Equivalent Thermal Conductivity Improvement of Stator Winding and Thermal Benefit for Air-Cooled Electrical Aviation Machine

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Abstract. Electrical machines with high power density are key enabling components of propulsion systems for flying cars. Air cooling system is widely utilized for electrical aviation machine for its compact and reliable composition. For air-cooled electrical machine, the equivalent thermal conductivity of stator winding is the main parameter in determining the thermal resistance inside the slot winding. To get a further understanding, the analytical evaluation method and improvement of the equivalent thermal conductivity of stator winding is studied. Furthermore, the influence of the improvement in equivalent thermal conductivity of stator winding on heat transfer path is investigated and thermal benefit and performance benefit are evaluated. The analysis shows that with the equivalent thermal conductivity of stator winding increases to 3 W/m·K, a 100 °C-temperature reduction can be achieved in the stator winding.

Keywords: Thermal conductivity · Electrical machine · Air cooling

1 Introduction

Flying cars as a new type of vehicle for urban air transportation and future travel, are getting more and more attention in the automotive and aeronautical fields, it has become an important development trend for the transborder integration of automotive and aeronautical technology and industry [1]. Electrical machines with high power density are key enabling components of propulsion systems for flying cars. The power density of electrical machines has gained great improvement with the rapid technological development of electric vehicles [2]. However, for flying cars applications, the power density of electrical machines needs to be further pushed to a higher level, like 10 kW/kg [3].

To increase power density of electrical machines, the technologies can be divided into three different approaches accordingly. First approach to improve power density is to adopt new electromagnetic designs, such as YASA topology [4], or the Halbach magnet array etc. [5]. The second approach is to utilize new type of materials to enable a higher magnetic loading with Fe-Co alloy and soft magnetic composite materials, or a higher electric loading with ultra-copper conductor composed of nanotube [6, 7].

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Lastly, through effective thermal management of air-cooled electrical machines, the current density of stator winding can be increased under temperature limits of winding materials [8–10]. Compared to liquid cooling system, air cooling system eliminates the pipes and pumps and consequently forms a neat and simple but robust cooling system which is suitable for flying cars applications [11].

In modern high power density electrical machine for aviation applications, copper loss is the dominant part in all losses including copper loss, core loss, eddy current losses etc. [12]. The heat dispassion path for copper loss in motor stator assembly can be divided into three parts. Firstly, the heat generated by winding at the bottom of slot is transferred to stator yoke via slot liner and then to the housing. Secondly, the heated generated by winding at the center of slot is transferred to stator teeth via slot liner and then to the stator yoke, finally to the housing. Thirdly, the heat generated in end-winding part is partly transmitted axially to winding inside slot and partly transferred to housing by heat convection or conduction process. Typically, the hotspot in stator winding lies in the end-winding and the winding in the center of the slot. The winding is composed of random-placed round copper conductor with insulation film and impregnation material. The radial and tangential equivalent thermal conductivity of winding is much lower than that of axial direction. Normally the equivalent thermal conductivity of winding (ETCSW) without impregnation material is 0.4 W/m·K in radial and tangential direction compared with 235 W/m·K in axially direction. The lower radial and tangential ETCSW causes large thermal resistance in heat path and consequently causes a high temperature rise inside slot winding. The calculation of ETCSW is proposed and researched by many studies [13–16]. The ETCSW can be increased by various ways, such as using impregnation materials with higher thermal conductivity or increasing the slot fill factor.

In this paper, the influence of the improvement in ETCSW on the thermal heat transfer in the investigated propulsion motor is analyzed based on the thermal modelling. And its benefits on thermal and electromagnetic performance are evaluated. This paper is structured as follows. In Sect. 2, the ETCSW is explained and its improvement method is given out. In Sect. 3, the analytical calculation of the ETCSW is carried out based on different material characteristics. In Sect. 4, the thermal and electromagnetic performance benefits of improvement for ETCSW are analyzed based on an investigated propulsion motor. Finally, the conclusions are drawn (Fig. 1).

Fig. 1. Slot winding of an electrical aviation machine

2 Equivalent Thermal Conductivity of Stator Winding

The ETCSW is a critical parameter for evaluating the thermal performance of stator winding. The calculation model of the ETCSW is usually complex because of the random placement of winding composition inside slot including impregnation material, insulation film and conductor etc. The ETCSW is determined by the physical properties and the proportion of the materials used to form the winding. Accurate calculation of the ETCSW enables a more authentic thermal analysis result of the winding inside slot. The analytical prediction of the ETCSW has already been studied by many studies. In this paper, the analytical calculation of the ETCSW is based on the method proposed in [17]. The subscripts c and p represent the conductors and the impregnation materials. The υ_c is the volume ratio equal to the slot fill factor.

$$k_e = k_p \frac{(1 + \upsilon_c)k_c + (1 - \upsilon_c)k_p}{(1 - \upsilon_c)k_c + (1 + \upsilon_c)k_p} \tag{1}$$

As is predicted in analytical calculation Eq. (1), the slot liner and impregnation material play great influence on the equivalent thermal conductivity of slot winding. Therefore, this analysis is limited to the slot liner and impregnation materials which are selected to improve the ETCSW.

In selecting the material for improving the ETCSW, thermal conductivity of winding material is a key parameter. Other important parameters are insulation thickness, the dielectric strength, the viscosity and also the working temperature [18]. Traditionally, the slot liner insulation material used in electric machines is composed of polymeric coating, polymeric films and papers, such as polyamide and polyaramid. These materials provide perfect electric insulation but poor thermal conduction because of their low thermal conductivity of 0.14 W/m·K. A highly thermally conductive insulation for electric machine is reported in [19], with thermal conductivity up to 1.8 W/m·K. Table 1 lists the parameters of the slot liner materials.

Table 1. Slot liner insulation material characteristics

Material	Nomex 410	APTIV 1102 film	AIN coating
Thickness	0.25	–	0.127
Dielectric strength (kV/mm)	8.25	200	650
Thermal conductivity	0.139	0.43	1.75
Tensile strength	29.6 kN/m	100 MPa	–
Insulation class	220 °C	–	300 °C

Table 2 lists the electrical, thermal and mechanical characteristics of three selected impregnation materials. In order to improve ETCSW, the thermal conductivity of impregnation material should be as high as possible. At the same time, in order to withstand the high voltage that may occur between coils, the dielectric strength and volume resistivity are also remarkably important parameters.

Table 2. Impregnation material characteristics

Material	Varnish	EpoxyLite	SbTCM
Thermal conductivity (W/m·K)	0.25	0.85	3.2
Dielectric strength (kV/mm)	80	20	10
Volume resistivity at 25 °C (Ω·cm)	10^{15}	10^{14}	10^{14}
Viscosity (Pa·s)	–	3.5	25

3 Analytical Calculation of Equivalent Thermal Conductivity of Stator Winding

In this section, The ETCSW is calculated using analytical model proposed in Sect. 2. Both radial and tangential thermal conductivity are verified over large range to confirm the proposed analytical method prediction accuracy. The geometry, material physical properties and the boundary conditions are assigned in the analytical calculation according to the model. Figure 2 shows the analytical results comparison of ETCSW under different impregnation materials. The thermal conductivity of impregnation material and slot fill factor are selected as study parameters.

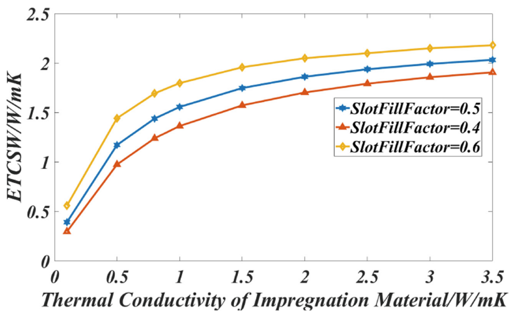

Fig. 2. Equivalent thermal conductivity of the slot winding

4 The Investigated Propulsion Motor and Thermal Modelling

4.1 The Investigated Propulsion Motor

This section analyzes the thermal benefits of the improvement of the ETCSW. A high speed PMSM for electric propulsion system is taken as a case study as shown in Fig. 3 and relevant parameters listed in Table 3. The machine employs a 10-pole 12-slot configuration with concentrated winding. The winding inside slot is composed of 0.15 mm slot liner and 45 strands of copper conductor with a 0.45 mm diameter. The slot fill factor is approximately 0.45. The machine is air-cooled by convection of 36 radial cooling fins placed at the outside of the housing. The fin thickness is 1.2 mm, height is 10 mm and with 35 mm length along the machine axial direction.

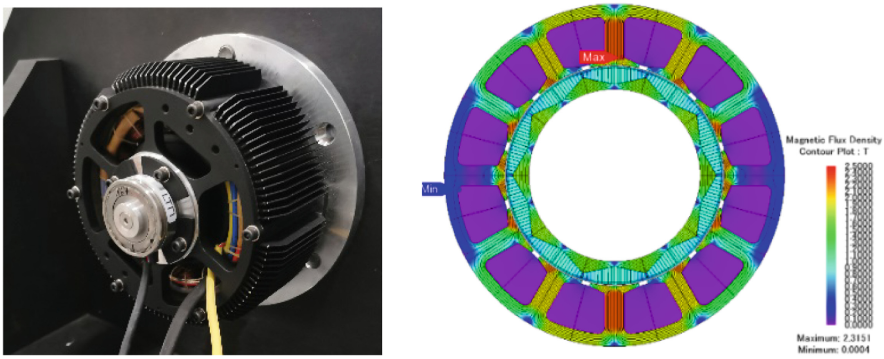

Fig. 3. Investigated propulsion motor.

Table 3. Table captions should be placed above the tables.

Machine data	Value	Machine data	Value
DC voltage	270 V	Rated speed	9000 rpm
Rated torque	4.5 N·m	Peak torque	9.35 N·m
Rated power	4.24 kW	Peak power	8.81 kW
Efficiency	95%	Working time at peak power	>120 s
Cooling	Air-cooled	Working temperature	−40–55 °C
Stator diameter	106 mm	Rotor diameter	56 mm
Active length	25 mm	Housing	Aluminum

4.2 Thermal Modelling of the Propulsion Motor

Lumped-parameter thermal network (LPTN) is widely used in thermal analysis of electric machines for its fast evaluation of electric motor with parameterized cooling and structure conditions. A LPTN thermal model in MotorCAD is developed to evaluate the thermal performance of the above-mentioned electric propulsion machine under varied ETCSW. A three-dimensional LPTN thermal model is established to account for the heat transfer in both radial and axial directions. In the axial direction, the motor active core is divided into three parts equally and one part for each end winding. In order to obtain a more accurate temperature distribution inside a stator slot, 20 thermal nodes are included with 5 layers in the radial direction. Figure 4 shows the thermal distribution of the motor under investigation in MotorCAD. The housing is cooled by forced air-convection; the corresponding heat transfer coefficient is assumed to be 200 W/m^2·K. A thermal isolation condition is applied to the two sides of the stator core.

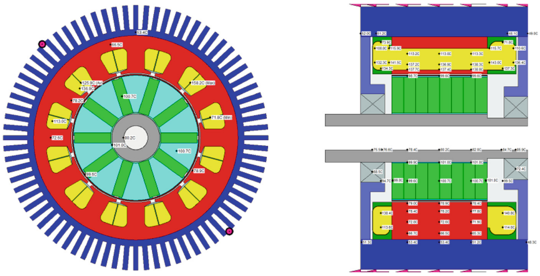

Fig. 4. Investigated motor thermal model in MotorCAD.

5 Thermal Benefits and Performance Benefits

The improvement of ETCSW enables the reduction of thermal resistance inside the slot winding, and a reduction of temperature rise in slot winding. The temperature reduction mechanism is that more heat flux inside the slot winding is dissipated through the slot liner and the stator teeth and yoke. In Fig. 5, the heat flux is divided into the heat flux through stator teeth (HF-Teeth-Winding), heat flux through stator yoke (HF-Yoke-Winding). It is clearly to see that with the increase of the ETCSW, the HF-Teeth-Winding and HF-Yoke-Winding shows the gradual growth. The TotalHF is the sum of HF-Teeth-Winding and HF-Yoke-Winding. The TotalHF grows from 188 to 201 W. However, the CopperLoss-TotalHF is the difference of copper loss and TotalHF. The CopperLoss-TotalHF decreased from 139 to 78 W with the ETCSW increased from 0.4 to 3 W/m·K. The heat flux reduction is the main reason behind the temperature rise reduction as shown in Fig. 5.

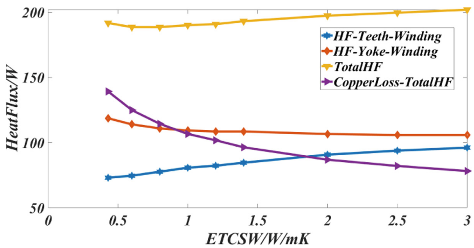

Fig. 5. Heat flux variation with ETCSW

The thermal benefit of the stator winding is shown in Fig. 6. With the ETCSW increases from 0.4 to 3 W/m·K, the maximum temperature decreases from 201 to 103 °C, which means the temperature rise in the slot winding is reduced. However, the minimum temperature remains nearly 85 °C. The temperature difference between maximum temperature and minimum temperature decreases from 120 to 18 °C, which means a more uniform temperature distribution inside the slot winding. For copper loss reduction, the copper resistance is positively correlated to the temperature. With the maximum temperature decreases, the winding resistance also decreases accordingly. Consequently, this results in a reduction in copper loss as shown in Fig. 7. The copper loss reduces from 330 to 280 W with the ETCSW improvement. The 50 W copper loss reduction implies a 1.1% efficiency improvement for the propulsion motor under investigation.

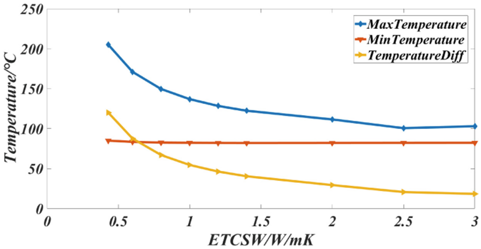

Fig. 6. Winding temperature variation with ETCSW

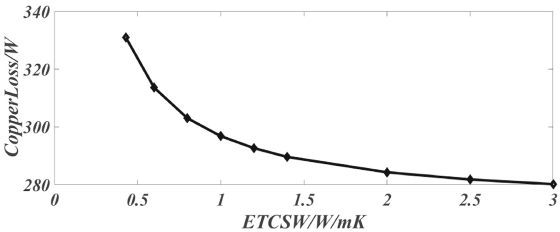

Fig. 7. Copper loss variation with ETCSW

6 Conclusion

The ETCSW has an important influence on determination of the temperature rise and distribution in the motor slot winding. The analytical calculation is widely studied by several researchers to provide fast and accurate evaluation of the ETCSW under various winding compositions. To get a further understanding of influence on the heat transfer path, this paper analyzed the improvement of the ETCSW. The heat flux for different heat transfer path was investigated under a case study motor. It shows that with the improvement of the ETCSW, the temperature rise and temperature difference is significantly reduced, for that nearly 100 °C temperature reduction is achieved when the ETCSW is increased to 3 W/m·K. The improvement of the ETCSW is proved to be an effective way to reduce the temperature rise inside the slot winding and consequently an effective way to increase the efficiency and power density of the electric motor.

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