Permanent Magnet Generator Design Solutions for Wind Turbines

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Topics: Wind Power

1. Introduction

Converteam is a worldwide specialist in power conversion and in offshore solutions. Wind energy needs power converters for energy conversion and transport. Converteam has realized wind turbine generators and their converters for several years. The company has decided to propose only direct drive solutions for future orders and is developing new concepts of permanent magnet (PM) generators in collaboration with the Energy department of FEMTO-ST Institute.

In order to be competitive in the market and to respect the environmental constraints, the international standards have to be respected and economic solutions are researched. Thus, the aim is to obtain a machine which has a low cost and a high efficiency. The full power converter, which is necessary to connect the machine to the grid, needs to be optimized too.

Firstly, a description of the common supply chains met in high power wind turbine applications is given. Secondly, advantages and drawbacks of the direct drive permanent magnet generators will be detailed in comparison with the other topologies. Then, the study will focus on the permanent magnet generators and improvements to increase their interest. A comparison between various permanent magnet generator designs focusing on active parts weight and efficiency is proposed.

2. High Power Wind Turbine Conversion Chains

In order to optimise energy production, the use of variable speed generators is required for large wind turbine, i.e. power production above 1 MW.

Four main topologies are met in the market for high power wind turbine systems.

The nominal generator speed is different according to the considered topologies.

2. 1. Doubly Fed Induction Generator (DFIG)

The most popular system is induction machine (see Fig.1). There are two reasons to explain this interest, firstly induction machine cost is lower than synchronous machine and secondly power electronics converter doesn't need to convert all the power but only around thirty per cent. These converters are used to modify the rotor properties and allow variable speed behaviour around the rated point.

To keep a good efficiency, an induction machine will be used at high speed (>1500 rpm).

To obtain this speed, the only way is to use a gearbox, the turbine speed is around 15 rpm for high power wind application, so that some gearbox's stage are necessary. Nevertheless with a three stages gearbox the power is limited at 5 MW.

The main suppliers are: Vestas, Gamesa, GE Wind, Nordex, Alstom wind …

2. 2. Synchronous Generator with Wound Rotor (SGWR)

With the experience in high power machines (oil, hydro or nuclear) where synchronous generator with wound rotor (or direct current machine in old installations) is used, it is not surprising to find this type of technology in wind turbine generator. This topology is met for a direct drive application (without gearbox). In this case, the working speed is the same that the turbine speed; thus at a given power the torque is more important than one obtained with the DFIG. Machines will have a big diameter and a short length; due to their form these machines may be called torque or ring generator.

This topology leads to expensive active parts and lots of auxiliaries are necessary to create the rotate field as we can see Fig. 2.

Two topologies of excitation exist: firstly with a brush to commutator contact, secondly with a rotating transformer and a diode bridge. This second solution is preferred because there are none mechanical contacts between rotated and fixed parts. To supply the rotating transformer, converters are necessary but their power is lower than the generator one.

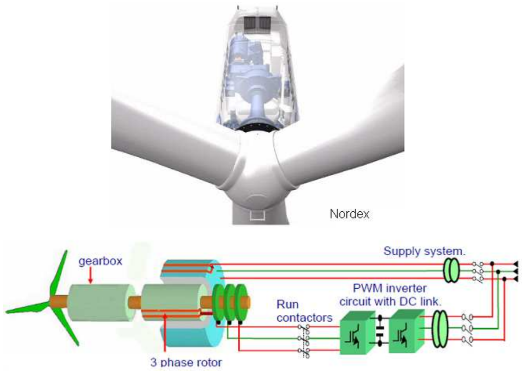


Figure 1: Nacelle scheme of a DFIG and description of the power chain.

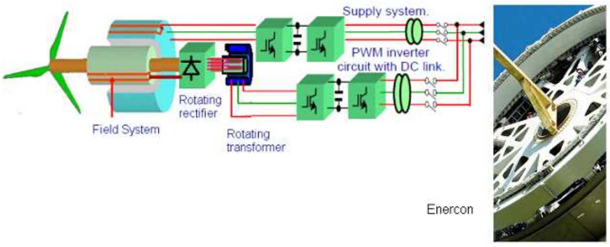


Figure 2: Power chain of the DDWR and picture of a machine.

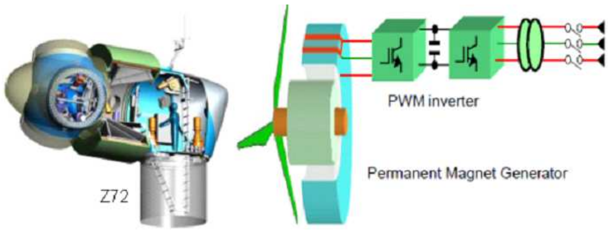


Figure 3: Nacelle scheme of DDPMG and description of it power conversion chain.

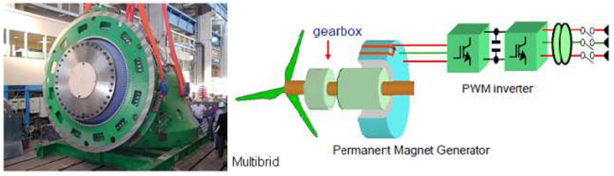


Figure 4: Picture of the multibrid generator and scheme of the power chain.

To work with variable speed, a full power converter is necessary to convert the electrical power provided by the stator of the machine. With such a power chain, the machine is able to produce energy for almost all wind speeds.

The main supplier is Enercon.

2. 3. Permanent Magnet Generator

In order to increase power density and to simplify field creation of the direct drive generator, a solution is to use permanent magnets instead of wound rotor. In this case the power chain is the same, as shown in Fig. 3.

The main suppliers are GE and Siemens.

2. 4. Hybrid Concept

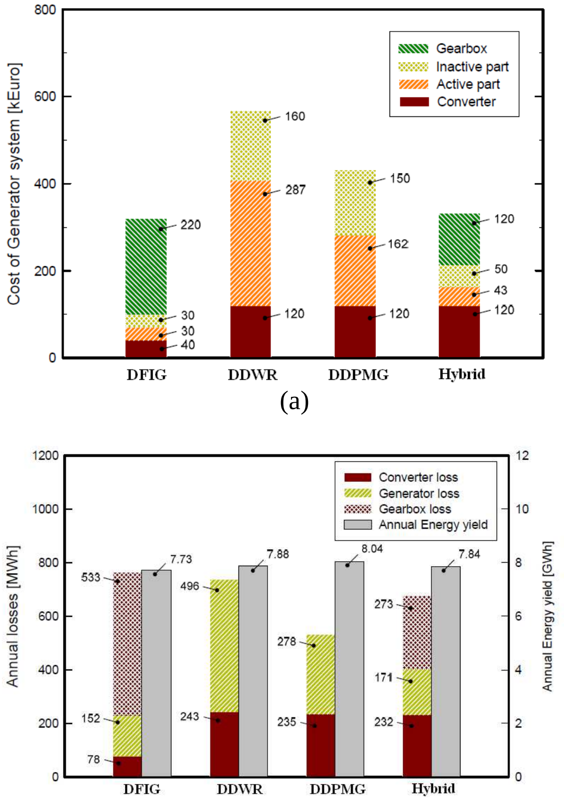
A hybrid concept, with permanent magnet machine and a gearbox having a low transformation ratio, leads to rotational speeds between 100 and 300 rpm and enables the reduction of the generator’s size.

The aim is to have a smaller generator than the direct drive options and a better efficiency than DFIG. The supply converter is designed for the full power (see Fig. 4).

The main supplier is Multibrid, electrical active parts are realized by Converteam.

3. Direct Drive Permanent Magnet Generator (DDPMG)

Some studies can be found in the literature concerning comparison between the different wind turbine topologies. For the four previous cases we can recall the works of H. Polinder. In [1], a comparison of cost and losses are given. The results are summarized in Fig. 5.



(a)

(b)

Figure 5: Comparison of wind turbine topologies in terms of cost (a) and energy (b)

3. 1. Magnets rather than Wound Rotor

The fact that no supply is necessary to create the rotate field is the main advantage of the permanent magnets. Most of the time, permanent magnets synchronous machines are called “brushless” to highlight this aspect.

With magnets the rotor weight and rotor losses are reduced.

In industry, most of permanent magnet machines have their magnets mounted at the surface of the rotor because there is an experience background, a mounting process which is under control and seems to be the easiest solution.

But, when magnets are mounted at the surface of the rotor, defluxing workings are more difficult to obtain because poles are not salient. These modes can be interesting when over speeds or over loads happen in wind turbine applications.

3. 2. Direct Drive rather than Gearbox

Even if gearbox is not the main cause of downtime, risk of failures is still important [2]. The strongest constraint is the necessary time for the replacement of the gearbox when it is out of order. And this time may be long, especially in offshore applications.

Losses for a permanent magnet generator are less important than for an induction one and machine is able to work on a larger wind speed range. Moreover, choosing permanent magnet generator, instead of DFIG, enables the reduction of the entire nacelle weight [3], limits the number of elements in the conversion chain and so reduces the risk of failures.

3. 3. Consequence

Focusing on the technology, solution with permanent magnets seems to be the best, because it leads to lower losses, lower total weight, lower risk of failures, more produced energy.

Therefore, direct drive permanent magnet generator is the topology which has been selected by the company to be suggested to the customers.

The main permanent magnets drawback is their cost, which is linked to the increase of the demand of rare earth magnets. Some risks must be taken in consideration too: demagnetisation, short circuit torque, bonding with other magnetic parts during the manufacturing, the use of non-magnetic tools.

4. Improvements

In spite of its technology benefits, we see that the cost of permanent magnet direct drive active parts is high. Thus, even if rules are not the same for active parts than for global turbine (i.e. to minimize the active parts cost doesn't necessary lead to minimize the wind turbine cost), we are going to propose some ways to optimise the active parts weight of the generator.

For the active parts design of a wind turbine generator, the main points which have to be taken in consideration are: power density optimization and losses reduction. These two aspects do not match because the weight increases when the losses decrease, see Fig. 6, then a compromise must be found.

Some solutions can increase the power density of the surface mounted permanent magnet machine and/or limit the losses:

- To reduce the copper with a concentrated winding and a fractional number of slot per pole and per phase [4];
- To modify the magnet's form and adapt the currents waveforms [5];
- To have an axial flux machine topologies instead of a radial[6];
- To use an outer rotor topology instead of an inner rotor one, if the diameter is constrained;
- To increase the phases number.

As some cases are ever been described in the literature we do not focus on these solutions. In the rest of the paper only influence of the phase number and the location of the rotor compare to the stator are presented. Nevertheless, in order to clarify the understanding it is necessary to describe the choice of the air gap flux density and currents waveforms.

4.1. Air gap flux density

In permanent magnet machines, two shapes can be considered for the air gap flux density waveform (Fig. 7) and the back electromotive forces (back-EMF) have similar shapes. For each of these cases, in order to obtain a constant torque, the current waveform in the slots will be different: the current will be sinusoidal when the flux density is sinusoidal whereas the current will be trapezoidal (nearly rectangular) when the flux density is trapezoidal.

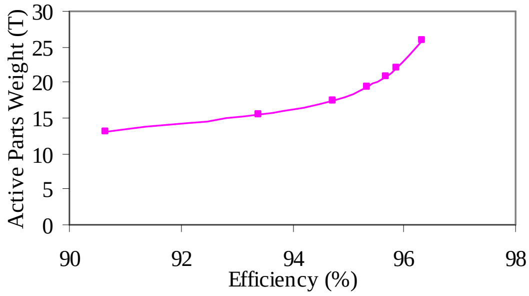
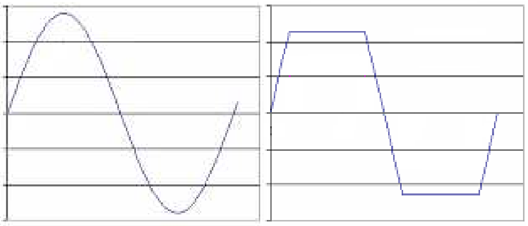


Figure 6: Evolution of the weight in function of efficiency.



(a) (b)

Figure 7: Different air gap flux density: (a) Sinusoidal and (b) Trapezoidal.

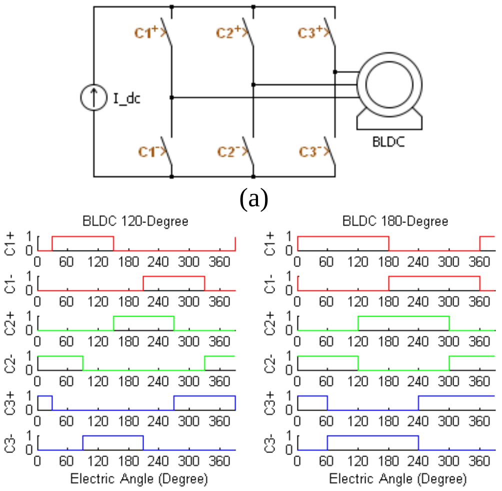
As the waveforms are similar to the classical alternative machines, when the waves are sinusoidal, the machine is called BLAC (brushless AC).

In the others case, as the principle is closed to the brushed DC machine, these machines are called BLDC (brushless DC).

Two control strategies can be used with rectangular currents to keep the torque constant [7]. In the first case, each phase is open circuited during a part of the period. With 3 phases, a phase must be supplied with a constant current during 120 electrical degrees, the switches command signals are adapted, as shown in Fig. 8.

In the second case, the phases are always connected so that they are fed with a constant current during 180 degrees as shown in Fig.8.

In order to have an air gap flux density as close as a square wave we need to have magnet width close to the pole pitch and a number of slots per pole and per phase equals to one. In this case, the air-gap flux density shape is given Fig. 9.



(a)

(b) (c)

Figure 8: Machine converter (a) scheme, (b) 120-degree control and (c) 180-degree control.

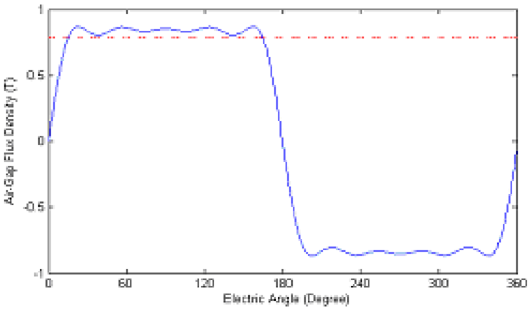


Figure 9: Air gap flux density when the magnet width is equal to pole shoe and its rms value (dotted lines).

To obtain a constant torque, the EMF waveforms should be constant during 180 electrical degrees, which is only a theoretical possibility. Indeed, due to flux leakages between two magnets, the flux density (and as a consequence the back EMFs) cannot be constant under the pole transition. Because of this, performances, in case of a 180-Degree, are not so interesting and it should be corrected.

4.2. Influence of Phase Number

To make a comparison between various machines for equivalent losses, the back-EMF peak values must be the same to have the same iron losses, and the current RMS values must be the same to have same copper losses. A comparison between the cases previously described is presented in Table 1. Real gain is obtained when the difference between back-EMF peak and RMS value is taken into account, this the correction mentioned in the previous section.

A comparison at equivalent losses can be interpreted as a comparison at equivalent active parts weight. Indeed, iron and copper volume are preserved and variations of magnet volume don't have a big influence on the total weight. In detail, to keep the same EMF peak value, in all cases, some geometric parameters can be preserved, as magnet thickness, air gap length and rotor diameter but the magnet width can vary. For the currents, with the same RMS value, keep the current density leads to a constant copper volume.

As a conclusion, BLDC machines have a better power density than the BLAC.

A drawback of BLDC motor is the difficulty to obtain a constant torque. With a 120-degrees converter it is necessary that the currents are perfectly rectangular and in phase with the back EMFs which must be constant on 120 electric degrees. With 180-degrees this becomes nearly unfeasible, as explained below.

The back EMFs are calculated by using finite elements simulations (FLUX2D) and they are plotted in Fig 10 for the example of a three-phased machine.. Torque is determined considering the currents as perfectly rectangular on 180 electric degrees; the waveforms are given in Fig. 11 for 3 phases.

We study now what it happens when the number of phases (i.e. the number of slots per pole in this case) increases. The winding scheme will have to be adapted according to the phase number (see Fig.12). For a phase number of 7 the back-EMF is given in Fig. 13 and the torque in Fig. 14.

Table 1: Comparison of the equations

Case	BLAC	BLDC 120-degrees	BLDC 180-degrees
With q phases (q being odd)			
Current Peak/RMS	$\sqrt{2}$	$\sqrt{\frac{q}{q-1}}$	1
EMF Peak/RMS	$\sqrt{2}$	$\sqrt{\frac{3q}{3q-2}}$	1
Power	$\frac{q}{\sqrt{2}}E_P I_{RMS}$	$\sqrt{q(q-1)}E_P I_{RMS}$	$qE_P I_{RMS}$
With 3 phases			
Power	$\frac{3}{\sqrt{2}}E_P I_{RMS}$	$\sqrt{6}E_P I_{RMS}$	$3E_P I_{RMS}$
Theoretical gain	1	1.15	1.41
Real gain	1	1.15	1.32

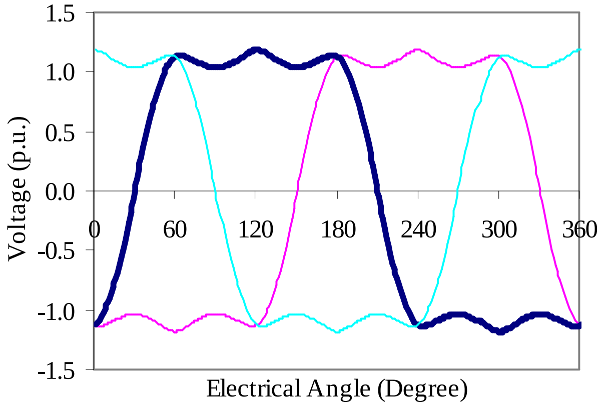


Figure 10: Back-EMFs in the 3 phases machine

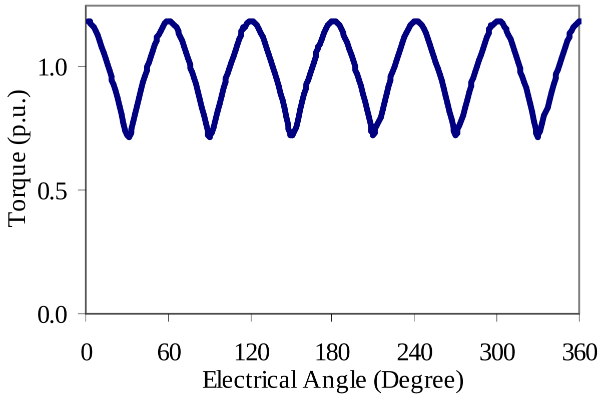
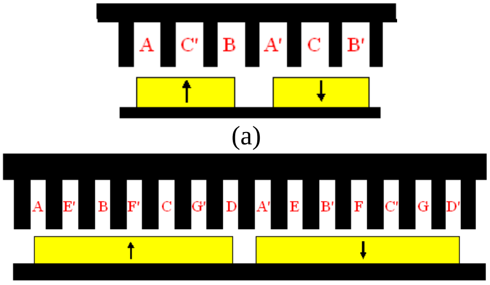


Figure 11: Torque with 3 phases



(a)

(b)

Figure 12: Winding connection under a pole pairs when the number of slot by pole and by phase is 1 for 3 phases (a) and for 7 phases (b)

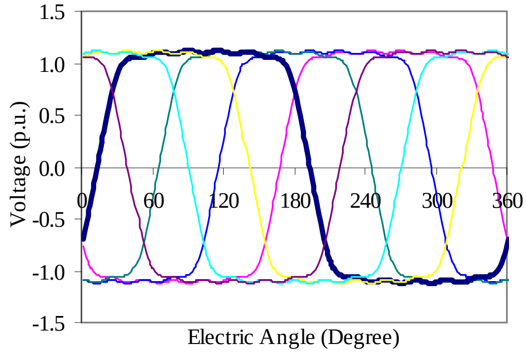


Figure 13: Back-EMFs in the 7 phases machine

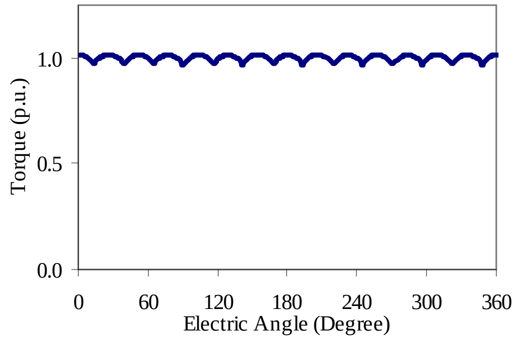


Figure 14: Torque with 7 phases

It appears that the modification of the phase number has an influence on the torque ripple which does not seem to be negligible. On the other hand, when the number of phases rises, its influence becomes small as shown in Fig. 15.

The torque ripple is characterized using (1).

$$\Delta\Gamma = \frac{\Gamma_{MAX} - \Gamma_{MIN}}{\Gamma_{MEAN}} \qquad (1)$$

Moreover the phase number can be limited by the teeth size, which can become too small and unfeasible when the pole number is high.

4.3 Rotor Location

Once again in the aim of increasing the torque density, two structures of surface mounted permanent magnet machine can be studied. These structures are given in Fig. 16. The difference between these two structures concerns the rotating part (rotor) which is placed with regard to the fixed part (stator). In the first case corresponding to the outer rotor topology, the stator is placed in the center of the rotor. For the inner rotor topology, the rotor is in the center. A comparison between these solutions is made in the next paragraph.

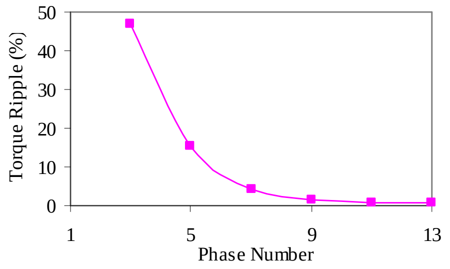


Figure 15: Evolution of the torque ripple with the phase number

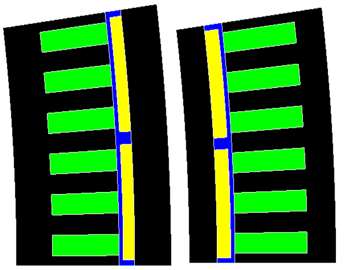


Figure 16: Scheme on a pole pair of outer rotor topology (left) and inner rotor topology (right)

Table 2: Specification

Power	3 MW
Speed	15 rpm
Pole pair	80
Outer stator diameter	<5 m
Efficiency	>94.5 %
Air gap	>5 mm
Active material weight	<24 T

5. Comparison of permanent magnet generators designs

Two machines respecting the specifications given in Table 2 are designed. The specifications correspond to a wind turbine application as one described in [8].

Previous results show that with a 180-degree converter and a trapezoidal flux density, the machine will have the best power density, so that this topology will be used for the designs.

To obtain the slightest heavy machine a minimization of the weight is made. To achieve this optimization, an analytical model is necessary to estimate the back-EMFs for this type of machine. This model is described below.

5.1. Analytical prediction of back-EMF

Radial component of air gap flux density can be determined with (2) and using (3)-(5) for inner rotor machines. These equations can also be adapted to analyze flux density of a machine with outer rotor as in [9].

$$B(r,\theta) = \sum_{n\ odd} n \cdot p \cdot (a \cdot r^{n.p-1} + b \cdot r^{-n.p-1}) \cos(n \cdot p \cdot \theta) \qquad (2)$$

with:

$$a = \frac{R_2}{R_3^{n.p}} \left(\frac{R_2}{R_3}\right)^{n.p} \cdot \left[(1+n.p)\left(\frac{R_1}{R_2}\right)^{2.n.p} + (1-n.p) - 2\left(\frac{R_1}{R_2}\right)^{n.p+1} \right] .c \qquad (3)$$

$$b = R_2^{n.p+1} \cdot \left[(1+n.p)\left(\frac{R_1}{R_2}\right)^{2.n.p} + (1-n.p) - 2\left(\frac{R_1}{R_2}\right)^{n.p+1} \right] .c \qquad (4)$$

$$c = \frac{2p}{\pi\left[1 - \left(\frac{R_1}{R_3}\right)^{2.n.p}\right]} \frac{1}{n.p.\left(1-(n.p)^2\right)} \sin\left(n.K_a \frac{\pi}{2}\right) B_{rc} \qquad (5)$$

where R_1 is the radius at the bottom of permanent magnets, R_2 is the radius at the top of permanent magnets, R_3 is the stator interior radius, K_a is the factor between magnet arc and pole shoe and B_{rc} is the corrected remanent flux density expressed in (6)

$$B_{rc} = \frac{1+\mu_R}{2\mu_R} B_r \qquad (6)$$

B_r is the remanent flux density of the permanent magnet and μ_R is the relative permeability of permanent magnet.

It is then possible to predict the flux density in a slotless machine, as in Fig. 17. But to take into account the slot effect it is necessary to correct the flux density with the relative air gap permeance, as in (7)

$$B_G(r,\theta) = B(r,\theta)\lambda(r,\theta) \qquad (7)$$

where the relative permeance λ is given by (8) and (9):

$$\lambda(r,\theta) = \begin{cases} 1-\beta\left(1+\cos\frac{\pi R_3}{0.8w_S}\theta\right) \;\; for\;\; 0\le\theta\le\frac{0.8w_S}{R_3} \\ 1 \quad for \quad \frac{0.8w_S}{R_3}\le\theta\le\frac{\pi R_3}{N_S} \end{cases} \qquad (8)$$

with

$$\beta = \frac{1}{2} - \frac{1}{2\sqrt{1+\frac{w_s^2}{4\left(g+{h_M}/{\mu_R}\right)^2(1+\upsilon^2)}}} \qquad (9)$$

Expression of υ is given [10], w_S represent the slot opening width, N_S is the slot number, g is the air gap length and h_M is the magnet thickness.

The flux density waveforms taking into account the slot effects are given in Fig. 18.

The back-EMF rms value is obtained with (10)

$$E_{RMS} = B_{G\,RMS} L R_G \Omega \qquad (10)$$

where L is the length of active parts, R_G is the air gap radius and Ω is the angular speed in rad/s.

Table 3 gives a comparison between the flux densities obtained with 2D finite-element simulations and the analytical model.

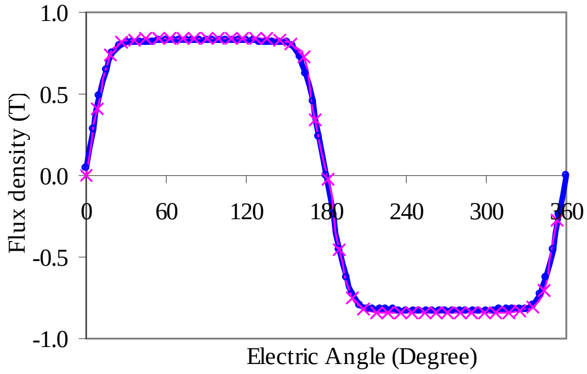
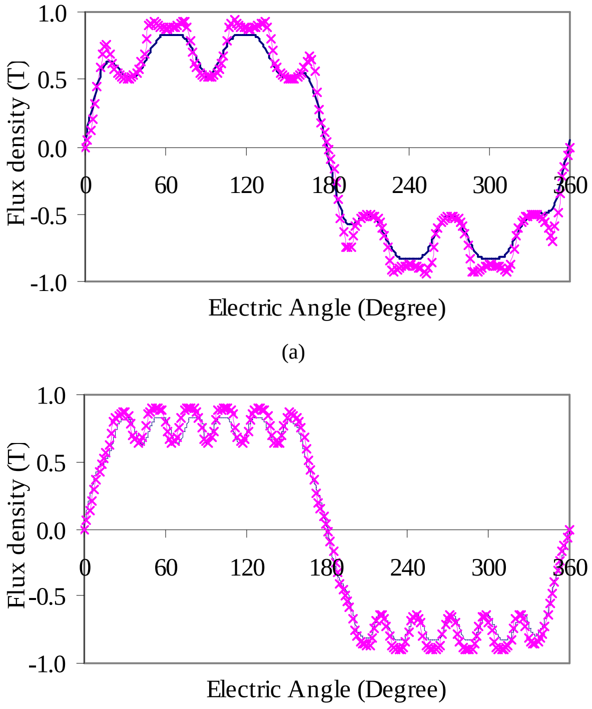


Figure 17: Air gap flux density without slot effects: Comparison between Finite-element (cross) and analytical

Table 3: Comparison between FE and analytical calculations

Method	FE	Analytical	Error (%)
B_{RMS} (T)	0.772	0.758	1.8
With 3 phases			
$B_{G\,RMS}$ (T)	0.693	0.638	8
E_{RMS} (V)	1563	1522	2.6
With 7 phases			
$B_{G\,RMS}$ (T)	0.731	0.69	5.6
E_{RMS} (V)	1647	1646	0.1



(a)

(b)

Figure 18: Air gap flux density: Comparison between Finite-element (cross) and analytical when the phase number is 3 (a), and 7(b)

Even if an error is made on the RMS flux density value when the slots are taking into account, this method gives a good estimation of the back-EMF.

5.2. Designs comparison

The stator external diameter is limited by the size of the impregnating tank, the characteristics of the two designed machines are presented in Table 4.

The torque ripple is always calculated assuming that the currents are perfectly rectangular.

Considering the design constraints of these machines, it appears that the active parts total weight decreases when the rotor is placed outer of the stator. This can be explained by the fact that the air gap diameter can be bigger when the rotor is out. Therefore only this case will be considered.

As it was foreseeable, amplitude of torque ripple is high; a design with 7 phases is made in order to limit the torque ripple. The main parameters of this design are given in Table 5.

Table 4: Comparison between the two designs

Parameter	Inner rotor	Outer rotor
Inner diameter (m)	4.72	4.78
Outer diameter (m)	4.98	5.06
Air gap diameter (m)	4.78	5
Air gap length (mm)	7	7
Magnet weight (T)	1.3	1.3
Iron weight (T)	11.6	11
Copper weight (T)	5.4	5.2
Total active parts weight (T)	18.3	17.5
Efficiency (%)	94.53	94.72
Torque ripple (%)	37	38.9

Table 5: Design with 7 phases and an outer rotor

Phase number	7
Inner diameter (m)	4.8
Outer diameter (m)	5.07
Air gap diameter (m)	5
Air gap (mm)	7
Magnet weight (T)	1.3
Iron weight (T)	12.1
Copper weight (T)	3.8
Total active parts weight (T)	17.2
Efficiency (%)	94.72
Torque ripple (%)	4.5

By keeping the same efficiency, increasing the phase number leads to a decrease of the torque ripple; it also appears that the weight decreases. Therefore this increase seems to correspond to an increase of the machine power density too.

All designs made are quite under the specified weight, which can be found in [8], for the same efficiency. In the paper mentioned, the generator is a conventional BLAC 3 phases machine. Difference on the weights agrees with the power gain given in Table 1, nevertheless this gap must be weighted by the fact that the diameter, the air-gap are different.

6. Comments

When the number of phases increases, using a 180-degrees or a (q-1)/q*180-degrees converter leads to fulfill the machine performances. But without a 180-degrees converter, torque ripple amplitude becomes greater. In fact, without other improvement, a 120-degrees converter permits to limit the torque ripple with 3 phases but if the number of phases is greater, a 180 degrees converter is preferable as shown in Fig. 19.

7. Conclusion

For a high power wind turbine application, direct drive permanent magnet generator seems to be the best technology: lower weight, lower losses and less failure risks. Nevertheless, it has some drawbacks, generator cost and size. Few improvements can be done concerning the size. In fact, less the speed is, higher the diameter should be; thus some restrictions can appear as the transport capabilities, but solutions are possible to increase the power density and limit the weight, and so the cost, of the active parts.

In the aim of increasing the machine power density, some solutions are proposed, and two points have been investigated. The first is the phase number; indeed in some cases the choice of the phase number can bring some advantages. But, this modification leads to increase the difficulty of the machine manufacturing and control. To achieve the control, models with fictitious machine could be use as proposed in [11].

The second point deals with the rotor position respect to the stator. When the overall volume is limited, the use of an outer rotor is a solution to reduce the weight of the machine's active parts. But, the impact on the non active parts has to be studied carefully.

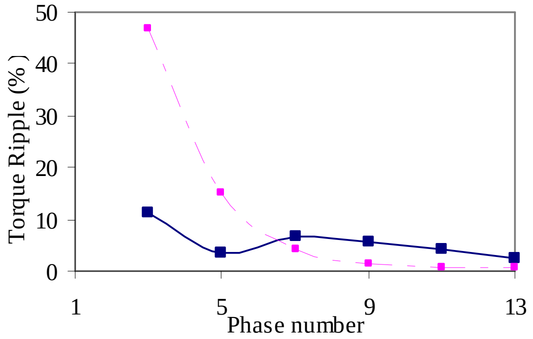


Figure 19: Evolution of the ripple torque with the phase number with a 180-degree converter (dotted line) and a (q-1)/q*180-degree converter.

Other solutions can be found in the literature, with multi generators [12] or where magnets are not mounted at rotor surface [13]. Because of the manufacturing constraints, which are given previously, these solutions are not studied by the company.

On the other hand, for the future wind turbine generators, Converteam develops a High Temperature Superconductors (HTS) machine [14].

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