Coupled Electromagnetic and Thermal Analysis of an Axial Flux PM Machine

Hendrik Vansompel1,2, Alireza Rasekh3, Ahmed Hemeida1,2, Jan Vierendeels3, and Peter Sergeant1,2

1Department of Electrical Energy, Systems and Automation, Ghent University, Ghent 9000, Belgium
2Department of Industrial Technology and Construction, Ghent University, Ghent 9000, Belgium
3Department of Flow, Heat and Combustion Mechanics, Ghent University, Ghent 9000, Belgium

The rotor discs in axial flux permanent magnet (PM) machines have similar properties as a radial fan, and therefore, the convective cooling may have a significant influence on the thermal design of these machines. To research the impact of convective cooling on the thermal properties of axial flux PM machines, a coupled electromagnetic and thermal model is introduced in this paper. This technique models a segment of the stator and the rotor only and links them together by analytical equations of the convective heat transfer at different boundaries of the machine model. This results in an accurate and time efficient multiphysics model. The coupled electromagnetic and thermal modeling technique is validated with measurements on a 4 kW axial flux PM machine having the yokeless and segmented armature topology.

Index Terms—Axial flux, multiphysics, permanent magnet (PM) machine, thermal analysis.

I. INTRODUCTION

As the rotor discs in axial flux permanent magnet (PM) machines have similar properties as a radial fan, the convective heat flux will have a significant influence on the thermal design of the machine.

In the design of axial flux PM machines, full 3-D multiphysics modeling [1] seems inevitable. Nevertheless, for the electromagnetic modeling, multilayer 2-D finite element method (FEM) [2], [3] is introduced as an alternative to 3-D FEM [1], [4]–[6]. This modeling technique reduces the computational time, while the influence on the accuracy remains very limited.

For the thermal modeling, this multilayer technique becomes impractical as the end effects are very important due to the relatively high inner to outer diameter ratio, which is typical for most axial flux PM machines.

Therefore, this paper introduces a thermal modeling technique that reduces the full transient 3-D-model, in which both Navier Stokes and thermal conduction equations are included, into a segment of the stator and the rotor where the convective heat flux equations in the volumes are solved, and the convective heat fluxes at the boundaries are defined by means of analytical equations. These analytical equations are a function of two dimensionless numbers [7] and are based on computational fluid dynamics (CFD) analysis. In this CFD, gravity is included so that the whole machine has to be modeled.

The advantage of the 3-D thermal FEM representing a segment of the stator and the rotor is a detailed temperature distribution in the different machine parts, which is less present when using 2-D FEM approximations [8], analytical equations [9], or lumped parameter models [10], [11]. Moreover, a detailed FEM is mostly required for the evaluation of advanced cooling systems [5], [12]–[14].

The coupled electromagnetic and thermal modeling technique is validated with thermographic measurements on a 4 kW highly efficient axial flux PM generator having the yokeless and segmented armature topology [5].

II. COUPLED ELECTROMAGNETIC AND THERMAL MODEL

A. Electromagnetic Modeling

As mentioned in Section I, the multilayer 2-D FEM technique [2] is used in the electromagnetic analysis. With respect to the coupled electromagnetic and thermal modeling, the calculation of the different power losses in the machine is the key point. These electromagnetic power losses will be the sources in the thermal modeling. In this analysis, the losses in the stator cores, the winding, and the PMs are considered.

The multilayer 2-D FEM technique is used to simulate the flux density distribution in the stator cores as a function of the rotor position. A posteriori, this flux density pattern is used to calculate the core losses using the principles of loss separation [15].

The detailed calculation of the eddy current losses in the PMs was done earlier for this prototype machine in [3]. Here, the multilayer 2-D FEM technique is used to reconstruct the magnetic flux density seen by a PM. Subsequently, this time varying magnetic flux density pattern is used to calculate the eddy current losses in the PMs.

As the thermal time constant is much different from the electric one, the time average values of the electromagnetic power losses are used as source terms in the thermal model.

B. Thermal Modeling

The key point in the thermal modeling is the introduction of analytical expressions for the convective heat transfer in disc type electrical machines, which is developed in [7].
Here, the flow is characterized by the rotational Reynolds number
\[ \text{Re} = \frac{\Omega D^2}{4\nu} \]  
and the gap size ratio
\[ G = \frac{2g}{D} \]
where
- \( \Omega \): angular velocity of the rotor;
- \( D \): diameter of the rotor;
- \( \nu \): kinematic viscosity of air;
- \( g \): thickness of the air gap.

The analytical equations are valid within the practical range of the axial flux PM machines, i.e., \( 4.19 \times 10^4 \leq \text{Re} \leq 4.19 \times 10^5 \) and \( 0.00333 \leq G \leq 0.04 \).

In this model, the following assumptions have been made.

1) The temperatures of the rotor surface, stator surface, and surrounding environment are isothermal.
2) Air is considered as an incompressible ideal gas, so its density varies with temperature and the other properties are independent of temperature.
3) Radiation effect between the rotor and the stator is considered to be negligible.
4) Buoyancy effect is considered.

The heat flux of the isothermal surface \( i \) defined in Figs. 1(a) and 2(b) is defined by
\[ \overline{q}_i = \overline{h}_i (T_{\text{surf},i} - T_{\text{ref},i}) \]  
where
- \( \overline{h}_i \): average convective heat transfer coefficient of surface \( i \);
- \( T_{\text{surf},i} \): temperature of surface \( i \);
- \( T_{\text{ref},i} \): average bulk fluid temperature of adjacent volume \( V_i \).

The bulky fluid temperature is expressed by
\[ T_{\text{ref},i} = a_i T_R + b_i T_S + (1 - (a_i + b_i)) T_A \]
where
- \( T_R \): temperature of the rotor;
- \( T_S \): temperature of the stator;
- \( T_A \): ambient temperature.

Subsequently, the average Nusselt number for each surface is expressed by
\[ \overline{N}u_i = \frac{\overline{h}_i l_i}{k} \]
where
- \( l_i \): characteristic length;
- \( k \): thermal conductivity of air.

The analytical approach assumes that the correlation which expresses the variation of \( a_i, b_i, \) and \( \overline{N}u_i \) with \( \text{Re} \) and \( G \) can be written as a product of two 1-D functions
\[ a_i = a_i^* f_i,1(G) \times f_i,2(\text{Re}) \]  
\[ b_i = b_i^* g_i,1(G) \times g_i,2(\text{Re}) \]  
\[ \overline{N}u_i = \overline{N}u_i^* y_i,1(G) \times y_i,2(\text{Re}) \]
The fitting of the coefficients for the different surfaces in the machine is done using CFD results. The values of the coefficients can be found in [7].

As the analytical equations (6)–(8) are used to express the convective heat flux at different boundaries in the machine, the thermal model can be simplified as follows.

1) The model for the stator and the rotor can be separated.

2) Due to thermal periodicity, only one segment of each is modeled.

This results in the models presented in Figs. 1 and 2 for the stator and the rotor, respectively.

Transient simulations on the stator and the rotor model are carried out. Inside both the geometries, the following equation is solved:

$$\rho_j C_{p,j} \frac{\partial T}{\partial t} + \nabla \cdot (-k_j \nabla T) = q_j$$

(9)

where

- $\rho_j$ density of material $j$;
- $C_{p,j}$ heat capacity of material $j$;
- $k_j$ thermal conductivity of material $j$.

The anisotropy of the laminated silicon steel stator cores and windings is included by specifying a tensor for the thermal conductivity rather than a scalar value.

The resulting temperature distribution at the stator and the rotor surface is used to calculate the reference temperatures expressed by (4). In addition, the temperature dependence on the electromagnetic losses, e.g., the temperature-dependent stator resistance is considered. This procedure is repeated until the temperature profile stabilizes.

To illustrate the possibilities of the coupled model, the influence of the rotational speed on the temperatures in the machine at no load is presented. A variation of the rotational speed has a direct influence on the rotational Reynolds number (1). By consequence, it has an influence on the bulky reference temperature (4) and the Nusselt number (5) through the analytical equations (6)–(8).

Whereas an increasing rotational speed results in increasing convective heat coefficients in the air gap and at the rotor backside, its corresponding higher frequency will result in increasing core losses in the stator cores as well.

In Fig. 3, the temperatures in the different parts of the machine resulting from the coupled electromagnetic and thermal analysis are presented for a speed range from 0 to 2500 r/min.

Temperature differences between stator cores and windings are negligible due to the good thermal contact and the high thermal conductivity of both materials. The temperatures in the magnets are significantly lower than those of the stator, which is a result of its direct mounting on the well, by convection, cooled rotor discs.

### III. Experimental Validation

The presented coupled electromagnetic and thermal analysis is validated on an experimental setup. In this setup, the axial flux PM machine prototype, shown in Fig. 4(b) and having the main characteristics listed in Table I, is used as a generator where it is powered by an asynchronous motor.

To measure the electromagnetic losses, the setup is equipped with a three-phase power analyzer and a torque sensor between both machines.

A detailed experimental validation of the electromagnetic properties, i.e., electromotive office, torque, and power losses, of the axial flux PM machine prototype was presented in [2]. Here, higher core losses were measured. These higher losses were explained by material degradation due to laser cutting. Therefore, a compensation for the source terms in the thermal model is done.

The validation of the coupled electromagnetic and thermal analysis is done at no load and at 1500 r/min, for a 1.5 mm air-gap thickness. Thermographic images using a Testo 875-2 were made every 3 min during 45 min.

The temperatures at the rotor and the stator surface can be derived from the thermographic images at the different points in time. Measured values are limited due to the thermal limits of the epoxy structural elements in the current preliminary prototype. This prototype was intended for the evaluation of the electromagnetic properties, and thermal optimization was not carried out at this moment. Notwithstanding the limited range of thermal measurements, good agreement with the simulated ones is found in Fig. 5. In addition, the recorded temperature distribution is very similar to the simulated one.

The measured and simulated temperature distributions are presented in Fig. 4(a) and in Figs. 1(b) and 2(b) for the stator and the rotor, respectively. Here, the huge temperature gradient over the epoxy compound in the stator and the rotor is clearly visible. As a consequence, the heat generated in the stator...
cores of the machine is evacuated radially through the machine winding and axially by conductive flux from the stator cores to the air gap where convective cooling from the stator to the rotor occurs. Despite the heat flux toward the rotor, good convective cooling at the backplane of the rotor results in a limited temperature of the PMs.

**IV. CONCLUSION**

In this paper, a coupled electromagnetic and thermal analysis of an axial flux PM machine was discussed. Analytical equations for the convective heat transfer were introduced and used to decouple the model for the stator and the rotor. As a consequence, thermal periodicity allowed to carry out the thermal simulations on a segment of the stator and the rotor only. Therefore, the simulation time is strongly reduced compared with fully coupled transient 3-D simulations, while thermographic measurements on a prototype machines proved the accuracy of the coupled model.

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**REFERENCES**


