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# Increasing the power density of e-motors by innovative winding design

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**Abstract**

In the future, the sustainable use of renewable energy is becoming more important. About 80% of the total world energy demand is actually derived from fossil fuels. Mobility currently uses over 50% of total global energy. Approaches for the efficient and sustainable energy use are electric and hybrid vehicles. An important component to power these cars is the electric motor. The economic and efficient design of an electric motor requires knowledge of the exact thermal conductivities of all components. A difficult parameter to determine and to improve is the thermal conductivity of the winding. This paper presents measurement results of an innovative motor winding with an improved thermal conductivity.



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*Keywords:* Electric motor; power density; thermal conductivity; winding

## 1 Introduction

A sustainable use of renewable energy is becoming more and more important. About 80% of the total world energy demand is actually covered by fossil fuels [1]. Mobility is currently responsible for more than 50% of the world's energy consumption [2]. Electric and hybrid vehicles are a promising approach for a more efficient and sustainable energy use. In these vehicles, conventional combustion engines are replaced by electric motors. One key challenge of this upcoming industrial application consists in finding novel ways to realize energy efficient electric motors characterized by a high level of power density. The power density is measured by the amount of mechanical output power per motor volume. The main limiting factor to increase the continuous power density is the thermal conductivity of its winding [3]. If an increased thermal conductivity of the winding can be reached, the cooling of the motor is improved and consequently additional power can be produced. Based on a new manufacturing process of winding bars, which allows a higher degree of design freedom [4,5], this paper addresses the research question of how this freedom can be successfully utilized to increase the thermal conductivity of the winding and thus to reach higher power densities of electric motors.

The paper presents two basic design approaches to increase the thermal conductivity of motor windings. Multiple design variants are produced and experimentally evaluated on a test bench built for this purpose. The findings allow a basic understanding of the factors which influence the thermal conductivity. The results also indicate the basic opportunity to increase the power density of electric motors by a smart winding design, and thus to support a more sustainable use of energy.

The paper is structured as follows: Section 2 gives a literature overview regarding thermal conductivity of motor windings and presents published methods to identify the thermal conductivity of defined winding probes. In section 3, the experimental setup to accurately measure the thermal conductivity of winding probes is introduced. Further, a method to minimise the measurement error of the setup is described. Section 4 presents the measurement results. At first, reference probes are measured to check the accuracy of the measurement setup. Then, the results of the winding probes are presented. In section 5 the measurement results are discussed and the factors, which improved the thermal conductivity of the winding, are determined. Section 6 concludes with an overview and an outlook for further research.



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## 2 Literature review

The continuous power density of an electric motor is limited by the thermal consistency of the used materials. Until now, in electric motor design "thermal analysis has received less attention than electromagnetic design. However, in the new century, the topic had started to receive more importance due to market globalization and the requirement for smaller, cheaper, and more efficient electric motors" [6]. Thermal analyses of electric motors are often performed by thermal simulations, which require accurate conductivity values as input. Since the thermal resistance of the winding is dominant compared to all the other thermal resistances, its conductivity is of major interest. A literature research about the thermal conductivity of the winding is summarized in figure 1. It can be seen that the found values spread over a wide range which is not suitable for accurate thermal simulations.

To understand the spreading of these values, the methods used to identify the thermal conductivity of the winding are analysed. Most publications describe a parameter adjustment of a FEM model [6] or an analytic model [7] in order to match the measured temperatures in a motor. All these methods have the disadvantage that for the precise determination of one parameter all the others have to be precisely known. Often these circumstances are not given. Another issue of these methods is that for every variation a new cost intensive motor has to be built. An alternative method is to measure the thermal conductivity in an experiment, but only little research was done in the measurement of the thermal conductivity of winding probes. Simpson et al. [8] for example describes a test setup which can measure the thermal conductivity of cubic winding probes. However, they do not treat the important topic of the measurement accuracy. Therefore, a measurement setup with an optimised measurement error is needed to investigate the thermal conductivity of winding probes with different filling factors and geometry parameters.

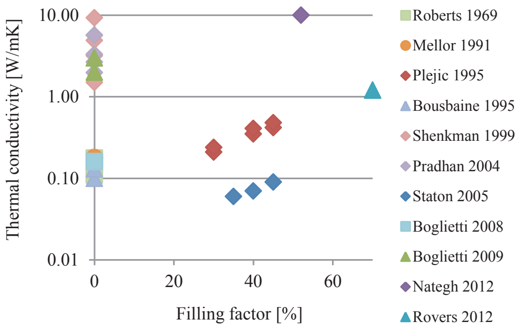


Figure 1: Thermal conductivities of windings of electric motors found in literature (values found without the filling factor information are shown at filling factor zero) [6, 7, 15, 16, 17, 18, 19, 20, 21, 22, 23]

New winding forms like twisted windings were only recently investigated. Van der Geest et al. presented a loss reduction of 60% by replacing parallel windings with twisted windings in an electric motor [9]. This new idea is also described in a recent patent where bars composed of twisted wires are inserted in an electric motor [4]. However, the influence of the twisted wires on the thermal conductivity has not been investigated yet.

To get accurate values for the thermal conductivity of winding probes and to do basic research to understand the influencing factors, a measurement setup is suggested. For the design of a precise measurement setup it is important to analyse and to minimize the measurement error. Using this setup fast and cost-saving measurements of a large amount of winding probes get possible. Further, the difference of the thermal conductivity of twisted- and parallel-wires can be shown experimentally.

## 3 Measurement of the Thermal conductivity

A Measurements setup, shown in Figure 2, is built to establish a basic knowledge of the windings thermal conductivity. To achieve comparable measurement results of the winding probes, a maximal measurement error of 8 % is required. Increased measurement reliability is achieved by a configuration where all measurements are done redundant. A minimisation of the measurement error is achieved through a geometry optimisation with the help of an analytical model. The assumptions which are made for the simplified analytic model are confirmed by a 3D-FEM simulation.

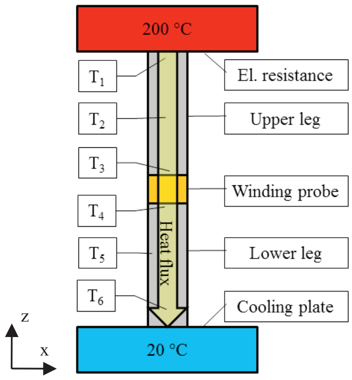


Figure 2: the schematic heat flux in z-direction

The thermal resistance of the winding probe is calculated by dividing the measured temperature drop over the winding probe through the measured heat flux traversing it. With the help of the geometrical parameter of the winding probe (height of the probe: $d$), the thermal conductivity can be determined [10]. To measure the described values, the winding probe is clamped between two metal legs. A heat flow is imposed on the top of the upper leg by electric resistances. This heat flow goes from the upper leg though the winding probe in the lower leg which is cooled by a cooling plate on the bottom side. The heat flux is calculated by the temperature drop in the two legs $T_1 - T_3$ which is measured by two thermocouples separated at a distance $d_{13}$ . The temperature drop over the winding probe $T_3 - T_4$ is measured by two thermocouples located near the probe in each leg. To compensate the temperature drop between the probe surfaces to the measuring point, a linear extrapolation of the three measured temperatures in the leg is done up to the probe surface. Since three measurements are performed in each leg, a redundancy for the linear interpolation is guaranteed. The redundancy of the heat flux is provided by measuring the heat flux twice, in the upper and in the lower leg. To finally calculate the thermal conductivity, an analytic model is done.