Prototype of an Axial Flux Permanent Magnet Generator for Wind Energy Systems Applications

A. P. Ferreira[1], A. M. Silva[2], A. F. Costa[2]
[1]School of Technology and Management, Polytechnic Institute of Bragança
Campus de Santa Apolónia, 5301-857 Bragança, Portugal
Tel.: +351 / 273303105, Fax: +351 / 273313051
[2]Department of Electrical and Computer Engineering, FEUP
R. Dr. Roberto Frias, 4200-465 Porto, Portugal
Tel.: +351 / 225081871, Fax: +351 / 225081443
apf@ipb.pt, morim@fe.up.pt, acosta@fe.up.pt
http://www.estig.ipb.pt, http://www.fe.up.pt

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Abstract

Small scale wind power applications require a cost effective and mechanically simple generator in order to be a reliable energy source. The use of direct driven generators, instead of geared machines, reduces the number of drive components, which offers the opportunity to reduce costs and increases system reliability and efficiency. For such applications, characterized by low speed of rotation, the axial flux permanent magnet generator is particularly suited, since it can be designed with a large pole number and high torque density.
This paper presents a double-sided axial flux permanent magnet low-speed generator, with internal rotor and slotted stators. Such a structure gives a good compromise between performance characteristics and feasibility of construction. Test results obtained from the prototype are reported.

Introduction

There is an active seeking to increase the percentage share of total electric energy supply from renewable sources. Wind energy is currently assumed as the lowest risk, with proven technology and no greenhouse-gas emissions or waste products. Large and medium-scale wind energy turbines have already proved themselves as cost competitive electricity generators in locations where wind resource is good enough. Small-scale wind turbines produce more costly electricity than those [1]. However they are an attractive choice to generate electrical power on rural areas where the installation of the distribution network is not economically reasonable or in autonomous applications.

A technological trend in wind energy conversion systems is the use of direct driven, variable speed turbines. Synchronous generators (permanent magnet or wound) allow the use of higher pole number which is in favour of gearless systems. The main benefits are the prevention of gear costs, oil leakage, gear maintenance and losses; furthermore, noise can also de reduced significantly by avoiding this transmission element [2].

Permanent magnet excitation over wound-rotor excitation reduces rotor losses and allows a significant decrease of the pole pitch, which translates in cost and mass reduction [3], justifying the trend moving towards the use of permanent magnets in synchronous generators. The feature of adjustable excitation current is lost in permanent magnet machines, but as the generator output is to be rectified so that it can be used for battery charging or grid connection through an inverter, this is not decisive [4].

Many types of PM synchronous generators have been used and proposed to convert wind energy: radial, axial and transverse-flux. A general comparison between the various types is difficult due to technological and manufacturing differences; several works have been done using different comparison procedures [5-7]. Transverse-flux machines are well known for their higher torque density, but their electromagnetic structure is more complicated than for radial and axial-flux machines. Axial flux machines are recognized for having higher torque density than their counterparts based on radial-flux. A comparison procedure using simple thermal considerations, for equal overall volume, equal losses per wasting surface unit, equal airgap, teeth, yokes flux densities and rotational speed of the two machine structures, bringing out the pole number influence, is reported in [8]. The torque density advantage of AFPM machine becomes more apparent in a design with a large number of poles.

One point in favour for radial-flux machines is that 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. To reduce the diameter of the axial-flux machine, while keeping the rated torque constant, the difference between inner and outer radius has to be increased. The inner diameter is, however, limited by the necessary space to place the windings. Because the maximum torque of an axial-flux machine is achieved when the inner radius is around 0.6 times the outer radius [9], a smaller inner radius will only decrease the rated torque. Consequently, the diameter of the axial-flux machine cannot be reduced as much as that of the radial-flux machine. One way of avoiding a large diameter is to stack a number of axial-flux machines with a small diameter on the same shaft.

This paper starts by discussing the possible structures of the axial flux permanent magnet low-speed generators; after the decision of the machine configuration, the design procedure is presented and finally, the prototype results and experimental test are carried out.

Axial Flux Permanent Magnet Machine Configuration

For axial flux machines, the minimum number of disks is two (single sided), but normally three disks (double sided) are used in order to get balanced axial forces and to increase the total airgap surface. The single sided axial flux permanent magnet machine topology has the drawback of a large uncompensated attractive force between the rotor and the stator, which implies the use of a bearing system capable of tolerating it [10]. For double sided axial flux machine structures, these mechanical concerns are cancelled out during machine operation because the double airgap system causes that the total axial force affecting the inner disk is negligible.

Regarding the stator(s) position(s) with respect to the rotor(s) position(s), slot or slotless stator(s) and the winding arrangements, several axial-flux machine types can be used, giving freedom to select the most suitable machine structure into the considered application. The double-sided axial flux permanent generator with internal rotor is chosen, mainly due to simplified manufacturing process, placing the rotor between two stators, which are easily fixed to the frame. Compared to the opposite structure, in which the stator is located between the rotors [11], more space is available for winding, but, on the other hand, the cooper losses are generally higher.

Stators Structure

Although generator designs can have any number of phases, most small scale wind turbine manufacturers require a three-phase machine.
Slotted stators increase remarkably the amplitude of the airgap flux density due to the shorter airgap and consequently this reduces the required amount of permanent magnets, which yields savings in the generator price. Slotting may evoke undesired torque pulsations, but if the two windings are connected in series, then one stator may be rotated over a certain angle (usually one half of the slot pitch) with respect to the other which results in reduced slot ripple and space harmonic components [12]. It should be noted also that in slotted stators, the leakage and mutual inductances are increased compared to the slotless stators, which is advantageous when using the generator connected to a solid-state converter, as it helps reduce the current ripple due to converter switching.

The concentrated windings have phase coils wound around separate teeth, meaning that the radial build of the machine is shorter than machines with distributed windings (Fig. 1) which have typically long end windings, because the coil of a phase must cross the other phase coils. Thereby, the overall space, required by the machine with concentrated windings is decreased; this procedure also solves the problem how to arrange the end windings in the limited space between the shaft and the inner radius of the stators, which can be a problem for conventional three-phase machines. Distributed windings use more insulation material than concentrated ones. This is translated to a more reliable insulation system and higher fill factors of concentrated windings.

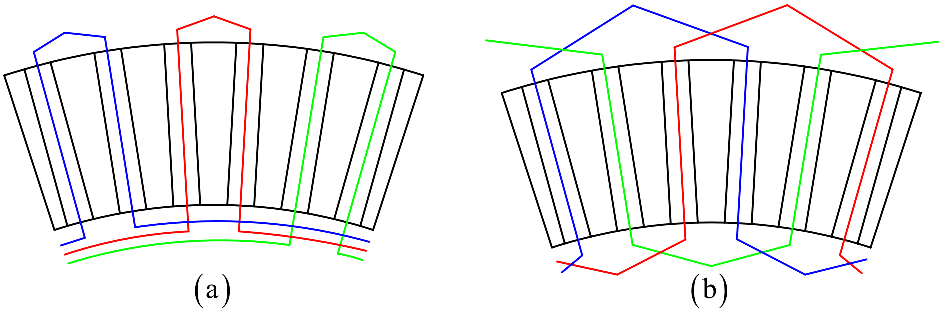

Fig. 1: Concentrated windings (a) and distributed windings (b) for a three-phase axial flux permanent magnet machine over a pole pitch.

Compared with a conventional distributed winding with one slot per pole and phase, the concentrated winding has a low fundamental winding factor. The average electromagnetic torque is proportional to the winding factor. Disregarding the end windings effects, an electrical machine with low winding factor needs to compensate its lower torque with higher current density, which leads to higher Joule losses compared to a machine with a winding factor equal to 1, for the same torque, assuming equal slot fill factor and comparable magnetic design [13].

It's currently assumed that concentrated windings are an effective way to reduce Joule losses in low-speed permanent magnet machines, due to shorter end windings. However they generate both odd and even harmonics, and some, also produce sub-harmonics in the MMF. All extra harmonics create additional flux in the machine which results in high eddy current losses in a solid rotor and in the permanent magnets, which may cancel the benefits of the shorter end windings.

Based on this discussion, slotted stators with three-phase distributed windings have been chosen to accomplish the axial flux permanent magnet generator prototype. The two stator windings are connected in series and the star connection is used to avoid circulating currents.

Rotor Structure

The permanent magnets in the internal rotor of a double sided structure may be located on the surface or inside the rotor disk. Thereby, the main flux may flow axially through the rotor disk or flow circumferentially along the rotor disk. With the permanent magnets located at the surface of the rotor disk, it is not necessary a ferromagnetic rotor core and the axial length is substantially reduced, which consequently improves the power density of the machine.

The chosen rotor structure consists in a holed non-magnetic disk to support the permanent magnets. Compared to the surface mounted permanent magnets in a non-holed rotor disk, this solution involves the machination and the manipulation of half magnet pieces. The flux path associated with this machine topology is shown in Fig. 2. The flux travels axially in the rotor structure and completes its path by returning circumferentially around the stators cores.

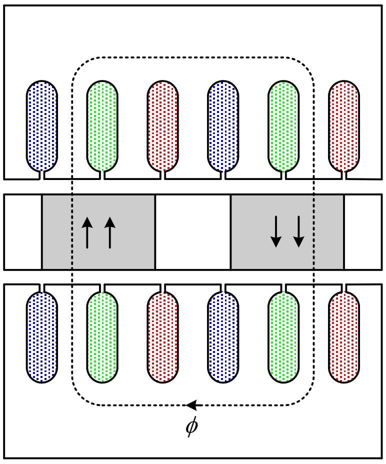

Fig. 2: 2D plane of the axial flux permanent magnet machine.

Design of an Axial Flux Permanent Magnet Generator

Fundamentals of Machine Design

Techniques such as finite element analysis provide accurate solutions for two or three-dimensional field distributions in complex geometries, which should be used to predict machine performance with similar precision. However these techniques require a detailed definition of the geometry and boundary conditions to be solved, which assumes that an initial design already exists.
The design procedure here presented consists in a preliminary approach to the design methodology of axial flux permanent magnet machines.

Assuming sinusoidal waveform for both the air gap flux density and phase current, the electromagnetic torque of a double-sided axial flux machine with internal rotor can be calculated as

$$T_{elm} = 4k_{w1}A_{in}B_{max}r_{out}^{3}\left(k_D - k_D^{3}\right), \qquad (1)$$

where r_{out} and k_D are the outer radius and the ratio between inner radius, r_{in}, and outer radius of the stator core, respectively, A_{in} is the linear current density on the inner radius of the machine, k_{w1} is the fundamental winding factor and B_{max} is the maximum value of the air gap flux density.

Based on specified values for the electric and magnetic loadings, no load EMF and output power of the machine can be estimated as follows.
For a given speed, n_s in r/s, the EMF induced per stator winding, with N_f numbers of turns per phase, by the rotor excitation system has the following form

$$E_0 = \pi\sqrt{2}n_s N_f k_{w1} B_{max}\left(r_{out}^{2} - r_{in}^{2}\right). \qquad (2)$$

The rms phase current of a 3-phase machine, expressed in terms of the linear current density on the inner radius is

$$I = \frac{\pi r_{in} A_{in}}{3N_f}. \qquad (3)$$

Therefore, the apparent electromagnetic power due two stators is

$$S_{elm} = 3\left(2E_0\right)I = 2\sqrt{2}\pi^2 k_{w1} n_s B_{max} A_{in} r_{in} \left(r_{out}{}^2 - r_{in}{}^2\right) \tag{4}$$

and the active output power is

$$P = \eta \varepsilon S_{elm} \cos\varphi \tag{5}$$

where η is the efficiency, φ is the power factor angle and ε is the phase voltage to emf ratio, lower than 1 for the machine's generator mode.

Basics on Design Procedure

The dimensioning of the prototype machine was done iteratively via analytical approach based on some simplifying assumptions.

Due to the low speed of the direct driven generator, a large number of poles should be chosen, in order to get a frequency not too low, and consequently, a large number of stator slots is needed to construct the multi-pole windings. The design of the prototype was made under geometrical constraints imposed by the available ferromagnetic material. Core outer radius was, therefore, limited to 9 cm. This geometrical constraint restricts the selection of slots and basically only slot numbers per stator equal or below 60 were feasible to employ. For distributed windings with one slot per pole and phase, with 60 slots per stator, the number of pole pairs is 10.

Due to the disk structure of the stators, the tooth width is minimum at the inside diameter of the stator disk. For this reason the minimum necessary dimensions of the teeth should be determined at the inside diameter of the stator, allowing consideration of saturation where this is more critical. Considering the maximum tolerable slot current density, which is limited by the desired steady-state temperature rise, and the dimensions of the slots, the linear current density may be considered as a design input.

An analytical design procedure, based on the equivalent magnet circuit approach and permanent magnet load line characteristics was used to estimate the magnetic loading, which determines the stator yoke dimensions and the specifications and dimensions of the magnets. The armature MMF due to stator currents is initially assumed zero (no-load condition) and the reluctances of the stator iron are absent as it is assumed infinitely permeable.

Under load condition, the most important effect of armature reaction field in surface permanent magnet machines is the possibility of partially or totally demagnetizing the magnets. This effect must be checked to avoid demagnetization risk of the permanent magnets. Dynamic behaviour of the permanent magnet was taken into consideration to guarantee that the magnet's operating point won't undergo the straight part of the demagnetizing characteristics with the worst loading conditions (short circuit at the machine terminals).
An effective way to stabilize the operating point against armature reaction is to raise the slope of the load line, increasing the length of the magnet. This solution is well adapted to the chosen configuration of the axial flux machine.
In the performed analysis the relative recoil permeability of permanent magnets was considered equal to 1, it was assumed that the remanent flux density is constant under an external field as well as uniform properties and magnetization throughout the axial direction of the magnets.

Prototype Machine and Test Results

Outputs of the design study are given in Table I as well as the main parameters of the axial flux permanent magnet prototype machine.
During the design procedure, the magnet occupation ratio, $\alpha_i = \gamma_i\left(r\right)/\tau\left(r\right)$, where $\gamma_i\left(r\right)$ is the width of the magnet and $\tau\left(r\right)$ is the pole pitch, was assumed constant along the radius of the stator. It

wasn't possible implement this design characteristic due to the high price of NdFeB magnets in non standardized forms. Axially magnetized cylinder NdFeB magnets, grade N30SH, available in the market were used, satisfying the magnet occupation ratio only at the average radius. Because the magnets are circular, the flux density they produce tends to fall in all directions from the centre. Fig. 3 shows the rotor of the prototype constructed.

Table I: Main parameters of the axial flux permanent machine prototype.

Parameter	Value
Axial motor length	5,62 cm
Airgap thickness	0,5 mm
Core inner radius	6,5 cm
Core outer radius	9 cm
Permanent magnet axial length	1 cm
Magnet occupation ratio (at average radius)	0,617
Number of pole pairs	10
Permanent magnet overall weight	0,262 kg
Rated speed	600 rpm
Rated torque	5,4 Nm
Rated power (at 600 rpm)	340 W
No-load phase voltage (rms value at 600 rpm)	80,6 V
Number of phases	3
Number of coils per stator	60
Number of turns per coil	24
Number of slots per pole and phase	1
Stator phase resistance (at 20ºC)	7 Ω
Linear current density (at average radius)	8,28 kA/m
Air gap peak flux density	0,61 T

Fig. 3: Views of the rotor disk and shaft.

One of the machine stators is shown in Fig. 4, during and after winding. Both end windings are available outside the frame. This renders possible changing the machine electrical connections from star to delta connection, changing the connection between the stators from series to parallel or running the machine using one stator only.

Fig. 4: One of the slotted stators, during and after winding.

Fig. 5 shows the prototype machine in the test bench. The machine under test has been driven by an induction motor fed by a frequency converter and loaded with a variable resistive load. The shaft torque has been measured by a torque transducer and the electrical power, current and voltage have been registered by a power analyzer.

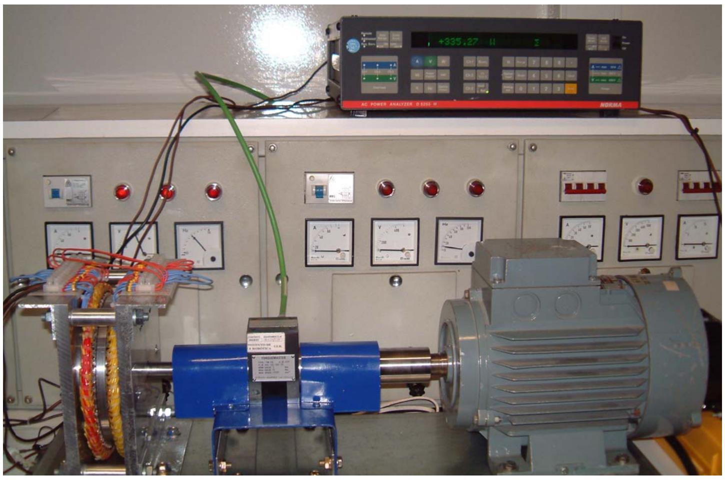

Fig. 5: Prototype machine in the test bench.

Several test runs were performed for the generator under load and no-load conditions.
The evaluation of the efficiency versus current for two different speeds is reported in Fig. 6. At the rated operating condition, with a resistive load, the efficiency was evaluated in 86% which is acceptable for a non optimized prototype.

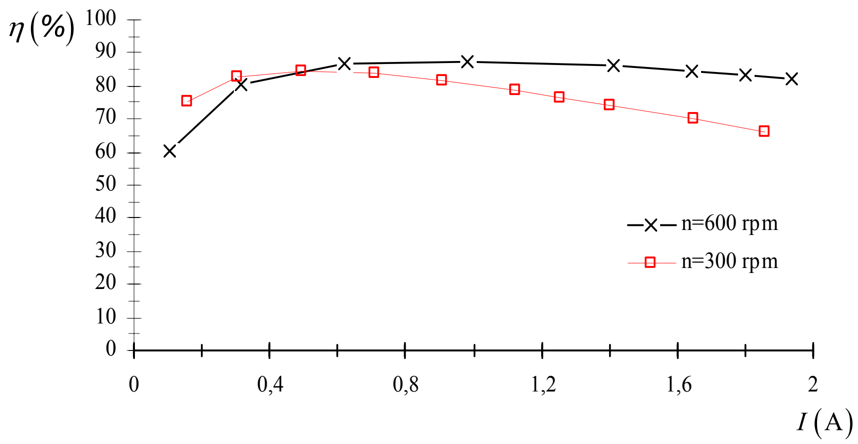

Fig. 6: Measured efficiency versus current for 300 rpm and 600 rpm.

Fig. 7 shows the no-load phase voltage waveform at the nominal frequency of 100 Hz. Such a waveform has a significant 23,1% third harmonic. The harmonic components are shown in Fig. 8, where U_{0h} is the component of the h harmonic frequency, $f_h = hf_1$, with $f_1 = 100$ Hz, being $U_{01} = 78{,}09$ V.

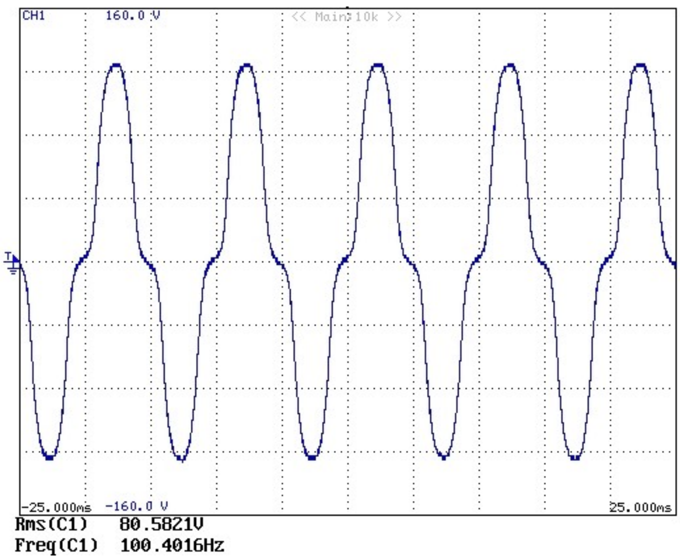

Fig. 7: No-load phase voltage at 600 rpm (voltage scale: 40 V/div; time scale: 5 ms/div).

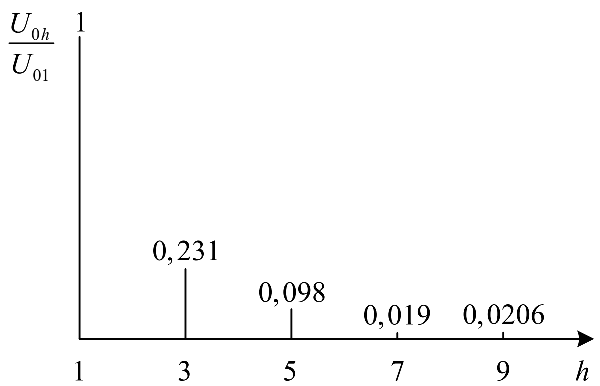

Fig. 8: Harmonic components in no-load phase voltage.

The harmonic content of the no-load phase voltage waveform would be substantially reduced if one stator was shifted one half of the slot pitch with respect to the other. Obviously, it should be expected a decrease of the rms value of the fundamental component as a consequence of the electrical phase angle resulting between the EMF's induced in the two active portions of each coil of the winding. Other technical solution to achieve substantial reduction of the no-load voltage harmonic content, based on magnet or slot skewing, increases the complexity of machine manufacturing.

Conclusion

Axial flux permanent magnet machines are being regarded as the most promising candidate for low speed direct driven applications, such as wind energy systems. Starting by a raw elimination among various possible structures, a decision was made for the configuration of an axial flux permanent magnet generator oriented to small scale wind power applications. A simple electromagnetic design model, considering the fundamental laws governing this type of machines was used to achieve and implement a prototype. This effort relies on a set of analytical expressions which lack the precision and accuracy that a final analysis deserves. Nevertheless, the obtained prototype accomplishes a good compromise between performance characteristics and feasibility of construction, validating further investigation and optimization of this machine structure.

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