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RESEARCH REPORT
on Rough Design of 10 and 20 MW Direct-drive Generators
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Abstract: The objective of this report is to design 10 and 20 MW permanent magnet (PM) generators for direct-drive wind turbines. Different large direct-drive generator concepts are reviewed to address the total mass and size of the generators as a function of the torque rating. A rough design of 10 MW and 20 MW direct-drive generators is given to estimate the mass, size and cost of the generators. Total mass of direct-drive and geared generators for large wind turbines up to 20 MW is estimated and compared as a function of the torque rating. This report concludes with the summary of design and comparison results of the different generator concepts.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public			Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

The objective of this report is to give a rough design of 10 and 20 MW direct-drive generators for wind turbines.

The direct-drive generator systems for wind turbines have been discussed as a better choice than the geared generator system in terms of the energy harnessed, reliability and maintenance problem [1][2][3][4][5]. The permanent magnet (PM) machine is superior compared to the electrically-exited machine in terms of the mass, cost, efficiency and reliability. For further wind turbine technology, it is expected to develop larger wind turbines to reduce the cost of energy production, especially for offshore. One of the objectives of UpWind project is up-scaling wind turbines up to 20 MW. In this report, PM generators are thus chosen for a rough design of 10 and 20 MW direct-drive generators for wind turbines.

When designing the electric machines including PM direct-drive generators, the electromagnetic design and the mechanical design are important points to consider. To minimize the active material and the inactive material is a goal of the designs.
In the consideration of only electromagnetic design, direct-drive generators are usually designed with a large air gap diameter and small pole pitches to increase the efficiency, to reduce the active mass and to keep the end winding losses small. Therefore the direct-drive generators with a large air gap diameter seem attractive to minimize the active material.

However considering the structural design of large direct-drive generators, the aspect is different with the electromagnetic design. Such direct-drive generators operate at low speed, so that high torque is demanded. High torque results in high tangential force and large air gap diameter of the generator. Large air gap diameter demands large mass of inactive material. When scaling up the wind turbine, the inactive mass is increased more and more.
Therefore it is an important issue to minimize the generator mass in both the electromagnetic design and the mechanical design for large direct-drive wind turbines.

Recently, McDodalds *et al* have discussed about the mass minimization of large direct-drive PM generators for 2, 3 and 5 MW wind turbines in [6]. Where, the optimum ratios of the axial length to air gap diameter K_{rad} of the generators have been chosen to minimize the total mass of the generators. It seems to indicate that the ratio K_{rad} is increased and the ratio of mass to torque m/T is kept or even decreased a little bit, when scaling up the turbines. These results have been obtained by the theoretical design, so that it is expected that the total mass including practical aspects will be larger than the mass by theoretical design.

In order to estimate the total mass of direct-drive generators, the mass to torque ratio m/T is used as a criterion because the mass of rotating machine is mainly belong to the torque to have enough strength.
This report starts with a short review of different direct-drive wind generators to address the mass, size, and torque rating. The power rating of the generators is from 1.5 MW up to 5 MW [6][7][8][9].
Secondly, a rough design of 10 and 20 MW direct-drive generators is given to estimate the mass, size and cost of the generators. In this design, it is assumed that the mass to torque ratio m/T of the generators is 25 kg/kNm, and the air gap speed of the generator rotors is 4 m/s by referring the values in [6]. Dimensions, material mass, cost and operation characteristics of 10 and 20 MW PM generators are drawn as the results of this design.
Next, in order to grasp the interrelationship between the mass and torque rating of rotating machines, the mass of gearboxes is investigated. The constructions of gearboxes are different with the direct-drive generators, but the mass and size of large direct-drive low-speed electric machines have been rarely discussed in references. Thus the mass to torque ratio m/T of gearboxes is dealt prior to estimate the mass of different generators. Total mass of direct-drive and geared generators for large wind turbines up to 20 MW is estimated and compared as a

function of the torque rating. The values of *m/T* of different generators are given by referring references [6][7][8][9][11].
Finally, the report concludes with the summary of design and comparison results as discussed in previous sections, and with some suggestions to estimate the mass of large direct-drive generators in further researches.

2. Large direct-drive generators for wind turbines

In order to address the mass, size and torque rating of large direct-drive generators for wind turbines, different direct-drive generators on the market and in literature are reviewed in this section.

The largest direct-drive wind turbine is currently E-126 (6 MW) of Enercon GmbH. The E-112 model (4.5 MW), which is the former version of E-126 model, is shown in Figure 1 [7]. The generator of E-112 is an electrically excited direct-drive machine, of which mass and diameter are about 220 ton and 12 m, respectively [6][8].

Figure 2 depicts a 1.5 MW PM direct-drive generator system manufactured Zephyros BV, currently Harakosan Europe [9]. The system uses single bearing and the generator is fully integrated in the structural design. The diameter of this generator is relatively small than the conventional electrically excited synchronous generator. In this configuration, the mechanical load path seems shorter than the traditional configuration with a main shaft. A cone shaped hollow structure with single bearing is used instead of a traditional main shaft with two bearings.

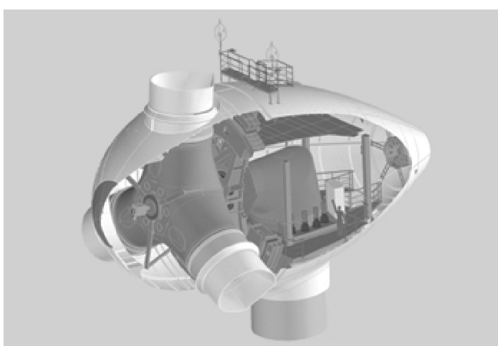


Figure 1: *Structure of 4.5 MW EESG DD. Source: Enercon GmbH [7]*

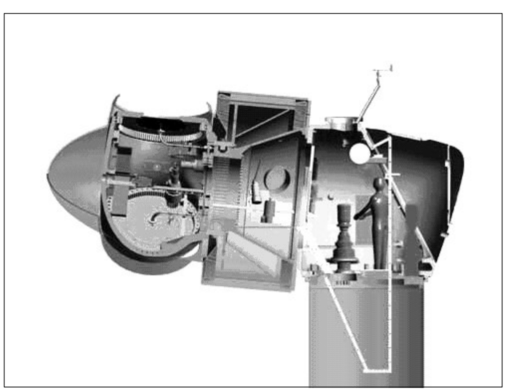
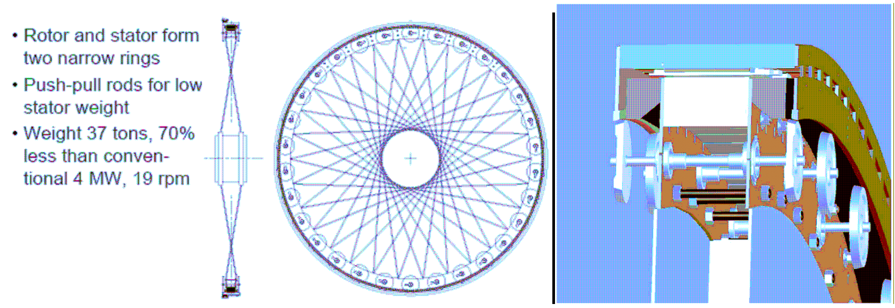


Figure 2: *Structure of 1.5 MW PMSG DD. Source: Harakosan Europe [9]*

A new direct-drive machine for wind turbines has been proposed in [8]. The fundamental idea of the machine - the NewGen (see Figure 3) is to reduce the stiffness demand by removing the load path from the rotor, the shaft and the stator by putting the bearings close to the air gap.



(a) (b)

Figure 3: *New-Gen generator [8]*

The reference [6] describes the mass minimization of conventional PMSG DD concept for different power levels: 2, 3 and 5 MW. In order to minimize the total mass of the generator, the ratio of axial length to air gap diameter K_{rad} has been optimized. Figure 4 depicts the structure of the rotor and stator considered.

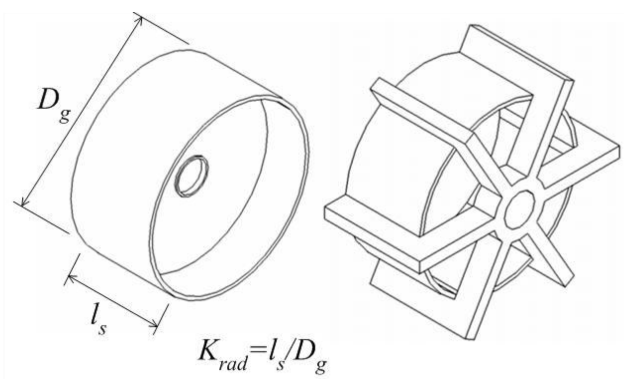


Figure 4: *Structure of the rotor and stator for structural optimization [6]*

Table 1 gives the parameter and the generator mass of 1.5 MW Zephyros [9], 4 MW NewGen [8], and 4.5 MW Enercon [7] wind turbines, respectively.
The ratios of *m/T* for the 1.5 MW (Zhphyros) and the 4.5 MW (Enercon) generators, which are 46.4 and 66.5 kg/kNm, are higher than the theoretically optimized 2, 3 and 5 MW generators [6]. It seems that the generator total mass in practical design will be larger than the theoretical design, because detailed parts for manufacturing are not considered in the theoretical design. The NewGen concept seems the lightest concept; it has the lowest *m/T*, which is about 18.4 kg/kNm. The total mass of NewGen concept (36.4 ton) seems to be competitive with DFIG 3G (about 35 ton) in mass [8].

The design parameters and results of the 2, 3 and 5 MW PMSG DD in [6] are summarized in Table 2. Figure 5 depicts the total mass as a function of K_{rad}. The K_{rad} of 2, 3 and 5 MW generators chosen as the optimum value are 0.2, 0.22, and 0.27 respectively. Considering the total mass and torque rating, the ratios of the total mass to torque rating *m/T* of 2, 3 and 5 MW generators are 25.5, 23.5 and 23.6 kg/kNm, respectively.
The mass of generators discussed in [6][7][8][9] is shown as a function of the torque rating in Figure 6.

Table 1 Parameters and Mass of 1.5, 4 and 4.5 MW direct-drive generators

Power	1.5 MW (Zephyros)	4 MW (NewGen)	4.5 MW (Enercon)
Generator type	PMSG	PMSG	EESG
Rotor speed [rpm]	18	19	13
Torque rating [kNm]	862	2010	3306
Diameter [m]	4	9	12
Total mass [ton]	40	36.9	220
Mass/torque [kg/kNm]	46.4	18.4	66.5
Remarks	Market available	140 kW prototype	Market available

Table 2 Parameter and Mass of 2, 3 and 5 MW PMSG DD [6]

Rated power	2 MW	3 MW	5 MW
Rotor speed [rpm]	19.5	16	12.5
Torque rating [kNm]	979	1790	3820
Air gap diameter [m]	4.3	5.1	6.1
K_{rad} [-]	0.2	0.22	0.27
Active mass [ton]	14.6	22.4	39.9
Inactive mass [ton]	10.4	19.6	50.1
Total mass [ton]	25	42	90
Mass/torque [kg/kNm]	25.53	23.46	23.56
Air gap [mm]	Air gap diameter / 1000		

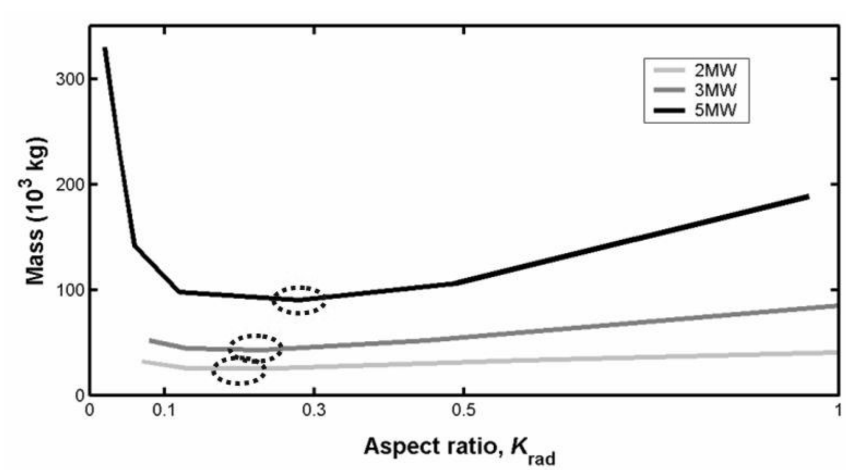


Figure 5: *Total mass of 2, 3 and 5 MW PMSG DD as a function of the ratio, K_{rad} [6]*

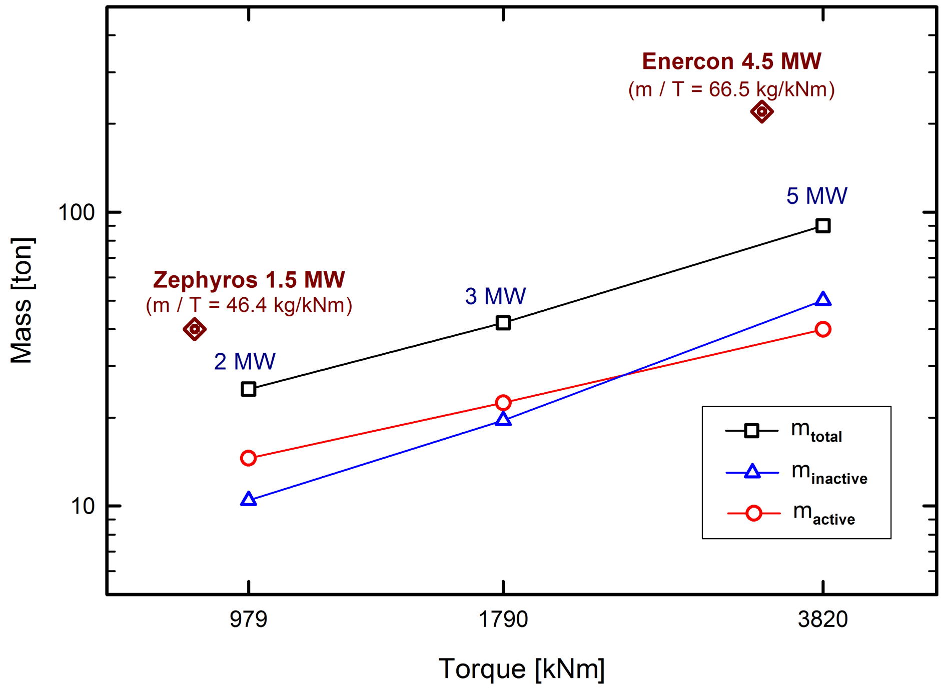


Figure 6: *Mass comparison of different direct-drive generators*

3. Design of 10 and 20 MW direct-drive PM generators

Table 3 gives the characteristics of 10 and 20 MW wind turbines, and the generator materials considered in this report. Figure 7 gives a cross section of the four pole pitches of the PM generator considered in this report. A full pitch winding with one slot per pole per phase is used. For the cost estimation of the generators, cost modelling in [12] is used in this design.

Table 3 Wind turbine and generator material characteristics

Wind turbine characteristics		
Rated grid power [MW]	10	20
Rotor diameter [m]	178	252
Rated wind speed [m/s]	12	12
Rated rotational speed [rpm]	8.6	6.1
Rotor blade tip speed [m/s]	80	80
Maximum aerodynamic rotor efficiency [%]	51.5	51.5
Mass density of air [kg/m^3]	1.225	1.225
Generator material characteristics		
Slot filling factor k_{sfil} [-]	0.65	0.65
Remanent flux density of permanent magnets B_{rm} [T]	1.3	1.3
Recoil permeability of permanent magnets μ_{rm} [-]	1.06	1.06
Resistivity of copper at 120 °C ρ_{Cu} [μΩm]	0.025	0.025
Loss modeling		
Eddy current losses in laminations at 1.5 T and 50 Hz P_{Fe0e} [W/kg]	1	1
Hysteresis losses in laminations at 1.5 T and 50 Hz P_{fe0h} [W/kg]	4	4
Maximum losses in the converter P_{convm} [kW]	300	600
Cost modeling [12]		
Power electronics cost [€/kW]	40	40
Laminations cost [€/kg]	3	3
Copper cost [€/kg]	15	15
Permanent magnet cost [€/kg]	25	25
Construction cost [€/kg]	3	3

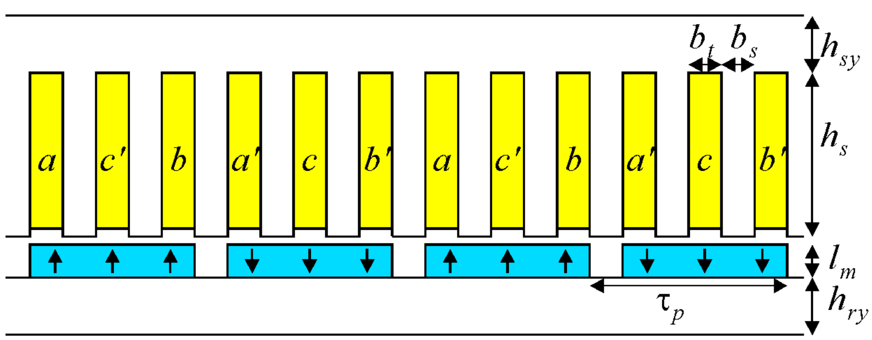


Figure 7: *A linear cross-section of a PM synchronous generator [1]*

The PM generator dimensions are determined based on a force density of 40 kN/m^2 [13][14]. In this design, the air gap speeds of generator rotors of 10 and 20 MW wind turbines are assumed as 4 m/s, which are similar with the speed for 2, 3, and 5 MW direct-drive generators in [6].
The ratios of total mass to torque *m/T* of the 2, 3, and 5 MW generators in [6] have been shown between 23.5 and 25.5 kg/kNm. These results seem to indicate that *m/T* can be assumed around 25 kg/kNm in the rough design, even though it does not include the practical aspects in design. The ratio *m/T*=25 kg/kNm is thus used in the design of 10 and 20 MW direct-drive PM

generators. Design results of these generators are given in Table 4 including dimensions, material mass and material cost. Figure 8 and Figure 9 depict the steady-state operation characteristics of 10 and 20 MW PMSG DD wind turbines, respectively.

Table 4 Design results of 10 and 20 MW RFPM Generators

Generator power P [MW]	10.6	21.2
Generator torque T [MNm]	11.77	33.19
Mass to torque ratio m/T [kg/kNm] (*assumed)*	25	25
Number of phase m [-]	3	3
Nominal current i_s [A]	613	611
Peak flux density above a PM in the air gap $B_{g.max}$ [T]	1.07	1.08
No-load voltage e_p [V]	6401	12845
Number of pole pair per a phase p [-]	140	196
Generator dimensions		
Air gap length l_g [mm]	8.88	12.52
Air gap diameter D_g [m]	8.88	12.52
Axial stack length l_s [m]	2.366	3.356
Aspect ratio K_{rad} [-]	0.266	0.268
Pole pitch τ_p [m]	0.1	0.1
Magnet length l_m [mm]	22.2	31.3
Rotor yoke height h_{ry} [mm]	40	40
Stator slot height h_S [mm]	80	80
Stator yoke height h_{sy} [mm]	40	40
Stator tooth width b_t [mm]	18	18
Stator slot width b_s [mm]	14.9	15
Generator material mass		
Laminations [ton]	63	127
Copper [ton]	14	27
PM [ton]	9	25
Construction [ton]	208	651
Total [ton]	294	830
Cost		
Generator active material [M€]	0.62	1.42
Generator construction material [M€]	0.62	1.95
Converter [M€]	0.4	0.8
Total [M€]	1.64	4.17

The active mass of 10 MW direct-drive PM generator with K_{rad}=0.16 is about 65 ton [12][15], which is lighter than the active mass with K_{rad}=0.266, about 86 ton. However, the total mass of 10 MW direct-drive PM generator with K_{rad}=0.16, which is about 325 ton, is larger than the total mass with K_{rad}=0.266, about 294 ton, because of the more heavy inactive part. For 20 MW direct-drive PM generator with K_{rad}=0.268, the active mass and total mass are estimated to about 175 and 680 ton, respectively.

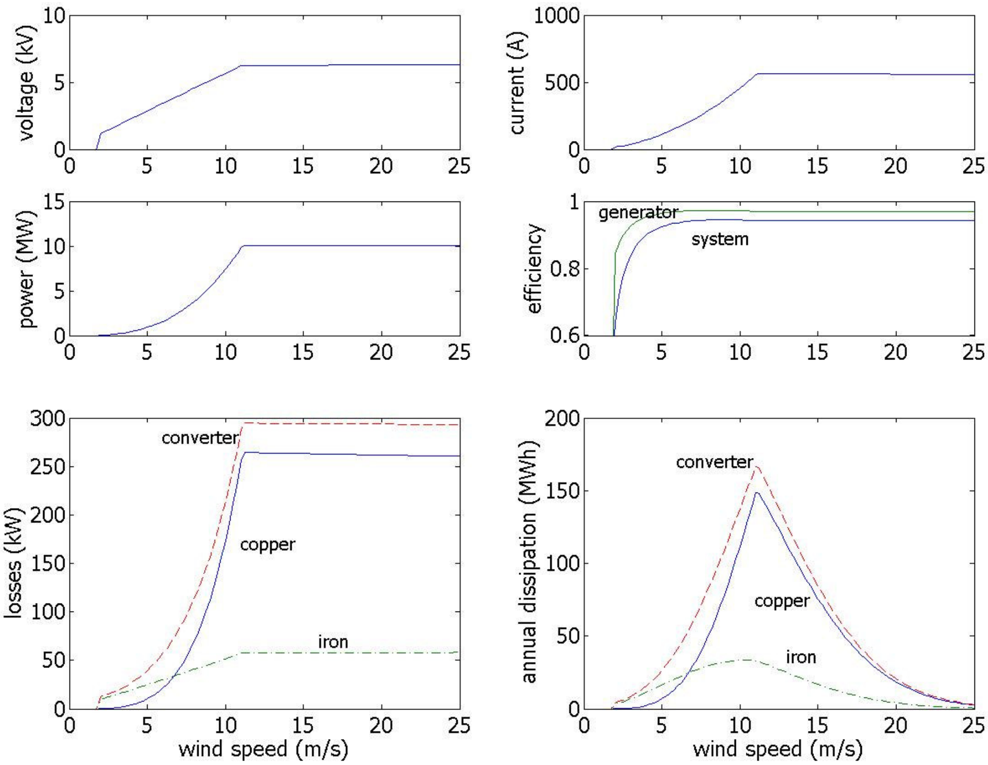


Figure 8: *Operation characteristics of 10 MW direct-drive PM generator*

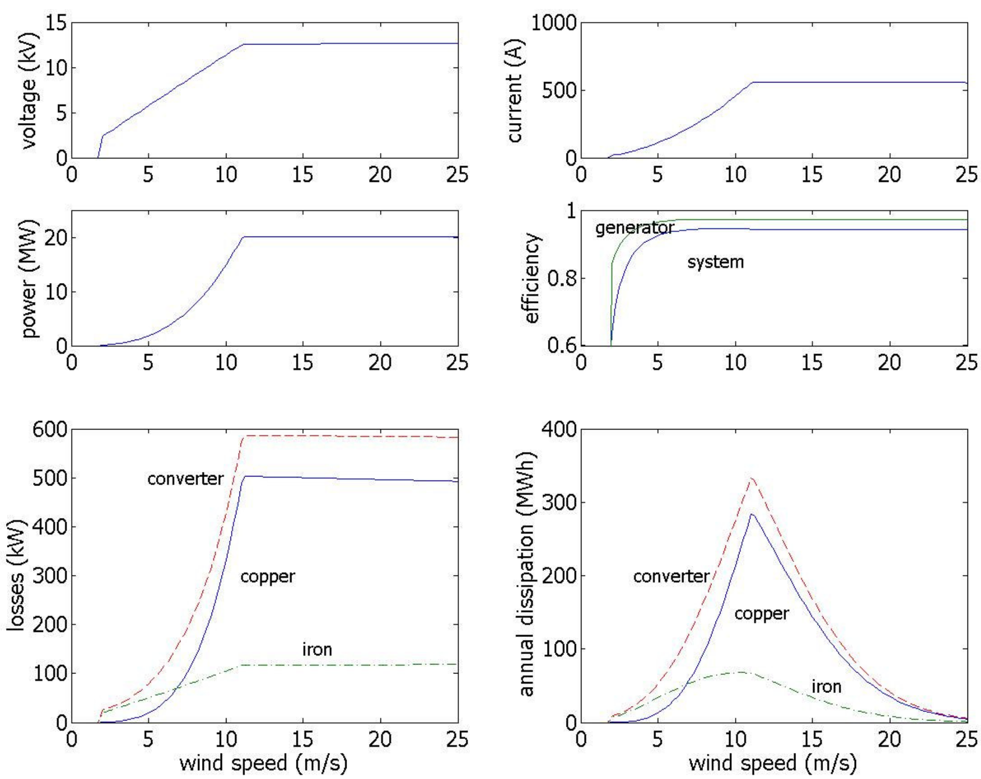


Figure 9: *Operation characteristics of 20 MW direct-drive PM generator*

4. Mass comparison of different generator systems

In structural design of rotating machines including electric machines and gearboxes, the size of such machines depends on the torque rating rather than the power rating. The mass of the machines depend on the size. Therefore it seems that the total mass of the rotating machines mainly depends on the torque rating.
If there are many references dealing with the size and mass of large low-speed direct-drive speed generators, then we can find some criteria with certain values to estimate the size and mass of the generators by using the data of the references. However, the mass and size of the generators have been rarely discussed in references, although the interest on large low-speed direct-drive has been increased. Therefore, firstly, the mass of gearboxes are investigated in this section. Secondly, the mass of different direct-drive generators up to 20 MW is estimated by using the *m/T* ratio as described in the previous section.

4.1 Mass estimation of geared generator systems

In order to investigate the interrelationship between the mass and torque rating of rotating machines, the mass of gearboxes is thus reviewed as a function of the torque rating in this section. The mass to torque ratio of different gearbox concepts in [10] is depicted in Figure 10, where the curve fitting mass *m* versus torque rating *T* is given as (1).

$$m = 0.0678 \times T^{0.7782} \quad (1)$$

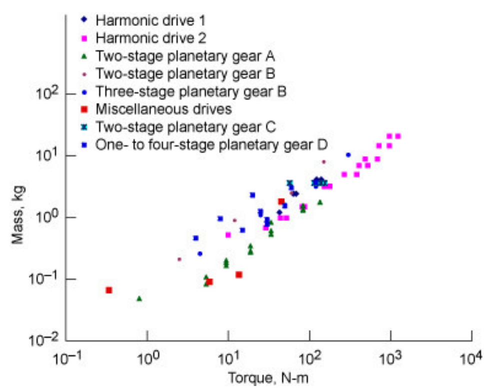


Figure 10: *Mass of gearbox as a function of the torque rating [10]*

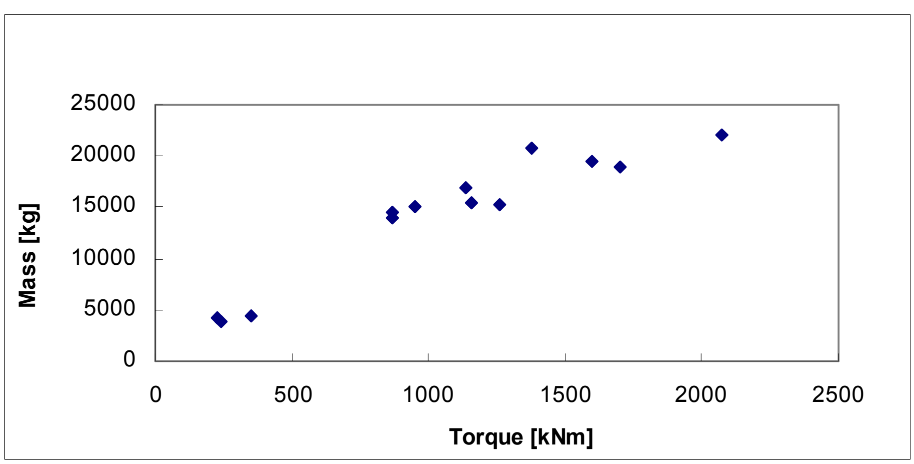


Figure 11: *Mass of gearbox for wind turbines as a function of the torque rating [11]*

The mass of the gearboxes of Bosch Rexroth AG for wind turbines is also investigated as a function of the torque rating in Figure 11. The torque of these gearboxes is between 230 kNm and 2070 kNm, which are for 660 kW and 3300 kW wind turbines [11].
Figure 10 and Figure 11 show that the mass is increasing as a function of the torque, but the slop of mass to torque is decreasing a little bit when the torque is increasing. Regarding the data of Figure 11, the mass to torque ratio m/T seems decreased roughly from 14 kg/kNm to 12.5 kg/kNm when the torque is increasing.

The mass of generator has not been included in Figure 11, so that total mass of geared generators must be larger than the mass of gearbox. In this report, the total mass of DFIG described in [8] is taken to define the ratio of mass to torque *m/T* of geared generators. The value of m/T for geared generators is assumed as the following for the mass estimation of geared generator system.

- A geared generator concept with *m/T*=17.4 kg/kNm

The mass of a geared generator concept (DFIG) is estimated in Figure 12 as a function of the power.

4.2 Mass estimation of direct-drive generator systems

Different direct-drive generators discussed in the previous section are compared based on the mass as a function of torque rating together with the geared generators. In this comparison, the value of the ratio *m/T* of each generator concept is assumed to have the same value. The generator concepts to compare are described as follows.

- New-Gen direct-drive generator concept with *m/T*=18.4 kg/kNm
- A traditional direct-drive PM generator concept with *m/T*=25 kg/kNm
- Zephyros direct-drive PM generator concept with *m/T=46.4* kg/kNm
- Enercon direct-drive EE generator concept with *m/T=66.5* kg/kNm

The mass of these four different direct-drive generator concepts are also estimated in Figure 12 as a function of the power.

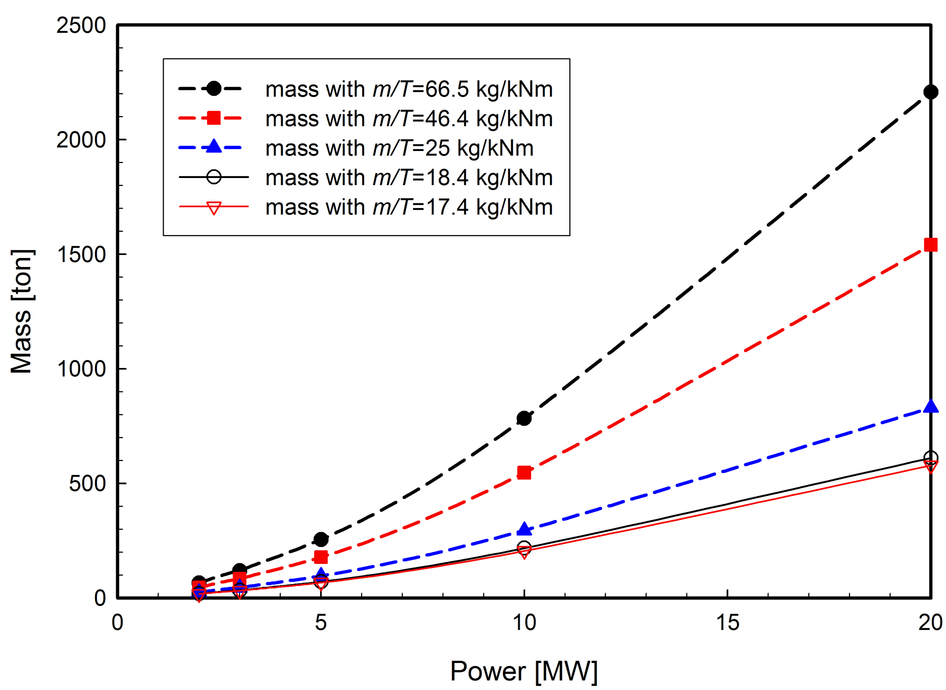


Figure 12: *Mass estimation of different generators concepts as a function of the power*

5. Conclusions

The mass of large direct-drive generators on the market and in literature has been addressed. Comparing total mass, *m* of different direct-drive generators as a function of the torque rating, *T*, NewGen concept seems to be competitive with DFIG 3G in total mass of generator. Enercon concept and Zephyros concept seem heavier than both NewGen and DFIG 3G concepts.

Rough design of 10 and 20 MW direct-drive PM generators have been drawn considering mass, cost and electromagnetic characteristics of the generators. In this design, the axial length to air gap diameter ratios, K_{rad} have been chosen to 0.266 and 0.268, respectively. Total mass of these generators has been estimated by assuming *m/T* is 25 kg/kNm, which is similar with the value of *m/T* of traditional direct-drive PM generator concepts by theoretical design. The electromagnetic mass and total mass of 20 MW direct-drive PM generator have been estimated to 2.1 times and 2.8 times of 10 MW, respectively. Thus it is expected that the inactive material is becoming dominant when scaling up direct-drive wind generators. Total cost of 20 MW has been estimated to 4.17 M€, which is 2.54 times of 10 MW (1.64 M€).

Different generators concepts such as direct-drive and geared generators have been compared based on the mass as a function of torque rating. In this comparison, the value of the ratio *m/T* of each generator concept is assumed to have the same value when the power is increased up to 20 MW.
However, in order to make these mass estimations accurate, it is required to ascertain the interrelationship between the mass and the torque rating of large direct-drive generators in further researches.

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