Possible Solutions to Overcome Drawbacks of Direct-Drive Generator for Large Wind Turbines

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1. Introduction

The objective of this paper is to give some solutions to overcome the limits of large direct-drive for wind turbines. Direct-drive wind turbines have been built to increase the energy yield, to reduce gearbox failures, and to lower maintenance problems [1][2]. In recent years, the size and power of wind turbines are increasing to reduce the cost of energy production. When the turbine is scaled up, the rotational speed of the blades is decreased further because the tip speed is kept constant. Thus high torque generator, which demands high tangential force and large air gap diameter, is required in large direct-drive wind turbines. This phenomenon makes direct-drive generators large and expensive. There are thus still different opinions about what is the most suitable generator system among existing wind turbine technologies. [3]

In order to make large direct-drive generators lightweight, some new generator concepts have been proposed by some authors. Spooner *et al.* have proposed a concept with a pair of spoke wheels to carry the rotor and stator of air gap winding radial flux permanent magnet (PM) machine [4]. Tavner *et al.* have described how the large number of pole pairs and air gap diameter affect the design of large and low speed direct-drive machines [5]. A new direct-drive wind generator, namely NewGen has been proposed to reduce the stiffness demand in construction by putting the bearings close to the air gap [6]. Bang *et al.* have defined the most suitable generator system for wind turbines as a generator system with maximum energy yield and minimum cost [3]. They have also proposed some promising solutions to maximize the force density and to minimize both the active and inactive material.

This paper gives some challenges and solutions of large direct-drive wind turbines. Thus this paper starts with the descriptions of the promising solutions proposed in [3]. Some additional solutions to the guiding and supporting systems of direct-drive generators are also proposed. Secondly, new direct-drive generator systems for 5 MW and 10 MW wind turbines are roughly designed considering the active parts, the inactive parts and the practical issues. For the design of active parts, the permanent magnet synchronous generator (PMSG) modelling in [1] is used. The mass of the new generator system is addressed by comparing with five different generator concepts. Furthermore, a new direct-drive generator downscaled is built to show a possibility of achieving the proposed solutions. Finally, summaries of this paper are drawn.

2. Problems statements of large direct-drive

A typical construction of the direct-drive generator for the wind turbine is given as Fig. 1. As represented in Fig. 1, the generator rotor of direct-drive wind turbine is directly connected to the rotor blade hub. Thus the direct-drive generators operate at low speed, so that high torque is demanded. High torque results in high tangential force F_t and large air gap diameter D_g of the generator. Direct-drive generator thus is large, heavy and hence expensive. When scaling up the turbine, this phenomenon grows more and more. In order to estimate the total mass of direct-drive generator in scaling up, the total mass to torque ratio is inducted as a criterion. The total mass to torque ratios of different generator concepts with different power levels have been addressed in [3]. The followings describe the generator type, the mass to torque ratio and the rated power of each concept.

Concept-1: EESG DD (Enercon concept, m/T=66.5 kg/kNm at 4.5 MW)
Concept-2: PMSG DD (Zephyros concept, m/T=46.4 kg/kNm at 1.5 MW)
Concept-3: PMSG DD (Theoretical design, m/T=25 kg/kNm at 2, 3 and 5 MW)
Concept-4: PMSG DD (NewGen concept, m/T=18.4 kg/kNm at 4 MW [6])
Concept-5: DFIG 3G (DFIG concept with m/T=17.4 kg/kNm at 3.5(4) MW [6])

Where, EESG DD means the direct-drive electrically-excited synchronous generator, PMSG DD means the direct-drive permanent magnet synchronous generator, and DFIG 3G means the doubly-fed induction generator with three-stage gearbox.
In this paper, the following is assumed for the total mass estimation of different generator concepts as a function of the power.

- The ratios of total mass to torque of each generator concept are constant in scaling up the turbines using same materials and same design technologies.

Generator total mass of the five different concepts described above is estimated up to 20 MW in Fig. 2. As given in Fig. 2, the direct-drive generators with conventional construction seem not attractive compared to DFIG 3G in a term of the mass. The mass competitiveness of direct-drive is decreased further in scaling up the turbines. Therefore it makes an issue to find a direct-drive generator concept with less material.

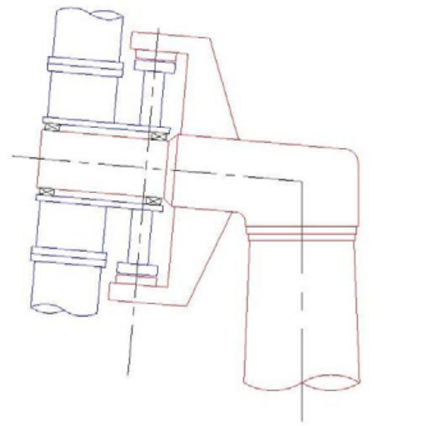


Fig. 1 A direct-drive generator construction for wind turbines

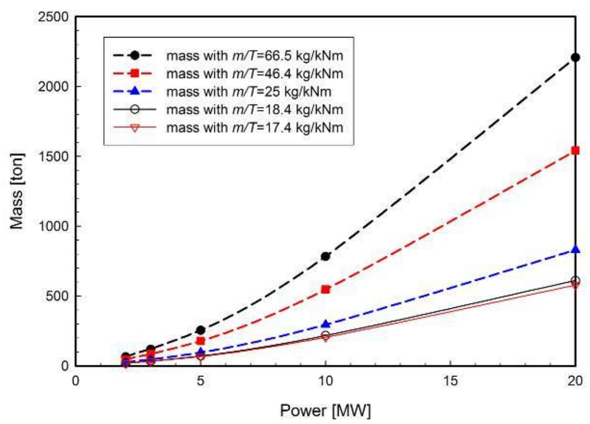


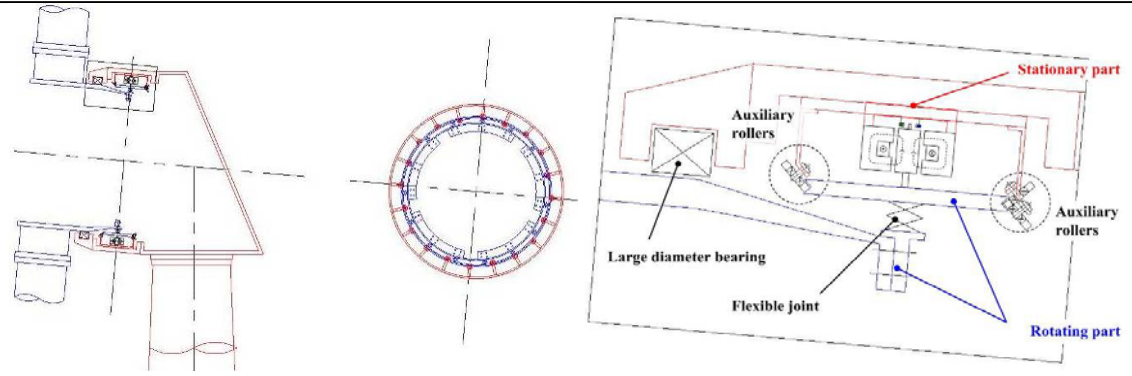
Fig. 2 Mass estimation of different generator systems for large wind turbines

3. Challenges of large direct-drive

Some promising direct-drive generator concepts for large wind turbines have been discussed in [3] in order to increase the force density and to minimize both the active material and the inactive material. The concepts use both a large bearing to guide and support the rotor blade hub, and auxiliary rollers to avoid the touchdown of the rotor on the stator and further damages as shown in Fig. 3. The rotating parts are represented with blue lines and the stationary parts are represented with red lines in Fig. 3(a). Fig. 3(b) illustrates the details of the cross section of the generator including the auxiliary rollers and the large bearing. However, if this concept with large bearing and auxiliary rollers need high accuracy and stiffness in constructing, the concept will not be attractive in

the consideration of the cost even though the inactive part is lightweight. Therefore it is also required to find promising bearing concepts for large direct-drive wind turbines.
In order to overcome the limits of large direct-drive and to improve the concepts proposed in [3], this paper focuses on the followings.

- New bearingless drive to minimize the structural mass
- Ring shaped generator without shaft and structure to transfer the torque.
- New guiding system for large diameter



(a) (b)

Fig. 3 Lightweight and modular direct-drive generator concept for large wind turbine [Ban2008]

3-1. New bearingless drive

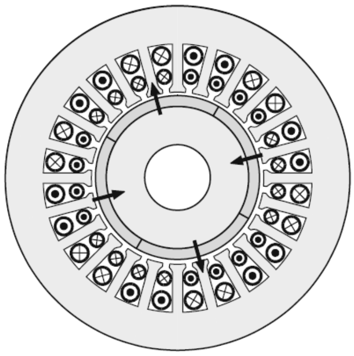
The role of the inactive part in the direct-drive wind generator can be defined as (1) maintaining the air gap between the rotor and the stator, and (2) transferring the rotational force from the rotor blade hub to the generator rotor. Heavy, strong and accurate structures and mechanical bearings have been used to perform the role in the case of traditional large direct-drive generator concepts. In order to achieve the minimization of the inactive mass (structural mass), the inactive part must perform its role without heavy, strong and accurate construction. Therefore, a new bearingless drive concept is introduced as a solution to minimize the mass of the inactive part.

A. Bearingless drive

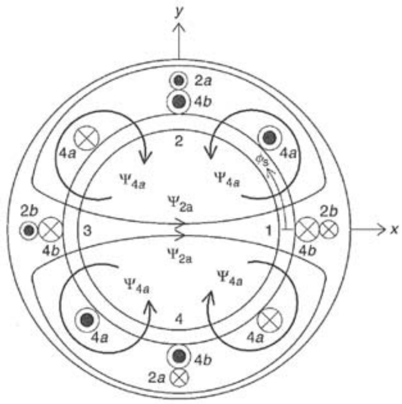
Bearingless drives have been used to solve a problem in some applications such as outer space, harsh environments, high speed and so forth. Different concepts of bearingless motors discussed by some authors can be classified into (1) PM bearingless motors, (2) synchronous reluctance bearingless motors, (3) bearingless induction motors, (4) switched reluctance bearingless motors, and (5) homopolar, hybrid and consequent-pole bearingless motors. Among such concepts of bearingless motors, the advantages of the PM bearingless motor have been summarized as follows [7]: (1) small size and lightweight, (2) high power factor and high efficiency, (3) suspension forces generated without excitation current in the main winding, (4) high inverter fault independence because magnetic suspension operates independently of the motor winding current.
Thus this section starts with a short description on the PM bearingless drives. A significant feature of bearingless motors is the bearing winding integrated into the motor. Fig. 4(a) depicts the principle of the winding construction using a 4-pole PM motor. In order to achieve extensive decoupling between the generation of the radial bearing forces and the torque, the windings are designed with different numbers of poles. [8] The winding arrangement of a primitive bearingless drive can be simplified as shown in Fig. 4(b), where the windings for 4-pole are 4a and 4b and the windings for 2-pole are 2a and 2b. Fig. 4(c) shows the rotor structure with inset type PMs. This structure consists of q-axis saliency and the PMs between the salient poles. Fig. 4(d) is a buried PM type rotor which improves radial suspension force generation because of the low PM magnetic reluctance. [7]

As described above, the bearingless drives need to control both the bearing force with bearing force winding and the torque with torque winding. Therefore the bearingless drives seem more complicate and expensive than the conventional electric machine drives. In the case of the large direct-drive wind generator, the inactive mass is given much weight in the total mass as described above. If the bearingless drive could contribute significant mass reduction of the inactive part, then the use of the bearingless drive can be acceptable for large direct-drive. In the case of the large direct-drive, the rotating part mass including both the active and inactive mass is very heavy. Thus it is expected that the power consumption to produce the bearing force for supporting the rotating part against the gravity will be large, even though the inactive mass is reduced. Therefore the followings must be satisfied to use the bearingless drives in large direct-drive.

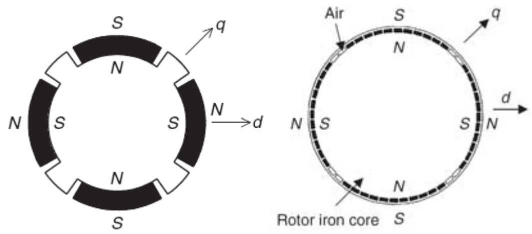
- remarkable mass reduction of the inactive part
- minimized power consumption to produce the bearing force
- simplified control and components



(a) Winding of a bearingless 4-pole PM motor. Outside: 4-pole torque winding; inside: 2-pole bearing force winding [Wol2006]



(b) 4-pole and 2-pole winding arrangements of a primitive bearingless drive [Chi2005]



(c) Inset type PMs (d) Buried type PMs [Chi2005]

Fig. 4 Conventional bearingless drive concepts

B. New bearingless drive concept

The new bearingless drive concept proposed in this paper uses the PMs and the iron cores in the rotor. The stator consists of the iron cores and the windings. Fig. 5 depicts the cross section of the new bearingless drive concept. This concept seems a double-sided axial flux machine. The moving direction of the rotor and the flux paths are described in Fig. 5(a) and (b). In the stable state, it is assumed that both the air gap 1 and the air gap 2 are the same. When the air gap 1 is different with the air gap 2, the difference can be informed by the gap sensor or by measuring the induced voltage of each stator winding. When the air gap 1 is larger than the air gap 2, the air gap 1 can be reduced by changing the magnitude and the direction of currents in Stator 1 and Stator 2 as shown in Fig. 5(b). When the rotor is tilted, this bearingless drive concept shown in Fig. 5(a) and (b) seems not enough to maintain the air gap. Therefore the concept can be improved as Fig. 5(c), where both the air gap 1 and the air gap 2 can be controlled even though the rotor is tilted to the perpendicular direction of the moving.

The changes of flux densities in different air gap lengths are roughly illustrated in Fig. 6, where the flux density *B* is represented as a function of the magnetic intensity *H*. $B_{air\ gap}$ is the flux density in the stable state. $B_{small\ air\ gap}$ and $B_{large\ air\ gap}$ represent the air gap flux density at a small air gap and a large air gap, respectively.

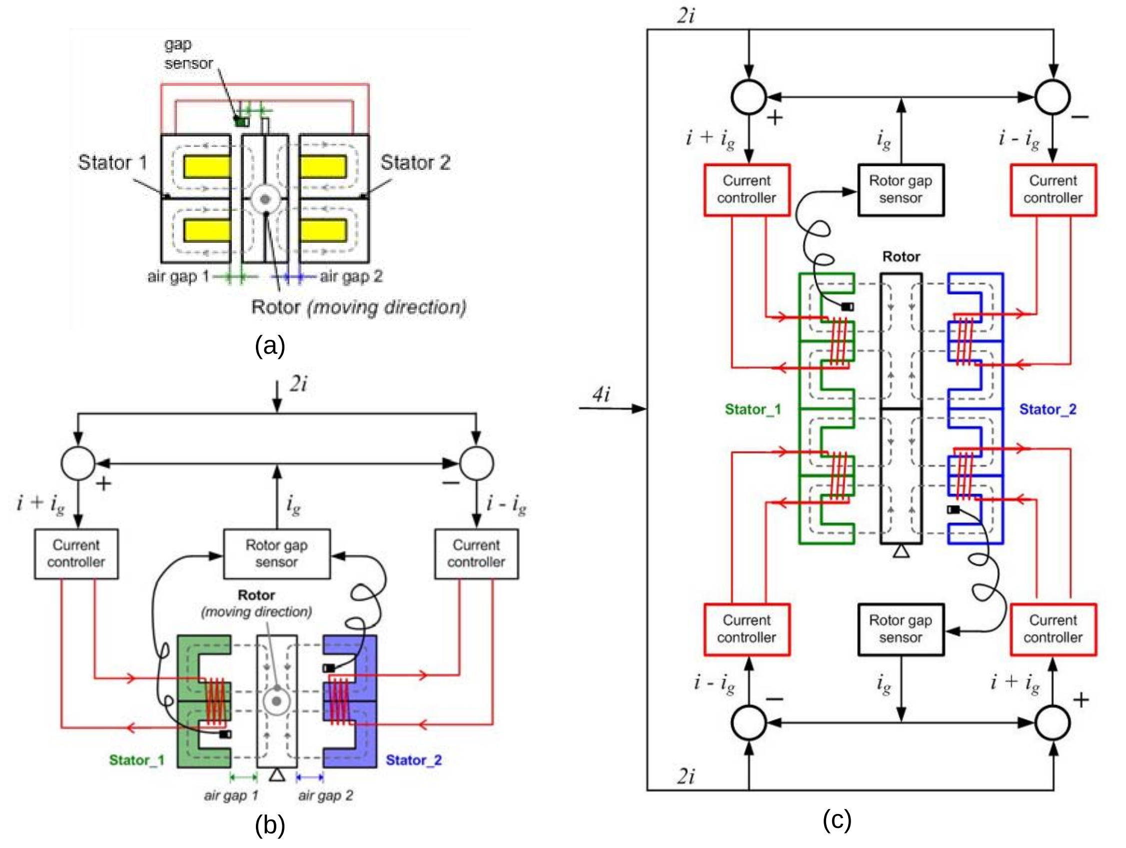


Fig. 5 A new bearingless TFPM machine concept

3-2. Ring shaped generator

Conventional direct-drive generators are generally constructed with one body or large bodies. Constructing a large direct-drive generator with one body or large body is difficult in manufacturing, assembling, transporting, installing and maintaining the generator. The difficulties carry out the cost increase.

When conventional generator systems are in failure of some components or parts, the operation of the system is stopped till the failure is repaired. In the case of large scale generators, the failure will be more serious than the failure of small scale generators.

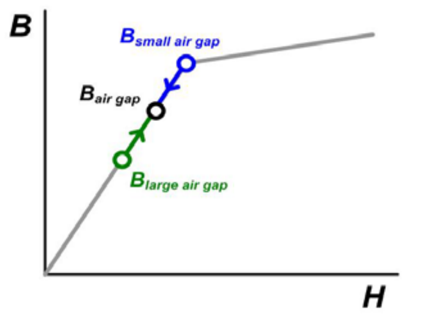


Fig. 6 Flux densities in different air gap lengths

In order to overcome the drawbacks of large direct-drive generators as describe above, and to reduce the structural mass remarkably, a ring shaped generator structure is introduce in this paper as Fig. 7. The ring shaped generator does not have the structure such as the shaft and the structural part to transfer the torque and to maintain the air gap. Therefore it can be possible to achieve the followings with the plural module construction.

- Easy manufacturing, assembly, transportation, installation and maintenance
- Continuous power generation in failures of some parts or components of generator system

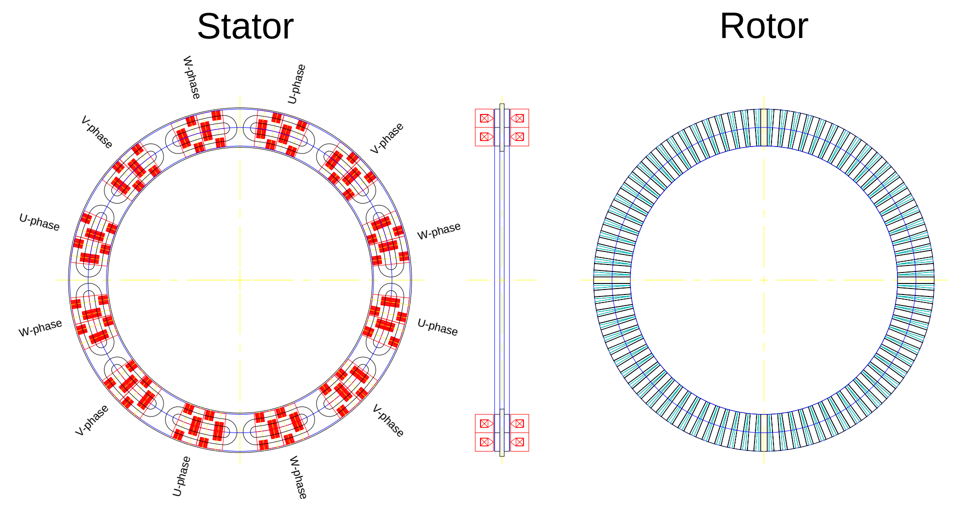


Fig. 7 A ring shaped direct-drive generator concept

3-3. New guiding system

Conventional direct-drive wind turbine concepts use the mechanical bearings to support and guide rotating structure and stationary structure. The drawbacks of conventional bearing systems which have mechanical contacts can be summarized as follows;

- The structure of the guiding system must be accurate in manufacturing and operating.
- It is difficult to use conventional bearing systems for very large diameter application.

In order to overcome the limits of conventional bearing systems in very large diameter applications, both a concept with the flexibility in guiding and a concept supporting easily heavy structure are required. The fluid bearing can be a candidate instead of the conventional bearings. If the wind turbines are operated at high speed, then the use of a fluid bearing will not be sufficient. However, large direct-drive wind turbines are operated at very low speed. Therefore it is possible to operate wind turbines without aligning the concentricity of both the rotor blades and the generator rotor by using the fluid bearing. It means the rotor blades and the generator rotor guided and supported by the fluid bearing could have larger tilting and tolerance compared to using the conventional mechanical bearing.

Therefore new guiding and supporting systems such as (1) buoyant rotating structure and (2) hydrostatic bearing which is a kind of the fluid bearing are proposed in this paper.

A. Buoyant rotating (moving) structure

By using the buoyancy force, very heavy structure can be floated easily in the fluid. Therefore it is possible to use the buoyancy force for supporting the heavy rotating (moving) structure such as the rotor of large direct-drive wind generator. The strengths using the buoyant rotating are summarized as the followings.

- Support heavy structure easily
- Reduce structural material for supporting
- Give flexibility in supporting heavy structure

B. Hydrostatic bearing

By using the hydrostatic bearing, it is possible to guide the rotating and stationary parts with the flexibility and relatively low accuracy. In some cases, the current in generator windings may be stopped because of some faults such as a control failure, an inverter fault and so on. In such cases, the hydrostatic bearings are sufficient not only to guide the generator rotor together with the bearingless drive, but also to prevent the touchdown of the rotor on the stator and further damage. The strengths using the hydrostatic bearing are summarized as the followings.

- Give flexibility in guiding heavy and large structure
- Prevent the touchdown of rotor on stator
- Maintain the air gap when the bearingless drive is in failure
- Reduce a peak power consumption of the bearingless drive

Fig. 8(a) depicts a buoyant structure in the stable state, and a buoyant structure in the unstable state is shown in Fig. 8(b). In the unstable state, the hydrostatic bearing can be used to make the buoyant structure stable as shown in Fig. 9. This buoyant structure can be applied for large direct-drive as represented in Fig. 10. Where, the rotating part is depicted with blue hatchings, and the stationary part is depicted with red hatchings. The inside of the rotating part is the air, and the fluid (green colour) is filled in between the rotating part and the stationary part. Therefore this rotating part is able to be supported by the buoyancy force without additional mechanical constructions to support. The hydrostatic bearing can be also applied for guiding this buoyant rotor structure.

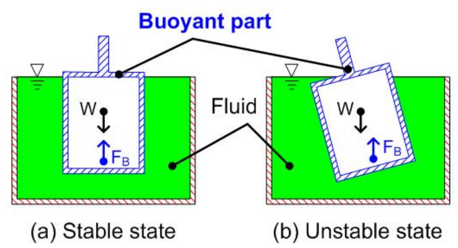


Fig. 8 Buoyant part in fluid

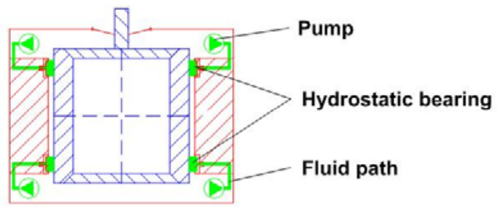


Fig. 9 Buoyant part with hydrostatic bearings

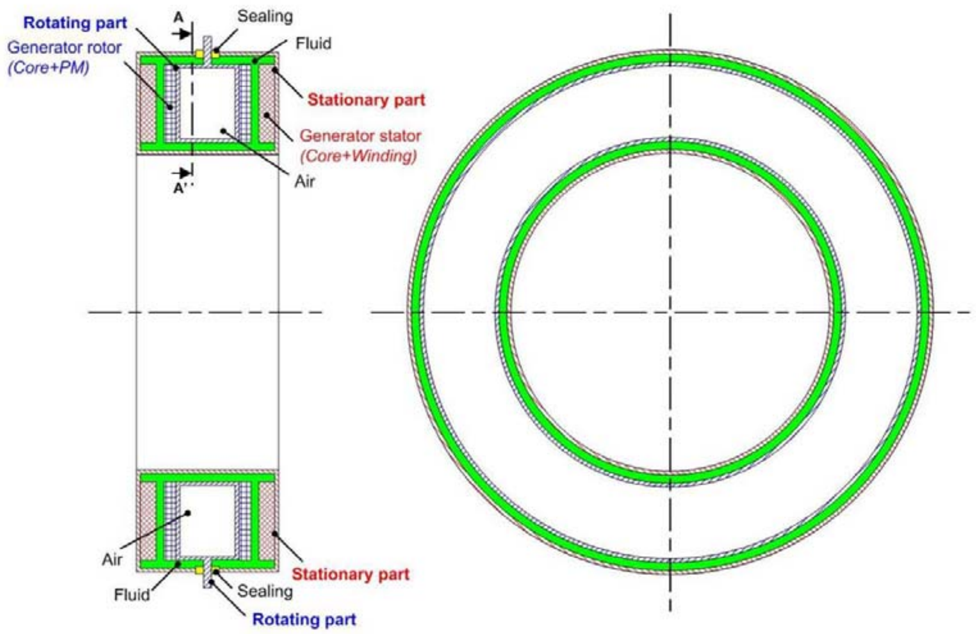


Fig. 10 Buoyant rotor concept for large direct-drive

4. Rough design of new direct-drive generators for large wind turbines

5 MW and 10 MW new direct-drive generators are roughly designed considering the parameters shown in Table 1. The generators have double-sided air gap with the axial flux permanent magnet (AFPM) configuration as shown in Fig. 11. The modelling characteristics of the turbine and generator in [1] are used for the rough design. The active masses of 5 MW and 10 MW generators are given in Table 2.

Table 1 Wind turbine parameters

Turbine specification		
Power [MW]	5	10
Speed [rpm]	12.1	8.6
Rotor blade diameter [m]	126	178
Rated wind speed [m/s]	12	12
Generator		
Air gap diameter [m]	6.3	8.88
Air gap length [mm]	6.3	8.88
Force density [kN/m^2]	40	40

Table 2 Active mass of the generator

Power [MW]	5	10
Copper [ton]	8.0	15.1
Stator iron [ton]	21.8	42.7
Rotor iron [ton]	10.1	20.9
PM [ton]	3.2	8.9
Total [ton]	43.1	87.6

Fig. 12(a) depicts the cross-section of the new direct-drive generator in tangential view. The active part such as the iron core, the PM, and the copper winding are distinguished with the structural part hatched. The structural part of rotating part is shown with blue hatches. In order to estimate the structural mass of the generator, the followings are assumed.

- Maximum normal pressure acting on the rotor and the stator is about 325 [kN/m^2].
- Maximum air gap deflection is smaller than 10% of the air gap length.
- Deflection of the stationary part is neglected, because the part is fixed on the nacelle structure.
- t_h and t_b of the stationary part are the same with the rotating part's.

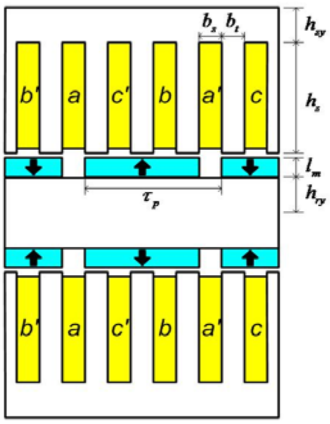


Fig. 11

The rotor structure is modelled considering the normal pressure acting on the rotor and the stator as Fig. 12(b). The normal pressure results in the deflection of the rotor structure from the bold lines to the thin lines. The maximum deflections in the rotor structure are defined as (1) and (2).

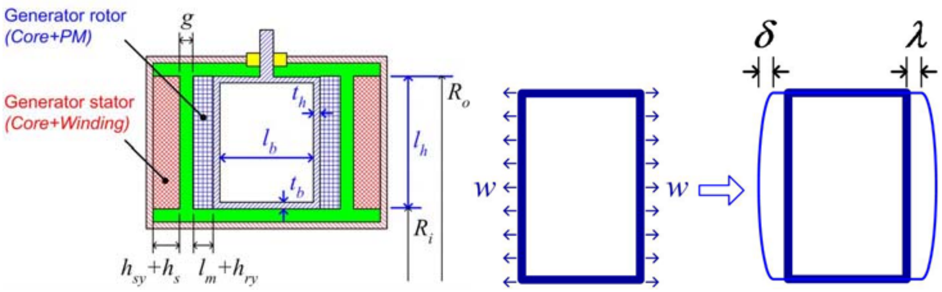
$$\delta_{\max} = 0.05g = \frac{5w \cdot l_h^4}{384E \cdot I} \quad (1)$$

$$\lambda_{\max} = 0.05g = \frac{l_b \cdot w}{4E \cdot A_b} \quad (2)$$

The inactive (structural) masses of the new generators are given in Table 3 including the mass of the fluid.

The total mass of different generator concepts is given in Table 4. Total mass of the new generator concept by the rough design addressed between the concept-3 and the concept-4.

In the rough design, general steel structure has been used for the inactive part construction. Therefore it must be considered to reduce the structural (inactive) mass further by the structural optimization.



(a) (b)

Fig. 12

Table 3 Inactive mass of the generator		
Power [MW]	5	10
Rotor part	9	62.4
Stator part	10.6	69.9
Fluid (water)	13.4	40.8
Total [ton]	33	173.1

Table 4 Generator total mass		
Power [MW]	5	10
Concept-1 [ton]	262	738.4
Concept-2 [ton]	183	515.2
Concept-3 [ton]	98.7	277.6
New concept [ton]	76.1	260.7
Concept-4 [ton]	72.6	204.3
Concept-5 [ton]	68.7	193.2

5. Generator prototype downscaled

As an early research step on the new generator concept, a downscaled generator prototype with the ring shape has been built as Fig. 13. The rotor and the stator of the generator consist of plural module structures. The experimental analyses are under going, so that the details on the experiments will be discussed later.

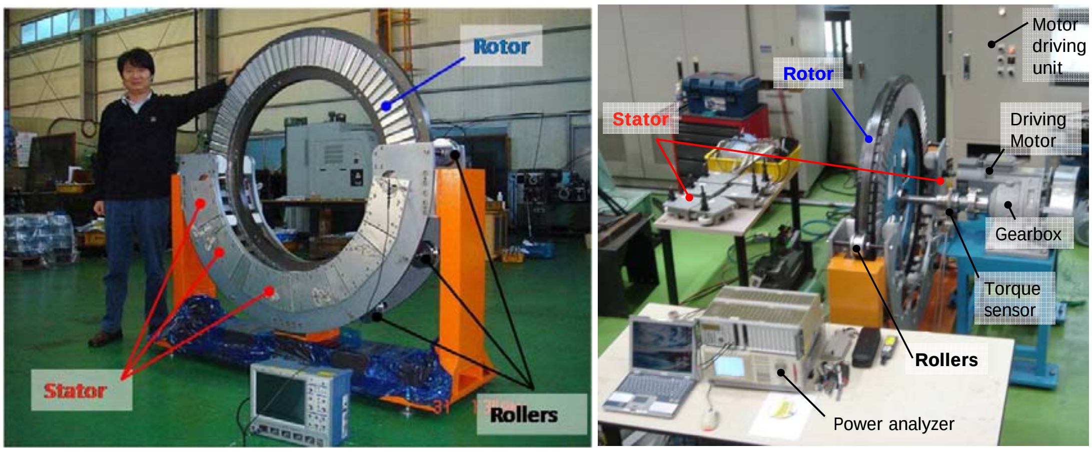


Fig. 13 Ring shaped generator prototype down scaled

6. Summary

In order to minimize the structural mass of large direct-drive generator, a new generator concept has been proposed with a ring shaped construction, a new bearingless drive, a new buoyant rotor structure and hydrostatic bearing systems. Rough design of the new generator concept for 5 MW and 10 MW has been done. Total mass of the new generator is estimated as 76.1 tonnes and 260.7 tonnes for 5 MW and 10 MW, respectively. Comparing with the five different generator concepts, the mass of the new concept is lighter than the concept-1 (EESG DD, Enercon concept), the concept-2 (PMSG DD, Zephyros concept) and the concept-3 (PMSGDD, theoretical design).
In the rough design, general steel structure was used for inactive part construction. Therefore it is expected that the inactive mass can be reduced further by the structural optimization.

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