

Promising Direct-Drive Generator System for Large Wind Turbines

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Keywords

direct-drive, wind turbine, doubly fed induction generator, synchronous generator, permanent magnet

Abstract

The aim of this paper is to review direct-drive generators and to suggest promising direct-drive generator concepts for large wind turbines. Different large direct-drive generators are compared based on the mass and the torque. Features of different PM machines are investigated to find promising machine type for direct-drive. The requirements and alternative solutions are suggested for both electromagnetic and mechanical design.

I. Introduction

The aim of this paper is to review direct-drive generators and to suggest promising direct-drive concepts for large wind turbines. Various wind turbine concepts have been developed to maximize the energy harnessed, to minimize the cost and to improve the power quality. Direct-drive wind turbines have been built to increase the energy yield, to reduce gearbox failures, and to lower maintenance problems [1][2]. A trend of wind turbines installed worldwide is scaling up in recent years. The space to install the turbines onshore is limited in some regions of Europe, and there are higher wind speeds with less turbulence offshore than onshore. The location for the installation thus is moving to offshore. However, the maintenance of offshore wind turbines is more difficult and expensive than that of onshore wind turbines. Therefore more simple, robust and reliable generator systems with high performance and low cost are required for (large offshore) wind turbines.

Direct-drive generator concepts are operated in low speed, thus high torque is demanded. High torque demands high tangential force and large air gap diameter of the generator. When scaling up the wind turbine this phenomenon is grown more and more. Thus the amount of material is increased to maintain the air gap in proper deflection against the stress between the rotor and stator. These result in that the direct-drive generator is heavy. There are still many arguments to make a conclusion of the most suitable generator system among existing wind turbine technologies such as direct-drive and geared generator concepts.

In this paper, in order to grasp the strengths and drawbacks of direct-drive generator concepts quantitatively, a comparison of direct-drive and geared generator systems in [1] is discussed based on the energy yield, cost, and mass. Secondly, different direct-drive generator concepts are addressed and compared including the design of 10 and 20 MW direct-drive generator with the permanent magnet (PM). Next, the features of different PM machines such as the radial flux machine, the axial flux machines and the transverse flux machines are investigated and discussed to identify the promising machine type. Finally, the promising concepts to be the most suitable and alternative solutions are suggested for both the electromagnetic and the mechanical structure for large direct-drive wind turbines.

II. Comparison of Different Generator Concepts

Different generator concepts such as direct-drive and geared drive have been discussed by a number of authors to address the features of each concept. The strengths and drawbacks of the direct-drive concept are summarized as the following.

- Strengths
 - Simplified drive train by omitting the gearbox
 - High overall efficiency and reliability
 - Low noise of the drive train
- Drawbacks
 - Large diameter and heavy mass / High cost

In order to address the strengths and drawbacks of the direct-drive concept quantitatively, the comparison of 3 MW direct-drive and geared generator systems in [1] is discussed based on the energy yield, cost, and mass. The comparison results are shown in Fig. 1 and Fig. 2.

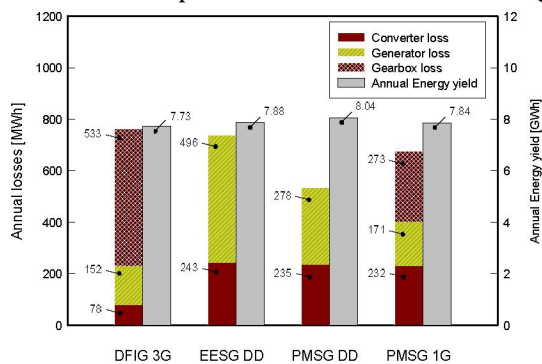


Fig. 1: Annual losses and energy yield of different generator system

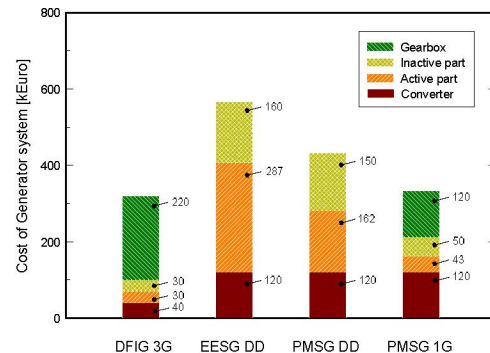


Fig. 2: Cost of different generator systems

These comparison results in [1] are summarized as the following.

- The doubly-fed induction generator system with three stage gearbox (DFIG 3G) seems lightweight and low cost solution.
- Considering the energy yield and reliability, the direct-drive generator systems seem to be more powerful compared to geared drive systems, especially for offshore.
- The direct-drive permanent magnet synchronous generator system (PMSG DD) is more attractive than other systems in terms of losses and energy yield.
- The permanent magnet synchronous generator with 1 stage gearbox (PMSG 1G) has the highest ratio of the annual energy yield to cost.
- The cost of PMSG DD is 32% higher, the cost of EESG DD is 77% higher, and the cost of PMSG 1G is 4% higher respectively compared to DFIG 3G.

If it is possible to reduce the cost of PMSG DD by the cost of DFIG 3G or lower than it, then the PMSG DD can be the most suitable generator system. Therefore to reduce the cost of direct-drive generator systems will be the most important issue in both the electromagnetic design and the mechanical design.

III. Large Direct-Drive Generators

The rotor of direct-drive generator for wind turbine is directly connected with the rotor hub. Thus, as stated above, the direct-drive concept is operated in low speed. When scaling up the wind turbine, the rotational speed is decreased more and more considering the tip speed limitation. In order to scale up the power of the direct-drive generator, the torque, T must be thus increased in inverse proportion to the decrease of the mechanical angular speed, ω_m by

$$P = T \cdot \omega_m. \quad (1)$$

The generator power, P can be also defined as a function of the tangential force density, F_d , the air gap diameter, D_g , the axial length, l_s and the mechanical angular speed as shown in (2).

$$P = \frac{\pi}{2} F_d \cdot D_g^2 \cdot l_s \cdot \omega_m \quad (2)$$

Since the torque is proportional to the air gap diameter squared, the direct-drive generator has a larger diameter to produce higher torque. This higher torque thus demands high tangential force and large air gap diameter of the generator. High tangential force and large air gap diameter result in the increase of materials to maintain the air gap in proper deflection against the normal stress between the rotor and stator. Therefore direct-drive generator concept, which is operated in low speed, has drawbacks such as high torque rating, large diameter, heavy mass, and high cost compared to the geared generator concept. The direct-drive concept thus is usually designed with a large diameter and small pole pitch to increase the efficiency, to reduce the active material and to keep the end winding losses small.

In order to address the features of large direct-drive generators, different direct-drive generators on the market and in literature are discussed. For very large scale, 10 and 20 MW PMSG DD designed are considered.

A. Conventional EESG DD: 4.5 MW

The largest direct-drive wind turbine is E-112 model (4.5 MW, EESG DD) of Enercon GmbH as shown in Fig. 3. The generator mass and diameter are about 220 ton and 12 m, respectively [2][7].

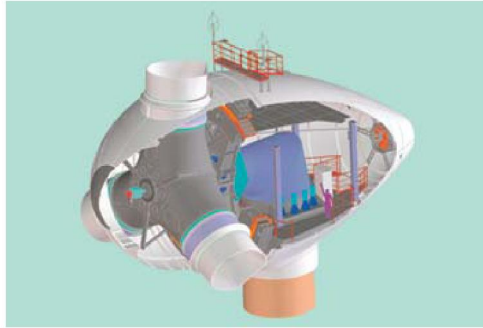


Fig. 3: Structure of 4.5 MW EESG DD. Source: Enercon GmbH.

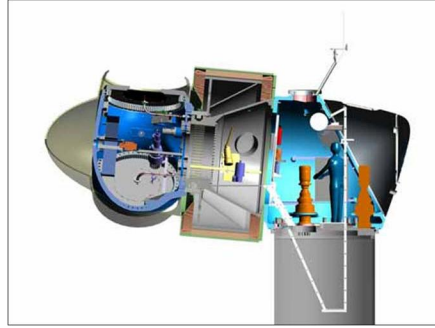


Fig. 4: Structure of 1.5 MW PMSG DD. Source: Harakosan Europe

B. Lightweight PMSG DD: 1.5 and 4 MW

Fig. 4 depicts a 1.5 MW PMSG DD manufactured Zephyros BV, currently Harakosan Europe. The generator is fully integrated in the structural design. The strength of this design is the relative big diameter, and the load path follows contrary to the traditional designs with a main shaft hence reduces mass.

Fig. 5(a) shows mechanical structures of direct-drive wind generators which have been proposed by Spooner et al [5]. The proposed generator has used a pair of spoke wheels to carry the rotor and stator of air gap winding radial flux PM machine. Tavner et al have described how the large number of pole pairs and air gap radius affect the design of the large, low speed, direct-drive machines (see Fig. 5(b)) [6]. They

have discussed and compared the output torque with the ratio of structural/active component mass of different machines.

A new type of direct-drive machine for wind turbines has been proposed. The machine is based on the idea to put the bearings to the air gap of the machine. The fundamental idea of the new generator - the NewGen (see Fig. 6) - design is to reduce the stiffness demand by removing the load path from the rotor, the shaft and the stator by the positioning of the bearings adjacent to the air gap. [7].

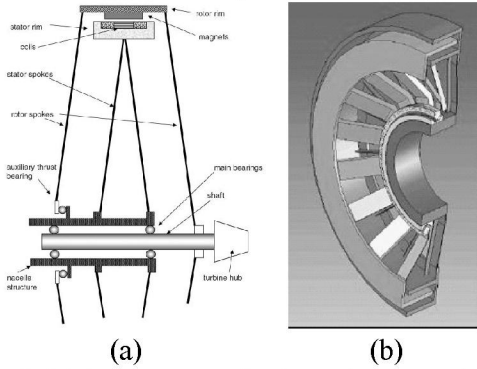


Fig. 5: Light structures for large low-speed direct-drive machine [5] [6]

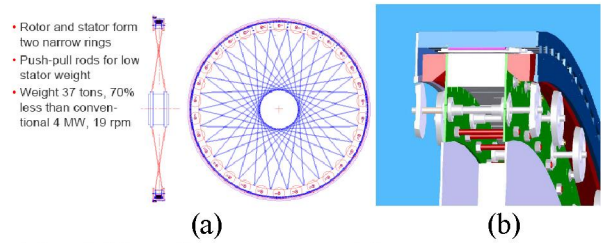


Fig. 6: New-Gen generator [7]

C. Conventional PMSG DD: 2, 3 and 5 MW

The optimization of conventional PMSG DD concept with different generator powers has been achieved for the mass minimization in [2]. The powers considered are 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 by theoretical designs. Fig. 7 depicts the structure of the rotor and stator considered, and Fig. 8 depicts the total mass as a function of K_{rad} , respectively. The K_{rad} of 2, 3 and 5 MW generators chosen as the optimum value are 0.2, 0.22, and 0.27 respectively.

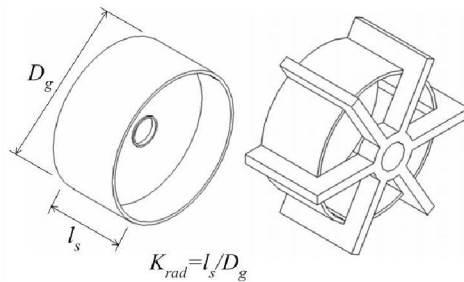


Fig. 7: Structure of the rotor and stator for structural optimization [2]

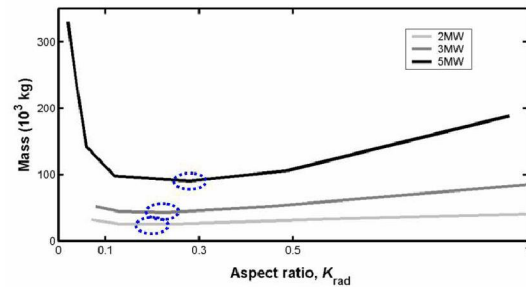


Fig. 8: Total mass of 2, 3 and 5 MW PMSG DD as a function of the ratio, K_{rad} [2]

D. Design of Conventional PMSG DD: 10 and 20 MW

Table I: 10 MW and 20 MW Wind turbine parameters

Rated power (MW)	10	20
Rotor speed (rpm)	10	7
Rotor blade diameter (m)	170	250
Rated wind speed (m/s)	12	12
Air gap diameter (m)	8	10.3
Axial length (m)	2.4	4.1
Air gap (mm)	8	10
K_{rad} (kg/kNm)	0.3	0.4

Wind turbine parameters of 10 and 20 MW PMSG DD are shown in Table I. The modeling characteristics of the turbine and generator in [1] are used to design 10 and 20 MW PMSG DD in this paper. The mass of a 10 MW PMSG DD system in [3][4] has been obtained with $K_{rad}=0.16$. In this paper, 10 MW generator with $K_{rad}=0.3$ is additionally considered to compare with the generator with $K_{rad}=0.16$. For 20 MW, K_{rad} is assumed as 0.4. Fig. 9 and 10 depict the steady-state operation characteristics of 10 and 20 MW PMSG DD wind turbines, respectively.

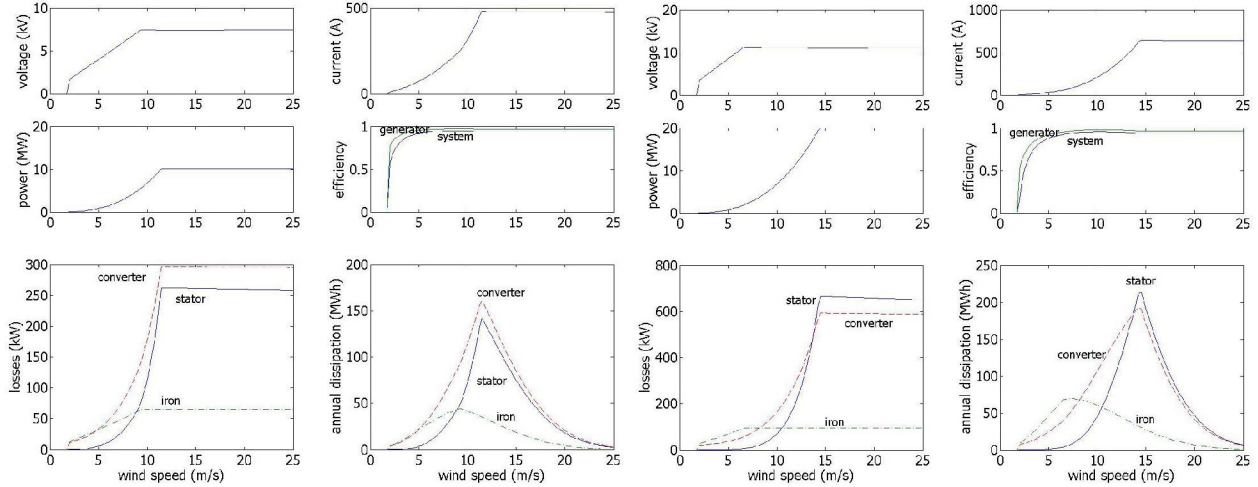


Fig. 9: Characteristics of 10 MW direct-drive PMSG

Fig. 10: Characteristics of 20 MW direct-drive PMSG

IV. Comparison of Different Direct-Drive Generators

Different direct-drive generators as discussed above are compared based on the mass as a function of torque. Table II gives the parameter and the mass of 1.5 MW Zephyros, 4 MW NewGen, and 4.5 MW Enercon wind turbines, respectively. The design parameters and results of 2, 3 and 5 MW wind turbines in [2] are summarized in Table III.

Fig. 11 gives the mass of different generators as a function of the torque rating. The K_{rad} of 2, 3, and 5 MW generators [2] chosen as the optimum value are 0.2, 0.22, and 0.27 respectively as stated above. The ratios of the total mass to torque rating, m/T are shown between 23 and 25 kg/kNm, when the mechanical construction of conventional direct-drive generator is optimized considering the optimum K_{rad} . These results seem that the ratio of total mass to torque, m/T can be assumed around 25 kg/kNm in the rough design, even though it does not include the practical issues in design.

As stated above, two different 10 MW PMSG DD have been discussed. The electromagnetic structure designed with $K_{rad}=0.16$ is lighter than the structure with $K_{rad}=0.3$. However, the total mass of the structure with $K_{rad}=0.16$ is more heavy than $K_{rad}=0.3$, because of more heavy inactive part. Assuming $K_{rad}=0.4$ and $m/T=25$ kg/kNm, 20 MW generator mass was gained by rough design. The total masses of the 10 and 20 MW generators thus are conjectured as about 240 ton and 680 ton respectively.

The total generator mass of 1.5 MW (Zephyros), 4 MW (NewGen) and 4.5 MW (Enercon) direct-drive wind turbines are also addressed in Fig. 11. The ratios of m/T for the 1.5 MW and 4.5 MW generators, which are 46.4 and 66.5 kg/kNm, are higher than the theoretically optimized 2, 3 and 5 MW concepts. These seem that the total mass of the generator in the practical design will be heavy compared to the mass in the theoretical design, because detailed parts for manufacturing are not considered in the theoretical design.

In this comparison of different direct-drive generator concepts, the NewGen concept is the lightest concept because of the lowest m/T compared to other concepts. The total mass of NewGen concept (36.4 ton) seems to be competitive with DFIG 3G (about 35 ton) in mass [7].

Table II: 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 III: Parameter and Mass of 2, 3 and 5 MW PMSG DD [2]

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	23.46
Air gap [mm]	Air gap diameter / 1000		

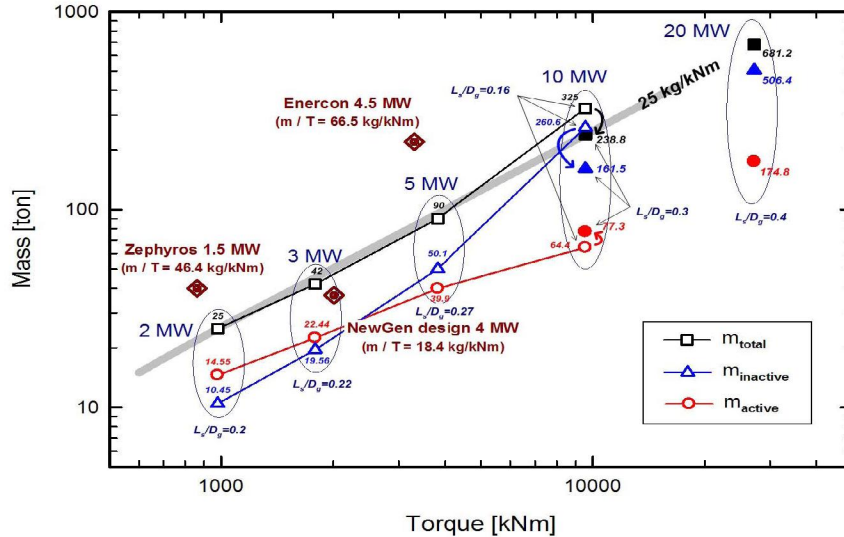


Fig. 11: Mass comparison of different direct-drive generators (2, 3 and 5 MW [2], 10 MW with $K_{rad}=0.16$ [3][4])

According to the comparison of different direct-drive generators as discussed above, the followings can be required in the optimization of the direct-drive generator.

- When scaling up, the total mass is significantly increased and the mass of inactive material is to be more dominant.
- To make large direct-drive concepts attractive, the concept with both low m/T and low cost is required in the construction of the active and inactive material.
- Lightweight inactive parts are potential to reduce the mass significantly.
- The radial flux machine has been mostly used in large direct-drive concepts.

- The ratio m/T of PMSG DD is lower than EESG DD.
- In order to find suitable PM machine type for direct-drive, it is thus required to investigate different PM machines such as the axial flux(AF) PM machine, the transverse flux(TF) PM machine including RFPM machine (in the next chapter).

V. PM Machines for Direct-Drive

The features of different permanent magnet (PM) machines such as the radial flux PM (RFPM) machines, the axial flux PM (AFPM) machines, and the transverse flux PM (TFPM) machines are investigated and discussed to find the most suitable machine type for direct-drive. Electric machines roughly consist of both the active part (electromagnetic structure) and the inactive part (mechanical structure) as stated above. The active part of PMSG DD includes the iron core, PMs and copper.

A. RFPM machine

The RFPM machine is producing the magnetic flux in the radial direction with PMs which are radially oriented. Most of the RFPM machines have a conventional inner rotor design but some outer rotor designs have also been presented in literature. The design of RF machines is simple and widely used. The structural stability of RF machines is easy to make sufficient. Most of the low speed megawatts wind generators are RF machines and these RF machines seem to be the most interesting machine type for the large scale direct-drive wind turbines. When using permanent magnets (PM) for the direct-drive generators, the generators can operate with good and reliable performance over a wide range of speeds. In manufacture, the simple way of constructing the machine with high number of poles is gluing PMs on the rotor surface. In RFPM machines, the length of the stator and the air gap diameter can be chosen independently. If necessary, the radial-flux machine can be made with a small diameter by using a long stator. Fig. 12 depicts a RF machine with surface mounted permanent magnets and a linear cross section of two poles.

RFPM machines (PMSG) have strengths as a better torque density than the RF electrically excited synchronous machine (EESG), so that these machines have been discussed in a number of literature. However, the presence of PMs makes the assembly more difficult and the structure more strong, especially in large machines. RFPM machines with general topology have been almost optimized in the electromagnetic design, so that it seems hard to reduce the active material mass and cost of the machines significantly.

B. AFPM machine

The AFPM machine is a machine producing magnetic flux in the axial direction with permanent magnets. AFPM machine can be classified into slotted machines and slotless machines. Fig. 13 depicts a slotted AFPM machine.

AFPM machine has the strengths compared to RFPM machines as the following.

- simple winding
- low cogging torque and noise (in slotless machine)
- short axial length of the machine
- higher torque/volume ratio

However, drawbacks of AFPM machines have been also discussed compared to RFPM machines as the following.

- lower torque/mass ratio
- larger outer diameter, large amount of PM, and structural instability (in slotless machine)
- difficulty to maintain air gap in large diameter (in slotted machine)
- difficult production of stator core (in slotted machine)

According to the survey on AFPM machines, the followings can be taken.

- slotless machines need a large outer diameter.

- mass of AFPM machine is heavier than RFPM machine.
- to maintain air gap, the construction must be strong or even complicated.
- stator core production is difficult in slotted machines.

Therefore to apply AFPM machines in direct-drive application for large scale wind turbine, these drawbacks must be solved or even improved significantly, since those cause cost increase and difficult manufacture.

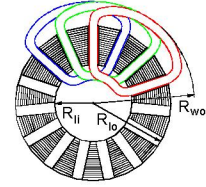
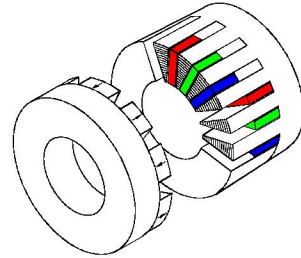
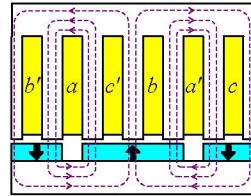
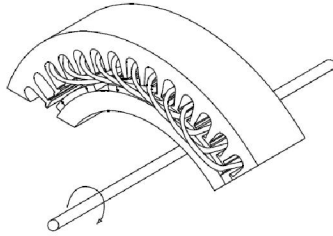


Fig. 12: Surface mounted RFPM machine

Fig. 13: Slotted AFPM machine [8]

C. TFPM machine

The transverse flux (TF) principle means that the path of the magnetic flux is perpendicular to the direction of the rotor rotation. The major difference of TFPM machine compared to RFPM and AFPM machines is that TFPM machine allows an increase in the space for the windings without decreasing the available space for the main flux. TFPM machine can also be made with a very small pole pitch compared with the other types. This feature results in higher induced voltage as shown in (3).

$$e_{\max} = N \cdot \phi_{\max} \cdot 2\pi \cdot f = N \cdot \phi_{\max} \cdot 2\pi \cdot \frac{v_g}{2\tau_p} \quad (3)$$

Where, N is the number of winding turn, ϕ_{\max} is the maximum flux linking the stator winding, f is the frequency, v_g is the moving speed and τ_p is the pole pitch.

Fig. 14 depicts a TFPM machine which is the flux concentrated single-sided type.

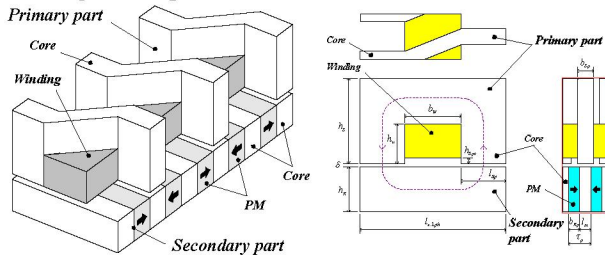


Fig. 14: Flux concentrated single-sided TFPM machine

According to the survey of references, the main strengths of TFPM machines can be summarized as follows compared to the longitudinal machines:

- higher force density
- considerably low copper losses
- simple winding

Contrary to the strengths, the construction of TFPM machine is more complicated compared to RFPM and AFPM machines, since TFPM machine has the flux path of three dimensions. TFPM machine with large air gap seems to be no more attractive because its force density is a little high or even low compared to RFPM machines [8]. These drawbacks make TFPM machine more unattractive. However in a number of literatures, various topologies of TFPM machine have been proposed to solve or improve the drawbacks, since the machine is more flexible and attractive to design and invent new topology in the

electromagnetic design. Each topology proposed in literature has one advantage at least to make TFPM machine attractive. If it is possible to solve the drawbacks by new topology adopting and combining the strengths of different topologies, the TFPM machine will be potential and attractive for large direct-drive concept.

VI. Promising Direct-Drive Generator Concepts

The generator system with both maximum energy yield and minimum cost can be defined as the most suitable generator system for wind turbines. To achieve that, the optimization of generator system is required to have high performance, high reliability, and low cost. As stated above, the direct-drive PM generator system has the highest performance and reliability compared to both the geared generator system and the direct-drive electrically excited generator system. Considering only the energy yield, the direct-drive PM generator system can be the most suitable system. However, the direct-drive generator system has drawbacks such as large size, heavy mass and high cost. In order to make the direct-drive PM generator system most suitable, it must be required to decrease the cost significantly.

In order to achieve the minimum cost of the PMSG DD concept, the amount of material must be reduced significantly. The construction must be also improved for easy production and transportation, and then the manufacturing cost can be also reduced. The requirements and suggestions for the most suitable direct-drive generator system are proposed considering the active part, the inactive part and the practical issues as the followings.

A. Reduce active material

- Plural module concept with short flux path results in the material reduction by decreasing slot pitch and height without increasing leakage flux as shown in Fig. 15.
- RF and AF machines are limited but, TF machine is potential configuration.
- The increased iron core area can produce higher induced voltage by the increased flux linkage as shown in (4). Fig. 16 depicts two promising concepts to increase the area for flux linking.

$$e_{\max} = N \cdot B_{\max,core} \cdot A_{core} \cdot 2\pi \cdot f \quad (4)$$

Where, $B_{\max,core}$ is the flux density in the iron core and A_{core} is the iron core area for the flux linkage.

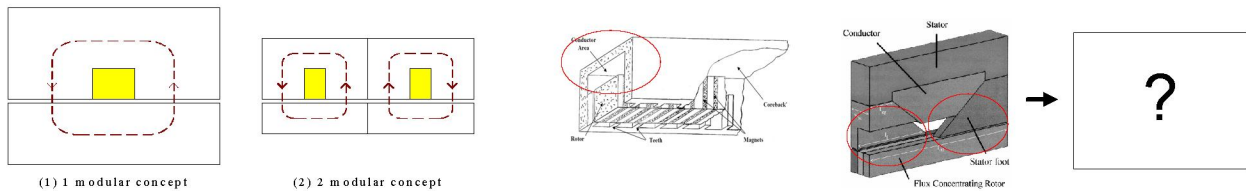


Fig. 15: Concept to reduce active material

Fig. 16: Concepts to increase the area for flux linkage

B. Reduce inactive material

- Machine with very lightweight construction to maintain the air gap
- Machine together with the magnetic bearing
- Machine which can control the air gap as shown in Fig. 17

C. Practical issue

- Modular construction to assemble and separate easily for easy transportation
- Modular concept of which each module can work individually: That means the generator concept can continue to produce the electricity during a few parts of generator are in failure.
- Flexible and very lightweight joint instead of heavy and stiff main shaft - to take the rotational force from the hub to the generator

A promising concept stated above is show in Fig. 18.

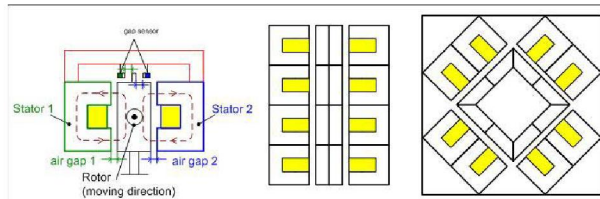


Fig. 17: Concepts to maintain air gap by the machine combined with magnetic bearing

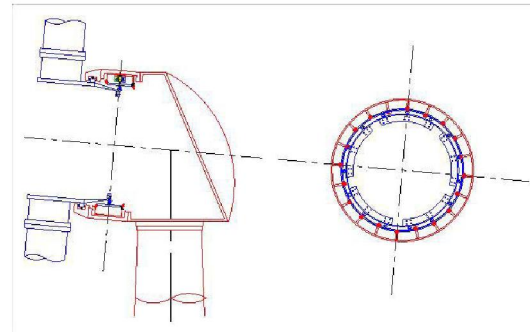


Fig. 18 : Lightweight and modular concept

VII. Conclusion

- The comparison of different generator concepts for wind turbines has been discussed. DFIG 3G is the lightest and low cost solution. PMSG DD has the highest energy yield.
- The total mass of different direct-drive generators has been investigated by the survey of large generators up to 5 MW and by the design of 10 and 20 MW PMSG DD. The ratio of total mass to torque, m/T for EESG DD is the highest, and a new concept with lightweight structure (NewGen concept) has the lowest value of m/T .
- In order to minimize the active material of PMSG DD, an electromagnetic configuration with shorter flux path is required. The TFPM machine is potential configuration to have short flux path than the RFPM and AFPM machine.
- A concept with very lightweight construction to maintain the air gap will be promising for large direct-drive concept. A concept with easy production and transportation is more attractive.

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