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Research Paper

Wafter design for totally enclosed electric machines

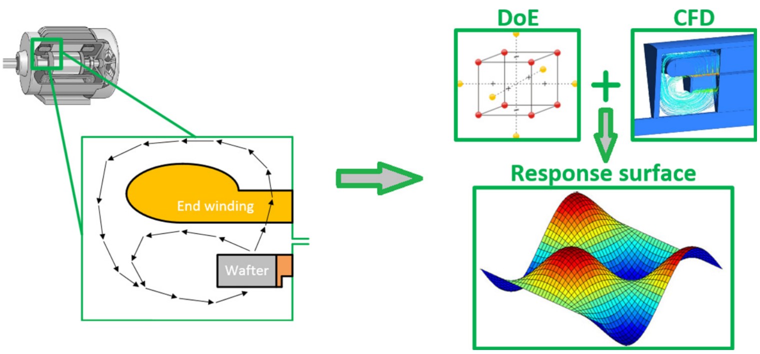
Marco Satrústegui *, Gurutz Artetxe, Ibon Elosegui, Miguel Martinez-Iturralde, Juan C. Ramos

Ceit and Tecnun (University of Navarra), Paseo Mikeletegi 48, San Sebastian 20009, Spain

HIGHLIGHTS

- Design criteria of wafters for totally enclosed electric machines.
- An experimentally validated CFD model for the modelling of electrical machines.
- Statistical models to predict the convective heat transfer in the end windings.
- The influence of wafters in the working temperatures of a particular machine.

GRAPHICAL ABSTRACT



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ABSTRACT

A computational fluid dynamics (CFD) model representing the effect of wafters in a totally enclosed electric machine is presented, introducing the most relevant theoretical assumptions and simplifications. The validation of the model is conducted through experimental measurements. From the CFD simulation data, a second-order response surface is developed using statistical tools, from which the wafters' influence on the convective heat transfer from the stator end windings is predicted. Wafter design criteria are obtained from the response surface information. Finally, a specific case is analysed, showing through CFD simulations that temperatures in the machine are reduced by including wafters in the design.

1. Introduction

Power density and rotation speed in electric machines have augmented significantly in recent years for many applications. This trend is resulting in an increase in losses for small volumes, and the cooling system is turning out to be a crucial aspect of the design. There are many options that provide very good cooling capabilities; liquid cooling through a jacket over the stator back iron is a widespread option [1–4], and direct oil-cooled systems provide very effective cooling throughout the machine [5,6], although it creates extra friction losses which could be very limiting as the rotation speed increases. Moreover, there are many combinations of both systems in the literature. For example, Equipmake Ltd. [7] proposed a dual cooling system that pushes oil through the slots and air through the rotor, Porsche [8] manufactured a 95 hp motor cooled with an oil jacket combined with an air induction system, and Lim in [9] developed an oil spray cooling system for in-wheel motors in electric vehicles.

This article focuses on totally enclosed cooling systems, which are widely used for traction applications, such as electric vehicles or trains [10]. This cooling arrangement shows significant limitations when it comes to rotor cooling [11], and the design also turns the end windings into a limiting factor, as they often become a

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* Corresponding author.
E-mail address: msatrustegui@ceit.es (M. Satrústegui).

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Nomenclature

Latin symbols

b_{wafter}	width of the wafter
CCD	central composite design
CFD	computational fluid dynamics
C_p	specific heat (J/kg K).
Cu	copper
$D_{Ext\text{-}Rotor}$	rotor external diameter (mm)
$D_{Ext\text{-}Stator}$	stator external diameter (mm)
DE	drive end
DoE	design of experiments
D_{Shaft}	shaft diameter (mm)
f	factorial in the parametric study
GCI	grid convergence index
$h_{endwinding}$	convective heat transfer coefficient in the stator end windings (W/m^2·K)
h_{tot}	mean total enthalpy
h_{wafter}	height of the wafters (mm)
$l_{end\text{-}air}$	distance between the end-plate and the end winding (mm)
$l_{endwinding}$	axial length of the stator end winding (m)
$l_{Stack\text{-}Stator}$	axial length of the stator stack (mm)
l_{wafter}	axial length of the wafters (mm)
N	rotational speed (rpm)
NDE	non-drive end
n	Number of parameters in the parametric study
p	pressure (Pa)
$P_{Cu,s}$	losses in the stator windings (W)
$P_{ventilation}$	ventilation losses inside the machine (W).
r_{ext}	external radius for the definition of the wafter height (mm)
r_{int}	internal radius for the definition of the wafter height (mm)
R^2	coefficient of determination of the statistical model
R_{uu}	electrical resistance of the phase u of the stator winding (Ω)
R_{vv}	electrical resistance of the phase v of the stator winding (Ω)
R_{ww}	electrical resistance of the phase w of the stator winding (Ω)
S_E	external energy source.
S_M	external momentum source
t	time
T	Temperature of the fluid
U_j	Flow velocity in direction j (m/s)
V	nominal voltage of the machine (Volts)
X_{wh}	non-dimensional parameter that defines wafter height
X_{wl}	non-dimensional parameter that defines wafter length
$z_{wafters}$	number of wafters in the design

Latin symbols

μ	Dynamic viscosity (Pa·s)
ρ	Density of the fluid (kg/m^3)
τ	Molecular stress tensor

hotspot in the machine [12]. However, many solutions to these problems are available in the literature: Polikarpova [13] included potting to enhance the heat transfer from the end windings to the water jacket; Micallef [14] proposed the attachment of some wafters to the rotor in order to increase convective capacity in the end windings; Fedoseyev [15] removed the energy from the rotor through a heat pipe within the rotor shaft and transferred it to a heat sink; Tighe [16] provided a comprehensive thermal analysis of three different cooling configurations, including a heat pipe in the shaft to enhance heat transfer in the rotor. In addition, Camilleri in [17] conducted a CFD (computational fluid dynamics) parametric study of the effects of including radial vents in the rotor.

Of all these solutions, the inclusion of wafters solves the overheating in the end windings and maintains the simplicity of the cooling system. The primary purpose of including wafters is to increase the convective heat transfer coefficient in the stator end windings, which translates into a temperature reduction in this zone, which is usually very critical in traction applications. However, the lack of information about their design complicates their implementation in new designs.

Although Micallef [14,18,19] has studied accurate CFD models that represent the effect of wafters in the end space of a specific machine, there are still no established criteria for easily implementing wafters in a cooling system. This article, therefore, focuses on obtaining a design procedure and some design criteria for this element in order to maximize the convective heat transfer in the end windings and minimize the possible hotspots in this zone.

The proposed design methodology focuses on wound windings, which are the most extended winding topology for these kinds of applications. However, new trends in this field, such as hairpin [20] or coil-form windings [21], are gaining ground. Therefore, an independent study of each kind of topology should be carried out in further research.

The entire study has been conducted via CFD simulations. The CFD model used in this article has been previously validated with experimental measurements, and it has been employed along with statistical tools with the aim of generating a second-order response surface model that is capable of predicting the influence of different parameters that define the wafters on the convective heat transfer in the end windings of the machine. Thus, this paper presents an innovative approach to designing wafters for totally enclosed machines, with the aim of reducing the temperatures in the machine and increasing the overall efficiency of the system.

The CFD model employed in this study is described in detail first, including detailed information about its geometry and its mathematical model. Secondly, the validation process is analysed, including information about the experimental measurements obtained and a comparison between the tests and the CFD results. Then, the proposed parametric study is detailed, defining the type of study and the parameters included in the analysis. Finally, the results are summarized, giving the details of the second-order models for the convective heat transfer and the ventilation losses for both the machines with and without wafters. In addition, the effect of including wafters in a particular machine is reported, the result being a significant decrease in the temperatures of the machine.

2. CFD model

As the flow pattern in the end space is not predictable, it would be almost impossible to analytically determine the airflow in this zone. Therefore, a reliable CFD model which could accurately represent the effect of wafters in the end space of an electric machine is presented. The electric machine modelled is described in the next section.