Fractional-Slot Concentrated-Winding Axial-Flux Permanent Magnet Machine with Core-Wound Coils

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***Abstract* - This paper presents the design, finite element analysis (FEA) and experimental verification of a single stator double rotor fractional-slot concentrated-winding (FSCW) axial-flux permanent magnet (AFPM) machine, with core-wound coils. The advantages that are obtained by adopting such coil construction, in terms of shorter end-winding connections, higher fill factor and mechanical robustness of the magnetic structure are highlighted. Machine performances both at no load and at rated load are analyzed through static FEA and a simple index is introduced, in order to compare induced losses in the permanent magnets for various machine configurations. The construction and experimental testing of a full scale prototype is described, in order to confirm the expected performances and to characterize the prototype in terms of losses, cogging torque and main machine parameters.**

***Index Terms*—Axial-flux permanent magnet (AFPM) machine, fractional-slot concentrated-winding, finite element analysis (FEA), cogging torque, losses.**

I. NOMENCLATURE

SPP – number of slots/pole/phase
l_{stat} – axial length of stator (tooth tip to tooth tip)
h_{slot} – slot height
w_{slot} – slot width
τ_s – slot pitch
R_o – outer radius
R_i – inner radius
N_c – number of coils
l_{cwt} – core-wound turn length
l_{twt} – tooth-wound turn length
l_{active} – length of active part of turn
$l_{cw\ end\ turn}$ – length of core-wound end turn
$l_{tw\ end\ turn}$ – length of tooth-wound end turn
P_{PM_loss} – eddy current losses in the permanent magnets
f_h – h-th time-harmonic frequency
B_h – flux density magnitude in the magnet associated with f_h
P_{mecc} – mechanical power
P_{el} – electrical active power
P_j – joule losses
$P_{no\ load}$ – no load losses
P_{add} – additional losses

II. INTRODUCTION

Fractional-slot concentrated-winding (FSCW) surface-mounted permanent magnet (SPM) machines have been the subject of significant and ongoing international research efforts in the past decade, [1]. It has been demonstrated that these machines can offer some significant advantages compared to standard SPM machines having overlapping, distributed windings. In particular, the use of non-overlapping, concentrated windings reduces the amount of copper used in the end-turns, thus reducing Joule losses, while the use of a fractional SPP can enhance flux-weakening capability, increase power density, reduce cogging torque and allow for fault tolerance [2]-[5].

Windings in FSCW SPM machines can be grouped into two basic categories: single layer (SL) or alternate teeth wound, and double layer (DL) or all teeth wound. These two types of windings have been extensively compared in literature in terms of torque production, torque ripple, rotor losses due to armature reaction, flux-weakening capability and fault tolerance. SL windings have a higher torque capability due to the fact that they generally have higher winding factors compared to their DL counterparts; however, SL windings produce increased torque ripple since the harmonic winding factors are also increased. Furthermore, SL windings produce an increased amount of mmf harmonics and sub-harmonics compared to DL windings; these mmf components which rotate asynchronously with the rotor induce losses in the PMs and in the rotor iron, thus the armature reaction rotor losses tend to be higher in the case of SL windings. From a field weakening perspective, SL windings are preferable since they possess an inherently larger self inductance; furthermore, they posses a much smaller mutual inductance, thus are better suited for fault tolerant applications.

Although the most significant amount of recent research on FSCW machines has been carried out on radial air-gap SPM machines, some research has also been done on axial air-gap (or axial-flux) permanent magnet (AFPM) machines. These machines are being increasingly used in a variety of industrial applications, for example in vehicle

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propulsion systems, [7]-[8]. Among the most significant contributions, Jack et al. [9] propose a single rotor double stator AFPM machine with 9 slots and 12 poles, i.e. SPP = 1/4, and a DL winding. In order to simplify machine construction, the stator core is formed from a strip-punched lamination while the teeth are made of compacted SMC. Di Gerlando et al. [10] propose a single stator double rotor AFPM machine with 36 slots and 38 poles, i.e. SPP = 6/19, and a DL winding. Marignetti et al. [11] propose a single stator single rotor AFPM machine with 24 slots and 28 poles, i.e. SPP = 2/7, and a SL winding: in this paper, in order to simplify construction, the stator core is made of SMC; furthermore, rotor losses have been found to be high particularly in loaded conditions. Jussilia et al. [12] propose a double stator single rotor AFPM machine with 12 slots and 10 poles, i.e. SPP = 2/5, and a DL winding. Plastic bonded magnets are used in order to reduce the eddy current losses induced by the mmf harmonics and by the stator slot openings.

In all the above designs, the armature coils are wound around the stator teeth (i.e., tooth-wound coils). On the contrary, this contribution investigates the design of a 10 kW FSCW AFPM machine having armature coils wound around the stator back-iron (i.e. core-wound coils), highlighting the advantages that are obtained by adopting such coil construction, in terms of shorter end-winding connections, high slot fill factor and mechanical robustness of the magnetic structure. Machine performance both at no load and at rated load has been analyzed through static finite element analysis (FEA) and a simple index has been introduced, in order to compare induced losses in the permanent magnets for the various machine configurations. A full scale prototype has been built and experimental tests have been performed in order to confirm the expected performances and to characterize the prototype in terms of losses, cogging torque and main machine parameters.

III. Machine Design

For the purpose of this investigation, no specific application has been targeted and therefore no particular constraints have been placed on machine design. However, requirements such as high torque density and mechanical robustness (which apply in general to lots of industrial and traction applications) still need to be fulfilled. For this reason, a 10 kW water-cooled single stator double rotor AFPM machine prototype has been designed, representative of an off-the-shelf, medium power SPM machine. The base speed has been set at 800 rpm, therefore the rated torque is fixed at 120 Nm.

The previous requirements can be satisfied by setting the outer radius of the stator to 148 mm and the inner radius to 100 mm, yielding an active length of the winding equal to 48 mm. Among all possible values, SPP = 2/5 has been selected because of the high fundamental winding factor (0.966). It has been decided to use 24 stator slots and 10 pole pairs, thus setting the rated supply frequency at 133.3 Hz. The stator is made of a 39 mm wide, index-punched, spirally wound lamination made of non-oriented M250-35 electrical steel. Each slot is 14 mm wide and the slot-to-tooth pitch ratio at the average radius is 0.43. The armature winding is made of a 6.3 x 1 mm flat ribbon conductor and each coil has 18 turns.

In order to obtain a rated back-emf equal to 84 V at 800 rpm, the rated rms flux linkage is set to 0.1 Vs (0.14 Vs peak flux linkage), and therefore the nominal torque is achieved with a 40 A rated current.

Twenty Nd–Fe–B permanent magnets are mounted on each rotor disk, facing the stator. The average width of the magnet is 29 mm, which is about 74% of the pole arc. The mechanical air-gap is chosen to be 2 mm. In order to achieve an average induction of about 0.8 T in the air-gap portion in front of the magnets, the permanent magnets' thickness is set to 5 mm. The main magnet properties are B_r = 1.23 T, H_{cB} = 8.9e5 A/m, and conductivity at working temperature is σ = 6.25e5 S/m. The rotor discs are made of soft iron and the magnets are glued on the discs. The total axial length of the machine's active parts, including both air-gaps, is 65 mm. Tab. I summarizes the rated values of the FSCW AFPM prototype.

TABLE I: Rated Values of the FSCW AFPM Prototype

Rated power	10 kW
Rated torque	120 Nm
Rated speed	800 rpm
Number of pole pairs	10
Number of slots	24
Rated back-emf	84 V
Rated current	40 A

IV. Winding Configuration

In [8] it is stated that for single stator double rotor AFPM machine configurations having SPP = 1 (full pitch winding), core-wound coils are to be preferred to teeth-wound coils. This coil layout always results in a non-overlapping winding (which is otherwise impossible to achieve) having the shortest possible end-turns, thus greatly reducing Joule losses. However, for machines having SPP < 1, non-overlapping concentrated windings with short end turns become possible also with tooth-wound coils; furthermore, the higher the number of pole pairs, the shorter the end turns. In this case, the advantages of one coil type with respect to the other are not as intuitive. In the following, a quantitative comparison is derived between the two layouts.

Fig. 1 shows a portion of the designed stator core, carrying tooth-wound coils (fig. 1a) or core-wound coils (fig. 1b); the coils are drawn for a SL winding although the subsequent analysis is valid for both SL and DL windings. Both coil arrangements require the same total number of coils and the same number of turns per coil, in