CI-11

Coupled Electromagnetic and Thermal Analysis of an Axial Flux PM Machine.

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I. Introduction

Due to their high torque density and an excellent efficiency, axial flux PM machines are favorable for vehicle propulsion and wind energy conversion. Although many effort was already done to simulate the electromagnetic properties of the machine using full 3D or multilayer-2D simulations, the work towards modelling of the thermal behavior is still very limited.

As the disc-shaped rotors will operate as a fan during rotation, convective heat transfer in the air gap will have a major influence on the thermal design of the machine. Rather than performing full 3D combined fluid and thermal analysis, empiric analytical expressions based on CFD are used in this work to define the convective heat coefficient in different parts of the machine. The final thermal simulations are carried out for the stator and rotor individually, where only a segment needs to be modelled due to thermal periodicity. As a result, the use of this coupled modelling technique results in a significant decrease of the overall simulation time.

The coupled electromagnetic and thermal modelling techniques are illustrated on a 4kW axial flux PM machine having the yokeless and segmented armature (YASA) topology. Finally, both the electromagnetic and thermal simulation results were validated on a preliminary prototype.

II. Coupled Electromagnetic and Thermal Modelling

In the first step of the analysis, the electromagnetic behavior of the machine is modelled. The results from the electromagnetic field computations are used to calculate the corresponding losses in post-processing. In a second step, these losses are used as the heat sources for the thermal simulations.

As the axial flux PM machine has an inherent 3D structure, multilayer-2D simulations [1] are used to obtain the electromagnetic properties such as flux-linkage, back-emf and (cogging) torque.

In postprocessing, the magnetic flux density pattern of the different layers in the core is used to calculated the core losses. The solutions for the air gap magnetic flux density pattern of each layer are combined and used for a time harmonic calculation of the eddy current losses in the permanent magnets [1]. Together with the Joule losses in the machine winding, the iron losses in the stator cores and eddy current losses in the PM's are used as the source terms in the thermal simulations.

As the thermal process is particularly slow with respect to the electromagnetic one, the time average values of the losses are chosen as a source in the thermal model. Instead of using full 3D combined fluid and thermal analysis, empirical equations derived in [2] are used to model the convective heat transfer from each of the surfaces near the air gap region. Next to an empirical formula for the convective heat coefficients of each surface, an expression for the reference temperatures is also derived using dimensionless numbers. The reference temperature is the bulk fluid temperature of the domain near each surface which can be expressed as a function of the average stator, rotor and ambient temperature.

The mean advantage of these empirical equations is that the stator and rotor can be modelled individually and that only a segment (Fig. 1) needs to be modelled due to thermal periodicity.

As the values of the reference temperatures are a function of the average stator and rotor temperature, iterative calculation is required as the temperatures in stator and rotor are a function of the thermal sources in the machine. Although some iterations are required, this modelling technique is significantly faster compared to full 3D combined fluid and thermal analysis.

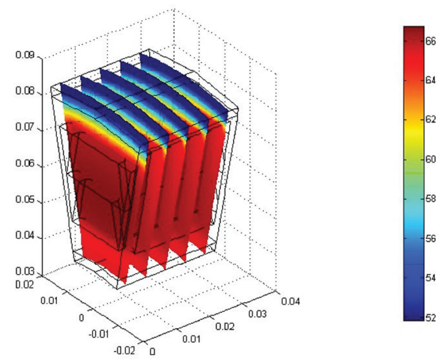
III. Validation

To validate the results from both the electromagnetic and thermal simulations, a preliminary prototype was constructed and tested into a measurement setup in generator mode. With the calculated electromagnetic losses as an input of the thermal simulations, good agreement between the thermal simulations (Fig. 1) and measurements (Fig. 2) was found.

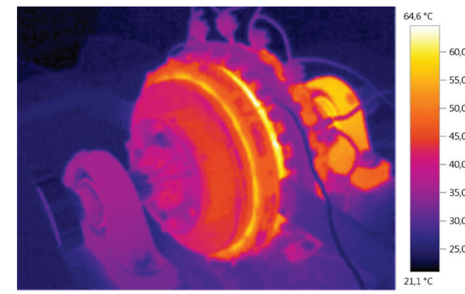
IV. Conclusion

In the presented modeling technique, electromagnetic simulations using a multilayer 2D model were used to evaluate the electromagnetic losses in the machine. These losses were used as the heat sources in the thermal simulations. Thanks to the use of empirical analytical formulas to predict the convective heat flux near the air gap region, fast evaluation of the temperature distribution in stator and rotor was made possible. The accuracy of the coupled modelling technique was validated on a preliminary prototype.

[1] Vansompel, Hendrik, Peter Sergeant, and Luc Dupré. "A multilayer 2-D–2-D coupled model for eddy current calculation in the rotor of an axial-flux PM machine." Energy Conversion, IEEE Transactions on 27.3 (2012): 784-791.
[2] Rasekh, Alireza, Peter Sergeant, and Jan Vierendeels. "A parametric-CFD study for heat transfer and fluid flow in a rotor-stator system." 11th World congress on Computational Mechanics (WCCM XI); 5th European conference on Computational Mechanics (ECCM V); 6th European conference on Computational Fluid Dynamics (ECFD VI). 2014.



Thermal simulation of a stator segment at 600rpm and no load (steady state).



Steady state temperature measurement on the prototype machine at 600rpm and no load (steady state).