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Direct - Drive Wind Turbines

Zoran Ivanovski Msc.

1. Introduction

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

During the last two decades various wind turbine concepts have been developed and built to improve the power quality, to maximize the energy harnessed and to minimize the cost. Such turbine concepts can be classified with a view to the generator system rotational speed and power regulation. 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 permanent magnet machine and the electrically excited machine. The comparisons of different generator systems for wind turbines can be summarized as the following. The direct-drive generator system, especially direct-drive permanent magnet generator system, is more superior in terms of the energy yield, reliability, and maintenance problem. The geared generator system has the advantages in terms of the cost, size, and weight. 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. In 2004 world market share of the direct-drive generator system has been around 20%, which is a sum of the share of both direct-drive electrically excited machines as 15% and direct-drive permanent magnet machines as 5%. 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.

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.

2. Comparison od 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.

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.

- 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 permanent magnet synchronous generator with one stage gearbox has the highest ratio of the annual energy yield to cost.
- 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 doubly-fed induction generator system with three stage gearbox (DFIG 3G) seems lightweight and low cost solution.
- Different generator systems can be arranged in the order of high cost as (direct-drive electrically

excited synchronous generator) > (direct-drive permanent magnet synchronous generator) > (permanent magnet synchronous generator with one stage gearbox) > (doubly-fed induction generator system with three stage gearbox).

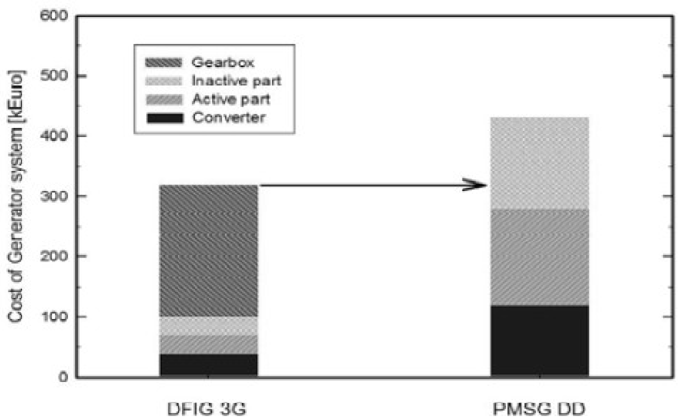

Fig. 1 Cost of 3 MW DFIG 3G and PMSG DD

Fig. 1 depicts the cost of both 3 MW doubly-fed induction generator system with three stage gearbox and direct-drive permanent magnet synchronous generator system including the gearbox, the inactive part, the active part and the converter. If it is possible to reduce the cost of direct-drive permanent magnet synchronous generator system by the cost of doubly-fed induction generator system with three stage gearbox or lower than it, then the direct-drive permanent magnet synchronous generator system can be the most suitable generator concept, because the energy yield of this system 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.

The necessity of new wind power system comes from recent studies which have shown that gearboxes are responsible for the greatest percentage of outage time*.

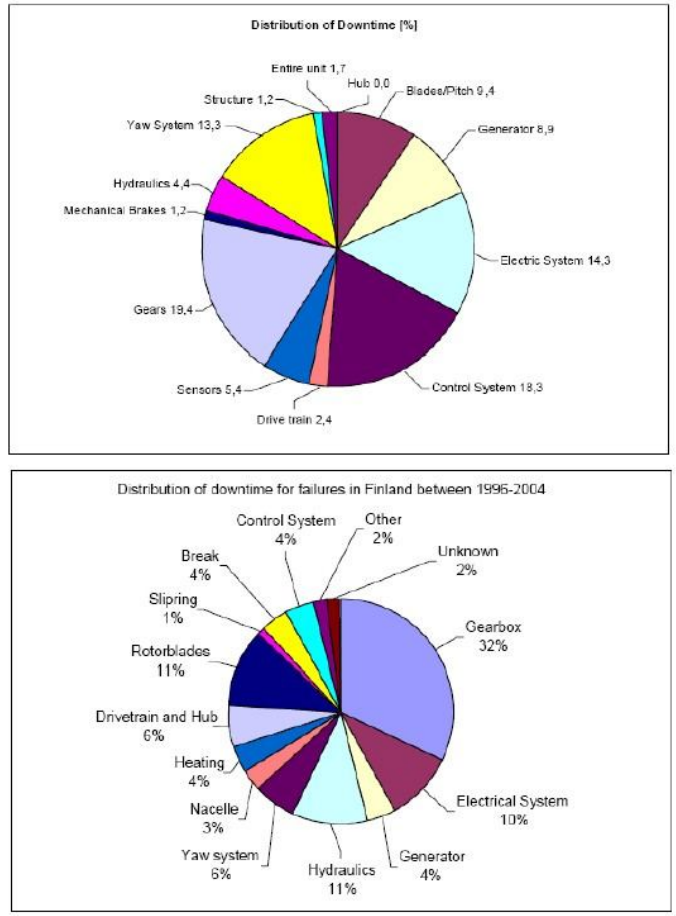

Fig. 2 Data for Sweden (above) and Finland (below, from J Ribrant's Master thesis)

Wind turbine manufacturers are turning away from the industry-standard gearboxes and generators in a bid to boost the reliability and reduce the cost of wind power.

In conventional wind turbines, the gearbox increases the speed of the wind-driven rotor several hundred fold, which radically reduces the size of the generator required. In the direct-drive generator for wind turbine, the rotor is directly connected to the rotor hub. Direct-drive generators operate at the same speed as the turbine's blades and must therefore be much bigger.

Even for a large direct-drive generator, with a diameter of several meters, the air-gap should not exceed a few millimeters, to avoid excessive magnetization requirements. This means that the mechanical construction has to be very rigid, in order to maintain the air-gap against the powerful force of attraction between the rotor and the stator. This stiffness requirement applies to the load path through the rotor, the shaft, the bearings and the stator. Thus the stiffness places a practical and economical limit on the diameter of a conventionally built generator.

* Johan Ribrant and Lina Margareta Bertling, "Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005" IEEE Transactions on Energy Conversion, Vol. 22, No. 1, March 2007

Because of that 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

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

Direct-drive generator has a larger diameter to produce higher torque because the torque is proportional to the air gap diameter squared. Thus higher torque demands large air gap diameter of the generator and high tangential force. This results in the increase of materials to maintain the air gap in proper deflection against the normal stress between the rotor and stator. Therefore the concept of direct-drive generator is operated in low speed and has the disadvantages such as high large diameter, heavy mass, torque rating and high cost compared to the concept of geared generator. That is why the concept of direct-drive generator is 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.

Direct-drive permanent magnet machines have several advantages compared to the electrically excited machines. They can be listed as:

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

Because of those advantages permanent magnet machines are considered as the promising electromagnetic structure for direct-drive generator.

3. Permanent Magnets

A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. Materials that can be magnetized are called ferromagnetic. These include iron, nickel, cobalt, some alloys of rare earth metals, and some naturally occurring minerals such as lodestone. Although ferromagnetic (and ferrimagnetic) materials are the only ones attracted to a magnet strongly enough to be commonly considered magnetic, all other substances respond weakly to a magnetic field, by one of several other types of magnetism.

An electromagnet is made from a coil of wire that acts as a magnet when an electric current passes through it but stops being a magnet when the current stops. Often, an electromagnet is wrapped around a core of ferromagnetic material like steel, which enhances the magnetic field produced by the coil.

The overall strength of a magnet is measured by its magnetic moment or, alternatively, the total magnetic flux it produces. The local strength of the magnetism in a material is measured by its magnetization.

3.1 Rare-earth magnets

Rare-earth magnets are strong permanent magnets made from alloys of rare earth elements. Developed in the 1970s and 80s, rare-earth magnets are the strongest type of permanent magnets made, substantially stronger than ferrite or alnico magnets. The magnetic field typically produced by rare-earth magnets can be in excess of 1.4 Teslas, whereas ferrite or ceramic magnets typically exhibit fields of 0.5 to 1 Tesla. There are two types: neodymium magnets and samarium-cobalt magnets. Rare earth magnets are extremely brittle and also vulnerable to corrosion, so they are usually plated or coated to protect them from breaking and chipping.

The term "rare earth" can be misleading as these metals are not particularly rare or precious; they are about as abundant as tin or lead.

The rare earth (lanthanide) elements are metals that are ferromagnetic, meaning that like iron they can be magnetized, but their Curie temperatures are below room temperature, so in pure form their magnetism only appears at low temperatures. However, they form compounds with the transition metals such as iron, nickel, and cobalt, and some of these have Curie temperatures well above room temperature. Rare earth magnets are made from these compounds.

The advantage of the rare earth compounds over other magnets is that their crystalline structures have very high magnetic anisotropy. This means that a crystal of the material is easy to magnetize in one particular direction, but resists being magnetized in any other direction.

Atoms of rare earth elements can retain high magnetic moments in the solid state. This is a consequence of incomplete filling of the f-shell, which can contain up to 7 unpaired electrons with aligned spins. Electrons in such orbitals are strongly localized and therefore easily retain their magnetic moments and function as paramagnetic centers. Magnetic moments in other orbitals are often lost due to strong overlap with the neighbors; for example, electrons participating in covalent bonds form pairs with zero net spin.

High magnetic moments at the atomic level in combination with a stable alignment (high anisotropy), results in high strength.

3.2 Types of Rare-earth magnet

Samarium-cobalt magnets (chemical formula: $SmCo_5$), the first family of rare earth magnets invented, are less used than neodymium magnets because of their higher cost and weaker magnetic field strength. However, samarium-cobalt has a higher Curie temperature, creating a niche for these magnets in applications where high field strength is needed at high operating temperatures. They are highly resistant to oxidation, but sintered samarium-cobalt magnets are brittle and prone to chipping and cracking and may fracture when subjected to thermal shock.

Neodymium magnets, invented in the 1980s, are the strongest and most affordable type of rare-earth magnet. Neodymium alloy ($Nd_2Fe_{14}B$) is made of neodymium, iron and boron. Neodymium magnets are typically used in most computer hard drives and a variety of audio speakers. They have the highest magnetic field strength, but are inferior to samarium-cobalt in resistance to oxidation and Curie temperature. Use of protective surface treatments such as gold, nickel, zinc and tin plating and epoxy resin coating can provide corrosion protection where required.

Originally, the high cost of these magnets limited their use to applications requiring compactness together with high field strength. Both raw materials and patent licenses were expensive. Beginning in the 1990s, NIB magnets have become steadily less expensive, and the low cost has inspired new uses such as magnetic building toys.

The current cheapest permanent magnets, allowing for field strengths, are flexible and ceramic magnets, but these are also among the weakest types. The ferrite magnets are mainly low-cost magnets since they are made from cheap raw materials- iron oxide and Ba- or Sr-carbonate. However, a new low cost magnet- Mn-Al alloy has been developed and is now dominating the low-cost magnets field. It has a higher saturation magnetization than the ferrite magnets. It also has more favorable temperature coefficients, although it can be thermally unstable. Neodymium-iron-boron (NIB) magnets are among the strongest. These cost more per kilogram than most other magnetic materials but, owing to their intense field, are smaller and cheaper in many applications.

China now controls 97 % of the supplies of rare-earth metals such as the neodymium vital for permanent magnets used in direct drive generators. It has recently introduced measures to restrict the resource to its own industry. Although neodymium is not that rare in the earth crust, the Chinese policy will create less supply and increasing prices. Hence it is vital to use the amounts available as economically as possible.

Since some years there is a Chinese policy to gain control of the mining of rare-earth metals, in most applications used in small although vital quantities. By means of domestic resources, buying of foreign mines and a low price policy this now has resulted in control of 97 % of the currently available extraction on earth. Recently China adopted restrictions to exports, thus effectively reserving the resources for its own industry.

The rare-earth metal neodymium amounts to almost a third weight-wise of the neodymium iron-boron alloy used in permanent magnets with outstanding properties. Applications creating need of large and increasing volumes of such magnets are motors for electrical cars and direct drive generators for wind turbines.

The 17 rare-earth metals generally appear together in ores found in many areas of the world, such as Inner Mongolia in China, South Africa, California, Estonia and Greenland. Due to China's low-price policy only mines in Estonia and those controlled by China are today in operation. It takes some years to open a new mine. The today closed Mountain Pass mine in California is expected to open already in 2011. Even if the currently restricted supply will alleviate in some year's time, extraction costs and increasing demand will increase the prices of high performance magnets. The much-increased use of neodymium magnets will probably raise prices also inside China. Thus it is important to use the material in an economical way.

In a direct drive generator the function of the otherwise used gearbox is substituted by more electrically and magnetically active material and by larger dimensions of the generator. The active material consists of the copper windings and the iron sheets of the stator, and of the permanent magnets of the rotor (in older designs electric magnetization is used). Since the amount of active material is inversely proportional to the diameter at the air gap between the rotor and the stator, it is possible to decrease the amount by increasing the diameter. On the other hand, in conventional designs the mechanical structure then gets very heavy. This is due to the long load paths between the central bearings and the air gap, in combination with a need to keep the structure very rigid in order to maintain the air gap at a few millimeters.

VG-Power in Vasteras, Sweden (ex ABB Generation), designed a 3 MW (NewGen - project) in cooperation with the wind turbine manufacturer Scanwind in Norway was supported by both the EU and by the Swedish Energy Administration.

The NewGen-concept implies that the generator rotor is supported by steel wheels around the periphery of the stator of the generator. This is a radical way to reduce the load paths and reduces the generator weight to at least half of that of today's typical direct drive PM generators. The reduction is even larger in comparison with generators with electrical excitation (Enercon). In a practical sense it means that railway technology is introduced in generator design, since such is based on steel wheels that roll on a rail of steel.

Chinese export restrictions and increased use will raise prices for high performance permanent magnets in the years coming. By building direct drive generators with large diameters the specific use may be cut to as little as a third.

4. The Transportation Problem

There are strong economic incentives to put wind turbines on tall towers, especially in areas where the height exponent is larger than the standard 0.14-0.20 values. For example, above forests the exponent often reaches 0.30-0.40. However, the most economic way to get a tall tower is to build a large turbine. Large turbines also have other benefits, such as less ground intrusion and less impact on the landscape. Unfortunately, one complication to this solution is that it is not possible to transport most turbines in the SMW class on ordinary roads, because the components are just too big.

The large nacelle, which follows with the use of a direct-drive generator, may seem to be a drawback, but instead it turns out to be an asset. The tradition is to end the aerodynamically active part of the turbine blade inwards at 10% of the blade radius, since the area inside only accounts geometrically for 1% of the turbine disc, which is considered reasonable to sacrifice. However the losses through this hole may be much larger - according to one source as much as 10%. By letting the active aerofoil extend all the way towards the spinner it is also possible to utilize this energy. Among the manufacturers of large wind turbines today, only Enercon has introduced this type of design, which is easier to accomplish if the inner part of the turbine blade is fixed.

5. 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 (TFPM)
- the radial (RFPM) and the axial flux machine (AFPM)
- the slotted and the slotless machine
- the surface mounted and the flux concentrating machine

Most of the RFPM machines have a conventional inner rotor design. 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.

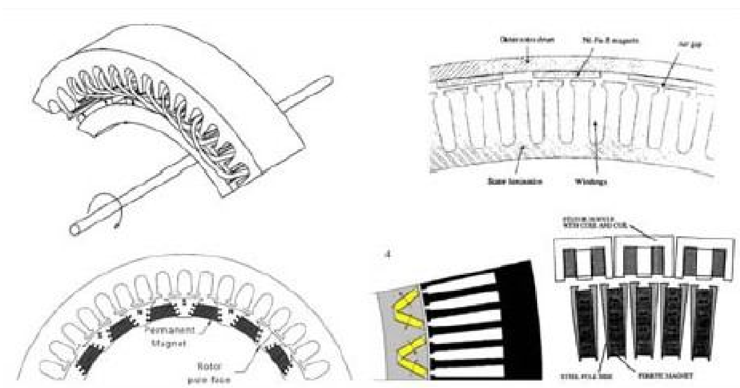

Fig. 3 Different RFPM machines

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.

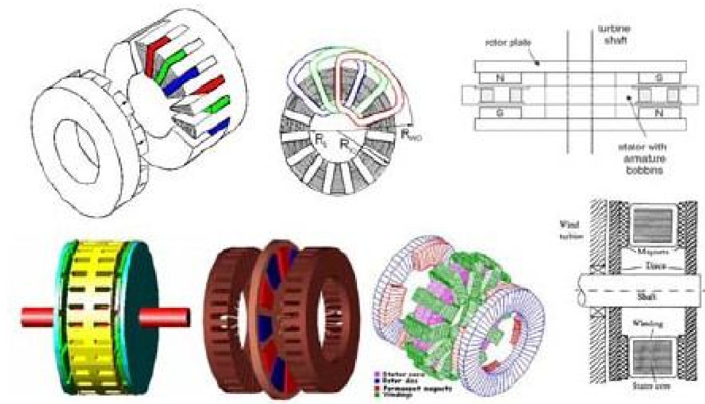

Fig. 4 Different AFPM machines

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.

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.

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.

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, KTFPM_Cost, is defined by:

$$K_{TFPM.Cost} = \frac{(Cost/Torque)_{RFPM}}{(Cost/Torque)_{TFPM}}$$

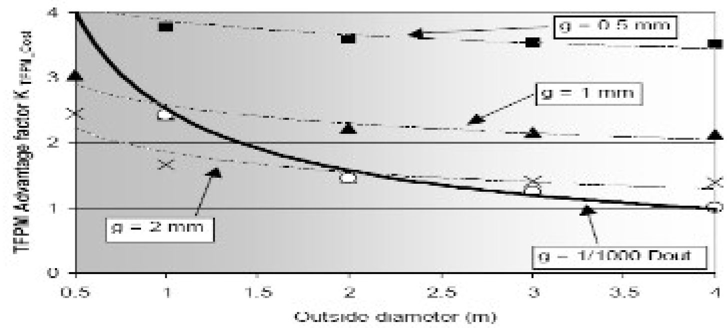

Fig. 5 Cost advantage factor of TFPM machine over RFPM machine

Table 1 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.)

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 1. 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.

6. Comparison of machines of different topologies

Analytical derivation of the torque density and mass of active material is possible for every topology. Such a mathematical model, based on the geometrical parameters of each topology, must also take into consideration the thermal characteristics of the machines.

The method used here is to building a large number of prototypes, and obtain sufficient information to draw a general conclusion.

Various machine topologies are compared with the well known characteristics of the Radial Flux Permanent Magnet (RFPM) machine built with surface magnets.

The criteria used for comparison are torque density (torque per volume), and cost/torque. These two criteria are identified as being critical for the integration of direct-drive generators in wind turbines.

6.1 Torque density

Wind turbine nacelle must be redesigned completely so direct-drive generators can be built with lowers diameters because today they have large diameters, leading to transportation and installation problems. This increases their length substantially, especially at powers above 1 MW. Power density becomes a very important criterion.

It is possible to increase the power density of a given machine, only by increasing its rotational speed. Therefore, it is not possible to compare machines having different rotational speeds, by using power density. Torque density is chosen, because it is independent of the choice for any rotational speed. This is true only up to a certain speed, which is largely above the typical speeds found in wind turbines.

Torque density is defined as:

$$T_d = \frac{T}{\left(\pi d_o^2 / 4\right) L_a} \qquad (3)$$

Where T is the machine nominal torque in kNm, T_d is the machine torque density in kNm/m3, d_o is the stator outer diameter (active outer diameter only), and L_a is the machine total axial length (active length only including stator end windings).

Torque density is presented as a function of diameter. All machines can be stacked in their axial length. For a given diameter, the torque density and cost/torque is the same for any number of machines stacked in their axial length.

6.2 Cost/Torque

Generator cost is critical for the acceptance of direct-drive on the market. For a given power, the topology chosen should minimize the cost of active material. However, cost/power cannot be used to compare machines of different rotational speeds. Cost/torque must be used for the same reason as explained above. Producing more torque requires extra magnet thickness, extra conducting material, and extra iron, which all lead to an increase in cost. However, it is difficult to obtain the cost for a machine from most authors. Estimation for cost was done from three assumptions:

A) Only active material is considered in costs. Manufacturing costs and costs for inactive material are not included.

B) Iron, copper and ferrite magnets have specific costs: 6 ECU / kg

C) Rare earth magnets have specific costs: 40 ECU / kg

6.3 Results Of Collected Data

“Torus” machine vs RFPM machine with surface magnets

Figure 6 shows that machines built with the “Torus” topology give torque densities twice higher than the torque densities of the RFPM machine with surface magnets.

However, the air gap winding requires that thick magnets be placed on the rotor. Figure 7 shows that machines designed with the “Torus” topology have a cost/torque for active material twice the cost/torque for the RFPM topology with surface magnets, for any given diameter.

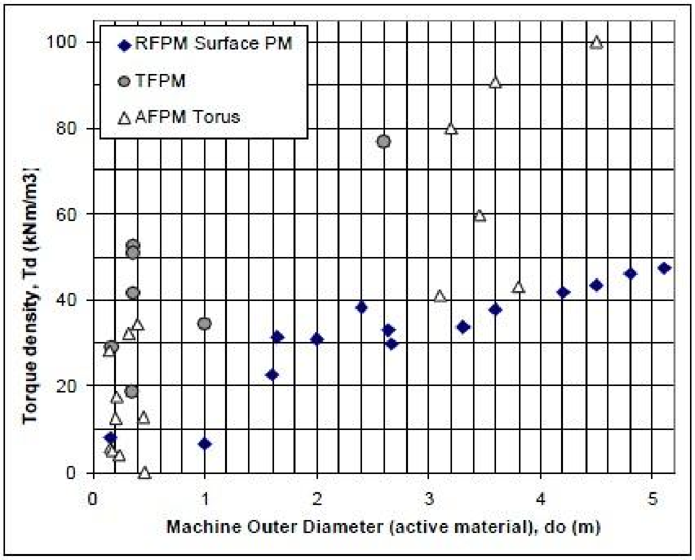

Fig. 6: Torque density for "Torus", TFPM and RFPM with surface magnets

4.2. Transverse Flux Permanent Magnet (TFPM) vs RFPM machine with surface magnets

Figure 6 shows that TFPM machines can be built with 2 to 3 times the torque density of RFPM machines with surface magnets.

Contrary to the "Torus" machine, where double torque density was reached at the expense of twice the cost per torque, the TFPM machine can reach lower cost per torque than the RFPM machine with surface magnets. Figure 7 shows it is possible to build TFPM machines with about half the cost/torque of the RFPM machine with surface magnets.

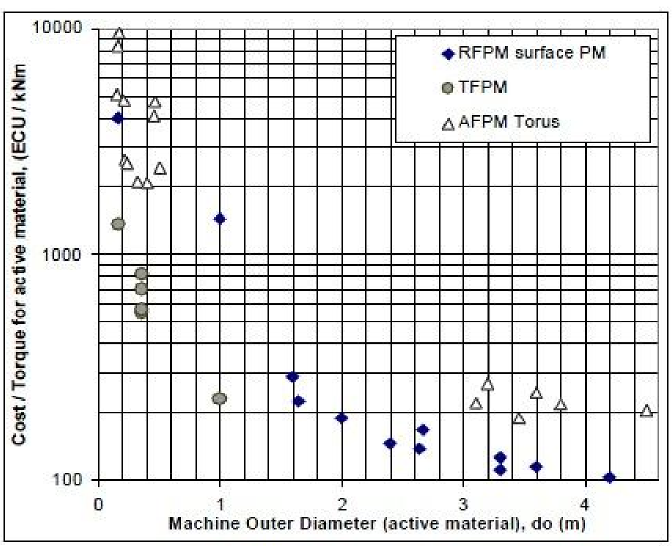

Fig. 7: Cost/torque for "Torus", TFPM and RFPM with surface magnets

Prototypes of RFPM machines built using ferrite magnets in flux concentration structure do not show superior characteristics over the RFPM machines built with surface magnets.

It is possible to build machines with twice the torque density and half the cost/torque of the RFPM machine with surface magnets, by using the TFPM structure.

7. 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 Krad 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

8. 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.

Industry's shift to direct-drive is a response to highly publicized gearbox failures but also direct-drive is adopted as a means of generating more energy at lower cost.

Permanent Magnet Direct-Drive turbines are the future of wind energy generation. It's a smart technology that can sense variable load demands and automatically adjust power output. By eliminating gearbox maintenance and most importantly, failure, all of our nearly 100 permanent magnet solutions provide increased up-time with 75% less upkeep and repair. The Permanent Magnet Generator and corresponding grid-tie inverter is able to produce a constant 60HZ AC power over a wider band of operation (from 20% to 125% of rated power) than traditional generators, which only have one or two power synchronization peaks (+/- 5%) that can produce the 60HZ AC required by the grid.

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