

Design for recycling of electric machines

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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Electromechanical Engineering Technology

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Vincent Van de Peer, May 2025

Preface

From a young age, I have been fascinated by the inner workings of the world around me, particularly when it comes to technology. My interest was especially drawn to moving vehicles such as cars, motorcycles, and anything with an engine. As a child, I often spent hours playing with electric scooters which eventually evolved into repairing and modifying them. Later, this curiosity expanded to working on mopeds. I was always very intrigued by how these machines operated and what I could change or improve about them to make them even better or faster.

This passion led me to pursue a professional bachelor's degree in Electromechanics with a specialization in Automation. During this program, I gained a broad understanding of how industrial systems function and are controlled. The curriculum focused on automating a wide range of industrial applications using PLC systems. Although the program provided me with a solid technical basis, I felt that there was more to explore. I wanted to step beyond the practical aspects and delve deeper into the theoretical side of the field.

To achieve this, I decided to continue my education with the Industrial Engineering program at Ghent University. This program offered a more in-depth exploration of the concepts that I had previously learned about, going into much more detail. This deeper understanding has been immensely valuable in helping me master the subject matter.

Now, I am in the final stage of this program. This thesis represents the culmination of my journey at Ghent University. The topic resonates strongly with my interests and aligns with my previous education. I am excited to contribute to an innovation that will help shaping the world of tomorrow.

I would like to take a moment to express my sincere gratitude to everyone who has supported me in this process. In particular, I am deeply thankful to my supervisors Prof. Peter Sergeant and Mohamed Ibrahim for their invaluable guidance and patience throughout this process. Their constructive feedback, encouragement, and willingness to share their knowledge have been essential in my progress. I truly appreciate the time and effort they have dedicated to helping me grow as an engineer. I also want to thank Tony Boonen for his mechanical help and useful tips during the assembly of the prototype. His hands-on support made a real difference when encountering practical issues. A big thanks as well to Vincent Gevaert for guiding me in the lab and being available whenever I had questions.

Finally, I'm really grateful to my family and loved ones for standing by me during this whole journey. Their support and encouragement meant a lot and helped me stay motivated through the ups and downs.

Explanation regarding the master's thesis and the oral presentation

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

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Abstract

The transition toward sustainable mobility and industry is accelerating globally, intensifying the demand for high-performance electric machines (EMs), particularly for electric vehicles (EVs). However, conventional motor designs often disregard end-of-life (EoL) considerations, making recycling and material recovery inefficient. This thesis addresses the challenge by exploring design strategies that enhance the recyclability of EMs, focusing on permanent magnet synchronous motors (PMSMs) with an interior permanent magnet (IPM) topology. Through an extensive literature review, key obstacles such as adhesive fixation, thermoset insulation/impregnation, and complex structural assemblies are identified. Innovative design concepts are proposed to overcome these limitations, including the use of thermoplastic insulation (PEEK), modular stator segments, mechanical fixation of magnets and recyclable materials like vitrimer/cleavable epoxies. A prototype is developed to validate the concept, incorporating the most impactful principles in the rotor part, specifically the elimination of adhesives and the mechanical fixation of the magnets. Electrical and mechanical simulations are conducted to assess performance. The results demonstrate that the design changes do not significantly affect the operating principle and have the potential to increase electrical performance of the machine by the elimination of radial and tangential rotor ribs, while greatly enhancing disassembly and material separation potential. The prototype does exhibit reduced performance due to certain practical design choices; however, these limitations are not inherent to the concept itself. Given the limited time and resources available, the primary focus was placed on developing a recyclable motor rather than on optimizing performance parameters. The developed prototype showed that adhesive-free mechanical fixation is both feasible and robust, enabling easy assembly and disassembly without compromising structural integrity. This approach enhances recyclability and offers a practical, sustainable alternative to traditional adhesive-based methods, providing a strong basis for future scalable motor designs.

Keywords: electric motor recycling, permanent magnet synchronous motor, design for disassembly, rare earth element recovery, sustainable engineering

Design for recycling of electric machines

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Abstract—The transition to sustainable mobility is driving demand for high-performance electric machines (EMs), particularly in electric vehicles (EVs). However, conventional designs of permanent magnet synchronous motors (PMSMs) often neglect end-of-life (EoL) considerations, hindering effective recycling. This study investigates design improvements for interior permanent magnet (IPM) machines that enhance recyclability without compromising core functionality. Key challenges include the use of adhesives, thermoset insulation, and integrated assemblies, all of which restrict disassembly. Proposed solutions include thermoplastic insulation (such as PEEK), modular stator design, mechanical magnet fixation, and recyclable materials such as cleavable/vitrimer epoxies. A prototype rotor implementing adhesive-free magnet fixation was developed. Simulations confirmed that these changes maintained functional performance while significantly improving ease of disassembly. Although certain performance trade-offs were observed due to time and resource constraints, the concept has proven to be both feasible and robust. This work demonstrates that EM designs can be made significantly more recyclable without major performance losses, offering a practical foundation for future sustainable engineering approaches.

Index Terms—electric motor recycling, permanent magnet synchronous motor, design for disassembly, rare earth

I. INTRODUCTION

EMs are critical to sustainability, especially due to the rise of EVs. In the EU, 22.7% of new car registrations in 2023 were electric [1], increasing the demand for sustainable EMs. However, current motor designs focus on performance and neglect the EoL stage, where disassembly and recycling are difficult. This is a problem for rare-earth elements (REEs) and copper, which are valuable but hard to recover.

This thesis addresses this issue by exploring new motor designs that prioritize recyclability. The goal is to create a working prototype that maintains technical performance while enabling easy disassembly and material reuse. A structured design process is used to define guidelines that support circular economy principles and sustainability in the motor industry.

Current EM designs pose major challenges at EoL due to their use of adhesives, thermoset resins, and complex assemblies that hinder disassembly and material recovery. The recycling process often relies on shredding [2], which mixes materials and thus reducing the quality of the output and making REE recovery nearly impossible. Insulation and impregnation materials are particularly difficult to remove,

requiring energy-intensive or environmentally harmful methods. Magnets are typically fixed into the rotor with strong adhesives, further complicating extraction and reuse.

Several design strategies have been proposed in literature to improve the recyclability and ease of disassembly of EMs. These include the use of soft magnetic composites (SMCs), aluminum windings, modular stator and rotor architectures, bonded or mechanically fixed magnets and the integration of recycled or alternative magnet materials such as ferrites or hydrogen-processed magnetic scrap.

Some approaches use teeth-wound windings, while others introduce structural innovations like carbon sleeves or segmented stators that could facilitate material separation. While some of these methods offer promising advancements in terms of disassembly and material recovery, they often come with trade-offs in performance, manufacturability, structural complexity, or scalability.

II. DESIGN FOR RECYCLING

A. Stator

The stator presents significant challenges for recycling, mainly due to the impregnation and insulation of the structure, which complicate the separation of the steel core from copper or aluminum windings. Current disassembly methods like burning or mechanical removal are energy-intensive and environmentally damaging. [3]

To address this, modular stator designs, such as those described in [4] and shown in Fig. 1, allow segment-level disassembly with overlapping windings while maintaining electromagnetic performance. This enables easier repairs and access to the windings, facilitating separation.

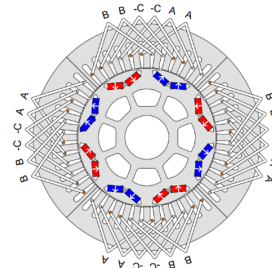


Fig. 1. (a) Modular stator [4]

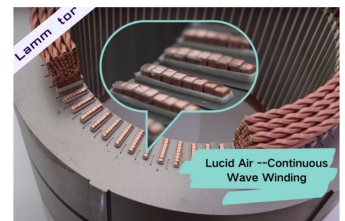


Fig. 2. (b) Continuous wave winding [12]

In terms of winding insulation, replacing traditional enamel with thermoplastic materials like PEEK offers advantages such as meltability and reusability, which enhance recyclability. PEEK coated wires demonstrate improved performance [5], but if embedded in thermoset resin, the recyclability benefits are lost.

Resin impregnation is another major obstacle, as thermosetting materials are hard to remove. Thermoplastic alternatives like polyamide (PA) show potential due to their high performance and recyclability, though they pose challenges in processing due to high melt viscosity. A solvent-based approach using PA6 in a calcium chloride/methanol solution has shown promise to reduce the high melt viscosity [6], though it introduces issues like residue removal and uncertain compatibility with copper windings. Recyclable epoxies such as vitrimers offer a solution by combining the strength of thermosets with reprocessability of thermoplastics [7]. They enable reshaping and recycling through dynamic bond exchange but can release harmful gases during processing. Cleavable epoxies, on the other hand, degrade under specific conditions like heat or pH, allowing controlled recycling.

Continuous wave windings could further improve recyclability by using a single conductor in a wave pattern, which reduces welds and increases copper fill factors [8] as shown in Fig. 2. The radial insertion method may eliminate the need for full impregnation, as the windings can be pressed into the slots to achieve a high fill factor, potentially simplifying disassembly and enhancing sustainability.

In conclusion, combining modular construction, thermoplastic insulation, recyclable epoxies, and continuous wave windings provides a promising path toward more recyclable stators, although further research is required to refine materials and validate their long-term reliability. With these ideas, we aim to provide a foundation for future research, although the focus of this research lies primarily on developing a rotor prototype, as significantly more progress can still be made in that area.

B. Rotor

The rotor presents the greatest opportunities for improving recyclability, as current designs often prevent disassembly due to the use of adhesives for magnet fixation, resulting in the loss of valuable materials such as NdFeB magnets during the conventional steel recycling route [9]. Efficient dismantling, especially non-destructive magnet removal, is essential to enable reuse or recycling. The goal is to redesign the rotor for disassembly while retaining performance and production feasibility. Inspired by Tesla's patented carbon sleeve design [10], a conceptual rotor was developed using mechanical clamping instead of adhesives. This enables magnets to be removed intact for reuse or directed to recycling if degraded. The design includes bolted connections to secure rotor components, enabling full disassembly.

Mechanical simulations were conducted on the concept idea using Siemens NX to test structural integrity. The first simulation, with regular bolts (b, top) in the axial direction (a)

as shown in Fig. 3, showed excessive displacement and failure under operational loads. Increasing bolt prestress reduced displacement but didn't solve the problem. A second identical simulation with fitted bolts (b, lower) showed much better rigidity, with acceptable displacement and stress levels due to the geometric interference, confirming mechanical feasibility. A third simulation added radial bolts shown in Fig. 3 (In brackets), reducing displacement further and improving stress distribution. These preliminary simulations mentioned above are not shown in detail here, as they primarily served as a simplified feasibility assessment. Detailed results based on the actual prototype will be presented in a later chapter. Positioning accuracy was enhanced by integrating locating features onto the plates as shown in Fig. 12, constraining all degrees of freedom and improving assembly alignment.

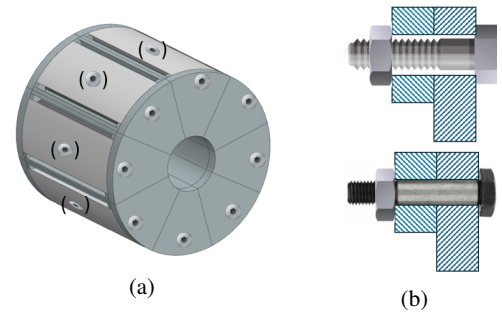


Fig. 3. Conceptual models: (a) axial bolts (& radial bolts), (b) regular vs fitted bolt

An alternative rotor design used only radial bolts to secure the core segments, as shown in Fig. 4. Simulations with countersunk bolts demonstrated minimal displacement and safe stress levels, validating the mechanical feasibility of this concept. This concept also allows for discrete skewing, which was not feasible with the original axial bolted design.

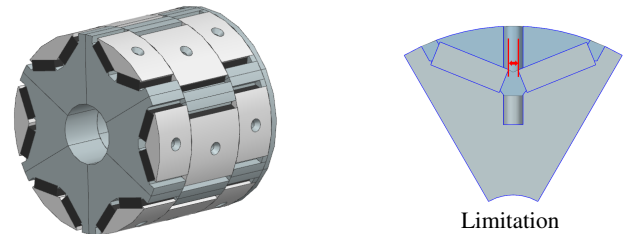


Fig. 4. Additional prototype: radial bolts

In conclusion, the rotor designs presented here enable non-destructive disassembly and effective material recovery without compromising structural performance. These concepts provide a foundation for further development and prototyping, with this thesis primarily focusing on the rotor due to its greater potential for recyclability improvements.

III. PROTOTYPE DESIGN AND SIMULATION

The previous chapter presented adhesive-free design methods to improve EoL recyclability, with simulations showing that bolted connections provide sufficient strength and allow disassembly, offering a sustainable alternative to glued or potted rotor assemblies. An 8-pole V-type PMSM rotor will be developed for the prototype, matching a 90mm $\times$ 70mm stator used in ongoing group research and fitting existing stator housing test stand at the lab.

A. Electrical modeling

The prototype motor design starts with an electromagnetic model built using Altair FluxMotor shown in Fig. 5, allowing early evaluation of performance. This approach helps identify design flaws and ensures compatibility with mechanical structures before physical prototyping. Ferrite magnets (Y35 grade, 18 $\times$ 10 $\times$ 6 mm) were chosen instead of stronger NdFeB magnets due to cost, thermal resistance and ease of handling. These magnets are off-the-shelf and magnetized along their length, arranged in a segmented configuration for easier assembly and reduced internal stress. The stator was recreated in FluxMotor based on the lab-available component, using standard slot and winding geometry with copper wires and basic cooling fins.

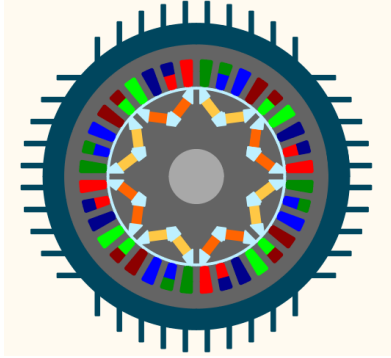


Fig. 5. Fluxmotor model

The rotor features an 8-pole, V-shaped configuration with ferrite magnets embedded in a solid iron core. Although this topology is not ideal for ferrite magnets due to poor flux concentration, it was chosen for its prevalence in current market designs. Solid steel was used instead of laminated steel to simplify prototyping, at the cost of increased eddy current losses. A 0.5 mm air gap was introduced to accommodate manufacturing tolerances, reducing torque density and magnetic coupling. Magnetic ribs are excluded, as shown in Fig. 6. This reduces flux leakage and ensures that most of the permanent magnet flux contributes to torque generation, leading to more efficient magnet use.

These suboptimal design choices were the result of prototyping constraints, including cost, material availability, supplier limitations, and production time, and are not inherent to the design concept itself!

In contrast, the elimination of magnetic ribs is a deliberate and impactful improvement, supported by prior research [11], as it enhances flux utilization and overall efficiency.

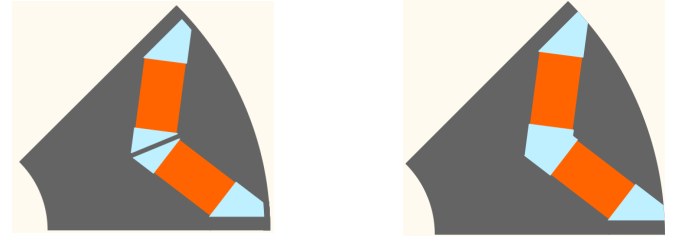


Fig. 6. Conventional versus prototype magnet topology

Electromagnetic simulations were conducted to validate the design's function rather than optimize performance. The results are listed in Table I.

Open-circuit tests at the target speed of 750 rpm showed consistent phase voltages (shown in Fig. 7) and low cogging torque, though flux density was limited by the use of ferrite magnets and a large air gap.

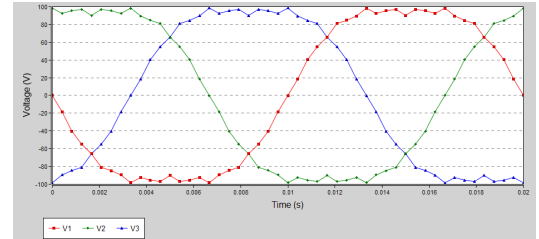


Fig. 7. Phase voltage - Open circuit

Performance mapping at the same speed and 5 A/mm² current density showed a torque of 5.26 Nm (shown in Fig. 8), efficiency of 80.8%, and losses of around 97.5 W, mainly from copper (Joule) losses.

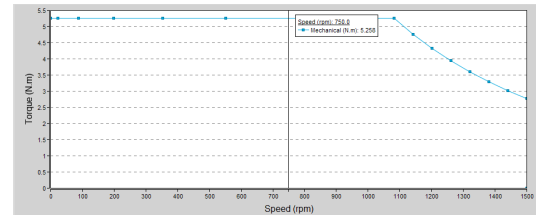


Fig. 8. Torque-speed characteristic - Performance mapping

Thermal simulation indicated winding temperatures stabilized at 80°C and magnets at 77°C, with conservative loss assumptions to ensure safe operation. Under ideal sinusoidal current, the motor showed a torque ripple of $\pm 16.3\%$, with ferrite magnets safely operating below demagnetization risk thresholds due to their favorable high-temperature resistance.

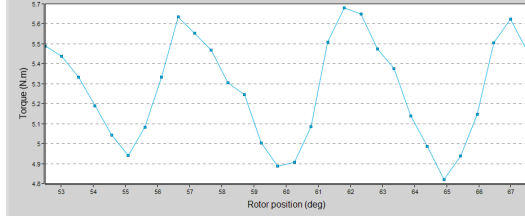
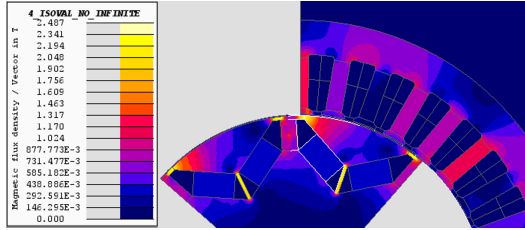


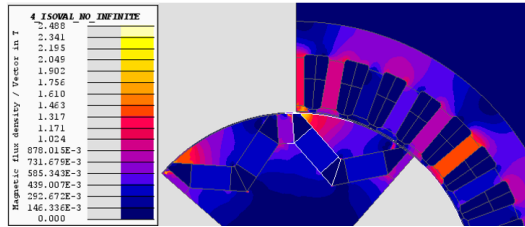
Fig. 9. Torque ripple - Working point

A step-skewed simulation with a 2.5° offset reduced torque ripple by 73.4% (down to 4.4%) at the cost of only 0.95% torque loss, demonstrating a practical way to improve smoothness (not implemented in prototype).

Finally, comparing the ribless rotor to a conventional ribbed design as shown in Fig. 6 and 10 showed significant benefits: the ribless version delivered higher torque (5.26 Nm vs 3.65 Nm), greater efficiency (80.88% vs 74.78%), and better power density (52.11 W/kg vs 35.98 W/kg). Although torque ripple was higher in the ribless model (16.31% vs 7.11%), the absence of magnetic ribs minimized flux leakage and improved overall performance. These results validate the ribless approach as an effective method for improving magnet utilization and simplifying recycling, despite prototyping limitations.



Conventional ribbed design



Prototype ribless design

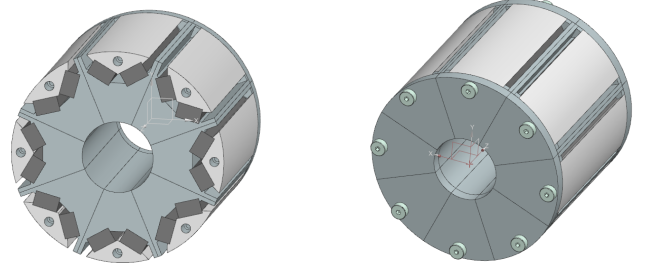
Fig. 10. Electromagnetic simulation

TABLE I
PERFORMANCE OF PROTOTYPE (RIBLESS DESIGN)

Parameter	Value
Rotational speed (rpm)	750
Mechanical torque (N-m)	5.26
Mechanical power (W)	413.75
Machine electrical power (W)	511.51
Machine efficiency (%)	80.88
Power density (W/kg)	52.11
Machine total losses (W)	97.76
Joule losses (W)	92.35
Iron losses (W)	5.40
Torque ripple (%)	16.31

B. Mechanical modeling

The mechanical design phase of the prototype translates the electromagnetic concept into a robust and recyclable 3D construction. The rotor features mechanically fastened parts using axial fitted bolts and two end plates with alignment elements as shown in Fig. 11 and 12, enabling high-speed operation and easy disassembly for recycling.



Interior section

Assembled rotor

Fig. 11. Prototype axial bolts

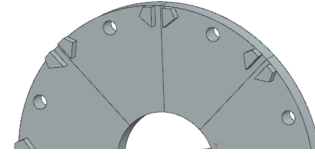
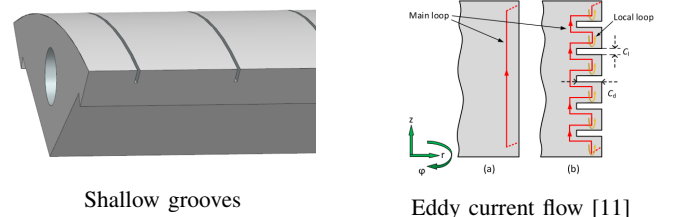


Fig. 12. Locating features plate

The rotor embeds the using mechanical clamping and temperature-resistant tape to absorb tolerances, improve friction, and enable precise, adhesive-free, and press-fit fixation. The core is made from solid C15 steel, selected for its machinability and magnetic properties, and is manufactured using CNC and wire EDM. The upper core parts, also made of solid C15 steel, retain the magnets using precision-fit shoulder bolts with a sliding tolerance fit, providing mechanical stability and ease of assembly. Although the solid steel construction increases the risk of eddy current heating, this is less critical due to the use of ferrite magnets.

A technique based on shallow surface grooves is proposed to reduce eddy current losses by disrupting straight axial current paths. As shown in Fig. 13, the groove pattern and current flow illustrate how these features act as barriers, forcing the eddy currents to follow longer, more resistive paths (b). This method, inspired by recent research, has demonstrated a reduction in eddy current losses by more than half [11].



Shallow grooves

Eddy current flow [11]

Fig. 13. Shallow groove feature and principle

While these grooves reduce losses and could be machined via CNC or wire EDM, they are not included in the current prototype due to manufacturing constraints. Two end plates made from non-magnetic AISI 316 stainless steel are used to prevent unwanted flux leakage and provide bolted assembly. They utilize the same fitted bolt system to ensure precise and consistent alignment.

Mechanical simulations conducted at 4500 rpm (equivalent to six times the normal speed) confirm that all components operate safely under extreme conditions, as illustrated in Fig. 14 and Fig. 15. The upper core parts experience maximum stresses of 234.73 MPa and a peak displacement of 0.0197 mm, both well below the allowable limits for C15 steel (275 MPa). If shallow grooves are implemented, they cause a slight increase in displacement but remain within safe margins. The lower core and magnets exhibit negligible stress levels. Additionally, the plates (189 MPa) and shoulder bolts (146.71 MPa) also remain within acceptable limits (235 MPa for AISI316 stainless steel and 1080 MPa for grade 12.9 bolts).

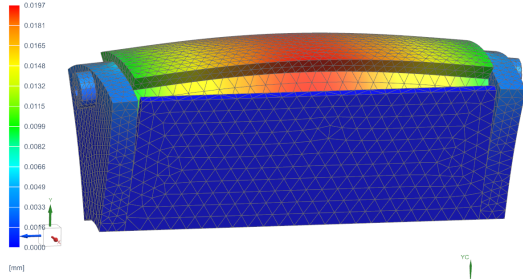


Fig. 14. Prototype displacement

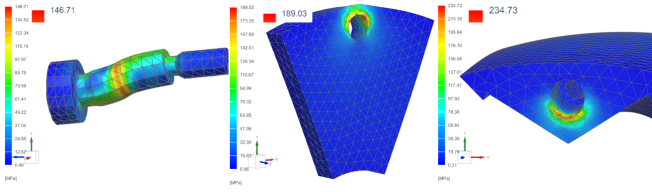


Fig. 15. Prototype Stresses

Overall, the design meets mechanical requirements and confirms the structural soundness of the prototype. To reduce computational load, only a single pole of the rotor was simulated, taking advantage of the design's symmetry. The simulations applied centrifugal forces to each component based on their mass, radius, and angular velocity, using the formula $F = m \cdot r \cdot \omega^2$, rather than modeling full rotational dynamics. Boundary conditions were defined using a cylindrical coordinate system to preserve realistic behavior in the θ -direction (rotational axis), while contact definitions simulated interactions between all structural parts.

A quick simulation of the radial bolt concept (Fig. 4) at 7500 rpm revealed promising structural behavior shown in Fig. 16, with peak stresses of 615 MPa in the countersunk bolts and 153 MPa in the upper core part, and a maximum displacement of just 0.0018 mm.

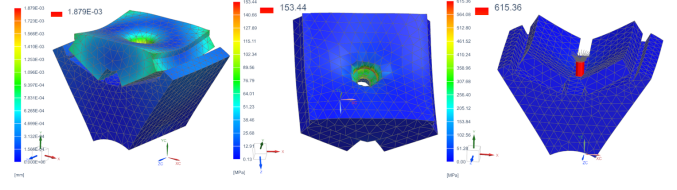


Fig. 16. Radial bolt concept displacement & stresses

IV. RESULTS

The main prototype, using an axial bolt concept, was 3D printed to evaluate the design's feasibility. The assembly process was straightforward, with components fitting together well and demonstrating strong mechanical connections and robustness. This confirmed that no design changes were needed before producing the final prototype. The primary focus, however, was on disassembly. The structure allows disassembly pole by pole by removing the upper core segment and its two magnet stacks. This method proved to be practical, although magnetic forces may affect the ease of the process. Overall, this approach validates proceeding from the 3D-printed model to the manufacturing of a fully functional rotor prototype.

The second, radial bolt concept was only explored through a 3D-printed model, intended to test conceptual feasibility rather than practical application. The design allowed for the skewing of rotor segments, however, the skewing required many separate components, significantly increasing assembly complexity and time. Although the segmentation offered valuable insights, this concept was not pursued further in this study, as choices need to be made regarding the direction of further development.

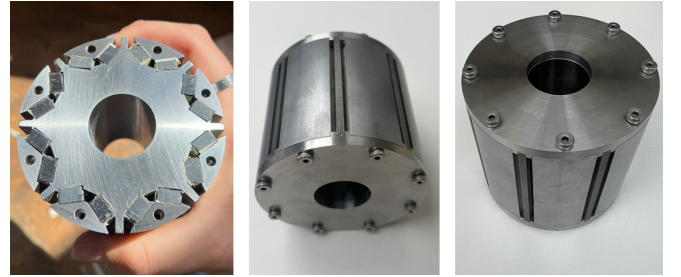


Fig. 17. Prototype final result

After successful evaluation of the 3D-printed models, a full-scale functional prototype using axial bolts was constructed based on detailed mechanical and electrical calculations, shown in Fig. 17. Magnet insertion was done manually using tape to accommodate small oversizing and ensure a secure press-fit. The tape helps reduce magnet movement, stress, and vibrations, effectively replacing adhesives. Once installed, the magnets were pressed into place, and bolts were used to lock them firmly. This process worked smoothly and suggested potential for future automation, which is important for scaling production.

Finally, a disassembly test of one pole was performed after full assembly. The test succeeded without issues, confirming

the design's practicality. Although some force was required due to press-fitting and magnetic forces, manual removal was achievable. This indicates that robotic or automated disassembly is realistic. However, future tests should consider the effect of using stronger NdFeB magnets, which might make manual disassembly more difficult and require specialized tools or support.

V. UPSCALING

The prototype rotor was initially built at reduced scale for practical testing. To assess real-world viability, it was upscaled by a factor of two in diameter and length (from $\varnothing 89 \times 70$ to $\varnothing 187 \times 140$) and its speed increased from 750 rpm to 7500 rpm. This significantly raised mass and centrifugal forces, outpacing the structural capacity of the original design.

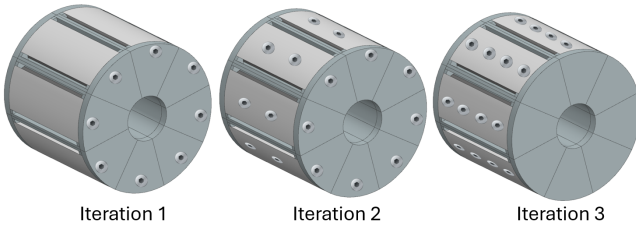


Fig. 18. Upscale iterations

In the first simulation conducted on the same but upscaled model, loads increased $44\times$ ($\sim$ mass/speed/radius) while bolt strength only improved $4\times$ ($\sim$ cross section), causing extreme overstresses. Adding two radial bolts in the second iteration reduced deformation tenfold and stresses in threefold due to the reduction in displacement. A third design iteration, utilizing only radial bolts, further enhanced load transfer and reduced overall stress levels. Although the bolt placement imposes a minimum spacing constraint between the magnets (Fig. 4), the results remain well within acceptable limits. The maximum displacement is 0.011mm, with peak stresses reaching 307MPa in the bolts and 229MPa in the upper core section.

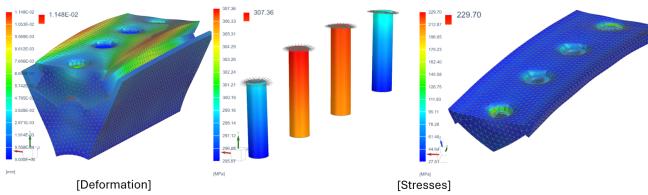


Fig. 19. Upscale iteration 3 stresses & displacement

VI. CONCLUSION

This thesis investigated how the manufacturing of electric machines, specifically PMSMs, can be adapted to support EoL recovery without changing their core architecture. Instead of optimizing purely for performance, the focus is on disassembly, material separation, and sustainability, which are key principles of a circular economy.

The work demonstrates that a recyclable and mechanically rigid rotor can be built using axial and/or radial bolted connections. The prototype shows that adhesive-free magnet fixation with axial bolts is practical for small motors with a high pole count. Axial bolts offer design flexibility, easier assembly, and avoid the spacing constraints required by radial bolts.

For larger motors under high speeds (such as EVs), radial bolts are preferred for their superior stress distribution and enhanced mechanical reliability. Although they require spacing between magnets (Fig. 4, right) and obstruct visual inspection inside the stator, these bolts can be preloaded to control deflections and enhance structural performance. However, their position near the rotor surface poses safety risks if they loosen during operation.

The findings confirm that the proposed designs are feasible and scalable, allowing for more recyclable electric machines without compromising core functionality and performance.

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Contents

List of Figures	xvii
List of Tables	xxi
List of Acronyms	xxii
1 Literature review	2
1.1 Critical materials	3
1.2 Challenges in recycling	3
1.2.1 Cores and windings	4
1.2.2 Impregnation	4
1.2.3 Insulation	5
1.2.4 Magnet Fixation	6
1.2.5 Magnets	6
1.3 Existing Design Approaches	9
2 Design for recycling	14
2.1 Stator	15
2.1.1 Construction	15
2.1.2 Insulation	16
2.1.3 Impregnation	17
2.1.4 Continuous wave winding	21
2.1.5 Concluding remark stator part	22
2.2 Rotor	23
2.2.1 Design for Dissassembly	24
2.2.2 First approach	25
2.2.3 Simulation	28
2.2.4 Position mechanism	36
2.2.5 Skewing	37
2.3 Rotor: Additional Design Proposal	38

2.3.1	Radial bolted connection	38
3	Prototype design and simulation	41
3.1	Electrical design	42
3.1.1	Magnets	42
3.1.2	Stator	44
3.1.3	Rotor	45
3.1.4	Final model	46
3.2	Electrical simulation	47
3.2.1	Open circuit	47
3.2.2	Performance mapping	50
3.2.3	Thermal simulation	53
3.2.4	Working point simulation: sine wave	54
3.2.5	Extra simulation: skewed variant	58
3.2.6	Electrical simulation results	59
3.3	Mechanical design	61
3.3.1	Core part	62
3.3.2	Upper core parts	63
3.3.3	Additional feature upper core parts: eddy current mitigation	65
3.3.4	Plates	68
3.3.5	Magnet fixation	70
3.4	Mechanical simulation	71
3.4.1	Upper core parts	72
3.4.2	Lower core part	74
3.4.3	Magnets	74
3.4.4	Plates	75
3.4.5	Shoulder bolts	75
3.4.6	Magnet load stresses on core	76
3.4.7	Mechanical simulation final remark	76
4	Results	77
4.1	Prototype 3D printing: Axial bolt concept	77
4.2	Prototype 3D printing: Radial bolt concept	78
4.3	Functional Prototype Construction	79
4.3.1	Magnet insertion	80
4.3.2	Final remark	81
5	Upscaling	82

5.1	Mechanical Effects of Geometric and Speed Scaling	83
5.1.1	Volume and Mass Increase	83
5.1.2	Radii	83
5.1.3	Effect of Increased Rotational Speed	83
5.1.4	Bending Stiffness Considerations	85
5.1.5	Effect of Scaling on Bolt Load Capacity	86
5.1.6	Concluding remark	87
5.2	First iteration: Base model	88
5.3	Second iteration: Addition of radial bolts	89
5.4	Third iteration: Only radial bolts	90
	Conclusion	91
	Future Work	92
	Sustainability reflection	93
	References	96

List of Figures

1.1	SPM vs IPM [2]	2
1.2	4KW Claw-pole motor[3]	9
1.3	Claw pole rotor [4]	10
1.4	Hybrid rotor structure[5]	11
1.5	Ferrite fir tree rotor[6]	11
1.6	Segmented Stator in HEV [7]	12
1.7	Carbon sleeve rotor[8]	13
2.1	Rotors of modern electric vehicles[9]	14
2.2	Modular rotor topology[7]	15
2.3	Completed stator winding with PEEK material[10]	17
2.4	Classification matrix of recyclable epoxy [11]	20
2.5	Continuous Wave winding Lucid Air [12]	21
2.6	Continuous Wave winding: conductors [13]	21
2.7	Experimental setup for the magnet disassembly.[14]	23
2.8	Tesla Model 3 rotor configuration [15]	24
2.9	Rotor comparison Tesla [16] [17]	25
2.10	First design approach	26
2.11	Additional radial bolt	26
2.12	Automated Bolt Installation Workflow – Visumatic [18]	27
2.13	Simulation modeling	28
2.14	Visualisation Framework	29
2.15	Final simulation model	29
2.16	First simulation: displacement	30
2.17	First simulation: increased prestress	31
2.18	Fitted bolt and dowel rod for precise positioning and fastening	31
2.19	Bolted connection	32
2.20	Second simulation: Displacement	33
2.21	Second simulation: stresses	33

2.22	Third simulation: Magnet contact pressure	34
2.23	Third simulation: Displacement	34
2.24	Third simulation: stresses	35
2.25	Position mechanism	36
2.26	Skewing desing	37
2.27	New approach: Radial bolts	38
2.28	Radial bolts: single pole	39
2.29	Radial bolts: displacement	39
2.30	Radial bolts: stresses	40
3.1	Ferrite magnets	43
3.2	Slot definition	44
3.3	Stator geometry	44
3.4	Magnet topology definition	45
3.5	Rotor geometry	45
3.6	FluxMotor model	46
3.7	Phase voltage versus time - Open circuit	48
3.8	Phase voltage versus angular position - Open circuit (Altair flux 2D)	48
3.9	Cogging torque versus angular position - Open circuit	48
3.10	Flux density in the airgap versus angular position - Open circuit	49
3.11	Mechanical torque versus speed - Performance mapping	50
3.12	Control angle versus speed - Performance mapping	50
3.13	Losses versus speed - Performance mapping	51
3.14	Efficiency versus speed - Performance mapping	52
3.15	Thermal simulation	53
3.16	Flux density airgap versus mechanical angle - Working point	54
3.17	Torque ripple versus rotor angular position- Working point	55
3.18	Magnet demagnetization	56
3.19	BH-curves comparison	57
3.20	Rotor discrete skewing	58
3.21	Cogging & torque ripple @2.5° skew	58
3.22	Conventional (ribbed structure)	59
3.23	Prototype (no ribs)	59
3.24	Prototype design	61
3.25	Core part	62
3.26	Induction motor	63
3.27	Upper core part	63

3.28	Fitted bolt M3x16	64
3.29	Section view bolted connection	64
3.30	H7/f9 tolerance ranges for a 4mm fit	64
3.31	Cross-sectional views of eddy current path [19]	66
3.32	Shallow grooves feature	66
3.33	Micro end mill	66
3.34	wire-EDM setup shallow grooves	67
3.35	Plate	68
3.36	Magnetic flux path plate	68
3.37	Section view bolted connection plate	69
3.38	Magnet oversize	70
3.39	Temperature resistant tape	70
3.40	Total displacement prototype	71
3.41	Stresses upper core prototype	72
3.42	Total displacement grooved prototype	72
3.43	Shallow groove stresses	73
3.44	Shallow groove profile w.r.t. machining	73
3.45	Stresses core prototype	74
3.46	Stresses magnets prototype	74
3.47	Stresses plate prototype	75
3.48	Stresses shoulder bolt prototype	75
3.49	Magnet load stresses on core	76
4.1	3D printed prototype assembly: axial bolts	77
4.2	3D printed prototype disassembly axial bolts	78
4.3	3D printed prototype: radial bolts	78
4.4	Prototype radial bolts: skewing configurations	79
4.5	Prototype parts	79
4.6	Magnet placement process	80
4.7	Magnet fixation process	80
4.8	Prototype final result	81
5.1	Exponential increase of centrifugal force with rotational speed (fixed dimension)	84
5.2	Elastic stiffness beam [20]	85
5.3	Second moment of area for a triangle [21]	85
5.4	Upscale: Base model	88
5.5	Upscale base model: deformation and stresses	88

5.6	Upscale: Iteration 2	89
5.7	Upscale base model: deformation and stresses	89
5.8	Upscale: Iteration 3	90
5.9	Upscale iteration 3: deformation and stresses	90
5.10	Circular economy flow [22]	93
5.11	Sustainable Development Goals[23]	95

List of Tables

1.1	Electrical Insulation in PMSM [24] [25][26]	5
3.1	Technical specifications of ferrite magnet FE-Q-18-10-06	43
3.2	Slot parameters	44
3.3	Stator parameters	44
3.4	Magnet topology parameters	45
3.5	Rotor parameters	45
3.6	Key properties of ferrite magnet grade Y35 [27]	55
3.7	Prototype (ribless design)	60
3.8	Conventional (ribbed design)	60
3.9	Properties of C15 steel	62
3.10	Properties of AISI316 steel	68

List of Acronyms

(H)EV (Hybrid) Electric vehicle.

CAD Computer Aided Design.

DfA Design for Assembly.

DfD Design for Disassembly.

EAf Electric Arc Furnace.

EDM Electrical Discharge Machining.

EM Electric Machine.

EoL End of Life.

FEM Finite Element Method.

HD Hydrogen Depreciation.

HDDR Hydrogen Disproportionation Desorption Recombination.

HPMS Hydrogen Processing of magnetic scrap.

IPM Interior Permanent Magnet.

NdFeB Neodymium-Iron-Boron.

PEEK polyetheretherketone.

PM Permanent Magnet.

PMSM Permanent Magnet Synchronous Motor.

REE Rare Earth Elements.

SMC Soft Magnetic Composites.

SPM Surface-mounted Permanent Magnet.

Introduction

Sustainability is reshaping industries worldwide, and electric machines (EMs) play a crucial role in this transition. With the global electric vehicle (EV) market projected to grow exponentially, the demand for high-performance EMs is increasing. In 2023, further progress in the uptake of EVs was made in all 27 EU Member States, with EVs accounting for 22.7% of new car registrations. In total, 2.4 million new EVs were registered, up from 2 million in 2022, marking a significant increase. Registrations of new battery EVs grew by 37%, reflecting the accelerating shift towards sustainable mobility[28]. However, the end-of-life (EoL) phase of these machines presents a significant challenge in achieving a circular economy, where resources are reused and recycled to minimize waste and environmental impact.

In recent decades, the shift toward sustainable technologies has intensified, driven by the need to reduce environmental impact and conserve critical raw materials like rare-earth elements (REEs). EMs play an important role in this transition, with applications ranging from industrial machinery to household appliances. One of the most significant changes has been the rise of EVs which utilize high-performance EMs. The benefits of electrification are widely recognized, but the EoL phase of EMs remains a critical challenge in the pursuit of a circular economy. Although sustainability awareness is growing, EMs remain primarily designed for efficiency and performance, with limited consideration for recyclability or material recovery [29]. The complexity of modern motor assemblies consisting of a variety of metals, permanent magnets, polymers and composite materials makes disassembly very difficult and thus recycling processes inefficient or even infeasible. This results in high costs, material losses, and environmental impact, particularly due to the difficulty of recovering the valuable REEs. Given the growing demand for EMs and the increasing scarcity of these resources, it is important to develop new designs that facilitate easier disassembly, reuse, and recycling.

This thesis explores design strategies for EMs that are optimized for EoL processing. The goal is to develop a prototype that balances performance with modularity, disassembly, and material recovery. **The Core Research Question Is:** *How can EM design be adapted to improve EoL recyclability without compromising mechanical integrity or basic performance?* By adopting a systematic and engineering-driven approach, this research aims to propose concrete designs that support the transition toward a more circular and sustainable EM industry. This thesis is structured as follows: Chapter 1 provides a literature review on critical materials, recycling challenges, and existing approaches in design for recycling. Chapter 2 introduces new design strategies to enhance recyclability, with a primary focus on rotor innovations, alongside improvements in stator construction. Chapter 3 outlines the development of a rotor prototype incorporating these principles, supported by electrical and mechanical simulations. Chapter 4 presents the results and Chapter 5 examines the scalability of the design for higher-performance applications. The thesis ends with a conclusion, directions for future research, and a sustainability reflection.

1

Literature review

The main 2 types of electric machines used in EVs today are Permanent Magnet Synchronous Motors (PMSMs) and induction motors. PMSMs are the most widely used because of their high power density, high efficiency, simple but rigid structure and high torque at low speeds, all of which are crucial properties in the automotive sector [7]. Within this category of motors, we distinguish between rotors with surface-mounted magnets (SPM) (a) and rotors with interior magnets (IPM) (b) [2]. In EVs, the IPM variant is dominant due to the great performance and

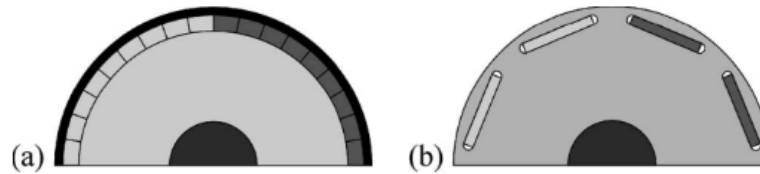


Figure 1.1: SPM vs IPM [2]

the extra reluctance torque, which improves overall output. The buried magnet design provides better mechanical integrity, allowing them to operate at higher speeds without the risk of magnet detachment and they are also better protected against overheating and thus magnet demagnetization. Additionally, IPM motors are better suited for flux weakening, which enables higher-speed operation without excessive voltage demand [30]. In this research, we will focus on PMSM type of machines, specifically those with an IPM topology. This choice is driven by the superior performance characteristics and the widespread application in modern EVs. A key aspect of these motors is the use of permanent magnets which contain REEs, materials that are considered critical due to their limited availability, geopolitical dependencies and essential role in advanced technologies[31]. China has historically dominated REE production, but its share has declined from 92% in 2010 to 58% in 2020[32]. Global efforts to diversify supply chains have increased due to geopolitical risks and past disruptions, such as the 2011 rare earth crisis[31]. However, REE supply remains unstable due to geographic concentration and historical issues.

Given the growing demand for EVs and the increasing strain in REE supply chains, understanding and optimizing the use of PMSM motors is crucial for technological advancements as well as resource sustainability.

1.1 Critical materials

To manufacture PMSMs, the use of critical materials is essential due to the working principles of these machines. An EM exists out of two primary components: the stator, which generates a rotating magnetic field, and the rotor, which follows this field and produces motion.

The stator and rotor cores are constructed mainly from a laminated stack of silicon steel sheets (also known as electrical steel) which are bonded together to minimize eddy current losses and enhance magnetic efficiency[33]. Soft Magnetic Composites (SMC) are also being researched as alternative because they provide multiple benefits compared to traditional electrical steel. Their isotropic nature, combined with versatile shaping capabilities, enables innovative 3D design solutions, allowing magnetic flux to be directed in multiple dimensions. Additionally, SMCs contribute to reduced weight and size, making them a favorable choice for some applications[33].

Within the stator slots, copper or aluminum windings are embedded to create the electromagnetic field that drives the rotor[34]. The IPM rotor features slots or cavities where rare earth magnets are inserted and securely fixed. Neodymium-Iron-Boron (NdFeB) is the most commonly used composition for these magnets due to its high energy density and strong magnetic properties. However, Samarium-Cobalt (SmCo) is also occasionally used, particularly in high-temperature applications where its superior thermal stability and corrosion resistance are advantageous[33].

1.2 Challenges in recycling

The way these machines are constructed introduces a big challenge when it comes to disassembling and recycling them at EoL. Over the past decades, technological equipment has primarily been designed following the Design for Assembly (DfA) principle[29]. This means that the focus has been on optimizing the manufacturing processes by simplifying assembly, reducing the number of components, minimizing labor costs whilst improving performance. However, DfA does not consider the ease of disassembly or the possibility for material separation, which are critical aspects for effective recycling and sustainability.

Currently, the recycling of small power EMs primarily relies on shredding[33]. During this process, the machines are cut into small pieces and then sorted either automatically or manually. However, there is a risk that different materials within the product may become mixed, leading to inefficient separation. While nonferrous metals can be separated from iron materials using magnetic separation, even minor contamination negatively impacts the quality of the recycling process.

1 Literature review

1.2.1 Cores and windings

The cores of the stator and rotor mainly consist of silicon steel and they are typically recycled alongside other types of steel[35]. Scrap steel is commonly processed in electric arc furnaces (EAF), where it is melted under intense heat from an electric arc and then refined to remove impurities[34]. Due to its laminated structure, electrical steel sometimes requires pre-treatment before entering the EAF process[34]. This involves chemical or thermal methods to strip away insulation layers, organic coatings, or adhesive bonding agents that might otherwise interfere with the refining process. Proper pre-treatment ensures higher purity in the recovered steel, making it suitable for reuse in high-efficiency applications. The shredding process used in recycling small power electrical machines risks contaminating recycled steel with materials like copper from the windings if not separated correctly. Even small amounts of material mixing (especially copper) can significantly reduce the quality of the recycled iron [33]. Aluminum windings offer a potential advantage for (stator) core recycling, as they do not contaminate the steel in the same way copper does[36]. Despite its higher resistivity compared to copper, aluminum is due to its low weight a suitable alternative in weight-sensitive applications such as the automotive industry [3]. However, the main objective remains to maximize material separation to enable optimal recycling processes.

In contrast, recycling Soft Magnetic Composites (SMCs) is significantly more complex due to their composite nature[34]. Unlike laminated steel, which consists primarily of a single material, SMCs are composed of high-purity ferromagnetic powder particles, each coated with a thin insulating inorganic layer[3]. However, the intrinsic brittleness of SMCs could offer an advantage during the disassembly phase, as their fragile structure may facilitate the mechanical separation of components such as windings, potentially simplifying recycling compared to conventional laminated cores [3] [37].

1.2.2 Impregnation

Impregnation in EMs is a process where the windings, typically in the stator, are treated with an insulating resin, varnish, or epoxy to improve mechanical strength, thermal properties, resistance to environmental factors and electrical insulation [38] [39]. The process involves submerging or coating the windings with resin, followed by curing through heat or chemical activation, ensuring that the material penetrates deeply into the winding structure in the stator slots. This helps maintain the motor's performance and reliability over time and is industry standard in high performance EMs[25]. The problem with these impregnating materials is that they are thermosetting polymers [24]. Once cured, they undergo a chemical reaction that makes them rigid and heat-resistant, preventing them from melting. This is a very big problem regarding EoL. To recover the windings, the impregnation must be removed, typically through pyrolysis (thermal decomposition in the absence of oxygen) to break down the thermoset material [40]. This process is highly energy-intensive and often damages the recovered materials. Chemical removal using solvents or acids can sometimes also be used to dissolve the impregnation, but both methods are far from optimal, causing big environmental and economic drawbacks [34].

1 Literature review

1.2.3 Insulation

High performance, high voltage machines require excellent electrical insulation between the conducting materials to ensure a safe and reliable operation. Proper insulation is crucial to prevent short circuits, electrical breakdowns and performance degradation over time. The different types of insulation found in an electric machine are:

Name	Function	Common Materials
Winding Insulation	Protects individual wires	Enamel coatings (polyurethane, polyester, polyimide)
Slot Insulation (Slot Liners)	Separates windings from stator laminations	Paper sheets, Nomex, Mylar
Impregnation Material	Holds windings in place and protects against environmental factors	Epoxy resin, polyester resin, varnish
Top Sticks	Provides mechanical stability and prevents winding movement	Fiberglass rods, laminated wood, epoxy composites
Phase and Ground Insulation	Provides additional protection against electrical short circuits and leakage to the stator core	Nomex, Kapton, mica-based insulation

Table 1.1: Electrical Insulation in PMSM [24] [25][26]

All of the insulation materials mentioned above play a crucial role in ensuring the proper functioning and reliability of an EM [25]. However, at the EoL stage of these machines, these materials pose significant challenges for recycling and reuse. The removal of insulation materials from EMs at EoL is particularly challenging because of their strong adhesion, complex composition, and resistance to degradation. All essential properties to ensure proper motor operation. Many of these materials, such as epoxy resins, varnishes, and polymer-based coatings are designed to permanently bond to components such as copper windings and stator laminations, making separation extremely difficult. In addition, insulation materials are heat resistant and chemically stable, which means that they do not easily break down or melt under typical recycling conditions. Instead, they require high-temperatures or chemical processes for removal, which can be energy-intensive and environmentally harmful. Furthermore, thermoset polymers, commonly used for impregnation and insulation materials, do not soften when heated but rather decompose into toxic gases, posing safety and pollution risks[24]. The combination of strong mechanical adhesion, resistance to physical and chemical breakdown and hazardous byproducts makes the efficient and sustainable removal of insulation materials one of the major obstacles in EM recycling [34]. This is particularly challenging, as effective removal of these materials is a crucial step in achieving proper material separation.

1 Literature review

The removal of these insulating materials to recover the copper or aluminum wires can be achieved through several methods. Via pyrolysis, the windings are heated in a controlled environment to break down the insulation without oxidizing the metals[26]. Another method is chemical stripping, which uses solvents or acids to dissolve the insulation while preserving the metallic core[34]. Mechanical removal involves physically scraping off the insulation with rotating brushes[34]. Additionally, laser-based stripping offers a precise and efficient solution, minimizing damage to the conductors while effectively removing the insulation [26].

1.2.4 Magnet Fixation

The permanent magnets in the rotor configuration of a PMSM are held into place by an adhesive bonding. This is essential for maintaining mechanical stability because loose or misaligned magnets can lead to imbalances, increased wear and even motor failure[41]. The fixation is often based on a partial or complete submersion of magnets with an adhesive or resin material.

The extraction of magnets fixed with adhesives presents significant challenges at EoL phase of EMs. Since the adhesive forms a strong bond with both the magnet and the surrounding structure, removal often requires mechanical force, chemical dissolution, or thermal degradation. Mechanical removal, by forcefully breaking the bond, can damage the magnets thus reducing their potential for reuse[14]. While chemical dissolution may be possible for some types of adhesives (typically ineffective for epoxy), often requires hazardous solvents that pose environmental and health risks [1]. Thermal methods, such as heating to break down the adhesive, can lead to magnet demagnetization and oxidation or the release of harmful fumes, complicating recycling efforts[1]. Additionally, the adhesive itself may contaminate recovered materials, reducing the efficiency of material separation and increasing processing costs[42].

1.2.5 Magnets

The recycling of permanent magnets from PMSMs presents several challenges due to the composition of the magnets and the complexity of recovery processes. PMSMs typically use NdFeB magnets, which contain valuable REEs such as neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb)[43]. While these materials are critical for high-performance applications, their recycling is complicated by factors such as demagnetization, oxidation, and contamination from coatings and surrounding motor components[14].

There are two main approaches in recycling NdFeB magnets: direct recycling and indirect recycling [31]. **Direct recycling** methods aim to recover and reuse the magnets with minimal processing, typically by using hydrogen decrepitation (HD) or Hydrogenation Disproportionation Desorption Recombination (HDDR)[34]. In hydrogen decrepitation, the magnets are exposed to hydrogen gas, which causes them to break down into a fine powder without significant contamination from the process itself[14]. This powder can then be reprocessed and sintered into new magnets, retaining much of the original material's performance.

1 Literature review

The HDDR process, on the other hand, is used to refine the microstructure of the recovered material, helping to restore magnetic properties closer to those of virgin magnets. It is an extension of the hydrogen decrepitation process and goes beyond simple decrepitation[44]. While these methods are energy-efficient and environmentally friendly, they are limited by variations in magnet composition and the potential degradation of properties due to oxidation [42]. For direct recycling of magnets, it is also important to begin with pure, uncontaminated magnet material[29]; therefore, shredded materials may be unsuitable. **Indirect recycling** on the other hand involves extracting the REEs from NdFeB magnets and reintroducing them back into the supply chain[42]. The two main techniques used for this are pyrometallurgical and hydrometallurgical processing. Pyrometallurgical recycling involves melting the magnets at high temperatures to separate the valuable rare earth metals from other elements[14]. While effective, this method requires significant energy input and can generate slag waste, reducing its overall sustainability. Hydrometallurgical recycling, on the other hand, uses acid leaching to dissolve the REEs, followed by solvent extraction or precipitation to recover purified materials[29]. This method can achieve high recovery rates but generates hazardous chemical waste that must be carefully managed. Both approaches require multiple processing steps, increasing costs and limiting economic feasibility. [14]

Paper[33] states that the recycling of NdFeB magnets rarely takes place outside of China, where the focus is primarily on recycling production waste. The reason for this is inefficient collection, technological difficulties and, especially, a lack of incentives. Recycling processes often target sintered magnets rather than bonded ones, as sintered magnets have a higher recycling value due to their superior energy product[45]. Currently, only 3 to 8% of REEs are being recycled worldwide, a figure estimated by the European Commission in 2020[29]. Other studies even report that less than 1% of REEs are actually recycled [46], which highlights the situation as being even more critical

Due to the challenges regarding the fixation of these magnets discussed in section 1.2.4, the magnet-containing rotors often undergo the conventional steel recycling route[43]. This involves shredding the rotor, melting it in a furnace, removing impurities, and refining it into new steel products. With these methods, the magnets and thus the REEs are lost to slag, making recovery nearly impossible[47]. To recycle REEs, magnets must be dismantled before processing, but this remains a significant challenge due to strong adhesives, complex integration and material sensitivity. Currently, no large-scale dismantling method exists, as most processes are labor-intensive, costly, and incompatible with diverse motor designs[43]. The European HARMONY project focuses on developing sustainable and flexible recycling processes for REEs from EoL permanent magnets, aiming to reduce Europe's dependency on imported critical materials[48]. A key aspect of HARMONY's success is the ability to easily remove magnets from used applications, such as electric motors. Simplifying dismantling is crucial because it enables more efficient and higher-quality material separation and thus recycling processes, minimizing material loss and supporting the creation of a closed-loop system that aligns with circular economy goals.

1 Literature review

Another challenge in magnet recycling is contamination from coatings, adhesives and motor components. Many NdFeB magnets are coated with nickel, epoxy or other protective layers that must be removed before recycling[14]. These coatings can be removed through hydrometallurgy using acids like sulfuric or hydrochloric acid or mechanical abrasion[42]. Thermal treatment above 350°C to carbonize epoxy coatings can also be used for easier mechanical removal[1]. Additionally, when magnets are extracted from PMSMs, they are often mixed with materials like copper, steel, and adhesives, making separation more complex. A gentle cleaning method using silicon carbide in a vibratory finishing process can also remove adhesive residues from magnets without damaging the magnetic material [1]. Poor material purity in the recovered magnets can result in reduced performance, making them less desirable for high-end applications[36].

1.3 Existing Design Approaches

With the increasing global demand for EVs, the need for sustainable and efficient EoL management of their components has become more pressing. One critical aspect of this is Design for Disassembly (DfD), a concept that focuses on making products easier to take apart for maintenance, repair, recycling and remanufacturing[49]. As EMs are complex systems made up of various materials, including REEs, copper, steel, polymers and composite components, efficient disassembly can significantly enhance material recovery, reduce waste, and lower the environmental impact of production and disposal.

Various designs have been explored and tested in literature to improve the ease of disassembling of EMs for repair, recycling, and EoL management. In this section, we will examine the methods already investigated and emerging innovations aimed at enhancing the sustainability and circularity of EV motor components.

Alatalo et al. [3] designed a 4 kW claw-pole motor for EVs, with a soft magnetic composite (SMC) stator core and axially magnetized NdFeB magnet rings in the rotor. The study states that the use of SMCs makes the motor easier to dismantle, as the brittle nature of the material allows for simpler access to the copper windings during recycling. To further enhance recyclability and reduce weight, aluminum windings were used instead of copper. By employing ring coils without end windings, they achieved a high fill factor of 0.8. This design lowered magnet weight by 40% compared to their reference motor. However, replacing copper with aluminum resulted in a 50% increase in winding losses, trading off some efficiency. Despite this, the use of aluminum reduced winding weight by 70%, striking a balance between weight reduction, performance, and recyclability.

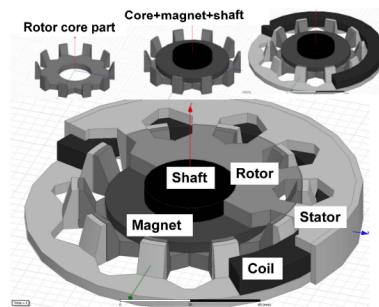


Figure 1.2: 4KW Claw-pole motor[3]

But SMCs face significant challenges for upscaling due to high iron losses, low magnetic permeability, and brittleness. These issues reduce efficiency, complicate manufacturing and increase costs, making SMC less suitable for larger EMs despite their claimed dismantling benefits.

1 Literature review

Despite the up-scaling difficulty, S. T. Lundmark et al. [50] improved the design of the previously developed claw pole motor in [3] by introducing segmented stator and rotor cores made from SMCs. This upgraded motor is designed to deliver 250 Nm of torque and 78 kW of power. A notable aspect of the design is a protection ring for the permanent magnets, which extends their lifespan. Additionally, the rotor and magnets are assembled without the use of adhesives, simplifying disassembly for recycling. The redesigned version achieves a similar efficiency of approximately 95%.

In [4], P. Upadhyay et al. investigated the potential of utilizing recycled NdFeB magnets in claw-pole machines for hybrid electric vehicles (HEVs). They developed a 48 V mild hybrid starter-generator that allows for the easy removal and replacement of magnets. The recycled magnets, sourced from EoL vehicle motors through HD processing, demonstrate a slight decrease in performance compared to virgin magnets, with only a minor reduction in peak torque. Furthermore, the recycled magnets exhibited a 15% lower resistance to demagnetization. The researchers concluded that using recycled magnets has a minimal impact on motor efficiency and contributes to a reduced environmental footprint. The design in this study is of particular interest, primarily because it facilitates the easy removal of the magnets, whether they are virgin or recycled. However, despite this advantage, one of the biggest challenges associated with claw-pole designs remains their complex mechanical construction. This complexity can lead to difficulties in manufacturing, assembly, and overall structural integrity at high speeds, which are critical factors to consider in the design and application of such systems.

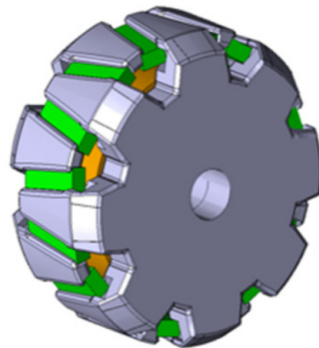


Figure 1.3: Claw pole rotor [4]

In [5], A. G. Gonzalez et al. explored ways to improve recyclability and efficiency of EMs through a modular design approach and the use of unconventional materials, such as amorphous cores as shown in Figure 1.4. This design strategically placed permanent magnet blocks between metal sheets to shield the magnets and minimize losses. E-shaped stator cores were utilized, and adhesives were avoided to simplify recycling. Despite these advancements, the study reported unexpected performance variations due to high eddy currents from welds, low torque density, poor power factor, and significant thermal issues.

1 Literature review

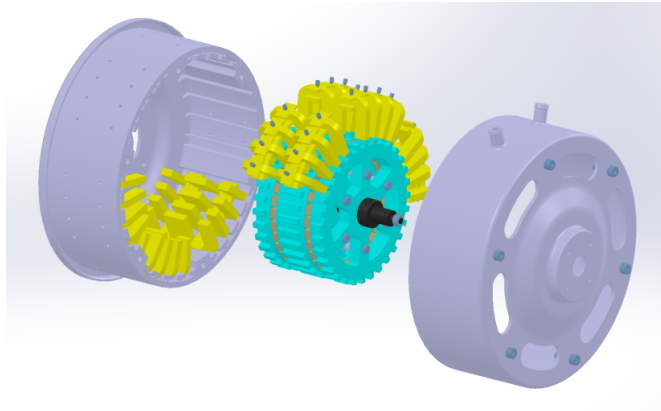


Figure 1.4: Hybrid rotor structure[5]

A. K. Jha et al. [51] developed an outer rotor Halbach cylinder motor for HEV applications, focusing on high torque density and reduced magnet usage without additional adhesives. The design delivered 41% more torque than conventional SPM motors, though with lower flux weakening performance. Bonded magnets were specifically chosen to minimize eddy current losses and simplify the manufacturing process compared to pre-magnetized sintered magnets, which are described as "difficult and complex" to produce. However, this choice comes with the trade-off in lower magnetic performance.

In [6], M. Kimiabeigi et al. developed spoke-type traction motors (Figure 1.5) utilizing cost-effective materials such as ferrite magnets and aluminum windings to achieve high performance for electric vehicles and boats. Their study evaluated two rotor designs, including a sophisticated fir-tree rotor configuration that incorporated ferrite magnets and aluminum windings, specifically designed for EVs. This paper seeks to replace traditional rare earth magnets with alternative options whilst incorporating a design that allows for removal of the magnets.



Figure 1.5: Ferrite fir tree rotor[6]

1 Literature review

Additionally, [46] provides the first detailed description of the production and testing process of hydrogen processing of magnetic scrap (HPMS) recycled bonded magnets (from recycled NdFeB material from hard disk drives) for a custom-built traction motor application, as also presented in Figure 1.5 and [6]. It compares these recycled magnets to ferrite magnets, assessing their size, volume, and magnetic properties. Through simulations, prototype testing, and comparisons, the paper demonstrates that HPMS recycled magnets can meet traction motor requirements, offering higher torque density, efficiency, and similar demagnetization performance as ferrite magnets. Additionally, they can be competitively priced, especially during periods of high REE material prices.

[7] reviews modularity techniques for stator manufacturing in permanent magnet machines used in domestic appliances, electric vehicles, more electric aircraft, and wind power generators. It introduces different modular topologies such as segmented stators with non-overlapping coils. This method makes disassembly and separation of copper and steel significantly easier. Due to the advantages of non-overlapping windings such as modular stator segments, short end windings, and high torque density, they have been adopted in certain (H)EVs, including the Honda Integrated Motor Assist, as shown in Fig.1.6.

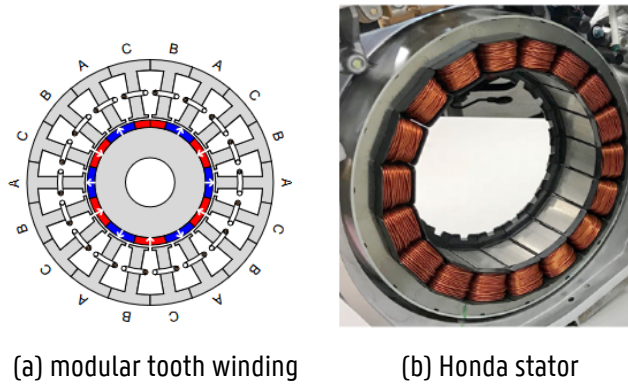


Figure 1.6: Segmented Stator in HEV [7]

Paper[7] also states that non-overlapping windings in modular machines come with several disadvantages. One significant drawback is the difficulty in generating reluctance torque, which is especially disadvantageous in the case of IPM rotors, as these typically produce a high reluctance torque. This limitation can impact the overall performance of the machine in applications where reluctance torque is essential. Furthermore, some non-overlapping winding topologies are prone to larger no-load torque ripple, which can pose challenges in maintaining smooth and stable operation. These issues collectively make non-overlapping windings less suitable for applications that demand low harmonic distortion, higher reluctance torque, and minimal torque ripple.

1 Literature review

One of the final design approaches I would like to discuss is the Tesla patented carbon sleeve rotor[52]. Although this motor was not specifically designed for recycling purposes, it incorporates several innovative concepts that present promising opportunities for enhancing recyclability in future EV designs.

This innovative rotor design eliminates radial and tangential iron ribs, which significantly reduces magnetic flux leakage and improves magnet utilization. As a result, the proposed design achieves higher torque density and allows for a substantial increase in maximum speed, up to 50% more than conventional designs[8]. Additionally, the paper states that the efficiency is slightly improved, reaching a maximum of 97.0%, and torque ripple under load is reduced by 18.8%, leading to smoother and more efficient operation[8]. The absence of iron ribs minimizes flux leakage and enhances field-weakening capabilities, which are crucial for maintaining performance at higher speeds. The carbon fiber sleeve provides significant mechanical stability, enabling the rotor to withstand higher centrifugal forces and operate at higher speeds without compromising structural integrity.

[8] also states that the proposed rotor design experiences lower rotor losses due to the increased magnetic resistance of the air-gap. It is mentioned that both iron and eddy current losses in the permanent magnets are reduced, making complex magnet segmentation unnecessary. However, these benefits come with challenges, including increased manufacturing complexity and cost due to the carbon fiber sleeve production and assembly. It also states that the elimination of iron ribs increases the risk of irreversible demagnetization during active short-circuit conditions, as there are no stray paths for magnetic flux.

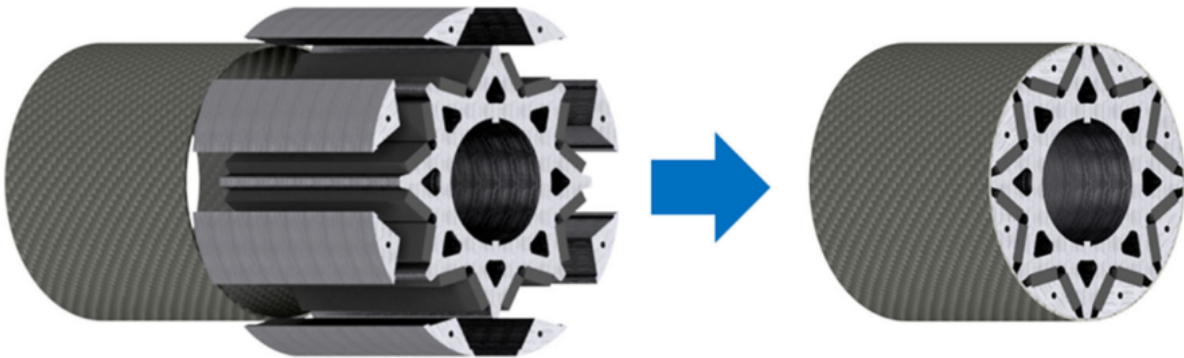


Figure 1.7: Carbon sleeve rotor[8]

The motor design is not specifically designed to facilitate EoL recycling, but it could potentially simplify the removal and reuse of magnets. Although, the patent mentions the use of adhesives for gluing the magnets to the rotor and the use of epoxy resin for the placement and fixation of the carbon fiber, a sleeve in general might make it easier to extract the magnets at EoL compared to conventional laminated rotor core constructions with embedded magnets.

2

Design for recycling

In modern EVs, the IPM structure is dominant. V-shaped, double V-shaped, or double-layer rotor topologies are the standard types of magnet configuration. This choice is motivated by the superior performance delivered by these types of machines, as explained in Chapter 1.

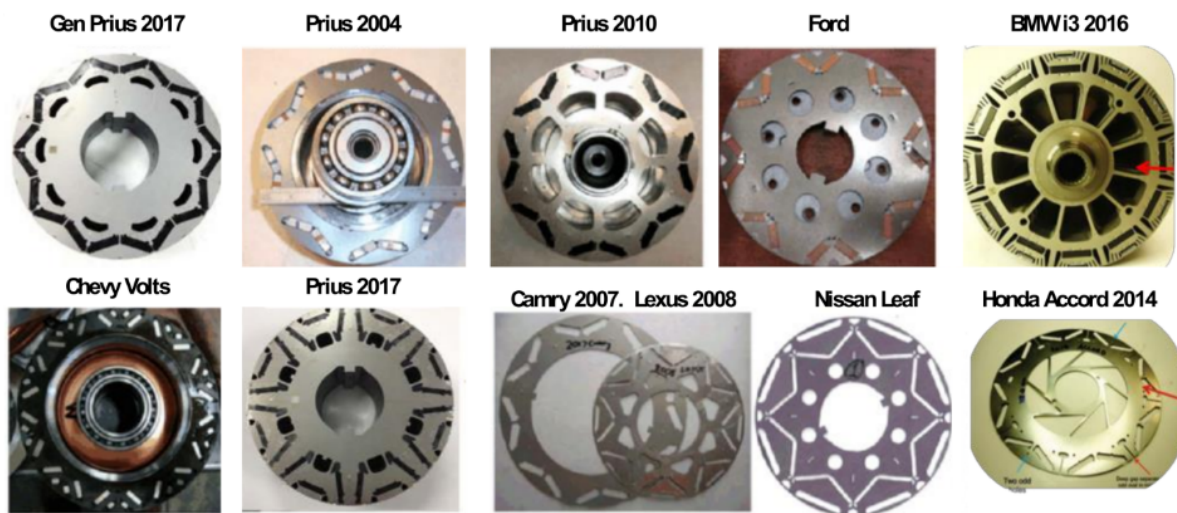


Figure 2.1: Rotors of modern electric vehicles[9]

From the existing literature discussed in Section 1.3, it is evident that most of the current design-for-recycling approaches are innovative and introduce creative concepts. However, these approaches differ significantly from the motor designs currently present in the EV market shown in figure 2.1. Many of these previously presented designs in literature face challenges related to scalability and performance, often compromising either due to sophisticated structural complexities or limited power density. The trade-offs involved in achieving recyclability frequently lead to reduced efficiency or increased manufacturing costs, making widespread adoption less feasible. Therefore, there is a pressing need to develop recycling-friendly motor designs that balance simplicity, efficiency, and high power density without significantly affecting performance or cost-effectiveness.

2.1 Stator

In the stator, the most challenging aspect of wire disassembly and material separation is the impregnation and insulation of the structure. The goal is to separate the steel core and copper or aluminum windings at EoL to enable efficient recovery and recycling of valuable materials, reduce waste, and minimize environmental impact. Today there are already some techniques being used such as burning away all the varnish and insulation in a furnace [53], or mechanically removing the windings from the stator yoke and removing the leftover insulation via the methods mentioned in Section 1.2.3. In either way, the insulation and impregnation material is lost and thus not negligible for reuse or recycling. Furthermore, these processes are highly energy- and time-intensive and have a significant environmental impact.

In Section 1.3, a range of alternative stator designs is examined, many of which aim to improve stator recyclability by using modular constructions, or replacing conventional materials with alternatives like SMCs or aluminum. While these approaches can significantly enhance disassembly and material recovery, they frequently introduce new challenges in terms of performance, efficiency, manufacturability, or cost, limiting their practical scalability.

2.1.1 Construction

Paper[7] introduces an interesting modularity aspect to the conventional construction of rotors from radial flux machines as we know today. Figure 2.2 (left) shows the stator of a 2010 commercial Prius PMSM machine, which

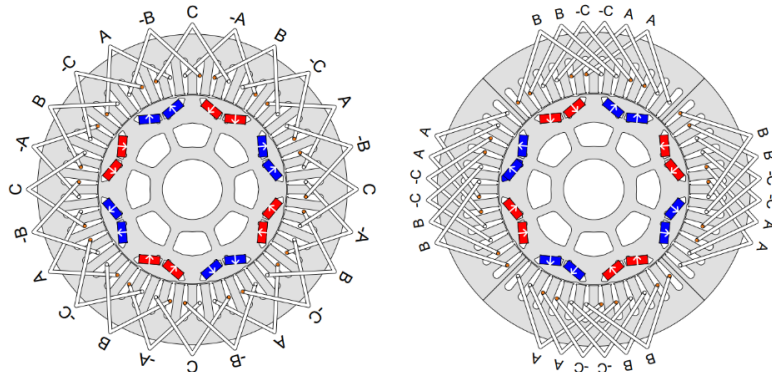


Figure 2.2: Modular rotor topology[7]

is well known for its application in EVs. Due to the complexity of the end connections in the overlapping winding structure, the stator cannot be divided into modular parts. An alternative winding architecture shown in Figure 2.2 (right) allows a modular stator design by arranging the end parts within a single pole pair. With this layout the machine falls into the partial physical decoupling category, while maintaining nearly identical electromagnetic

2 Design for recycling

performance in both configurations[7]. This principle might be a viable option to optimize the recyclability of these machines whilst still incorporating overlapping windings.

This concept enables the repair of the stator in cases of issues such as short circuits, cable breaks, or overheating damage. It requires only the dismantling and rewinding of a single segment, which, due to the modular design, is significantly easier to perform. The modularity provides improved access to the windings and offers more space to work, simplifying the repair process. In addition, this approach minimizes material waste and lowers maintenance costs, making it a more efficient and sustainable solution for stator configurations. A modular approach will also facilitate the separation of the stator windings at EoL, allowing optimized recycling processes [3] [33].

2.1.2 Insulation

In EMs, each conductor is individually insulated to ensure safety, efficiency, and reliable performance. This insulation prevents electrical currents from interfacing with other wires or conductive parts, reducing the risk of short circuits, overheating, and equipment damage. The materials used for this are listed in table 1.1. An alternative to this standard enamel insulation is polyetheretherketone (PEEK). This is a high-performance, semi-crystalline thermoplastic polymer known for its exceptional mechanical and chemical properties. PEEK has been around since the late 1970s, but it is currently the subject of recent research due to its exceptional properties and expanding applications in various high-performance industries.[54]

The advantage of using a thermoplastic material for insulation in electric motors is that it can be melted and reprocessed multiple times. This property makes it easier to remove the insulation by applying heat, allowing it to be separated cleanly from the windings without damaging the underlying materials. Additionally, once removed, thermoplastic insulation can be melted down, purified, and re-extruded into new products, making it highly recyclable. This ability to reuse the material not only reduces waste but also minimizes the need for new raw materials, making thermoplastics a more sustainable choice for insulation in EMs.

The Belgian manufacturer Bekaert commercially offers PEEK-insulated copper wire under the name Ampact™, a technology designed for high-voltage electric motors (800V and above)[55]. According to Bekaert, the wire provides several key advantages, including higher power density, extended driving range, faster and more efficient production, reduced CO₂ emissions and strong resistance to cooling oils[56].

In a case study by Zeus Industrial Products, Inc. [10], the use of PEEK-insulated wires and PEEK slot liners in stators was found to improve performance compared to traditional insulation materials. The PEEK insulated wire demonstrated greater stiffness and rigidity, improving resistance to coil movement during startup, surge, and similar conditions, thus enhancing the reliability and durability of the motor.

2 Design for recycling

Furthermore, the PEEK slotliner insulation showed superior tear resistance and effectively maintained its shape, including cuff formation.



Figure 2.3: Completed stator winding with PEEK material[10]

Although PEEK materials initially required a period of familiarization for the manufacturing personnel who manually wound the stator, they were quickly able to adapt their standard installation techniques without additional limitations. The study also indicated that during the resin impregnation process, the PEEK materials behaved similarly to conventional insulation materials, ensuring effective insulation and minimal partial discharge activity. However, from a recycling perspective, embedding the PEEK-insulated components in thermoset resin, as done in this case study, significantly undermines the meltability and recyclability of the thermoplastic material at EoL, effectively negating its key advantages in terms of sustainability benefits that thermoplastic insulation could provide. Additionally, PEEK is significantly more expensive than traditional materials, so the use should be justified by ensuring its benefits can be fully realized.

2.1.3 Impregnation

As discussed in the previous chapter, impregnation stands out as the most significant obstacle to the recyclability of the stator component in EMs. While the use of thermoplastic PEEK as winding insulation offers superior performance along with meltability and recyclability potential, these advantages are nearly nullified by the resin impregnation process.

The materials used in today's machines (listed in table 1.1) are chosen based on their electrical insulation properties, thermal conductivity, mechanical strength and penetration capability into the windings. These resins typically cure through chemical reactions triggered by mixing with hardeners or catalysts (two-component systems), by applying heat (thermal curing) to accelerate the curing process, by exposure to UV light (photo-curing) or simply through solvent evaporation. In impregnation materials, chemical and thermal curing methods are the most common. [24]

2 Design for recycling

Thermoplastic alternatives

The first and most obvious possibility to solve the issues related with the conventional impregnation materials is to choose a **thermoplastic resin material** rather than a thermosetting. Because of the easy applicability, low cost, and excellent performance of the thermosetting impregnation resins currently used in the industry[24], not a lot of research has been done on this topic.

An example of a high performance thermoplastic material is polyamide (PA), commonly known as nylon. It presents a group of crystalline polymers distinguished by their chain structure, such as PA-6, PA-6,6, PA-11, PA-4,6, and PA-12. With high melting points between 200 and 300°C, polyamides maintain their solid-state properties at elevated temperatures, although their stiffness decreases rapidly with heat. They offer excellent impact resistance, partly due to moisture absorption, as well as good wear resistance, making them ideal for technical applications like bearings and gears.[57] Therefore, these polymers could potentially serve as a viable alternative for impregnation in EM stators based on their properties.

One of the major challenges with thermosetting polymers is their high melt viscosity combined with the high processing temperature. This makes it difficult to perform winding impregnation in the stator slots effectively. Current motor impregnation methods include dipping, vacuum potting, and trickling [39]. Dipping immerses pre-heated components in resin for full coverage; vacuum potting uses vacuum to eliminate air bubbles and ensure thorough filling and trickling rotates the stator while applying low-viscosity resin for uniform penetration of windings. Due to the high melt viscosity of thermosetting polymers, most of these methods are not deemed feasible. Vacuum potting appears to be one of the most promising options, but it still presents significant challenges in effectively filling all small cavities deep within the windings. The proposed modular stator design in 2.1.1 could simplify this process by providing better access to the windings. Nevertheless, the impregnation process will still need to be modified and may even need to incorporate techniques from injection molding processes to ensure adequate filling and protection.

Paper [58] investigates an impregnation process of large-tow carbon-fiber woven fabric with polyamide 6 (PA6) using a solvent-based method to reduce the high melt viscosity. The study explores how dissolving PA6 in a calcium chloride/methanol solution improves resin penetration into the fiber bundles, addressing the challenge of high melt viscosity in thermoplastics. The findings demonstrate that this method significantly enhances impregnation quality, reduces void content and thus improves mechanical properties of the impregnated application. This knowledge can be beneficial for the impregnation of stator windings, where ensuring uniform resin distribution is critical. The method used to remove these additives involves water immersion to eliminate the calcium chloride and methanol solution, which could introduce corrosion concerns. Despite the potential advantages, there are several challenges in applying this method to winding impregnation. One major issue is solvent removal and residue, as complete elimination of calcium chloride (CaCl_2) and methanol is critical. Remaining traces could lead to voids or defects within the impregnated structure. Additionally, there are compatibility concerns with stator windings, as the study focuses on carbon fiber, which has different wetting properties compared to insulated magnet wire, meaning PA6 adhesion to conductor and existing insulation coatings may not be as effective.

2 Design for recycling

Recyclable epoxies

Due to the difficulties associated with finding alternative thermoplastic polymers as a substitution for conventional impregnation materials, we seek alternatives. A widely used material for impregnation today is epoxy, which has a highly flexible and versatile preparation, allowing for a wide range of applications. Epoxy resin is known for its lightweight nature, strong dimensional stability, excellent mechanical strength, superior insulation properties and resistance to corrosion, making it widely used in electrical equipment[59]. However, its three-dimensional network structure, while essential for enhancing performance, also makes recycling and removing difficult. This leads to resource waste and economic losses, posing a significant challenge in sustainable material management. A relative new class of polymers called **vitrimers** could solve this limitations.[11]

Epoxy-Based Vitrimers

For more than 50 years, synthetic polymers have been classified into two main categories: thermosets, known for their outstanding mechanical properties but require an irreversible curing process, and thermoplastics, which can be melted and reprocessed but typically have lower thermal and mechanical performance[60]. In [61], it is stated that vitrimers represent an innovative class of polymers that combine the strength and durability of thermosets with the moldability and recyclability of thermoplastics. The article explains that, unlike traditional thermosets, which undergo an irreversible curing process, vitrimers maintain a covalently cross-linked network while allowing bond exchange reactions at elevated temperatures. This enables reshaping, welding, and recycling of the material. Furthermore, the paper discusses how this unique property makes vitrimers particularly valuable for high-performance applications where both mechanical robustness and sustainable material use are critical. Additionally, it highlights how some vitrimer-based composite materials can be rapidly processed, reprocessed, and recycled through solution-based methods (see cleavable epoxies). By addressing the limitations of both thermosets and thermoplastics, this paper suggests that vitrimers have the potential to revolutionize the composites industry by improving manufacturing efficiency, reducing waste, and facilitating more sustainable material lifecycles. The paper [61] also expects that these malleable vitrimer resins will be cost-competitive with conventional epoxy resins when developed to a similar scale.

[40] focuses specifically on epoxy-based vitrimers designed for applications in the electrical industry. It explores the use of disulfide bonds as dynamic covalent cross-links, enabling these vitrimers to undergo self-healing, reshaping, and full recyclability. Unlike traditional epoxy resins, which are difficult to recycle because of their permanent cross-linked structure, disulfide-based vitrimers can be mechanically reprocessed by hot pressing or chemically degraded and reconstituted using reducing agents (see cleavable epoxies). The paper highlights the high electrical insulation properties, mechanical strength retention and thermal stability of these materials, making them suitable for components such as insulation bushings and transformer casings. Furthermore, it discusses how these vitrimers can be efficiently degraded and reformed, providing a sustainable alternative to conventional epoxy systems. By integrating recyclability with the superior performance of epoxy resins, this study demonstrates how vitrimers can enhance the durability, repairability, and environmental impact of materials used in electrical applications, potentially extending its use to stator winding impregnation.

2 Design for recycling

However, the incorporation of disulfide bonds influences the material properties, making it essential to precisely control their content. The vitrimer system investigated in this study required high-temperature curing, which led to the release of sulfur-containing gases during both curing and degradation. Large-scale degradation could contribute to environmental pollution. Therefore, future research will prioritize developing milder curing and degradation methods for disulfide epoxy resins.[40]

Cleavable epoxy variant

As outlined in [11], recyclable epoxies include not only vitrimers but also cleavable variants. The key difference lies in how their polymer networks respond to external conditions. Epoxy vitrimers are thermosets with dynamic covalent bonds that enable stress relaxation and network rearrangement at elevated temperatures without losing crosslink density. This allows them to be reformed and recycled like thermoplastics, through bond exchange mechanisms, without depolymerization. In contrast, cleavable epoxides rely on labile bonds that break under specific stimuli such as heat, pH, or chemicals, leading to network degradation. Unlike vitrimers, they generally cannot be reshaped simply by heating and are instead recycled through bond cleavage. Common dynamic bonds in vitrimers include esters, disulfides, imines, and boronic esters, while cleavable epoxides often feature acetals, carbonates, or phosphate linkages. Notably, some vitrimers with disulfide or imine bonds may also act as cleavable epoxides under certain conditions, like the epoxy based vitrimers designed for electrical applications as substitute for petroleum-based epoxy resin in [40], discussed in the previous part on Epoxy-Based Vitrimers.

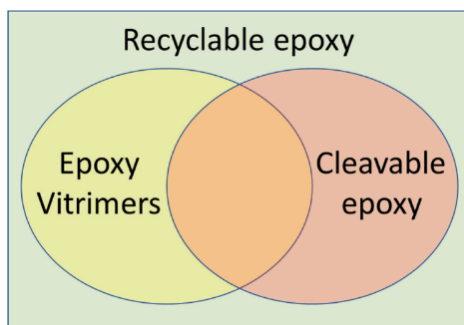


Figure 2.4: Classification matrix of recyclable epoxy [11]

The terms “vitrimer” and “cleavable epoxy” are sometimes used interchangeably in literature, even though they refer to different concepts. However, some systems can fall into both categories, as shown in Figure 2.4. In general, we can state that:

- **Vitrimer:** Polymer networks with dynamic covalent bonds that enable reprocessing and reshaping, typically by heat.
- **Cleavable:** Polymer networks with labile bonds that break under specific stimuli, enabling controlled degradation and recycling through chemical (solution-based) methods.

2 Design for recycling

2.1.4 Continuous wave winding

Continuous wave winding technology marks a major step forward in EM design. Unlike conventional hairpin windings, that require many individual conductors and welds, continuous wave windings uses a single, uninterrupted conductor shaped into a wave-like pattern across the stator as shown in Figure 2.5. This approach drastically reduces weld points, improves reliability and enables higher copper fill factors[62]. The production and winding process is particularly well suited for high levels of automation and can be scaled accordingly to achieve high production volumes [63]. The result is a more compact, thermally efficient, and mechanically stable stator with superior power density that is suitable for mass production as showcased with the Lucid Air stator shown in Figure 2.6, making it ideal for modern high-performance EMs.

The assembly method is the reason why this can be an important technology towards improving the recyclability of EM stators. These windings are radially pressed into the stator core [62] rather than shoved in axially such as conventional hairpin windings. Because of this principle, we get fill factors that are nearly complete. This W-pin winding is a modern flat-wire stator winding technique that uses a continuous wave-shaped conductor inserted into the stator slots. It's considered a strong principle because it significantly increases the slot fill factor, reducing resistance and improving efficiency[64]. The design minimizes end winding height, lowers copper usage, and simplifies assembly by reducing the number of welds compared to conventional hairpin designs. Although impregnation is still applied today, it is often less critical and in some cases potentially unnecessary with continuous wave winding, as the high slot fill factor already ensures strong mechanical and thermal stability compared to conventional winding technologies. Varnishing could then possibly be limited to the end windings, where mechanical freedom is greater. These small end windings are easier to treat with a coating or resin due to the available space and the less critical need for deep penetration compared to the interior of the stator slots. However, this concept of eliminating impregnation has not yet been experimentally validated and requires further investigation to assess its feasibility and long-term reliability.

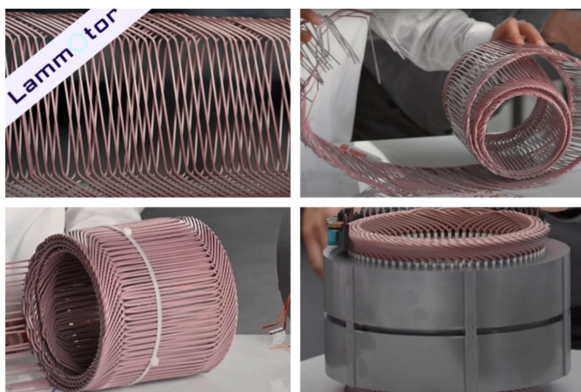


Figure 2.5: Continuous Wave winding Lucid Air [12]

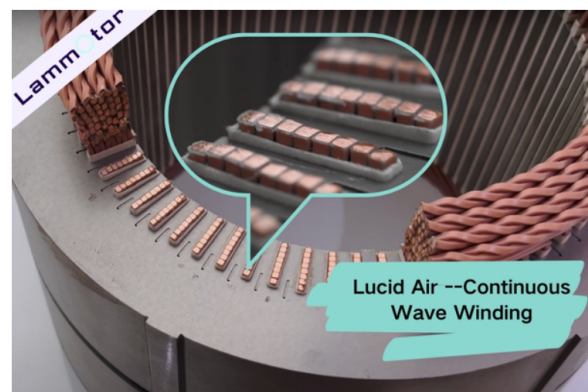


Figure 2.6: Continuous Wave winding: conductors [13]

2 Design for recycling

The W-pin design contributes to sustainability by simplifying disassembly, enabling easier removal and replacement of the windings during recycling or maintenance, without extensive rework or damage to surrounding components[65].

Continuous wave winding combines the weld-free continuity of conventional round wires with the performance and compactness of hairpin designs [65]. This makes W-pin windings not only efficient but also forward-looking in terms of manufacturing and recyclability.

2.1.5 Concluding remark stator part

The combination of a modular stator design, thermoplastic cable insulation, and recyclable epoxies for impregnation presents a promising approach to significantly improve the recyclability of EM stators. The modular design would allow for easier disassembly, repair and EoL separation, reducing material waste and simplifying maintenance procedures. Thermoplastic insulation, such as PEEK, offers the advantage of meltability and reusability, addressing one of the major limitations of traditional insulation materials in terms of recyclability.

The introduction of recyclable epoxies as alternative impregnation material could be a breakthrough in overcoming major recycling challenges regarding EM design. Vitrimers, with their dynamic covalent networks, enable reshaping, repair, and reprocessing, making them well-suited for sustainable motor manufacturing by simplifying the separation of stator windings at EoL. Similarly, cleavable epoxies incorporate labile bonds that break under specific stimuli such as heat, pH, or chemicals, allowing controlled degradation for efficient disassembly and material recovery. Together, these materials offer a promising framework for fully recyclable stator constructions. However, further research is needed to optimize their formulations and processing techniques, particularly regarding viscosity, curing behavior and compatibility with thermoplastic insulation and various winding structures to meet the high-performance demands of EMs. By incorporating continuous wave windings, high slot fill factors could provide substantial mechanical and thermal stability, potentially reducing or eliminating the need for stator slot impregnation. Still, the long-term reliability of these materials and concepts under operational stresses such as thermal cycling and mechanical loads must be thoroughly validated.

While the concepts discussed for the stator present promising advancements in recyclability, this thesis primarily focuses on the rotor section, as there is still significantly more progress to be made in this area due to the complexity of recycling due to the irreversible construction as stated in Section 1.2. The stator-related innovations outlined here will not be explored or tested in further detail, as strategic choices must be made in terms of prototyping within the available time and resources.

2.2 Rotor

The rotor offers the greatest potential for improvement, as it is often recycled through conventional steel routes, as mentioned in Section 1.2.5, due to the inability to dismantle the construction, resulting from its integral design and the use of adhesives. These rotors contain significant amounts of valuable materials like NdFeB magnets, which experience low to none recycling efficiencies during this processing. As a result, dismantling is expected to play a crucial role in recovering these materials[47]. In particular, REEs present in permanent magnet rotors are lost to the iron fraction and subsequent smelting during the classical steel recycling route. To prevent this loss, it is essential to separate the magnet-containing rotors to enable efficient and maximized recycling.

The research project “Recycling of components and strategic metals from electric drive motors—MORE” [1] explored various scenarios for disassembling permanent magnet motors from EVs down to the rotor and stator level. The most important step is to remove the magnets, which is very difficult with the existing rotor constructions. Mechanical methods involved the pressing of a stamp on the magnets to break the adhesive bond, as also investigated in [14] and shown in figure 2.7. This imposes critical stresses and possible damage to the magnets that rule out direct reuse. Also, this approach is very unconventional and difficult to scale up, especially with the high variety in geometries and adhesive types/strengths/dosings may lead to significant differences in the feasibility and results of the separation.

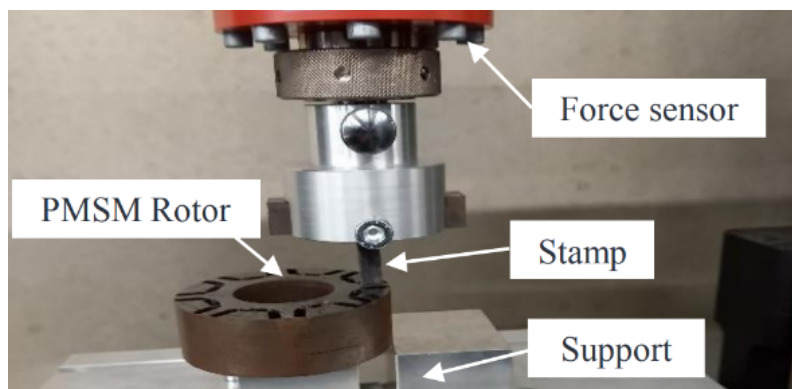


Figure 2.7: Experimental setup for the magnet disassembly.[14]

For effective recycling, it is crucial that magnets can be recovered in an efficient and non-destructive manner. This allows for the possibility of direct reuse in other applications if the magnets remain in good condition, which is feasible as stated in [66], [42] and [6]. If direct reuse is not feasible, alternative recycling methods, such as those outlined in 1.2.5 can still be considered as second path. These recycling processes require a high level of material purity to operate efficiently, which can be achieved through a design that facilitates easy magnet removal.

2 Design for recycling

2.2.1 Design for Dissassembly

Efficient rotor disassembly at EoL is clearly a critical consideration in the design of the next-generation EMs. The design must meet the performance requirements of the EV industry while also being feasible for large-scale production. A quote from Elon Musk states; "Manufacturing is underrated and design is overrated." This quote highlights that while engineering and designing a prototype in a lab is one aspect, the real challenge and value lies in efficient large-scale manufacturing. Therefore, it is important to remain closely aligned with the proven foundations of current motor designs. Many creative or complex concepts never progress beyond the laboratory due to manufacturing and limitations.

That is why re-engineering existing machine topologies into more favorable designs is considered essential for enabling the transition towards more recyclable products. A design that embraces the technologies used today, which have already proven their performance and reliability over the past years, combined with minor structural changes that could potentially even improve performance while enabling disassembly at EoL in combination with significantly reducing the use of non-recyclable materials. The main objective of the design will be the mechanical clamping of the magnets in the rotor. Due to this clamping, we ensure structural integrity and keep the magnets in place without the need for additional adhesives or resins. As a result, this mechanical clamping can also be reversed in a non-destructive manner. This approach enables the separation of magnets from used motors into two distinct streams. The first consists of magnets that are in good condition and can be directly reused in other applications. The second stream includes magnets that are (partially) degraded, suboptimal, or no longer meet performance requirements. These can be processed in their pure form and directed into established recycling paths, ensuring maximum material recovery.

Motors used in EV applications today are mostly V-type IPM PMSMs, as shown in Figure 2.1, often incorporating various additional features and geometries to enhance performance. As a reference for a base model of a V-type rotor, a Tesla Model 3 topology with six poles and a single V-shaped magnet arrangement is used, as it is a relatively simple construction without too many additional features, which can be added later, but would only complicate the initial design process.



Figure 2.8: Tesla Model 3 rotor configuration [15]

2.2.2 First approach

The first design inspiration was drawn from Tesla's patented carbon sleeve rotor configuration [52]. This motor is also discussed in [8] and at the end of chapter 1. The design integrates buried permanent magnets with a lower and upper iron stack secured using a carbon fiber sleeve to eliminate radial and tangential rotor iron ribs, reducing magnetic flux leakage. Flux barriers extend to the rotor's outer diameter, allowing the sleeve to secure the magnets and iron stacks under high centrifugal forces. The investigation [8] concluded that comparing this rotor concept with buried permanent magnets and a carbon fiber sleeve to a state-of-the-art conventional rotor topology, with a fixed permanent magnet mass of 1.3 kg for simulation, gives the following results:

- High mechanical strength and maximum speed due to the carbon fiber sleeve.
- Efficient magnet utilization with minimal flux leakage, despite a large total air gap.
- Strong field-weakening capability.
- Low rotor losses without requiring permanent magnet segmentation.
- Reduced cogging torque and torque ripple under load, eliminating the need for skewing.
- Higher risk of irreversible demagnetization due to the removal of magnetic stray paths.
- Increased manufacturing complexity for sleeve production, shrinking, and edge effect control.

The motor was designed to achieve high torque density and maximum speed within the confined space of vehicles. Its rotor core consists of upper parts and a lower stack, as shown in Figure 1.7. The use of a carbon sleeve to secure the upper stacks and magnets may improve disassembly compared to conventional designs. However, the continued use of adhesive for the magnets and epoxy-coated carbon sleeve in this rotor still poses challenges for recycling. Additionally, the carbon sleeve design features an increased amount of magnet material compared to the conventional Tesla Model 3 rotor, as shown in Figure 2.9.

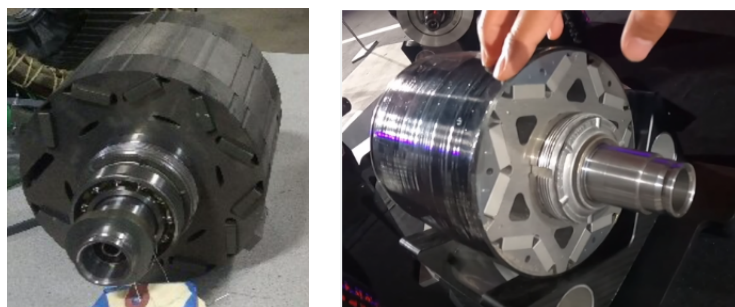


Figure 2.9: Rotor comparison Tesla [16] [17]

2 Design for recycling

Conceptual design

In this first design, the principles of the carbon sleeve rotor are combined with a purely mechanical and removable joint. This is achieved by securing the lower (2) and upper (3) parts of the core via a plate (1) using bolted connections. This approach allows the rotor to be dismantled at EoL with minimal structural modifications, providing direct access to the magnets. As a result, adhesive bonding the magnets is not justified. This design incorporates improvements from the carbon sleeve motor, such as the elimination of radial and tangential rotor iron ribs, without the need of increasing the air gap to fit the sleeve.

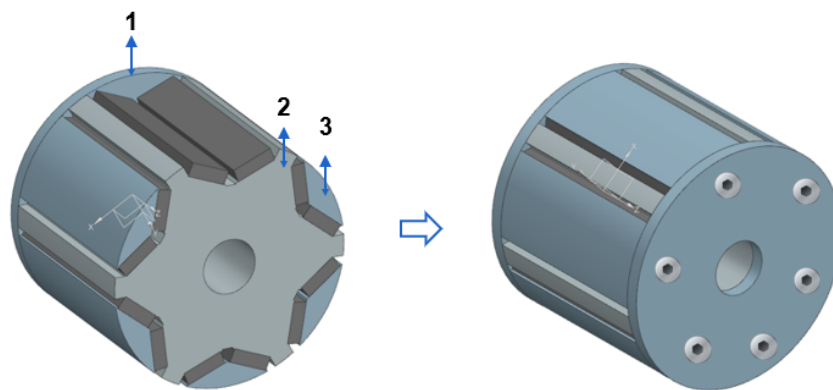


Figure 2.10: First design approach

For longer rotor configurations where increased deflection occurs, at very high rotational speeds or when a specific preload on the magnets is required, a radial bolt can be added to enhance structural integrity. The position of the magnets, mainly the minimum spacing between them, serve as limiting parameters for the maximum suitable bolt diameter as shown in figure 2.11. Further adjustments to the magnet placement may be necessary to accommodate the desired bolt size.

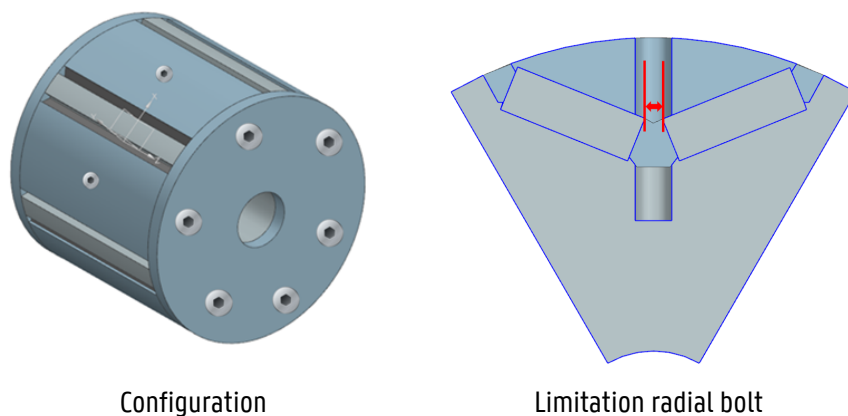


Figure 2.11: Additional radial bolt

2 Design for recycling

Validation of Automation

Compared to conventional laminated rotors, where the magnets are simply inserted into predefined slots and fixed with an adhesive, this approach introduces additional challenges from a manufacturing perspective. The assembly process becomes more complicated due to the increased number of individual components that must be carefully handled, aligned, and secured during assembly. Unlike adhesive-based designs, which provide immediate fixation and structural reinforcement, this method requires precise mechanical fastening to ensure that all parts remain in place throughout the process. This added complexity may lead to longer production times, the need for specialized fixtures, and stricter tolerances to maintain overall rotor integrity and performance. Traditionally, bolt tightening has been a manual task, requiring workers to apply precise torque using handheld tools. With the rise of robots and cobots (collaborative robots), this operation can now be largely automated. For the feasibility and scalability of this research, it is important to investigate whether existing systems or methods are already available to automate this process. This ensures that the choice for bolted connections, which is not yet used in such applications, can be justified as a well-founded design decision in the production of these machines.

An example of such system is the Power Driver machine from Visumatic [18], which is designed for fully automated bolt installation in rotor assemblies. This machine integrates an automatic screw feeding system, ensuring a continuous supply of fasteners and a servo-controlled rotary part indexer, which precisely positions components for accurate fastening. Equipped with torque-controlled drivers, it applies the correct force to each bolt, ensuring consistency and reliability. Advanced sensorized fixtures prevent misalignment and improve assembly quality. The system is optimized for heavy duty applications with similar bolt arrangements compared to our design, making it ideal for securely fastening bolts into structures such as rotors while minimizing manual intervention and increasing production efficiency.

The Power Driver machine workflow is illustrated in Figure 2.12. In (a), the rotor rotates to the angular position where a bolted connection is required. In (b), the rotor stops at the designated position, and a bolt is automatically fed into the tool. The tool then lowers (c) and tightens the bolt to the specified torque. Once the fastening is complete, the tool retracts to its original position (d). The cycle then repeats as the rotor advances to the next predetermined location to install the next bolt.

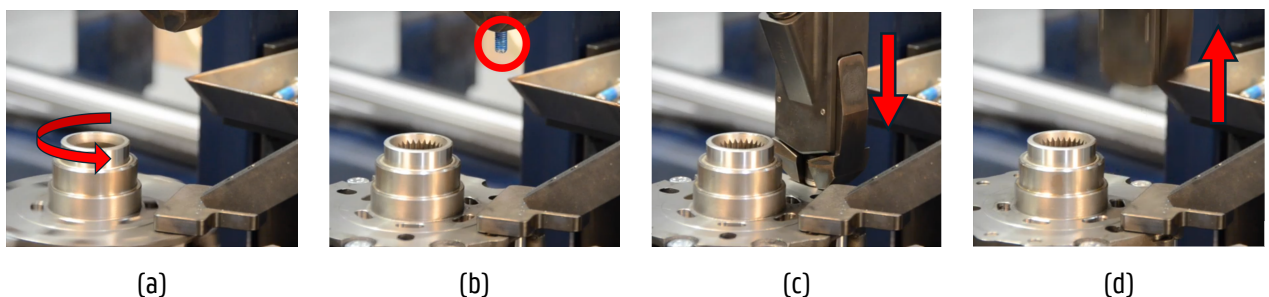


Figure 2.12: Automated Bolt Installation Workflow – Visumatic [18]

2 Design for recycling

2.2.3 Simulation

Since we have not yet made any changes to the magnetic configuration, we will conduct the electrical simulations later, once the actual prototype is developed. Instead, we will first focus on preliminary mechanical simulations to demonstrate the feasibility of this concept before proceeding with the electrical analysis. Mechanical simulations were performed using Siemens NX FEM software. Only a single pole was modeled to reduce computation time, as symmetry ensures identical stress and displacement across all poles. All stresses are von Mises (MPa) and deformations are in millimeters (mm).

To achieve a representative model, specific constraints and simulation objectives are defined. The blue constraints in (a) illustrate the boundary conditions necessary to simulate a single pole instead of the full rotor. At the base, where the rotor's axis would connect, a fixed constraint is applied, assuming a rigid bond. On the sides, a symmetrical constraint is placed to ensure that the isolated pole behaves as it would within the complete assembly. This constraint maintains the flank angles throughout the simulation by employing a cylindrical coordinate system, specifically in the Theta direction, which represents rotation around the Z-axis. Figure 2.14 shows this behavior, where the rotational speed increases with $n_1 \ll n_2$. For illustration, a cylindrical system is also shown in Figure 2.14. In (b) the simulation objects are shown in yellow. These represent the contact definitions between the surfaces

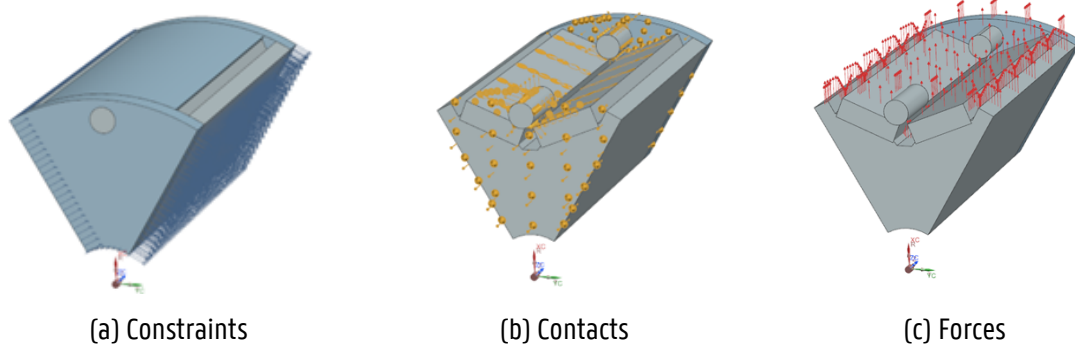


Figure 2.13: Simulation modeling

that interact during the simulation. These contacts include the cylinders engaging with the holes in the upper part of the core and the plates on the exterior. Additionally, contact occurs between the magnets and both the upper and lower part of the core, as well as between the plates and the front faces of the upper and lower part of the core. Finally, the forces acting on the structure must be assigned. Since only a single pole is simulated, it is not possible to apply a rotational speed directly. Instead, the centrifugal forces for each component are calculated based on their weight, radius, and the desired simulation speed using the following formula $F = m \cdot r \cdot \omega^2$. These forces are then applied to the upper flanks of each object. This forces are illustrated in (c), where the upper part of the core is not displayed for visualization purposes.

2 Design for recycling

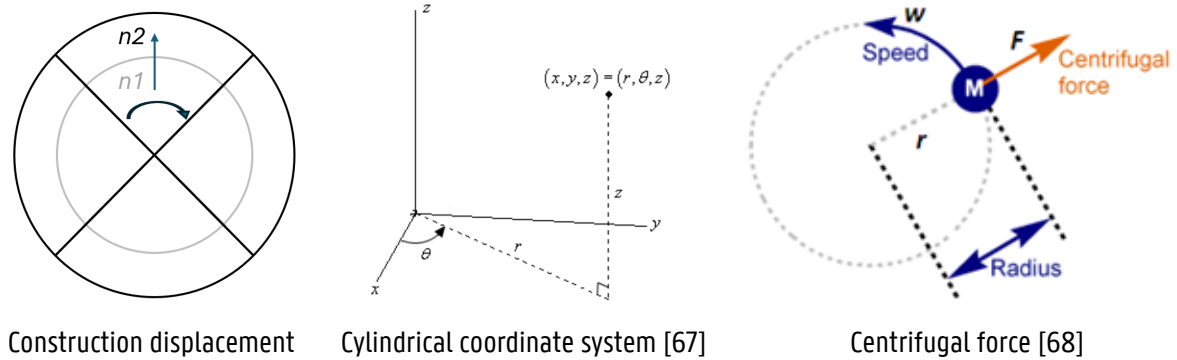


Figure 2.14: Visualisation Framework

A mesh is generated on the structure to discretize the geometry for FEM analysis. With the meshing complete, the structural simulation begins. General construction steel is initially assigned to validate design feasibility. Detailed material selection and final prototype simulations will follow in a later chapter.

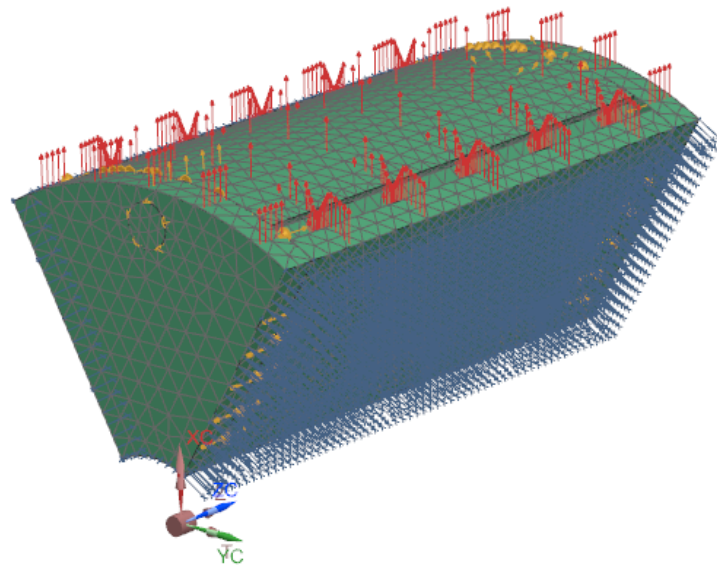


Figure 2.15: Final simulation model

For this first analysis, a rotor with a diameter of 90 mm and a length of 70 mm is simulated (the full rotor is shown in Fig. 2.10). The choice of these dimensions is made to align with the prototype that will be developed in a later stage. The rotational speed is set to 7500 RPM, which is relatively high for a motor of this size. This high speed is deliberately chosen to expose potential weak points in the structure and explore ways to reinforce them.

2 Design for recycling

First simulation

This first simulation is conducted with regular M6 bolted connections. These bolts are preloaded with a force of 9900N, which is the reference value derived from the VDI 2230-1 guideline for a grade 8.8 bolt.

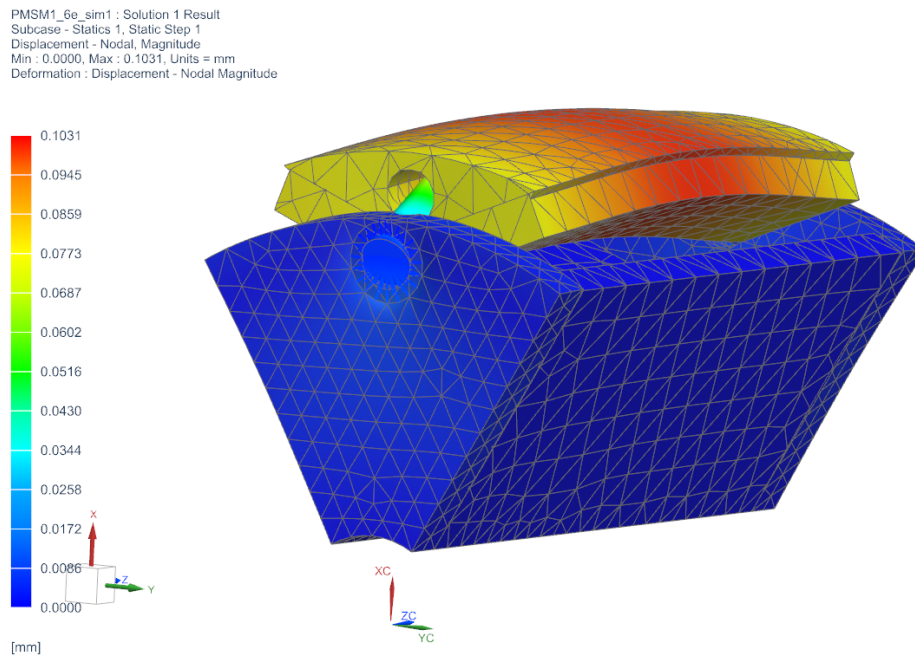


Figure 2.16: First simulation: displacement

This initial simulation clearly reveals a structural failure. As illustrated in Figure 2.16, the displacement indicates that the upper part of the core, along with the magnet, became loose and shifted in the radial direction (exaggerated visualization, see scale for dimensions in millimeters.). This poses a significant concern in terms of safety and structural integrity, as well as a potential risk of motor failure due to possible contact with the stator. The most substantial portion of the displacement occurs precisely at the location of the bolted connection, where the shift is most pronounced. Only a minor fraction of the total maximum displacement of 0.1031 mm can be attributed to the bending of the upper section. This highlights a critical weakness in the design that must be addressed to enhance the rotor's stability and reliability.

A bolted connection of this type can only transfer force through the pre-stress applied to the bolt, which creates a frictional interface between the plate and the upper part of the core. This means that the load is transmitted solely through friction, rather than direct shear through the bolt itself. If the pre-stress is insufficient or if external forces exceed the frictional resistance, slippage can occur, compromising both the stability and structural integrity of the assembly. Therefore, ensuring adequate bolt pre-load and surface conditions is crucial to maintaining a secure and reliable connection.

2 Design for recycling

To overcome this problem, the prestress is increased to 17,000 N, which corresponds to the VDI 2230-1 guideline for a grade 12.9 bolt.

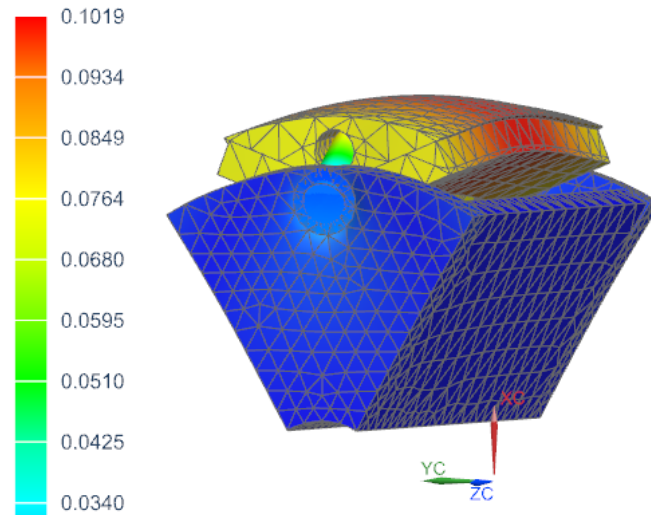


Figure 2.17: First simulation: increased prestress

This adjustment resulted in a minor reduction in maximum displacement; however, it still does not guarantee a rigid structure. This is because the preload acts in two opposite directions, effectively canceling out in terms of contact pressure. As a result, contact pressure is only caused by upper core elongation and slight plate inclination, but is insufficient as shown in this simulation. Even with a grade 12.9 bolt and significant prestress, the friction alone cannot securely hold all components in place during operation. Moreover, a standard bolt does not provide absolute and fixed geometric positioning due to the inherent clearance between the bolt and the hole. This lack of precise positioning can further lead to additional instability and misalignment, further compromising the structural integrity of the assembly.

Due to the complications mentioned above, a geometrically interlocking connection such as a dowel rod or fitted bolt is needed as shown in Figure 2.18. The choice will depend on the material properties and specific conditions, e.g. solid steel vs. electrical laminated steel and the possibility to apply threads in the upper parts of the core. If threading is not feasible, an alternative solution for fitted bolts could be utilizing a through-hole with a dowel rod secured by nuts at the plate.



Dowel rod

Fitted bolt

Figure 2.18: Fitted bolt and dowel rod for precise positioning and fastening

2 Design for recycling

Second simulation

In the second simulation, we aim to address the issues related to structural displacement and rigidity from the first simulation. To achieve this, the standard M6 bolts are replaced with fitted bolts. These fitted bolts ensure a precise and fixed geometric positioning by eliminating the clearance between the bolt and the hole, thereby preventing unwanted movement. Unlike regular bolts, which rely solely on friction for load transfer, fitted bolts create a form-fit connection that enhances stability and minimizes displacement under operational forces. This modification is expected to significantly improve the overall structural integrity and reliability of the assembly.

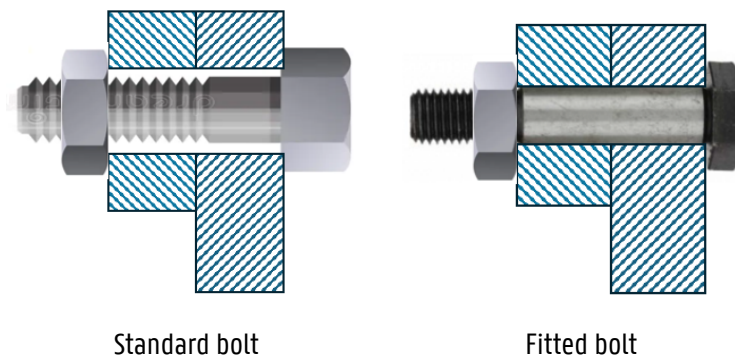


Figure 2.19: Bolted connection

These fitted bolts are capable of transmitting force through two mechanisms: both form-fit (positive locking) and force-fit (friction-based locking). This is schematically illustrated in Figure 2.19. For this second simulation, we neglect the pre-loading of the bolt and consider only the geometric form-fit connection for force transmission. By doing so, we simplify the simulation while adopting a more conservative approach, ensuring that the final results remain reliable and robust. This method allows us to focus solely on the geometric mechanical interlock provided by the fitted bolts, eliminating the influence of friction and giving a clearer understanding of how the geometric constraints contribute to structural stability.

The results from this simulation are shown in Figure 2.20 and Figure 2.21. The rotor model deforms as one rigid structure, with no movements occurring between individual components. The maximum displacement is 0.0374 mm, which is a very acceptable value considering that the air gap between the rotor and the stator is generally in the tens of a millimeter.

2 Design for recycling

PMSM1_6e_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.0000, Max : 0.0374, Units = mm
Deformation : Displacement - Nodal Magnitude

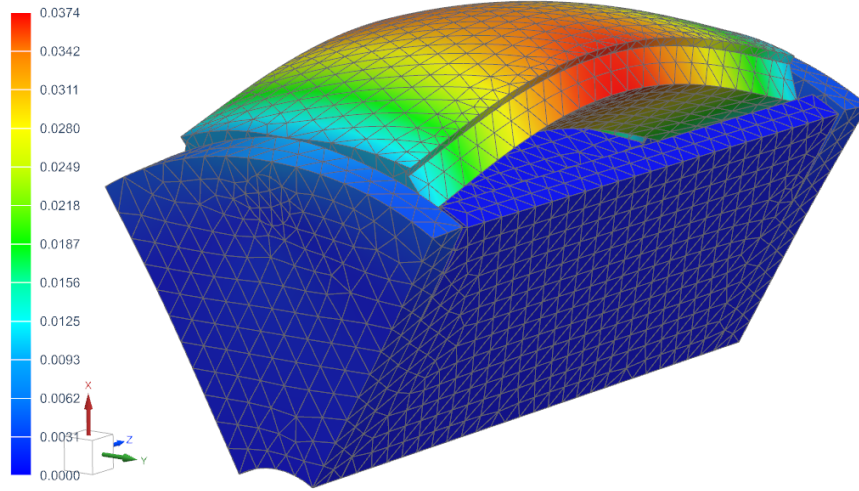
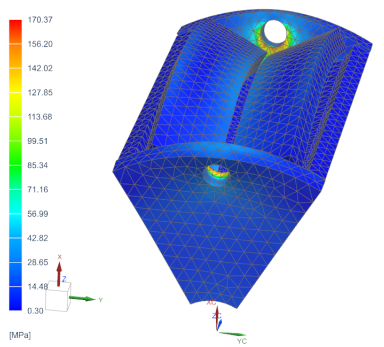


Figure 2.20: Second simulation: Displacement

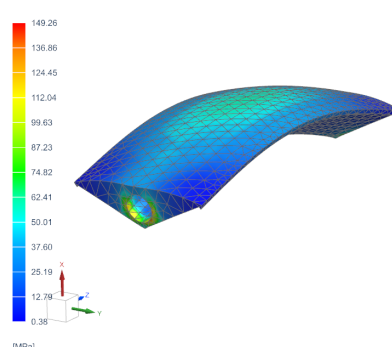
The highest stresses in the model occur, as expected, around the region of the bolted connection where the load is transferred mainly through shear. As shown in Figure 2.21, the stresses remain relatively low, even considering the high rotational speed of 7500 RPM. The maximum stresses in the plate, the upper core part, and the fitted bolts are respectively 170 MPa, 149 MPa, and 95 MPa. All these values fall within safe and workable limits, meaning that we do not anticipate any issues with material selection. As a result, standard materials can be used instead of requiring high-strength materials.

PMSM1_6e_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Stress - Elemental, Averaged, Von-Mises
Min : 0.30, Max : 170.37, Units = MPa
Deformation : Displacement - Nodal Magnitude



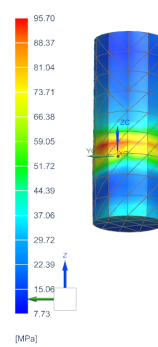
Lower core part, plates and magnets

PMSM1_6e_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Stress - Elemental, Averaged, Von-Mises
Min : 0.30, Max : 149.26, Units = MPa
Deformation : Displacement - Nodal Magnitude



Upper core part

PMSM1_6e_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Stress - Elemental, Averaged, Von-Mises
Min : 0.30, Max : 95.70, Units = MPa
Deformation : Displacement - Nodal Magnitude



Fitted bolt

Figure 2.21: Second simulation: stresses

These results are promising for further examination of this design in the scope of mechanical feasibility and structural integrity.

2 Design for recycling

Third simulation

Although the results from the second simulation were very promising, in certain cases, such as at very high rotational speeds or with rotors of considerable axial length, displacement and stresses may exceed safe limits. To address this, a third simulation is conducted to evaluate the effect of an additional radial bolted connection, as previously discussed in Section 2.2.2. For this simulation, an extra bolted connection is introduced, as shown in Figure 2.11. A conventional M4 bolt is used, with a prestress of 1500 N. This prestress is necessary to ensure a secure connection and also provides the advantage of applying a compressive stress on the magnets as shown in Figure 2.22 when stationary.

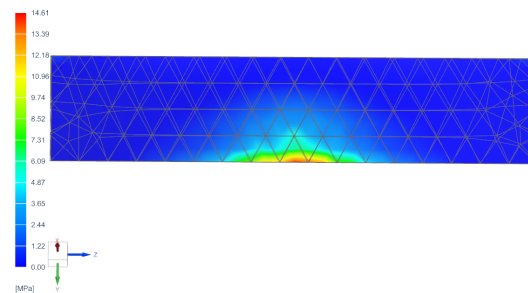


Figure 2.22: Third simulation: Magnet contact pressure

During operation, the additional bolt significantly reduced displacement, as shown in Figure 2.23. The maximum displacement is now approximately 0.006318 mm, representing a sixfold reduction compared to the second simulation, while maintaining the same rotational speed of 7500 RPM. Additionally, the displacement is more uniformly distributed. Notably, the area where the radial bolt is introduced was previously the location of the greatest displacement.

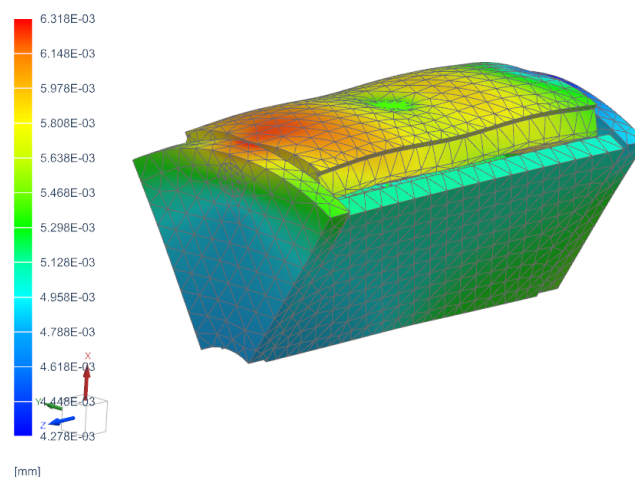


Figure 2.23: Third simulation: Displacement

2 Design for recycling

As a result of the additional radial bolt and the corresponding reduction in displacement, the stresses are also significantly reduced. This is illustrated in Figure 2.24, where the magnets are set to invisible to reveal the placement of the radial bolt. The maximum stress in the entire structure is now 155 MPa. The most significant stress reduction occurred around fitted bolts in the upper parts of the core and the plates, where the highest stress levels have been reduced by more than half in comparison with the second simulation.

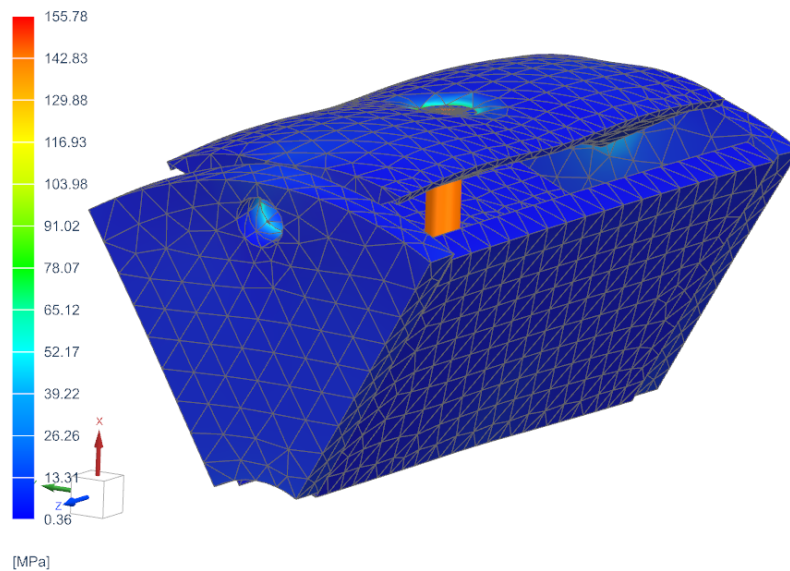


Figure 2.24: Third simulation: stresses

Concluding remark

The simulations provide valuable insights into the mechanical feasibility of the proposed rotor design. The first simulation revealed significant structural weaknesses, with excessive displacement and insufficient force transmission compromising rigidity. Increasing the bolt prestress slightly improved the results but did not ensure a secure connection. The second simulation showed major improvements by introducing fitted bolts, significantly reducing displacement to 0.0374 mm and ensuring the rotor deforms as one rigid structure. Additionally, stress levels remained within safe limits, allowing the use of standard materials instead of high-strength alternatives. Further reinforcement in the third simulation with an additional radial bolt led to a sixfold reduction in displacement and a more uniform stress distribution. This enhancement improved structural integrity and helped introduce a compressive stress on the magnets, further securing their positioning. Overall, the second and third simulations confirm the design's mechanical feasibility and structural robustness. The optimized configuration effectively addresses the weaknesses identified in the initial analysis, providing a solid foundation for further development, including electrical simulations and prototype testing. **It is important to note that these calculations are based on a simplified model and serve as an initial feasibility assessment. A more detailed and accurate simulation will be conducted during the prototype design phase to further refine and validate the results.**

2 Design for recycling

2.2.4 Position mechanism

The fitted bolt connection ensures precise positioning of the upper part of the core; however, it does not restrict rotational movement around its axis. As a result, these components still have degrees of freedom relative to one another. We also cannot rely on the face contacts with the magnets to ensure precise positioning, as they always have dimensional factory tolerances. To achieve a stable and rigid structure, all positions must be fully constrained through absolute geometric enclosure, meaning the plates and both the lower and upper parts of the core must be firmly attached and in direct contact with each other. This requirement is not yet fulfilled in the current design.

By introducing locating features on the plates, as shown in Fig. 2.25, a fixed and absolute positioning is achieved between the plate (grey) and both the lower (pink) and upper (red) parts of the core. This combination of geometric enclosure and mechanical fastening removes all translational and rotational degrees of freedom, ensuring the components act as a single rigid body under load. Additionally, the locating features simplify assembly by providing intuitive, self-aligning contact surfaces, reducing misalignment and improving consistency and repeatability across all assemblies, beneficial for both production and operation. To ensure the effectiveness of this constraint, tight tolerances on the mating surfaces and locating features are essential, as any deviation may affect rigidity and precision.

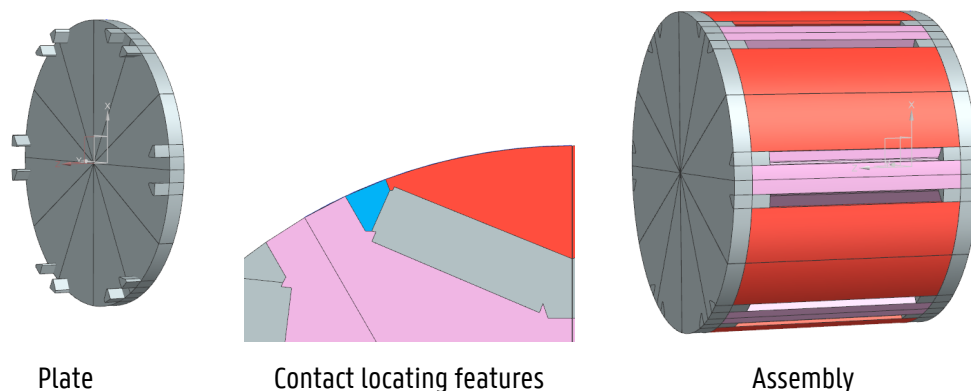


Figure 2.25: Position mechanism

In Figure 2.25, the middle image highlights the positioning feature (blue), showing face-to-face contact between the flat surfaces of the plate and the upper core parts. Together with the fitted bolt, this ensures exact positioning of the assembly. These locating features are intended only for positioning and not for transmitting mechanical loads.

2.2.5 Skewing

While skewing is not always applied in automotive electric motors[69], due to factors such as manufacturing complexity or design compromises, it remains a widely adopted technique in general motor design. Skewing reduces cogging torque, torque ripple, and magnetic locking, resulting in smoother rotation with less vibration and noise. These advantages are particularly important in applications requiring smooth and quiet operation. In the current design, continuous rotor skewing can be implemented without structural adaptations. Its integration highlights the potential for future motor development. The shown design in Figure 2.26 uses conventional block magnets, resulting in a line contact at the plate ends (d) rather than full face contact, whereas inclined-end magnets would enable full face contact in skewed slots but increase manufacturing costs [70].

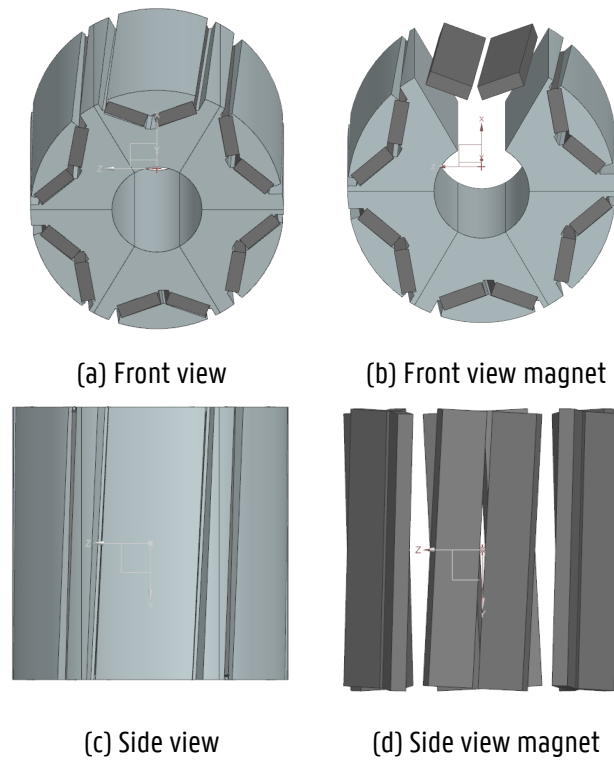


Figure 2.26: Skewing desing

The drawback of this design is that it is more difficult to produce, as all orthogonal planes in the axial length have been eliminated; only skewed or inclined planes remain, complicating the manufacturing processes. While continuous skewing provides exceptionally high torque quality, it is expensive and challenging to model [70]. In contrast, the conventional step-skew approach is much simpler to model during the design phase and is therefore more commonly used in PMSMs, but it requires a different design approach as described in Section 2.3.1. This section was intended only to demonstrate the feasibility of such an approach.

2.3 Rotor: Additional Design Proposal

2.3.1 Radial bolted connection

In the previous chapter, the design used bolts in axial direction that connect the upper parts of the core to the plate, transferring loads in shear through fitted connections. An additional radial bolted connection was proposed to reduce stress and deformation or to apply a specific level of prestress if needed. In this additional design, the radial oriented bolted connections are solely responsible for transmitting the forces through tensile stresses and for maintaining structural integrity. We continue using the same 6-pole V-shaped topology as in the previous simulations. A key advantage of this design is the ability to apply discrete skewing to the topology, similar to the Tesla design shown in Figure 2.9, which was not feasible in the previous configuration. This opens new possibilities for optimizing magnetic performance and reducing torque ripple. Furthermore, the design allows a more evenly distributed application of prestress on each individual magnet, improving mechanical stability and reducing local stress concentrations during operation.

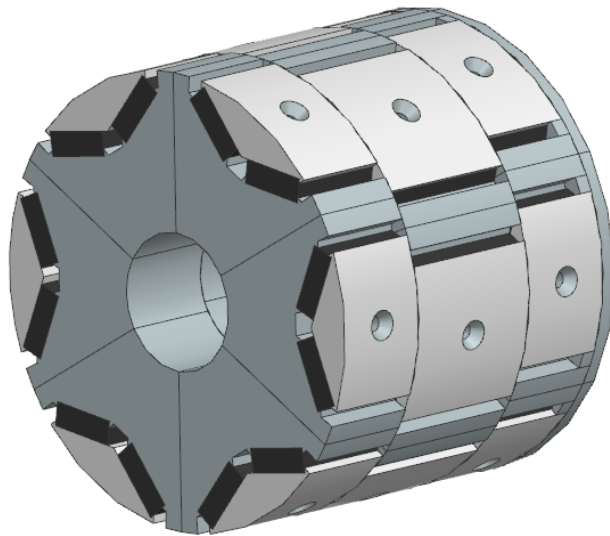


Figure 2.27: New approach: Radial bolts

This design, shown in Figure 2.27, incorporates the radial bolted connections shown in Section 2.2.2. In this example, a discrete skewing has been applied; however, it is not essential to the core design principle. The positional locking of the individual outer core pieces is achieved at the rotor ends using the same plates with locating features (only one is shown), as described in Section 2.2.4. The wider (central) outer core pieces are held in place by the flat clamping action between the outer stacks on both sides. Countersunk bolts ensure that all upper core parts are fully constrained, leaving no remaining degrees of freedom.

2 Design for recycling

Simulation radial bolt design

In this simulation, countersunk bolts are used. The analysis is performed on a single pole, following the same methodology as described in Section 2.2.3. The rotor dimensions remain identical to the previous design (90mm × 70mm) and the simulated rotational speed is again 7500rpm.

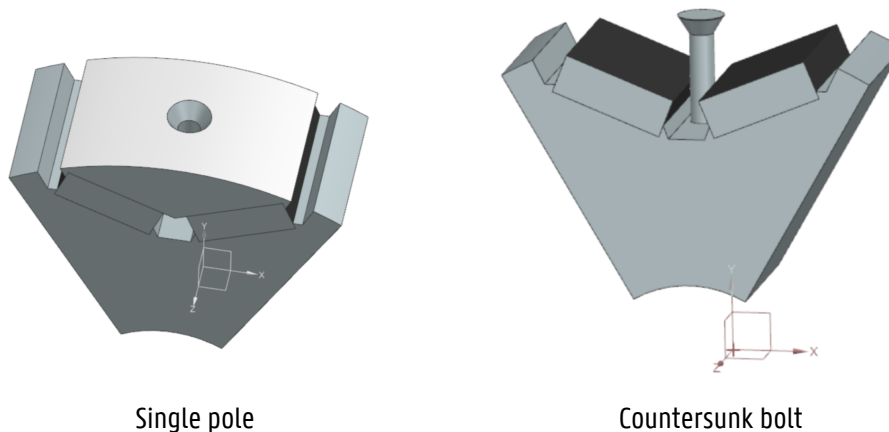


Figure 2.28: Radial bolts: single pole

The simulation focuses on the middle stack, as its greater length compared to the two outer stacks makes it the most critical in terms of mechanical behavior. Therefore, if this central stack remains within acceptable limits for displacement and stress, the shorter outer stacks will also stay within safe margins.

The simulation uses M3 countersunk bolts, each with a preload of 3000 N. This preload applies prestress to the magnets and prevents their detachment at high rotational speeds. Figure 2.29 shows the resulting displacements within the structure. The maximum displacement is 0.0018 mm, which is well within acceptable limits.

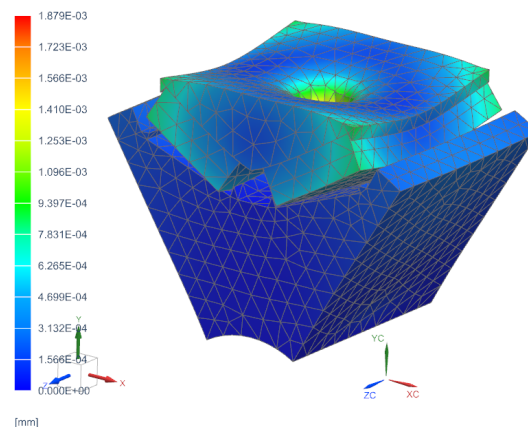


Figure 2.29: Radial bolts: displacement

2 Design for recycling

As expected, the highest stress concentrations appear in the tension-loaded bolts, reaching up to 615MPa. While relatively high, this remains within the allowable limits for grade 8.8 bolts and is therefore acceptable for this application. In the upper core part, the highest stresses occur beneath the contact surface of the bolt heads, reaching 153MPa. This is well within the strength limits of standard structural steel and does not pose a concern for mechanical integrity.

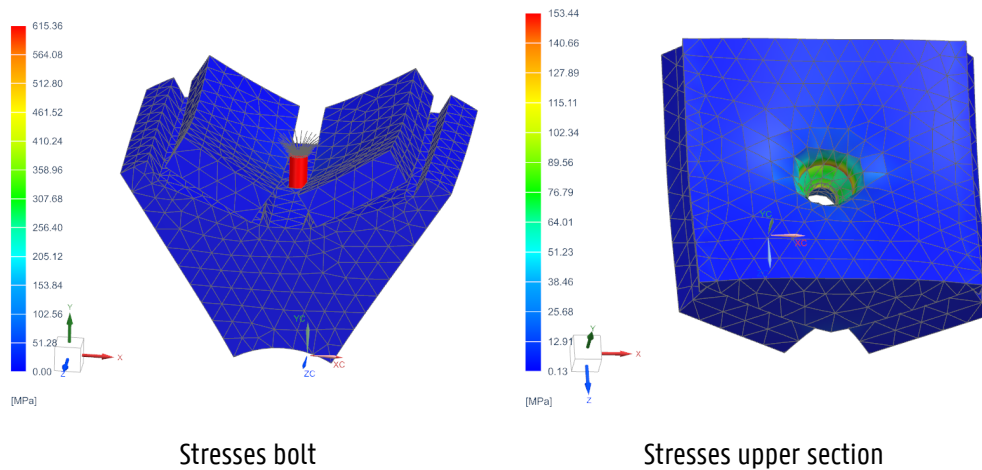


Figure 2.30: Radial bolts: stresses

Based on these results, the mechanical feasibility of this concept has also been successfully demonstrated. The stresses and displacements remain within acceptable limits, confirming that the design is structurally sound under the given operating conditions. This not only validates the proposed design but also highlights its potential as a viable design strategy for future PMSM developments.

3

Prototype design and simulation

In the previous chapter, several design methodologies were explored with the goal of facilitating magnet removal at the end of the product's life cycle, while deliberately avoiding the use of adhesives or glues for component fixation. These choices were driven by the desire to improve recyclability and enable easier disassembly in line with circular economy principles. FEM simulations conducted on these concepts showed promising results, demonstrating that bolted connections can provide sufficient mechanical fixation while also allowing for disassembly. These findings highlight the potential of such fastening strategies as a viable alternative to conventional potted/glued structures, laying the groundwork for more sustainable and modular PMSM designs.

For the prototype, we will adhere to the V-type PMSM rotor configuration, as discussed in Section 2, due to its advantages in performance and structural design. The prototype will feature an 8-pole V-shaped rotor within a 90mm × 70mm stator layout. This configuration aligns with ongoing research within our group, which focuses on motors of similar dimensions. Since the main focus of this work is the rotor design, access to a stator housing test stand is essential to validate the prototype under real operating conditions.

As the necessary components and equipment for such a test stand are already available at the university, the prototype will be designed to match the mechanical and dimensional requirements of this existing setup.

3 Prototype design and simulation

3.1 Electrical design

The design process of this prototype begins with the development of an electromagnetic model, which serves as the foundation for evaluating the machine's performance. For this phase, we will use Altair FluxMotor, a dedicated simulation tool for designing and analyzing electric rotating machines. The software enables rapid prototyping and early-stage performance assessments based on key design parameters such as geometry, materials, winding configuration, and cooling methods. With FluxMotor, we can perform preliminary simulations such as efficiency mapping, torque-speed characteristics, and thermal behavior before committing to a physical build. These early simulations are crucial for validating the electromagnetic concept, identifying potential design flaws, and supporting informed decisions about further mechanical integration. The aim of this phase is to ensure that the electromagnetic model & performance of the rotor matches the intended specifications and can be integrated effectively into the mechanical structure of the prototype.

3.1.1 Magnets

The first set of design decisions must be made based on the available magnet geometry. Since we rely on off-the-shelf magnets, our initial step involves identifying which types and dimensions can be sourced within a reasonable timeframe. Unlike typical industrial design processes, where magnets can be custom-made in large quantities to meet specific performance requirements tailored to the chosen topology and construction, we do not have that flexibility in this research context. Due to limitations in time and resources, we must work with readily available components, which introduces constraints that influence the overall design approach from the outset. In consultation with my supervisor, we have decided to use ferrite magnets instead of the conventional NdFeB magnets typically used in the vast majority of PMSMs, despite NdFeB's superior magnetic strength. This decision is based on several practical considerations relevant to this prototyping phase.

- **Cost-effectiveness:** Ferrite magnets are less expensive than neodymium magnets, making them a more suitable choice for experimental setups with limited budgets.
- **Ease and safety during assembly:** Due to their lower magnetic strength, ferrite magnets are easier and safer to handle manually, reducing the risk of injury or damage during (manual) assembly.
- **Thermal demagnetisation:** Ferrite magnets are less sensitive to demagnetisation at elevated temperatures compared to standard NdFeB types, offering more thermal design margin.
- **No need for protective coating:** Unlike NdFeB magnets, which are prone to corrosion and typically require a protective coating (e.g., nickel), ferrite magnets are chemically stable and do not require any surface treatment, simplifying handling and integration. This also enables small geometric adjustments, such as shortening the length to fit the desired 70mm rotor, with each magnet segment measuring 18mm.

3 Prototype design and simulation

Thus, since the primary objective of this prototype is to investigate the mechanical feasibility of the design rather than to optimize electromagnetic performance, the use of ferrite magnets presents an adequate and practical solution for this specific purpose. The final choice was made to use ferrite magnets size 18x10x6 grade Y35 that are magnetized over the length.

Property	Value
Magnetization direction	Magnetized along the length
Magnet grade	Y35
Coating	None
Holding force	approx. 630 g (approx. 6.18 N)
Shear force	approx. 130 g (approx. 1.24 N)
Max. operating temperature	250°C
Weight	5.2 g

Table 3.1: Technical specifications of ferrite magnet FE-Q-18-10-06

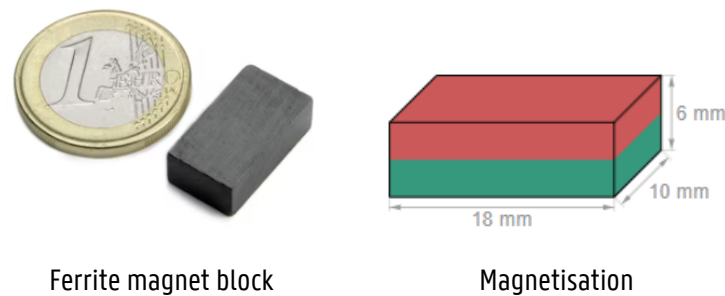


Figure 3.1: Ferrite magnets

Now that the selection of magnets for our design has been finalized, we can proceed with developing the rotor geometry in FluxMotor. This marks the start of the electromagnetic modeling phase, where the physical dimensions and placement of the magnets are translated into a detailed virtual representation of the rotor.

In this design, the magnets will be arranged in a segmented configuration, placed sequentially behind each other, rather than as a single continuous block. This segmentation offers several mechanical advantages: It reduces internal stresses from thermal expansion or centrifugal forces at high speeds and simplifies manual assembly, as handling one solid magnet is harder due to its stronger magnetic force. Additionally, segmented magnets make future maintenance or repairs easier, as individual segments can be replaced without replacing the complete magnet stack. This approach supports our broader goal of improving serviceability and promoting a more modular, circular design philosophy.

3 Prototype design and simulation

3.1.2 Stator

For the stator part, we will recreate the physical stator from the lab into fluxmotor to be able to perform representative simulations.

Parameter	Value
HS (mm)	14.2
WS2 (mm)	6.4
H1 (mm)	0.6
WS1 (mm)	4.2
H0 (mm)	0.7
W0 (mm)	2.2

Table 3.2: Slot parameters

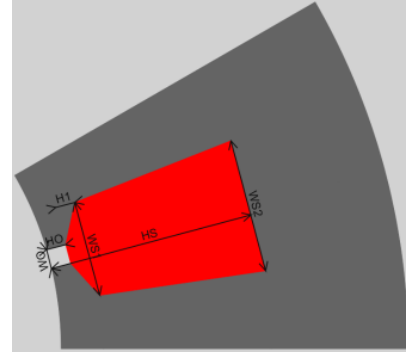


Figure 3.2: Slot definition

Parameter	Value
Stator outer diameter (mm)	134.8
Stator inner diameter (mm)	90
Stator length (mm)	70
Lamination material	M400-50A
Lamination thickness (mm)	0.5
Number of stator slots	36
Number of turns per coil	66
Wire diameter (mm)	0.56
Wire material	copper

Table 3.3: Stator parameters



Figure 3.3: Stator geometry

The stator housing does not incorporate any advanced or specialized cooling features. Instead, conventional cooling fins are included in the simulation, allowing the motor to dissipate heat primarily through natural convection. This standard approach provides sufficient thermal management for this prototype, as the stator is an off-the-shelf component that is already properly dimensioned.

3 Prototype design and simulation

3.1.3 Rotor

The 8-pole V-shaped rotor design incorporates ferrite magnet blocks measuring 10mm × 6mm. A key design consideration in this configuration is the height of the upper sections of the core. These sections must provide adequate space to accommodate a bolt while also being sufficiently tall to resist bending moments. It is important to note that parameters T2 and W2 are set to zero, as the corresponding ribs are obsolete in this design and would introduce a magnetic short circuit. Instead, the upper section is mechanically secured using bolted connections.

Parameter	Value
TM (mm)	6.0
WM (mm)	10.0
C1 (deg)	140.0
C2 (deg)	20.0
T2 (mm)	0
W2 (mm)	0
VM (deg)	120.0

Table 3.4: Magnet topology parameters

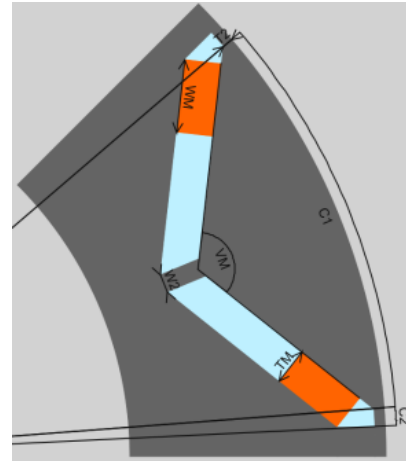


Figure 3.4: Magnet topology definition

Parameter	Value
Outer diameter (mm)	89
Inner diameter (mm)	27
Length (mm)	70
Number of poles	8
Material	Iron (solid)
Magnets	Y35

Table 3.5: Rotor parameters

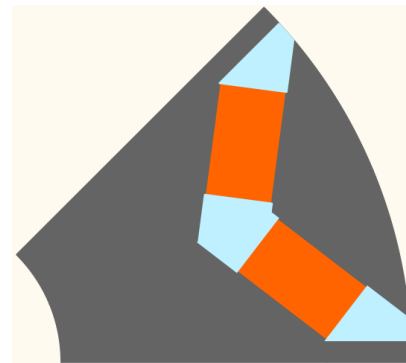


Figure 3.5: Rotor geometry

Note that the rotor material used in the simulation is iron. Ideally, conventional laminated electrical steel would be used, but due to time constraints and limited prototyping resources, this was not feasible for the current stage. Eddy-current losses in synchronous machines are generally low, as they are not exposed to a time-varying magnetic field (only spatial harmonics contribute to these losses). Additionally, ferrite magnets are used, which offer good thermal resistance. Given these factors, the choice for a solid rotor construction was made for this prototype. In a future development phase, solutions are explored to reduce these losses.

3 Prototype design and simulation

3.1.4 Final model

Figure 3.6 represents the final model of the motor. In the next part, simulations will be conducted on this

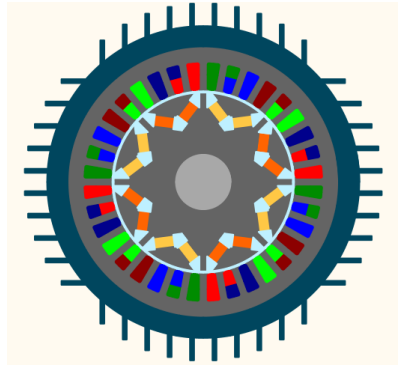


Figure 3.6: FluxMotor model

model. The goal of this thesis is not to optimize the motor design for performance or efficiency, but to introduce design methods that facilitate recycling and magnet removal. Some practical choices have already been made that compromise the model's potential performance.

- **Use of ferrite magnets instead of neodymium magnets:** Off-the-shelf ferrite magnets were selected due to their lower cost and good (thermal) stability. However, their magnetic performance is significantly lower than that of neodymium magnets, which limits the achievable flux density in the machine.
- **Suboptimal combination of ferrite magnets with a V-shaped topology:** The chosen V-shaped rotor geometry is not ideal for ferrite magnets. Most rotor topologies using ferrite magnets focus on flux-concentration techniques, such as spoke-type designs or V-topologies with small VM angle, which are better suited for lower strength magnets.
- **Use of solid iron instead of laminated electrical steel:** To simplify the prototyping process and reduce manufacturing complexity, the rotor is modelled from solid steel. However, this increases eddy-current losses, as there is no lamination to interrupt circulating currents. Although losses are typically low in synchronous machines, space harmonics can still cause them, particularly in a solid rotor core.
- **Relatively large air gap (0.5 mm):** The air gap is larger than typically desirable, which negatively affects torque density and magnetic coupling. This value was chosen intentionally to allow for manufacturing tolerances, as the rotor will be produced by a foreign supplier with whom we have no prior collaboration. The increased gap ensures a safe margin during assembly.

Several of these choices were driven by the practical constraints of the prototyping phase, such as cost, material availability, and limited production time, and are therefore not inherent to the design itself but only to this specific prototype.

3 Prototype design and simulation

3.2 Electrical simulation

Although a full performance optimization of the motor design is not being pursued at this stage, detailed electromagnetic simulations are being conducted to ensure that the developed model behaves as expected and contains no fundamental design flaws. The aim is not to build a high-performance machine at all costs, but rather to develop a motor that prioritizes recyclability and sustainability, while still meeting functional performance requirements within the scope of this project.

Using simulation results as a guide, we will rely on engineering intuition and insight to evaluate how the motor responds to certain design variations. This approach provides a deeper understanding of the motor's electromagnetic behavior and its sensitivity to changes, even without a detailed optimization study. In doing so, we aim to balance practicality and performance, ensuring the resulting prototype remains functional and reliable. After the initial design phase in FluxMotor, the motor is exported into Altair Flux 2D, where a more detailed and accurate representation can be created. Both software tools are used throughout the simulation process: FluxMotor for rapid prototyping and performance evaluation, and Altair Flux 2D for more refined analysis and to verify the accuracy of results obtained in FluxMotor. The results have been thoroughly cross-validated using both tools to ensure accuracy. All simulations presented in the following chapter were performed in FluxMotor with a current density of 5 A/mm^2 and a rotational speed of 750 rpm, unless otherwise specified.

3.2.1 Open circuit

The open-circuit test is used to evaluate the behavior of the electrical machine when it is not connected to a load. During this test, the rotor is rotated at a constant speed of 750 rpm while the stator windings remain unpowered. This allows for the analysis of key magnetic and electrical characteristics without the influence of a current.

From the open-circuit test, several important characteristics can be obtained:

- **Back emf phase voltage:** The voltage induced in each stator phase as a result of the rotating magnetic field. Consistency with design expectations and a clean waveform are signs of a well-performing machine. The simulation was first performed in FluxMotor (Figure 3.7) and then exported and validated in Altair Flux 2D (figure 3.8). To avoid redundancy, the results will not be shown twice each time. In this case, both are presented to demonstrate the validation process.

3 Prototype design and simulation

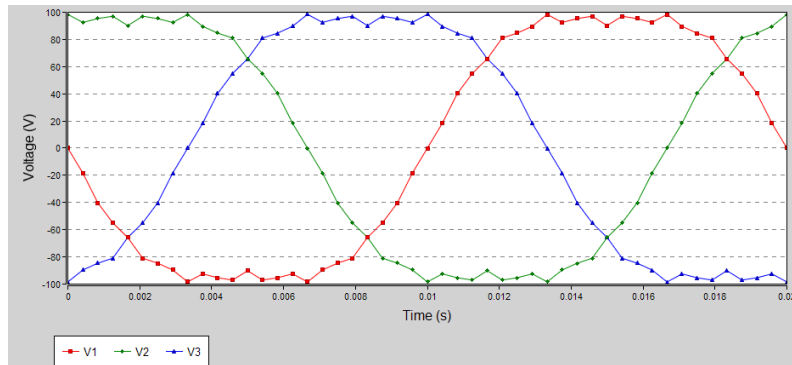


Figure 3.7: Phase voltage versus time - Open circuit

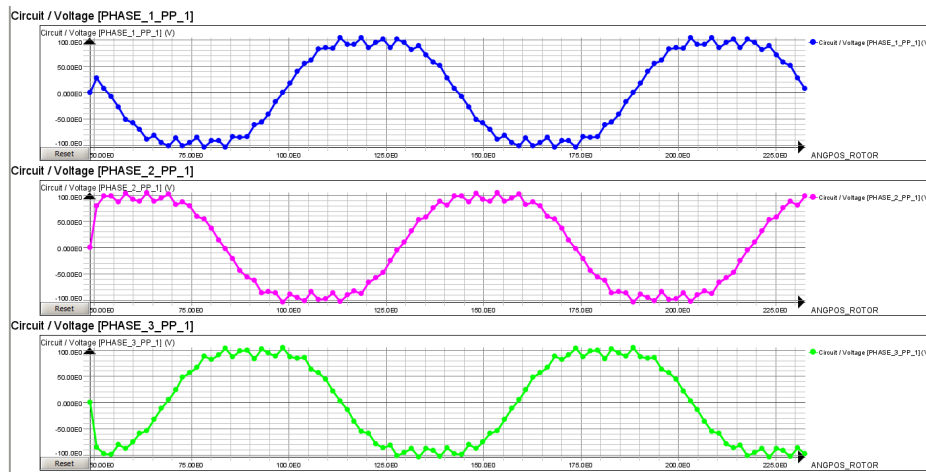


Figure 3.8: Phase voltage versus angular position - Open circuit (Altair flux 2D)

- **Cogging torque:** The torque variation caused by the interaction between the rotor magnets and the stator slots in the absence of current. A low cogging torque contributes to smoother operation, better control, and higher overall performance in electric machines.

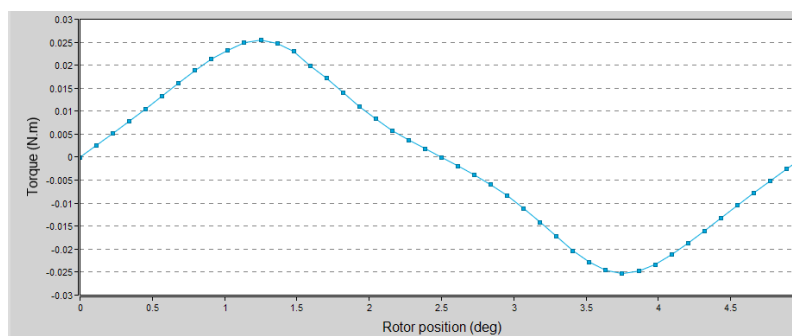


Figure 3.9: Cogging torque versus angular position - Open circuit

3 Prototype design and simulation

- **Air gap flux density:** The distribution and magnitude of magnetic flux across the air gap, provides insights into the magnetic performance and design efficiency. In the open-circuit test, a consistent pattern and uniform distribution of the air gap flux density are key for smooth torque production and low cogging torque. The absolute flux density is relatively low due to the use of ferrite magnets in V-shape and a larger air gap, as explained in Section 3.1.4.

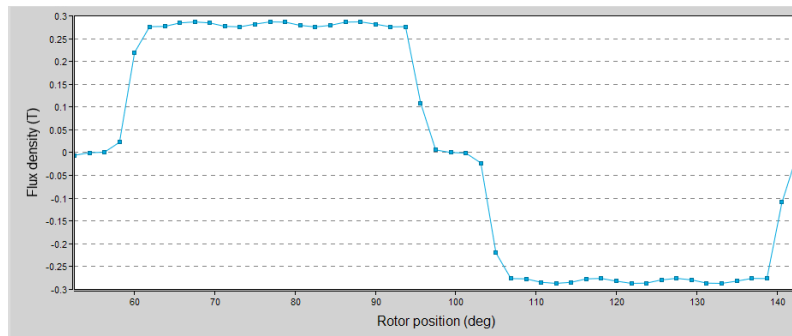


Figure 3.10: Flux density in the airgap versus angular position - Open circuit

3 Prototype design and simulation

3.2.2 Performance mapping

The motor performance test provides important insights, such as the torque-speed characteristic of the machine (Figure 3.11) and the optimal control angle (Figure 3.12) that maximizes torque output. These results can later be used to evaluate the motor's behavior at a specific operating point.

The parameters used for this simulation are a maximum current density of 5.0 A/mm² and a maximum line-to-line voltage of 400V (rms). Additionally, the winding temperature was set to 80°C and the magnet temperature to 77°C (see thermal simulation 3.2.3).

- **Torque-speed characteristic:** According to the torque-speed characteristic, the base speed point is 1073 RPM. However, for the purpose of this study, we will focus on the motor's performance at 750 rpm, as this lies within the scope of our research objectives. The mechanical torque output is 5.25 Nm and the control angle is 35.81 degrees.

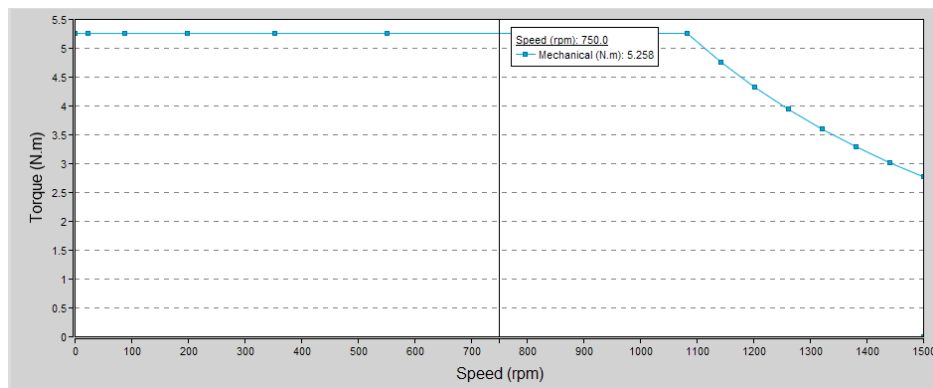


Figure 3.11: Mechanical torque versus speed - Performance mapping

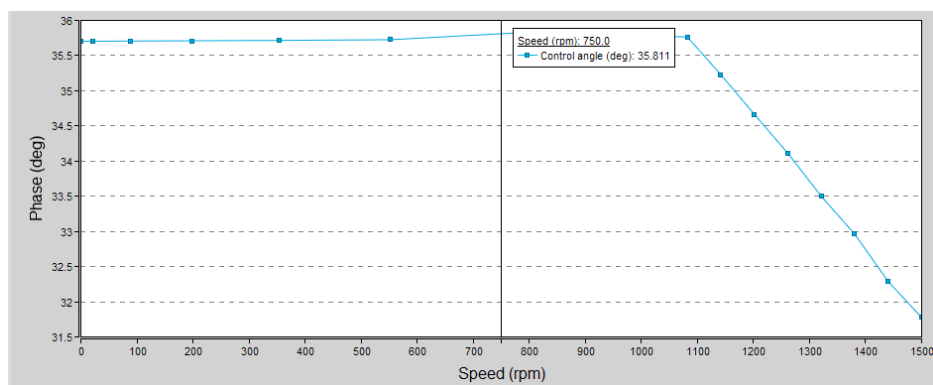


Figure 3.12: Control angle versus speed - Performance mapping

3 Prototype design and simulation

- **Losses:** The graph 3.13 shows the machine losses as a function of rotational speed. At the intended operating point of 750 rpm, total losses are approximately 97.56 W. The dominant contribution comes from Joule losses at about 92.13 W, indicating that copper losses in the windings are the primary source of losses. Stator iron losses account for only 5.43 W, and mechanical losses are neglected in this simulation.

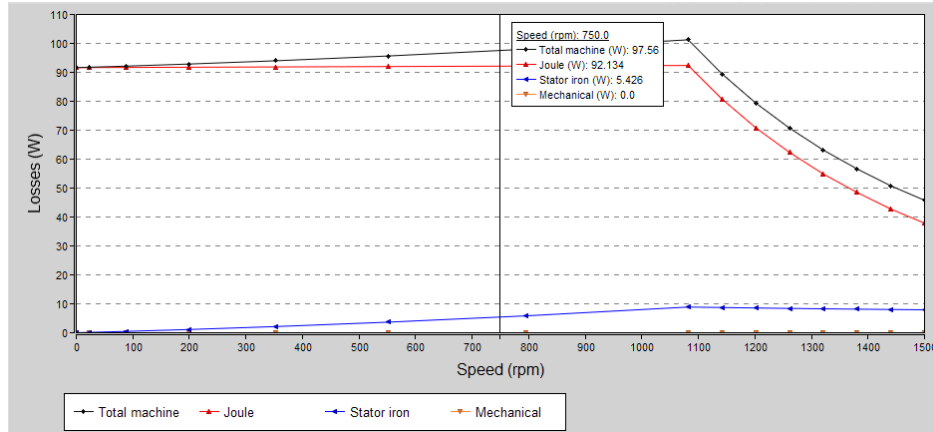


Figure 3.13: Losses versus speed - Performance mapping

The Joule losses (copper losses) in the windings can be calculated based on the current and resistance per phase, providing an additional check for validation.

- Phase current: $I = 1.232 \text{ A}$ (0.56 mm & 5 A/mm²)
Phase resistance: $R = 20.113 \Omega$ (at 80 °C)

Per-phase copper loss:

$$P_{\text{phase}} = I^2 \cdot R = (1.232)^2 \cdot 20.113 = 1.518 \cdot 20.113 \approx 30.52 \text{ W}$$

Total copper losses (3 phases):

$$P_{\text{total}} = 3 \cdot P_{\text{phase}} = 3 \cdot 30.52 \approx 91.56 \text{ W}$$

The calculated values closely match the results from the simulation.

3 Prototype design and simulation

- **Efficiency:** The efficiency map illustrates the machine's efficiency across a range of speeds and mechanical torques. At the chosen operating point of 750 rpm and 5.25 Nm, the machine achieves an efficiency of 80.8%.

In general, the machine demonstrates higher efficiency in the high speed and moderate torque regions, where it reaches values above 90%. At lower speeds, the efficiency drops significantly due to the relatively higher impact of quasi constant losses.

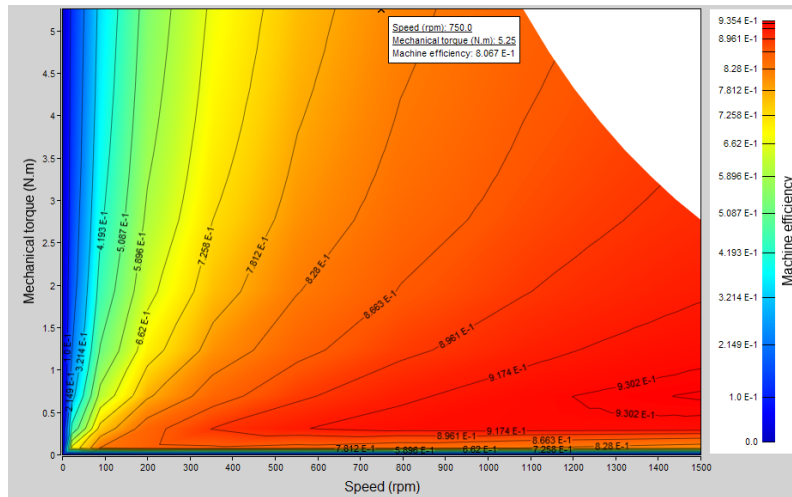


Figure 3.14: Efficiency versus speed - Performance mapping

3 Prototype design and simulation

3.2.3 Thermal simulation

Thermal simulation provides detailed insights into the temperature distribution across the motor components, including the stator, rotor, shaft, and frame. It evaluates heat transfer mechanisms such as conduction, convection, and radiation based on parameters like thermal resistances and convection coefficients. This allows for the prediction of component temperatures under steady-state operating conditions, helping to assess cooling performance and thermal limits.

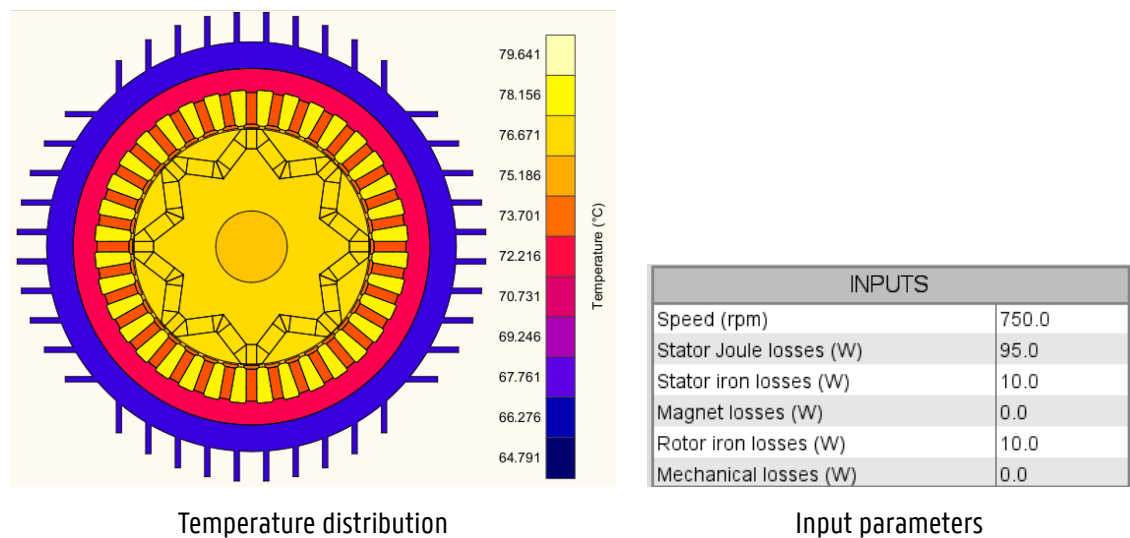


Figure 3.15: Thermal simulation

The loss values used in this thermal simulation are based on those obtained from the performance mapping shown in Figure 3.13. Mechanical losses have again been neglected, and magnet losses are set to zero, as the machine uses ferrite magnets instead of NdFeB magnets, which are typically more prone to eddy current losses due to their high electrical conductivity.

Stator iron losses have been deliberately overestimated compared to the calculated values to introduce a safety margin. This conservative approach ensures that thermal predictions remain within safe limits. For the rotor iron losses, the same value has been assigned as for the stator. In reality, these losses are expected to be significantly lower, as they mainly result from space harmonics, which are difficult to model accurately. Additionally, the rotor is not laminated and the rotor grooves discussed in Section 3.3.3 are not included. This absence of structural features further justifies the use of a generous loss margin to avoid underestimating the rotor's thermal load.

As a result, the windings reach a temperature of approximately 80°C, while the magnets stabilize around 77°C. The thermal expansion coefficients of steel and ferrite are closely matched, minimizing thermal expansion stresses.

3 Prototype design and simulation

3.2.4 Working point simulation: sine wave

The working point simulation is used to evaluate the steady-state electromagnetic performance of an electric machine under ideal sinusoidal current excitation. This setup assumes perfect inverter behavior (free from harmonics and PWM effects) allowing for a clear assessment of the machine's performance at a specified operating condition, namely: a speed of 750 rpm, a current density of 5.0 A/mm² and a control angle of 35.811°. The temperature settings during this simulation are consistent with those obtained from the thermal analysis.

From the open-circuit test, several important characteristics can be obtained:

- **Flux density in airgap:** The graph illustrates the flux density in the air gap as a function of the mechanical angle over one quarter of the rotational cycle (0°–90°). The waveform exhibits periodic variations caused by the interaction between the rotor magnets and the stator teeth. Distinct steps and peaks in the profile suggest the influence of slotting effects and magnetic saturation. These characteristics are important for understanding the magnetic loading of the machine and evaluating torque ripple and potential local saturation effects.

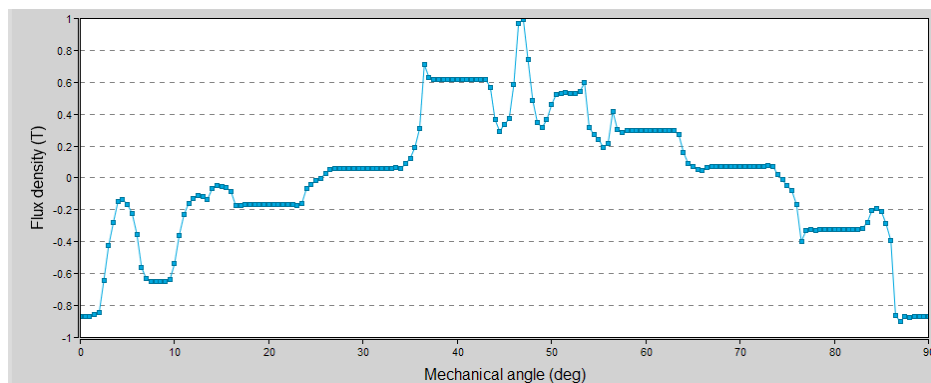


Figure 3.16: Flux density airgap versus mechanical angle - Working point

- **Torque ripple:** The graph shows the mechanical torque ripple as a function of rotor angular position, highlighting the periodic fluctuation of torque around its average value during operation. The average torque is 5.268 Nm, with a peak-to-peak ripple of 0.8596 Nm, which corresponds to a $\pm 16.3\%$ variation compared to the mean torque level.

3 Prototype design and simulation

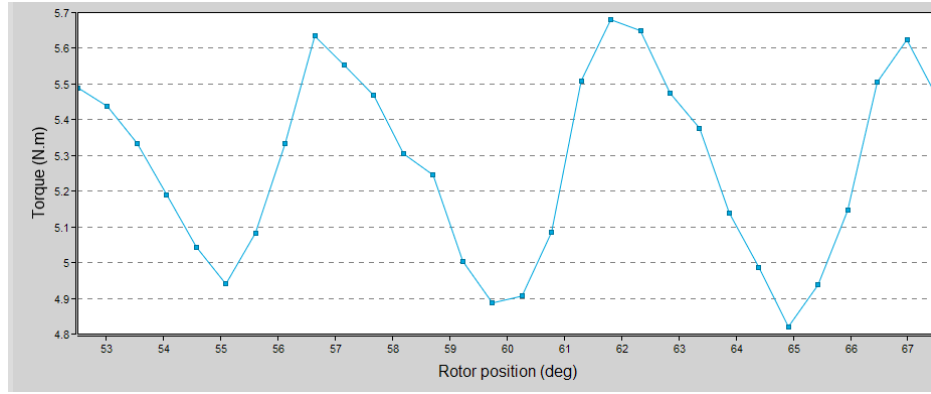


Figure 3.17: Torque ripple versus rotor angular position- Working point

Skewing the rotor is a commonly used technique to reduce torque ripple by smoothing variations in magnetic interaction along the axial length of the machine. This effectively lowers both torque ripple and cogging torque, leading to quieter operation and better performance. In our design, skewing is feasible, as shown in Sections 2.3.1 and 2.2.5. However, it comes with trade-offs: a slight reduction in average torque, a minor drop in efficiency due to longer magnetic paths and increased manufacturing complexity and cost. While skewing is effective, it must be weighed against design goals and production constraints. It is not required for our prototype, but a simulation is included in Section 3.2.5 to show the potential benefits.

- **Magnet behavior: demagnetization:** It is important to evaluate the risk of magnet demagnetization during operation, especially under elevated temperatures, as high thermal stress combined with opposing magnetic fields can drive the magnets beyond their safe operating point, potentially resulting in irreversible performance loss.

Property	Value
Remanent Induction B_r	0.40 T
Energy Product $(B \times H)_{\max}$	30 kJ/m ³
Intrinsic Coercivity H_{cj}	190 kA/m
Reversible Temp. Coefficient of H_{cj}	0.003 K ⁻¹

Table 3.6: Key properties of ferrite magnet grade Y35 [27]

3 Prototype design and simulation

The coercive field H_c indicates the strength of the magnetic field needed to cancel out the magnet's induction. The magnet operates in zone 1 as seen from the simulation data in figure 3.18 retained from FluxMotor, meaning that the applied field remains far below 50% H_c , thus there is no risk of demagnetization.

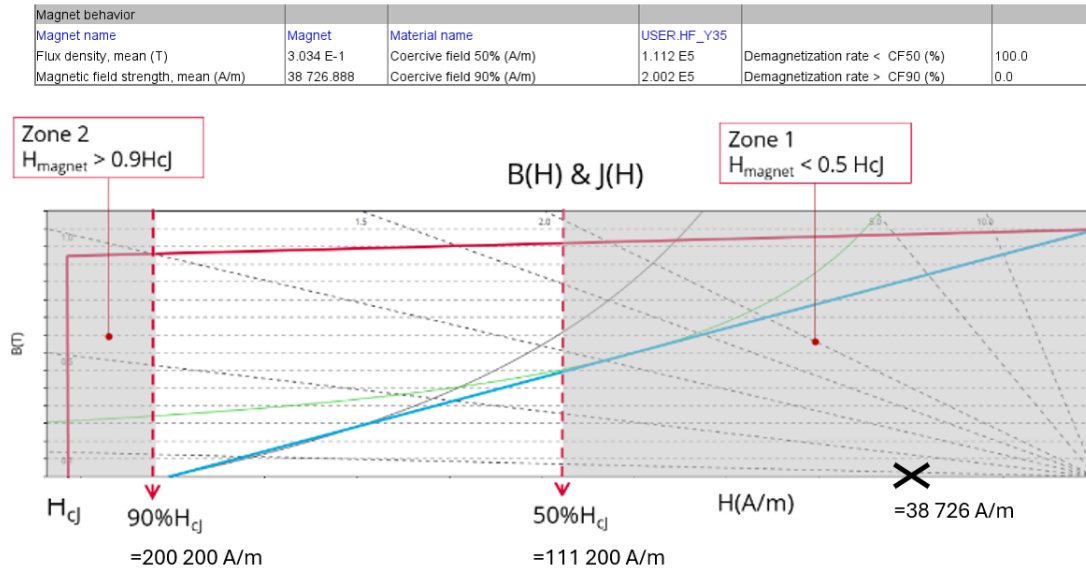


Figure 3.18: Magnet demagnetization

Ferrite magnets (such as Y35) have lower magnetic strength (energy product) but are far more resistant to high temperatures. While their remanence gradually decreases with rising temperature, their coercivity actually increases, making them more resistant to demagnetizing fields. This behavior shifts the knee point to a much lower risk region on the curve, providing protection against a demagnetization field in thermally demanding applications. However, while ferrites resist demagnetization better at high temperatures, their usable flux density drops due to decreasing remanence.

In contrast, NdFeB magnets offer very high magnetic strength at room temperature but are highly sensitive to elevated temperatures. As temperature increases, both remanence and coercivity drop. This makes them prone to demagnetization, especially when operating near or beyond the critical point on their magnetization curve known as the knee point. Crossing this knee point, which shifts to a more susceptible zone on the graph when heated, results in irreversible loss of magnetization, as the material can no longer recover its original magnetic properties.

3 Prototype design and simulation

Figure 3.19 visualizes the phenomena described by showing the BH curves of both magnet types at different temperatures.

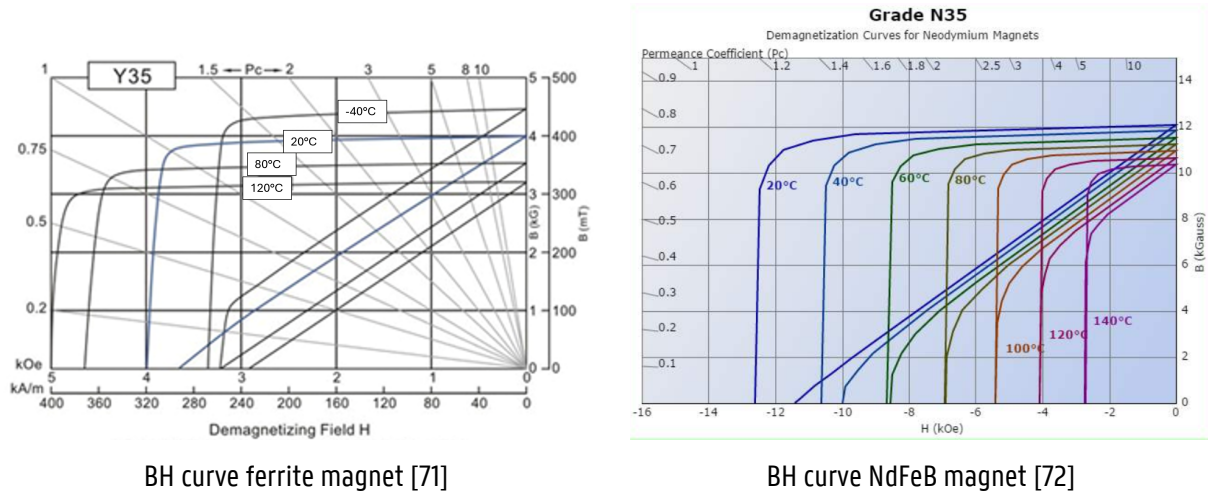


Figure 3.19: BH-curves comparison

Despite their thermal sensitivity, NdFeB magnets are the industry standard in high-performance electric motors due to their superior magnetic strength and energy density, enabling compact and efficient motor designs. However, this also means that demagnetization must be carefully monitored and managed in thermally demanding applications.

In our prototype, we use ferrite magnets, so strict temperature limitations regarding demagnetization are not a major concern; however, this ferrite magnet utilization is solely due to the practical choices made described in Section 3.1.4. For future research and development, stronger NdFeB magnets should be utilized, as their superior properties make them the preferred option for PMSM applications.

3 Prototype design and simulation

3.2.5 Extra simulation: skewed variant

Discrete skewing is a common technique used in electric machines within the automotive industry. The design approach that enables this is discussed in Section 2.3.1. In this brief section, we evaluate the torque ripple and cogging torque of a skewed variant of our specific prototype and compare the results to those of the non-skewed model. The simulations were performed using the same settings and values, with no geometric or simulation parameter change other than the skewing.

Figure 3.17 shows that the torque ripple has a periodicity of 5° . To effectively reduce this ripple, a discrete skewing of 2.5° (half the ripple period) is applied in this FluxMotor simulation. Skewing by half the period causes opposing ripple components to cancel each other out, which helps to flatten both the cogging torque and overall torque ripple, resulting in smoother motor operation.

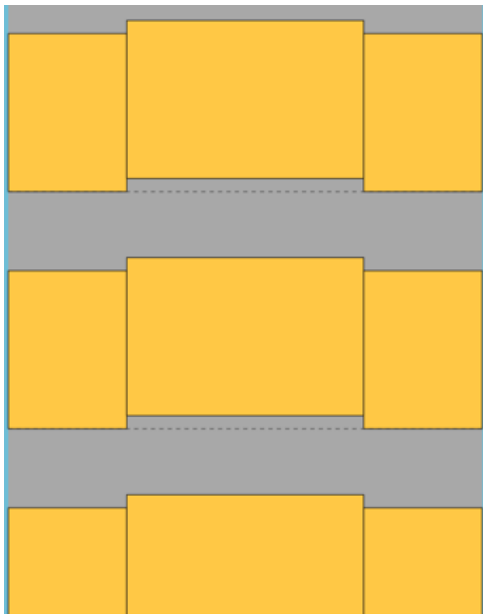


Figure 3.20: Rotor discrete skewing

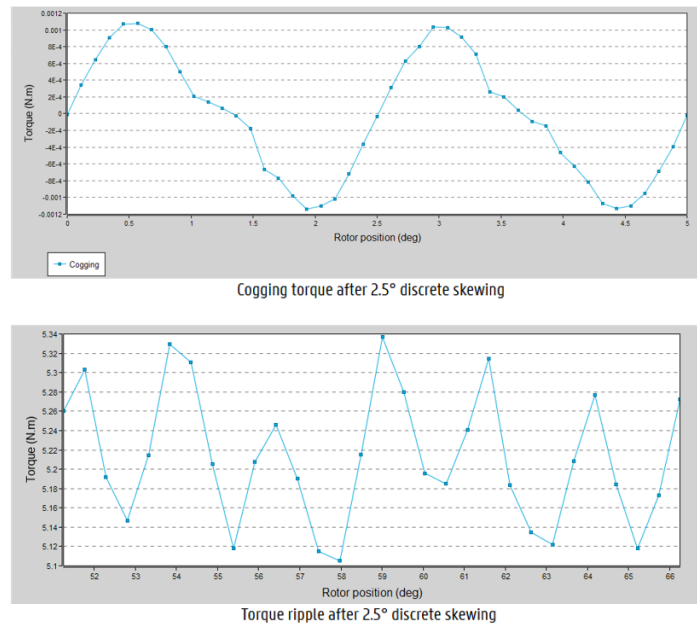


Figure 3.21: Cogging & torque ripple @2.5° skew

The torque ripple was effectively reduced from 16.3% to 4.4%, which represents a reduction of 73.4% in torque ripple, significantly improving the smoothness of the motor's operation. On the other hand, the average torque saw a slight decrease, dropping from 5.26 Nm to 5.21 Nm, which corresponds to a loss of 0.95% in average torque. This simulation was performed solely to demonstrate the effect of skewing on torque ripple reduction, and no further application or optimization of these results is pursued within this study. The primary focus here is on showcasing the reduction in torque ripple at the cost of a minor loss in average torque.

3 Prototype design and simulation

3.2.6 Electrical simulation results

Despite the negatively impacting design choices made during prototyping, as discussed in Section 3.1.4, it is important to emphasize that **these compromises are not inherent to the design itself, but rather the result of limited production capabilities and time constraints**. In future iterations, these issues can easily be avoided without requiring any structural changes to the core design.

In contrast, our concept introduces an improvement that offers inherent benefits beyond the limitations of the current prototype: the elimination of conventional radial and tangential ribs, which form magnetic bridges in the core, as seen in Figure 3.22. In traditional IPM designs, these ribs are a primary source of magnetic flux leakage, as the flux follows a path through the ribs without contributing to torque production, leading to inefficient use of expensive PMs. By removing the ribs, flux leakage is minimized, allowing nearly all of the PM flux to pass through the air gap and contribute to torque generation. This results in more efficient utilization of the PM volume, as visualized in Figure 3.23. The simulation was performed in Altair Flux 2D at the defined working point using FEM analysis for accurate and detailed results.

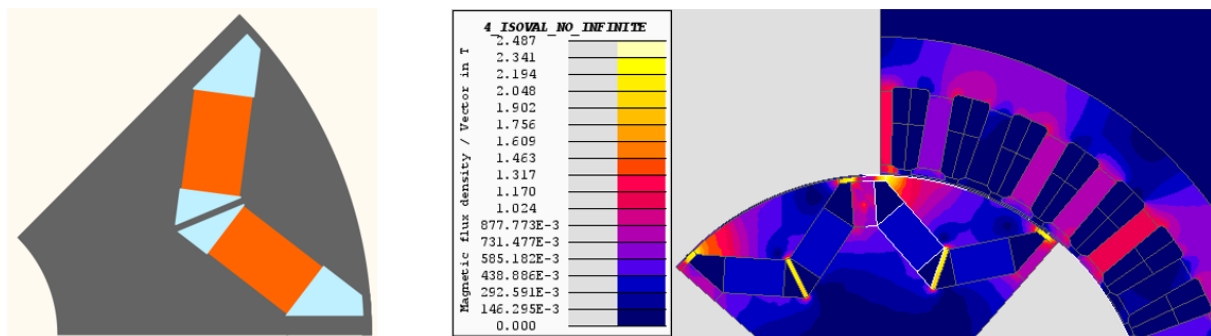


Figure 3.22: Conventional (ribbed structure)

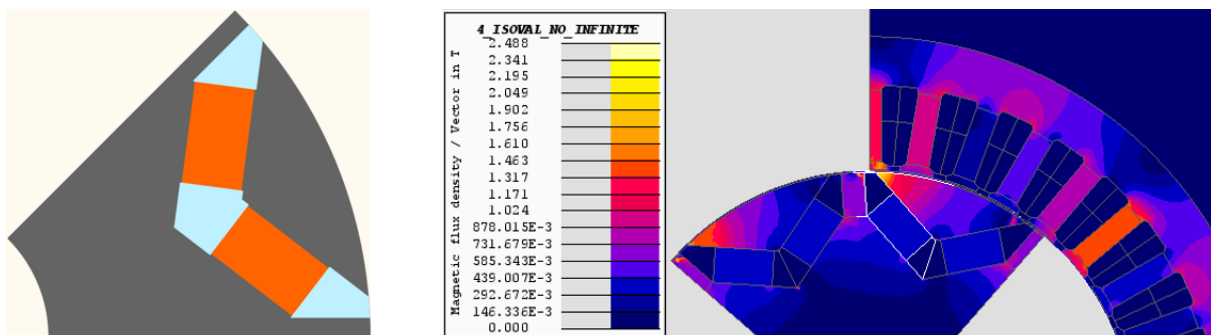


Figure 3.23: Prototype (no ribs)

3 Prototype design and simulation

All simulations in this chapter have been performed on the ribless prototype design. However, in this section, a simulation has also been carried out on a conventional ribbed design as shown in Figure 3.23 to enable a direct comparison at the working point (750 rpm, 5A/m²).

Table 3.7: Prototype (ribless design)

Parameter	Value
Rotational speed(rpm)	750
Mechanical torque (N·m)	5.26
Mechanical power (W)	413.75
Machine electrical power (W)	511.51
Machine efficiency (%)	80.88
Power density (W/kg)	52.11
Machine total losses (W)	97.76
Joule losses (W)	92.35
Iron losses (W)	5.40
Torque ripple (%)	16.31

Table 3.8: Conventional (ribbed design)

Parameter	Value
Rotational speed(rpm)	750
Mechanical torque (N·m)	3.65
Mechanical power (W)	287.16
Machine electrical power (W)	384
Machine efficiency (%)	74.78
Power density (W/kg)	35.98
Machine total losses (W)	96.84
Joule losses (W)	92.35
Iron losses (W)	4.48
Torque ripple (%)	7.11

The comparison between the ribless prototype and the conventional ribbed design reveals several key performance differences. At the same rotational speed of 750rpm, the ribless motor achieves a significantly higher mechanical torque of 5.26Nm compared to 3.65Nm for the ribbed version. Consequently, the mechanical power output is also higher for the ribless machine, reaching 413.75W, whereas the ribbed machine delivers only 287.16W. This improvement in performance is reflected in the overall efficiency: the ribless design operates at 80.88%, which is notably better than the 74.78% efficiency of the ribbed version. Additionally, the power density increases significantly from 35.98W/kg to 52.11W/kg, which is a crucial factor in traction motors for vehicles where maximizing performance while minimizing weight is essential. One trade-off becomes apparent in the torque ripple: while the ribbed design shows a ripple of 7.11%, the ribless machine experiences a significantly higher torque ripple of 16.31 %, which may affect mechanical smoothness and noise. This can be reduced through skewing and is not considered problematic in our design.

Overall, the ribless design offers a clear advantage in torque and efficiency.

3 Prototype design and simulation

3.3 Mechanical design

Following the completion of the electrical design and simulation phase, we now shift our focus to the mechanical design of the rotor prototype. In this stage, the goal is to translate the established electromagnetic topology into a practical and manufacturable 3D construction. The design-for-recycling principles discussed in Chapter 2 will serve as the foundation for this process, particularly with regard to the rotor. Various refinements and design decisions will be discussed, with a focus on creating a robust, modular, and recyclable construction.

The prototype design is shown in Figure 3.24. It uses fitted bolted connections along the axial length, along with two end plates featuring integrated locking elements to ensure mechanical integrity with accurate alignment and fixation of the rotor components. The axial bolts are evenly distributed around the rotor circumference, providing geometric fixation to withstand centrifugal stresses during high-speed operation. This configuration ensures structural robustness while also enabling non-destructive disassembly, which is essential for future reuse or recycling. The interior section of the rotor shows how ferrite magnets are embedded within V-shaped cavities in the rotor core. These cavities are designed to mechanically clamp the magnets in place, providing primary support, while the end plates offer additional axial retention. This approach eliminates the need for adhesives or resins, which are difficult to remove at EoL and often contaminate or even disrupt recycling streams. The entire assembly is fully mechanical, supporting easier disassembly and a more sustainable component lifecycle. The two base plates are designed not only to secure the structure but also to act as alignment guides during assembly, reducing the risk of misalignment and ensuring consistent fit across multiple units. Overall, the design balances manufacturability, structural performance, and recyclability.

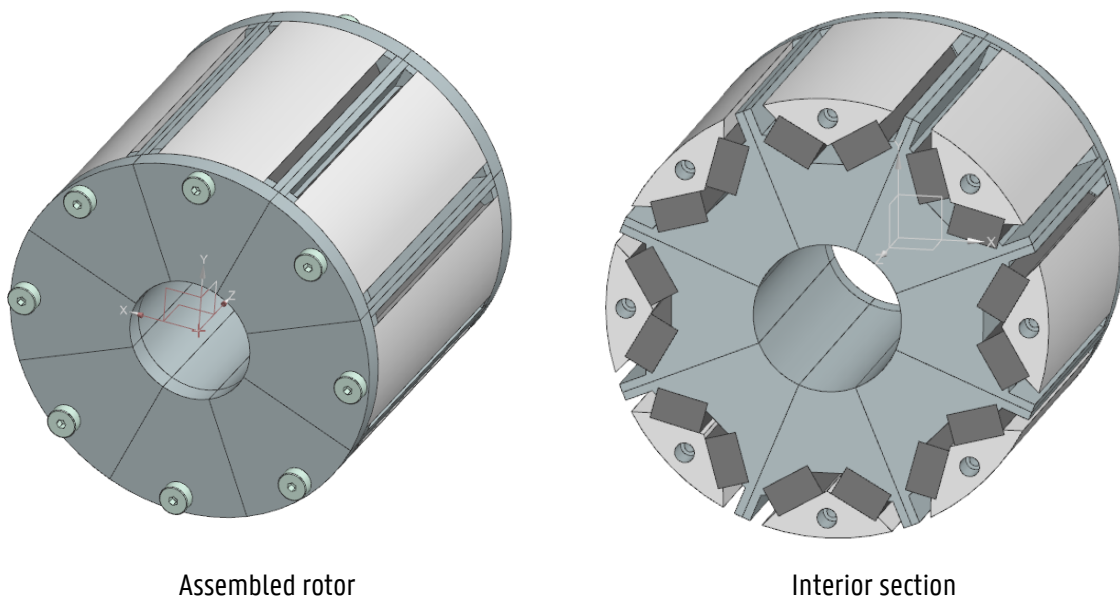


Figure 3.24: Prototype design

3 Prototype design and simulation

3.3.1 Core part

The core part of the rotor construction is the main structural element responsible for transmitting torque from the magnets to the shaft. As explained in Section 3.1.3, this component will be manufactured from solid steel due to limitations in available manufacturing methods. After reviewing the materials provided by the manufacturer, C15 steel was selected for its low carbon content and the presence of silicon, which improves both machinability and magnetic performance. The geometry has been optimized for manufacturability, ensuring efficient and accurate production. The part will be produced using a combination of CNC machining and wire EDM (Electrical Discharge Machining), allowing for precise shaping of all features while maintaining tight tolerances.

EDM is a non-contact manufacturing process that removes material using electrical discharges. In wire EDM specifically, the tool (a thin wire) is separated from the workpiece by an insulating fluid (typically deionized water). When an electrical potential is applied, the fluid breaks down and a spark bridges the gap, striking the workpiece. This discharge vaporizes a tiny portion of material, which is then flushed away by the circulating fluid. Unlike conventional machining methods, the hardness of the material has little to no effect on this process, making EDM particularly effective for hard or difficult-to-machine materials.[73]

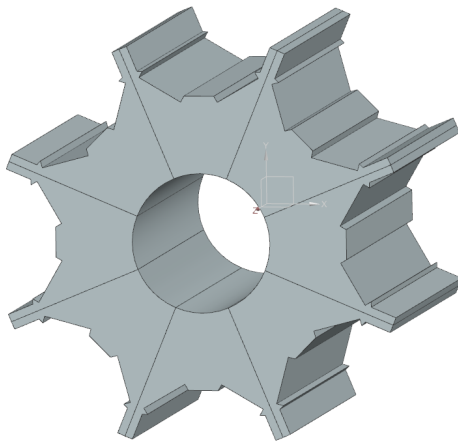


Figure 3.25: Core part

Property	Value
Material Name	C15
C content	0.15%
Mn content	0.40%
P content	0.045%
S content	0.045%
Si content	0.045%
Cr content	0.10%
Yield Strength	275 MPa
Tensile Strength	450 MPa
Elongation	19%
Density	7850 kg/m ³

Table 3.9: Properties of C15 steel

The connection to the shaft will be achieved through a press fit on a grooved axle. The shaft we intend to use is repurposed from an old induction motor shown in figure 3.26. Using a micrometer the diameter is precisely measured of the smooth section of the shaft to be 29.650 mm. The grooved section of the axle shows a peak-to-peak diameter of 30.035 mm. It has been decided to machine the bore of the rotor core to an exact diameter of 29.650 mm, with a tolerance range of +0.1 mm / -0.0 mm. This allows the part to slide smoothly over the ungrooved section, while creating a press fit over the grooved section. The grooves are expected to deform slightly during

3 Prototype design and simulation

assembly, thereby ensuring a secure mechanical connection. To further reinforce the fit, Loctite 638 retaining compound can be applied. This adhesive fills any remaining micro-cavities between the shaft and the bore, hardens after curing, and contributes to a rigid and reliable bond between the components. This presents no issues regarding EoL, as the bond readily breaks at elevated temperatures (above 260°C).

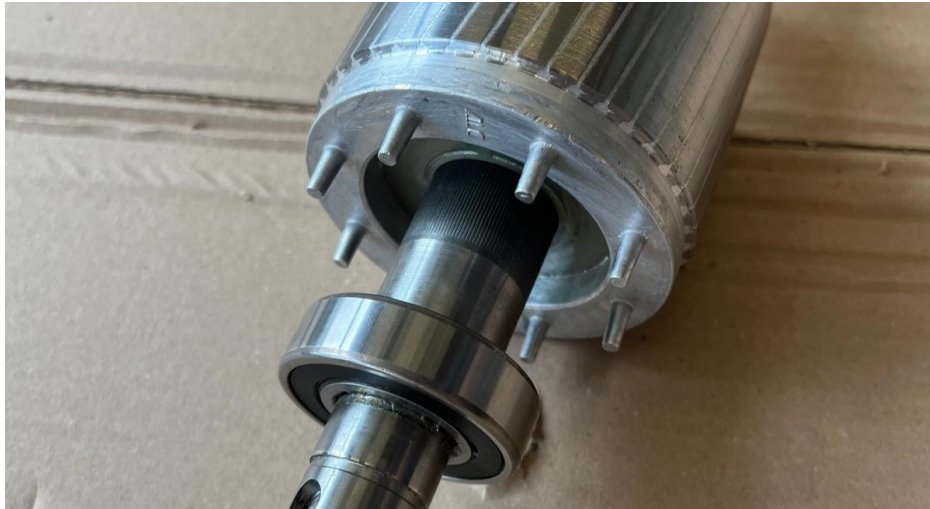


Figure 3.26: Induction motor

3.3.2 Upper core parts

The eight upper core segments are manufactured from the same C15 steel as the main core and will be produced using CNC machining. Their primary function is to securely retain the magnets in place, even at high rotational speeds.

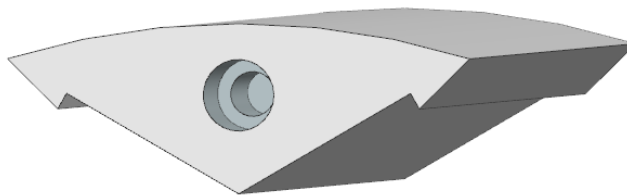


Figure 3.27: Upper core part

This component features stepped holes with two different diameters, designed to accommodate a precision fit bolt and its threaded section. The first section of the hole, with a diameter of 4 mm, is intended for the sliding fit of the bolt's smooth flank, while the final section, with a 2.5mm diameter, is foreseen with an M3 metric threading.

3 Prototype design and simulation

The bolt used for this fixation is the ISO 7379-4-M3-16-NI, as illustrated in Figure 3.28. This is a shoulder bolt (or precision bolt) with a nominal shaft diameter of 4mm and a thread of M3×0.5. The smooth (shoulder) section of the bolt is manufactured to an f9 tolerance grade, ensuring a precise fit in the mating components. This particular bolt is a grade 12.9 according to the ISO 898-1 standard for metric fasteners, which corresponds to an ultimate tensile strength of 1200MPa and a yield strength of 1080MPa.



Figure 3.28: Fitted bolt M3x16

The section view of the bolt in the upper core parts is shown in Figure 3.29. The red lines indicate the intersecting threads in the part, while the blue lines represent the fitted bolt sliding connection. Since the bolt has an f9 tolerance grade, the hole should be machined to a grade that provides a close sliding fit. This is necessary not only for ease of assembly, but also to allow the required rotation for fastening the bolt.

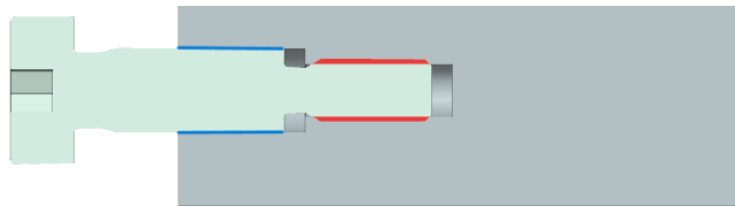


Figure 3.29: Section view bolted connection

The chosen fit for the hole is chosen to a H7. This makes a H7/f9 that ranges between the following values:

		12	μm	4.012				-10	μm	3.990
4 H 7	=	4		=		4 f 9	=	4		=
		0	μm	4.000				-40	μm	3.960

Figure 3.30: H7/f9 tolerance ranges for a 4mm fit

The minimum clearance is calculated as 4.000mm (hole) - 3.990mm (shaft) = 0.010mm (10μm), and the maximum clearance as 4.012mm - 3.960mm = 0.052mm (52μm). This fit ensures a slight but consistent clearance between the parts, making it easy to assemble while still keeping everything in place accurately.

3 Prototype design and simulation

3.3.3 Additional feature upper core parts: eddy current mitigation

Since the prototype is constructed out of solid C15 steel instead of conventional laminated steel due to practical reasons, we should be aware of the increase in eddy currents in our construction. Eddy current losses in the rotor of PMSMs, though relatively low due to the quasi-DC magnetic field, can still cause excessive temperature rise, potentially exceeding the thermal limits of the permanent magnets and leading to irreversible demagnetization[74]. In our specific prototype, this risk is significantly reduced due to the use of ferrite magnets, which are inherently less susceptible to irreversible demagnetization under elevated temperatures compared to rare-earth magnets. Nevertheless, demagnetization remains a critical phenomenon to consider during the design and operation of PM machines, especially under fault or overload conditions. Eddy currents induced by high-frequency magnetic fields tend to concentrate near the surface of the solid rotor, a phenomenon known as the skin effect [19]. Therefore, it is particularly important to address this issue in the upper regions of the core, where the effect is most pronounced.

One way to improve the performance of soft magnetic Fe-Si cores in electrical machines is by **increasing the silicon content** to around 6.5% [19]. This enhances magnetic permeability and reduces eddy current losses, both critical for efficient electromagnetic operation. However, at this silicon level, the material becomes highly brittle, making it difficult to process using conventional techniques such as cold rolling. For this reason, the silicon content in conventional Fe-Si laminations is typically limited to around 3.5% [75]. This issue does not apply in our case. EDM, for example, operates without applying mechanical forces to the workpiece, so the process is largely unaffected by material hardness. As a result, it is well-suited for machining very hard or brittle materials with high precision. Therefore, in theory, higher silicon contents could be used in our material without encountering the processing limitations of conventional methods. In practice, however, this is not feasible for our prototype, as such compositions are not commonly available. We are therefore limited to the materials offered by our supplier.

Additionally, the incorporation of **special geometric patterns** offers a complementary method that can be combined with previous strategies to further reduce eddy current losses. A recent study by Ajamloo et al. at Ghent University [19] introduces a novel IPM rotor concept that uses additive manufacturing to eliminate rotor ribs. This innovation enables more efficient use of magnet material, while also improving torque performance and power density. The study proposes the use of shallow grooves on the rotor surface as an effective way to reduce eddy current losses. Figure 3.31 presents cross-sectional comparisons of rotors with (b) and without (a) grooves, along with the corresponding eddy current paths. In rotors without grooves, eddy currents tend to flow in straight lines along the axial direction. The addition of shallow grooves disrupts these paths, forcing the currents to follow longer, more resistive routes. As a result, the eddy currents are weakened due to the increased resistance and extended path length.

3 Prototype design and simulation

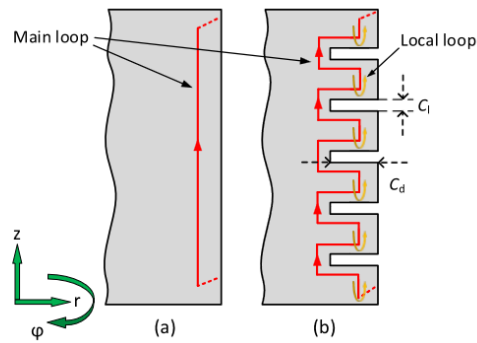


Figure 3.31: Cross-sectional views of eddy current path [19]

Since our prototype shares similar dimensions and operating speeds with the machine presented in the referenced study, we adopt the evaluated groove parameters from that design, configuring our rib-less IPM rotor with 10 shallow grooves, each 1.5 mm deep (C_d) and 0.2 mm wide (C_l). The study reports that the eddy currents are reduced by more than half due to the groove features[19].

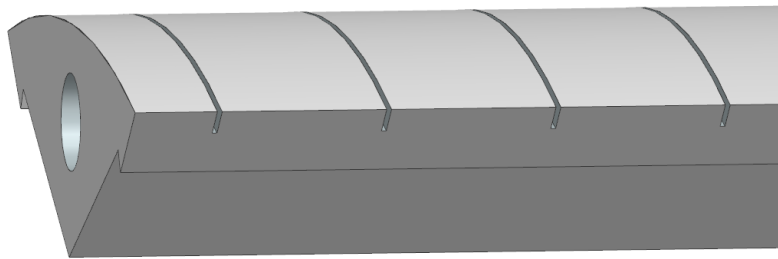


Figure 3.32: Shallow grooves feature

These grooves could technically be machined on the same CNC machine as the parts themselves, using micro end mills. However, since these tools are extremely delicate and designed for high-precision applications, they are too specialized for this purpose. Machining the grooves this way would not only be very expensive due to rapid tool wear and the high risk of breakage, but also very time consuming, making it an impractical solution overall.



Figure 3.33: Micro end mill

3 Prototype design and simulation

An alternative could be the use of a wire EDM process to cut the grooves. Wire EDM is commonly used to cut complex 2D shapes or profiles from electrically conductive materials. Most machines position the wire vertically while moving the workpiece along the X and Y axes. The wire typically ranges from 0.100 mm to 0.33 mm in diameter. During cutting, electrical discharges occur primarily along the leading 180 degrees of the wire, resulting in a kerf that is wider than the wire itself. The actual kerf width depends on the power settings but is generally about one-third larger than the wire diameter [73].

A possible setup is shown in Figure 3.34. The upper core part moves along the Y-axis, followed by a rotation around the X-axis to machine grooves with consistent depth. Once a groove is completed, the core shifts along the X-axis to position for the next groove. This coordinated movement enables the formation of multiple evenly spaced grooves with uniform depth.

(These features will not be included in our prototype due to the complexity involved in producing them as a one-off. Since we do not currently have access to this type of dedicated setup, manufacturing them would be both time-consuming and costly. As explained earlier, this will not affect the functionality of our prototype.)

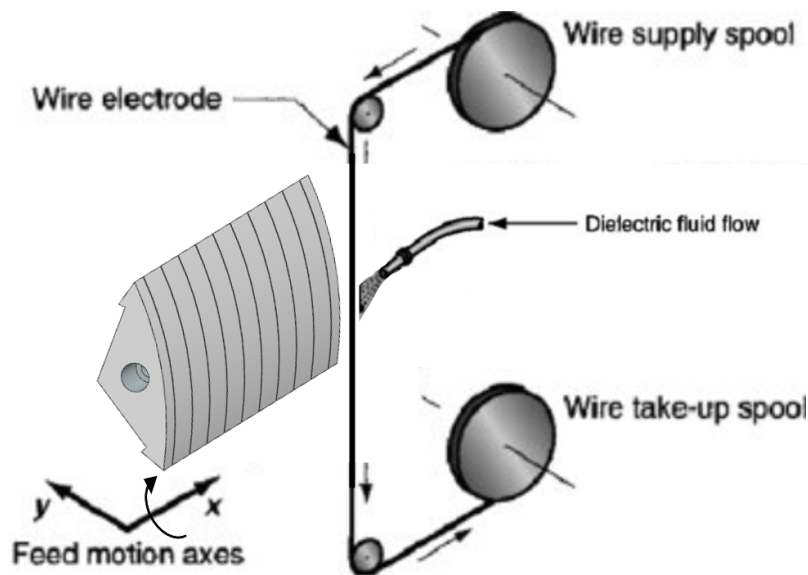


Figure 3.34: wire-EDM setup shallow grooves

3 Prototype design and simulation

3.3.4 Plates

On both sides of the rotor stack, two plates are mounted to secure the upper core components using fitted bolted connections. These plates feature precise locating elements that ensure proper alignment, guaranteeing full contact between all parts and providing complete constraint. These plates play a critical structural role by transmitting the dominant centrifugal forces acting on the magnets and upper core parts, effectively holding the entire assembly together under high-speed operation.

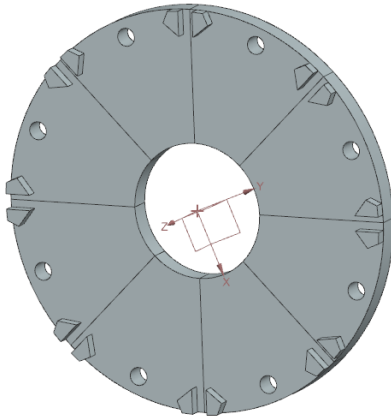


Figure 3.35: Plate

Property	Value
Material Name	AISI316
Yield Strength	235 MPa
Tensile Strength	600 MPa
Elongation	61%
Relative permeability	1.008
Density	8000 kg/m ³

Table 3.10: Properties of AISI316 steel

The selected material for these plates is AISI 316 stainless steel, chosen specifically for its non-magnetic properties. Its key characteristics are listed in Table 3.10. AISI 316 has a relative magnetic permeability of around 1, meaning it conducts magnetic flux similarly to air. This is essential to prevent the formation of unintended magnetic leakage paths between adjacent magnets and poles, as illustrated in Figure 3.36 (the sketch is not to scale and serves to illustrate the concept rather than show precise geometry), as well as at the positioning features. Using a magnetic material in this location would distort the magnetic field distribution by allowing significant flux to pass through, negatively affecting the system's performance.

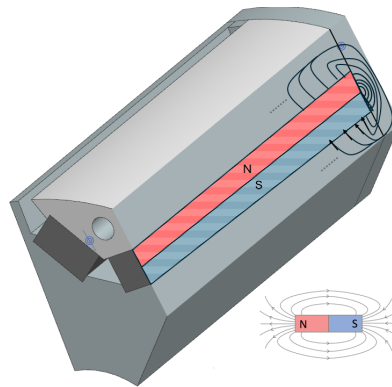


Figure 3.36: Magnetic flux path plate

3 Prototype design and simulation

The eight holes for the fitted bolts use the same H7/f9 fit as described in Section 3.3.2. The central hole has a diameter of 29.8 mm, allowing for a smooth fit over the 29.65 mm shaft. The plate itself is 5 mm thick, which must be sufficient to withstand the stresses and bending moments introduced at the bolted connections.

It is important to note that the fitted bolts feature a short dead zone (red circles in Figure 3.37) at the beginning of their length, which reduces the effective contact area. Since stress is given by $\sigma = \frac{F}{A}$, this reduced area results in higher localized stresses. This has been accounted for in the part design. Ideally, bolts without this dead zone would be used to maximize the effective load-bearing surface.

An alternative solution could involve the use of washers to better distribute the load by retracting the dead zone. However, this would introduce 16 additional small components into the assembly, increasing both complexity and assembly time.

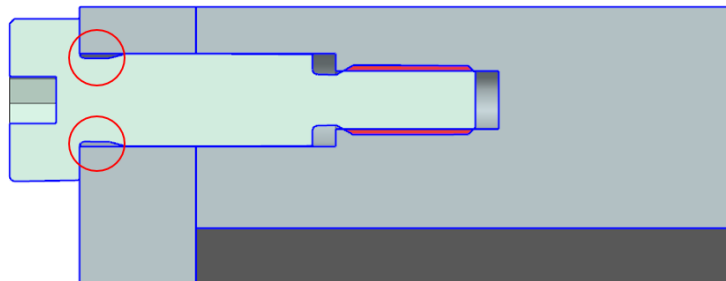


Figure 3.37: Section view bolted connection plate

3 Prototype design and simulation

3.3.5 Magnet fixation

The magnets are held in place between the upper and lower parts of the core with the help of upright edges. Because the magnets were not yet in possession during engineering and production, and they have a factory tolerance of ± 0.2 mm in width (10mm nominal) and ± 0.1 mm in height (6mm nominal), the design must account for possible dimensional variations. To prevent assembly issues, the magnets have intentionally been modeled 0.3mm larger in both width and height. This ensures that the magnets will always fit securely, even in the case of maximum manufacturing deviations. Any remaining clearance can be compensated by using high-temperature Kapton or Nomex tape. These tapes are available in very thin thicknesses, as low as 25 μm , allowing for fine fitting adjustment without significantly affecting overall dimensions. The use of tape between the magnet and rotor core offers several advantages. It enables full-face contact between the magnet and its surroundings, ensuring a stable positioning and eliminating any play. This indirect surface mating reduces the risk of movement during operation, thereby improving mechanical stability and increasing the overall lifetime of the magnets and rotor.

In the case of our prototype, even standard paper tape would be sufficient, as the maximum operating temperature is limited to 80°C, which is well below the thermal limit of paper-based tapes. This method offers an efficient and reliable way to secure the magnets without the need for resins or adhesives.

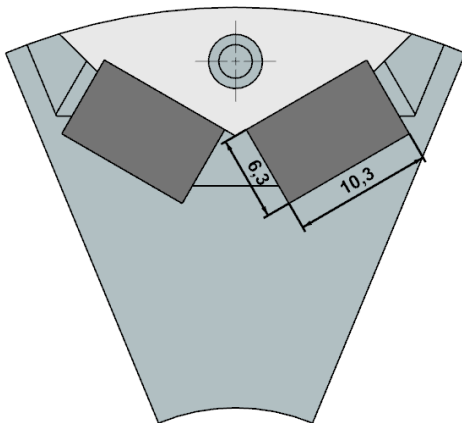


Figure 3.38: Magnet oversize



Figure 3.39: Temperature resistant tape

An additional advantage of using tape is that it allows the magnets to be slightly press-fitted into the rotor structure. By deliberately designing a very small interference fit where the combined thickness of the magnet and tape is marginally oversized relative to the slot dimension. The compressibility of the tape ensures that the magnets can still be positioned without excessive force. During assembly, the tape deforms slightly, creating a clamping effect between the magnet and the core. This compressive interface increases friction and helps lock the magnets firmly in place, further improving mechanical retention without the need for adhesives or complex fixtures. However, this approach requires precise design and testing, as even a slightly excessive oversize can prevent proper assembly or cause deformation of the surrounding structure.

3 Prototype design and simulation

3.4 Mechanical simulation

For the mechanical simulation of the prototype, the same methodology is applied as in the initial preliminary simulations described in 2.2.3. However, this time the simulation is conducted using the final prototype model & components and carried out in a more thorough and detailed manner. The initial simulations were primarily intended for validating the design principle. In this simulation, the actual materials used in the final design have been assigned to each component, and the CAD model of the shoulder bolt has been included to ensure an accurate representation. The simulated speed is 4500 rpm, which is 6 times the intended speed for the prototype design.

Structural deformation

In the first view shown in Figure 3.40, the deformation of the entire pole is displayed. The maximum deformation occurs at the upper part of the core, measuring 0.0197 mm, which is very low. Therefore, there is no need to implement an additional radial bolt in the middle, as shown in Figure 2.23.

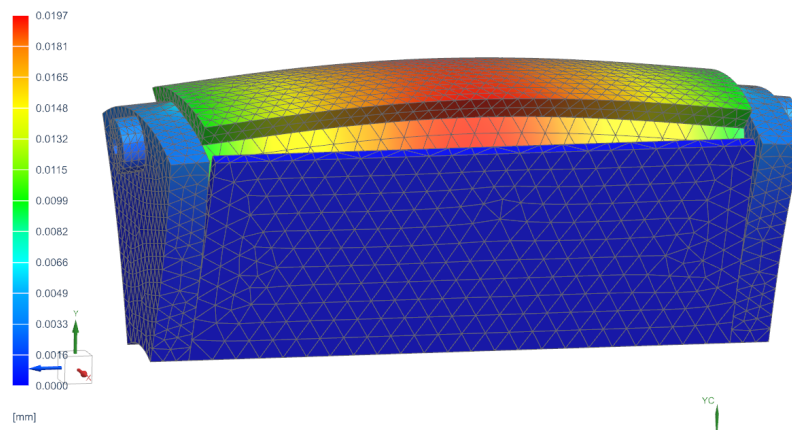


Figure 3.40: Total displacement prototype

In the following sections, the stresses on the individual parts will be evaluated. Please note that the deformation shown in all images is highly exaggerated to improve visibility (see displacement scale in mm).

3 Prototype design and simulation

3.4.1 Upper core parts

In the upper core sections, the highest stress concentrations occur at the lower region of the bolt interface, reaching 234.73 MPa. These stresses are compressive and remain below the allowable limit of 275 MPa. Although the addition of a radial bolt, as discussed in Section 2.2.3, could help reduce these stress levels, it is deemed unnecessary for this specific case.

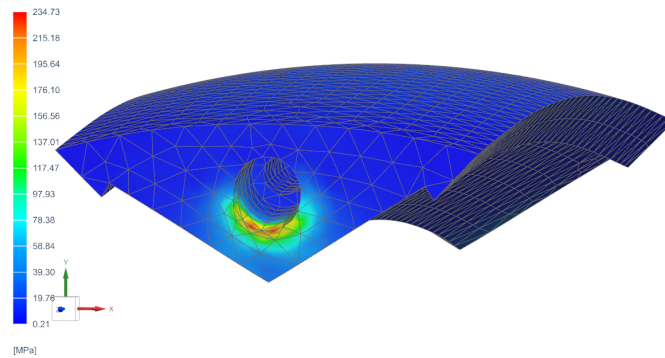


Figure 3.41: Stresses upper core prototype

With shallow groove features

The simulation was repeated with the addition of shallow groove features to reduce eddy currents. Although these grooves are not included in the current prototype, they could be implemented in the future or with design updates. The introduction of the grooves led to a slight increase in displacement, from 0.0197 to 0.0213 mm, which remains within safe limits. This increase is attributed to a reduction in the critical cross-sectional area, which affects the stiffness of the structure.

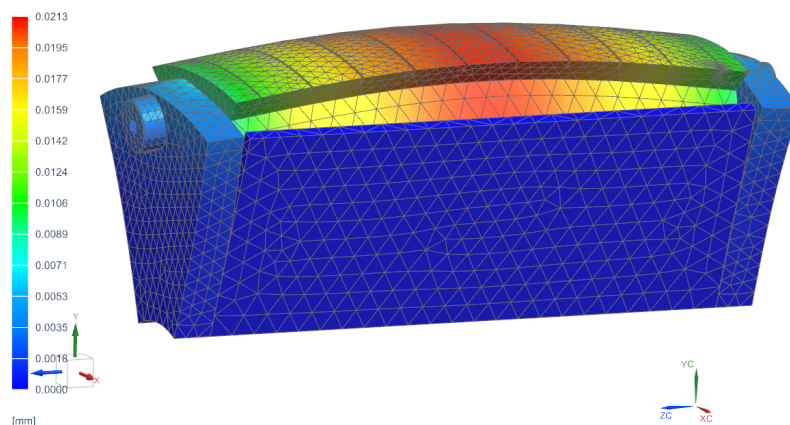


Figure 3.42: Total displacement grooved prototype

3 Prototype design and simulation

The stresses in the shallow grooves reach up to 174.0 MPa in the most critical region, which remains well below the 275 MPa limit. As expected, these stresses are concentrated at the sharp corners of the geometry, where stress concentrations naturally occur due to the deflection.

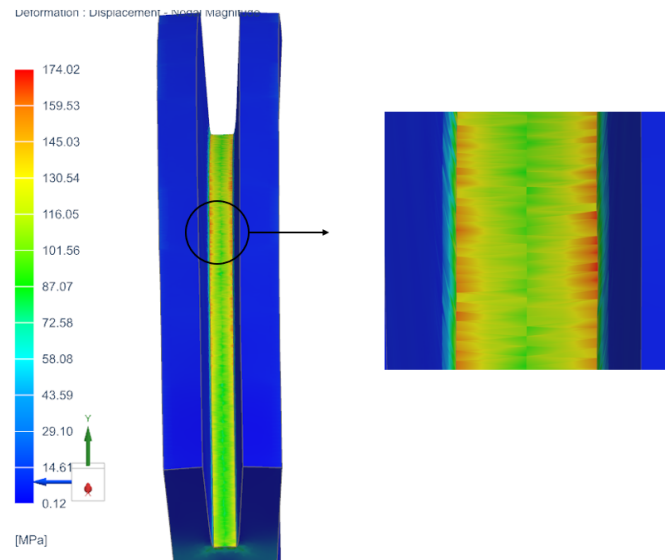


Figure 3.43: Shallow groove stresses

These shallow grooves can be machined with either a squared or rounded profile, depending on the selected manufacturing process. Rounded grooves are especially effective at reducing peak stresses by distributing stress concentrations more evenly. This makes wire EDM a favorable technique for producing these features, as it naturally creates rounded edges.

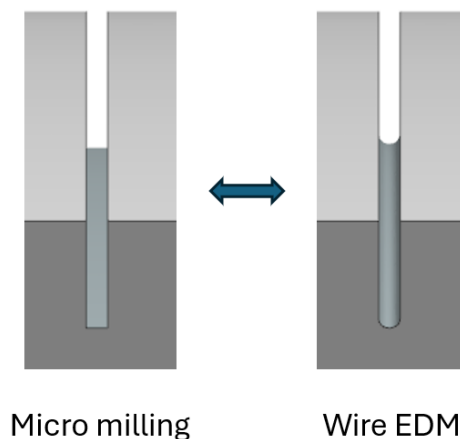


Figure 3.44: Shallow groove profile w.r.t. machining

3 Prototype design and simulation

3.4.2 Lower core part

The core experiences relatively low stress levels due to its large surface area, which enables effective force distribution, and the inherent rigidity of its solid structure. As expected, the maximum stresses are found at the contact points between the upright edges and the magnets, reaching 3.7 MPa, well below the 275 MPa limit for C15 steel.

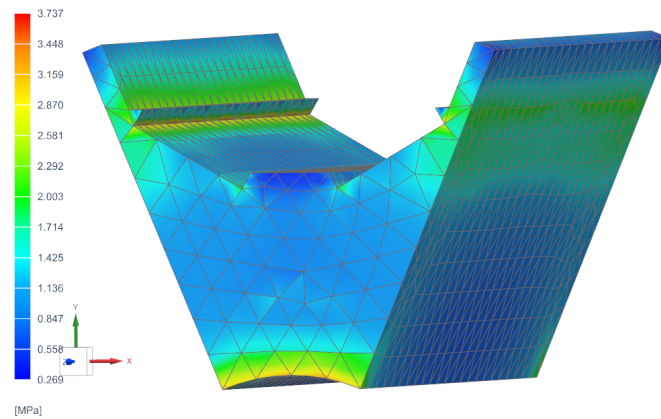


Figure 3.45: Stresses core prototype

3.4.3 Magnets

The magnets experience relatively low stress levels, with a maximum of 27.94 MPa. In this simulation, they are modeled as solid components to simplify the analysis and reduce computational time. However, the actual prototype uses segmented magnets, which will significantly reduce tensile stresses caused by bending moments at the upper faces. As a result, primarily compressive stresses will remain, which the magnets are much better suited to withstand. Ceramic ferrite magnets can endure compressive stresses up to 895 MPa and tensile stresses up to 34 MPa [76].

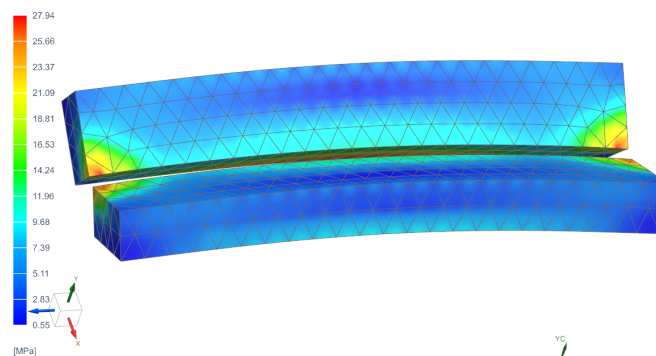


Figure 3.46: Stresses magnets prototype

3 Prototype design and simulation

3.4.4 Plates

The plates experience a maximum stress of 189.03 MPa at the upper region of the bolted connection, which is expected and remains well below the 235 MPa limit. This stress is primarily caused by deformation of the upper core section and the bolt exerting a pulling and stretching force on the hole. Although adding a radial bolt could help reduce this effect, it is not considered necessary in this case.

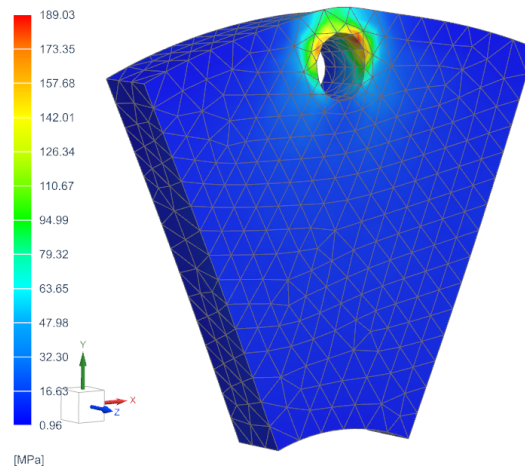


Figure 3.47: Stresses plate prototype

3.4.5 Shoulder bolts

The shoulder bolts are subjected to a stress of 146.71 MPa, well below their maximum allowable limit of 1080 MPa. Although bolts of a lower strength grade would theoretically be sufficient for this application, grade 12.9 bolts were used due to their greater availability.

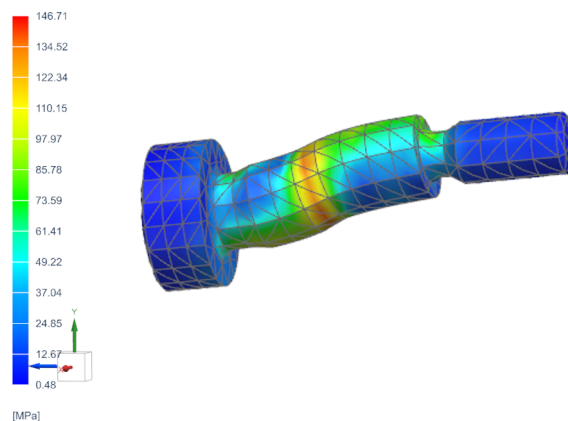


Figure 3.48: Stresses shoulder bolt prototype

3 Prototype design and simulation

3.4.6 Magnet load stresses on core

In the previous simulations, the effects of rotational speed were analyzed. In this additional simulation, the focus shifts to the stresses induced in the core components by the magnetic forces exerted by the magnets. These forces are transferred to the core structure, ultimately producing torque on the shaft. To approximate this effect, a torque equal to six times the motor's nominal maximum torque, namely 36 Nm, is applied as a force acting only on the magnets. Given that the center of mass of the magnets is located at a radius of $r = 35.908 \text{ mm}$, the resulting force acting on the magnets is calculated as:

$$F = \frac{M}{r} = \frac{36\,000 \text{ N} \cdot \text{mm}}{35.908 \text{ mm}} \approx 1002.6 \text{ N}$$

(It should be noted, however, that in reality the magnetic forces are distributed throughout the rotor and not applied exclusively to the magnets. Therefore, the actual forces experienced by the magnets will be significantly lower than in this simplified simulation.)

This simulation is performed under standstill conditions to isolate the effects of this force. The results shown in Figure 3.49 indicate very low stress levels, with a maximum of 11.243MPa. This was expected due to the large surface area available for distributing the applied forces.

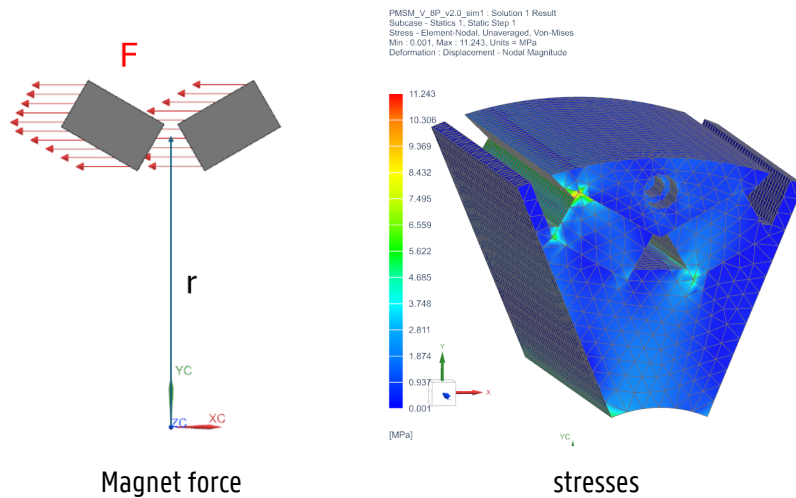


Figure 3.49: Magnet load stresses on core

3.4.7 Mechanical simulation final remark

All von Mises stresses and displacements remain within the allowable limits for each component and its corresponding material, even at six times the nominal rotational speed of 4500 RPM. This confirms that the prototype is both safe and properly dimensioned. While the addition of a radial bolt could further reduce stresses and displacements in future iterations or faster speeds, it is not required for this application.

4

Results

In this chapter we will discuss the results of the prototyping in scope of the assembly- and disassembly principles

4.1 Prototype 3D printing: Axial bolt concept

The first version of the prototype was 3D printed to assess the practical feasibility and compatibility of the structural components. The components were easy to assemble and demonstrated strong mechanical connections and overall robustness. These results confirm that the design is sound and does not require modifications prior to the production of the final prototype.

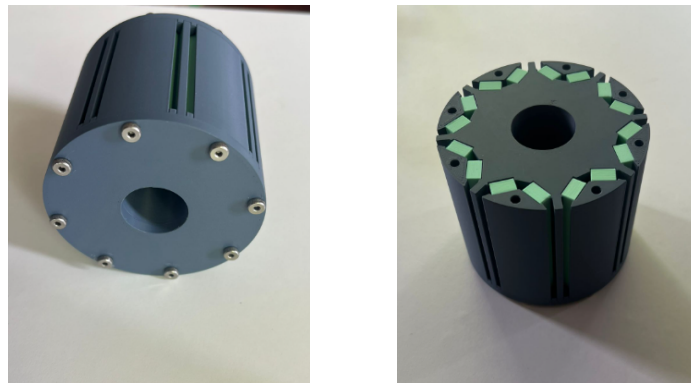


Figure 4.1: 3D printed prototype assembly: axial bolts

Assembly is one aspect, but the primary focus of this thesis lies in the disassembly of the structure at EoL. The design enables disassembly pole by pole by removing the upper core segment along with the two corresponding magnet stacks, as shown in Figure 4.2 (left). In this example, the plate was also removed, although this step is not strictly necessary. On the right side of Figure 4.2, all magnets have been separated from the structure. This approach allows for straightforward insertion and removal of the magnets; however, in practice, magnetic forces may influence the ease of disassembly.

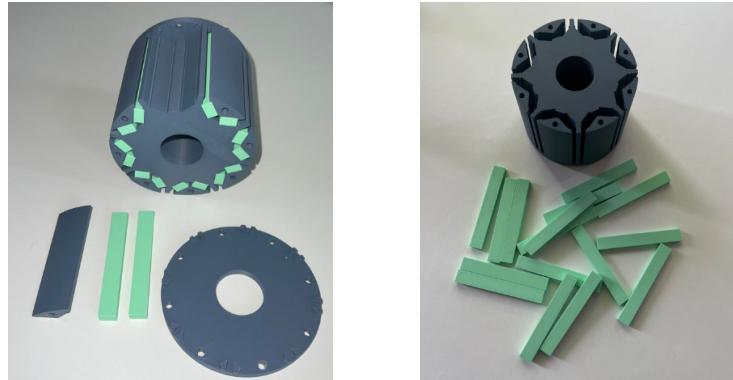


Figure 4.2: 3D printed prototype disassembly axial bolts

Based on these results, we can proceed with the manufacturing process to produce a functional rotor using this design for real-world application.

4.2 Prototype 3D printing: Radial bolt concept

An additional prototype concept, introduced in Chapter 2.3.1, was also explored. While this design was not developed in detail or intended for production in functional materials, a 3D printed model was created to demonstrate its conceptual feasibility and to visualize the assembly approach.

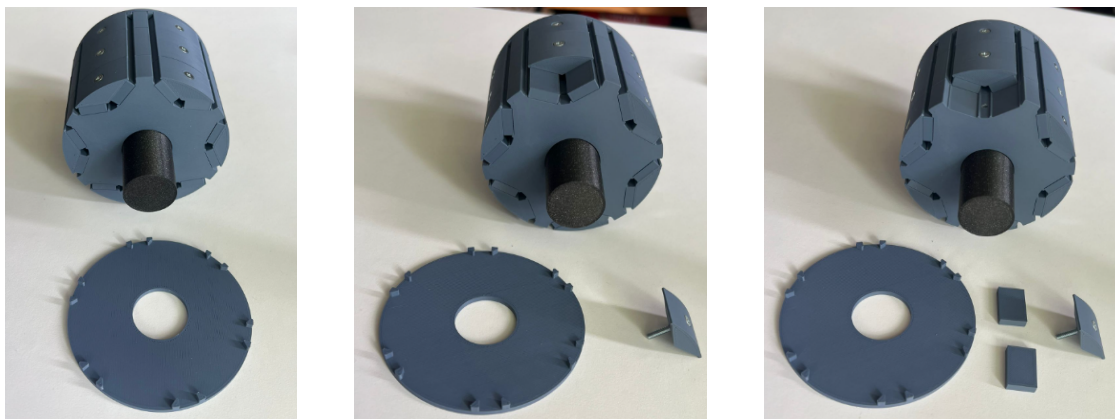


Figure 4.3: 3D printed prototype: radial bolts

Although the concept allows for discrete skewing of the rotor segments, as illustrated in figure 4.4, this flexibility comes at the cost of increased assembly time. The large number of individual components required for a skewed configuration significantly complicates the assembly process. The prototype consists of three independently slidable segments, enabling various skew topologies to be visualized. While this modularity offers valuable insight

4 Results

on skewing potential, the complexity of assembly suggests that further refinement would be needed to make the concept practical for real-world applications or scalable production.

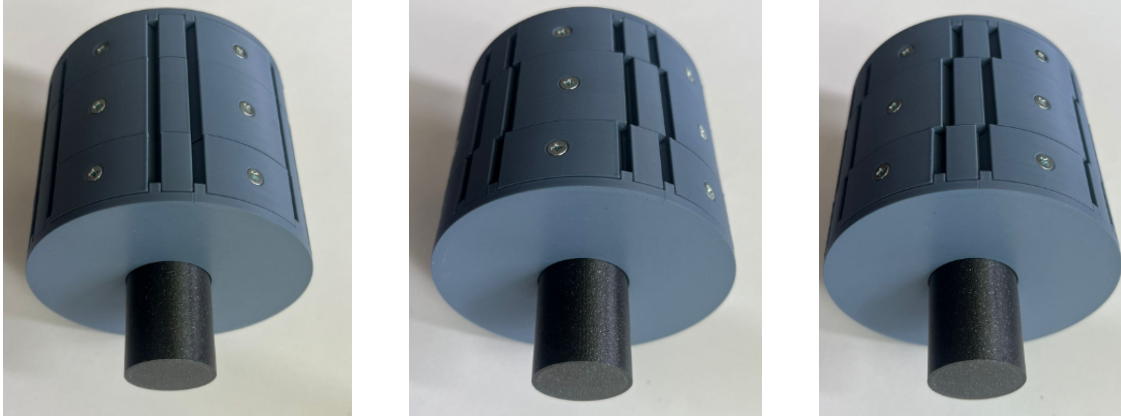


Figure 4.4: Prototype radial bolts: skewing configurations

4.3 Functional Prototype Construction

Following the successful construction and evaluation of the 3D-printed prototype, the next phase involves building the full-scale functional prototype using axial bolts, based on the detailed mechanical and electrical simulations and design. All components described in Chapter 3 have been manufactured using the specified materials and processes, and all the parts are shown in Figure 4.5.



Figure 4.5: Prototype parts

4.3.1 Magnet insertion

The magnets are manually inserted into the slots with the aid of paper tape, as shown in Figure 4.6, which compensates for the slight oversize present due to manufacturing tolerances. This ensures a press-fit assembly, holding the magnets securely in place restricting free movement. Additionally, the tape may help reduce stresses and vibrations acting on the magnets. In this design, the tape serves as a substitute for adhesives or resins commonly used in similar applications.



Figure 4.6: Magnet placement process

Once the magnets are properly positioned and covered with tape from the top, the installation of the upper part of the core can proceed. The tape is applied in such a way that it slightly presses the magnets into their slots, while also creating a small height oversize. This condition is illustrated in Figure 4.7 (red circle). During assembly, force is applied to compress the excess tape material, thereby generating a compressive stress that securely holds the magnets in place. A fitted bolt is then inserted to lock the position, and subsequently tightened to ensure a stable and reliable magnet fixation.



Figure 4.7: Magnet fixation process

4 Results

The manual installation process was carried out successfully and proved to be quite manageable. The magnets were securely held in place, with no issues or unexpected complications encountered during assembly. This smooth procedure is an encouraging indication of the robustness and practicality of the design. It also highlights the potential for future automation, which is a crucial factor for scaling up production and implementing this concept in real world applications and future research. The fact that the process can be reliably performed by hand suggests that, with appropriate adjustments, it could be effectively adapted in automated manufacturing systems.

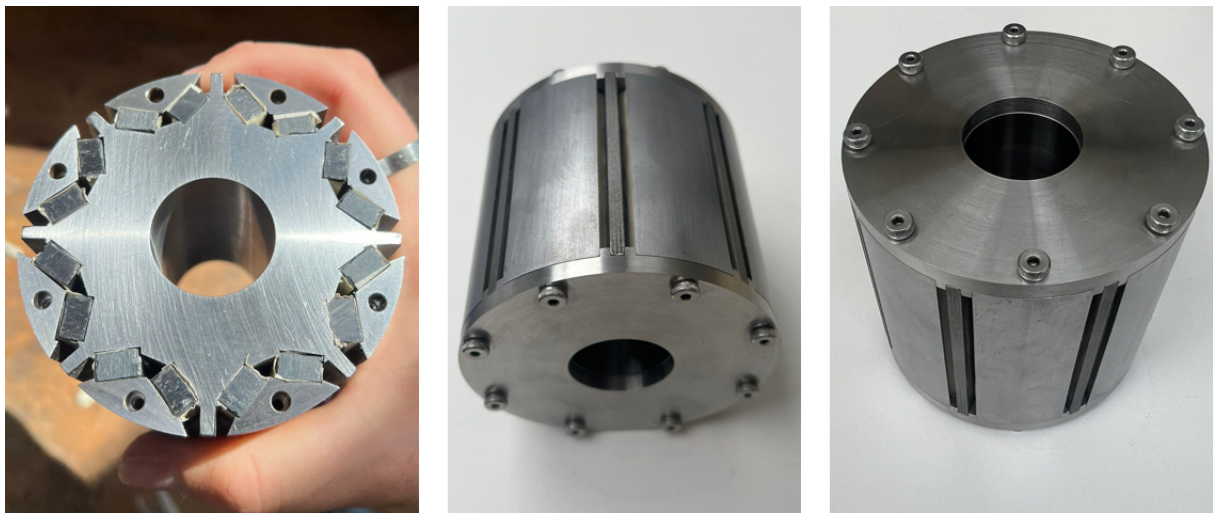


Figure 4.8: Prototype final result

4.3.2 Final remark

To conclude this chapter, a practical test was performed by disassembling one of the poles after full assembly. This reverse operation was carried out successfully and without any issues, further validating the core concept of our design. While some force was required to remove the magnets, due to their tight press-fit in the slots and the additional magnetic forces, manual removal proved to be feasible. This indicates that automated or robotic disassembly should be entirely achievable. However, future investigations should consider the impact of using stronger NdFeB magnets instead of ferrite. Given their significantly higher magnetic strength and the limited gripping surface on the small magnets, manual removal may become more challenging, potentially requiring tooling or assistance.

5

Upscaling

The prototype developed in this thesis was designed and tested at a reduced scale to enable practical manufacturing, assembly, and validation. However, to assess the viability of this design for real-world applications, particularly in the context of EVs or industrial machinery, it is essential to evaluate how it performs under more demanding conditions. This chapter investigates the mechanical implications of up scaling the rotor design to twice its size (diameter and length), as well as increasing the rotational speed in tenfold, from 750 RPM to 7500 RPM.

While various aspects of motor performance are affected by such scaling, this study focuses exclusively on the mechanical consequences, in alignment with the thesis primary focus on rotor construction and design. As physical dimensions and speeds increase, mass and centrifugal forces scale non-linearly, placing significantly higher mechanical loads on structural components. The goal of this chapter is to assess how these increases affect stress distribution, deformation, and the integrity of critical fastening mechanisms.

Using a combination of analytical analysis and mechanical simulations, this chapter identifies key challenges that arise when scaling the rotor and evaluates whether the core design principles, particularly modularity and recyclability, can be preserved under these new conditions.

5.1 Mechanical Effects of Geometric and Speed Scaling

5.1.1 Volume and Mass Increase

Assuming the same material is used and the geometry remains similar, the mass of the rotor scales directly with its volume. Volume V of a rotor is approximately proportional to the product of its cross-sectional area and its length:

$$V = \frac{\pi}{4} D^2 \cdot L \quad (5.1)$$

If we scale both the diameter D and the length L by a factor of 2:

$$V_{\text{scaled}} = \frac{\pi}{4} \cdot (2D)^2 \cdot (2L) = \frac{\pi}{4} \cdot 4D^2 \cdot 2L = 8 \cdot \left(\frac{\pi}{4} \cdot D^2 \cdot L \right) \quad (5.2)$$

Hence, the volume and, by extension, the mass of the upscaled rotor becomes:

$$m_{\text{scaled}} = 8 \cdot m_{\text{original}} \quad (5.3)$$

This **eightfold increase in mass** significantly affects the mechanical loads, particularly the centrifugal forces acting on rotor components due to the rotational motion.

5.1.2 Radii

When scaling the dimensions by a factor of 2, the radius also increases by a factor of 2. Since the radius r is defined as half of the diameter D , scaling the diameter by 2 results in:

$$r_{\text{scaled}} = \frac{1}{2} \cdot (2D) = 2r$$

This increase in radius further amplifies effects such as centrifugal forces, which are proportional to the radius.

5.1.3 Effect of Increased Rotational Speed

In addition to geometric scaling, the increase in rotational speed has a significant impact on the mechanical loads within the rotor. This effect grows exponentially, as centrifugal force depends on the square of the angular velocity.

5 Upscaling

The general formula for centrifugal force F_c acting on a mass m rotating at a radius r with angular velocity ω is:

$$F_c = m \cdot r \cdot \omega^2 \quad (5.4)$$

$$\omega = \frac{2\pi n}{60} \quad (5.5)$$

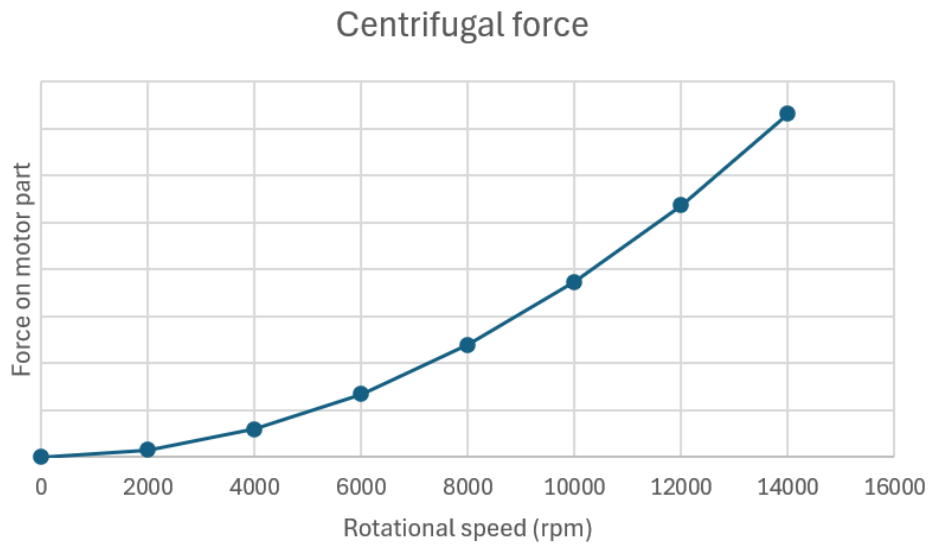


Figure 5.1: Exponential increase of centrifugal force with rotational speed (fixed dimension)

From this, it becomes clear that centrifugal force increases with the square of the rotational speed. For example, doubling the rotational speed results in a fourfold increase in centrifugal force, assuming constant mass and radius, as illustrated in Figure 5.1. This quadratic relationship implies that even modest increases in RPM lead to **exponentially higher forces** acting on rotor components. Consequently, when designing for higher rotational speeds, it is critical to account for the rapidly escalating mechanical loads, as they can significantly affect material stresses, component deformation, and the overall reliability of fastening mechanisms. An increase in rotational speed from 4500 RPM to 7500 RPM results in a centrifugal force that is approximately 2.77 times greater, since centrifugal force is proportional to the square of the rotational speed:

$$\frac{F_{c, 7500}}{F_{c, 4500}} = \left(\frac{7500}{4500}\right)^2 = \left(\frac{5}{3}\right)^2 = \frac{25}{9} \approx 2.77.$$

However, in our upscaling study, both the mass and radius also increase, further amplifying the resulting forces.

5.1.4 Bending Stiffness Considerations

In this part, we investigate what the relationship is between bending stiffness and geometric upscaling. To illustrate this, a simplified triangular section representing the upper core part is analyzed. The section is fixed on both sides at the centroid and subjected to a point load in the middle. This setup is intended to provide a general understanding of bending behavior before detailed simulations of the actual components are conducted.

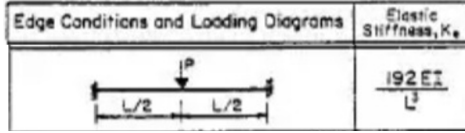


Figure 5.2: Elastic stiffness beam [20]



Figure 5.3: Second moment of area for a triangle [21]

Bending stiffness is defined by the product of the material's Young's modulus E and the second moment of area I_x , divided by the cube of the span length L , multiplied by a geometry-dependent constant. For a beam fixed at both ends and loaded in the center, the relation becomes:

$$k = \frac{F}{\delta} = \frac{192EI_x}{L^3} \quad (5.6)$$

For a triangle with base b and height h , the second moment of area about the base is given by:

$$I_x = \frac{bh^3}{36} \quad (5.7)$$

In the case of 2× uniform scaling:

- The base and height double: $b \rightarrow 2b, h \rightarrow 2h$,
- The characteristic length L doubles: $L \rightarrow 2L$,
- The second moment of area increases as follows:

$$I_{x,\text{scaled}} = \frac{(2b)(2h)^3}{36} = \frac{2b \cdot 8h^3}{36} = 16 \cdot \frac{bh^3}{36} = 16I_x \quad (5.8)$$

Substituting into the bending stiffness formula:

$$k_{\text{scaled}} = \frac{192E \cdot 16I_x}{(2L)^3} = \frac{3072EI_x}{8L^3} = 384 \cdot \frac{EI_x}{L^3} = 2 \cdot \frac{192EI_x}{L^3} = 2k_{\text{original}} \quad (5.9)$$

5 Upscaling

When the beam (upper core part) is uniformly scaled in all dimensions (length, width, and height), the spring stiffness k increases linearly with the scaling factor. This means that if the component is doubled in size, its bending stiffness also doubles. In other words, the structure becomes proportionally stiffer as it grows, but no mechanical advantage is gained through scaling, the stiffness simply scales with size. This linear relationship is important to consider in design, as it implies that the stiffness per unit size remains constant during uniform scaling; however, centrifugal forces increase more rapidly with size, resulting in greater deflection in the scaled structure.

5.1.5 Effect of Scaling on Bolt Load Capacity

When upscaling a mechanical design, the dimensions of the bolts increase alongside with those of the structural components to maintain structural integrity. Specifically, if the rotor is scaled up by a factor of two in both diameter and length, it is reasonable to proportionally scale the bolt dimensions.

- d be the diameter of the bolt,
- h the length of the bolt,
- A the stress area (cross-sectional area),
- S the total cylindrical lateral surface area.

The stress area for a circular cross-section is:

$$A = \frac{\pi d^2}{4} \quad (5.10)$$

The lateral surface area of the cylindrical bolt is:

$$S = \pi dh \quad (5.11)$$

If both the diameter and the length are doubled during the upscaling process:

$$d_{\text{scaled}} = 2 \cdot d \quad \text{and} \quad h_{\text{scaled}} = 2 \cdot h \quad (5.12)$$

Then both the stress area and the surface area scale as follows:

$$A_{\text{scaled}} = \frac{\pi(2d)^2}{4} = 4 \cdot A \quad (5.13)$$

5 Upscaling

$$S_{\text{scaled}} = \pi(2d)(2h) = 4\pi dh = 4 \cdot S \quad (5.14)$$

This means that the **the load capacity of the bolt increases by a factor of four, as does the surface area available to transfer the load in shear**, assuming the same material and loading conditions. As a result, the upscaled bolts are better suited to handle the increased mechanical forces arising from the higher mass and rotational speed.

5.1.6 Concluding remark

In conclusion, geometric and speed scaling significantly amplify the mechanical loads acting on the rotor system. As demonstrated by a scaling of 200%, the mass increases eightfold due to volume scaling ($8 \times m$), the radius doubles ($2 \times r$), and the centrifugal force further increases by a factor of approximately 2.77 due to the higher rotational speed. Combining these effects, the total increase in mechanical load can be approximated by:

$$F_{\text{scaled}} = F_{\text{original}} \cdot 8 \cdot 2 \cdot 2.77 = F_{\text{original}} \cdot 44.32$$

Meanwhile, the load capacity of the bolts scales proportionally with their cross-sectional area:

$$A_{\text{scaled}} = 4 \cdot A_{\text{original}}$$

And the bending stiffness increases in direct proportion to the dimensional scaling:

$$k_{\text{scaled}} = 2 \cdot k_{\text{original}}$$

This disparity highlights a key challenge in upscaling: while the loads increase by a factor of 44.32, the structural bolt load capacity increases only by fourfold and the bending stiffness merely doubles. As a result, the structural criticality becomes more pronounced, making additional design considerations essential to ensure mechanical integrity under scaled conditions.

5.2 First iteration: Base model

The first simulation assesses the mechanical behavior of the rotor after a uniform geometric scaling by a factor of two, operating at a rotational speed of 7500 RPM. This represents a direct upscale of the original prototype without any design modifications, aimed at evaluating the baseline mechanical effects of such scaling.

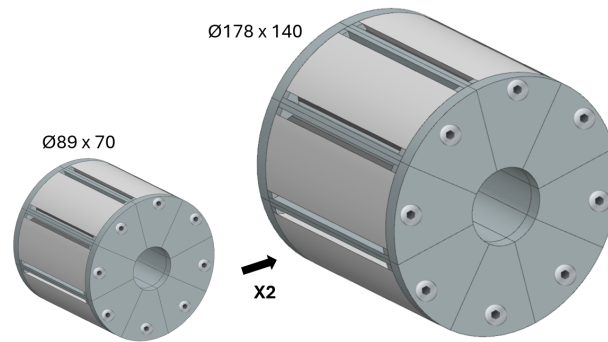


Figure 5.4: Upscale: Base model

The rotor's load increases by a factor of 44, while the bolt strength increases only by a factor of four and the bending resistance only doubles. Although the bolts have been proportionally scaled by doubling their diameter and thus quadrupling their cross-sectional area, this increase is not sufficient to compensate for the significantly higher mechanical loads and deflections. As a result, the load-to-capacity ratio of the critical connections worsens, making the overall structure mechanically weaker.

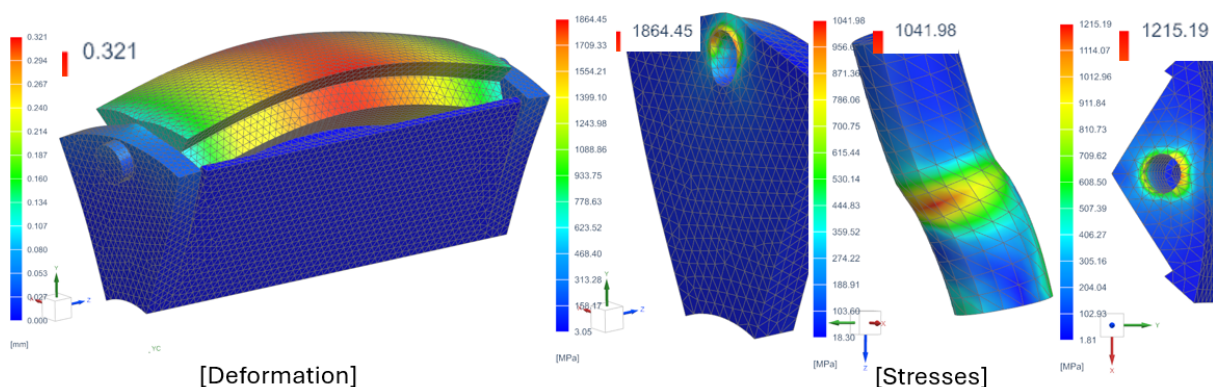


Figure 5.5: Upscale base model: deformation and stresses

The simulation clearly demonstrates that the resulting stresses and displacement in the upscaled model exceed acceptable limits. Although the components were proportionally scaled, the structure lacks sufficient mechanical strength, confirming that simple geometric upscaling is insufficient without additional reinforcement or design adjustments.

5.3 Second iteration: Addition of radial bolts

From the first upscaling simulation, it is evident that the highest stresses occur in the plates and upper core parts. These stress concentrations are primarily caused by deformation, which induces both shear loads and bending moments. Due to the excessive stress and deformation observed, this second iteration includes two additional radial bolts of the same diameter as the axial ones ($\varnothing 4 \text{ mm} \times 2 = \varnothing 8 \text{ mm}$), each preloaded with 13000 N to help reduce peak stresses and deformation.

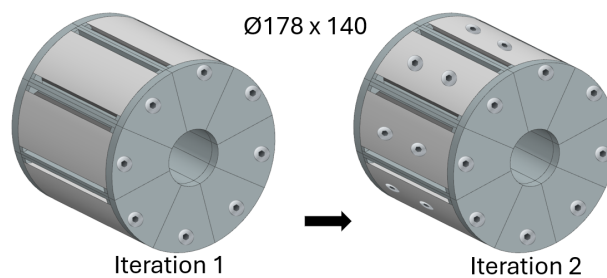


Figure 5.6: Upscale: Iteration 2

The simulation shows a tenfold reduction in overall deformation and a threefold decrease in the maximum stresses within the supporting plate. Additionally, the radial bolts experience higher tensile stresses than the shear stresses observed in the axial bolts. This improvement is mainly due to reduced structural deflection, which lowers the induced bending moments. As a result, the mechanical loads are redistributed more uniformly, increasing the proportion of shear force and promoting a more balanced and efficient stress distribution within the fitted bolts, as well as in the adjacent regions of the plates and upper sections of the rotor core.

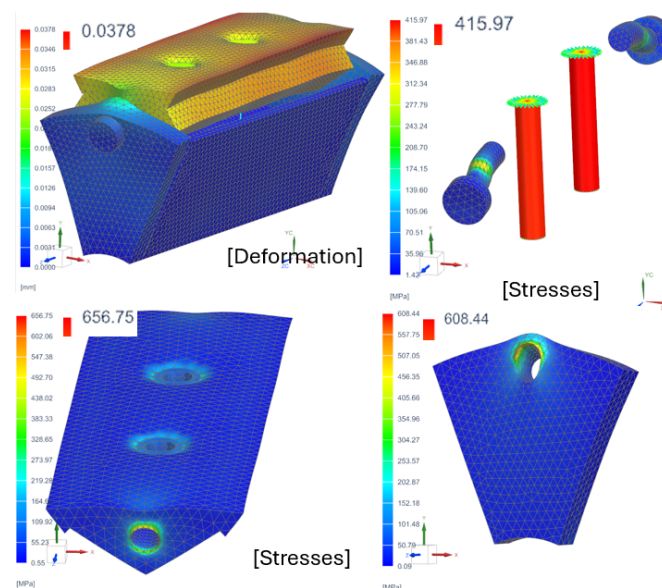


Figure 5.7: Upscale base model: deformation and stresses

5.4 Third iteration: Only radial bolts

The second iteration shows a significant improvement but still results in stress levels that would require the use of high-strength materials. The elevated stresses in the axial bolts, plates, and upper parts of the core are mainly caused by a combination of shear and bending, rather than pure shear, leading to localized stress concentrations. In the third iteration, the same number of bolts is retained, but all are reoriented radially. This configuration places the bolts primarily under tensile load, the condition in which they are most effective, leading to improved and more reliable load transfer. The bolts retain the same dimensions as used in iteration two and are prestressed with 13600 N.

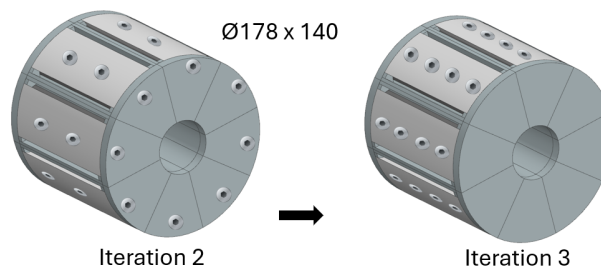


Figure 5.8: Upscale: Iteration 3

The simulation once again shows a clear reduction in both deformation and overall stress levels. The stresses in the bolts remain well within safe limits and can be reliably handled using grade 5.8 bolts or higher. Likewise, the stresses in the upper core regions stay within acceptable thresholds for common structural steels.

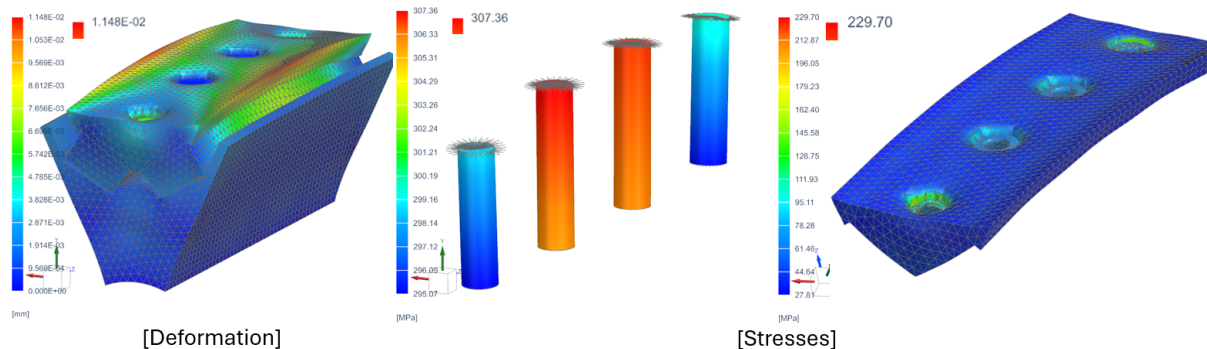


Figure 5.9: Upscale iteration 3: deformation and stresses

With a total centrifugal force of 54,350 N acting on the upper core and magnets, and four bolts of 8 mm in diameter, the resulting stress per bolt is $\sigma = \frac{F}{A} = \frac{54,350}{4 \cdot \frac{\pi \cdot 8^2}{4}} \approx 270.3$ MPa (assuming even load distribution). This closely matches the FEM results, though the calculated value is slightly lower due to ideal conditions.

Conclusion

This thesis explored how the constructional approach of electric machines, particularly permanent magnet synchronous motors, can be modified to support end-of-life recovery of materials more effectively without altering their fundamental architecture. Rather than prioritizing peak performance, the research emphasized ease of disassembly, material separation, and long-term sustainability, key elements of a circular economy.

A central outcome of this work is the demonstration that it is feasible to construct a mechanically stable and recyclable rotor using bolted connections, either axially or radially aligned or a combination of both. The developed prototype confirmed that adhesive-free magnet fixation using axial bolts is practical for small-scale motors featuring a high pole count. For these smaller machines, axial bolts offer clear advantages in terms of manufacturing simplicity, design flexibility, and the absence of constraints such as spacing between magnets, which is required for radial bolts.

The upscaling study highlighted a key insight: for larger and more demanding motor configurations, incorporating radial bolts is the preferred method due to their superior stress distribution (purely tensile) and mechanical reliability under high loads. Furthermore, this approach allows additional radial bolts to be added according to the criticality of the situation providing extra strength and flexibility. Although they require dedicated space between the magnets, which introduces certain geometric constraints, their structural advantages make them particularly well-suited for high-performance applications, where greater stresses and deflections can occur. This design also enables the bolts to be preloaded, helping to counteract these effects and providing further reinforcement. But unlike axial bolts, radial bolts are positioned at the air gap of the rotor's outer surface, making them more critical in terms of operational safety. Any loosening due to vibration could result in catastrophic failure if a bolt and its secured components were to shift into the air gap and come into contact with the stator. Furthermore, these bolts cannot be visually inspected without completely disassembling the rotor from stator, adding another layer of complexity to their use. To overcome the issues with bolt loosening due to vibrations and operating conditions, the use of a medium-strength threadlocker such as Loctite 243 offers an effective solution. Loctite 243 is designed to prevent fasteners from loosening under vibration or shocks and remains effective within a temperature range of -55°C to 180°C [77]. Despite its locking performance, it allows for disassembly using standard hand tools without the need for heat, making end-of-life servicing simple and reliable.

These findings underscore that design-for-recycling strategies are not only technically viable but can be adapted to different motor scales and applications. This thesis demonstrates that recyclability and sustainability can be designed into electric machines without fundamentally compromising their functionality, providing a strong foundation for more circular and responsible engineering practices in the electric machine industry.

Future Work

The work presented in this thesis lays a foundational framework for incorporating design-for-recycling principles into electric machine development, with particular focus on PMSMs. While the prototype and simulations demonstrated that sustainability and traditional motor design can coexist, there is significant opportunity to further develop and industrialize these concepts, not only through geometric upscaling but also through performance enhancement by using for example laminated cores, NdFeB magnets with different topologies, advanced winding and insulation materials/technologies and state-of-the-art cooling systems to better align with real-world high-performance motor applications.

The main direction for future work is the practical integration of the innovative design elements proposed in this study into commercially viable motor systems. This includes developing standardized manufacturing processes for modular stator segments, adopting recyclable materials such as PEEK or vitrimer/cleavable epoxies, and implementing mechanical fixation methods for both magnets and windings that could eliminate the need for adhesives and impregnation. While the main rotor-related concepts were validated through prototyping in this thesis, the stator-related techniques were only theoretically explored and should be thoroughly tested in future research with a dedicated prototype, following a similar approach. These strategies must then in a later stage be validated in large-scale production environments to confirm their feasibility and long-term reliability. Moreover, real-world testing of motors designed with these principles will be critical. While simulation data provides confidence in the mechanical and electromagnetic integrity of the concepts, experimental validation under real operating conditions (thermal cycling, mechanical wear, and long-term performance) is necessary to fully understand the real life behaviour.

Another promising direction involves collaboration with manufacturing and recycling industries to co-develop disassembly techniques tailored to the proposed motor architectures. This includes automating (dis)assembly processes and optimizing material recovery based on motor-specific designs. In this context, the integration of dismantling-friendly features, such as standardized access points or reversible fasteners, can enhance the potential of EoL processing.

Finally, future studies should also evaluate the lifecycle cost-benefit analysis of these sustainable designs compared to conventional counterparts. This includes not only the upfront manufacturing and technical specifications, but also the environmental and economic impacts across the motor's entire life cycle, from material extraction to disposal or reuse. Additionally, the potential role of government policy should be considered, including regulation or subsidies that could support the adoption of these sustainable technologies.

The continuation of this work will contribute meaningfully to the evolution of EM design, supporting a more circular economy while maintaining the technical standards required for next-generation electric vehicles and industrial applications.

Sustainability reflection

This thesis on the Design for Recycling of Electric Machines supports global sustainability by addressing the environmental and resource challenges caused by the growing use of electric motors, particularly in EVs. By integrating principles of modularity, ease of disassembly, and the use of recyclable materials, the work directly contributes to a more circular economy. These proposed methods align with the European Union's Circular Economy Action Plans & regulations and address critical obstacles in recycling REEs and metals, which are essential to the green transition.

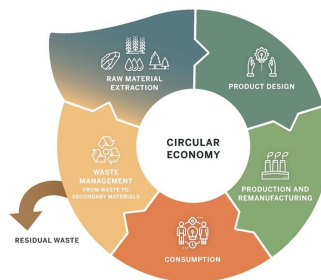


Figure 5.10: Circular economy flow [22]

Circular Economy Policies and regulation

Critical Raw Materials Act (CRMA)

In 2023, the EU proposed the Critical Raw Materials Act[78] to ensure a secure and sustainable supply of critical materials, which explicitly includes improving recycling of materials like rare earths used in electric motors. The Act is “aimed at boosting EU supply and improving recycling of critical raw materials, among which permanent magnets”. This directly relates to this thesis, as one of the central challenges addressed is the recycling of Nd-FeB permanent magnets from motors. By demonstrating methods to enable and simplify magnet removal and proposing magnet-friendly design (mechanical fixation instead of glue), the work aligns with the CRMA's goals. If the Act leads to specific requirements, for instance, mandatory labeling of magnet content or minimum recycling efficiencies for motors, the design principles here would aid compliance. The CRMA also highlights the strategic importance of these materials for European industries (including automotive and renewable energy sectors), so improving their recoverability is a matter of economic security as well as environmental sustainability. This thesis contributes knowledge that supports the implementation of the Critical Raw Materials Act (CRMA), helping align academic research with policy objectives related to critical material sustainability. It is noteworthy that industry groups have commented on the need for balanced regulations in the CRMA so as not to overload manufacturers who are already contributing to sustainable mobility. By providing solutions, this work helps lower the burden: if motors are easier to recycle, compliance with any new recycling targets or material sourcing requirements will be less challenging for manufacturers, including small producers of electric vehicles or machines.

5 Sustainability reflection

Circular Economy Action Plan (2020)

The Circular Economy Action Plan (2020)[79], as part of the European Green Deal, outlines a complete strategy to make sustainable products the norm and keep resources circulating in the economy as shown in Figure 5.10. A important emphasis is placed on the design phase: new initiatives seek to introduce requirements that products be designed for durability, repairability, and recyclability. In March 2022, for instance, the European Commission proposed a Sustainable Products Initiative (SPI)[80], including a proposal for an Ecodesign for Sustainable Products Regulation, to broaden ecodesign criteria beyond energy efficiency to include product lifespan and EoL recoverability. The work done in this thesis foresees and supports such regulatory shifts. By developing design strategies that enhance recyclability, this thesis presents an example of how the upcoming ecodesign requirements could be met in practice. If regulations begin to mandate, for example, a certain recyclability rate or disassemblability score for EMs, the methods investigated here (like modular stators, elimination of certain adhesives and mechanical fixation) could become compliance solutions for manufacturers.

End-of-Life Vehicles Directive

The European Union's End-of-Life Vehicles Directive (2000/53/EC) [81] aims to minimize waste specifically from specifically scrapped vehicles by setting ambitious targets and guidelines for reuse, recycling, and recovery of vehicle components. It requires that the vast majority of a vehicle's materials can be reclaimed at EoL (e.g. 85% reuse/recycling and 95% recovery by weight by 2015) in order to reduce landfill waste and pollution (Directive 2000/53/EC). This directive also emphasizes designing vehicles for easier dismantling and materials separation, thereby improving the environmental performance of all actors in a vehicle's life cycle. As EVs become increasingly dominant in the fleet, ensuring that their components, especially critical parts like PMSMs, meet these circular economy goals is essential. EVs contain valuable materials (such as rare-earth magnets and copper) that the directive seeks to keep in productive use, so designing EV motors for recyclability supports both compliance with the law and broader sustainability objectives. As part of the Circular Economy Action Plan (2020)[79], the European Commission announced its intention to revise the End-of-Life Vehicles (ELV) Directive to better address emerging technologies, such as electric vehicles and battery packs. The European Union's End-of-Life Vehicles Directive (2000/53/EC) was originally adopted in 2000 and remains in force today, with its most recent amendment dating from 30 May 2018.

This Master's thesis supports the ELV Directive's goals by proposing design-for-recycling strategies for electric machines. Key recommendations include avoiding adhesives in motor assembly, using recyclable options instead of non-recyclable resins, and adopting modular designs for easy disassembly. Eliminating permanent adhesives allows clean separation of components like rotors, stators, and magnets, aiding metal and magnet recovery. Replacing thermosets with thermoplastics enables reprocessing of these materials rather than discarding them. Modular architectures, such as bolted sub-assemblies, allow individual components to be replaced, reused, or recycled. These measures enhance material recovery, reduce waste, and help manufacturers meet Directive

5 Sustainability reflection

2000/53/EC targets. In EVs, such designs ensure powertrain components support don't hinder compliance with recycling quotas. Since PMSMs are also used in sectors like renewable energy and industry, improved recyclability advances sustainability and resource efficiency more broadly, reinforcing the ELV Directive's objectives.

Contribution to the Sustainable Development Goals (SDGs)



Figure 5.11: Sustainable Development Goals[23]

This thesis supports several United Nations SDGs, particularly:

- **SDG 9 – Industry, Innovation and Infrastructure:** The proposed motor design principles, such as mechanical magnet fixation and modular components, promote sustainable industrial practices. These solutions enable more maintainable and recyclable electric machines, contributing to resilient and resource-efficient infrastructure.
- **SDG 12 – Responsible Consumption and Production:** This thesis supports sustainable material use by replacing thermosetting insulation and adhesives with recyclable and reusable variants, significantly reducing waste and environmental impact. It also enhances magnet efficiency by eliminating magnetic bridges, enabling better magnet utilization.
- **SDG 13 – Climate Action:** Enhanced recyclability contributes to lower life cycle emissions, as recycling metals and REEs requires significantly less energy than primary extraction through mining[42]. This supports the de-carbonization of both manufacturing and EoL processing. The proposed designs also enable the direct reuse of components, which is even more energy-efficient and environmentally friendly, further reducing ecological impact and advancing circular economy objectives.

In summary, the research aligns engineering design with sustainability principles, contributing meaningfully to global efforts in circular economy, clean industry, and climate mitigation.

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