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Research paper

Convective heat transfer prediction in disk-type electrical machines

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HIGHLIGHTS

- We discuss the convective heat transfer modeling in disk type electrical machines.
- Bulk fluid temperatures adjacent to each surface are predicted by a linear formula.
- The use of bulk fluid temperature makes the correlation more generally applicable.
- The proposed correlations are independent of the ambient temperature.
- Convective heat transfer for stator reaches a minimum at a certain gap size ratio.

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ABSTRACT

This paper presents correlations to assess the average convective heat transfer in axial flux permanent magnet machines based on numerical simulations. The rotor–stator system is enclosed in a cylindrical chamber, and all the surfaces within the machine are considered isothermal, each on their own temperature. CFD simulations have been performed for different ranges of the rotational Reynolds number, $Re = \omega R^2/\upsilon$, the gap size ratio, $G = s/R$ and the surface temperature of the rotor, the stator and the cover. The average convective heat transfer coefficients for all surfaces are defined. The bulk flow temperature has been taken into account as the reference temperature instead of the ambient temperature to calculate the average heat transfer coefficient. The latter is typically used in literature to describe the heat transfer between the rotor and the stator, but the heat transfer coefficient is then only applicable for a given surface temperature of the rotor and the stator, which is a serious drawback. Therefore, in order to calculate the bulk fluid temperature, we average the values of fluid temperature adjacent to the corresponding surface; by doing so, the average convective heat transfer in the gap becomes independent of the ambient temperature. Thereafter, for estimating the bulk fluid temperature, a linear correlation between the surface temperature of the rotor, the stator and the cover is made. The unknown coefficients of that linear equation are found with the aid of the least squares method. Afterward, the appropriate equations for the mean Nusselt number are given through curve fittings. The proposed empirical correlations are applicable to various geometries and boundary conditions. Results are compared with the available data in literature and good agreement has been found. It is shown that, for a given Reynolds number, there is a gap size ratio for which the average convective heat transfer of the stator surface in the gap reaches a minimum. Moreover, it can be concluded that the proposed correlation is a quite versatile tool for thermal modeling of disk type electrical machines.

1. Introduction

Disk type electrical machines are beneficial in electrical engineering applications that demand high power density, high efficiency, compact construction, and very strict geometrical constraints. In electrical vehicles, disk type motors with high efficiency can be used as “in-wheel” motor [1]. In hybrid electric vehicles, disk type motors can be – thanks to their short axial length – inserted between the internal combustion engine and the gear box [2]. In literature, many papers are published about axial flux machines, in particular about yokeless and segmented armature (YASA) axial flux machines: these machines have two rotors, and an inherently high power density and efficiency [3].

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Although it is imperative to have a comprehensive knowledge of the heat transfer in such a machine for an efficient design, less attention has been paid to the thermal modeling aspects. In fact, overheating usually has a negative effect on the efficiency and may even have a fatal aftermath on the performance of the machine itself. In particular, the temperature of the magnets should be sufficiently below the critical temperature (e.g. $T_c = 150$ °C for SH type NdFeB magnets) to avoid demagnetization. The remanent flux density of NdFeB magnets decreases with temperature. The resistivity of the copper winding in the stator goes up with temperature (about 0.4%/K) and it negatively affects the efficiency of the machine. On the other hand, the iron losses and the windage losses slightly decrease with increasing temperature, so that in a minority of the machines the total losses are more or less independent of the temperature [4]. In the majority of the electrical machines, however, the total losses increase at higher temperature, and the different individual losses terms (copper loss, iron loss, losses in magnets, windage loss…) are always a function of the temperature. This means the surface temperature distribution should be known in order to compute accurately the machine's efficiency. Thus, in order to predict the temperature of the material within the machine, the designers must take into account the factors of heat transfer including the shape, the rotational speed and the air-gap size between rotor and stator. Furthermore, due to the lack of precise thermal modeling, the designer should provide excessive cooling through the external ventilator, resulting in an excessive energy consumption which in turn deteriorates the energy efficiency. Therefore, it is very important to supply sufficient cooling in order to maintain both a long life time and high reliability of such machines.

It is now widely accepted that accurate modeling of the fluid mechanics in the air-gap between rotor–stator is of great practical concern in electrical machine applications. Daily and Nece [5], to the knowledge of authors, pioneered the problem of fluid flow in the discoidal configuration. Arora and Stokes [6] presented the exact solution of the steady state flow between two parallel infinite rotating disks taking into account the viscous dissipation effects. Their work was followed by Owen and Rogers [7] who investigated the heat transfer in various rotor–stator configurations. The problem of the flow field between rotating disks enclosed by a cylinder has been investigated by Bhattacharyya and Pal [8]. They showed that the similarity solution is useful in describing the flow between finite disks for smaller values of the Reynolds number. Di Leonardo et al. [9] studied experimentally the swirling flow between a stationary and rotating disk with fixed closed end. They observed that the flow structure resembles to the Batchelor solution, with two boundary layers and a core rotation as a solid body for the rotational Reynolds number, $Re = 80$. Andersson and Lygren [10] examined the turbulent flow between a rotating and a fixed disk through large eddy simulation (LES). They concluded that the mean flow affects the near-wall vortices for both the narrow-gap and wide-gap cases.

Besides, a number of studies have been undertaken to provide the fundamental understanding of the heat transfer in the discoidal systems [11–14]. Yuan et al. [15] investigated the turbulent heat transfer on the stator and the flow characteristics in the gap between the disks. They found that there is an optimum rotor–stator distance where the heat transfer on the stator side reaches a maximum. Boutarfa and Harmand [16] conducted an experiment to examine the flow structure and the local convective heat transfer in the air-gap of a rotor–stator configuration. They presented a correlation for the local Nusselt number as a function of the Reynolds number and the gap ratio. This work followed by Pelle and Harmand [17] who took into consideration the presence of an axial inflow that comes through the stator and impinges the rotor. They indicated that the multiple holes in the stator can improve the cooling of the rotor only for certain ranges of the gap size ratio and the Reynolds number. Poncet et al. [18] studied the problem of an unshrouded rotor–stator system by an improved Reynolds stress model. They identified three flow regions namely a jet-dominated flow area at low radii with zero tangential velocity, a mixed region at average radii and rotation-dominated flow region at upper radii. Howey et al. [19] measured experimentally the stator heat transfer in a rotor–stator system and showed that the local Nusselt number increases at the periphery due to ingress of air towards the stator. Furthermore, CFD simulations have been applied increasingly to study the thermal design of disk type electrical machines [20–23]. Moradnia et al. [24] studied the cooling of an electrical generator using the frozen-rotor concept. They showed that this numerical scheme is highly beneficial because it predicts the same velocity distribution as in the experiment. Pyrhönen et al. [25] constructed a thermal model based on CFD results to analyze the temperature distribution in the machine. They demonstrated that using copper bars as extra heat carriers in the construction and using high-conductance potting material in the end windings of a liquid jacket-cooled machine can be beneficial for the cooling purpose. However, one of the shortcomings of the CFD methods is that they involve time consuming processes which consume up to months to yield an accurate result. Additionally, their results are limited to the geometry under investigation as well as to the imposed boundary conditions.

Most of the aforementioned studies, for simplicity, have used the air ambient temperature as the reference temperature to calculate the convective heat transfer coefficient in the gap between the rotor and the stator [26–29]. By doing so, the estimated convection coefficient becomes dependent on the ambient temperature which is an unwanted effect. Besides that, it results in a limited applicability of those correlations. By contrast, in this paper, the average bulk fluid temperature has been calculated and used as the reference temperature. In this way, the convective heat transfer coefficients and the mean Nusselt numbers in the gap will be independent of the ambient temperature as well as the corresponding surface temperature.

The objective of this work is to present parametrized correlations that are able to fully predict the convective heat transfer in the disk type electrical machines; in particular, axial flux permanent magnet synchronous machines (AFPMSMs). These empirical equations are constructed based on the CFD results, and are able to accurately estimate the average heat transfer coefficient for all surfaces within the machine for variable geometries and boundary conditions. Details of the proposed method and the results are discussed in the following sections.

2. Problem description

Fig. 1 shows the actual configuration of the rotor–stator in a typical AFPMSM. The simplified configuration of the discoidal system has been illustrated in Fig. 2, where the left disk represents the rotor and the right one is the stator. The rotor–stator system is enclosed in a cylindrical cover. The case study consists of two rotors and one stator in the middle. Hence, a symmetry plane has been defined to halve the computational cost. The flow is characterized by the rotational Reynolds number, $Re = \omega R^2/\upsilon$, and the gap size ratio, $G = s/R$, where ω is the angular velocity of the rotor, R is the diameter of the disks, υ is the kinematic viscosity of air and s is the air-gap distance. This model has been constructed in the practical range of AFPMSMs namely $4.19 \times 10^4 \leq Re \leq 4.19 \times 10^5$ and $0.00333 \leq G \leq 0.08$. For the considered disks of 75 mm radius, this range of Reynolds number corresponds to rotor tip velocity of 10–100 m/s. The following assumptions for constructing the model have been made: