Optimized Design Considering the Mass Influence of an Axial Flux Permanent-Magnet Synchronous Generator With Concentrated Pole Windings

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In this paper, the efficiency optimization of an axial flux permanent-magnet synchronous generator with concentrated pole windings is examined for a 3.6 kW/2000 rpm combined heat and power application. Because the efficiency of the machine is important, specific measures are taken in order to reduce losses in the machine: thin laminated grain oriented material in the teeth, concentrated pole windings, and segmented magnets. A study of the influence of a limited set of geometry parameters on the efficiency of this type of machine is done, using both analytical and finite-element methods. In the analytical as well as in the finite-element model, the inherent 3-D geometry of the axial flux machine is approximated by multiple 2-D models at different radii in circumferential direction. Afterwards, the influence of mass on the optimal values of the geometry parameters and the efficiency is considered, and it is found that mass can be seriously decreased with only a small reduction in efficiency. Finally, the results of both methods are compared with measurements on a prototype to evaluate their validity.

***Index Terms*—Axial flux machine, efficiency, finite-element methods, optimization, permanent-magnet generators, sustainable energy.**

I. Introduction

THANKS to the high torque output at low speeds, the axial flux permanent-magnet synchronous machine (AFPMSM) is very suitable for, e.g., wheel motors [1] and direct drive wind energy applications [2]. AFPMSMs exist in different topologies and geometries, each having their advantages and disadvantages. The AFPMSM discussed in this paper is a single-stator double-rotor type with concentrated pole windings [3] (Fig. 1). Concentrated pole windings are preferable to distributed pole windings because of the ease in construction and the short coil ends. The short coil ends allow to reduce the power losses in the copper windings.

Although the nominal speed is 2000 rpm, a machine with 16 poles is chosen, leading to a rated frequency of 267 Hz. To avoid high iron losses in the stator teeth, thin laminated grain-oriented (GO) magnetic material is used. GO-material has the advantage over nonoriented (NO) material, because of the better magnetic characteristics when the flux direction in the major part of the teeth has only an axial component [4].

Although a multiphase system for concentrated pole windings is proposed in [5], a regular three-phase system is used in this paper. In order to obtain a high winding factor, the number of teeth is set to 15 resulting in a winding factor of 0.951 for the 16-pole machine [6].

In [7], the stator teeth are constructed by a single iron strip that is wound in a spiral construction. However, in the present paper each tooth is made separately and the winding is added before placing the tooth into the machine stator. This modular approach has many advantages, i.e., easy to fit winding, each tooth can be easily replaced, etc. The construction of the tooth itself is not an obvious case. Theoretically each lamination has a different geometry [Fig. 2(a)], which makes the lamination production complicated and expensive. Therefore, in this paper it is chosen to work only with two different lamination geometries that are stacked as shown in Fig. 2(c). This stack configuration has the advantage over Fig. 2(b) that the theoretical 3-D geometry is better approximated.

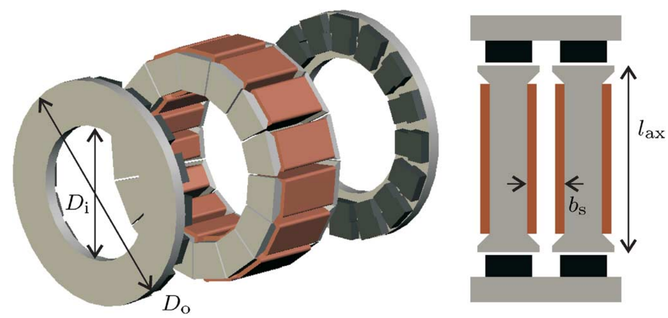

Fig. 1. Topology of the PMSM showing the parameters to optimize. (a) Overview. (b) Detailed view of a tooth pitch.

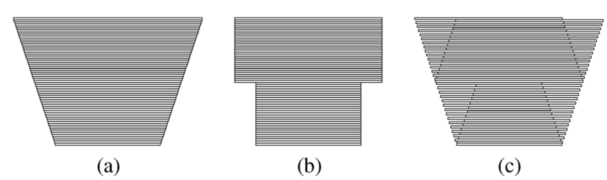

Fig. 2. Different stack configurations of the laminations: (a) ideal full overlap, (b) full overlap with two different lamination types, and (c) alternated with two different lamination types resulting in zones with only partial overlap.

In [8], the losses in the rotor discs, caused by the stator magnetomotive force (MMF) harmonics, are reduced by using soft magnetic composite (SMC) instead of solid construction steel. As the magnets are closer to the air gap than the rotor discs, the rotor loss is reduced by segmenting the magnets rather than by using SMC. Therefore, the rotor discs in this paper are made of 8

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mm thick solid construction steel on which the 16 T-shaped segmented magnets are glued. The magnets from Vacuumschmelze have a remanence of 1.26 T and are segmented in order to reduce eddy-current losses.

So far, thin laminated grain-oriented material in the teeth, concentrated pole windings, segmented magnets, and a high winding factor were introduced to improve the efficiency of the AFPMSG. In this paper, however, the influence of a limited set of four parameters which define the global design of the AFPMSG, is studied. Three of these four parameters are related to the global dimensions of the AFPMSG and are thus related to the mass of the AFPMSG. Actually, active mass should be used instead of mass, because only the masses of materials that participate in the energy conversion are included, i.e., mass of magnetic material, mass of copper windings, and the magnet mass. Masses related to the mechanical structure are thus not included here. However, an increase of active mass requires a more robust mechanical construction and thus the mass of the entire machine will increase. The materials of teeth, magnets, rotor back-iron, and windings are fixed during the optimization, making the material cost proportional to the masses of these materials. The material cost is not taken into account in the optimization. However, as the material cost is proportional to the masses of the active materials, less active mass will result in a lower material cost.

The goal of this research is to investigate the mass influence on the efficiency of the AFPMSG. The study of cogging torque and torque ripple, which is the object of much recent research [9]–[11], has not been extensively examined in this paper. However, due to the combination of 16 magnets and 15 stator teeth, the machine has no symmetry and therefore the cogging torque and torque ripple are expected to have a small period and amplitude.

II. Analytical and Finite-Element Model

Despite the inherent 3-D geometry of the AFPMSG, analytical models as well as FEM are very often 2-D models taken at the average diameter. Although the computation time is low compared to 3-D FEM, these models are often not accurate enough. A compromise between both computation time and accuracy is found in [12] and [13] where a “quasi 3-D” approximation is proposed. This “quasi 3-D” approximation defines multiple 2-D models at different radii in circumferential direction. Afterwards, the global solution is found by a weighted summation of the contribution of each computation plane (CP). The number of computation planes is again a tradeoff between calculation time and accuracy. Due to the many evaluations in the optimization procedure, only two computation planes with equal thickness are used in the preliminary design [Fig. 3(a)]. Once the optimization is performed, a more accurate approximation of the selected geometry is performed using six computation planes with unequal thickness [Fig. 3(b)]. In order to take the T-shaped magnet and the lamination stack configuration into account, at least two CPs are necessary. Experimentally, it was found that 6 CPs with nonequal thickness are enough to achieve sufficiently accurate simulation results.

A. Analytical Model

An analytical model of the air-gap flux density distribution allows the calculation of important design parameters like the electromotive force (EMF) and cogging torque. The air-gap flux density distribution can be expressed as

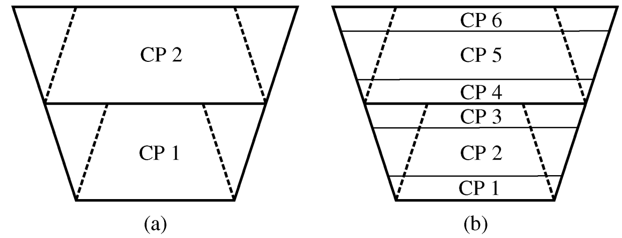

Fig. 3. Sectioning of the 3-D in geometry into the different computation planes (CP): (a) used in the optimization, and (b) used in simulations.

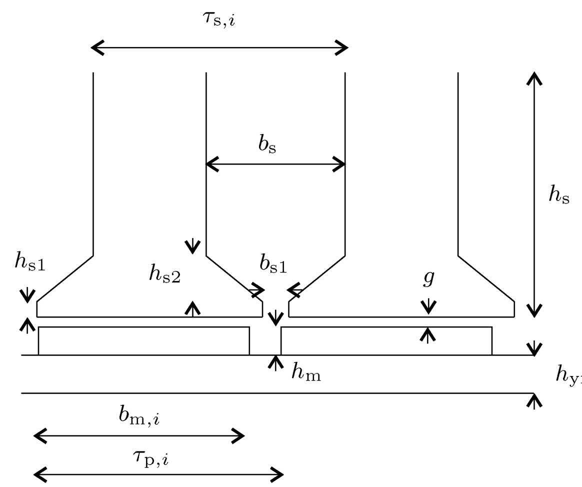

Fig. 4. Geometry parameters of the AFPMSG in a CP.

$$B_{\mathrm{ag},i}(x) = \tilde{\lambda}_i(x) B_i(x) \tag{1}$$

where $B_i(x)$ is the flux distribution in the ith CP caused by the permanent magnets calculated by (2) which is proposed in [14]

$$B_i(x) = -\sum_{n=1,3,5,\ldots}^{\infty} \frac{\frac{8B_\mathrm{r}}{n\pi}\sin\left(\frac{\alpha_{\mathrm{p},i} n\pi}{2}\right) \mathrm{e}^{-\frac{n\pi g'_i}{\tau_{\mathrm{p},i}}} \cos\left(\frac{n\pi x}{\tau_{\mathrm{p},i}}\right)}{\left(\mathrm{e}^{-\frac{2n\pi g'_i}{\tau_{\mathrm{p},i}}}+1\right) + \frac{\mu_\mathrm{m}\left(-\mathrm{e}^{-\frac{2n\pi g'_i}{\tau_{\mathrm{p},i}}}+1\right)\left(\mathrm{e}^{-\frac{2n\pi h_\mathrm{m}}{\tau_{\mathrm{p},i}}}+1\right)}{\left(\mathrm{e}^{-\frac{2n\pi h_\mathrm{m}}{\tau_{\mathrm{p},i}}}-1\right)}}. \tag{2}$$

In these equations, Q_s is the number of slots, B_r the remanent flux density of the permanent magnets, and $\alpha_{\mathrm{p},i}$ is the ratio between the magnet width $b_{\mathrm{m},i}$ and the pole pitch $\tau_{\mathrm{p},i}$. All other parameters are defined in Fig. 4.

The effect of the slot openings is modeled by the relative permeance function $\tilde{\lambda}_i(x)$ introduced in [15] given by

$$\tilde{\lambda}_i(x) = \frac{\lambda_i}{\frac{\mu_0}{g+h_\mathrm{m}/\mu_\mathrm{m}}} \tag{3}$$