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Research paper

Heat-transfer improvements in an axial-flux permanent-magnet synchronous machine

Juha Pyrhönen [a], Pia Lindh [a], Maria Polikarpova [a], Emil Kurvinen [b, *], Ville Naumanen [c]

[a] Department of Energy Engineering, Lappeenranta University of Technology, P.O. Box 20, 53851 Lappeenranta, Finland
[b] Department of Mechanical Engineering, Lappeenranta University of Technology, P.O. Box 20, 53851 Lappeenranta, Finland
[c] Visedo Oy, Tuotantokatu 2, Lappeenranta, Finland

HIGHLIGHTS

- Cooling of axial flux permanent magnet generator was studied.
- Copper bars was introduced to transfer heat from the stator teeth to liquid cooling pool attached to the end shields.
- Addition to copper bar the performance of aluminium-oxide potting material was studied.
- The calculated and measured values were in good agreement.
- The cooling was improved significantly.

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ABSTRACT

Axial-flux machines tend to have cooling difficulties since it is difficult to arrange continuous heat path between the stator stack and the frame. One important reason for this is that no shrink fitting of the stator is possible in an axial-flux machine. Using of liquid-cooled end shields does not alone solve this issue. Cooling of the rotor and the end windings may also be difficult at least in case of two-stator-single-rotor construction where air circulation in the rotor and in the end-winding areas may be difficult to arrange. If the rotor has significant losses air circulation via the rotor and behind the stator yokes should be arranged which, again, weakens the stator cooling. In this paper we study a novel way of using copper bars as extra heat transfer paths between the stator teeth and liquid cooling pools in the end shields. After this the end windings still suffer of low thermal conductivity and means for improving this by high-heat-conductance material was also studied. The design principle of each cooling system is presented in details. Thermal models based on Computational Fluid Dynamics (CFD) are used to analyse the temperature distribution in the machine. Measurement results are provided from different versions of the machine. The results show that significant improvements in the cooling can be gained by these steps.

1. Introduction

Heat transfer of an axial-flux permanent-magnet (AFPM) machine is studied and innovative improvements are suggested. As industrial power range axial-flux machines often have cooling problems improved heat transfer mechanisms are needed. Previous studies applied forced air cooling for an axial-flux machine [1,2]. In this study a liquid-cooled, two-stator-single-rotor, axial-flux, permanent-magnet machine is used as an example. Heat transfer from the machine parts is not efficient enough in case of the water jacket cooling only but it must be significantly improved to reach the targeted performance of the machine. As copper has high thermal conductivity bars made of this metal were used as extra heat transfer paths from the stator teeth to the water jacket in the AFPM machine studied. Axial holes were drilled from the water jacket in the middle of the stator teeth and 8 or 6 mm copper bars were assembled water tightly in these holes to improve the thermal conductance from the stator to the water jacket. 60 mm of the copper bars lengths locate themselves inside the teeth and 10 mm in the cooling water. According to the knowledge of the authors similar idea has not been reported earlier although it is know that different additional heat paths have been tested inside coils. Galea et al. [3] have investigated thermal improvement technique by assembling a heat path from the centre of a slot to the cooling

* Corresponding author. Tel.: +358 505 695969; fax: +358 5621 6799.
E-mail address: emil.kurvinen@lut.fi (E. Kurvinen).

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arrangement. Conductors have been directly cooled [4,5], but that technique may be relevant only in case of large machines due to difficult arrangements and high expenses.

Aluminium-based materials as heat path are discussed as the prototype machine was also equipped with aluminium-oxide-based potting material Ceramacast 675-N. The axial-flux machine has a composite rotor and two tooth-coil-winding stators. The machine is cooled by indirect water cooling including outer frame (bearing shields) water jackets. Potential applications of the machine construction can be found in highly integrated systems with constrained space for the electrical machine.

In early 2000s, the use of thermoplastic materials was investigated to enhance the cooling of electrical devices. With the target to improve the component performance, Neal et al. tested a thermoplastic material in a brushless DC (BLDC) machine [6]. In early 1990s, epoxy resin with a high thermal conductivity was proposed as a material to encapsulate the end windings of an axial-flux machine, thereby providing a low-resistance thermal bridge to the machine stator frame, which can be either air or water cooled. Utilization of epoxy resin was further developed, especially, for automotive applications [7,8]. Crescimbini et al. tested a thin epoxy resin layer with a thermal conductivity of 1.9 W/(Km) on a 15 kW AFPM machine in a heavy-duty hybrid electric vehicle (HEV) application [8]. Lately, thermally conductive plastics have been used as heat paths for instance by Hoerber et al. [9] to improve the cooling and facilitate component manufacturing. In the study of Hoerber et al. the material under investigation has a thermal conductivity of 2 W/(K m). Aluminium nitride (AlN) compound was tested by Yao et al. [10] in a permanent magnet motor to dissipate heat from stator. In these tests the machine was studied without a rotor. In our study instead, the permanent magnet synchronous machine (PMSM) was driven at its rated speed and loaded. The thermal material applied to end windings was Ceramacast 675-N, the thermal conductivity of which is 100 W/(K m) [11]. Recently also thermoelectric cooling [12] and high conductivity metal foams [13] have been developed and the performance of those could be studied when utilized in a motor.

Liquid cooling solutions have become widely adopted as more powerful electrical machines are necessary for instance in hybrid drive applications [14]. The high power densities and the varying operating conditions with short high-power peaks in vehicle applications place heavy requirements on the machine cooling. Large and noisy fans with high power consumption are inefficient for applications of this kind. Liquid cooling enhances heat transfer thereby enabling higher current density and total losses to achieve higher power [1,15]. Cooling jackets embedded in the housing have become common in medium-power induction machines [16], and also permanent magnet machines [17]. This type of cooling is designed to remove the heat losses of the stator copper winding and the stator iron thereby preventing the propagation of heat towards the rotor. In this study the cooling jacket solution is thermally improved by copper heat paths as well as Ceramacast material between the end windings and the frame cooling. CFD thermal analysis is applied to simulate the temperature distribution, as this analysis demonstrated its effectiveness in previous works. Chang [18] used CFD to analyse the thermal behaviour of 2.35 MW electrical motor with forced air cooling. Torriano et al. [19] and Kolondzovski et al. [20] applied 3D CFD to analyse heat transfer in air cooled machines.

2. Prototype machine

A tooth-coil AFPM prototype generator with 75 kVA target power having 12 stator slots and 10 poles was constructed to gain experience concerning the electrical and, especially, thermal performance of the machine. Machines equipped with tooth-coil windings have lately attracted lots of interest because of their low manufacturing price. For example they have been studied in hybrid traction applications in Refs. [21,22]. The rotor structure of the test machine is illustrated in Fig. 1.

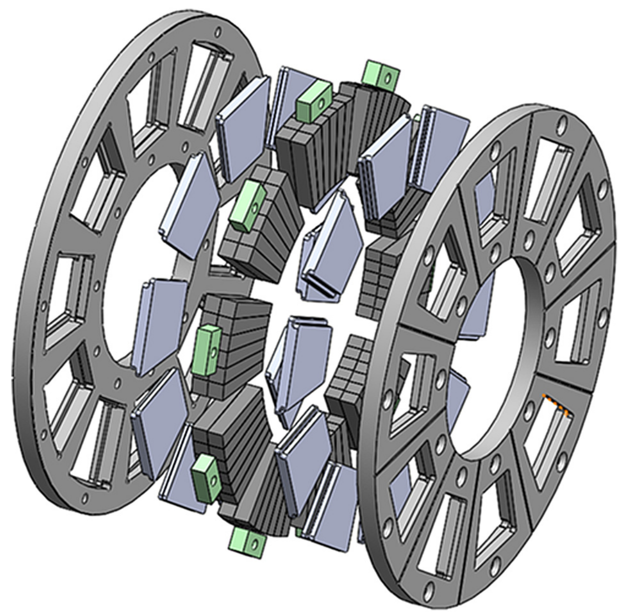

Fig. 1. Rotor structure of the 75 kVA axial flux generator. From left to right, glass fibre bodywork, 10 pole shoes made of laminated steel to avoid high permeance and current linkage harmonic losses in the magnets, 10 segmented magnets.

The bodywork of the rotor is made of electrically nonconductive material, in this case impregnated glass fibre, in order to have a light-weight rotor and to minimize the iron losses in the rotor. The permanent magnet is glued to the fibre glass bodywork, steel laminates are inserted on top of each magnet to diminish eddy current losses and, finally, the glass fibre body is connected to the shaft with a fixing element. Each pole module consists of one steel laminate layer, a permanent magnet core (six segments in the radial direction in two layers) and another steel laminate layer. The steel lamination layer also protects the permanent magnets from the risk of demagnetization during short circuits. The rotor structure was originally designed to act also as a fan for the rotor cooling; for instance, there is air space between the permanent magnet poles and between the glass fibre parts to improve air circulation. Unfortunately, a mistake during manufacturing resulted in restricted rotor air flow. This harmed the fan effect significantly. This study considers the actual prototype structure where the inner cooling of the machine takes place by other means than circulating air. The photo of the rotor construction in Fig. 2 shows the hollow spaces reserved for air circulation and the air inlet, which is obviously too small to circulate air.

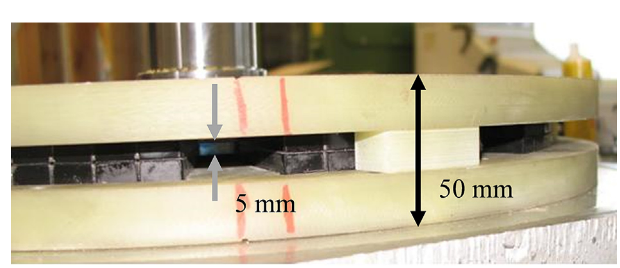

Fig. 2. Rotor structure's glass fibre bodywork and permanent magnets after assembly.