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Thermal modeling of an asymmetrical totally enclosed permanent magnet integrated starter generator

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Abstract

Some electromechanical systems involve totally enclosed electrical machines. In these cases, forced internal air cooling, for instance by the use of fans, is nearly impossible. However, in the same time, permanent magnet machines have to expel their internal rotor losses. In this context, an accurate estimate of heat exchange transfers and heat sources are important, for instance for the determination of the temperature distribution. This can be used for future designs of the same type of machine. This paper details the thermal modeling of a totally enclosed permanent magnet machine, such as an integrated starter generator (ISG). For this purpose, a lumped parameter network is built. Thermal conduction, convection and radiation heat transfer modes are considered. Losses are calculated using both analytical expressions and (coupled) electromagnetic finite element analysis (FEA). Simulation results are compared and validated with experimental data.

Keywords: Thermal analysis; Electrical machine; Lumped parameter model; Experimental validation

1. Introduction

An accurate modeling of energy conversion systems, particularly electrical machines, is necessary for an efficient design optimization of these devices. Thus, taking into account different physical aspects allows the building of reliable physical models that can be used in design-optimization processes [14]. Especially in the context of electrical machines, it is known that the electromechanical energy conversion is significantly influenced by temperature levels and variations.

Generally speaking, temperature limits the efficiency of the machine and is involved in the definition of several physical constraints (critical temperature in magnets, windings insulation thermal limit . . .). Hence, considering thermal phenomena in the design of electrical machines is necessary in order to take account of these important constraints, and then to lead to reliable results concerning their power density, performances and compactness.

This paper details the thermal modeling of a Totally Enclosed Permanent Magnet Machine (TEPMM) used as an Integrated Starter Generator. This machine has a high complexity from a thermal point of view, as the following features are found:

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– Asymmetrical structure;
– Inner convection phenomena;
– Enclosed design;
– Exclusively natural convection cooling.

Analytical expressions are used to calculate thermal resistances, capacitances and sources. Simulation results are compared to experimental data obtained from experiments on a real prototype of the ISG.

Nomenclature (*main variables*)

h_{rd} (W/(m^2 K))	Radiation heat transfer coefficient
h_c (W/(m^2 K))	Convection heat transfer coefficient
h_{ct} (W/(m^2 K))	Contact heat transfer coefficient
Nu	Nusselt number
P_r	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
S (m^2)	Heat exchange surface
Ta	Taylor number
T_f (K)	Fluid temperature
T_s (K)	Surface temperature
ω (rad/s)	Rotation speed

2. Lumped parameter model of the ISG

2.1. Description of the ISG

The ISG is used inside hybrid vehicles, to start the internal combustion motor in starter mode, and to charge batteries in generator mode. It consists of a radial flux permanent magnet machine with three-phase-system supply. With a total number of 48 stator slots, the machine has 4 pairs of poles and 2 slots per phase and pole. The rotor contains 8 buried parallelepiped-shaped NdFeB magnets.

As shown in Fig. 1, the machine is equipped with 54 cooling fins placed around the stator yoke. A clutch disk is mechanically linked to the shaft; it is covered with an aluminum flange during rotating tests. On the other side of the machine, another aluminum cylinder-shaped cover is fixed to the test bench.

In addition to the existence of the clutch disk that increases heat transfers towards the rotor, the aluminum cover used for protection reasons makes the machine more confined and then strongly self-heated. Internal and external convection and radiation phenomena should then be considered carefully.

If, as shown in Fig. 2, symmetry properties can be considered for the active parts of the machine (iron, windings and magnets) [11], the environment is asymmetrical (in the axial direction). Therefore, from the thermal point of view, one can distinguish two very different sides: the clutch and the bearings sides (see Fig. 1).

Internal phenomena take place inside the inner air in both clutch and bearing sides. Thermal phenomena in airgap are difficult to model and to check experimentally. Hence, the ISG presents all the main difficulties that should be considered when modeling electrical machines: the airgap, the windings (and end-windings), cavities and external heat transfers [17].

2.2. Thermal network modeling

Lumped parameter models are known for their simplicity, flexibility and good level of accuracy. They are also rapid and permit the modeling of both steady state and transient regimes [9]. For these reasons, this method provides a simple but effective solution to take account of tridimensional heat flux paths. This aspect is used and is presented in this paper.