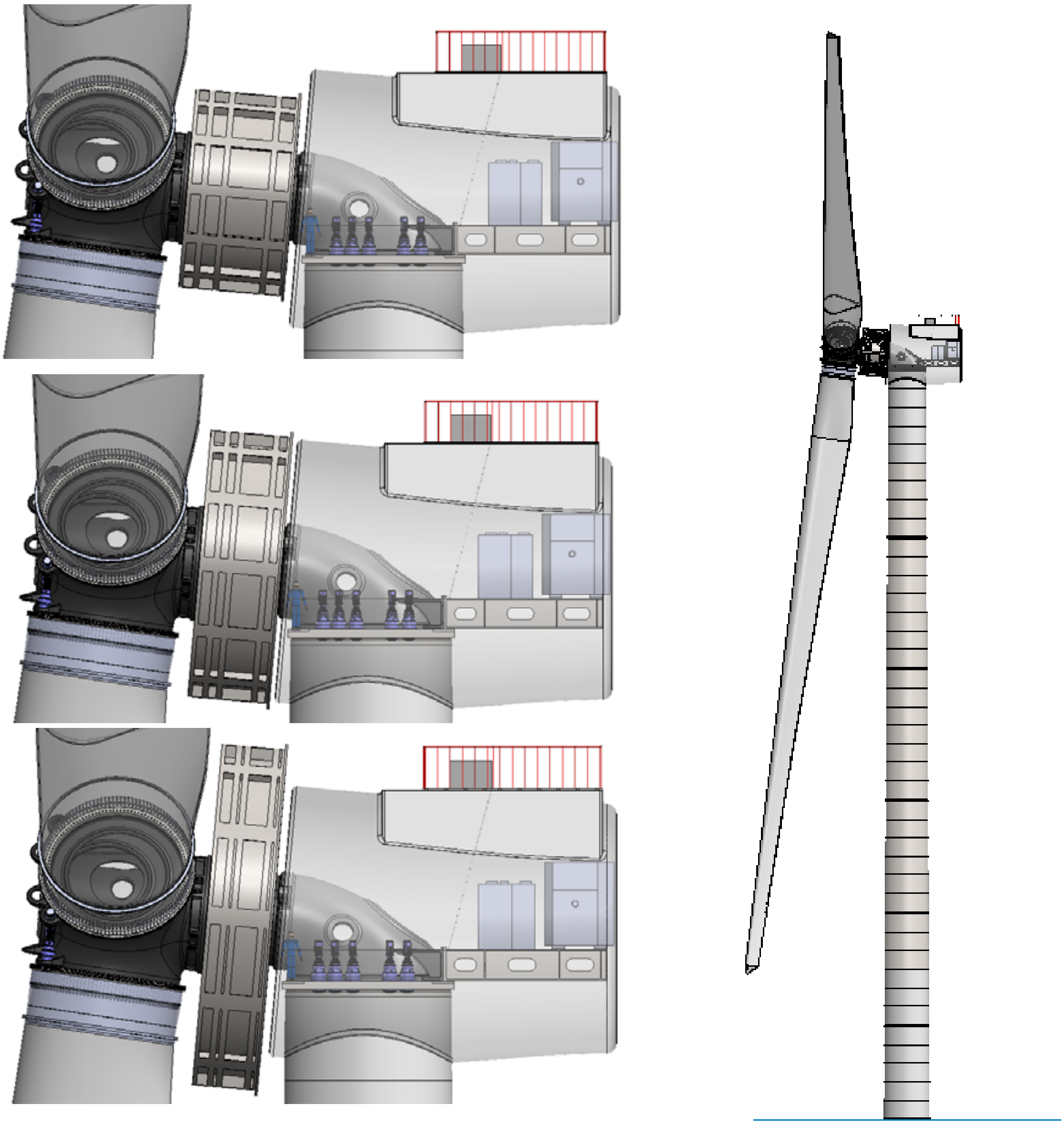
	SCDD1	SCDD2	SCDD3	CC	Unit price	HTSC1	HTSC2	HTSC3
	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[kg]	[kg]
Torque transmission	8,000	8,000	8,000	CC2	5	40,000	40,000	40,000
Generator kingpin	13,000	13,000	13,000	CC1	4	45,500	45,500	45,500
Rotor structure	81,000	93,000	104,000	FC2	3	243,000	279,000	312,000
Stator structure	49,000	46,000	51,000	FC2	3	147,000	138,000	153,000
Total structure	151,000	160,000	176,000			475,500	502,500	550,500
Gen active parts mass [4]:	153,000	118,000	96,000		-	706,000	579,000	509,000
Total	304,000	278,000	272,000			1,181,500	1,081,500	1,059,500

The outcome is interesting as it shows that the final difference in mass and cost is relatively small.

3.5 Concept 2 SCDD, 10 MW concept with downwind rotor mounted SCDD generator

In Figure 3-8 the R&N concept of the downwind rotor mounted SCDD generator is presented for the different 3 generator configurations

Figure 3-10: Concept 1-SCDD, with SCDD1, SCDD2 and SCDD3



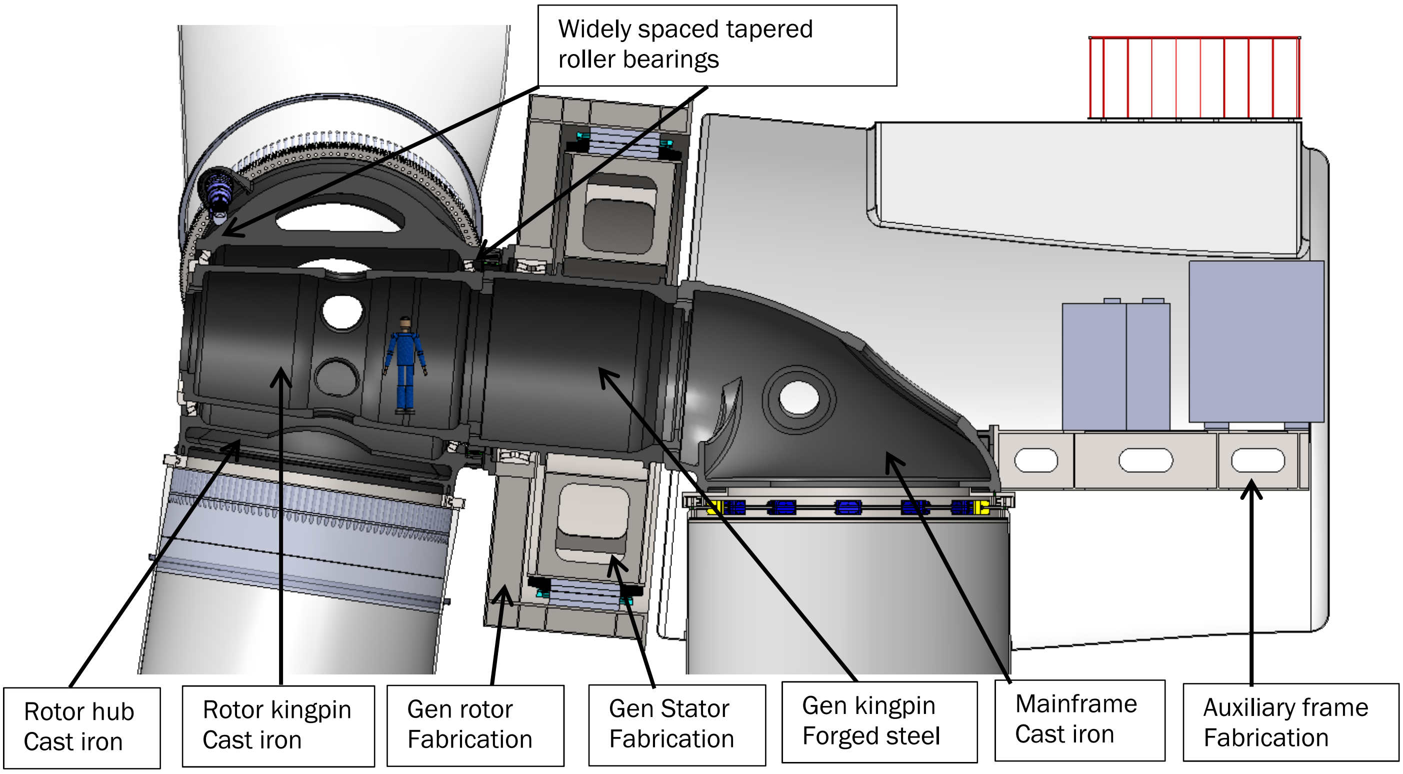
For all three configurations there is sufficient clearance between the generator and blades due to the blade cone angle and there is also enough space between the generator and the tower because of the drivetrain tilt angle.

The generator concept now determines the amount of rotor overhang. The smallest diameter generator (SCDD1) moves the rotor quite far forward which does not necessary means this is a problem, possibly even an advantage resulting in more blade-tower clearance.

In this configuration the generator kingpin is a main load path component. The generator kingpin and the bolted connections need to be designed to transmit the rotor loading.

Having the generator between the rotor and the mainframe requires taking down the rotor in the event of a complete generator exchange.

Figure 3-11: Cross section Concept 2-SCDD, SCDD2 example



Also in this concept like in SCDD1, the shape of the rotor king pin and generator kingpin are chosen as large as possible utilising strength of the component and efficient bolted connections.
The access in SCDD2 is similar as to SCDD1 with the main difference of the location of the generator opening opportunities of better access directly from the mainframe side especially when the generator is located inside the nacelle cover.

The dimensions and masses of the main structural components are the same as for concept SCDD1 and specified in Table 3-2 and Table 3-3. The only main difference is the generator design that is slightly different.

Table 3-4: Concept 2 SCDD generator concept mass and cost price estimation (reference wind turbine 10MW 178m rotor)

	SCDD1	SCDD2	SCDD3	CC	Unit price	HTSC1	HTSC2	HTSC3
	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[kg]	[kg]
Torque transmission	8,000	8,000	8,000	CC2	5	40,000	40,000	40,000
Generator kingpin	60,000	46,000	39,000	CC1	4	210,000	161,000	136,500
Rotor structure	83,000	96,000	106,000	FC2	3	249,000	288,000	318,000
Stator structure	37,000	41,000	44,000	FC2	3	111,000	123,000	132,000
Total structure	188,000	191,000	197,000			610,000	612,000	626,500
Gen active parts mass [4]:	153,000	118,000	96,000		-	706,000	579,000	509,000
Total	341,000	309,000	293,000			1,316,000	1,191,000	1,135,500

The cost of the generator is slightly higher than for concept 1 SCDD mainly due to the higher cost of the generator kingpin. Also for concept 2 SCDD, the final differences in mass and cost between the different generator concepts is relatively small.

4 NACELLE CONSTRUCTION FOR MAGNETIC PSEUDO DIRECT DRIVE GENERATORS

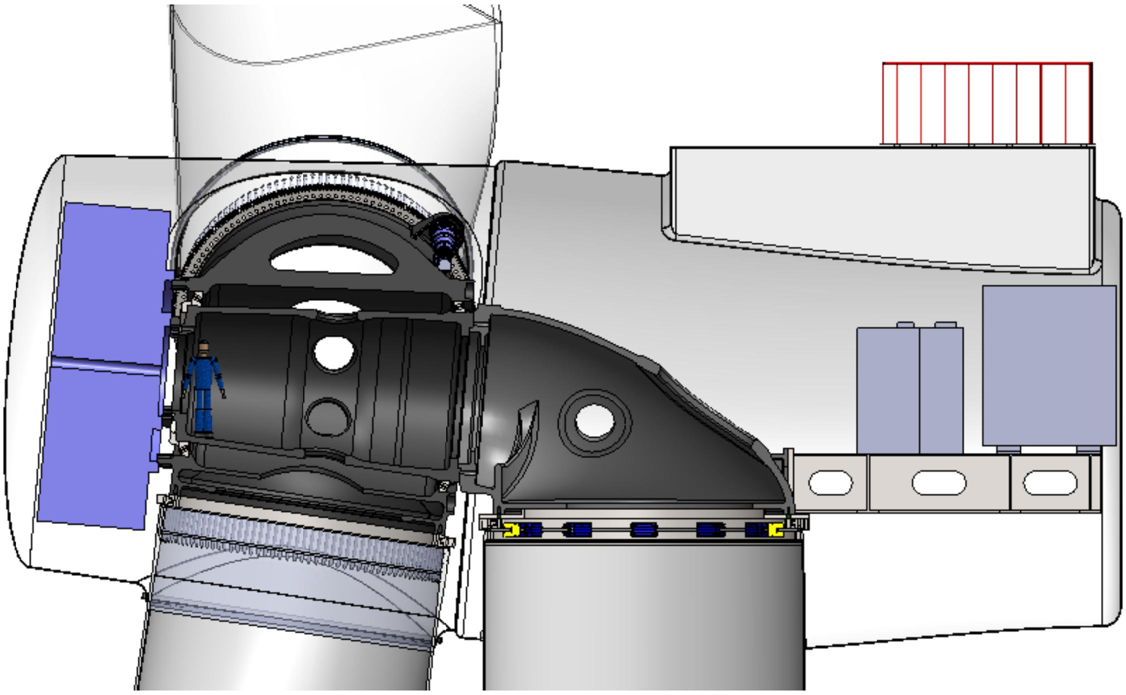
4.1 Introduction

In this section the two configurations of the magnetic pseudo direct drive generator designs are investigated. Based on the smaller PDD dimensions it was of interest to investigate the upwind rotor position as well as the integration of the generator in a more convention lay out.

4.2 Concept 1-PDD

The rotor nacelle structure for Concep1-PDD can be the same as for Concept1-SCDD presented in Section 03.4 and therefore just one additional plot is presented in this paragraph.
All the general dimensions and masses of the concept structure can be found in Table 3-2 and Table 3-3 of concept-1 SCDD.

Figure 4-1: Cross section Concept 1-PDD

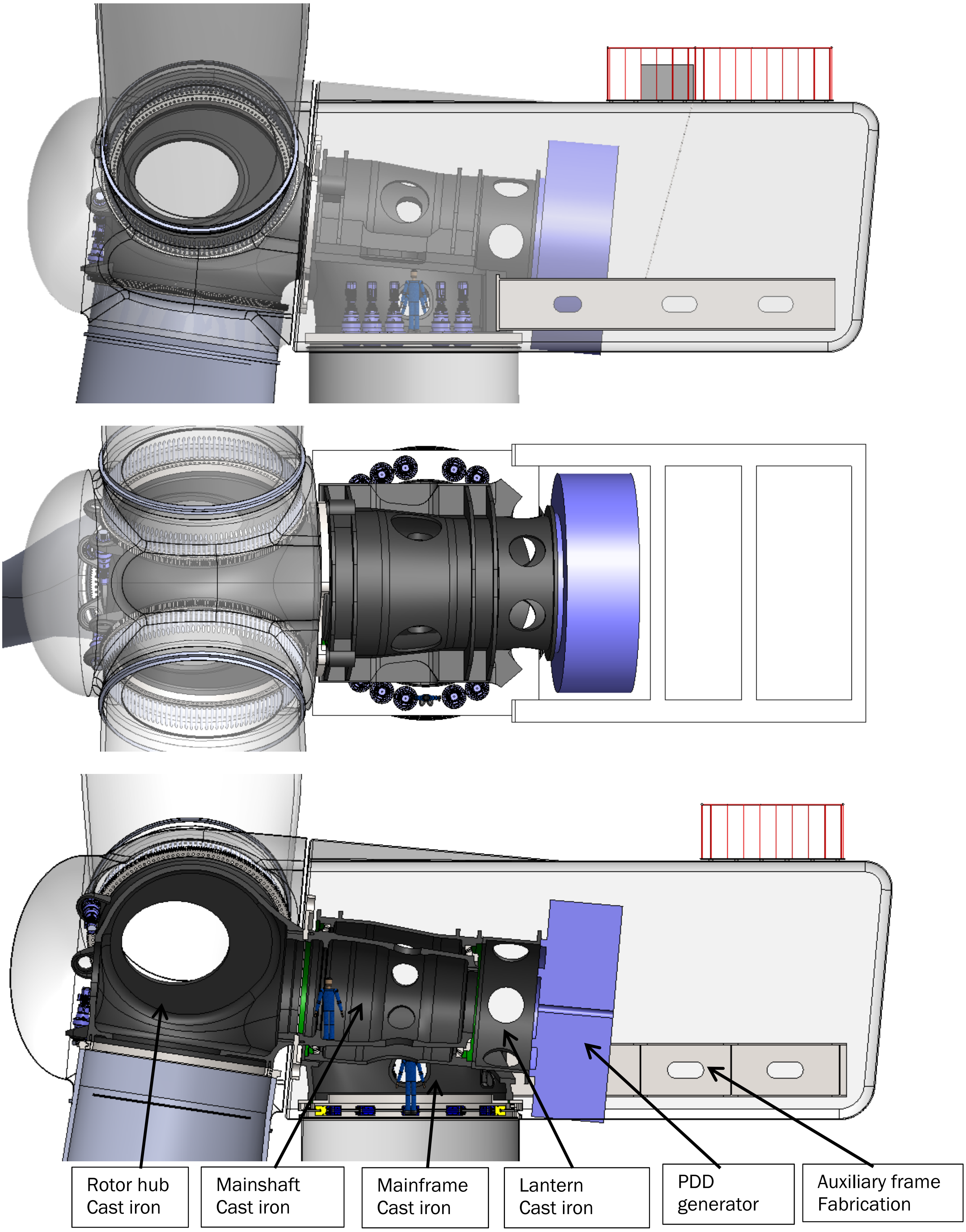


The PDD generator is more compact than the SCDD generator design and is easy to integrate within the rotor spinner cover.

As no detailed CAD model is available of the PDD, no CAD design work is performed on a possible torque only connection between the rotor hub and the generator rotor. It is assumed that this can be design in a same way as for Concept1-SCDD.

4.3 Concept 2-PDD

The assembly of Concept 2-PDD shows that it is possible to integrate the PDD generator in what could be called a more conventional rotor nacelle layout.



The size of the generator is still very large in comparison with a conventional gearbox or generator and can therefore not be easily located anywhere above the tower. In this relative conventional concept layout the generator must be located further backward and fall behind the tower top.

To mount the generator to the structure the choice is made create and extender (lantern) that is bolted to the back of the main bearing housing. The space inside the lantern can be used for a torque only coupling device.

It is important to realise that for this concept the outer part of the PDD is stationary. Feedback from Magnomatics is that this PDD configuration can be created.

For this size of machine (200m rotor) it is likely that tapered roller bearings can still be supplied although limits are reached. For the 252m and 278m rotor sizes of this configuration, currently no TRB's can be supplied.

Direct access to the hub could be established by large holes in the main bearing housings and smaller holes in the mainshaft. The generator is located inside the nacelle cover what is a good location for maintenance. It could be possible to lift out the generator through a top hatch in the nacelle cover but this might not be easy due to the large diameter of the generator.

Table 4-1: General dimensions of the main load carrying components

		Dimension[m]
Hub	Pitch bearing interface outer diameter	5.2
	Mainshaft outer diameter interface	3.2
	General casting thickness outer shell	0.11
Mainshaft	UW bearing seat diameter	3.17
	DW bearing seat diameter	2.55
	Total length	4.8
	General casting thickness outside bearing region	0.12
Mainbearing housing	UW bearing seat diameter	3.6
	DW bearing seat diameter	3.1
	Total length	4.62
	General casting thickness outside bearing region	0.1
Mainframe	Height at centre x	2.05
	Yaw bearing interface outer diameter	5.65
	General casting thickness outside main interfaces	0.14

5 CONCEPT MASS AND COST COMPARISON

Table 5-1: Mass and cost for 10MW 198m rotor concepts, focus on main structural components

	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD	Cost category	Unit price	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD
	[kg]	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[€]	[€]	[€]
Hub	110,000	110,000	110,000	98,000	CC1	4	385,000	385,000	385,000	343,000
Pitch Bearings	28,000	28,000	28,000	28,000	SB	15	420,000	420,000	420,000	420,000
Other Rotor parts	18,000	18,000	18,000	18,000	CC1	4	63,000	63,000	63,000	63,000
Total Rotor (excl blade)	156,000	156,000	156,000	144,000			805,000	805,000	805,000	763,000
Main Bearings	5,000	5,000	5,000	5,000	TRB	30	150,000	150,000	150,000	150,000
Kingpin	50,000	50,000	50,000	0	CC1	4	175,000	175,000	175,000	0
Mainshaft	0	0	0	46,000	CC1	4	0	0	0	161,000
Mainframe	73,000	73,000	73,000	51,000	CC2	5	365,000	365,000	365,000	255,000
Yaw bearing	9,000	9,000	9,000	9,000	SB	15	135,000	135,000	135,000	135,000
Lantern	0	0	0	11,000	CC2	5	0	0	0	55,000
Main bearing housing	0	0	0	67,000	CC2	5	0	0	0	335,000
Mass other Nacelle parts	35,000	35,000	35,000	35,000	OP	10	350,000	350,000	350,000	350,000
Total Nacelle	172,000	172,000	172,000	224,000			1,175,000	1,175,000	1,175,000	1,441,000
Total R&N structure	328,000	328,000	328,000	368,000			1,980,000	1,980,000	1,980,000	2,204,000

Table 5-2: Mass and cost for 10MW 178m rotor concepts, focus on main structural components, scaled from 198m rotor concept

	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD	Cost category	Unit price	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD
	[kg]	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[€]	[€]	[€]
Hub	86,000	86,000	86,000	76,000	CC1	4	301,000	301,000	301,000	266,000
Pitch Bearings	22,000	22,000	22,000	22,000	SB	15	330,000	330,000	330,000	330,000
Other Rotor parts	15,000	15,000	15,000	15,000	CC1	4	52,500	52,500	52,500	52,500
Total Rotor (excl blade)	123,000	123,000	123,000	113,000			631,000	631,000	631,000	596,000
Main Bearings	4,000	4,000	4,000	4,000	TRB	30	120,000	120,000	120,000	120,000
Kingpin	39,000	39,000	39,000	0	CC1	4	136,500	136,500	136,500	0
Mainshaft	0	0	0	36,000	CC1	4	0	0	0	126,000
Mainframe	57,000	57,000	57,000	39,000	CC2	5	285,000	285,000	285,000	195,000
Yaw bearing	6,000	6,000	6,000	6,000	SB	15	90,000	90,000	90,000	90,000
Lantern	0	0	0	9,000	CC2	5	0	0	0	45,000
Main bearing housing	0	0	0	52,000	CC2	5	0	0	0	260,000
Mass other Nacelle parts	30,000	30,000	30,000	30,000	OP	10	300,000	300,000	300,000	300,000
Total Nacelle	136,000	136,000	136,000	176,000			931,500	931,500	931,500	1,136,000
Total R&N structure	259,000	259,000	259,000	289,000			1,562,500	1,562,500	1,562,500	1,732,000

The rotor hub mass of 86 ton presented in Table 5-2 is smaller than the hub mass of 105.5 ton presented in table 9 of the 20 MW Reference Wind Turbine document [5].

Table 5-3: Mass and cost for 20MW 252m rotor concepts, focus on main structural components, scaled from 198m rotor concept

	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD	Cost category	Unit price	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD
	[kg]	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[€]	[€]	[€]
Hub	190,000	190,000	190,000	168,000	CC1	4	665,000	665,000	665,000	588,000
Pitch Bearings	49,000	49,000	49,000	49,000	SB	15	735,000	735,000	735,000	735,000
Other Rotor parts	24,000	24,000	24,000	24,000	CC1	4	84,000	84,000	84,000	84,000
Total Rotor (excl blade)	263,000	263,000	263,000	241,000			1,400,000	1,400,000	1,400,000	1,323,000
Main Bearings	9,000	9,000	9,000	9,000	TRB	30	270,000	270,000	270,000	270,000
Kingpin	85,000	85,000	85,000	0	CC1	4	297,500	297,500	297,500	0
Mainshaft	0	0	0	79,000	CC1	4	0	0	0	276,500
Mainframe	126,000	126,000	126,000	87,000	CC2	5	630,000	630,000	630,000	435,000
Yaw bearing	13,000	13,000	13,000	13,000	SB	15	195,000	195,000	195,000	195,000
Lantern	0	0	0	19,000	CC2	5	0	0	0	95,000
Main bearing housing	0	0	0	115,000	CC2	5	0	0	0	575,000
Mass other Nacelle parts	50,000	50,000	50,000	50,000	OP	10	500,000	500,000	500,000	500,000
Total Nacelle	283,000	283,000	283,000	372,000			1,892,500	1,892,500	1,892,500	2,346,500
Total R&N structure	546,000	546,000	546,000	613,000			3,292,500	3,292,500	3,292,500	3,669,500

The rotor hub mass of 190 ton presented in Table 5-3 much smaller than the hub mass of 278 ton presented in table 9 of the 20 MW Reference Wind Turbine document [5].

Table 5-4: Mass and cost for 20MW 278m rotor concepts, focus on main structural components, scaled from 198m rotor concept

	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD	Cost category	Unit price	Concept 1-SCDD	Concept 2 SCDD	Concept 1 PDD	Concept 2 PDD
	[kg]	[kg]	[kg]	[kg]	[-]	[€/kg]	[€]	[€]	[€]	[€]
Hub	242,000	242,000	242,000	214,000	CC1	4	847,000	847,000	847,000	749,000
Pitch Bearings	62,000	62,000	62,000	62,000	SB	15	930,000	930,000	930,000	930,000
Other Rotor parts	30,000	30,000	30,000	30,000	CC1	4	105,000	105,000	105,000	105,000
Total Rotor (excl blade)	334,000	334,000	334,000	306,000			1,777,000	1,777,000	1,777,000	1,679,000
Main Bearings	11,000	11,000	11,000	11,000	TRB	30	330,000	330,000	330,000	330,000
Kingpin	109,000	109,000	109,000	0	CC1	4	381,500	381,500	381,500	0
Mainshaft	0	0	0	101,000	CC1	4	0	0	0	353,500
Mainframe	160,000	160,000	160,000	111,000	CC2	5	800,000	800,000	800,000	555,000
Yaw bearing	16,000	16,000	16,000	16,000	SB	15	240,000	240,000	240,000	240,000
Lantern	0	0	0	25,000	CC2	5	0	0	0	125,000
Main bearing housing	0	0	0	146,000	CC2	5	0	0	0	730,000
Mass other Nacelle parts	55,000	55,000	55,000	55,000	OP	10	550,000	550,000	550,000	550,000
Total Nacelle	351,000	351,000	351,000	465,000			2,301,500	2,301,500	2,301,500	2,883,500
Total R&N structure	685,000	685,000	685,000	771,000			4,078,500	4,078,500	4,078,500	4,562,500

6 TRL LEVELS OF 10 AND 20 MW STRUCTURES AND COMPONENTS

6.1 10 MW size wind turbines

It is very likely that the presented 10MW layouts are all feasible for production because all the components are within the envelope of currently available technology.

6.2 20 MW size wind turbines

European foundries of large cast components currently have capacity ranging 100-150 ton. The masses presented in Table 5-3 and Table 5-4 show that the masses for some of the cast components are (far) beyond the current available casting capacities of European foundries. Currently it seems not plausible to assume that the casting industry will drastically increase their capacity to be able to cast components of more than 200 ton.

The supply of main bearings for the 20MW concepts might be a problem. In the current investigations the widely spaced tapered roller bearings in combination with the kingpin configuration has the best change in resulting in a working solution for the 20MW concepts. This has not been investigated in detail with the bearing supply industry.

The blade bearing is one of the most critical components. The largest currently available pitch bearing solutions are still far outside the required loads envelope for rotor diameters in the range of 250-280m. This means that another design approach must be found for the pitching/torque control of the rotor.

7 DESIGN INTEGRITY OF THE DIFFERENT DESIGNS

For all of the key components of concept-2 PDD 10MW (Hub, mainshaft, main bearing housing, lantern, mainframe) high level FEA and strength analysis (fatigue and extreme) has been performed[1]. Based on the results of this analysis it can be said that the components were reasonable well optimized; the strength assessment results showed that the structures were well loaded results and only in localized areas the extreme yield limit or fatigue damage level was exceeded.

The other concepts are using many of the same size and shaped components as used for concept-2 PDD. It is therefore assumed that the components developed for these other concepts also result in plausible designs and strength requirements.

The kingpin- rotor hub of concept-1/2 SCDD configuration is substantially different to the hub–mainshaft configuration of concept-2 PDD (also different load path in rotor hub) that it would be good to execute a high level FEA on this structure. The same can be said for the concept-1/2 SCDD mainframe design.

[1] This work was performed under the commercial contract and for this reason no detailed information can be disclosed

8 CONCLUSIONS

The concept investigations have shown that it is possible to manufacture 10MW machines with rotor diameters up to 200m or even slightly above within the envelope of currently available technology, although being on the limit.

It can be concluded that it is unlikely that a 20MW concept can be created as a scaled up version of one the presented 10MW concepts because many components are outside the envelope of currently available technology and it is questionable if this will change in the next decades. Increasing the current supply limits requires heavy investment from the supply industry which seems unlikely as the supply number will not be large. It is therefore recommended to consider a different design approach for this size of machines.

When comparing the different designs it can be noted that the differences between the first three concepts 1-SCDD, concept 2-SCDD and concept 1-PDD are more or less the same. Concept 2-SCDD with the generator downwind from the rotor is slightly heavier and has a larger rotor overhang than the concepts with the generator upwind from the rotor.

Concept 2-PDD is very different from the other three and is a more conventional which might suit a lot of manufacturers. With some additional components it becomes a heavier structural concept. The loading of the main bearings (especially the upwind main bearing) will be loaded more severe than in the kingpin concepts and could prove to become critical already for the 178-198m rotors.

9 REFERENCES

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[3] Innwind.EU, SMART DESCRIPTION OF DELIVERABLES, 1st Submission, Agreement n.: 308974, Co-ordinator, DTU Wind

[4] TUD, “Electromagnetic Design of 10 MW Superconducting Generator”, H. Polinder, Dong Liu, 2016

[5] Innwind document, Task 3.1-3.4, Deliverable D3.42, “First assessment of performance indicators of Superconducting direct drive and Pseudo magnetic direct drive generators”, 13 September, 2013

[6] Technical University of Denmark, “Variation of Extreme and Fatigue Design Loads on the Main Bearing of a Front Mounted Direct Drive System”, TORQUE 2016, IOP Publishing, Asger Bech Abrahamsen and Anand Natarajan