Doctoral Dissertation
Doctoral Program in Electrical Engineering (36th Cycle)

Analysis and Design of High-Speed Induction Machines for Submerged Cryogenic Pumps

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Summary

This thesis aims at investigating proper methodologies for the analysis and design of high-speed induction machines for submerged cryogenic pumps. Attention is paid to the magnetic characterization of electric steels at cryogenic temperature, the electromechanical and thermal modeling of cryogenic induction machines as well as the definition of general guidelines for their design. The research in all its aspects is supported by dedicated experiments performed on different machines. A three phase high-speed cryogenic induction machine is designed and tested. The prototype, rated 15 kW at 13500 rpm, is built using conventional materials for electric machines and integrated in a single-stage submerged cryogenic pump operating with liquid nitrogen at 100 K.

The magnetic and energetic characterization of silicon-iron and cobalt-iron electric steels aims at comparing their behavior at room and at the liquid nitrogen temperature of 77 K. Overall, minor changes are observed in the *B-H* curves of the steels. The increase of the magnetic losses at cryogenic temperature is due to enhanced dynamic loss phenomena in the silicon-iron steels and mostly increased hysteresis losses in the cobalt-iron sample.

The study of the electromechanical modeling of cryogenic induction machines targets at defining a unified strategy for their steady-state analysis and is based on the per-phase equivalent circuit. The performance of a conventional fractional-kilowatt industrial motor are investigated experimentally at room and at the liquid nitrogen temperature. The results show that the cryogenic temperature mostly affects the resistive parameters of the machine because of the change in the electric conductivity of copper, aluminum and laminations. The experimental analyses demonstrate that the loss balance in the machine is significantly different at cryogenic temperature with respect to that at room temperature. To complete the analysis, the electromechanical behavior of the studied machine equipped with a superconducting rotor cage is explored and studied analytically.

The analysis of the steady-state thermal modeling of cryogenic induction machines focuses on the simplified analysis of the temperature distribution in one of the most critical machine components: the copper windings at the stator. Experiments are performed on an industrial induction machine for submerged cryogenic pumps. The results show that the use of temperature sensors might not be appropriate to study the winding hotspots; hence, dedicated tests are performed under dc supply to determine the average winding temperature. A simplified

thermal model based on two-dimensional finite-element simulations is proposed to study the distribution of temperature in the stator windings. It is shown that the proposed model can provide credible results and is appropriate for the initial design studies of cryogenic machines. Nevertheless, additional investigations on the thermal properties of materials and the fluid flow conditions are necessary to improve the proposed model and make it more general.

The design of a 15 kW, 13500 rpm high-speed induction machine is studied to increase the power density of an already existing industrial motor for submerged cryogenic pumps. The high-speed design is intended for an innovative single-stage pump concept. The objective of the study is to assess the high speed motor concept in industrial cryogenic pump drives. The motor is tested on site; the electromagnetic losses as well as the distribution of temperature in the active parts of the machine are studied with detailed numerical models. It is shown that the iron losses under different operating conditions always play a relevant role in the electromagnetic loss balance of the machine. The electromagnetic and thermal studies highlight that the designed machine delivers the desired performance with a relatively safe increase of the temperature in the copper stator winding and in the active parts in general.