Different 600kW designs of an axial flux permanent magnet machine for wind turbines

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Abstract: This work describes the application of a novel axial flux permanent magnet generator with a nominal power of 600 kW for wind turbine applications. The generator is specially designed to have a simple robust construction with a high efficiency, a low weight-to-power ratio and a controlled output voltage over a wide speed range. To prove the feasibility of the concept, a mono-phase prototype was build and tested. Based on the calculation model, various machines were designed for wind turbine applications. Different constructions are presented to fulfill different machine requirements such as power, efficiency, dimensions and weight, both for gearless direct drive systems and for systems with a gearbox. Several conclusions can be made. The direct drive machines are compared with the machines driven by a gearbox. Double sided flywheel generators with a large diameter compared to the length of the machine are compared with double sided stacked generators with a smaller diameter-length ratio. The advantages and disadvantages of high stacked U-cores in combination with rectangular magnets in relation to low stacked U-cores with cylindrical magnets are explained. Finally alternative solutions are proposed in order to further reduce the diameter of the machine.

Key-Words: Permanent magnet machines, AC machines, axial flux machines, direct drive wind turbines

1 INTRODUCTION

The use of permanent magnet (PM) machines has become attractive for use in wind turbines because nowadays the available permanent magnet materials are price competitive and have high temperature resistance and coercive field strength [1, 2]. In addition, the required power electronic converters for output power control have undergone a major evolution.

Because of the fact that the cost, weight, and maintenance needs of mechanical gearing between the wind turbine and the electrical generator pose a serious limitation to the further increase in wind energy conversion systems power ratings, direct coupled–low speed permanent magnet generators (PMG) are under development [3, 4]. Especially for direct drive systems, where the high number of pole pairs implies an impracticable building of the wounded rotor generator, a permanent magnet machine can be an interesting solution. Another advantage of permanent magnet synchronous generators (PMSG) is that they do not require any external excitation current [5]. A major cost benefit in using the PMSG is the fact that a diode bridge rectifier may be used at the generator terminals since no external excitation current is needed.

Most permanent magnet motors and generators have a radial magnetic field. In the case of flywheel generators, axial flux machines, in which the magnetic field is parallel to the rotational shaft, are possible too [1, 6]. There are also many alternatives for the design of axial flux or disk-type PM machines: with or without armature slots, with internal or external PM rotors, and with surface-mounted or buried permanent magnets [6].

In order to obtain a new design that combines a high efficiency, a simple robust construction and a high power-to-weight ratio, VITO started with the design and construction of an experimental axial flux machine with U-shaped stator and cylindrical permanent magnets in the rotor (AXIFUS).

2 EXPERIMENTAL DESIGN

VITO developed a new axial flux machine with U-shaped stator coils and interior cylindrical PMs. This was named AXIFUS, for AXIal Flux generator with U-shaped Stator coils. The main advantage of this design is a simple and robust construction combined with a low weight-to-power ratio and a high efficiency. The generator uses standard components for the permanent magnets (cylindrical) and stator silicon steel (U-cores) [7, 8]. The winding of the stator coils is kept simple by using coil formers for the standard U-cores. Once a set of standard components is selected, new machines can easily be redesigned for other demands.

In order to facilitate and accelerate the design process, a calculation model was developed based on a combination of analytical calculations and finite element calculations [7] which are solved respectively in excel and FEMLAB. It is possible to enter the system design parameters, such as efficiency, maximum power, no-load voltage and the dimensions, and calculate by an iterative process the required key machine design parameters, such as air gap, number of U-cores, height of U-cores, … . When these geometric parameters such as air-gap, U-core or PM dimensions of the machine change, other finite element parameters must be entered in the analytical model.

To validate and optimize the calculation model, a mono-phase prototype was build and tested [7, 8]. Since the aim of the research was to prove the feasibility of the concept, instead of taking into account the optimal dimensions by the construction of the prototype, standard available material was used.

The prototype of AXIFUS is a mono-phase, one-sided machine. The "one-sided" implies that there is one rotor and one stator opposite to the rotor. A double-sided machine can also be constructed: in this case there is one rotor with a stator on both sides of the rotor. Although for a double-sided machine the forces on the rotor would be more symmetrically distributed and both the starting torque and torque cogging can be reduced by rotating one stator with respect to the other, the prototype is realized by one stator and one disk-type rotor (Figure 1). The outer stator diameter of the machine is 0,3 m and the total active weight is 9,3 kg.

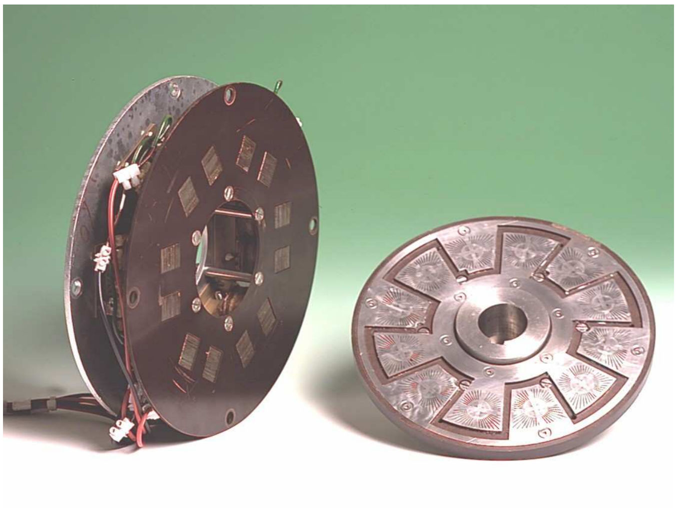

Fig. 1: Stator and rotor of the prototype of AXIFUS

Several experiments were conducted on the prototype to observe the performance of the generator.

Figure 2 presents the measured and analytically calculated values of the output power of a machine with an air gap of 3 mm as a function of the stator current for different rotor speeds and for a resistive load.

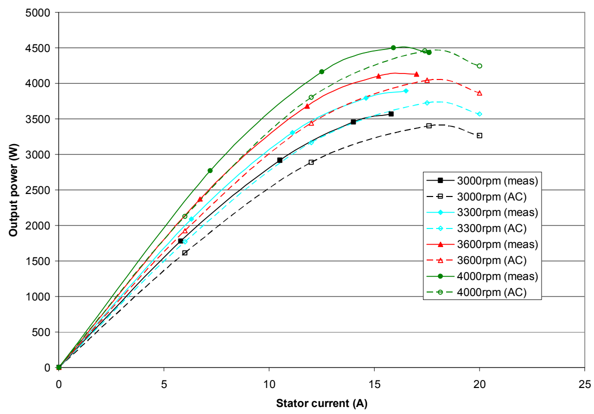

Fig. 2: Measured (meas) and analytically calculated (AC) values of the output power of a machine with an air gap of 3 mm as a function of the stator current for different rotor speeds and for a resistive load

The measured value of the maximum power output and no-load voltage at a rotor speed of 4000 rpm and an electrical frequency of 400 Hz are respectively 4.500 W and 419 V. For rotor speeds of 3.000 rpm, 3.300 rpm, 3.600 rpm and 4.000 rpm, the calculated value of the maximum power output is respectively 4,7 %, 4,3 %, 2 % and 0,9 % smaller than the measured value. The difference between the calculated and the measured value of the no-load voltage is larger: the calculated value is respectively 14 %, 13,5 %, 12,3 % and 11,9 % smaller than the measured value. This manifests itself in figure 3 in the shift of the calculated stator current by maximum power output to higher values compared to the measured ones.

Previous calculations have shown the effects of the different design parameters of AXIFUS on a 5 kW and 30 kW machine for wind power applications [8].

3 DESIGN OF A 600 KW AXIFUS FOR WIND TURBINES

Based on the calculation model, different machines with a maximum power of 600 kW are designed to see the effects of the design parameters such as efficiency, power-to-weight ratio, rotation speed, air gap and dimensions on the output of the machine.

Since the rotor of the prototype consisted of cylindrical permanent magnets, the rotors of the first designs for a 600 kW machine were all build up in the same way, by the same cylindrical NdFeB permanent magnets with a diameter of 40 mm and a length of 10 mm. The basic principle of the configuration of AXIFUS is shown in figure 2. For the 600 kW machines a double sided design is used, which means that a second rotor disc and U-cores are added at the back of the rotor in figure 3.

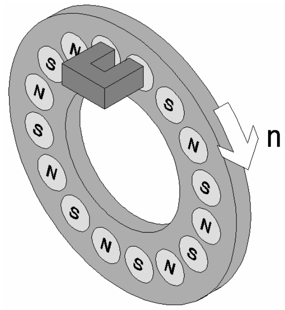

Fig. 3: Basic principle of AXIFUS

The calculations were done for different 600 kW machines: a generator driven by a gearbox, a gearless design and a stacked machine that consists out of 3 double sided machines. Table 1 shows the most important design parameters for these 600 kW generators.

	With gear box (1:25)	Direct drive	Direct drive 3 stacked rotors
# U-cores / stator	115	564	333
Average radius cores (mm)	1706	8366	4939
diameter generator (mm)	3532	16852	9998
Air gap (mm)	1,5	1,5	1,5
Speed (rpm)	375	15	15
Stack height U-cores(mm)	25,2	25,2	25,2
Magnet height (mm)	40 (diameter)	40 (diameter)	40 (diameter)
Weight generator (kg)	351	1718,9	3008
P_{max} (W)	639087	600577	602237
weight/power	0,55	2,86	4,99
Efficiency by P_{max}	94,3	92,9	89,7

Table 1: different designs of a 600 kW AXIFUS generator

The machine driven by a gearbox has the highest efficiency and the smallest weight-to-power ratio and machine diameter. When one wants to exclude the regular maintenance and the cost of the gearbox, a direct driven generator is necessary. However, since AXIFUS is an axial flux machine, the diameter of the generator becomes very large and the weight-to-power ratio is higher compared to the machine with gear box. An alternative design is the machine that consists of a stack of 3 double sided machines. In this case, the diameter becomes smaller, but also the efficiency and the power-to-weight ratio become smaller.

To decrease the diameter of the machine, an alternative design was suggested. Instead of using cylindrical permanent magnets, rectangular ones were used. The new configuration is shown in figure 4.

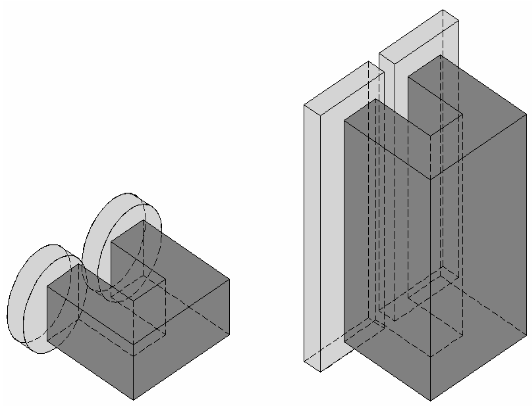

Fig. 4: configuration with cylindrical permanent magnets and with rectangular ones

For this new configuration with the rectangular permanent magnets calculations were done for two direct driven 600 kW machines: the one consisting out of 1 double sided machine (flywheel type), the other one out of 3 double sided machines. The most important design parameters of these machines are shown in table 2.

	Direct drive	Direct drive 3 stacked rotors
# U-cores / stator	296	176
Average radius cores (mm)	4431	2651
diameter generator (mm)	9059	5499
Air gap (mm)	1,5	1,5
Speed (rpm)	15	15
Stack height U- cores(mm)	100,8	100,8
Magnet height (mm)	117	117
Weight generator (kg)	2493	4453
P_{max} (W)	604573	604305
weight/power	4,12	7,37
Efficiency by P_{max}	92,911	89,2

Table 2: design parameters of a 600 kW generator with rectangular permanent magnets

For both machines the diameter becomes a bit more than 0,5 times the diameter of the corresponding machine with the cylindrical magnets. The weight-to-power ratio however is higher and the efficiency stays about the same.

To further decrease the diameter of the machine a third configuration was considered: instead of using 1 circle of magnets on the outside diameter of the rotor, one could use more circles of magnets (figure 5).

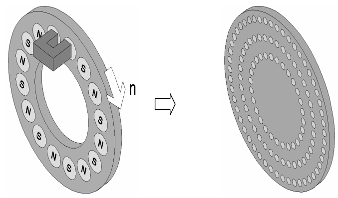

Fig. 5: basic principle of AXIFUS to the principle of using magnets on more than 1 rotor radius

The following table 3 shows the power that corresponds with the number of U-cores on an average rotor radius for a double sided direct driven machine with a rotational speed of 15 rpm.

# U-cores / stator	Average radius cores (mm)	P_{max} (W)
230	1746	78496
212	1613	65629,82
194	1479	53906,39
176	1346	43332,22
158	1212	33913,59
140	1079	25656,3

Table 3: Maximum power for a double sided direct driven generator with the magnets on different rotor radii

A generator consisting of a stack of two double sided machines with magnets placed on the 6 circles as described in table 3, will have a maximum power output of 602 kW and a machine diameter of 3.612 mm. This machine also has a big construction advantage since the forces between the magnets and the cores are now more spread over the rotor surface. However, there is also a disadvantage, namely a higher number of electronic converters is needed since the frequency of the generated voltage differs for the different radii.

4 CONCLUSIONS

In this work the embodiment and design trade-offs of an axial flux permanent magnet machine with U-shaped stator, suitable for utility interface of wind turbines, is presented.

The concept can be realized with standard components and offers the flexibility to meet a wide range of system requirements (efficiency, power, volume, weight, …).

A calculation model has been developed and optimized with a prototype. Test results on the prototype have proven feasibility of the concept. For rotor speeds between 3.000 rpm and 4.000 rpm, the calculated value of the maximum power output is between 4,7 % an 0,9% smaller than the measured value.

Based on the calculation model, various 600 kW AXIFUS configurations were evaluated for wind energy applications.

The direct drive machines were compared with the machines driven by a gearbox. Double sided flywheel generators with a large diameter compared to the length of the machine were compared with double sided stacked generators with a smaller diameter-length ratio. The advantages and disadvantages of high stacked U-cores in combination with rectangular magnets in relation to low stacked U-cores with cylindrical magnets were explained. Finally an alternative solution to further reduce the diameter of the machine was proposed.

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