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Chapter

Introduction

High speed Active Magnetic Bearing (AMB) supported drives are presented with emphasis on nuclear applications. Typical electrical machines used in high speed applications are listed with the focus on induction machines. The problem statement is given, followed by the specific mechanical design, issues to be addressed and methodology. The chapter is concluded with an overview of the dissertation.

1.1 Background

The McTronX research group focuses on AMB supported drives for high speed applications. The AMBs replace conventional bearings and allow for very high rotational speed without limiting the shaft diameter. Although small precision bearings are capable of high speeds, the limiting operating speed decreases dramatically with an increase in diameter. This limiting diameter results in a reduced shaft stiffness which will influence rotor stability at high speeds. On the other hand the diameter of a shaft, incorporating AMBs, is only limited by the maximum allowable surface speed of the magnetic material on the shaft.

Therefore, replacing conventional bearings with AMBs will enable higher rotational speeds and most rotating machines benefit from an increase in rotational speed. For instance turbo machines become more efficient and electric motor's size decreases [1]. In the case of flywheel applications the energy stored is a function of the rotating speed squared.

In the past gas and steam turbines were obvious choices for compressor and blower drives due to their high operational speeds, efficiency, power density and availability [1]. Traditional electric motors are also used for high speed applications. However, a mechanical gearbox is required in order to achieve the high operating speeds, therefore, decreasing efficiency, power density and reliability, while increasing cost. Due to the development in frequency converters variable high speed alternating current (AC) motors are widely used with the limiting parameter in most instances the mechanical strength [2].

1.1.1 High speed machine classification

The term "*high speed*" is a relative term and could be interpreted differently by both electrical and mechanical engineers. From a mechanical point of view the term "*high speed*" entails complex design and stress analysis and for an electrical engineer it might mean high operating frequency (>50 Hz). In order to illustrate the mechanical thinking one should look at the main forces acting on a rotating machine namely centrifugal forces. When considering an infinitesimally small ring element the centrifugal force acting on the element is given by (1.1)

$$F = mr\omega^2 \tag{1.1}$$

where m is the element's mass (kg), r is the element's radial distance from the centre of rotation (m) and ω is the rotational speed (rad/s) [3]. From (1.1) it is found that a rotor with a large diameter rotating at a relative low rotational speed can experience the same forces as a small diameter rotor operated at a high rotational speed. Therefore machine speed classification cannot necessarily be done only on rotational speed; the geometry must also be considered. One way of classifying "*high speed*" is by calculating the surface speed of the rotor. The literature shows that surface speeds over 120 m/s can be classified as high speed [4].

1.1.2 High speed machine applications

In the search for cheap and sustainable energy the answer may lie in the development of the high temperature reactor (HTR). Helium is used as coolant in the closed cycle and is propelled by a blower system. One particular application for a variable high speed direct drive system is therefore, a helium blower. The drive enables the blower to be operated at different speeds in order to obtain different coolant pressures. Helium is selected for the application due to the fact that it is chemically and radiological inert and possesses a high heat capacity [5].

1.1.3 High speed machine selection

Typically used electric machines for high speed applications are switched-reluctance machines (SRMs), permanent magnet (PM) and induction machines (IMs) to name but a few [6]. Wen L Soong [7] compares these three machines in a specific application. The tradeoff study shows that the IM is the preferred design due to the relative good efficiency and lower cost. An IM was specified for this project due to the particular application requirements, the experience of the research group and the relative low cost.

The basic concept of a cage induction machine is illustrated in Figure 1-1 and Figure 1-2. The induction machine can be divided into two major components namely the stator and rotor. The stator consists of a laminated core with three phase windings. The rotor has a laminated core that contains a squirrel cage constituting conductive bars and end rings. In order for the rotor to rotate three sinusoidal currents displaced in phase by 120˚ are applied to the stator windings. The applied current produces a radially rotating magnetic field which induces currents in the conductive bars. The end rings connects the rotor bars and completes the circuit. The interaction between the magnetic fields in the rotor and stator causes the rotational motion of the rotor.

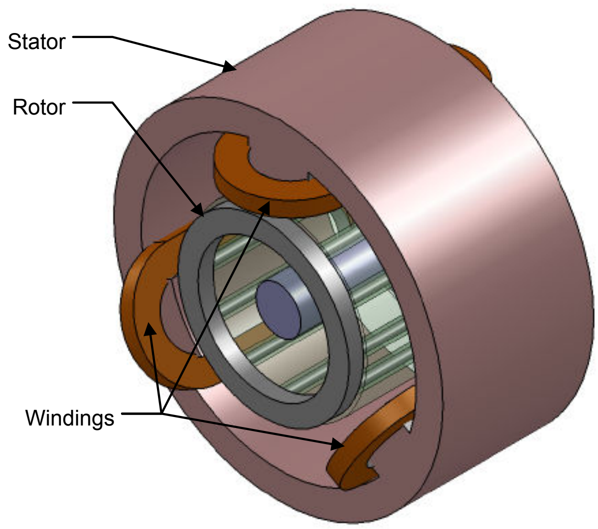

Figure 1-1: Simple illustration of complete induction machine

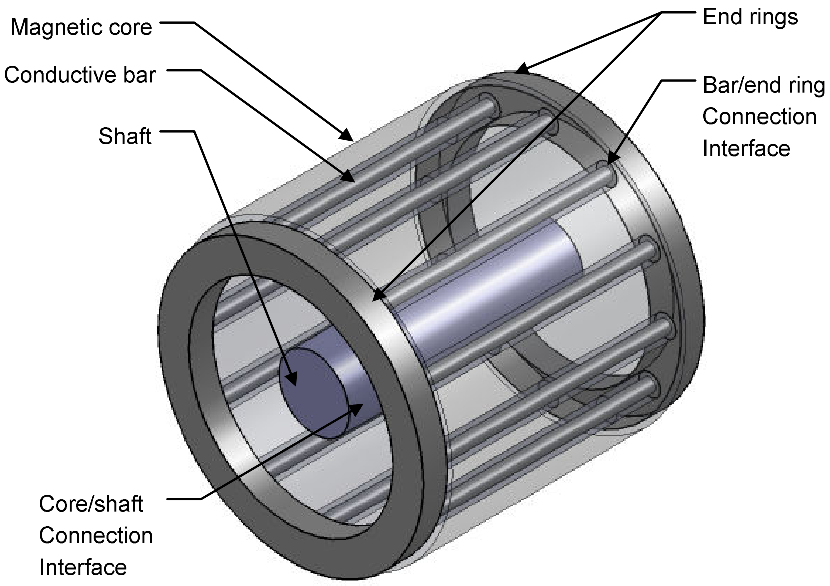

Figure 1-2: Induction machine cage rotor illustration

1.1.4 High speed machine mechanical design challenges

With the realization of high speed electric machines, emphasis is put on the mechanical design in terms of material selection, strength analysis and the manufacturing. Traditional die-cast rotors and magnetic core/shaft connection methods cannot withstand the forces due to high rotating speeds. As a result the use of advanced materials and innovative manufacturing and assembly procedures are required in order to deliver safe, reliable and cost effective high speed IM. Section 1.3 shows all the mechanical considerations in more detail for the development of a high speed IM.

1.2 Problem statement

The McTronX research group is currently developing an AMB supported high speed induction machine drive system that will facilitate tests in order to verify the design capability of the research group. Figure 1-3 shows a section view of the system and highlights the main components namely the axial AMB, radial AMB 1 and 2, induction machine stator section, backup bearings and induction machine rotor section.

The focus of this project is the mechanical design and manufacturing of the induction machine rotor section as illustrated in Figure 1-2, conforming to the design specifications listed in Table 1-1. The mechanical design and manufacturing of the high speed induction machine rotor will include selection of rotor topology, material selection, strength analysis and specifying manufacturing and assembly procedures. Rotor dynamic analysis can also be seen as part of the mechanical design, however, this is beyond the scope of this particular project and is done by an alternative resource as part of the backup bearing module design [8].

Table 1-1: Design specifications

Specification	Quantified	Description
Machine type	IM	Induction machine
Maximum operating speed N_{max}	25,500 r/min	Maximum operating speed, over speed 27,000 r/min
Ambient operating temperature *T*	80 °C	All calculations are done with the assumption that the components are at an ambient temperature
Factor Of Safety (*FOS*)	2	The Von Mises equivalent stress should be ≤ half the material yield strength at the operating conditions
Shaft OD	80 mm	The shaft OD is determined by the rotor dynamic analysis.
Rotor core OD	123 mm	Rotor core OD, determined by the electromagnetic design
Rotor core axial length	177 mm	The rotor core length is determined by the electromagnetic and rotor dynamic designs

1.3 Issues to be addressed

Considering the induction machine rotor as illustrated in Figure 1-2, the mechanical design of the rotor can be divided into six primary design issues. Figure 1-4 shows the six primary issues and their secondary issues [9] [10]. Although the rotor design can be divided into distinct issues not one of these issues can be addressed without considering the implications to other primary and secondary issues. The considerations must include strength analysis, electromagnetic performance, manufacturing processes and assembly of the components.

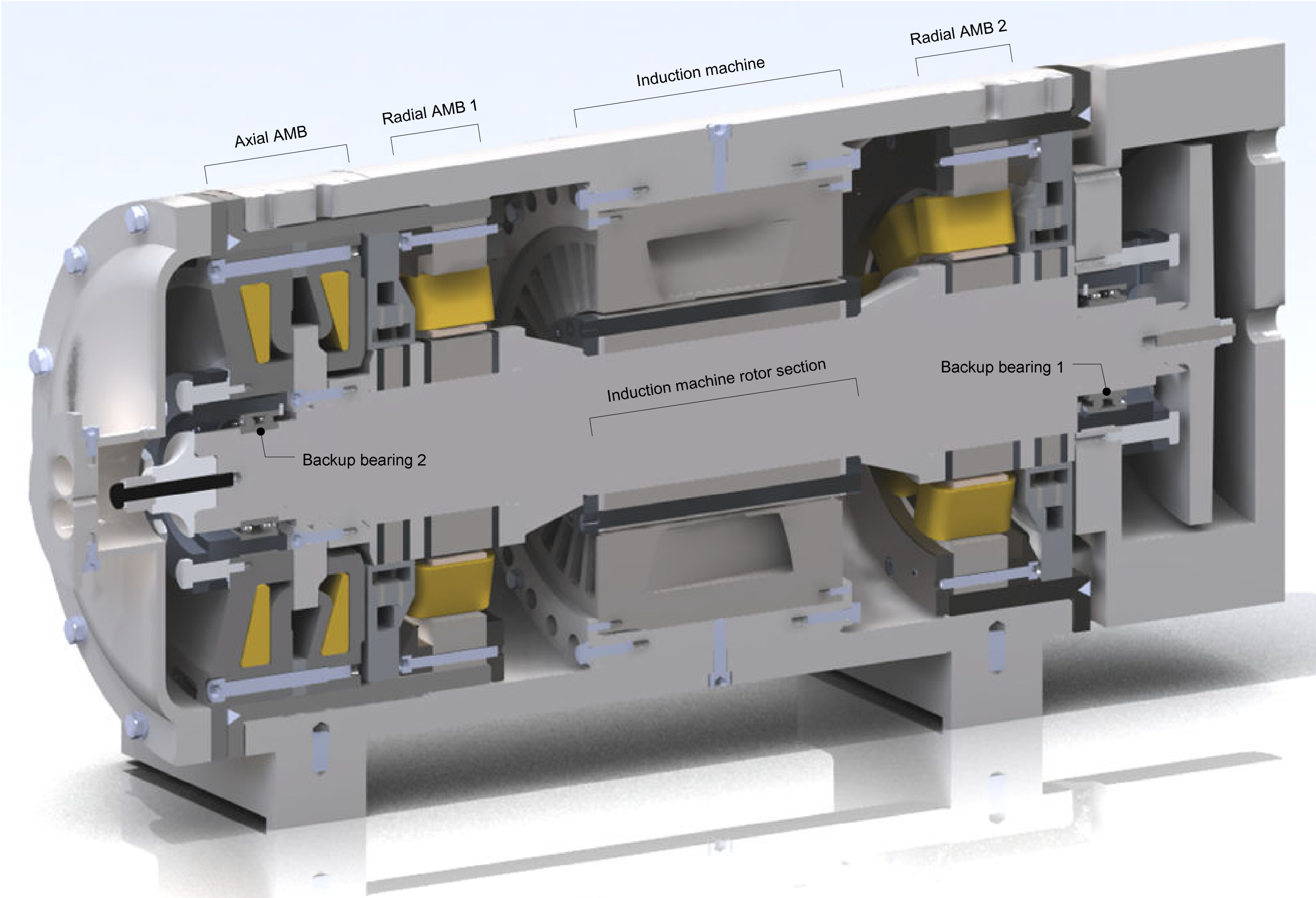

Figure 1-3: AMB supported high speed induction machine assembly

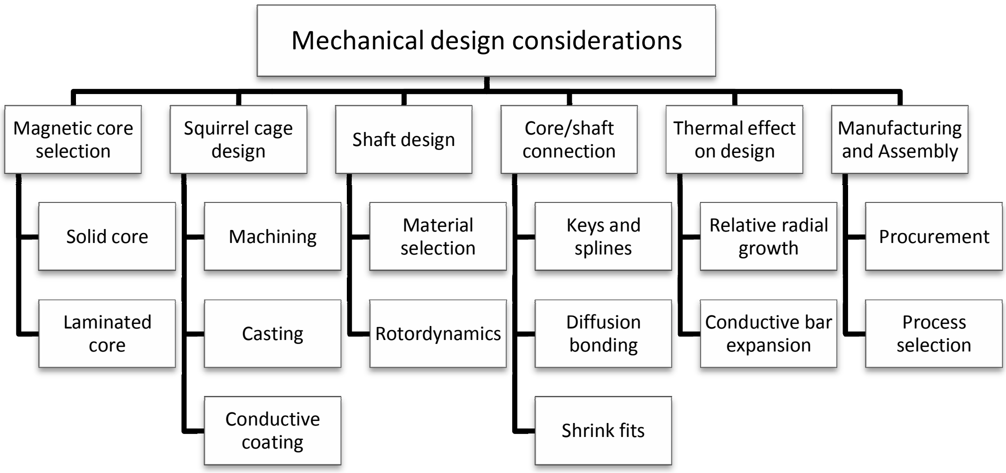

Figure 1-4: Induction machine rotor's main design considerations

1.3.1 Magnetic core selection

Typically used magnetic cores are laminated and solid cores. The laminated core is made up of a number of thin laminated plates and the solid core a solid cylinder made of ferromagnetic material. Both these designs have their mechanical and electrical advantages and limitations. From an electromagnetic point of view the laminated core is the desired design. This dramatically improves the efficiency of the machine by limiting eddy current losses [11]. The design however presents mechanical limitations: The laminated core limits the shaft diameter therefore lowering the rotor's critical frequencies. The laminated core/shaft connection also presents unique design problems due to the limiting yield strength of traditionally used laminations and the cost of high strength lamination material.

The solid rotor has huge benefits from a mechanical point of view, however, it is not ideal from an electromagnetic point of view [2]. The rotor core of a solid rotor is made of a ferromagnetic material. This design's electromagnetic performance is very poor and can be enhanced by slitting the core. Another improvement is to attach non-magnetic end rings with good conductivity, to the ends of the core. The ultimate improvement is adding a squirrel cage or a good conductivity coating onto the core, however, after these modifications the efficiency is still below that of the laminated core [2].

1.3.2 Squirrel cage design

Traditional induction machines make use of casting methods to manufacture the squirrel cage [12]. A typical casting method is cold-chamber die-casting [10] [13]. Aluminium is the most widely used material due to favourable casting and electrical properties [14]. However more recently copper is used in the casting process due to the better electrical properties compared to aluminium. The high melting point however, makes casting extremely difficult [15].

Another method of manufacturing the squirrel cage is by fabricating all the components individually. This however is a labour intensive and costly option, with very tight dimensional tolerances. When the conductive bars and end rings are machined individually the end ring/bar connection also becomes critical. Verification and validation of the low resistive connection is required to ensure a high electromagnetic efficiency. End ring/bar connections can include welding, low temperature brazing [9] as well as taper and parallel interference fits [3] [16] [17] [18].

As mentioned before a solid core with a conductive material coating on the surface can be used in place of a squirrel cage. Although this design is suitable for very high speeds the electromagnetic performance can be seen as the limiting factor [11]. The magnetic core/conductive coating, connection can also present design problems at very high speeds.

1.3.3 Selection of the magnetic core/shaft connection

Traditional low speed induction machines generally make use of splines on the shaft in order to transmit the generated torque [12]. Other methods used are diffusion bonding and shrink fits [10]. Two types of shrink fits will be investigated. One is where both the hub (outer ring) and shaft materials are purely elastic [3] and the other where a partially plasticized hub and purely elastic shaft are considered [19]. Verification and validation of the stress in the components, due to the connection type will be shown.

1.3.4 Shaft design

The shaft design is driven by the magnetic core/shaft connection and whether the machine is to be operated under or above the first critical frequency [9]. AMB design also influences the shaft design in terms of the length of the shaft required to accommodate the AMBs. Rotor dynamic analysis is a fundamental part of a variable speed drive design due to the wide operating speed range [20]. The laminated core influences the rotor dynamics due to the smaller outer diameter of the shaft, however, it is shown to contribute to the stiffness of the rotor [11]. Literature on the effect of shrink fits on rotor stability is investigated and it is found that slippage at the interface at speeds above the first critical frequency causes rotor instability due to internal friction [21] [22].

1.3.5 Implications due to elevated operating temperature

The design specifications indicate that the machine will be operated at an elevated temperature of 80°C. Due to the different materials used in the magnetic core and squirrel cage assembly, the operating temperature is a critical consideration. With the differences in thermal expansion coefficient, the relative growth of the components should be considered [9]. The temperature will also affect the interface connections due to the relative radial growth of the shaft and hub materials.

1.3.6 Manufacturing and assembly procedures

From the concept design phase it is imperative that the manufacturing procedures are considered to ensure the hardware can be manufactured [23]. The rotor assembly should also be considered throughout the early design phase to minimize special tools and jigs that may be required for assembly.

1.4 Research methodology

1.4.1 Magnetic core selection, shaft design and core/shaft connection

From the literature it is apparent that a compromise between the mechanical and electrical designs is required for an optimum magnetic core design. The design parameters influencing the decision are the maximum operating speed, operating temperature, rotor dynamics, core/shaft connection and machine efficiency requirements. Using an iterative design process both the electromagnetic and mechanical requirements can be incorporated in the final design. The mechanical design will include material selection, strength analysis and selection of manufacturing and assembly procedures. Stress due to the core/shaft connection, high rotational speed and temperature will be considered. Analytical stress calculations using a MATLAB® program will be verified with FEM using SolidWorks® Simulation and validated with strain gage measurements. Some stress validation was done in a previous project that served as an introduction for this project and will be introduced were applicable.

1.4.2 Squirrel cage design

The squirrel cage design is done in parallel with the magnetic core design due to their interdependencies. The type of manufacturing process used will depend on the squirrel cage design, number of rotors to be produced and the material selected. The rotor assembly procedure will be considered as part of the squirrel cage design. Special care should be taken to ensure a good electrical connection at the end ring/bar interface. The contact resistance will be measured to validate the design.

1.4.3 Implications due to elevated operating temperature

The thermal effect can only be analyzed once the material selection of all the components has been completed. SolidWorks® Simulation will be used for the analysis. However, if the materials could be selected in such a way that there is a relative small or even no difference in their thermal expansion coefficients, temperature change will have no effect on the design.

1.4.4 Manufacturing and assembly procedures

The manufacturing processes and the manufacturing ability of the local manufacturers will contribute significantly to the designs selected for the specific components. It is also important for the research group to be aware of all assembly problems for future developments.

1.5 Dissertation layout

Chapter 2 presents detail on the mechanical design considerations. The discussion includes work done on similar designs and other possible solutions. The chapter concludes with a critical overview of the literature to align it with the problem statement, after which initial design decisions are presented.

Chapter 3 starts with a discussion on the iterative design process required for the development of a high speed active magnetic bearing (AMB) supported induction machine (IM) rotor. The discussion is followed by conceptual and preliminary design sections. These sections describe the design tools used for the detail design. Verification and validation of the design tool, using analytical calculations, finite element analysis (FEA) and strain gage measurements are addressed. The chapter also includes the detail mechanical design, comprising material selection, selection of IM rotor topology and detail stress analysis.

Chapter 4 is dedicated to the manufacturing and assembly processes of the intricate IM rotor section. The importance of design for manufacture and assembly (DFMA) is emphasised and how it influences the final design. The problems encountered are discussed and both the failed and successful assembly attempts are described. The chapter also includes detail stress analysis of the IM rotor section to ensure the rotor section is not over-stressed due to the assembly process.

Chapter 5 presents the verification and validation on a system level and compares the final design to the design requirements. All discrepancies are investigated and interpreted. The investigation includes both FEA and analytical calculations. The interpreted results are discussed as well as the successful testing of the rotor.

Chapter 6 concludes the dissertation and describes how the design considerations presented in the problem statement were addressed. The discussion includes both the shortfalls of the final design and proposed solutions. Finally the chapter is concluded with a summary describing to what extent the research process was mastered.

1.6 Conclusion

The chapter starts with an introduction to the advantages of AMBs and why it is more appropriate for high speed applications than conventional mechanical bearings. The term “high speed” is interpreted and a proposed classification method is described. An introduction to electrical machines suited for high speeds is given and the IM is described in more detail. These discussions lead to the formulation of the problem statement and later to the mechanical design issues to be addressed and methodology. The chapter is concluded with a description of the dissertation layout.

The derived problem statement lead to the issues to be addressed and methodology. The following chapter investigates these mechanical design considerations in order to formulate an optimum design solution.