Review of Generator Systems for Direct-Drive Wind Turbines

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***Abstract*- The objective of this paper is to review direct-drive and geared generator systems and to identify suitable generator concepts for direct-drive wind turbines. The comparison of different generator systems in literature is discussed with the criteria based on the energy yield, cost, and weight. Different promising permanent-magnet (PM) machines proposed in literature are also discussed to find suitable generator type, because direct-drive PM machines are more superior in terms of the energy yield, reliability and maintenance problem. Finally, suitable concepts to overcome the disadvantages of direct-drive are suggested considering both electromagnetic and mechanical structure.**

I. INTRODUCTION

Various wind turbine concepts have been developed and built to maximize the energy harnessed, to minimize the cost, and to improve the power quality during the last two decades. Such turbine concepts can be classified with a view to the rotational speed, the power regulation, and the generator system. When considering the construction of the generator system, the turbines can be classified into the direct-drive and the geared concepts. When focusing on the generator type, the generator system can be classified into the electrically excited (EE) machine and the permanent magnet (PM) machine. The comparisons of different generator systems for wind turbines have been proposed in a number of literatures. The comparisons can be summarized as the following. The geared generator system has the advantages in terms of the cost, size, and weight. The direct-drive generator system, especially direct-drive PM generator system, is more superior in terms of the energy yield, reliability, and maintenance problem. However, the geared drive system has been mostly used on the market of wind turbines, even though the direct-drive system is superior in performance as discussed above. The world market share of the direct-drive generator system has been around 20%, which is a sum of the share of both direct-drive EE machines as 15% and direct-drive PM machines as 5%, in 2004 [1]. Considering the current market status, it is expected that to make the direct-drive concept attractive compared to the geared concept will be the most important issue.

In order to identify suitable generator concepts for direct-drive wind turbines, the comparisons of different generator systems in literature are discussed with the criteria based on the energy yield, cost and weight. According to the review of different generator systems in literature and on the market, it can be expected that the direct-drive PM generator system with both light construction and low cost could be the most suitable system. Consequently that generator system could be defined as the most suitable generator concept with the maximum energy yield and the minimum cost. In order to find the most suitable concept, thus promising different PM machines are investigated and discussed such as the radial flux, the axial flux and the transverse flux machines. Finally, the expected suitable direct-drive concepts are suggested considering both electromagnetic and mechanical structure.

II. DIRECT-DRIVE AND GEARED GENERATOR SYSTEMS

A. Comparison of direct-drive and geared generator systems

Different direct-drive and geared generator systems of the wind turbines have been discussed by a number of authors. The 1.5 MW wind turbines with the electrically-excited direct-drive generator system have been compared to the doubly-fed induction generator system with a gearbox in [2][3]. The top masses of the direct-drive generator and the DFIG with a gearbox were also compared in [4]. The benefits of direct-drive PM machines such as the elimination of the excitation losses and the reduction of the weight of active material have been discussed in [5], [6], [7], [8], [9] and [10].

Grauers has presented a comparison between the direct-drive radial flux PM synchronous generator (PMSG) connected to a forced-commutated rectifier and the three stage geared traditional squirrel cage induction generator (SCIG) for wind turbine systems. The rated power from 30kW up to 3MW has been investigated [6]. Lampola has compared the total weight of the 500 kW direct-drive PM generator systems and the geared drive induction generator system [8]. Recently, Polinder *et al* have compared 3 MW direct-drive and geared generator systems based on the energy yield, cost, and mass [10]. The advantages (+) and disadvantages (-) of different generator concepts with different output power are simply summarized in Table 1. According to the comparison of different direct-drive and geared generator systems discussed in literature, the features of the systems can be 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 superior compared to other systems in terms of losses and energy yield.
- The permanent magnet synchronous generator with one stage gearbox (PMSG 1G) has the highest ratio of the annual energy yield to cost.
- Different generator systems can be arranged in the order of high cost as EESG DD > PMSG DD > PMSG 1G > DFIG 3G.

Fig. 1 depicts the cost of both 3 MW DFIG 3G and PMSG DD including the gearbox, the inactive part, the active part and the converter. 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 concept, because the energy yield of PMSG DD is the maximum. 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.

Table 1 Advantages and disadvantages of different generator systems

		DFIG 3G	EESG DD	PMSG DD	SCIG 3G	PMSG 1G
0.5 & 3 MW Grauers ('96)	• Diameter • Axial length • Mass			(-) (+) (-)		
1.5 MW Böhmeke *et al* ('97, '98)	• Cost • Mass		(-) (-)			
Böhmeke *et al* ('03)	• Tower head mass	**0.8 - 5MW**	**0.3 - 4.5MW** (-)			**1, 3MW**
0.5 MW Annon ('96)	• Annual E. Yield			(+)		
3 MW Polinder *et al* ('06)	• Mass • Cost • A.E.Y.	(+) (++) (--)	(--) (--) (+)	(-) (-) (++)		(+) (+) (-)

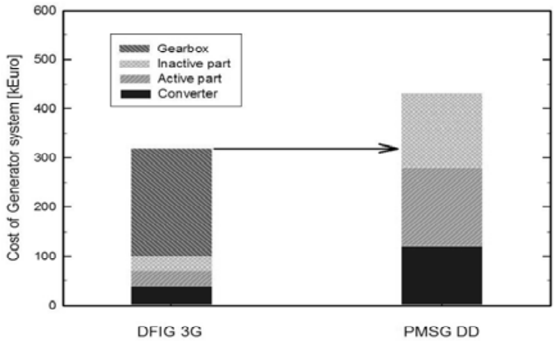


Fig. 1 Cost of 3 MW DFIG 3G and PMSG DD

B. Promising direct-drive concepts

The rotor of direct-drive generator for wind turbine is directly connected to 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

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

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).

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

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 the disadvantages 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. [11]

PM machines are considered as the promising electromagnetic structure for direct-drive generator in this paper, since the PM machines have the advantages compared to the electrically excited machines as the following.

- High energy yield and light weight
- No additional power supply for the field excitation, Higher reliability without slip rings
- Improvement in the efficiency
- Higher power to weight ratio

Different large direct-drive generator concepts on the market and in literature are considered and discussed to address the features of different mechanical structures and to find the promising mechanical structure for direct-drive generator.

III. ELECTROMAGNETIC STRUCTURE FOR DIRECT-DRIVE

The PM machines can be classified by both the direction of flux path and the structure as the following.

- the longitudinal and the transverse flux machine
- the radial and the axial flux machine
- the slotted and the slotless machine
- the surface mounted and the flux concentrating machine

However, this paper mainly classifies the PM machines to three concepts such as the radial flux PM (RFPM) machine, the axial flux PM (AFPM) machine and the transverse flux PM (TFPM) machines. Details of each concept are discussed in this chapter.

A. *RFPM machines*

The RFPM machine is producing the magnetic flux in the radial direction with PMs which are radially oriented. The radial flux machines with surface mounted magnets have been discussed in [6][8][12] and [13]. The radial flux machine is economically a better choice for large scale direct-drive wind turbines compared to the axial flux machine. The radial flux machine with surface mounted magnets seems to be a good choice for the design of a large scale direct-drive wind generator [6][8]. The radial flux PM machine with flux concentration has been discussed and compared to the machine with surface mounted PM in [7][14]. A direct-drive modular PM synchronous generator for variable speed wind turbines has been discussed with attractive features. The stator module of the generator is divided circumferentially into a large number of E cores, each carrying a coil which may be wound on a bobbin and fitted prior to assembly of the generator. Rotor module consists of a large number of blocks with permanent magnet and steel pole side [15][16][17]. The cancellation of the noise and vibration was discussed and an alternative damping system was described about this modular generator [18][19]. A mathematical model of the modular machine was described and its predictions were compared with measured losses [20]. Wu *et al* also described a surface mounted PM machine, which is a small outer-rotor, direct-drive type for wind turbines. They discussed the optimization techniques including the starting torque of the machine by using the finite element analysis [21]. The design and finite element analysis of an outer-rotor PM synchronous generator were also presented for the direct-drive wind turbines by Chen *et al* in [22]. Several advantages of the outer-rotor machine were identified in this reference. A direct-drive PM synchronous generator for 1.5 MW wind turbine was designed by conventional magnetic equivalent circuit method and was analyzed by the finite element method for the design verification [23]. A direct-drive PM wind generator of 500 kW at 40 rpm was designed, and its electrical performance was calculated by the finite element method [24]. Five different direct-drive PM machines, which are a surface mounted PM type, an inset surface mounted PM type, an outer rotor surface mounted PM type, a V-shaped buried PM type, and a tangentially magnetized PM type, have been investigated and compared to design the PM machines with better efficiency and less weight than the induction machine with its gearbox in [25]. According to [25], the rotor with V-shape magnets is not appropriate for design with high pole numbers. Outer rotor type is lighter than inner rotor type when comparing the active material weight as a function of the pole numbers. The inset PM type is slightly lighter than the surface mounted PM type. The tangentially magnetized PM type gives the best performances in the application. The design of a direct-drive, surface mounted PM wind generator and the control strategy for pitch control have been discussed with the rated power of 20 kW at 110 rpm in [26] [27]. Hanitsch and Korouji have designed a rare earth PM radial flux generator for wind turbine with new topology, which is constructed from two rotors and one stator and by short end windings. It improves the performance of the machine by reducing the weight, increasing the efficiency and reducing the cost of active materials [28]. Fig. 2 depicts different RFPM machines proposed and discussed by a number of authors.

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.

RFPM machines (PMSG) have the advantages such 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 and the cost of the machines significantly.

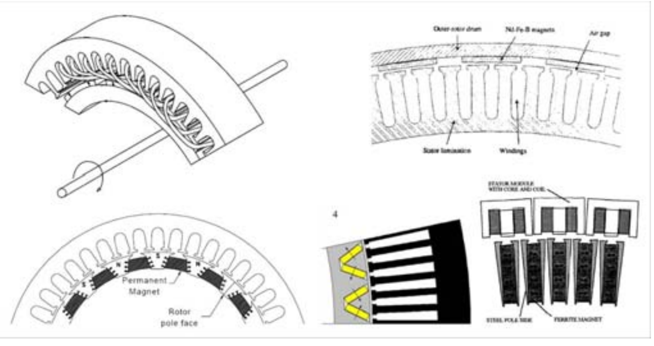


Fig. 2 Different RFPM machines

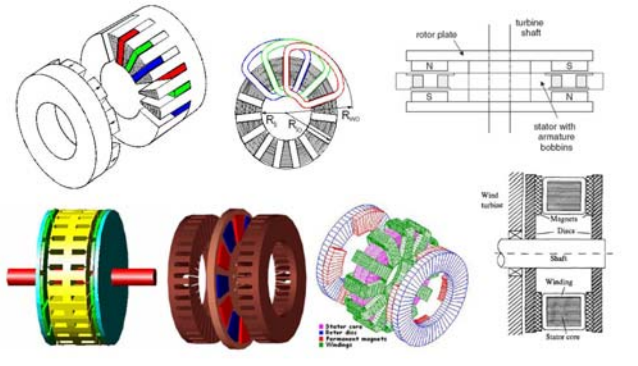


Fig. 3 Different AFPM machines

B. *AFPM machines*

The AFPM machine is a machine producing magnetic flux in the axial direction with permanent magnets. Fig. 3 depicts different AFPM machines such as slotless, toroidal-stator, slotted, coreless machines. A slotless, toroidal-stator PM machines have been discussed with several advantages such as the compactness, the short axial length, the suitable integration with the engine and others in [29][30] [31]. An axial flux PM generator named Torus for a direct-drive variable speed wind turbine application. They described the perceived advantage of the Torus configuration and discussed the design of a 5 kW at 200 rpm. The Torus machine is a slotless, toroidal-stator, double-sided, axial, disc-type, permanent magnet, brushless machine [32]. The direct-drive, low-speed, axial flux PM synchronous machine for 100 kW wind turbine has been proposed considering both mechanical and electromagnetic designs in [33][34]. The stator is toroidal with the iron sheet core to avoid eddy currents, and the winding is wound directly on the toothless stator core. The design and development of an axial-flux PM generator for a direct-drive generator with small-scale wind turbine has been described in [35]. The generator consists of two rotor discs with PM located around its periphery. The stator is made of non-magnetic non-conducting material and has a number of bobbin-wound armature coils located around its periphery. The generator produces 1 kW at 300 rpm or 2 kW at 500 rpm with an electrical efficiency substantially greater than 90%. Caricchi *et al* proposed a new axial flux PM machine topology to apply to the ship propulsion. In designing an axial flux PM machine devoted to ship propulsion systems, the machine weight should be particularly taken into the consideration, since the achievement of a high torque to weight ratio results in a great saving of active materials and reduces the machine costs. The machine proposed by Caricchi *et al* is characterized by the synchronous counter-rotation of the two machined rotors, to apply to the ship propulsion. Such a new machine topology can find application in the direct driving of two counter-rotating propellers, which may be used in ship propulsion systems to recover energy from the rotational flow of the main propeller slip stream. The use of an axial flux PM machine having counter-rotating rotors allows an improvement in terms of weight and efficiency, since the epicyclic gear otherwise required for the motion reversal can be avoided. Significant design characteristics were evaluated for the axial flux PM machines having the rated power in the range from 1 MW to 20MW [36]. Caricchi *et al* proposed slotless axial flux PM machines in references [37][38]. Sahin described a high speed, slotted, double-stator, internal rotor type axial flux machine [39]. Eastham *et al* proposed a novel direct-drive brushless PM axial flux machine for aircraft drive. This machine must have the best possible power-to-weight ratio together with the conflicting attribute of high efficiency. One form of machine under the consideration for the drive follows the multiple surface ideas that have been proposed for machines with high power density. Conventional machines use only one cylindrical surface within the machine to generate torque. However, machines such as the ship propulsion under development generate torque on coaxial cylindrical surfaces within the machine volume. Multiple disc machines are also possible and again produce a larger total torque producing surface. They have been applied to gas turbine generators and versions having two discs are in use for wind turbine applications [40]. The potential application of soft magnetic composite (SMC) material was discussed to apply to the low speed, direct-drive, axial flux PM wind generators by Chen *et al*. Comparative design studies were conducted on PM generator for wind turbines of different configurations with both lamination core and SMC core [41]. Parviainen discussed about an analytical method to perform the preliminary design of surface mounted, low speed, PM axial flux machines with one-rotor-two-stators configuration. A performance and construction between the low speed radial flux and axial flux PM machine were compared in the power range from 10 kW to 500kW at 150-600 rpm [42]. Vizireanu *et al* discussed a 9-phase, 2.7MW axial flux generator with two PM outer rotors and one interior 9-phase stator [43]. Vizireanu *et al* also presented a comparative study for different configurations of a 9-phase concentrated winding PM synchronous generator for direct-drive wind turbines of 5MW output power [44]. The structural mass of axial flux PM machines for a range of typical wind turbine ratings was analyzed and discussed in a reference [45]. Okazaki *et al* have proposed the axial flux motor for the ship propulsion. This motor is a liquid nitrogen cooled high-temperature superconducting motor, and it has a shape of stacked disks. Each disk contains several coils those are used as the rotor or the stator [46].

AFPM machine has the advantages 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, the disadvantages 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 disadvantages must be solved or even improved significantly, since those cause cost increase and difficult manufacture.

C. TFPM machines

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.

In cases of [8][47], the weight of 55 kW transverse flux machine is about half of the total weight of an asynchronous machine with a gearbox. Transverse flux machine seems to be suitable for direct-drive applications because of its high specific torque, although it has a large number of individual parts and special methods of manufacturing and assembly [48]. The surface-mounted TFPM machines have been discussed by Weh [49], Harris [50][51], Bork and Henneberger [47] and others. The flux-concentrating TFPM machines have been discussed by Weh in [52][49][53][54], Lange in [55], Mecrow in [56], Mitcham in [57], Voyce in [58], Maddison in [59], and Blissenbach in [60]. Dubois also have discussed about different topologies of TFPM machines in [7][61][62][63]. The double-side TFPM machine were discussed in [52][49][53][55][56][57][58]. E-core TFPM has been discussed in [53]. References such as [54][59] and [60] have discussed the claw pole TFM. Maddison has compared the single-sided, the single-sided bridged, and the double-sided TFM with the claw pole TFM in [64]. A new concept of a transverse flux machine was proposed by Henneberger and Bork in [47]. Dubois has reviewed various transverse flux permanent magnet machines such as the surface-mounted TFPM machine and the flux-concentrating TFPM machine which have a radial air-gap configuration [7]. Dubois has proposed a new single-sided TFPM machine with flux-concentration, single-winding and toothed rotor [7][63]. A combination of a modular, transverse flux, axial air-gap configuration and toroidal stator winding was proposed to apply to a permanent magnet generator for wind turbines by Muljadi *et al* in [65]. The toroidal stator winding can be easily assembled and automated for production and the winding is exposed to open air, which improves cooling. A modified design of the transverse flux machine, which offers a high torque density, was proposed for the electric propulsion of ships by Mitcham *et al* in [66][57].

Rang *et al* discussed two typical topologies of TFPM, which are the double-sided double-winding type and the double-sided single-winding type with C-core stator in [67]. This reference also discussed an analytical design approach about the second topology. The topologies of this reference are same with what was discussed by Mitcham *et al*. The specific sizing and force density equations of the TFPM were discussed and the TFPM, of which topology is same with [52], was compared with the squirrel cage induction machine in [68][69] by Huang *et al*. Harris *et al* compare the relative advantages and disadvantages of three different topologies of TFPM machines, which include a single sided surface mounted PM machine, a single sided surface mounted PM machine with stator bridges, and a double sided flux concentrating PM machine [70]. They also discussed about power factor of the transverse flux machine in [71]. Hasubek *et al* proposed a transverse flux machine with the stator with PM and the passive rotor. The force density of the transverse flux machine was discussed and compared to different longitudinal machines [72]. They also discussed about an analysis of the design limitations of the machine in [73]. In this reference, useful pole pitches, PM widths, and rotor pole width were proposed. An analytical approach was proposed to dimension and analyze the performance of a transverse flux machine. The ratios of Torque/Active mass and Toque/Volume were compared to different transverse flux machines by Arshad *et al* in [74]. French *et al* discussed the TFM, which was an axial flux type, to apply to ships and an optimized torque control strategy was also presented in [75]. A configuration of TFM for the ship propulsion was proposed with discussions of a theoretical analysis and some experimental results. A condition monitoring technique for a TF machine was also proposed by Payne *et al* in [76]. In [77], an axial type TFPM to reduce the torque ripple was discussed by Kastinger *et al*. A TFPM with intermediate poles, which was proposed by Zweygbergks in 1992, was discussed and compared to a conventional surface mounted TFPM in [78] by Arshad *et al*. Husband *et al* introduced the transverse flux machine of 2 MW output power for ship propulsion. The TFPM was a type of the double-sided single-winding TFPM machine with C-core stator arrangement in [79]. Njeh *et al* investigated of the cogging torque of a single-side claw pole TFPM machines [80]. Lu *et al* discussed a new torque equation, the estimation of inductance, an analytical model, and the power factor of a surface mounted PM transverse flux machines [81][82][83][84]. The principle, topologies, present research situations, and disadvantages of different TF machines were discussed by Shi *et al* in [85]. The design, performance analysis, and experimental results of the surface mounted PM transverse flux machine have been discussed by Guo *et al*. to investigate the potential of soft magnetic composite in [86][87]. The effect of the pole overlap for the TF machines with stator poles of claw-pole type and flux concentrating rotor has been discussed by Maddison in [59]. That results a maximum 6% increase in torque output, at 30% overlap. This means that the overlap factor should be 0.65 to achieve the maximum output. An optimization of a single-sided claw pole TFPM machine has been also discussed considering with the overlap between adjacent stator teeth by Masmoudi *et al*. in [88]. The maximization of the output torque and the minimization of the cogging torque were discussed with considering the overlap. The maximum torque is produced under the overlap of 30 %. Bao *et al* discussed for cogging torque reduction of a double-sided, single-winding TFPM machine with C-core arrangement. A new double-sided single-winding TFPM machine with C-core stator was suggested with considering the reduction of power losses [89][90][91]. The cogging torque analysis of a transverse flux machine was discussed by Schmidt [92]. The concept of this machine is same with what was proposed in [53], which is a double-sided TFPM machine with flux-concentration and single-winding in U-core arrangement. Wer *et al* have presented about the reduction of the cogging torque of the TFPM machine by an optimal current control [93]. Gieras has discussed the analysis and performance characteristics of a three-phase single-sided flux concentrating TFPM with outer rotor in [94]. Power factor analysis of TFPM machine was discussed by Zhao *et al* [95]. Fig. 4 depicts different TFPM machines which have been suggested and discussed by a number of authors.

According to the review of different TFPM machines, the main advantages 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 advantages, 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 [96].

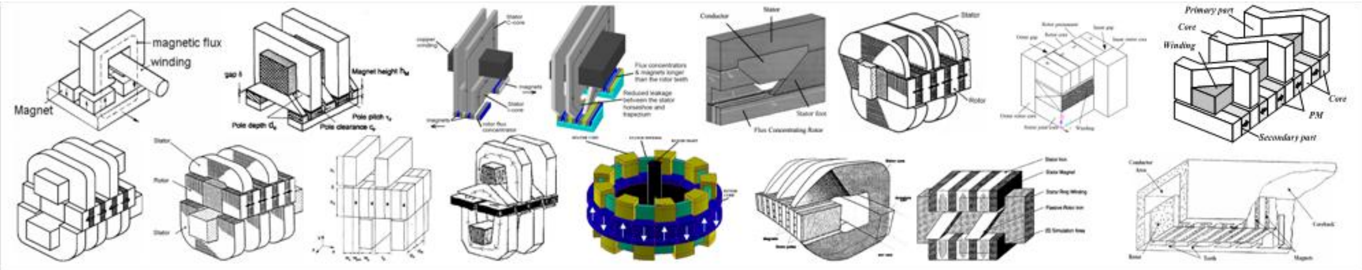


Fig. 4 Different TFPM machines

These disadvantages make TFPM machine more unattractive. However in a number of literatures, various topologies of TFPM machine have been proposed to solve or improve the disadvantages, 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 disadvantages by new topology adopting and combining the advantages of different topologies, the TFPM machine will be potential and attractive for large direct-drive concept. Fig. 5 depicts that TFPM machine provides a significant cost advantage in active material over RFPM machine for small air-gap. However, the cost advantage of TFPM machine is reduced when the air-gap length is on the increase over 3-4 mm. TFPM cost advantage factor, K_{TFPM_Cost}, is defined by (3).

$$K_{TFPM.Cost} = \left(Cost/Torque\right)_{RFPM} \Big/ \left(Cost/Torque\right)_{TFPM} \quad (3)$$

The application of TFPM machines for direct-drive large scale wind turbines will be hard in the case of the existing disadvantages including the reduced cost advantages in large air-gap as mentioned above. Therefore a new topology with electromagnetic optimization is necessary to solve or improve the disadvantages significantly.

Large direct-drive wind turbines of different manufacturers are reviewed and summarized as Table 2. According to the review, the followings, which are verifying the advantages and disadvantages of RF, AF and TF machines, can be taken.

- The RF machines have been mostly used for large direct-drive.
- The AF machine is not used over 1 MW scale.
- TF machine is not used for larger machines with large air gap.

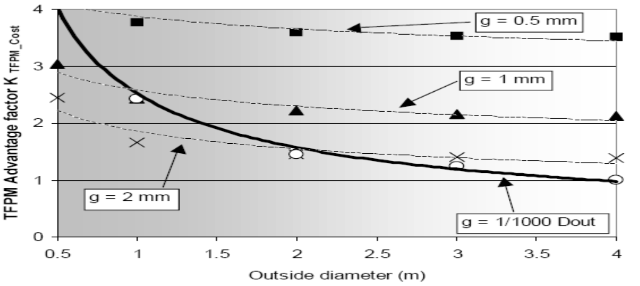


Fig. 5 Cost advantage factor of TFPM machine over RFPM machine [96]

Table 2 Large direct-drive wind turbines of different manufacturers

Generator Type	Power / Speed	Manufacturer
EESG (RF)	4.5 MW / 13 rpm	Enercon
PMSG (RF)	1.5(2) MW / 18(23) rpm	Zephyros
PMSG (RF)	2 MW / 24 rpm	Mitsubishi
PMSG (RF)	3.5 MW / 19 rpm	Scanwind
PMSG (RF)	1.5 MW / 23 rpm	Leitwind
EESG (RF)	1.65 MW / 20 rpm	MTorres (N.A.)
PMSG (RF)	2.5 MW / 14.5(16) rpm	Vensys
PMSG (RF)	1.5 MW / 19 rpm	Goldwind
PMSG (AF)	0.75 MW / 25 rpm	Jeumont (N.A.)

IV. MECHANICAL STRUCTURE FOR DIRECT-DRIVE

A. *Conventional structure*

The largest direct-drive wind turbine is E-112 model (4.5 MW, EESG DD) of Enercon GmbH as shown in Fig. 6. The generator mass and diameter are about 220 ton and 12 m, respectively [97][98].

The optimization of conventional PMSG DD concept with different generator powers has been achieved for the mass minimization in [97]. The powers considered in [97] 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.

The modeling characteristics of the turbine and generator in [10] have been used for the 10 MW PMSG DD, and wind turbine parameters of 10 MW PMSG DD [99][100] are shown in Table 3.

Fig. 6 Structure of EESG DD. Source: Enercon GmbH.

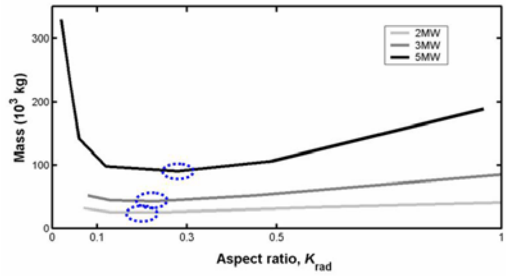


Fig. 8 Total mass of 2, 3 and 5 MW PMSG DD as a function of the ratio, K_{rad} [97]

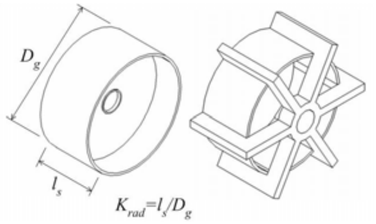


Fig. 7 Structure of the rotor and stator for structural optimization [97]

Table 3 10 MW PMSG DD parameters

Rated power (MW)	10
Rotor speed (rpm)	10
Rotor blade diameter (m)	170
Rated wind speed (m/s)	12
Air gap diameter (m)	10
Axial length (m)	1.6
Air gap (mm)	10
K_{rad} (kg/kNm)	0.16

B. Lightweight structure

A 1.5 MW PMSG DD manufactured by Zephyros BV, currently Harakosan Europe is shown in Fig. 9. The generator is fully integrated in the structural design. The advantages of this design are the relative big diameter, and the load path follows contrary to the traditional designs with a main shaft hence reduces mass.

Fig. 10(a) shows mechanical structures of direct-drive wind generators which have been proposed by Spooner *et al* [101]. 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. 10(b)) [102]. 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. 11) - 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 [98].

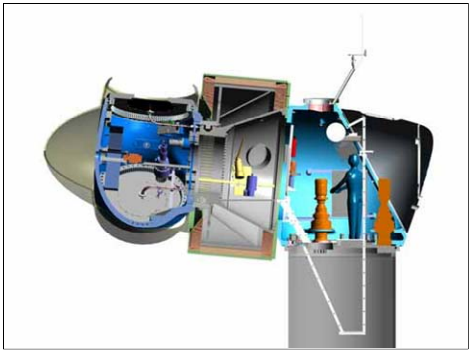
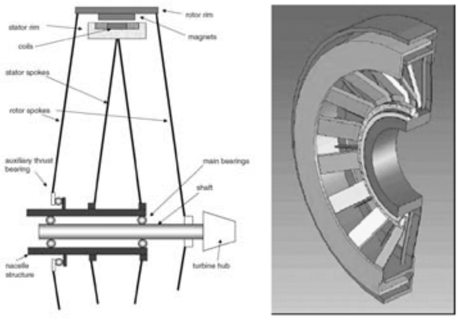


Fig. 9 Structure of 1.5 MW PMSG DD. Source: Harakosan Europe



(a) (b)

Fig. 10 Light structures for large low-speed direct-drive machine [101][102]

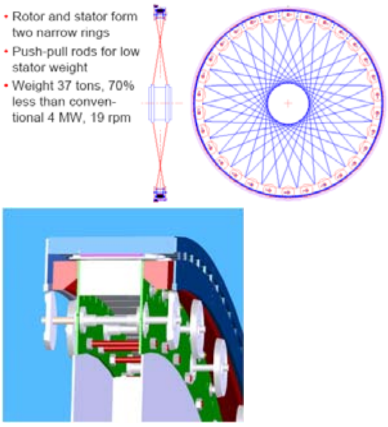


Fig. 11 New-Gen generator [98]

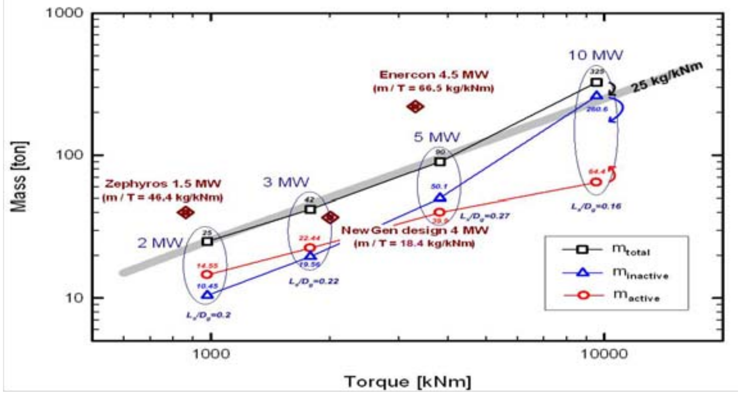


Fig. 12 Mass of different large direct-drive generators as a function of the torque

C. Mass comparison of large direct-drive generators

Different direct-drive generators as discussed above are compared based on the mass as a function of torque. Fig. 12 gives the mass of different generators as a function of the torque rating. The K_{rad} of 2, 3, and 5 MW generators [97] 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.

Total mass, active mass and inactive mass of a 10 MW PMSG DD with K_{rad}=0.16 [99][100] are about 325, 65 and 260 ton, respectively. When the K_{rad} of the generator is increased, it is expected that total mass will be decreased even though the active mass will be increased.

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. 12. 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 [98]. When scaling up, the total mass of conventional direct-drive construction is significantly increased and the mass of inactive material is to be more dominant.

V. EXPECTED SUITABLE CONCEPTS FOR DIRECT-DRIVE

The direct-drive generator system has disadvantages such as large size and heavy mass, which result in high cost, compared to the geared generator system as stated above. These disadvantages thus make the direct-drive system unattractive in the production, transportation, installation and maintenance. However, considering only the energy yield, the PMSG DD system is the best concept. If the cost of PMSG DD can be decreased as the same or even lower than DFIG 3G, then the PMSG DD can be defined as the most suitable generator system. How can we achieve the PMSG DD with the minimum cost? In order to decrease the cost, the amount of material must be reduced significantly. The construction of the PMSG DD must be also improved for easy production, transportation, installation and maintenance for the cost reduction.

The requirements and suggestions to achieve the most suitable direct-drive generator system are summarized for both the electromagnetic structure and the mechanical structure as the followings.

A. Electromagnetic structure

The electromagnetic structure can be defined as the structure to produce the electrical power. In order to reduce the amount of electromagnetic material, the plural module concept with short magnetic flux path can be a solution. The plural module concept results in the material reduction by decreasing both the slot pitch and slot height. According to the comparison results of different PM machines as discussed above, the RFPM and AFPM machines are limited to reduce the electromagnetic material, since the pole pitch is decreased and the leakage flux is consequently increased when decreasing the slot pitch to make the magnetic flux path short. However, the TFPM machine has potential to use the plural module concept for the material reduction, because the pole pitch is not decreased when decreasing the slot pitch.

In low speed electric machines, the copper loss is dominant than the iron core loss because of low electrical frequency. In order to reduce the copper loss, the concept with HT (High Temperature) superconducting coil which has simple winding construction can be an alternative.

B. Mechanical structure

The mechanical structure can be defined as the structure to maintain the air gap between the rotor and stator and to take the rotational force from the rotor blades. In order to reduce the amount of structural material of direct-drive generator, the following concepts can solutions or alternatives.

- Concept with the optimum K_{rad} in conventional structure
- Concept with lightweight structure
- Concept with additional magnetic bearing to maintain the air gap
- Concept which can control the air gap without additional magnetic bearing

C. Practical issues

- Modular structure for easy production, easy transportation and easy assembly in the field
- Each module can work individually
- Flexible and lightweight connection between the rotor blade hub and the generator rotor - instead of the heavy, stiff and accurate main shaft

VI. CONCLUSION

According to the comparison on direct-drive and geared generator concepts, the DFIG 3G is the lightweight and low cost concept. The PMSG DD concept has the highest energy yield compared to both the geared generator concept and the EESG DD concept. Different PM machines such as the RFPM, AFPM and TFPM machines have been discussed to address the advantages and the disadvantages of the machines. The RFPM machine has been mostly used for large direct-drive, because of its simple and stable structure, and higher power density. The AFPM and TFPM machines have not been used for large direct-drive, because of their disadvantages as discussed above. Conventional structure and lightweight structure of large direct-drive generator concepts over 1.5 MW up to 10 MW in literature and on the market have been discussed considering the mass comparison. The optimum torque to mass ratio of conventional PMSG DD concept has been expected as 25 kg/kNm. When scaling up, the total mass of conventional DD construction is significantly increased and the inactive mass (structural mass) is to be more dominant. The PMSG DD with the minimum cost has been defined as the most suitable generator concept. The expected suitable concepts of both the electromagnetic and mechanical structure have been suggested for cost reduction.

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