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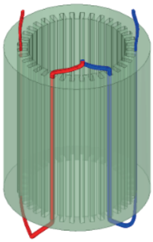
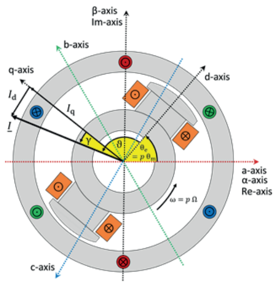
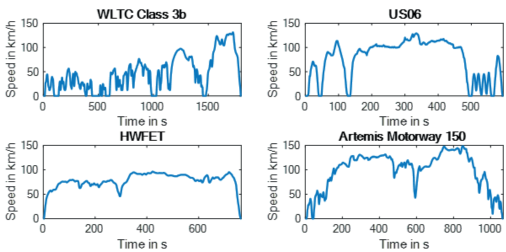
An Assessment of Wound-Rotor Synchronous Machines with Hairpin Windings for Automotive Traction Drives







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An Assessment of Wound-Rotor Synchronous Machines with Hairpin Windings for Automotive Traction Drives

Dipl.- Ing. Daniel Bachinski Pinhal

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„For my parents,

Nilza Bachinski Pinhal

and

Nelson Moreira Pinhal”

Abstract

This thesis investigates research gaps identified in the field of electrical machines for automotive traction applications: The wound-rotor synchronous machine as traction machine for full-electric vehicles and the usage of hairpin conductors to build up its armature's windings.

Although the wound-rotor (i.e. current-excited) synchronous machine has been researched, designed and manufactured for decades, its adoption in variable speed drives targeting automotive vehicles is still remarkably limited. Employing a wound-rotor synchronous machine, the field current, and thus, the rotor flux can be tuned to improve performance criteria (e.g. efficiency) for every operating point. This opens the way to more sophisticated motor control strategies in a variable speed drive. In this thesis, it will be shown that the active control of the field current has a notable impact on the optimal motor control strategy and finally on the overall performance of the traction machine. Although this additional degree of freedom clearly increases the complexity of the machine control, it offers an opportunity to develop electric variable speed drives further tailor-fitted to demands of automotive applications (e.g. high efficiency in partial-load operation).

The second key topic covered by this thesis is the usage of hairpin windings in the machine's armature. Using this approach, prefabricated U-shaped conductors (i.e. the hairpins) are shaped by means of bending processes, inserted into the armature's slots and then connected to each other to realize the phase windings. Since these processes are well suitable for mass-production, the usage of hairpin windings is promising means to avoid bottlenecks during manufacturing of electric machines. However, the usage of hairpin windings is also linked to considerable drawbacks. Increasing the number of conductors per slot drastically increases the complexity and manufacturing time of the winding. Hence, hairpin windings are usually characterized by a low number of turns per phase and solid conductors with a large cross-sectional area. Since the armature conductors of a wound-rotor synchronous machine carry time-dependent currents, the ohmic losses in the hairpin windings may increase significantly due to eddy-currents and decrease the overall efficiency of the electric drive. The evaluation of the impact of eddy-current effects in the armature conductors of automotive traction machines is not trivial. Due to the variability of the operating points of traction machines in automotive applications, classical design rules aiming for an optimal conductor size are not applicable. This raises the question if and in what extent does the usage of hairpin windings affect the overall performance of the machine in an electric vehicle.

This thesis will employ analytical and numerical methods to quantify the additional ohmic losses introduced by eddy-current effects. Furthermore, the manufacturing process of hairpin windings and considerations when choosing the EM's winding layout will be clarified. To analyze both key topics of this thesis simultaneously and investigate the interplay between the variability of operating points and the impact of eddy-currents, a machine model will be proposed that is able to capture effects such as eddy-currents and core saturation while still requiring short calculation times. An exemplary wound-rotor synchronous machine will be introduced, analyzed and discussed to demonstrate the usage of the assessment methods proposed.

The analyses' results in this thesis show that a proper choice of the control strategy used to determine the machine's feeding is a key to increase its performance in variable speed drives. A loss minimization control strategy allows achieving high efficiencies even for partial-load operation. When standard driving cycles are employed to characterize driving maneuvers, the impact of eddy-current effects in the machine's performance is notable but still relatively low compared to the impact of other system parameters (e.g. control strategy, recuperation, etc.). This shows that hairpin windings are a reasonable approach to avoid bottlenecks in a large-scale production of electric machines as currently required to satisfy the demands of the automotive market. The analyses' results in this thesis show no evidence that the manufacturing steps and constraints required by hairpin windings impose a general restriction on their application in electric machines for automotive traction drives.

Although this thesis focuses on wound-rotor synchronous machines with hairpin windings, multiple methods and workflows developed can be transferred to similar analyses in adjacent areas of investigation. Although the method for creation of computational fast machine models cannot be applied to other machine types directly, it can be adapted for this purpose. Moreover, methods for calculation of eddy-currents inside hairpins and driving cycle simulations as described in this thesis are applicable independently of the electrical machine type investigated. In addition, the calculation of the optimal feeding (i.e. the optimal control strategy) of the wound-rotor synchronous machine is equally valid for designs employing wound armature windings made of wire.

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Unterhaching, April 2021

Daniel Bachinski Pinhal

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