Influence of the Cooling Duct Geometry and of the Active Part Material Properties on the Cooling Behaviour of Thermal Highly Stressed Traction Induction Motors

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Abstract. The cooling duct geometry strongly influences the cooling behaviour of air cooled, closed and thermal highly stressed traction motors. This topic is described at different cooling concepts and laminations. In particular the cooling concept double air cooled system is explained.

Also the properties of the active part materials influence the cooling behaviour of traction motors. In particular the thermal properties of electrical sheets at elevated temperatures are discussed in this work.

This work aroses from the PhD thesis [12] of the main author with the topic "Optimization of The Cooling Concepts of Air Cooled, Closed and Thermal Highly Stressed Traction Induction Motors with the Target Conflict between the Electromagnetic and Thermal Designing". This article bases on the article *[11]*.

Key words: Traction motor, lamination, cooling concepts, cooling ducts, electrical sheet, magnetic properties

1. Introduction

Self-ventilated, closed induction machines tend to be used as traction motors for local railway. These motors must be extremely robust and exhibit a high power density owing to the enormous impact loads, rough ambient conditions, long expected service life (usually 30 years), confined space requirements in the bogie and high expected initial outputs. However, certain cost and weight limits must not be exceeded.
The author discusses in his PhD thesis the subject of optimizing the cooling concepts of air cooled, closed and thermal highly stressed traction induction motors with the target conflict between the electromagnetic and thermal designing. The content of this article is examined in more detail in the doctoral thesis, while further publications on this subject field are planned.
This article addresses the influence of cooling duct geometries and active part material properties (in particular of electrical sheets) on the cooling behaviour of thermal highly stressed traction induction machines. These influences occur in sundry air-cooled machines and depend on the relevant cooling concept.

2. Cooling Duct Geometry

A. Cooling Concepts

The impact of the cooling duct geometry on the thermal behaviour depends on the cooling concept. There are several cooling concepts of air cooled traction motors:

1) Open, forced ventilated
2) Open, self-ventilated
3) Encapsulated, surface cooled

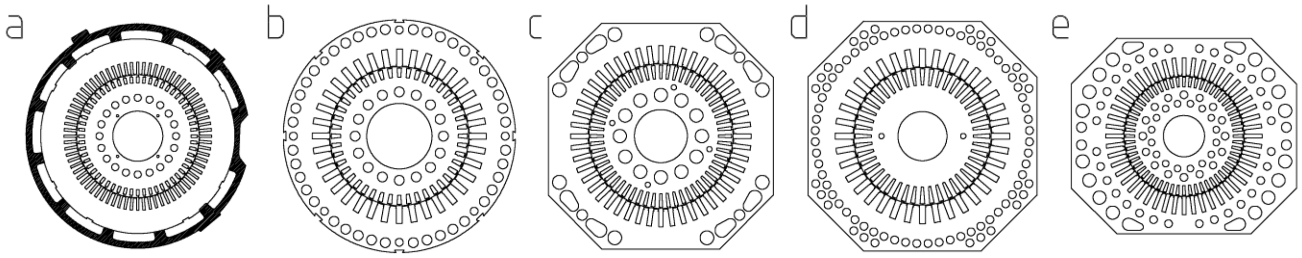

Fig. 1. Laminations for several open (a-c) and encapsulated (d, e) cooling concepts

4) Encapsulated, self-ventilated

There are big differences between the laminations, which are used for the different cooling concepts, see Fig. 1. This work presents the encapsulated, self-ventilated traction motor with inner cooling circuit (double air cooled system, DACS) in detail.

B. Double Air Cooled System (DACS)

The Fig. 2 shows the longitudinal cross section of a DACS traction machine and Fig. 3 shows a typical lamination of a DACS machine.

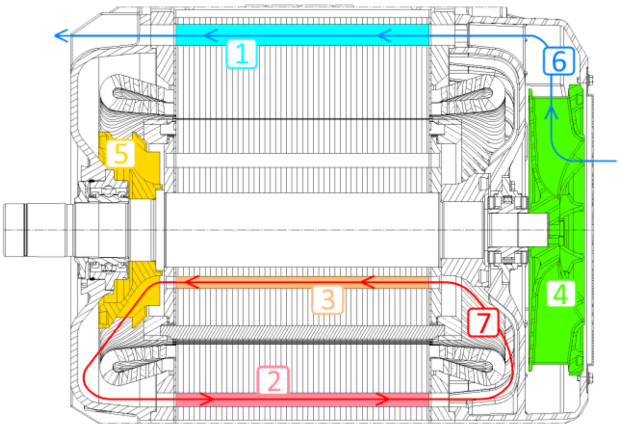

Fig. 2. Longitudinal cross section of a closed, self-ventilated traction induction machine (DACS cooling concept): 1) outer stator cooling duct, 2) inner stator cooling duct, 3) rotor cooling duct, 4) outer fan, 5) inner fan, 6) outer cooling circuit and 7) inner cooling circuit

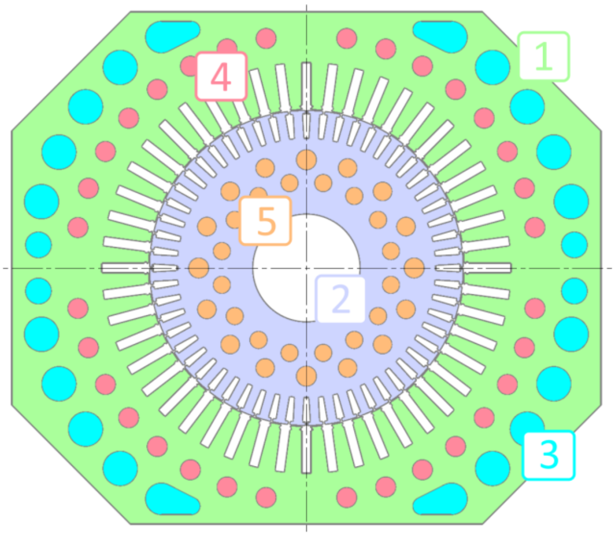

Fig. 3. Sectional view of a lamination of a closed, self-ventilated traction induction machine (DACS cooling concept): 1) stator lamination, 2) rotor lamination, 3) outer stator cooling ducts, 4) inner stator cooling ducts and 5) rotor cooling ducts

The cooling concept bases on two independent cooling circuits – on the outer cooling circuit (Fig. 2, labelling 6) and on the inner cooling circuit (Fig. 2, labelling 7). Actually, the outer cooling circuit is not a closed circuit, because the cooling air is sucked in by the outer fan (Fig. 2, labelling 4) on the non drive end-side, is pressed through the outer stator cooling ducts (Fig. 2, labelling 1) and leaves the machine on the drive end side. This machine is encapsulated, because there is no contact of the outer cooling air with the active part (winding, airgap or rotor).

All losses, which are produced in the machine, dissipate over the outer cooling circuit to the ambient (except the radiative and convective heat transfer on the motor surface). The inner cooling circuit is fed by the inner fan (Fig. 2, labelling 5) and is encapsulated from the ambient. The inner cooling air flows through the inner stator cooling ducts (Fig. 2, labelling 2) and through the rotor cooling ducts (Fig. 2, labelling 3). Because of the reverse direction of the inner cooling circuit (relating to the outer circuit) the maximum winding temperature occurs after approximately of 2/3 of the axial length of the lamination core (seen in flow direction of the outer cooling circuit). The main function of the inner cooling circuit is to balance the temperatures inside the machine.

C. Lamination Designs

The calculation method as described in *[11]* was applied to various lamination designs (see examples in Fig. 4) and compared.

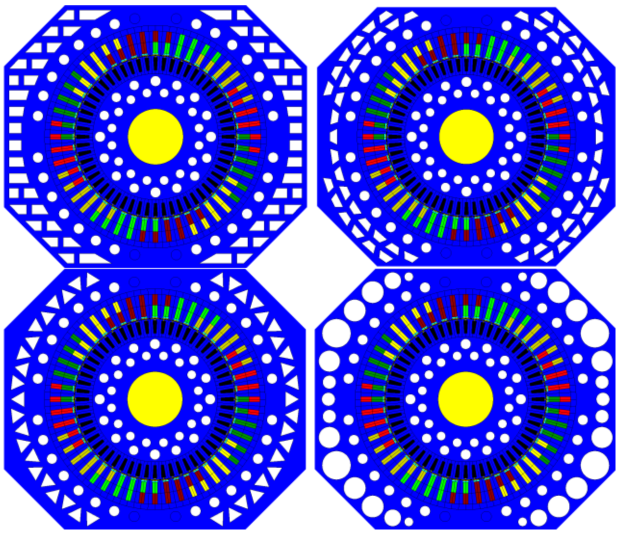

Fig. 4. Sectional views of various lamination designs

The most important aspects when designing new lamination geometries involve sundry design specifications as well as certain boundaries so that the laminations can also be used for serial production of traction machines:

- Minimum size of the cooling ducts (issue of impurities)
- Minimum distance between two neighbouring stamped edges
- Minimum distance to the outer edge
- Minimum radii in corners and on tips

- Maximum stamped edge length (issue of max. possible stamping force)
- Small number of different duct geometries in a lamination
- Machinability of the clamping plates
- Castability of the bearing plates and their cooling ribs

This task formulation – as optimal as possible a lamination design in thermal and electromagnetic terms with consideration of all necessary boundary conditions for use in traction machines – is currently tackled in the author's doctoral thesis. This calculation method is verified by measurements on a test motor with optimized lamination design. This measurements will be presented in further publications.

3. Material Properties

This section deals with the materials utilized in the active part of the induction motor. These characteristics are essential for the detailed knowledge of the operational behaviour of the traction motor. Accurate material properties are required to reach plausible simulation results [4, 9]. Especially for highly stressed traction motors with elevated temperatures the influence of the temperature on the material properties should be considered.

The active part of an induction machine consists of following parts (see also Fig. 5):

1) Laminated stator core
2) Stator winding
3) Air gap
4) Laminated rotor core
5) Squirrel cage

These parts mainly consist of the three materials: Electrical sheets, copper and isolation materials. In this work the focus is on the electrical sheets and on the properties at elevated temperatures (up to 300 °C).

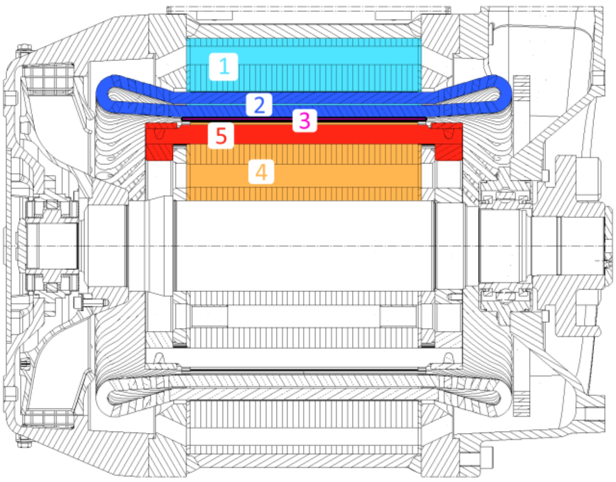

Fig. 5. Longitudinal cross section of an open, self-ventilated traction induction machine: 1) laminated stator core, 2) stator winding, 3) air gap, 4) laminated rotor core and 5) squirrel cage

Electrical sheets are used for the guidance of the magnetic flux in electrical machines [5]: Because of the time-varying magnetic fields it is necessary to reduce eddy currents. Eddy currents can be minimized by using a laminated core and special alloys. The main alloying element for reducing the electrical conductivity is silicon.

A. Temperature Influence on the Magnetic Properties

The temperature has a big influence on all magnetic properties of iron [8]: At the Curie temperature the ferromagnetic behaviour skips to a paramagnetic behaviour, because the disoriented forces of the thermal movements counter the directing force of the molecular field. Therefore the saturation polarisation decreases with increasing temperature. This behaviour strongly depends on the annealing. Because of decreasing inner forces (decreasing crystal anisotropy) the magnetizability at lower field strength increases and the coercivity decreases with rising temperature. The remanent flux density increases at lower temperature (approx. < 0 °C) and decreases at higher temperatures (approx. > 0 °C) with increasing temperature. The hysteresis losses decrease with rising temperature. All these magnetic properties are valid for iron. The magnetic behaviour of electrical sheets is basically equal. In this case the magnetic properties are improved by the alloy composition.
The saturation polarization of ferromagnetic materials usually decreases with increasing temperature. Regarding the coercivity and the permeability of electrical sheets there is no general temperature behaviour noticeable, because they depend strongly on the alloy composition and the annealing. The Curie temperature strongly depends on the alloy composition. A typical value of the Curie temperature for electrical sheets used in traction motors (M400-50A) is approx. 750 °C. [3, 10]

Measurements [6] verify the above statements about electrical sheets regarding the saturation polarization and the iron losses. By increasing the temperature from 30 °C to 90 °C the iron losses decrease approx. by 15 %. Because of the small temperature difference the measured saturation polarisation decreases only by 0,3 %. Fig. 6 shows the measurement results (Epstein frame measurements) with different temperatures of the electrical sheet.

The reason for the decreasing iron losses is the linear dependence of the eddy current losses and the electrical conductivity, see (1).

$$p_{\mathrm{w}} = \frac{1}{6} \cdot \sigma \cdot d^2 \cdot \pi^2 \cdot \hat{B}^2 \cdot f^2 \qquad (1)$$

where p_{W} are the eddy current losses, σ is the electrical conductivity, d is the thickness of the electrical sheet, B is the flux density and f the frequency.

At higher frequencies the decrease of the iron losses is more distinct, because the eddy current losses increase quadratically and the hysteresis losses linearly with the frequency.

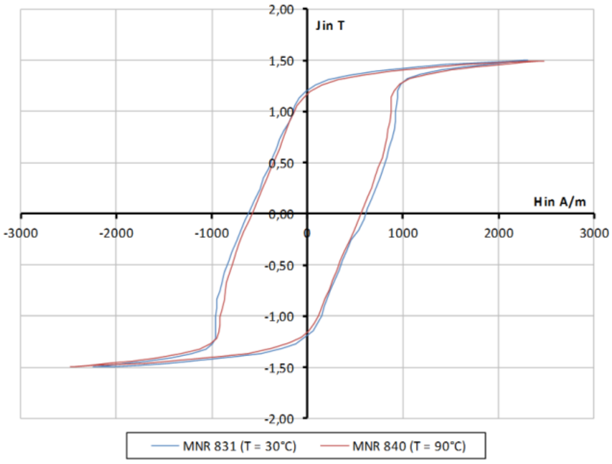

Fig. 6. Hysteresis loop at 30 and 90 °C with a supplied frequency of 1000 Hz [6]

B. Temperature Influence on the Thermal Properties

For electrical sheets the Wiedemann-Franz-Lorenz-Law (see (2) [2]) is not valid, because this law is only valid for pure metals and not for alloys.

$$\frac{\lambda}{\sigma \cdot T} = 2{,}44 \cdot 10^{-8} \frac{\mathrm{V}^2}{\mathrm{K}^2} \qquad (2)$$

where λ is the thermal conductivity, σ is the electrical conductivity and T the temperature.

The thermal conductivity and the electrical conductivity depend on the alloy composition. With increasing portion of silicon the thermal and electrical conductivity decrease. Therefore electrical sheets with low losses (high portion of silicon) have a poor thermal conductivity [7, 9]. According to the Matthiessen-Law the electrical resistance R of an alloy is defined as in (3) [1]:

$$R = R_{\mathrm{id}} + R_{\mathrm{Rest}} \qquad (3)$$

where R_{id} is the ideal resistance and R_{Rest} is the residual resistance.

The ideal resistance of a pure metal increases with increasing temperature. The reason for this are the thermal lattice vibrations because of the increased thermal atomic motion. The residual resistance is temperature-independent and is caused by impurity and lattice distortions.

C. Temperature Influence on the Operation of the Traction Motor

The temperature-dependency of the thermal conductivity of the electrical steel has an influence on the operational performance of a traction motor. Because of the increased thermal conductivity at elevated temperatures the heat losses can be transferred easier from inside (losses source – stator winding) to outside (heat sink – cooling ducts) of the machine. Therefore, the heat dissipation of a warm machine is better than at cold condition.

Fig. 7 shows the results of a thermal conductivity sensitivity analysis of a thermal finite element simulation. As expected the temperature of the lamination stator core increases with increasing conductivity. Hence also the radiative and convective heat transfer on the motor surface get higher. Therefore the stator winding temperature decreases at high conductivity.

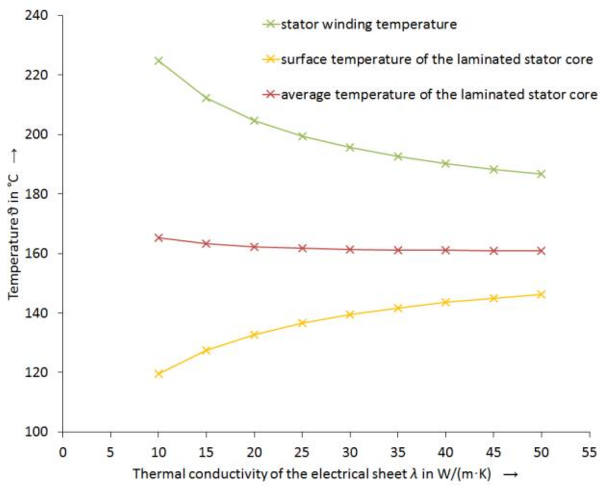

Fig. 7. Thermal conductivity sensitivity analysis of the electrical sheet with a thermal finite element simulation for a traction motor nominal point

In the next step a spatial temperature dependent thermal conductivity of the electrical sheet is considered in the simulation. Fig. 8 shows the results. The influence on the simulated stator winding temperature is very low, if the reference value of the conductivity is well chosen.

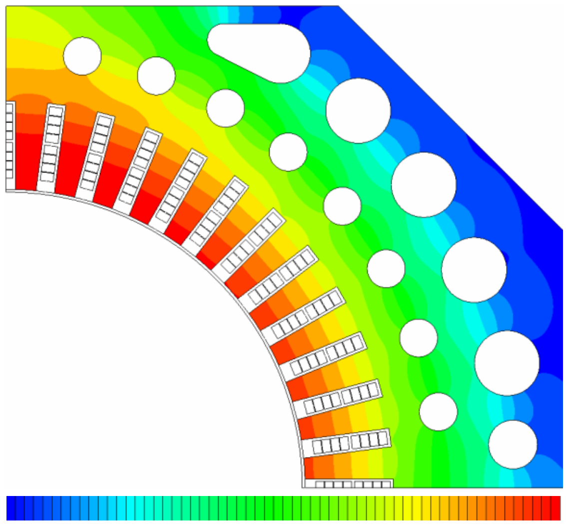

Fig. 8. Finite elements simulation results, temperature dependent thermal conductivity of the electrical sheet, values from 29,8 (blue) to 32,8 W/(m·K) (red)

The temperature-dependency of the magnetic properties at elevated temperatures has only very small influence on the operational performance of a traction motor and can therefore be neglected. The iron losses decrease at elevated temperatures (see chapter 3.A). On the one hand the saturation polarization decreases in high saturated areas (teeth) and therefore the magnetization current increases. On the other hand in areas with low saturation (the main parts of the yoke) the magnetization current decreases (as described in chapter 3.A).

4. Conclusion

The presented work explains the cooling concept DACS and the influence of the cooling duct geometry on the cooling behaviour of the traction motor. In further works a detailed view to optimized cooling ducts arrangements should be done.

The temperature-dependency of the thermal properties of the materials utilized in the active part of the traction motors is not negligible at highly stressed traction machines. Especially the behaviour of electrical sheets changes with elevated temperatures. These aspects should be considered at the electromagnetic and thermal calculation of traction machines. Further works will present the thermal behaviour of copper and of isolation materials.

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