Mechanical design and manufacturing of a high speed induction machine rotor

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by

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DECLARATION

I, the undersigned, hereby declare that the work done in this project is my own original work.

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ABSTRACT

The McTronX research group at the North-West University designs and develops Active Magnetic Bearings (AMBs). The group's focus shifted to the design and development of AMB supported drive systems. This includes the electromagnetic and mechanical design of the electric machine, AMBs, auxiliary bearings as well as the development of the control system.

The research group is currently developing an AMB supported high speed Induction Machine (IM) drive system that will facilitate tests in order to verify the design capability of the group. The research presented in this thesis describes the mechanical design and manufacturing of a high speed IM rotor section. The design includes; selecting the IM rotor topology, material selection, detail stress analysis and selecting appropriate manufacturing and assembly procedures.

A comprehensive literature study identifies six main design considerations during the mechanical design of a high speed IM rotor section. These considerations include; magnetic core selection, rotor cage design, shaft design, shaft/magnetic core connection, stress due to operation at elevated temperatures and design for manufacture and assemble (DFMA). A critical overview of the literature leads to some design decisions being made and is used as a starting point for the detail design. The design choices include using a laminated cage rotor with a shrink fit for the shaft/magnetic core connection.

Throughout the detail design an iterative process was followed incorporating both electromagnetic and mechanical considerations to deliver a good design solution. The first step of the iterative design process was, roughly calculating the material strengths required for first iteration material selection followed by more detailed interference fit calculations. From the detail stress analysis it became apparent that the stress in the IM rotor section cannot be calculated accurately using analytical methods. Consequently, a systematically verified and validated Finite Element Analysis (FEA) model was used to calculate the interferences required for each component. The detail stress analysis of the assembly also determined the allowable manufacturing dimensional tolerances. From the detail stress analysis it was found that the available lamination and squirrel cage material strengths were inadequate for the design speed specification of 27,000 r/min. The analysis showed that a maximum operating speed of 19,000 r/min can be achieved while complying with the minimum factor of safety (FOS) of 2.

Each component was manufactured to the prescribed dimensional tolerances and the IM rotor section was assembled. With the failure of the first assembly process, machine experts were consulted and a revised process was implemented. The revised process entailed manufacturing five small lamination stacks and assembling the stack and squirrel cage afterwards. The end ring/conductive bar connection utilises interference fits due to the fact that the materials could not be welded. The process was successful and the IM rotor section was shrink fitted onto the shaft.

However, after final machining of the rotor's outer diameter (OD), inspections revealed axial displacement of the end rings and a revised FEA was implemented to simulate the effect. The results indicated a minimum FOS ≈ 0.6 at very small sections and with further analytical investigation it was shown that the minimum FOS was reduced to only 1.34.

Although the calculations indicated the FOS was below the minimum prescribed FOS ≥ 2, the rotor spin tests were scheduled to continue as planned. The main reasons being that the lowest FOS is at very small areas and is located at non critical structural positions. The fact that the rotor speed was incrementally increased and multiple parameters were monitored, which could detect early signs of failure, further supported the decision.

In testing the rotor was successfully spun up to 19,000 r/min and 27 rotor delevitation test were conducted at speeds of up to 10,000 r/min. After continuous testing a secondary rotor inspection was conducted and no visible changes could be detected.

The lessons learnt leads to mechanical design and manufacturing recommendations and the research required to realise a 27,000 r/min rotor design.

Keywords: *Induction machine, rotor section, laminations, magnetic core, squirrel cage, shrink fit, material, finite element analysis, factor of safety, contact pressure, tangential stress, Von Mises, high speed.*

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LIST OF ABBREVIATIONS

AMB	Active Magnetic Bearing
AC	Alternating current
IACS	International annealed copper standard
EDM	Electrical-discharge machining
IM	Induction Machine
SRM	Switched-reluctance motor
PM	Permanent magnet
r/min	Revolutions per minute
HTR	High temperature reactor
OD	Outer diameter
ID	Inner diameter
FOS	Mechanical factor of safety
CP	Contact pressure
RMS	Root mean squared
EES	Engineering equation solver
PCD	Pitch circle diameter
FEA	Finite element analysis
FEM	Finite element model
CNC	Computer numerical control

List of symbols

m	Element mass
r	Radial distance from centre
ω	Rotational speed
T_m	Melting temperature
N_{max}	Maximum operating speed
σ_{max}	Maximum allowable stress
σ_y	Yield strength
σ_{ut}	Ultimate tensile strength
σ_r	Radial stress
σ_t	Tangential stress
σ_{VM}	Von Mises equivalent stress
σ_p	Bearing stress
E	Modulus of elasticity
μ	Friction coefficient
α	Thermal expansion coefficient
ρ	Density
υ	Poisson ratio
D_r	Maximum calculated outer diameter
F_r	Reaction force
P_m	Lathe motor power
F_A	Axial cutting force
F_H	Resultant cutting force
F_C	Tangential cutting force
a	Depth of cut

V	Cutting speed
ECT	Equivalent chip thickness
CFA	Chip flow angle
CEL	Chip edge length
f	Feed rate
Q	Metal removal rate
K_p	Power constant
K_c	Specific cutting force
C	Feed factor
W	Tool wear factor
e	Machine tool efficiency factor
L	Length
A	Cross sectional area
K_B	Bearing stress distribution concentration factor
K_t	Patterson stress concentration factor