AN AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS GENERATOR FOR A GEARLESS WIND ENERGY SYSTEM

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ABSTRACT
In low speed applications such as wind energy conversion systems, 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.
The Axial Flux Permanent Magnet (AFPM) generator is particularly suited for such application, since it can be designed with a large pole number and a high torque density.
This paper presents the design, construction and experimental validation of a double-sided AFPM synchronous generator prototype, with internal rotor and slotted stators. Design objectives embrace achieving a good compromise between performance characteristics and feasibility of construction, which results in a cost competitive machine.

KEYWORDS
Permanent magnet generators, Axial flux machines, Machine design methods, Direct energy conversion.

I. INTRODUCTION

There is an active seeking to increase the percentage share of the total electric energy supply from renewable sources. Among them, wind energy is currently assumed as the lowest risk, with proven technology and no greenhouse-gas emissions or waste products. One of the areas where technological advances have played a major role in the last years is the development of innovative direct driven, variable speed wind 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 gear losses; furthermore, noise can also be reduced significantly by avoiding this transmission element, very important for on shore turbines (Polinder, *et al.*, 2005). Compared with the

alternative solution based on the variable speed geared doubly fed induction generators, synchronous generators have the disadvantage of requiring the grid side converter to be rated to match the rated power of the generator, which precludes a complex and expensive option at current prices. However, for small or medium power ratings, this is less severe.

PM excitation over wound-rotor excitation reduces rotor losses and allows a significant decrease of the pole pitch, with cost and mass reduction (Grauers, 1996), which justifies the trend moving towards the use of PM excitation in synchronous generators. The feature of adjustable excitation current is lost in PM excitation, but with the generator connected to the grid/load via an electronic converter, as is the case, this is not decisive (Ferreira, 2000).

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 (Chen*, et al.*, 2005; Dubois*, et al.*, 2000; Sitapati, Krishman, 2001). 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 (Cavagnino*, et al.*, 2002). 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 (Gieras*, et al.*, 2004), 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 AFPM machines; the design procedure is then presented and finally, the prototype results and experimental test are carried out.

II. AFPM MACHINE CONFIGURATION

For AFPM 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 AFPM machine construction 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 (Parviainen, Kontkanen, 2005). 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 with respect to the rotor(s) positions and the winding arrangements, slot or slotless stator(s), several axial-flux machine types can be used, giving freedoms to select the most suitable machine structure into the considered application. The double-sided AFPM 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 (Chalmers, Spooner, 1999), more space is available for winding, but, on the other hand, the cooper losses are generally higher.

A. Slotted or Slotless Stators

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 half a slot pitch) with respect to the other which results in reduced slot ripple and space harmonic components (Platt, 1989). It should be noted also that in slotted stators, the leakage and mutual inductances are increased compared to the slotless stators, which is favourable when using the generator connected to a solid-state converter, as it helps reduce the current ripple due to converter switching (Gieras, *et al.*, 2004).

B. Concentrated Windings or Distributed Windings

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 3-phase machines. Distributed windings use more insulation material than concentrated ones. This translates to a more reliable insulation system and higher fill factors of concentrated windings.

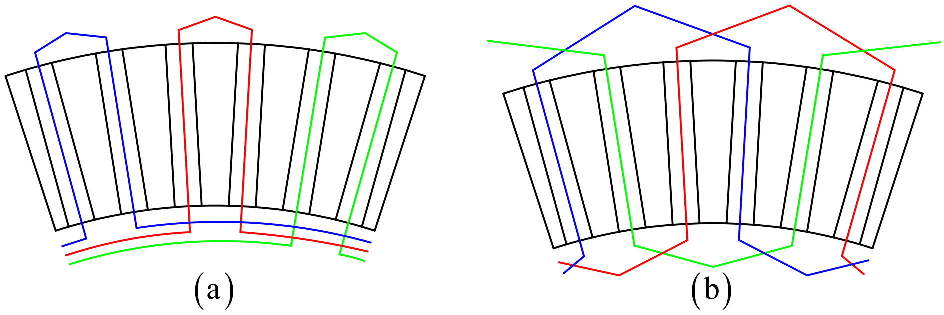

Fig. 1: (a) Concentrated windings and (b) distributed windings of a three-phase AFPM machine over a pole pitch.

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's 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 (Magnussen, Sadarangani, 2003).
It's currently assumed that concentrated windings are an effective way to reduce Joule's 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; this 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 3-phase distributed windings have been chosen to accomplish the AFPM generator prototype. The two stator windings are connected in series and the star connection is used to avoid circulating currents.

C. 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 reduced substantially, 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 (Fig. 2). Compared to the surface mounted permanent magnet in a non-holed rotor disk, this solution involves the machination and the manipulation of half magnet pieces.

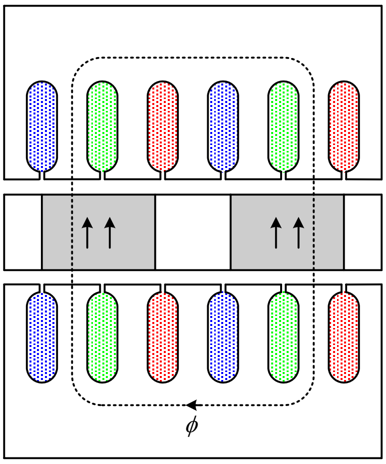

Fig. 2: 2D plane of the AFPM machine.

III. DESIGN OF AN AFPM GENERATOR

A. 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 AFPM 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

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

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 AFPM 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

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

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

$$I = \frac{\pi r_{in} A_{in}}{3N_f}. \tag{3}$$

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.

B. Basics on Design Procedure

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

IV. PROTOTYPE MACHINE AND TEST RESULTS

The prototype constructed is not a result of any optimization process. With the prototype machine the operational results generated by the developed analytical design have been verified.

Outputs of the design study are given in Table 1 as well as the main parameters of the AFPM prototype machine.

During the design procedure, the magnet occupation ratio, $\alpha_i = \gamma_i(r)/\tau(r)$, where $\gamma_i(r)$ is the width of the magnet and $\tau(r)$ 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. Fig. 3 shows the rotor of the prototype constructed.

Axial motor length	5,62 cm
Airgap thickness	0,5 mm
Core inner radius	6,5 cm
Core outer radius	9 cm
PM axial length	1 cm
Magnet occupation ratio (at average radius)	0,617
Number of pole pairs	10
PM overall weight	0,262 kg
Rated speed	600 rpm
Rated torque	5,4 Nm
Rated power (at 600 rpm)	340 W
EMF (rms value at 600 rpm)	79,4 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	7 Ω
Linear current density (at average radius)	8,28 kA/m
Air gap peak flux density	0,61 T

Table 1: Main parameters of the AFPM prototype.

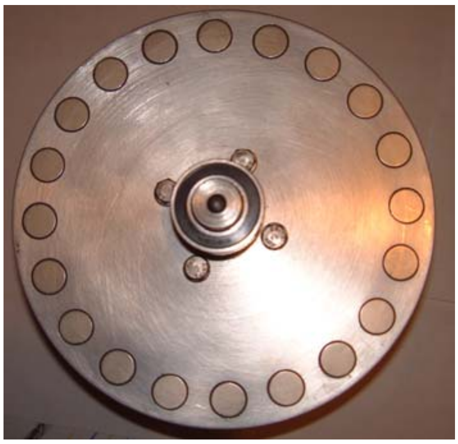

Fig. 3: Rotor of the prototype constructed.

One of the machine stators is shown if 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 stator from series to parallel or running the machine using one stator only.

Fig. 4: One of the 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 has been registered by a power analyser.

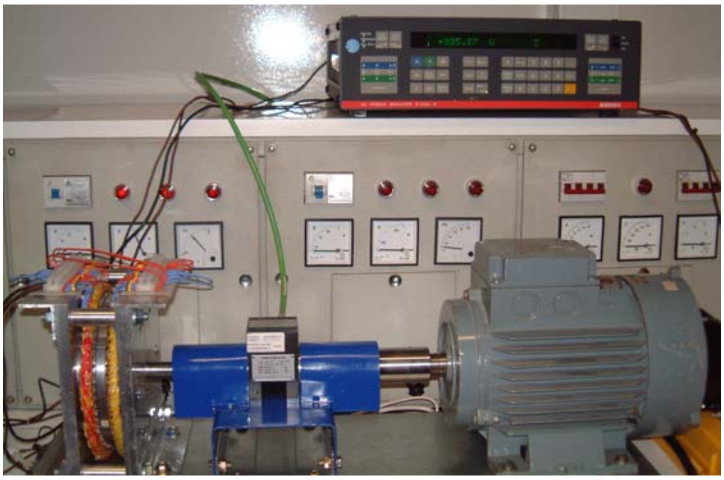

Fig. 5: Prototype machine in the test bench.

Laboratory tests were carried out on the machine prototype in order to evaluate significant quantities for several values of both rotor speed and stator winding current. Measured phase voltage and efficiency versus current for two different speeds are reported in Fig. 6 and Fig. 7, respectively. Efficiency at the rated operating condition was evaluated in 86% which is acceptable for a non optimized prototype.

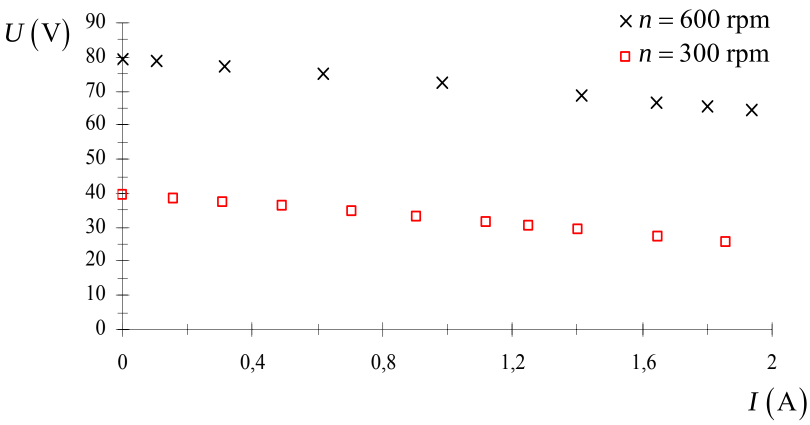

Fig. 6: Measured phase voltage versus current for 300 rpm and 600 rpm.

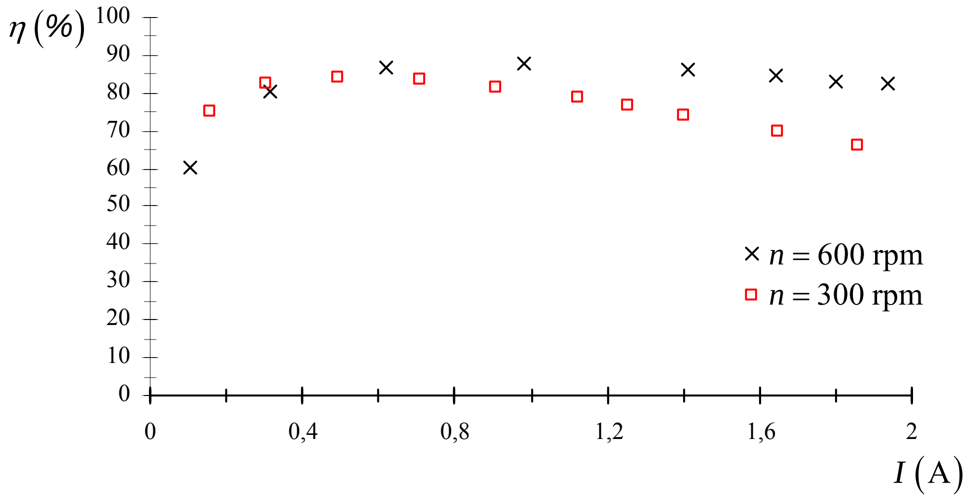

Fig. 7: Measured efficiency versus current for 300 rpm and 600 rpm.

V. CONCLUSIONS

Starting by a raw elimination among many possible structures, a decision was made for the configuration of an AFPM generator oriented to gearless wind power conversion systems.
Based on an analytical procedure, an output of a candidate design was achieved and implemented. This effort relies on a set of analytical expressions which lack the precision and accuracy that a final analysis deserves. Nevertheless, the obtained prototype achieved a good compromise between performance characteristics and feasibility of construction, validating further investigation and optimization of this AFPM machine structure.

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