OPTIMUM DESIGN ASPECTS OF A POWER AXIAL FLUX PMSM

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The paper presents an axial flux permanent magnet synchronous machine (PMSM) with one disk rotor between two stators, which are wound in a concentrate winding type with sub unitary number of slots/pole/phase – a tooth-coil technology. Some structure, design and FEM analysis elements are presented. Aspects of the average performances obtained in the steady state operation mode are highlighted by digital simulation.

1. **INTRODUCTION**

The permanent magnet synchronous machines (PMSM) have been used in an increasing number of applications since the introduction of rare-earth permanent magnets PMs. The main reason for using rare-earth PMs (e.g. NdFeB) is to introduce higher flux densities than other hard magnetic materials, which makes the motors more suitable for variable speed drive applications [1]. These machines have higher efficiency, power factor, output power per mass and volume, and better dynamic performances than other electrical machines. Thus, an axial flux PMSM is an attractive candidate, e.g. in ships propulsion systems, due to its qualities mentioned above and due to its simple mechanical configuration [2]. Moreover, modularity (several axial machines having the rotors mounted on a common shaft forming a multidisk machine) is also important especially when modifying the configuration of a ship propulsion system is a design requirement. In a double-sided machine, the disk with PMs rotates between the cores of two stators. This way, the internal type machine allows getting higher torque density in comparison with the external one which has one stator between two rotors. However, the disadvantage is that the distributed windings have end-windings of significant length when compared to coil conductors' active part. This results in a poor machine performance, as a significant part of the machine copper (i.e. more than 50% from the total copper in most machine designs) by producing heat instead of torque [3]. Concentrated windings can solve these problems. They have several advantages as: simple design, easier arrangement (e.g. closer vicinity of PMs to the exciting coils) and higher efficiency.

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Torque quality is essential for variable speed drive applications. There are two undesired pulsating torque components in PMSMs: the torque arising harmonic content of voltage and current waveforms (ripple torque) and the torque caused by the attraction between rotor PMs and the angular variation of stator reluctance(cogging torque). Many techniques for undesired pulsating torque minimization can be found in literature [1], and most of these techniques can be applied to axial flux PMSM. However, the high manufacturing cost of the axial flux machines will be even higher when these techniques are applied. For instance, skewing stator slots will not only boost the manufacturing cost of the axial flux machine stator but will complicate the manufacturing process as well. In these circumstances, a better proposal would be to select a pole and slot combination with a built-in geometric asymmetry that will give a higher average performance, as well as a lower cogging torque. *This is the only method, which does not reduce the power of the machine in the same time with the cogging torque.* Tooth-coil windings are generating also some winding fields. In order to avoid these undesirable effects, a large magnetic air-gap can be used. Thus, the aim of this paper is to propose a very compact construction that will meet the requirements for a robust, high torque density, 1 MW class, low speed PMSM.

2. **SPECIFIC DESIGN ELEMENTS**

The main default parameters of this novel axial flux PMSM are presented in Table 1. The machine consists of two stators and one disk type rotor as shown in Fig. 1 [4-7]. Each toroidal stator core is wounded from an electrotechnical laminated silicon steel tape; each stator core ring structure has opened slots on one side (or on both sides for stators of a multidisk machine).

Table 1

Default parameters of the axial PMSM

Rated torque	T [Nm]	65×10^3
Rated speed	n [rpm]	160
Rated voltage	V [V] Y	2 × 625
Rated power factor	$\cos\varphi$	1
No. of slots/pole/phase	$q = Q/2p/m = z/n$	21/20/3
Air gap length	δ[mm]	2 × 3
Permanent magnet	type	Nd-Fe-B
Remnant flux density	B_r [T]	1.25
Relative permeability	μ_r	1.05
Rated current density	G [A/mm^2]	5.0

A three-phase, double layer concentrated winding type (tooth-coil winding) is mounted into the slots of one side of the stators (or of each stator side in case of a multidisk machine). Thus, by having an appropriate short-pitching, the two-layer fractional slot winding degenerates into a tooth-coil winding [8]. The classical slot division into top and bottom layers changes into a side by side arrangement of the coils (see also the explanation sketch in Fig. 2).

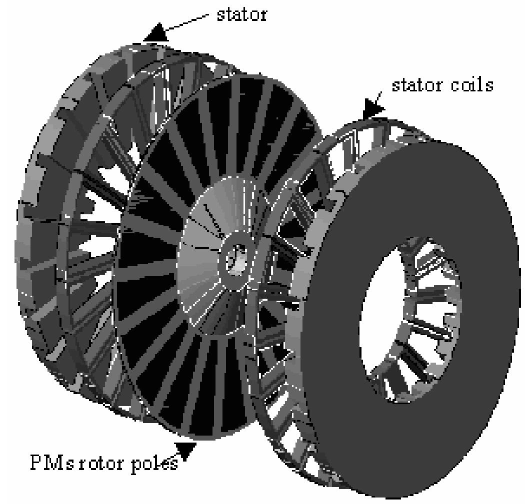

Fig. 1 – Scheme of the axial flux machine.

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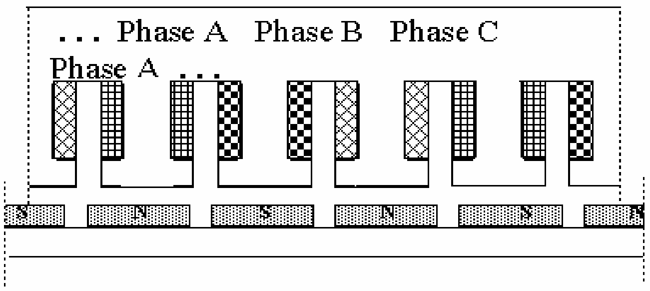

Fig. 2 – Tooth-coil winding (explanation sketch).

It is possible to obtain a high winding factor by choosing a good slot/pole combination [8, 9]. According to the voltage vector graph method [9], it has been obtained a high winding factor, $k_w = 0.953$, for the two layer concentrated winding with $q = 21/20/3$. Its sub- and super-harmonic winding factors may be calculated by using the formula:

$$\frac{\nu}{p} = \pm\frac{1}{n}(2mg + 2), \quad g = 0; \pm 1; \pm 2; \pm 3; \pm \ldots \tag{1}$$

Thus, it has been obtained the following sub- and super-harmonics: 2/20, -4/20, 8/20, –10/20, 14/20, –16/20, –22/20, –28/20, 32/20, –34/20, 38/20. The corresponding winding factors are: 0.126, –0.190, 0.033, 0.498, 0.530, –0.609, –0.946, –0.59, 0.498, –0.489, 0.166.

Fig. 3 illustrates the radial end-winding build of axial flux machines with equal active lengths: the single-layer concentrated winding has almost twice the radial end-winding build, compared to double-layer windings. The machine with double-layer concentrated windings has a great potential to be the most compact unit among the three types of axial flux electrical machines [9]. This assures also the best end-winding fixing system against the magnetization pulse power side effects (in magnetizing inductor mode of operation).

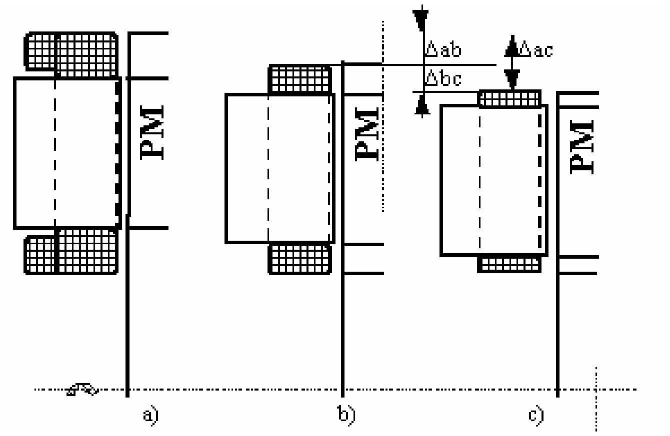

Fig. 3 – Comparison of the radial build of three axial flux machines with:
a) distributed, b) single-layer and c) double-layer concentrated windings.

The rotor core is fabricated with non-magnetic stainless steel in a disk form, and fixed to the shaft between the two stators, carrying axially magnetized NdFeB magnets forming the poles. The poles are inserted into holes opened in the rotor core disk; the disk and the PM poles have the same width and both are covered by a nonmagnetic plate (which is also part of the magnetic air-gap). The PMs being part of the magnetic air gap the axial flux PMSM has a linear behavior even under overload.

3. **FEM ANALYSIS ELEMENTS OF THE AXIAL PMSM**

The simulation of the axial flux PMSM can be done by using a simplified model in which a cylindrical cutting plane is introduced at the mean radius of the rotor poles. This axial section is unfolded into a 2D surface. The FEM modeling can be performed on such a surface. A simple, quasi 3D analysis method can be also performed by dividing the machine into three or more segments in radial direction [4-7].

Due to the asymmetry of the magnetic and electric circuits (q = 21/20/3 number of slots/pole/phase), it is necessary to consider an integer FEM field model (one stator only). Thus, Fig. 4 shows the no-load magnetic flux distribution for one relative position stator-rotor and the corresponding, quasi-sinusoidal air-gap magnetic flux density waveform along the opened, central circumference; the plane shown in the Fig. 4 is located at the axial section on the stator average diameter (here just half of the stator is represented due to the lack of space).

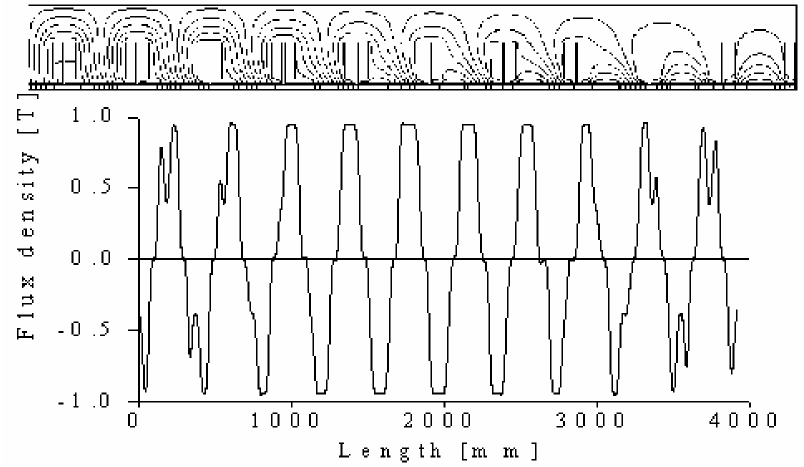

Fig. 4 – 2D FEM calculation of flux distribution in no-load operation
(half of a stator view only) and flux density variation at the air-gap level.

The fractional slot windings generate integer orders harmonics (both even and odd numbers). In the Wye connected three phase windings all harmonics, which are multiplies of three, are missing since their sinusoidal waves locally cancel each other. The even harmonics which appear in the magnetomotive force cancel also each other especially in the two layer windings because the bunch coil of one pole is shifted by an angle of π radians from the next coil. The two-layer fractional slot winding also produces sub- and super-harmonics.

The FFT analysis of the radial magnetic flux density variation along the air gap yields the magnitudes of the harmonics in the waves (Fig. 5). The rms value of each voltage harmonic induced in one stator phase by each magnetic flux density harmonic is given by:

$$E_{\nu} = 4.44\ \nu\, f_1\, k_{w\nu}\, N \frac{2}{\pi} B_{\nu} \frac{\tau}{\nu} l_s\,, \tag{2}$$

where: v is the harmonic order, f_1 – frequency of the fundamental, k_{wv} – winding factor for v-th harmonic, N – number of turns per phase, B_v – max. value of the v-th harmonic of the radial component of the magnetic flux density, τ – pole pitch for the fundamental wave along the air gap, l_s – active length of stator stack.

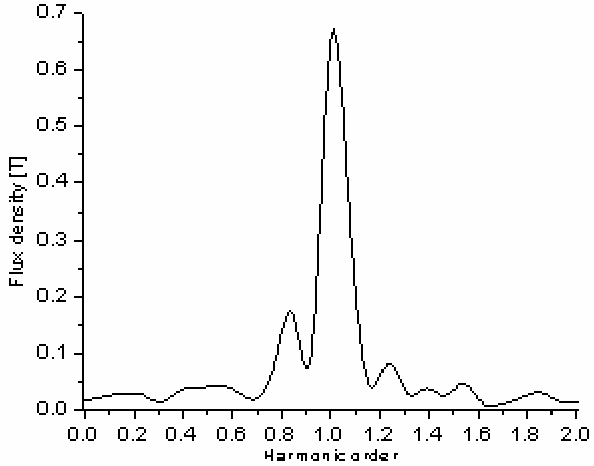

Fig. 5 – FFT analysis: harmonics of the magnetic flux density.

Finally, the resultant rms value of the emf induced in one phase of the stator winding is calculated as:

$$E = \sqrt{\sum_{v} E_v^{\,2}} . \tag{3}$$

The obtained value validates also the basic design calculation.

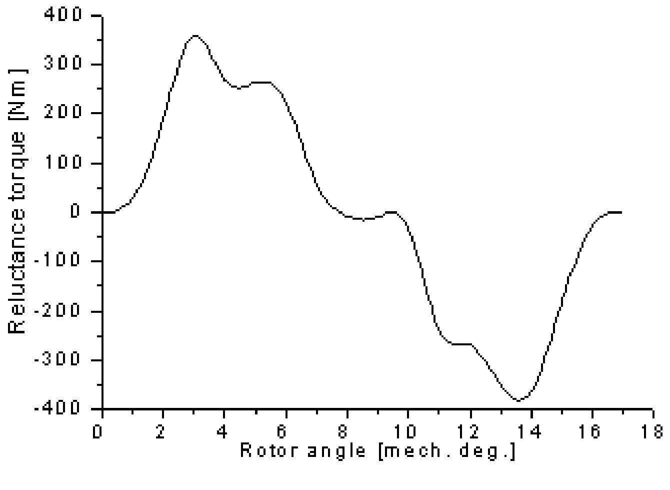

Fig. 6 – FEM calculated reluctance torque.

The reluctance torque of the axial flux machine was calculated for a slot pitch covered by a pole pitch using a 2D FEM code. The results are shown in Fig. 6. By using the discrete Fourier analysis, we obtained also the corresponding harmonics spectrum presented in Fig. 7.

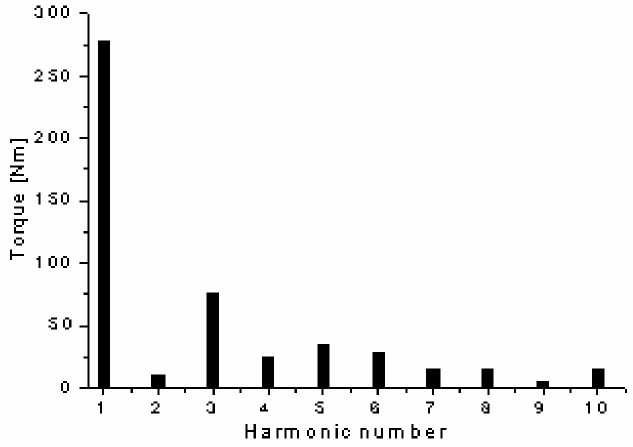

Fig. 7 – Harmonics spectrum of the reluctance torque.

The resulting cogging torque is shown in Fig. 8: it should be noted that the number of cogging periods per rotor revolution is given by the least common multiple (LCM) of the pole and slot numbers [9].

Thus, one slot pitch has 20 cogging periods, which means LCM = 20 × 21 = = 420 periods for one revolution. This is a high cogging frequency with low amplitude. The peak-peak value of the cogging torque is 0.7 kNm, being only a fractional percentage of the rated torque.

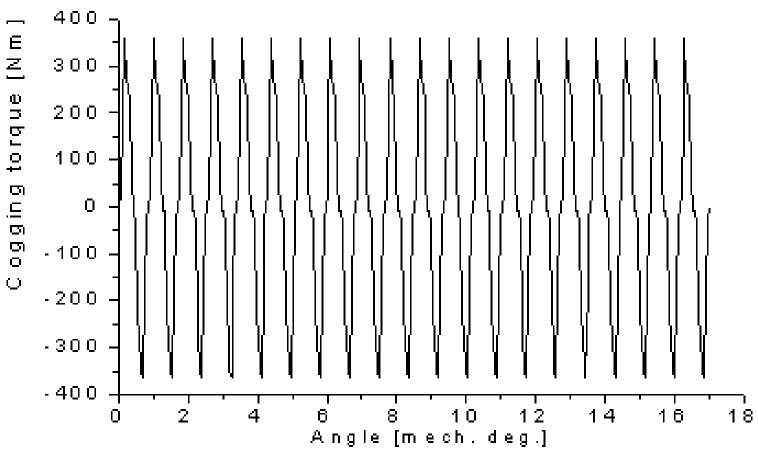

Fig. 8 – Cogging torque for a slot pitch; there are 20 cogging periods for one slot pitch, i.e. 420 periods for one revolution.

4. **CONCLUSIONS**

A double-layer, tooth-coil winding (a concentrated winding with a sub unitary number of slots per pole and phase, e.g. 21/20/3), offering small winding overhangs as well as simple windings and insulating techniques, can facilitate the construction of an performant axial flux PMSM.

The large effective air-gap allows avoiding the parasitic effect of a wide spectrum of tooth-coil winding fields. Therefore, the proposed axial flux PMSM has a linear behavior between torque and current up to max. 200 % rated current (four minutes) due to the fact that the PMs thickness is part of the magnetic air-gap.

The selected LCM of 420, results in a peak to peak value of about 1.25 % of the calculated cogging torque which is a small percentage of the rated torque. This is a very efficient and low cost method for minimizing the cogging torque which could be applied also to axial flux machines. Another advantage of the concentrated winding is that all the coils are in immediate proximity of the stator surface, which improves the quality of PMs rotor poles magnetizing process.

On the other hand, in comparison to a machine with distributed windings, the increased leakage inductance, results in higher winding losses and a need for higher inverter rating, but lower field weakening current in the constant power operation region.

Thus, based on the experience of a previous axial flux PMSM realization and on the successful magnetization of a PMSM rotor requiring the same level of energy, a model of the before presented machine is currently under consideration.

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