GENERATOR TOPOLOGIES FOR DIRECT-DRIVE WIND TURBINES, AN ADAPTED TECHNOLOGY FOR TURBINES RUNNING IN COLD CLIMATE.

M.R. Dubois, H. Polinder, J. A. Ferreira
Delft University of Technology, Lab. Of Electrical Power Processing
Mekelweg 4, 2628 CD, Delft, The Netherlands
m.dubois@its.tudelft.nl, h.polinder@its.tudelft.nl, j.a.ferreira@its.tudelft.nl

ABSTRACT: The direct-drive option actually suffers from high costs, which make most of the wind turbine manufacturers reluctant to implement direct-drive in their products. Several machine topologies, such as the radial-flux, axial-flux and transverse-flux permanent magnet generators are investigated. The investigation focuses on the ability of each machine topology to reduce the costs of Direct-Drive generators and converters. The Transverse-Flux Permanent Magnet machine appears as a good choice for cost reduction.

Keywords: direct-drive wind turbines, permanent magnet generators.

1. INTRODUCTION

Wind turbines require an electromechanical converter, in order to convert the rotary motion of the blades into electrical power. Several technologies have been developed to achieve this task, and the development continues. The latest developments include a permanent magnet direct-drive generator, connected to an IGBT-based electronic converter [1].

The direct-drive technology, using a permanent magnet generator is especially interesting for wind turbines that are erected in cold countries. The absence of a gearbox indeed excludes the need for lubricating oil, which in gearbox systems may contribute to the early failure of the gears, for such cold environments.

Even though the direct-drive technology offers several advantages over the geared technologies, it has not yet achieved competitiveness in terms of selling price.

This paper presents three technologies of electromechanical conversion. Each of them is discussed in terms of its advantages and drawbacks. The main drawback of the direct-drive technology is the higher selling price. Three topologies of permanent magnet generator topologies are investigated, and their respective manufacturing costs and active material costs are discussed.

2. PROS AND CONS OF EXISTING CONVERSION TECHNOLOGIES

Nowadays, several technologies may be used for the electromechanical conversion in wind turbines. The electromechanical converter may be generally referred to as a component or group of components, which converts the rotary motion created by the blades, into electrical power. In most cases, this electrical power must be compatible with the requirements of the public electricity company.

Three main technologies have been developed and used by the different wind turbine manufacturers. These technologies are:

- Gearbox and induction generator (IG) with double stator winding;
- Gearbox with doubly-fed induction generator (IG) with power converter;
- Direct-Drive generator with power converter.

These three systems are shown in fig. 1, 2 and 3.

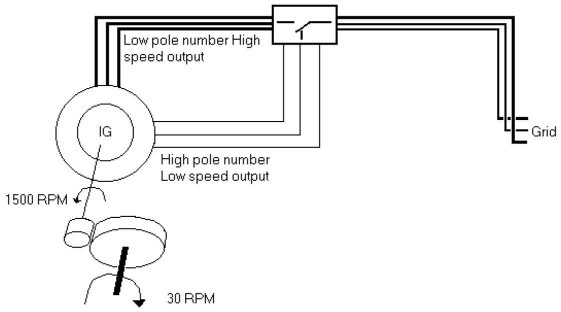

Figure 1: Gearbox and induction generator with double stator winding

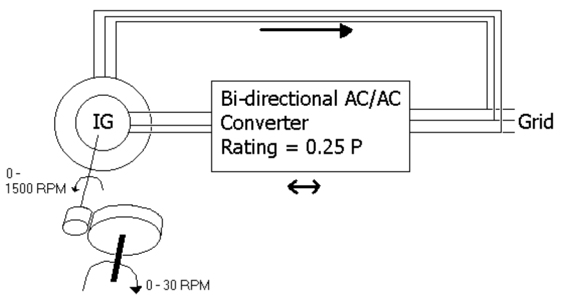

Figure 2: Gearbox with doubly-fed induction generator with power converter

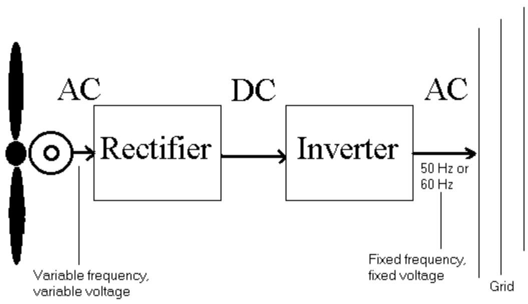

Figure 3: Direct-Drive generator with power converter

These three technologies all have their pros and cons. The perfect electromechanical converter should have the following qualities:

- High reliability;
- No maintenance;
- Highest energy extraction;
- High power efficiency;
- High Grid power quality;
- Low cost;
- Small size.

Unfortunately, none of the three technologies shown in fig. 1,2 and 3 meet these seven (7) qualities.

RELIABILITY

The gearbox has recently been a major cause of wind turbine failure [2]. Even though most of the problems have been addressed timely, the gearbox will remain a component considered as “fragile”.

Gearbox reliability must especially be examined very closely, in the case of operation in very cold areas. Gearboxes must be lubricated, and oil viscosity increases substantially with decreasing temperatures. For example, motor oil AMSOIL 10W-30 has a Pour Point of –48 ^{o}C, and a Borderline Pumping Temperature of – 40 ^{o}C [3]. Such conditions are likely to occur a few nights per year in cold countries. Unfortunately, no data could be located by the author, on the reliability of gearboxes operated in cold climates. But it is expected that cold oil temperatures will have an effect on the gearbox reliability. The premature wear-off of the gearbox cogs could be avoided by proper heating of the oil supply system.

In any case, the gearbox represents a component with direct mechanical contact, and long or mid-term erosion of the cogs material is inevitable.

The slip rings also represent an element with possible early failure. As shown in table 1, the doubly-fed induction generator (IG) and the wound-rotor direct-drive generator have slip rings (or brushes), which may reduce overall reliability. In [4], generator reliability has been investigated, and it appears that 25 % of all repairs on generators with brushes were due to brush failures.

As far as reliability is concerned, the direct-drive technology, using a permanent-magnet generator is the best choice. It eliminates the gearbox and any kind of brushes.

Table 1: Pros and Cons with respect to Reliability

RELIABILITY			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Average	- Squirrel cage IG	- Gearbox
Gearbox with Doubly-fed induction generator	Least		- Gearbox - Wound-Rotor IG - Brushes on IG
Direct-Drive Generator	Best	- No Gearbox - PM version has no brushes	- Wound rotor version has brushes

MAINTENANCE

Table 2 indicates how the three technologies rank with respect to maintenance. Again, the gearbox oil is a major concern, because it requires regular replacement, along with regular replacement of the oil filter.

In addition to the gearbox maintenance, the doubly-fed technology also requires regular inspection of the generator brushes. The same applies to the direct-drive generator with wound-rotor. In this respect, the permanent magnet direct-drive generator represents the best choice for low maintenance activities.

Table 2: Pros and Cons with respect to Maintenance

MAINTENANCE			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Average	- No brushes	- Gearbox needs oil & filter replacement
Gearbox with Doubly-fed induction generator	Least		- Gearbox needs oil & filter replacement - Brushes on IG
Direct-Drive Generator	Best	- No Gearbox - PM version has no brushes	- Wound rotor version has brushes

ENERGY EXTRACTION

Table 3 shows the three topologies, and how they perform with respect to the extraction of energy from the wind.

Table 3: Pros and Cons with respect to Energy Extraction

ENERGY EXTRACTION			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Least		- 2 Constant speeds
Gearbox with Doubly-fed induction generator	Average	- Partly variable-speed	
Direct-Drive Generator	Best	- Fully variable speed	

Fig. 4 illustrates the power extraction of a wind turbine for different wind speeds. It is displayed in fig. 4 for a fully variable speed system, and for a technology using 2 constant speeds. Fig. 4 shows that a fully variable-sped system extracts more energy than the constant-speed system. The use of 2 speeds allows to keep a good level of energy extraction, but it is still below the total energy yielded by the fully variable-speed system.

The doubly-fed induction generator allows variable-speed operation. The degree of speed variation depends upon the converter power rating. In most of the cases, the converter power rating is limited to 25% of the nominal turbine rating, in order to keep the cost and the losses as low as possible. Very good energy extraction can be reached with such converter rating, especially if the converter is made bi-directional.

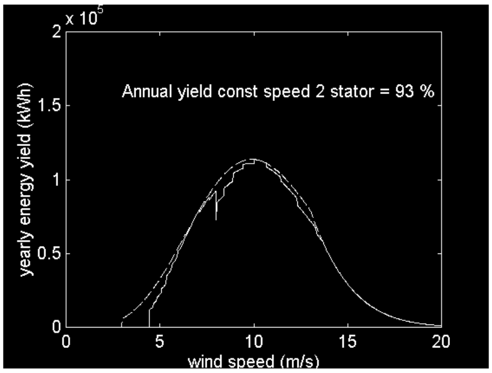

Figure 4: Yearly energy extraction from the wind as a function of wind speed. Dotted line = fully variable speed system, Solid line = constant speed system with 2 constant speeds.

EFFICIENCY

Table 4 shows the three topologies, and how they perform with respect to electrical efficiency.

Table 4: Pros and Cons with respect to Electrical Efficiency

EFFICIENCY			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Average	- No converter	- Gearbox losses
Gearbox with Doubly-fed induction generator	Average	- Low losses in converter	- Gearbox losses
Direct-Drive Generator	Average	- No Gearbox	- Power Converter losses

As pointed out in [5], the electrical efficiency of the electromechanical conversion technology depends on the average wind speeds. At high average wind speeds, the gearbox technologies will show better efficiency, while at lower average wind speeds, the direct-drive technology will have better efficiency. This is mainly caused by the gearbox, which shows constant losses, even at low speeds. For those reasons, the same rank is given to the three technologies (see table 4).

It must be pointed out that efficiency can be substantially increased in the direct-drive technology, if permanent magnets are used. In [6], a 750 kW direct-drive wind turbine is designed, where the rotor electromagnets consume 15 kW of power at nominal wind speed. This represents 2 % of the nominal turbine power.

GRID POWER QUALITY

Table 5 shows the three topologies, and how they perform with respect to power quality. Power quality is described in [7] and is required by the electricity network, in order to have a continuous and purely sinusoidal voltage waveform, with constant amplitude and frequency.

Table 5: Pros and Cons with respect to Grid Power Quality

GRID POWER QUALITY			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Least		- “Shadow effect” causes strong current fluctuations
Gearbox with Doubly-fed induction generator	Best	- Variable speed lowers current fluctuations	- Converter harmonics must be filtered out
Direct-Drive Generator	Best	- Variable speed lowers current fluctuations	- Converter harmonics must be filtered out

In wind turbines, three main effects are to be considered, i.e.:

- Current fluctuations caused by the blades passing the tower (so-called “shadow effect”);
- Various current amplitudes caused by variable wind speeds;
- Voltage harmonics caused by power electronics.

The last type of disturbance can be overcome, if sufficient filtering is provided at the output of the converter. However, the first two types of disturbance have time constants much too large to be filtered by passive electrical components. Strong grid connection is required to reduce the effects of these disturbances on the network.

Besides the solution of strong grid connection, the first type of distrubance can be largely reduced if a variable-speed wind turbine is used. Fig. 5 illustrates the power output of a constant-speed wind turbine (data taken from [7]).

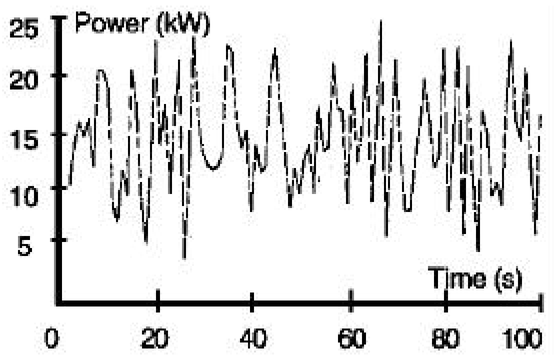

Figure 5: Power fluctuation of a constant-speed wind turbine

Fig. 6 illustrates the power output of a variable-speed wind turbine subjected to the same wind conditions. The difference is explained by the ability of the variable-speed system to reduce or increase speed in case of torque variation. The big inertia of the turbine rotor is used to store mechanical energy, and therefore acts as a natural filter.

Since both the direct-drive technology and the doubly-fed induction generator operate in variable-speed mode, they offer a substantial advantage compared to the constant-speed system.

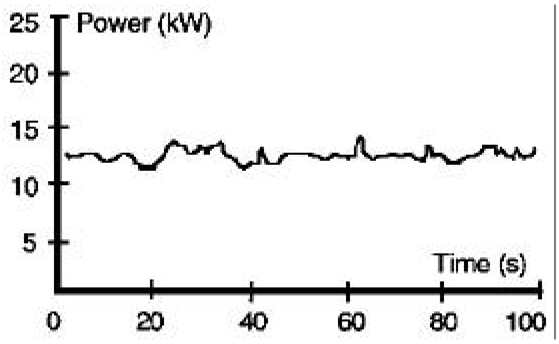

Figure 6: Power fluctuation of a variable-speed wind turbine

COST

Table 6 shows the cost performance of the three technologies.

Table 6: Pros and Cons with respect to Cost

COST			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Best	- High-speed IG - No Converter	- Gearbox
Gearbox with Doubly-fed induction generator	Average	- High-speed IG - Converter rated only 10% to 25 %	- Gearbox
Direct-Drive Generator	Least	- No gearbox	-Low-speed generator -Converter rated 100%

The difference between the direct-drive technology and the doubly-fed induction generator is shown in more details in fig. 7. The data of fig. 7 on the doubly-fed system is the result of the author's personal enquiry. The cost of direct-drive technology is taken from [8].

As indicated in fig. 7, the direct-drive generator is much more expensive than the generator of the geared technology. This is due to the very high torque rating demanded for a direct-drive generator.

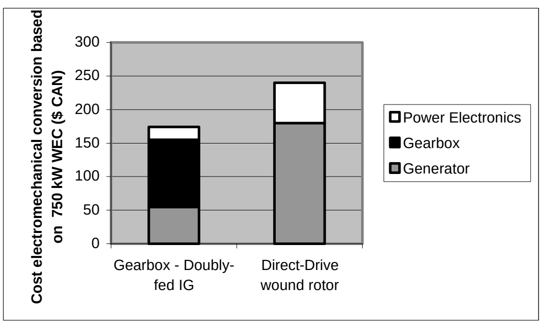

Figure 7: Comparison of costs between direct-drive conversion (with wound-rotor) and doubly-fed IG with gearbox

SIZE

Table 7 indicates the performance of the three technologies, with respect to size.

Table 7: Pros and Cons with respect to Size

SIZE			
TECHNOLOGY	RANK	PROS	CONS
Gearbox with 2 – Stator induction generator	Best	- Height approx. 1 m - Light	
Gearbox with Doubly-fed induction generator	Average	- Height approx. 1 m - Light	- Converter requires additional space
Direct-Drive Generator	Least		- Height between 3.2m to 7.6m - Heavy

3. INVESTIGATION OF DIRECT-DRIVE TOPOLOGIES

Among the conversion technologies presented in the last section, it appears that the direct-drive technology offers good performance with respect to reliability, maintenance, energy extraction and grid power quality. This is especially true for a permanent magnet generator. However, direct-drive suffers from a high capital cost and a large diameter. It must be mentioned that the data presented in fig. 7 was for a radial-flux direct-drive generator using electromagnets in the rotor. The use of permanent magnets instead of electromagnets reduces the generator mass substantially. However, permanent magnets are much more expensive than electromagnets, on a per kg basis. As pointed out in [9], permanent magnets will not substantially decrease the total cost of active material compared to a wound rotor (in the case of a radial-flux direct-drive generator).

In order to obtain the full benefits of the direct-drive technology, we must investigate the following aspects:

- permanent magnets must be used;
- cost must be reduced;
- diameter must be reduced.

In this section, we will investigate three types of permanent magnet generator topologies. The investigation will be focused on ways of reducing the costs of the direct-drive generator.

The three topologies investigated are:

- Axial-Flux Permanent Magnet (AFPM) generator with slots;
- Radial-Flux Permanent Magnet (RFPM) generator;
- Transverse-Flux Permanent Magnet (TFPM) generator.

They are shown in fig. 8, 9 and 10.

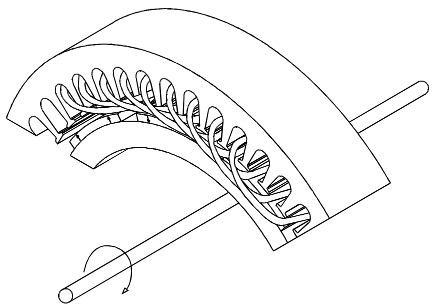

Figure 8: RFPM (Radial-Flux Permanent Magnet) machine

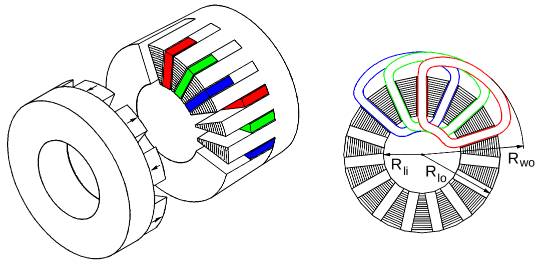

Figure 9: AFPM (Axial-Flux Permanent Magnet) machine with slots

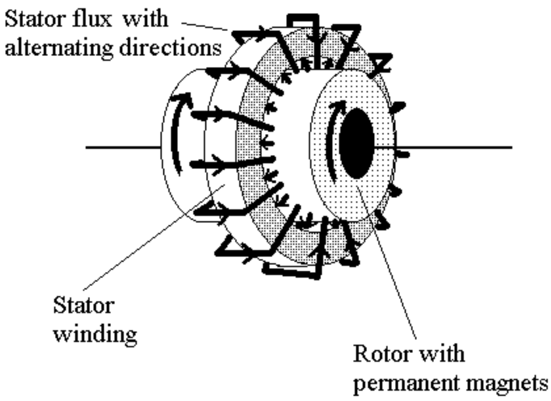

Figure 10: TFPM (Transverse-Flux Permanent Magnet) machine (general principle).

These three machines and their principles are well described in literature [10], [11], [12]. It must be noted that fig. 10 only shows the general principle of the TFPM machine. Many variants exist, which cannot be all described in the paper. As reported in [13], the best TFPM machines use permanent magnets in flux concentration mode. We will consider this type of machine for our analysis.

4. COST REDUCTION IN DIRECT-DRIVE GENERATORS

The production cost of a generator is mainly composed of the following items:

- Manufacturing costs (especially winding);
- Cost of magnetically active material;
- Cost of mechanical support structure.

In the remaining of the paper, the focus is made on the active material, and the manufacturing of windings.

4.1 Production of windings in machines

The production of windings is a very lengthy task in the construction of electrical machines. The production costs could probably be substantially reduced if an easier winding method was used.

In the case of the RFPM machine and AFPM machine with slots, each copper coil must be:

- preformed;
- protected;
- insulated;
- inserted into slots;
- connected to the next coil.

In most of the cases, these 5 production steps require many hand-made operations.

In the case of the TFPM machine, the winding has the following characteristics:

- Ring winding;
- Single coil;
- Fully automated winding is possible.

The TFPM principle has therefore an interesting potential for a substantial decrease in production cost, due to the simplicity of its winding.

4.2 Cost of active material in PM machines

In [14] [15], the subject of active material cost is analyzed for the three machine configurations considered here. Based on extensive optimization of these three machine topologies, it appears that the RFPM machine leads to lower active material costs than the AFPM machine with slots.

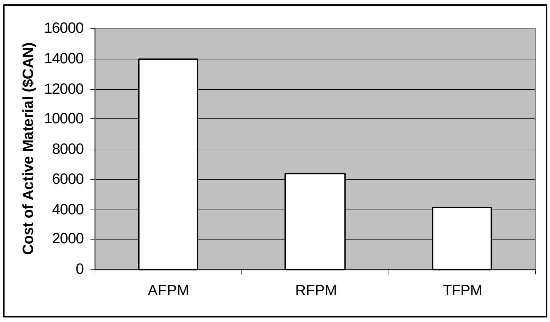

Figure 11: Cost of active material for a RFPM, AFPM and TFPM machine of power 100 kW. Diameter = 1 m, rotational speed = 46 rpm, air gap = 1 mm.

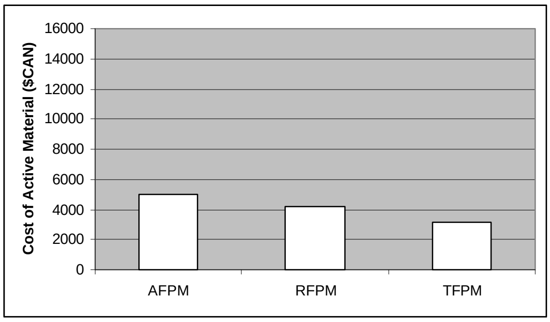

Figure 12: Cost of active material for a RFPM, AFPM and TFPM machine of power 100 kW. Diameter = 2 m, rotational speed = 46 rpm, air gap = 2 mm.

The main advantage of the AFPM machine is to provide a very compact machine. As shown in [14], the AFPM machine with slots is 2 to 5 times shorter than the RFPM machine, provided that they both use the same diameter.

The TFPM machine represents a significant improvement in the amount of active material mass and cost, compared to the RFPM and AFPM machines. This is illustrated in fig. 11 for the example of a 100 kW direct-drive generator designed with the three technologies. Fig. 11 uses a diameter of 1 meter, where fig. 12 uses a diameter of 2 meters. In both figures, the costs are calculated using specific costs of 55 $CAN/kg for permanent magnets, 4 $CAN/kg for copper and 3 $CAN/kg for laminated steel.

As the diameter increases, the cost of active material is substantially reduced. This is shown in fig. 12. Also, the differences between the three topologies are decreased. It must be noted that the most critical parameter for the TFPM machine is the air gap thickness. If the air gap thickness could be maintained at 1 mm, even for a 2-meter diameter machine, the difference between the RFPM and the TFPM would be comparable to the one observed in fig. 11.

5. DIAMETERS OF DIRECT-DRIVE GENERATORS

In section 2, we have emphasized the fact that size is one of the weak points of the direct-drive technology. The different direct-drive generators on the market, or being currently developed have rather large diameters (see table 8).

Table 8: Survey of direct-drive generators on the market.

Manufacturer	Power (kW)	Diameter (m)
Tohoku	300	3.2
Genesys	600	More than 3
Jeumont	750	3.6
Lagerwey	750	5
Enercon	1500	5
ABB (Windformer)	3000	7.6

All direct-drive generators have diameters above 3 meters. The main problem related to the large diameters is mainly related to transportation, where wind turbines sites must often be accessed via narrow roads.

In reality generator diameter and generator active material costs are related. The larger the diameter, the lower the cost of active material. This is why it is not expected that generator diameters will decrease substantially.

It must be mentioned that the TFPM topology is not suited for very large diameters, because large diameters call for large air gaps. It appears that TFPM machines do not perform very well for air gaps larger than 2 mm. If TFPM machines emerge as a future direct-drive technology, they will certainly have diameters well below 3 meters.

6. CONCLUSION

Pros and cons of three (3) technologies of electromechanical conversion in wind turbines have been investigated. The direct-drive technology provides many advantages, namely high reliability, low maintenance, high energy extraction and high grid power quality. The direct-drive technology is probably the most suitable to the implementation of wind turbines in cold climates, because no lubrication is needed. Among the direct-drive topologies, the use of permanent magnet generators is especially attractive, due to the higher efficiency and the absence of slip rings.

In order to obtain the full advantages of the direct-drive technology, the cost of the direct-drive generator needs to be decreased. At this moment, the direct-drive technology is still at least 30% more expensive than the doubly-fed induction generator with gearbox.

Three (3) topologies of permanent magnet direct-drive generators have been studied. The Transverse-Flux Permanent magnet topology is promising for the reduction of costs. The TFPM machine has the advantage of easy winding manufacturing, and lower material costs. In order to obtain the benefits of the TFPM machine, the air gap thickness must remain below 2 mm.

7. REFERENCES

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