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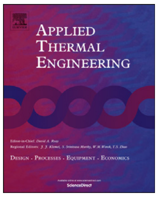

Research paper

Analysis of relevant aspects of thermal and hydraulic modeling of electric machines. Application in an Open Self Ventilated machine

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HIGHLIGHTS

- Coupled hydraulic and thermal models for an OSV induction machine are presented.
- Different approaches to calculate some parameters for electric machines are proposed.
- The use of dimensionless correlations for the calculation of convection is suggested.
- The results from the models are compared against reference values, and then analyzed.
- The relative importance of some parameters through a sensitivity analysis is reasoned.

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ABSTRACT

Prediction of the thermal behavior of electric motors in the early design stage is crucial in any design process. The most popular prediction methods are analytical, and based on the lumped parameter model approach. These methods require experimental data in order to obtain accurate results, but this data is often not available. This paper deals with the problem of the lack of experimental data for an Open Self-Ventilated (OSV) Induction motor and reviews some of the most controversial parameters in thermal modeling, such as the bearings model and the axial conductivity of the lamination stack. Due to the nature of the OSV machine, through ventilation is also investigated, and a hydraulic model with improvements focused on rotational effects observation is presented. Moreover, the heat transfer in end spaces and ducts is studied, using dimensionless analysis correlations, along with focusing on new hydraulic phenomena, such as the development of the flow and the roughness effect. An implementation of a thermal circuit for an OSV machine that has good agreement with reference results is used to compare heat transfer coefficients used regularly for Totally Enclosed Fan Cooled (TEFC) enclosures. Finally, a sensitivity analysis is carried out on some parameters to determine their importance.

1. Introduction

The thermal analysis of electric machines has been an interesting research field for both industry and investigators, since the capabilities of modern-age computers make it possible to run hard-to-achieve calculations in a relatively short time. During the past two decades, there have been several developments in this research field [1], from the first, yet simpler, thermal networks that represents the main paths of heat flows [2,3], to the advanced and very parameterized thermal networks that models all the thermal paths [4] and for such a variety of applications like the analysis of very large machines [5] or the study of the heating produced by faults [6].

Lumped Parameter Thermal Models (LPTM) have been of great interest for researchers [2,7,8]. The LPTM is the main tool for a fast yet accurate thermal analysis. Additionally, in combination with coupled electromagnetic models [9,10] and hydraulic models [11], it permits machines to be designed by taking into account every thermal aspect from the very first steps of the design process. However, a common drawback to this approach can make it useless to a designer: there is a need for experimental data in order to tune

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parameters that are very important in order to obtain accurate results. Although several commercial software packs, such as Motor-CAD [12], have provided experimental data through the years and are reliable for working with a specific design, this data may not be contrasted for a special motor topology.

In this article, some alternative methods for calculating key parameters for a thermal analysis are presented, focusing on conduction and convection in some parts of the machines. The methods presented, some of which are selected from an extensive literature review, can provide reference values for a design from scratch. Although the selection criteria were applied to an OSV machine topology, they can be applied to other topologies. They also allow an adjustment when experimental data is available. The parameters examined in this article are:

- The equivalent axial thermal conductivity for a magnetic stack.
- A bearing model.
- The rotational effects for through ventilation models.
- The heat transfer coefficients for ventilation ducts.
- The heat transfer coefficients in end space zones.

First, a thermal model for an Open Self Ventilated (OSV) motor with form-wound windings is presented, with the methodologies for calculating the above mentioned parameters, and coupled with a through ventilation model. The results obtained with this model have been compared with results from reference software Motor-CAD and with an adjusted model from a motor manufacturer. Finally, a sensitivity analysis has been run on the parameters in order to determine their importance in the overall design results.

2. Description of the thermal model

A thermal model for an OSV machine has been implemented in Matlab [13]. A cutaway view of the machine and its parts can be seen in Fig. 1. To model the machine, the thermal hypotheses proposed in Ref. [3] are used to represent the thermal behavior in generic cylindrical elements, with the following modifications in the model of thermal resistances:

- In a practical case, there would be a considerable temperature difference between the input and output sides of the machine, caused by the self-ventilation. Therefore, a non-symmetric model must be implemented.

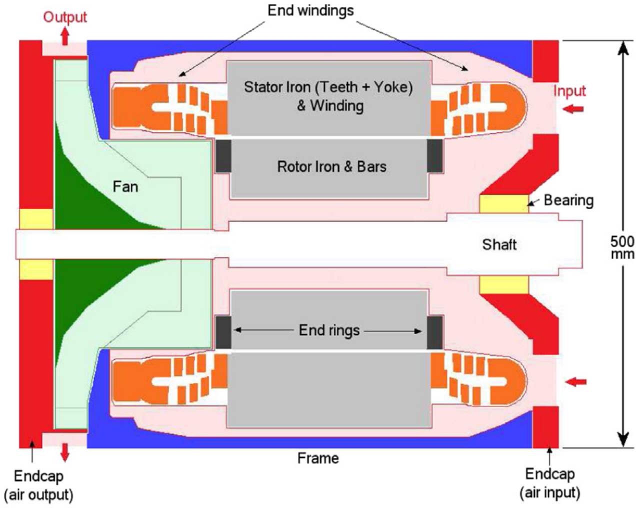

Fig. 1. Solid elements of the machine (cutaway view).

- In order to reduce the size and complexity of the thermal circuit, the negative resistances that account for variations of the temperature due to heat generation are removed from the generic component given in Ref. [3].

To represent a general cylindrical component, a reduced thermal network of 4 resistances was used (Fig. 2). The expression for calculating these resistances can be seen in Eqs. (1)–(3); the first two equations represents heat transfer in the radial direction, and the last equation represents the axial direction. The losses, P, are represented as current generators and attached to each component, where needed.

$$R_1 = \frac{1}{4\pi\,\lambda_{\mathrm{rad}}\,L}\left[\frac{2r_{\mathrm{out}}^2\ln\left(\frac{r_{\mathrm{out}}}{r_{\mathrm{in}}}\right)}{r_{\mathrm{out}}^2 - r_{\mathrm{in}}^2} - 1\right] \tag{1}$$

$$R_2 = \frac{1}{4\pi\,\lambda_{\mathrm{rad}}\,L}\left[1 - \frac{2r_{\mathrm{out}}^2\ln\left(\frac{r_{\mathrm{out}}}{r_{\mathrm{in}}}\right)}{r_{\mathrm{out}}^2 - r_{\mathrm{in}}^2}\right] \tag{2}$$

$$R_3 = R_4 = \frac{L}{2\pi\,\lambda_{\mathrm{ax}}\left(r_{\mathrm{out}}^2 - r_{\mathrm{in}}^2\right)} \tag{3}$$

The stator yoke and teeth, frame and end caps, rotor yoke and bars, axis and bearings were thermally represented in the model using cylindrical components. The resulting thermal circuit is shown in Fig. 3, where each node represents the temperature of the cited parts and thermal resistances representing the heat paths. The losses generators for each parts can be noticed where used. Convection paths can be seen with a discontinuous line.

A single-node approximation is used for the temperature inside the slot, $T_{w,s}$, with two connected nodes for calculating the end-winding temperature, T_{endw1} and T_{endw2}, one for each side. A cuboidal approach [14] is used to represent heat transfer in the three dimensions of the form-wound windings, instead of solutions more suitable for random-wound windings, such as layered models [15]. The effective thermal conductivities were calculated using a weighted average based on the insulation layers thicknesses [12].

2.1. Equivalent thermal conductivity of magnetic stack in axial direction

The heat transfer in the magnetic stack has been modeled using two different thermal conductivities, one for the axial direction and one for the radial direction [3]. The problem with the conductivity in the axial direction is the value to be taken of this parameter, due to the complexity of the materials involved and the interface gaps [12,15].

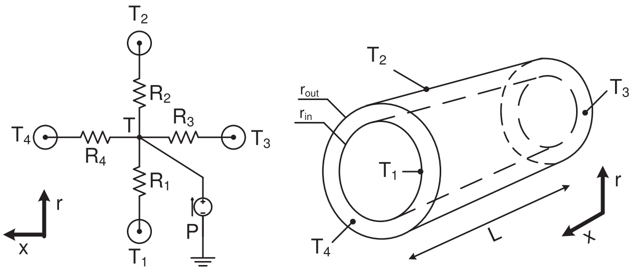

Fig. 2. Generic model for a cylindrical component.