
6

Chapter

Conclusions and recommendations

This chapter concludes the dissertation with an overview of the work done with reference to the problem statement described in section 1.2. Shortfalls of the current design are presented and discussed. This leads to proposed solutions by implementing the lessons learnt during the mechanical design. Finally the chapter is concluded with a summary of the work done.

6.1 Shortfalls of current IM rotor section design

During the mechanical design of the IM (Induction Machine) rotor section, budgetary, time and electromagnetic constraints, limited the mechanical design. The following sections point out, some of the critical limitations and recommends possible solutions.

6.1.1 Magnetic core-type and material selection

Solid magnetic cores are the preferred IM rotor core for high and very-high speed applications from a strength and rotor rigidity point of view. However, the solid core has a much lower efficiency compared to a laminated rotor core, even if modifications are made to the solid core to improve its efficiency.

The decision was made early in the design phase, that a laminated core will be used, even if it meant changing the design specifications. The choice was motivated by the fact that the research group wanted to verify their laminated core design capability and all the lessons learnt could be applied to an improved follow-up design.

6.1.2 Material selection and detail stress analysis

The initial design specification stated an operating speed of 25,500 r/min with an over speed of 27,000 r/min. However, the specification could not be met, largely due to the relative high FOS (factor of safety) included in the specifications and the limiting yield strength of the selected lamination material.

The material selection was limited by both the budget and time schedule. As a result the lamination material with the highest yield strength, while satisfying the electromagnetic performance and was readily available, was selected. The limited yield strength enforced a reduction in the maximum operating speed, in order to maintain a FOS greater than 2. Effort was put in to ensure the stress

calculations and finite element analysis (FEA) done on critical components were correct. The design chapter shows the systematically verified and validated design tools used in the detail design.

From the FEA models used in the detail design it is suggested that the lamination material will require a minimum yield strength of 900 MPa, for the current rotor, to be operated at 27,000 r/min and 80°C. However, the lamination material's yield strength is not the only restriction. The squirrel cage material, configuration and connection types are also important limiting factors and are discussed in the following section.

6.1.3 Squirrel cage material selection and construction

The primary function of the squirrel cage is to create a low resistive electrical flow path for the induced currents. Traditionally the primary material property required is excellent electrical conductivity. In high speed applications, however, the end rings should be able to support itself, resulting in a high strength requirement.

Copper or copper alloys are the preferred material for a squirrel cage, from an electromagnetic efficiency point of view. However, due to the high density of the material, a very high strength copper is required for high speed applications. The squirrel cage material selection was limited by the same budget and time constraints as the lamination material. Due to the availability and price, aluminium 7075-T6 was selected for the end rings. The conductive bars had slightly lower material strength requirements and aluminium 2024-T3 was selected. The material selection was encouraged by strength, low resistivity and the availability of the material in the correct rough form, to minimize the amount of material to be removed.

The selection of the 7000 and 2000 series high strength aluminium implied that welding, brazing or any other high temperature bonding process was disqualified, resulting in an alternative end ring/conductive bar connection required. The assembly of the cage into the magnetic core, further complicated the choice of connections. Both ends of the bar used an interference fit to connect the end rings and bars. The one being a regular parallel fit and the other utilising a dowel pin forced into an undersized hole to bring about the interference at the end ring/bar interface.

After assembling the squirrel cage the low resistive end ring/bar connection was validated using a test setup where the actual electrical contact resistance was measured.

6.1.4 Manufacturing dimensional tolerances

From the detail stress analysis documented in the design chapter it is apparent that the dimensional tolerance of the rotor OD and shrink fitted components' ID was critical. The tolerance range was extremely small in order to ensure the shrink fitted components do not lose contact at maximum operating conditions. At the same time the amount of interference should be limited to ensure the components are not over stressed. The conductive bars and slots were also critical components and the interface dimensions had relatively small dimensional tolerance ranges.

The extremely small dimensional tolerance range specified, required precision manufacturing in temperature controlled workshops. This increased the cost dramatically and was only viable because one prototype was manufactured.

6.1.5 IM rotor section assembly process

The assembly of the IM rotor section was no trivial exercise, in fact chapter 4 shows that it took a second iteration to successfully assemble the IM rotor section. During this process components had to be remade and the assembly process was revised.

The revised assembly process, where smaller lamination stacks were machined individually and assembled after manufacturing, worked well. Shrink fitting the conductive bars into the one end ring and using a dowel pin to bring about the interference fit at the other end ring, was also done with relative ease. However, the shrink fit of the IM rotor section onto the shaft was a daunting task and was a high risk process. If the IM rotor section got stuck before it was in position, it would have had to be forced into position using a hydraulic press. This could have removed material at the interface and influenced the amount of interference, without really knowing to what extent. Fortunately this was not the case and the IM rotor section was shrink fitted successfully.

6.1.6 Summary

Due to budgetary and time schedule constraints the materials available for selection were limited and the maximum design speed had to be revised. However, extensive effort was put in maximizing the limiting speed while having a material FOS ≥ 2 .

What was disappointing is the fact that after all the effort to ensure the components were manufactured to their exact required sizes, everything was undone by the uncontrolled machining of the outer diameter of the rotor. Due to the axial displacement of the end rings the FEM results indicate a FOS of 0.6. However, after further analysis of the results the analytical calculations show a minimum FOS of about 1.34.

Although the minimum FOS was below the prescribed FOS ≥ 2 , the decision was made to continue with the rotor test as scheduled. The main reason being, the section with the lowest FOS was not at a critical structural position. The rotational speed was also increased incrementally and many parameters were monitored to ensure the rotor was operated safely. The fact that the test took place in a specially designed test facility also reinforced the research group's confidence.

After the successful design, manufacture and testing of a 19,000 r/min IM rotor section, the lessons learnt can be applied to a revised design. By implementing the design considerations proposed below, the maximum operating speed of 27,000 r/min could become a reality.

6.2 Proposed solutions

The proposed design solutions for the considerations described in the problem statement were introduced and motivated throughout the document. However, constraints limited the effectiveness of the solutions and some recommendations to improve the design are presented here.

6.2.1 Material selection considerations

In order to obtain the required high strength lamination material at a reasonable price, one can manufacture the laminations from a high strength alloy steel and apply the isolating coating afterwards. This was done with great success in some designs as described in [7] and [9]. However, in order to obtain the high mechanical strength, some compromises on the electromagnetic properties will have to be made.

During material selection for any shrink fitted component, a reduced material density will have huge benefits. Not only will the component require less of an interference fit, thus reducing the stress, but also reduce the spin-up stresses. This is due to the centrifugal force being directly proportional to the density of the material. Furthermore, the weldability of the hub and shaft material should also be considered during the design. Selecting lamination, end ring and conductive bar material that can be welded, brazed, soldered or diffusion bonded, can solve most of the interface connection and assembly problems.

6.2.2 Reduction in factor of safety

Due to the experimental nature of the IM design and the high risks involved in rotating a 45 kg rotor suspended in the air at 19,000 r/min. While one can understand the use of a conservative material stress FOS, aircraft designers utilise FOS as low as 1.2 in order to make their designs viable. It is recommended that effort be put in to establish a more appropriate FOS for the follow-up design. The best method to establish an adequate FOS is to design test rotors for destructive testing.

During these tests it is essential to monitor the contact at the shrink fit interface, in order to validate the design tools further and establish exactly when the hub component loses contact with the shaft. It will also be of great interest to know exactly what happens, in terms of rotor stability, when this occurs. Some work has been done on this subject [22], however, there are some discrepancies in the method of creating the interference fit and how the amount of interference is measured.

6.2.3 Proposed magnetic core/shaft connections

The critical limiting factor for this IM rotor section design, is the high material strength requirements. Although high speed rotors demand high strength materials, the shrink fit required for the magnetic core/shaft connection is the main contributor to the stress in the magnetic core. Utilising another type of connection could reduce the strength requirements dramatically and increase the operating speed. However, Table 2-2 illustrates that the shrink fit is a widely used connection type for laminated cores and is at this stage the preferred connection type. None the less the following sections describe other possible connection types that should be considered in future designs.

Diffusion bonding could be utilised when the material selection allows it. A detail investigation on the high temperature process is required, especially what the effect is on the strength and electromagnetic properties of the lamination material. The effect on the isolation coating on the laminations should also be considered. The use of the diffusion bond will increase the maximum allowable rotation speed considerably and although the efficiency might decrease, the increase in speed could be so dramatic that the compromise is justified.

Elastic plastic shrink fitting is another connection type which should be investigated in more detail. In an elastic plastic shrink fit the hub material is partially plasticised while the shaft is completely elastic. This could reduce the required dimensional tolerances and the material strength can be better utilised. However, the permanent deformation of the hub material at the ID, will relieve the interference fit and reduce the contact pressure. Work on the subject is described in [19] [45] [44] and this type of connection is implemented in solid outer discs. This is not representative of an IM core and the fact that the maximum stress is no longer at the ID of the hub, but rather at the conductive bar slots, should be the main consideration.

6.2.4 Assembly process

Due to the relatively large interference required at the shaft/magnetic core interface, a large temperature differential was required. Because the shaft could not be cooled sufficiently, the IM rotor section's temperature had to be increased to 250°C. Due to the difference in thermal expansion coefficients between the materials used in the rotor section, the squirrel cage could not be fully assembled before the rotor section was shrink fitted. Therefore, the one end of the conductive bars was only connected to the end ring after the components reached ambient temperature.

However, if the shaft can be cooled sufficiently, the rotor section will not have to be heated to such high temperatures, therefore, eliminating the dowel insert at the one end ring completely. Furthermore, if the rotor section does not require a large temperature differential for the shrink fit, the squirrel cage can be permanently connected before shrink fitting the rotor section.

6.2.5 Alternative machine rotor design layouts

Alternative IM rotor section layouts, could decrease the material strength requirements, possibly without a large compromise on the electromagnetic efficiency or manufacturability. Although, some design layouts are presented here, a detail electromagnetic design and manufacturability study is required, to make a final recommendation.

In a technical presentation by Dr. Mhango, he introduced an IM rotor section layout as illustrated in Figure 6-1. The layout consists of the lamination stack, end rings, conductive bars and end stops. The end stops restrict the axial displacement of the end rings at high temperature operation. Another function of the end stops is to aid in holding the magnetic core on the shaft [4].

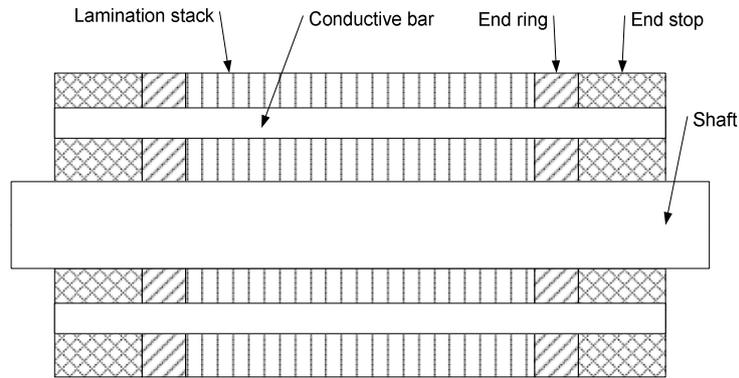


Figure 6-1: Mhango's alternative IM rotor section layout [4]

Alternatively the IM rotor section as described throughout this document can be used with the addition of a containment sleeve as illustrated in Figure 6-2. One drawback of the containment sleeve is that the electromagnetic air gap will increase and it will influence the machine's electrical efficiency. From a mechanical perspective, the containment sleeve will require a high strength material, with a high modulus of elasticity. The material will also require a low magnetic permeability and a good electric conductivity. Inconel 718 is a possible material. Another possibility is MMCC Al/Al₂O₃ which is a continuous fibre aluminium matrix composite. However, both these materials are extremely expensive and have limited availability.

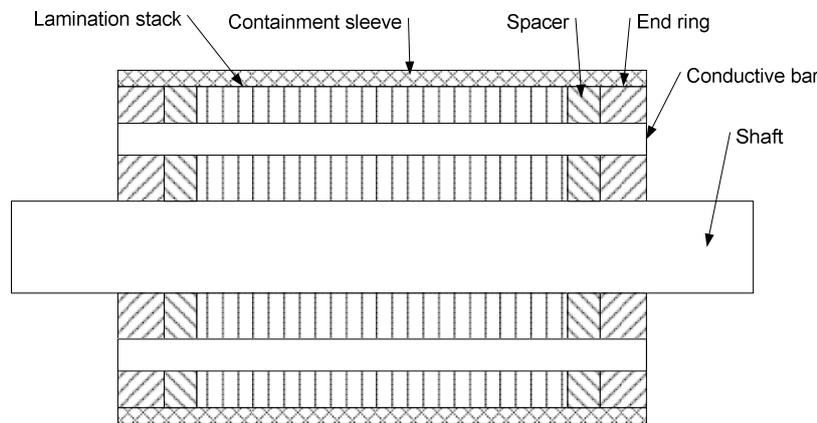


Figure 6-2: Illustration of a containment sleeve

6.3 Conclusion

The focus of this project was the mechanical design and manufacture of a high speed Induction Machine rotor section. This involved rotor layout and material selection, detail stress analysis and manufacturing and assembly process selection.

A comprehensive literature study lead to some design decisions being made as a starting point for the detail mechanical design. The detail stress analysis showed that it would be difficult to analytically calculate the stress in the IM rotor section. With this in mind a system was put in place to systematically

verify and validate the use of a FEM. This and other design tools were implemented throughout the detail mechanical design and stress analysis of the IM rotor section.

The manufacturing and assembly of the IM rotor section were successful after the first attempt failed. The stress analysis indicated that the design specification of a FOS ≥ 2 was met. However, after the final machining of the rotor's OD, calculations show that the minimum FOS was reduced to about 1.34.

After evaluating the situation, the decision was made to continue with the testing of the rotor and the rotor was incrementally spun up to 19,000 r/min. After numerous spin and rotor delevitation tests, the rotor was removed and inspected. The inspection revealed that there was no visible change in the rotor and the machine was assembled again.

For continuous operation of the rotor at the maximum operating conditions, it is advised that a detail stress analysis is done in order to establish a new maximum operating speed where the FOS is above 2.

6.4 Closure

The aim of this project was the design and development of an IM rotor section to be used for testing to verify the research group's all-round design capability. The project formed an integral part in the successful development of a high speed induction machine drive system. The project produced a rotor section that was successfully operated at its maximum operating speed and could be used for various test to perform both verification and validation on the entire system.

Although the design solution presented does have some shortcomings and can be optimised, the scientific approach implemented to formalise and address the problem statement was success.

