ANALYSIS OF A HIGH POWER DENSITY AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS MACHINE WITH ACTIVE COOLING

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Abstract - **The article discusses the synthesis and analysis of a high-power-density axial flux permanent magnet synchronous motor (AFPMSM) with active cooling. The research included electromagnetic and thermal analysis. In the electromagnetic part, numerical analysis employing 3D finite element method were carried out to analyze the influence of machine geometry and current density on the overall machine performance and the achieved power density. In the thermal approach, an active cooling concept with a cooling channel located in the winding was analyzed. Numerical thermodynamic models of the winding were developed, based on which the various approaches of the investigated solution were considered and their impact on improving the power density of the machine assessed.**

I. INTRODUCTION

Given the growing interest in electrically powered aircrafts and development of generally called electromobility, scientists and engineers from many centers around the world are seeking for electric motor structures of high power density [1]-[3]. In the research field on high power density electrical machines, the axial flux machines are getting more and more attention due to ability to achieve by optimization higher power density levels than in classical machines of radial direction of the main flux [4]. Core saturation and current density in the winding should be pointed out first as key limiting factors of increasing power density in electric machines.

The paper focuses on the synthesis and analysis of a high power density axial flux permanent magnet synchronous motor with active direct cooling of the winding, designed to allow for high values of current density. The machine has no ferromagnetic core in the stator. As is has been demonstrated among others in [4], axial flux motors (AFM) are characterized by increased torque values compared to radial flux motors. This is because the *AFM* structure provides a larger working area of the flux interacting between rotor and stator. In addition, the reduction of the machine's dimensions in the z-axis allows it to increase its dimensions in the radial direction, which also translates into increased torque.

In the design of electrical machines, one of the main factors determining power is the thermal efficiency of the system. The winding is selected to flow a certain amount of current through it. In addition, magnets are also sensitive to thermal loads that cause demagnetization. The best solution to overcome these problems is the use of active cooling systems. Active cooling systems allows for dissipating excessive heat; however, they are simultaneously source of design problems due to the increased weight and complexity of the powertrain system. In addition, application of active cooling systems in aircrafts needs of proper selection of coolants due to high variation of temperatures and pressures during on ground and in flight operation of the powertrain system.

II. HIGH POWER DENSITY AXIAL FLUX MACHINE STRUCTURE

The structure of the proposed machine has been shown in Fig. 1. The electromagnetic circuit of the machine consists of stator coils forming a three phase concentrated winding, and two mechanically fixed rotors formed by axially magnetized arc segmented permanent magnets and back iron.

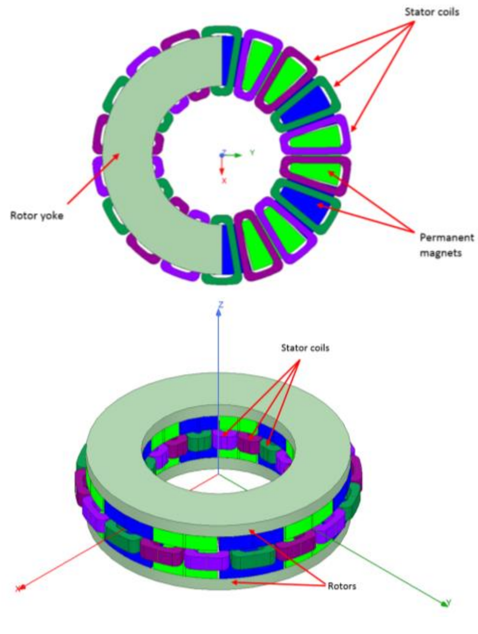

Fig.1. Structure of studied AFPMSM

The machine has been designed assuming typical power level required from the propulsion system of C-23b aircraft type, i.e. 200 kW, it has been assumed that machine will cooperate with reduction gear of the gear ratio about 10:1. Therefore machine rated speed has been assumed to be equal to about 20 000 rpm.

The machine performance, in terms of achieve power density, has been determined by means of 3D finite element method. The derived characteristics of the output torque T, power density, losses and the determined efficiency η taking into account changes in current flow Θ are shown in Figure 2.

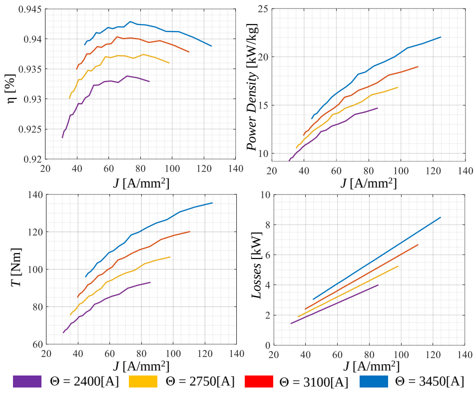

Fig.2. Determined torque and efficiency characteristics of the machine

III. WINDING THERMAL MANAGEMENT (THERMAL APPROACH)

Traditionally, heat is dissipated from the windings through wire-to-wire conduction and air circulation across the winding surface. However, wire insulation and air gaps significantly limit the bulk winding conductivity, reducing it by two orders of magnitude compared to solid copper without insulation and air gaps. This form of cooling, known as passive cooling, operates without forced air flow (E.g. fans). The development of additive manufacturing (AM) technology, especially the use of metal 3D printers, offers significant potential to enhance cooling capacity by introducing cooling channels [5]. This is particularly effective with coolants possessing higher volumetric heat capacity than air. Certain dielectric liquids, such as some alcohols or hydrocarbons, demonstrate high heat dissipation potential when in direct contact with the conductor.

To demonstrate cooling capability, a conjugate heat transfer (CHT) analysis of ethanol flow through two channels parallel to the current flow was conducted. The channel cross-section equals 10% of the winding cross-section, which is formed by 7x7 mm. Various coolants, coolant flow rates, and current densities were analysed, with results presented in Figure 3. Heat from current flow was modelled as a constant volumetric heat source ranging from 10.8 to 172 MW/m³, corresponding to 25 to 100 A/mm² at copper room temperature resistivity. After computations, the current density for a given volumetric heat source is corrected for the resistivity at the given temperature.

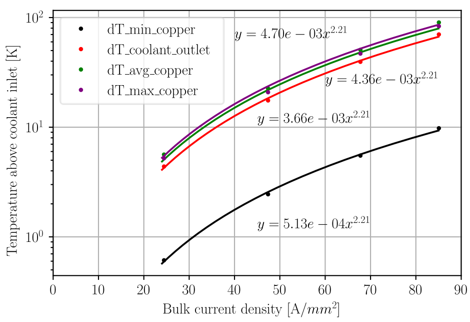

Fig. 3. Temperature profile of winding and coolant for different current density

The CHT analysis offers the opportunity to evaluate the influence of mass flux and thermal properties of coolant on the average heat transfer coefficient for a given winding geometry. These results are depicted in Figure 4. Notably, water and ethanol exhibit significant potential in dissipating heat, as demonstrated by the outlier when compared to typical air cooling. The validity of using computational fluid dynamics (CFD) to assess heat transfer coefficients is clear when a high-quality computational mesh with fully resolved boundary layers is employed. This requires the centroid distance of the first layer of computational grid cells to have a y+ value of approximately 1 (non-dimensional wall distance). The accuracy of using y+ as a mesh metric is supported by comparing CFD results with experimental data in literature[6].

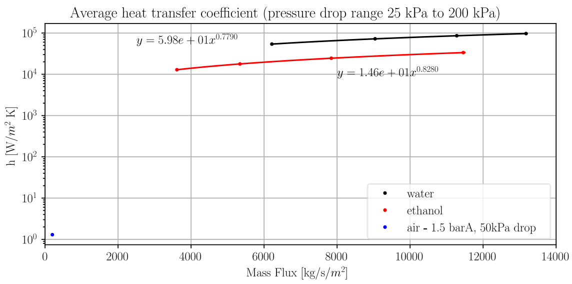

Fig.4. Average heat transfer coefficient in pressure drop range from 25 kPa to 200kPa

IV. CONCLUSIONS

In summary, winding cooling analysis showcases the potential for improving cooling capacity through new technologies opportunities and coolant selection. The axial flux motor, coupled with additive manufacturing capabilities, presents a significant opportunity to enhance power density by improving cooling efficiency. The more detail about modeling techniques as well as detailed description of research will be presented and discussed during the conference and included in the full version of the paper.

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