Heat-Transfer Improvements in an Axial-Flux Permanent-Magnet Synchronous Machine

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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.

Keywords:

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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. Gaela et al. [3] have investigated thermal improvement technique by assembling a heat path from the centre of a slot to the cooling 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/(Km). 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/(Km) [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 [15, 16]. Cooling jackets embedded in the housing have become common in medium-power induction machines [17], and also permanent magnet machines [18]. 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 [19] used CFD to analyze the thermal behavior of 2.35 MW electrical motor with forced air cooling. Torriano et al. [20] and Kolondzovski et al. [21] applied 3D CFD to analyze 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 [22, 23]. The rotor structure of the test machine is illustrated in Fig. 1.

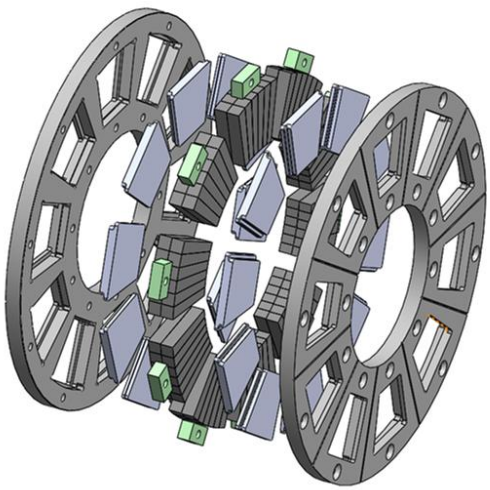

Figure 1: Rotor structure of the 75 kVA axial flux generator. From left to right, glass fibre bodywork, 10 pole shoes made of laminated steel to avoid high permeance and current linkage harmonic losses in the magnets, 10 segmented magnets.

The bodywork of the rotor is made of electrically nonconductive material, in this case impregnated glassfibre, in order to have a light-weight rotor and to minimize the iron losses in the rotor. The permanent magnet are 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.

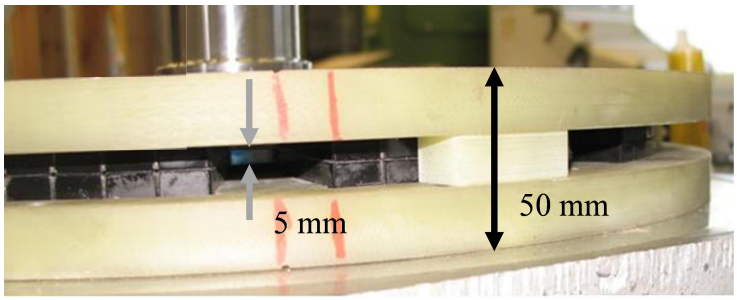

Figure 2: Rotor structure's glass fibre bodywork and permanent magnets after assembly.

The machine is required to give at least 1.5 p.u. peak torque at the rated speed of 1900 rpm. Table 1 summarizes the prototype parameters.

Table 1: Prototype machine parameters

Apparent power, S_n	75	kVA
Nominal current, I_n	123	A
Nominal voltage, U_n	500	V
Nominal speed, n_n	1900	rpm
Rated frequency, f_n	158	Hz
Stator outer diameter, D_so	390	mm
Stator inner diameter, D_si	250	mm
Stator band width, w	70	mm
Stator stack length, l	19	mm
Number of pole pairs, p	5	-
Number of winding turns, N_s	48	-
Number of stator slots, Q_s	12	-

The electrical machine values were computed with 3D FEA. The model shown in Fig. 3 is utilizing Cedrat's Flux 3D program. The total axial length of the machine is 195 mm. The permanent magnet average width is 70 mm (six segments), the height is 30 mm, and the stator stack width is 70 mm. The remanent flux density B_r of the permanent magnet material is 1.15 T at 120 °C, and the steel material used is M400-50A. Originally the machine had an indirect liquid cooling system, which consisted of a liquid cooling area in the bearing shields. Six litres per minute inlet water at 15 °C was used to cool the bearing shields but despite the cool water the cooling of the machine was far from efficient enough. As the machine was developed step by step three cooling cases were studied:

a) water jacket (covers the machine wide bearing shields and has 0.05 m^2)
b) water jacket and one copper bar as extra heat path in each tooth to improve heat transfer from the stator teeth to the water jacket.
c) increased water jacket surface that now covers 0.1 m^2 and three copper bars in each stator tooth. Finally also the end winding of stator 2 was potted with Ceramacast-material.

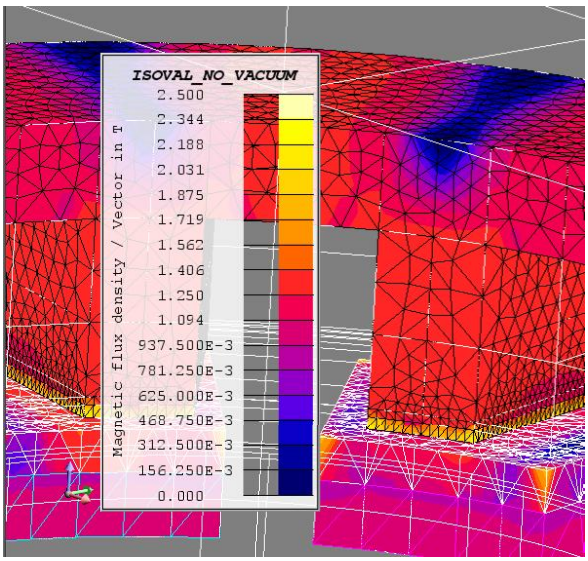

Figure 3: Finite element model in Cedrat's Flux 3D program

Cooling case c) is schematically illustrated in Fig. 4. The places of the copper bars in the teeth are shown in Figs. 5 and 6.

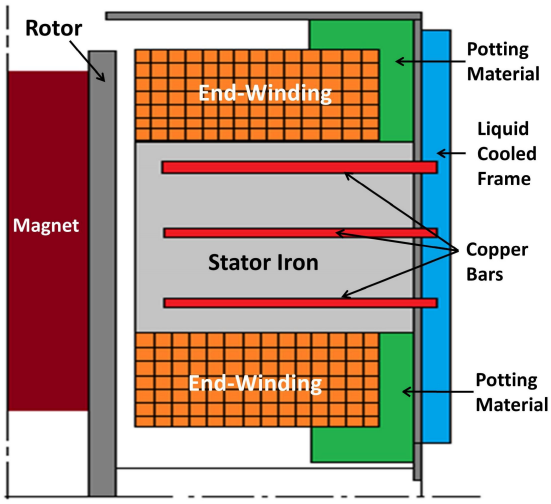

Figure 4: Indirect stator cooling systems having end winding potting (Ceramacast) and copper bars as extra heat transfer paths from stator teeth to cooling liquid.

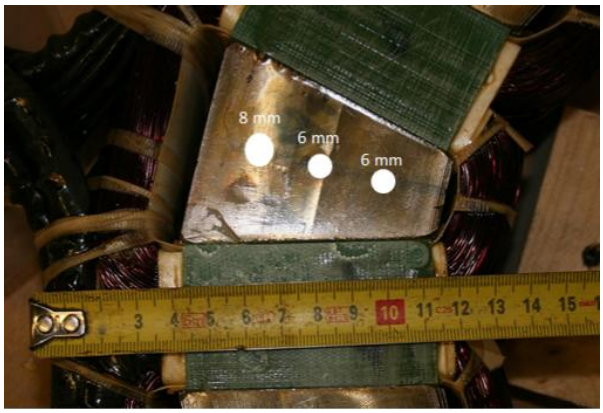

Figure 5: Stator seen from the air gap side. The white dots indicate the positions of the copper bars which improve the heat transfer from the teeth to the water jacket located in the bearing shields.

Figure 6: Assembling of the copper heat paths through the end shields.

3. Thermal design

The machine is, especially, designed for easy manufacturing. For this purpose it has totally open wide slots and tooth-coils. Such a construction makes the rotor vulnerable for increased eddy-current losses. The aim of the 3D CFD analysis was to predict the temperature distribution of the machine with all tested cooling systems. The 3D CFD model of the machine is meshed using Gambit and solved by Fluent. The bearings, outer air, and mechanically coupled devices are not included in the thermal model developed.

For the turbulence modelling, the standard $k - w$ turbulence model, the energy model, and the standard wall function were employed. The CFD analysis was accomplished by applying the convection heat transfer coefficient ($480 \frac{W}{\mathrm{m^2K}}$) on the back surface and a water temperature of 17 °C. One should

take care to study carefully the speed range used because the heat transfer coefficient may vary significantly as a function of speed [24]. As the stator cannot be shrink-fitted to the frame, the thermal contact resistances between the stator yokes and the bearing shields are taken into consideration. It is often assumed that all the heat generated by the machine is removed by the liquid flow in the housing. In this study, instead, it is assumed that a small proportion of heat may be dissipated to the environment by natural convection through the end shields and the shaft. The convection outside the machine is defined as free convection for air and heat transfer caused by end shield interaction [25].

The convection heat transfer coefficient is small in the air between the end winding and the liquid cooled housing due to the insignificant air velocity and acts effectively as a thermal insulator for the winding produced losses. Heat transfer in this region should be improved either by filling it with a high-conductivity potting material or by increasing the air velocity and therefore convection in the area. The above models with, liquid jackets three copper bars per tooth and different potting arrangements were calculated for 75 kW motoring load, and the temperature results of the simulations are listed in Table 2. According to the simulation the temperature may decrease by utilising potting material in the end winding area.

Table 2: Calculated temperatures at 75 kW motoring load for the machine having the copper heat transfer bars in teeth

Machine part	75 kW load non-potted stator temperature, °C	75 kW load potted stator temperature, °C
Air gap side	135	130
Slot Winding	135	130
Air gap	124	118
Stator iron	102	100
Rotor iron (laminate)	110	105
Rotor magnets	110	105

4. Measurement results

The measurement results provide essential information to verify the electro thermal computations. The prototype machine was originally designed to work as a 75 kVA generator. In the experiment the machine was, however, driven as a motor and a 355 kW induction machine was acting as a load

generator (Fig. 7). The machine was measured with three different cooling topologies.

Figure 7: Measurement arrangement for the prototype axial-flux machine.

Pt-100 sensors were utilized in the temperature measurements. Sensors were placed at the top area of a slot, in the centre area of the slot, at the bottom of a slot, in the middle of the slot between the coils and in the end winding areas. In one stator there are 14 sensors total. First, the motor was warmed up to a stable temperature, and after that, the output and input powers were measured. Calculated and measured electrical values at the nominal point are shown in Table 3. These loss values were applied to the heat computations. During the rated load measurement, the Pt-100 sensors indicated temperatures close to 155 °C on the stator. Obviously the original machine did not cool when operated at the desired power. Further heat load tests were then performed with a 75 kW load to ensure that the insulation should not be damaged. The same heat load test with 75 kW power at stabilized temperature was performed 1) with the original stator structure, 2) with the same stator having one copper heat path per a tooth and 3) with the stator having three copper heat path per tooth and the Ceramacast potting material in end windings of the other stator of the motor.

Table 3: original machine values 75 kW motoring load

Value	Computed	Measured
Current [A]	123	123
Copper losses [W]	1200	1200
Stator iron losses [W]	675	-
Rotor iron losses [W]	150	-
PM losses [W]	225	-
No-load losses, [W]	-	2450
Additional losses (mechanical friction), [W]	2550	1250
Total losses [W]	4800	4900
Efficiency	0.94	0.94

In the following the machine's thermal behaviour evolution is reported step-by-step

A) One Copper bar as extra heat conductor per tooth The original axial-flux machine having only water cooling jacket was first run with 75 kW load at its nominal speed. The first set of copper bars was inserted in the stator teeth to improve the heat transfer. The effect of the copper bars was clear and the temperatures diminished by about 15 °C in the windings. The measured temperatures at 75 kW of the original machine and the version with 1 copper bar per tooth are shown in Fig 8. The temperature differences were 18 °C inside a slot as depicted in Fig 8. This confirmed the theoretical heat transfer evaluations and demonstrated the effect of the extra heat transfer paths created by the copper bars.

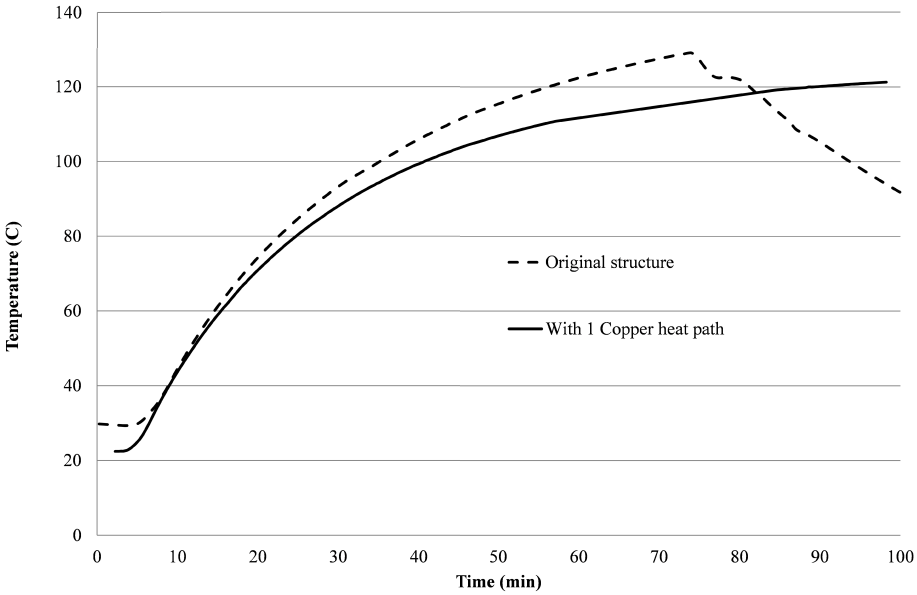

Figure 8: Temperatures at 75 kW motoring load, inside a slot. The starting temperature has no significance and the cooling conditions of the machine are exactly the same in both tests. The figure shows that the original construction is not capable of operating at continuous 75 kW power. However, the improved cooling arrangement manages 75 kW operating power when cool cooling liquid is used

B) Three Copper bars per tooth as extra heat conductors. Hence, more copper bars were inserted and the end windings of one of the stators were potted. Table 4 reports the thermal behaviour at 75 kW motoring load at nominal speed. The given temperatures are the average values of three sensors, one in each phase. Because there is a constant temperature difference between the machine's two stators, the temperatures of both stators are shown separately in Table 4.

Table 4: Temperatures at 75 kW motoring load at stabilized temperature

Temperature sensors place	Original stator 1	Stator 1 with 1 copper bar	Stator 1 with 3 copper bars no potting
End winding, frame side	146	130	120
End winding, air-gap side	147	132	119
On top of the slot	139	121	113
In the middle of slot	149	133	122
At bottom of slot	120	103	93
Temperature sensors place	**Original stator 2**	**Stator 2 with 1 copper bar**	**Stator 2 with 3 copper bars with potting**
End winding, frame side	137	123	111
End winding, air-gap side	138	123	113
On top of the slot	129	113	109
In the middle of slot	140	125	117
At bottom of slot	110	93	75

Stator 1 was hotter as the air gap at that side was slightly shorter. According to measurements one copper bar per tooth improved the cooling by lowering the temperature with several Celsius degrees. The temperatures in the end windings stabilised to values which were 15 °C lower than in the original stator (in stators 1 and 2). According to the measurement results the copper bars clearly improved the cooling of the machine. Next both stators were equipped with three copper bars in each tooth. This further decreased the temperatures in the end windings by app. 10 °C at 75 kW load. The end winding area of stator 2 had also potting material and according to measurements at 75 kW potting decreased the temperatures in the windings by $1-2\,^{\circ}\mathrm{C}$. It can be concluded that copper bars in the teeth and potting material around the end windings provide high-conduction heat transfer paths and may be recommended in cases of insufficient cooling. The material cost of utilizing copper heat paths are rather small as the copper price was approximately 5 € per kilogram. In the prototype motor utilizing three copper heat paths per tooth the extra material cost is approximately 50 €. Naturally, drilling the holes adds some cost. However, the potting material utilized in this machine caused extra cost of 1000 € for one prototype machine due the high Ceramacast price which is approximately 160 € per litre.

Drilling tooth material from the original design changed the machine

magnetic circuit and increased the iron losses to some degree. As a result the efficiency of the altered versions suffered slightly. It can be seen in the measurements as increased low power current and decreased efficiency. The currents as a function of power are depicted in Fig. 9 for all three cases. One may note that for the original machine structure only two points were measured because the cooling of machine was not sufficient. From the results it can be seen that the cooling structure with three copper bars and potting material around the end winding area has lower current at high power range when compared to the structure having only 1 copper bar. This may be explained by the lower copper losses and improved efficiency at high power.

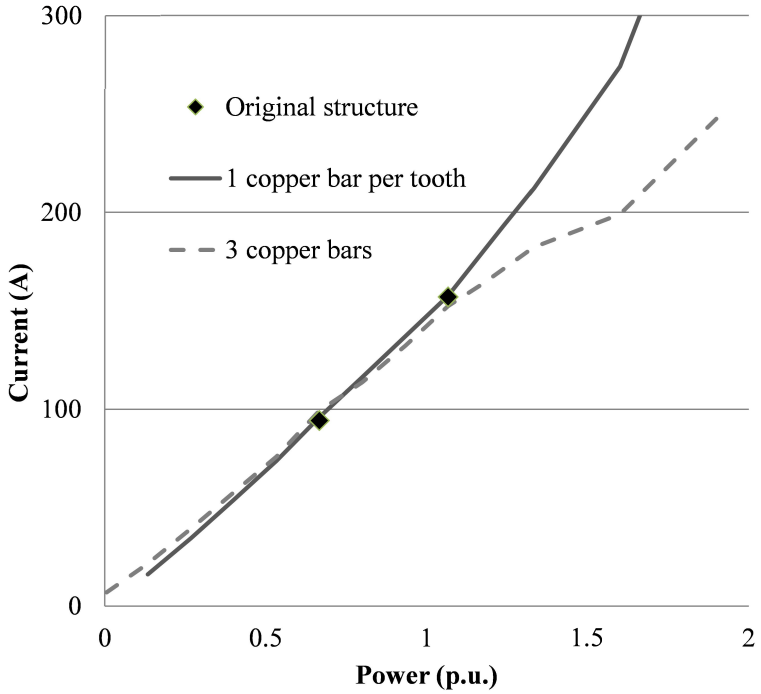

Figure 9: Current as a function of power for all three cases studied.

The input powers were measured with a Yogokawa PZ4000 power analyzer, and the output/shaft values were recorded using a Magtrol torque transducer placed on the shaft. The efficiencies of all studied the versions are shown in Fig. 10. The efficiencies of original machine shown in Fig. 10

are not straight comparable to modified structures with copper bars due the temperatures of original machine were not measured at stabilized temperature - these are temporal efficiency values.

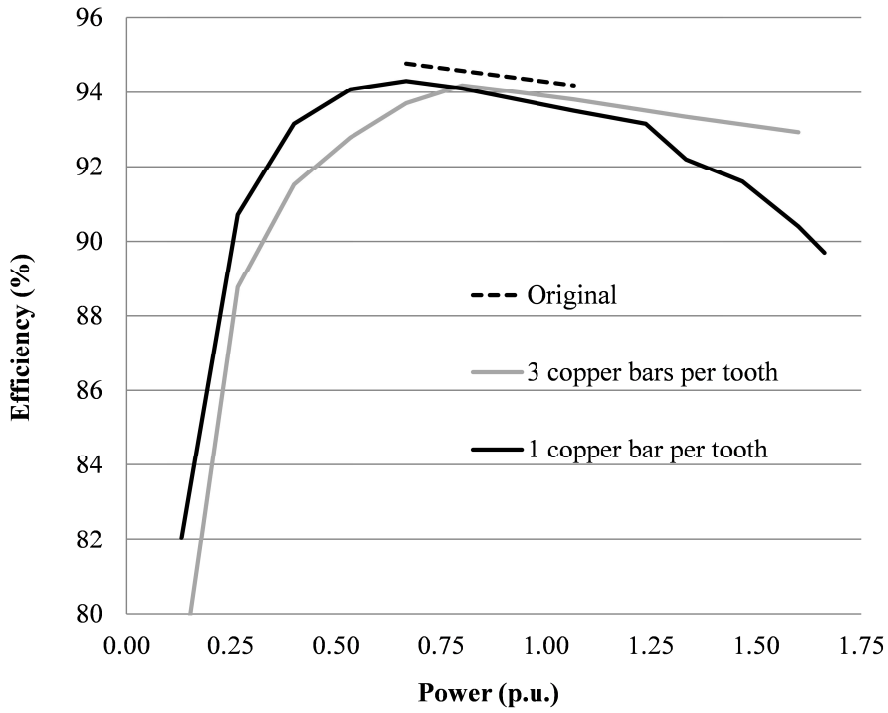

Figure 10: Machine efficiencies as a function of load with 75 kW as the base load

Clearly the efficiency is improved in case of three copper bars as extra heat paths improve the cooling and the conductors remain at lower temperatures reducing Joule losses. The solution with 1 copper bar gives higher efficiencies at low torque area when compared to the solution with three copper bars and vice versa. This is because the machine's current with the three-copper-bar-solution is lower at high torque area. The stator iron losses could not be separately measured: The original structure has 675 W rated point calculated iron losses in each stator and the structure with 1 copper bar has 683 W and the one with three copper bars has 698 W. This may be obvious because the steel area decreases as holes for coppers bars are drilled in teeth.

5. Conclusions

This paper focuses on cooling system improvements of an axial-flux PM machine. The thermal conductance is improved by 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. The copper bars improved the thermal behaviour significantly. It can be also concluded that potting of the stator of the axial machine can reduce the temperatures of the machine in an efficient way. It is, however, also possible to conclude that axial-flux machines easily suffer from heat transfer problems. In this case the targeted power level of the machine was finally not reached even though significant improvements in the design were implemented.

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