The Production Process Chain of Axial Flux Motors: A Comparative Study

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***Abstract*— As the global transition to electrification and green energy intensifies, the significance of advanced electric motor technology grows. Axial flux motors (AFM) stand out with their unique design and inherent advantages, positioning them as a promising solution in this sustainability-driven shift. This paper presents a comparative analysis of the manufacturing process chain for AFMs, crucial components in diverse sectors such as electric vehicles, renewable energy systems, and industrial automation. AFMs offer distinct advantages over traditional radial flux motors, including high power density, compact size, and efficiency, underscoring the importance of optimizing their production process for enhanced performance and reliability. Beginning with an overview of AFM technology and its wide application potentials and topologies, the paper examines each stage of a potential manufacturing process chain. These stages encompass design and engineering considerations, winding techniques for stator components, fabrication methods for core laminations, and magnet assembly processes. By examining various methods and processes, their impact on impact on automation, manufacturability, production efficiency as well as quality will be assessed, and the crucial role of AFMs in promoting sustainable technological advancements across industries and in shaping a greener future is highlighted.**

Keywords*— *electric motor, axial flux motor, manufacturing, electric motor production, process chain

I. Introduction And Motivation

The advancement of electric motor technology has been pivotal in shaping the landscape of various industries, from automotive to renewable energy sectors [1, 2]. Traditionally, electric motors have predominantly relied on radial magnetic flux configurations, wherein the magnetic field propagates radially across the motor's stator and rotor. However, recent years have witnessed a notable transition towards electric motors characterized by magnetic fields with axial working direction [3]. This shift has been motivated by several factors, ranging from the pursuit of enhanced efficiency, power, and torque density as well as space restrictions to addressing specific design constraints and application requirements. [4]

Macroscopically, the production steps required to manufacture an axial flux motor (AFM) do not differ fundamentally from the manufacturing of a radial flux motor (RFM) in terms of the components to be realized. However, the many different design options and their respective design features for AFMs mean that the actual technologies for the production of AFMs are still largely uncharted [3]. Especially, the production technologies for the first large quantities and new motor topologies pose some huge challenges and have not yet been fully researched and developed, leaving room for optimization. Therefore, in-depth investigations and adjustments to production technologies are still required, with a focus on automated and large-scale series production of AFM.

In this paper, the authors examine the fundamental differences in the production process chains of AFMs and RFMs as well as the influence of different motor topologies and architectures on the respective characteristics of the used processes and process chains. Using one defined AFM topology as an example, process alternatives for each process step are presented and discussed through a comparative study. A subsequent evaluation concerning the technical process characteristics as well as the resulting automation potentials and limitations reveals the process suitability and performance metrics of the processes. Finally, possible optimization potentials along the process chain are identified and an optimized process chain is recommended for the investigated AFM process architecture.

Through this comparative approach, the authors aim to explain the inherent motivations for this paradigm shift in motor development, provide insight into the technological progress, and contribute to the science-based advancement of AFM technology that is driving this change. By examining the fundamental processes used to produce AFMs, a comprehensive understanding will be provided that will influence future motor design, efficiency, and overall system integration.

II. State Of The Art

This chapter initially addresses the basic topologies of AFMs and their characteristics and differences, before moving on to the manufacturing of electric motors and its associated production processes and chains. Thereby, the focus lies on the general production of electric motors, followed by the specifics of radial and axial flux motors and their components.

A. Different Topologies of Axial Flux Motors

AFM exhibit a diverse array of topologies, each carefully designed to meet specific application requirements and performance criteria. Fig. 1 shows a basic classification of different topologies of permanent magnet-exited AFMs by [4].

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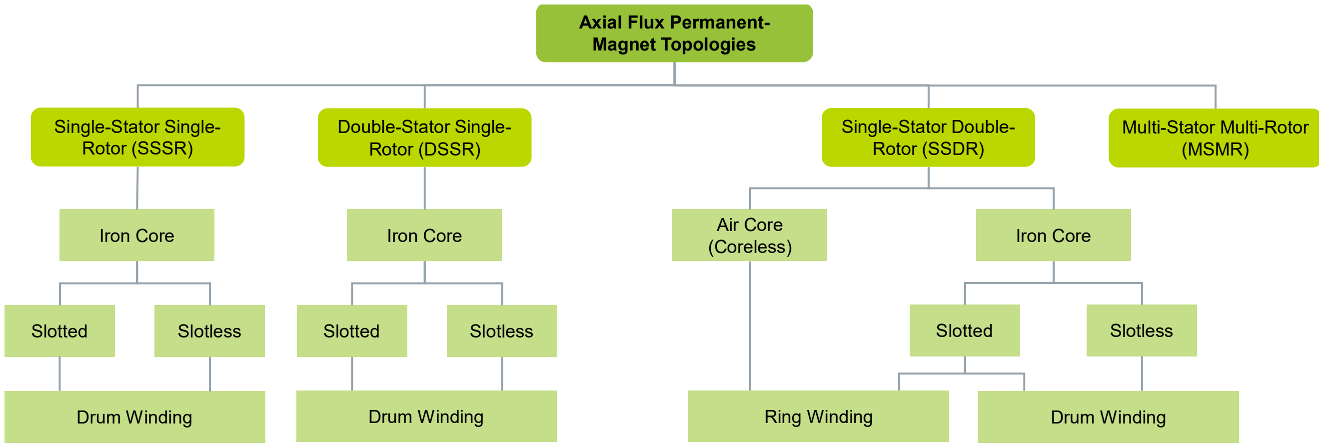

Fig. 1. Classification of different topologies of axial flux permanent-magnet motors [4]

Among these configurations, the single stator, single rotor AFM stands as a fundamental design, featuring a single rotor and stator disk assembly. This topology emphasizes simplicity and compactness, making it particularly suitable for applications where space is at a premium. Conversely, the double stator, single rotor AFM configuration introduces a second stator alongside the primary rotor, increasing power density and torque capabilities. This topology is often preferred for applications that require increased power output in a confined space. In contrast, the single-stator, dual-rotor AFM integrates a secondary rotor alongside the primary stator, providing increased torque output. This configuration is advantageous in scenarios requiring increased power and redundancy, such as aerospace and electric vehicle propulsion systems. In addition, the multi-stator, multi-rotor AFM configuration combines multiple stator and rotor assemblies to provide unprecedented levels of performance, redundancy, and fault tolerance. This topology is particularly beneficial in high-demand applications where reliability and operational resilience are paramount, such as industrial automation and renewable energy generation. The individual designs can be further categorized according to their various components. A distinction is made between the basic structure of the stator, which can consist of an iron or air core. There are also differences in whether individual teeth or one laminated core are used. [4]

In addition to the subdivision of the stator, the structure of the rotor can also be used for further classification. However, this study is not intended to outline the various motor topologies, but merely to show that there is a very wide variety of different topologies in the field of axial flux motors, which in turn entail an even greater variety of possible manufacturing technologies for their production. Flexible, automatable, and cost-effective manufacturing technologies for all components are therefore essential to ensure reliable large-scale production of various axial flux motors in the future.

B. *The General Production Process Chain of Electric Motors*

The electric motor manufacturing process chain is a complex and multi-dimensional task that involves a series of precisely sequenced steps to transform raw materials into high-performance electromechanical devices. Fig. 2 shows the general process chain for manufacturing an electric motor. The process begins with the careful selection of materials, which plays a critical role in determining the performance, efficiency, and durability of the final product. Key materials include soft magnetic laminations for the cores, high-

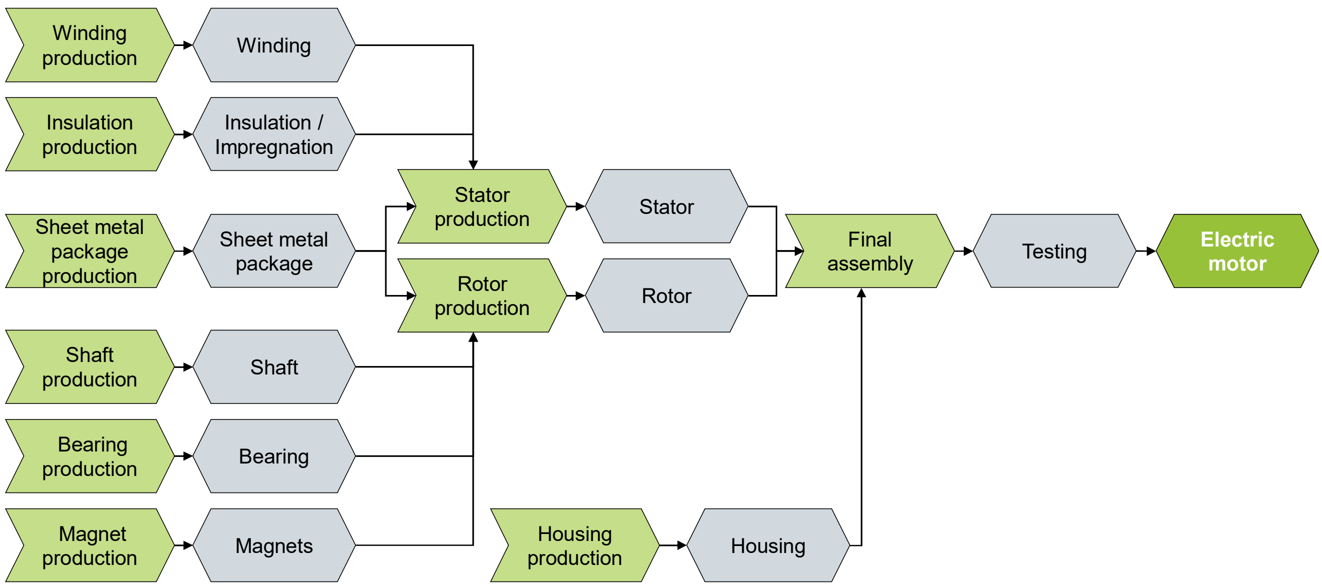

Fig. 2. The general process chain for manufacturing an electric motor comprises a large number of processes (based on [5])

conductivity copper wires for the windings, (permanent) magnet material for the rotors, insulation materials to protect against electrical breakdown, and various structural components such as housings, bearings, and shafts. These materials undergo strict quality control to ensure compliance with high standards and specifications. [5]

The production processes for the various assembly components of the electric motor are highly specialized techniques, such as precision machining, stamping, or laser cutting. In this first phase, the individual components such as magnetic laminations are formed into rotor and stator cores, the copper wire is wound into coils, and secondary components such as bearings, shafts, and housings are manufactured. The assembly phase of the manufacturing process then brings these individual components together to form complete motor units. This stage requires careful attention to detail to ensure proper alignment, fit, and functionality of all components. In addition, the assembly process may involve the use of adhesives, fasteners, and other securing methods to ensure structural integrity and long-term reliability. After assembly, electric motors undergo extensive testing and validation procedures to evaluate their performance characteristics and ensure compliance with regulatory standards. These tests may include insulation resistance, torque, temperature tolerance, and durability under various operating conditions. [5]

III. Differences in the Production Process Chains of Radial and Axial Flux Motors

The process chains for manufacturing electric motors for automotive applications are similar for most types of motors. Despite the completely different topology and geometry of a comparable RFM and AFM (c.f. [6]), a seemingly similar overall process chain can be applied for the manufacturing of the components of the stator and rotor. Within the individual processes, there might be still major differences as shown in [7]. The process chains for manufacturing stator and rotor components of radial and axial flux permanent magnet motors are shown in Fig. 3. To enable a better comparison of the process chains, RFM and AFM are both equipped with permanent magnet rotors.

To manufacture an RFM, the stator core is first packaged from individual electrical sheets [8]. The slots for the windings are fitted with slot base insulation paper to protect the primary insulation of the wire from damage when it is drawn into the laminated core and to increase the dielectric strength between the laminated core and the winding [9]. Traditional winding methods such as flyer winding, needle winding, or form coils such as hairpins can be used for winding [10]. After the windings have been drawn into the stator lamination stack, they have to be contacted according to the winding scheme. Processes such as laser welding, soldering, and hot crimping are available for this [11]. To reduce the resulting installation space, the winding head is formed and compacted. Once the insulation strength of the stator has been tested, the laminated core including the windings is impregnated using dipping or trickling processes [12]. [13]

The rotor of a permanent magnet RFM is also a laminated stack of electrical sheets. Depending on the requirements, the magnets can be attached in a specific pattern on the surface or buried in the laminated core [14]. In the case of an electric machine with buried magnets, the next step is to bond the magnets into the cavities using adhesives or resins. Once assembled, the rotor is checked for imbalance and can be balanced by subtractive or additive processes if necessary [15]. The magnets are then magnetized as a whole in the rotor using a pulse magnetizer [16]. The rotor and its attachments are then checked for geometric characteristics to ensure the rotor is ready for assembly. To ensure the desired performance characteristics, the rotor must also be tested for its magnetic properties. [13]

Compared to RFM, the process chain for manufacturing the stator and rotor components for AFM is somewhat shorter. This is because some processes can be saved by the AFM design. The compacting and forming of the winding head, which is used in the RFM stator, can be omitted in the stator of the AFM. Furthermore, the insulation step for slot insulation (not impregnation) is often omissive with AFM. In the rotor, the processes of magnet application and magnet fixation can be combined into one process for AFM. As the rotor disk has a flat geometry, the magnets used are flat-shaped and attached to the surface of the rotor disk. Thus, they do not have to be mounted in cavities or on a curved surface as in RFMs. This also means that less complex magnet geometries can be used, which simplifies mounting and bonding.

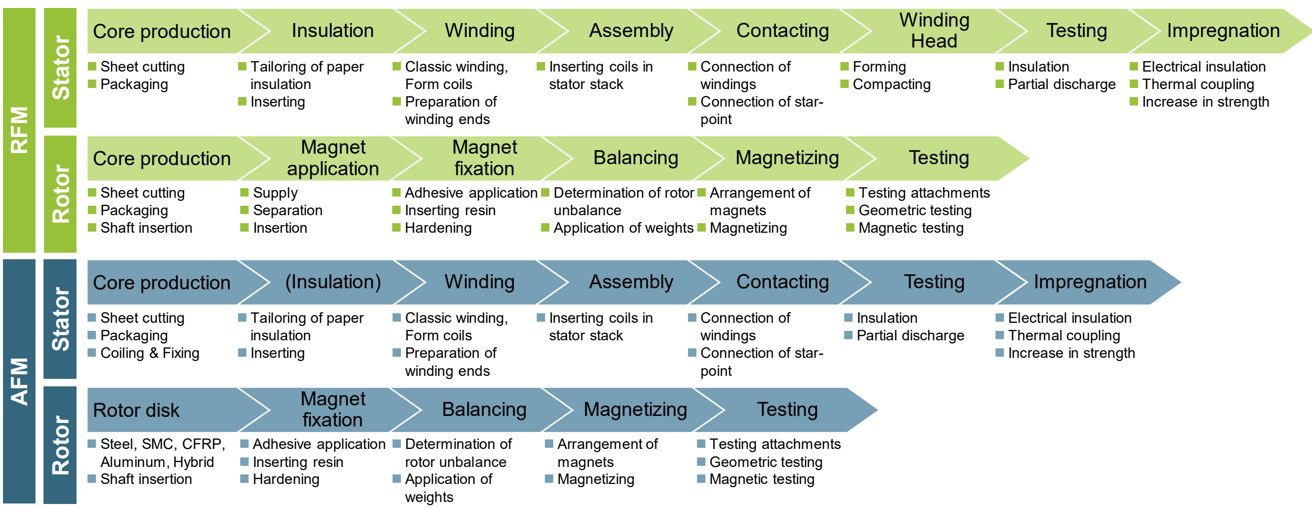

Fig. 3. The process chains for manufacturing stator and rotor components of radial and axial flux permanent magnet motors

Although the process chain for AFM appears to be shorter macroscopically than the one of RFM, this does not mean that it is any less complex. For this reason, a comparative study is carried out for selected processes in the following chapter.

IV. Comparative Study Of Process Chain Alternatives for An Exemplary Axial Flux Motor Topology

This chapter investigates with the help of a comparative study process technology alternatives for manufacturing a defined AFM topology. The investigation systematically analyses various process alternatives for the manufacturing steps of both the stator and rotor. Each process is evaluated based on suitability and quality metrics.

A. Topology of a Single-Stator Single-Rotor (SSSR) Axial Flux Motor with an Iron-Cored-Slotted-Drum-Winding-Configuration

To perform the envisaged comparative study, a defined AFM topology is used as an example. Based on this topology the process alternatives for each process step are analyzed and discussed. The selected AFM configuration is a Single-Stator Single-Rotor (SSSR) topology with an iron-cored-slotted-drum-winding configuration. This supposedly simple topology is already sufficient to demonstrate the multitude of possible manufacturing processes and variants. Fig. 4 shows the basic structure and a CAD model of the chosen SSSR under consideration.

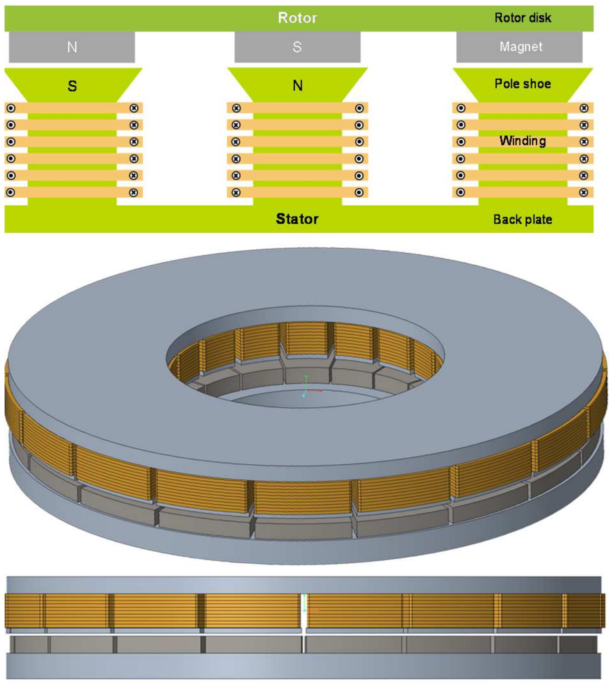

Fig. 4. The basic structure and CAD model of the exemplary SSSR AFM

The topology of the exemplary AFM consists of 18 laminated and coiled teeth in the stator, which are connected via a laminated backplate. In the SSSR machine considered here, not only the stator but also the rotor can be equipped with a laminated backplate to close the magnetic flux between the surface-mounted magnets. However, this is not possible for other AFM topologies. By adding a second rotor, for example, using just one stator backplate would lead to imbalances in the magnetic field.

The flexibility of the individual technologies is therefore of particular importance when setting up a process chain for the manufacture of AFM. In the following chapter, the process suitability of the various technologies for the different process steps is examined in more detail.

B. Potential Process Alternatives for the Consecutive Process Steps in Stator and Rotor Manufacturing

Looking at the possible processes for the manufacturing of the SSSR with two laminated backplates, it is noticeable that the stator as well as the rotor need a lamination stack. In other words, in both cases, electrical sheets have to be cut, stacked, and packaged. Furthermore, the magnets need to be attached to the rotor disk. The stator requires windings for the individual teeth and the windings must be electrically contacted as well as impregnated before proceeding to testing and final assembly.

In simplified terms, the manufacturing processes for the components of this AFM can be divided into six main types of processes, namely electrical sheet cutting, packaging of the sheets, magnet fixation, winding of the coils, contacting, and impregnation. For each of these process types, different production technologies are available and listed in Tab. I.

TABLE I. Production Technologies for the Chosen Manufacturing Processes

Sheet Cutting	***Core Packaging***	***Magnet fixation***	***Winding***	***Contacting***	***Impreg-nating***
Laser cutting	Welding	Caulking	Flyer winding	Soldering	Dipping
Rotary cutting	Riveting	Press-In	Linear winding	Laser welding	Dip rolling
Slot stamping	Brackets	Gluing	Needle winding	Resistance welding	Trickling
Punching	Bonding varnish	Injection molding	Toroidal winding	Ultrasonic welding	VPI
SMC	Sheet interlocking		Form coil	Ultrasonic crimping	Injection molding
	Injection molding		Trickling	Hot crimping	Potting

In the following, each of these process technologies is briefly presented for its suitability for use within the AFM process chain and then evaluated according to the criteria of automation capability, cycle time, flexibility, and costs. At the same time, a specific criterion is used for each process, which evaluates the process quality, for example.

C. Evaluation of Process Characteristics and Quality for the Considered Manufacturing Processes

To determine the most appropriate technologies for each process step, the various technologies are compared to each other using evaluation matrices. The rating scale ranges from very poor (--) to neutral (0) to very good (++) and represents a comparative evaluation for large production volumes and the considered SSSR as presented in III.A. Starting with the manufacturing process of electro sheet cutting all process steps are executed in the following.

Several processes can be used to manufacture the iron cores for rotor and stator. The evaluation matrix for electrical sheet cutting is shown in Fig. 5. In laser cutting, the individual laminations, including the slots, are cut from straight electric sheets. Because of the computer-controlled cutting process, the automation capability is very high. However, the cycle time is limited due to the individual processing of each sheet. Laser cutting allows a high degree of design freedom and keeps tool wear to a minimum. The investment and operating costs of laser systems are very high in comparison. Rotary cutting can be very well automated in the context of the AFM, as the coiled raw material can be wound directly into the final geometry after processing, resulting in a continuous process flow. Manual handling can be eliminated or at least be reduced to a minimum. The continuous process flow results in the minimal cycle times of all processes considered for volume production. Rotary cutting performs worse in terms of flexibility of sheet design freedom and tool wear but is the most cost-effective production technology in comparison. Slot stamping and punching are widely used technologies in the industry. However, the process is not flexible due to the tool movement required to separate the sheets, and cannot utilize the advantages that result from the different AFM geometry. This results in increased effort and long setup times when changing tools. Soft magnetic composites (SMC) on the other hand cannot compete in terms of costs and cycle times as well as their inferior magnetic properties. However, SMC can be very attractive in AFM with complex flux design. [17, 18]

	Laser cutting	Rotary cutting	Slot stamping	Punching	SMC
Automation capability	++	++	+	+	-
Cycle time	-	++	0	+	--
Flexibility	++	-	-	-	0
Tool wear	++	-	-	-	+
Costs	--	+	0	-	--

Fig. 5. Evaluation matrix for electro sheet cutting

The evaluation matrix for the stacking and packaging processes, which must be carried out for all the lamination processes, but not SMC, is shown in Fig 6. In addition to the suitability for series production, the most important criterion for series production when stacking and packaging the individual electrical sheets is the influence on the magnetic flux. The introduction of additional metallic components and the short-circuiting of the laminated sheets have a negative impact on the magnetic flux and the propagation of eddy currents in the laminated cores. [8, 19, 20]

	Welding	Riveting	Brackets	Bonding varnish	Sheet interlocking	Injection molding
Automation capability	++	-	0	+	++	+
Cycle time	+	0	+	-	++	--
Flexibility	+	+	-	0	--	++
Influence on magnetic flux	--	+	0	++	-	++
Costs	0	+	++	+	+	-

Fig. 6. Evaluation matrix for stacking and packaging the iron cores

To avoid this problem, the individual sheets can be fixed together by employing baking varnish or injection molding. However, these positive influences on the magnetic properties are offset above all by disadvantages in the cycle times. For this criterion, as well as for automation, sheet interlocking stands out in particular. Likewise, welding can be automated very well. Here, however, a conductive joint (short circuit) is created between the individual sheets, which in turn has a negative effect on losses. Brackets are the most cost-effective solution. Due to the mostly limited installation space in AFM, riveting cannot be used in many cases for process-related reasons. [8, 19]

	Caulking	Press-In	Gluing	Injection molding
Automation capability	+	-	++	+
Cycle time	++	+	-	--
Flexibility	-	--	++	0
Bonding quality	-	++	0	+
Costs	+	0	-	--

Fig. 7. Evaluation matrix for permanent magnet fixation on the rotor disk

For magnet fixation the evaluation results are shown in Fig. 7. The individual magnets must be fixed in the rotor to transmit the resulting torque to the rotor disk and at the same time to retain the magnets in place despite the attraction and repulsion forces and high centrifugal forces in working mode. In principle, either pre-magnetized magnets can be applied directly, or non-magnetized magnets can be used first and the entire rotor can then be magnetized in one step. The magnets can either be secured on the rotor in semi-open cavities with a material or a positive fit. In the case of caulking, the rotor is formed radially from the outside to secure the magnets with the bent laminated core. For press-in, the magnets are usually pressed into the cavities with an oversize. The sacrificial layer of the magnets is scraped off to ensure a tight fit in the cavity. Gluing and injection molding can eliminate the need for mechanical attachment. In this case, a full-surface material bond is created, which guarantees the best bonding quality. In terms of automation capability, gluing the magnets onto the rotor disk stands out as the most suitable process. Due to the high tool costs and complex tool geometries, injection molding the magnets is the least suitable method both in terms of cycle times and overall costs. [21–23]

	Linear winding	Flyer winding	Needle winding	Toroidal winding	Form coil winding	Drawing-In
Automation capability	++	+	+	--	0	-
Cycle time	++	0	-	--	+	0
Flexibility	0	-	-	--	+	0
Fill factor	+	+	-	0	++	--
Costs	++	+	+	--	-	0

Fig. 8. Evaluation matrix for the winding processes

Regarding the winding of the (copper) coils for the individual teeth, a distinction can be made between direct and indirect winding methods. The evaluation matrix is shown in Fig. 8. Form coil winding and drawing-in are indirect winding processes, as the coils are formed outside the stator and then inserted into the slots. The remaining methods in the matrix can be classified as direct winding processes. Due to its excellent automation capability, cycle times, and low costs, linear winding has become a standard process in the manufacturing of many electrical machines and AFM. The good copper fill factor, which influences the efficiency and performance of the electric machine mainly, can only be beaten by the form coil. Hereby, a perfect usage of the slot geometries with preformed coils can be observed. Due to their inherent complex tool movements, toroidal, flyer, and needle winding have limitations, particularly in terms of flexibility. [10]

	Brazing	Laser beam welding	Ultrasonic welding	Resistance welding	Hot crimping	Ultrasonic crimping
Automation capability	-	++	0	0	0	0
Cycle time	+	++	--	0	+	+
Flexibility	++	+	-	0	+	-
Contact quality	+	+	++	++	0	+
Costs	+	-	+	0	0	+

Fig. 9. Evaluation matrix for the contacting processes

The process of contacting the winding ends of the stator coils according to the winding scheme (c.f. Fig. 9) can be done with six different technologies. Hereby, adequate access to the stator and the winding ends is crucial. Processes such as ultrasonic and resistance welding as well as ultrasonic crimping require sufficient space for their tools. In the case of AFM, this space is usually only available on the outside of the stator. If additional joints need to be done on the inside of the stator, these methods are often not feasible. The inherently non-contact nature of laser welding means that it stands out here. Brazing and hot crimping can also not compete with laser welding in terms of automation capability. Furthermore, laser welding protrudes in terms of cycle times. However, the high investment costs are disadvantageous for laser welding and are only worthwhile for large quantities. Ultrasonic and resistance welding offer the best contact quality. [11]

	Dipping	VPI	Injection molding	Dip rolling	Trickling	Potting
Automation capability	0	-	0	++	++	+
Cycle time	--	--	0	+	+	+
Flexibility	+	+	--	0	-	+
Post-processing	--	--	+	-	++	++
Costs	+	-	--	+	+	-

Fig. 10. Evaluation matrix for the impregnation processes

The last evaluation matrix focuses on the impregnation and insulation technologies and is shown in Fig 10. Here, again, six different process technologies are compared with each other. Dipping is supposedly the simplest process, in which the component to be impregnated is completely immersed in a resin bath until all areas are fully impregnated. Dip rolling, on the other hand, immerses the component only as far as necessary on one side and then rotates the component to impregnate the rest. This saves some of the post-processing required for dipping. In contrast to these two dipping processes, with trickling the resin is applied directly and metered at the appropriate points via a nozzle. The VPI (vacuum pressure impregnation), injection molding, and potting processes use additional tools and in some cases pressure or vacuum to inject a resin or mold around the component. In terms of automation, dip rolling and trickling have the best capabilities. However, dip rolling is associated with a high level of post-processing. This also applies to dipping and VPI (vacuum pressure impregnation). The injection molding process is rather disadvantageous due to its high costs and limited flexibility. Potting excels in terms of post-processing, cycle time, and flexibility. However, this also applies to trickling. [12]

V. Findings Of The Evaluation And Identification Of Possible Optimization Potentials

This chapter discusses the findings of the comparative study, its limitations, and the preferred technologies for a process chain. In order to develop a potentially suitable process chain for the serial production of the previously chosen SSSR AFM, a selection must be made for each process step. Due to the special geometry and the difficult accessibility of this topology, not every evaluated method is suitable for the production of this kind of AFM. Based on the previous evaluation matrices, a decision matrix is now drawn up, in which the respective results are summarized as well as the preferred technologies for a possible process chain visualized. The decision matrix is shown in Fig. 11.

Process step	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5	Technology 6
Electro sheet cutting	Laser cutting	Rotary cutting	Slot stamping	Punching	SMC	
Packaging of sheet metal	Welding	Riveting	Brackets	Bonding varnish	Sheet interlocking	Injection molding
Magnet fixation	Caulking	Press-In	Gluing	Injection molding		
Winding	Linear winding	Flyer winding	Needle winding	Toroidal winding	Form coil winding	Drawing-In
Contacting	Brazing	Laser beam welding	Ultrasonic welding	Resistance welding	Hot crimping	Ultrasonic crimping
Impregnation	Dipping	VPI	Injection molding	Dip rolling	Trickling	Potting

Fig. 11. Decision matrix for the manufacturing of the SSSR AFM

Laser cutting and rotary cutting perform best for cutting electrical sheets. Due to the better cycle time and suitability for series production, rotary cutting is preferred. Laser cutting is better suited for prototyping and low-volume production, but also allows for more complex stacked designs. Due to the radial stacking of the rotor, the sheet must be bent to the radius of the finished part. This makes rotary cutting particularly suitable for this step, as it is ideal for processing coiled sheet material. The processed sheet material can then be rolled directly into the final geometry.

The bonding varnish process is well-suited for stacking and packaging the core sheets. In this process, the coated sheets are fused under pressure and temperature. The fact that the surfaces are bonded over a large area results in high mechanical strength and electrical insulation between the individual sheets. The absence of additional fastening elements and short circuits ensures that the magnetic flux is not impaired.

Gluing is the most suitable method to fixate the magnets, as it does not negatively affect the magnetic flux, and it allows greater freedom in the design of the magnet shapes or their arrangement. Besides its flexibility, gluing is a well-known process with multiple automation solutions. The accessibility of the cavities in the rotor disk of the axial flux machine is also not an obstacle.

Due to the stator design, which has a back plate and pole shoes, not all winding methods are suitable for winding the individual teeth. Due to the small distances between the teeth and the pole shoes, which affect the accessibility of the grooves, only needle winding can be used for this AFM design. Linear, flyer winding, or form coils are not suitable in this case due to the required kinematics and poor accessibility with backplate and pole shoes, although they had better evaluation results.

Since the windings of this AFM topology can be contacted not only on the outer circumference but also on the inner circumference, whereby the winding head and thus the overall diameter of the machine should be kept as small as possible, a contacting method is required that is suitable for the poor accessibility on the inner circumference. Due to its non-contact nature, the laser beam welding process is particularly suitable for this contacting task and therefore chosen.

Trickling is selected for the impregnation and insulation step. In addition to low post-processing, trickling also has high automation potential, reasonable cycle times, and costs. The discrete application of the resin means that all required areas can be reliably impregnated. However, this also represents a drawback of the process, as the nozzle position and resin dosage must be guided in a very defined manner, which results in a loss of process flexibility.

As this rather simple example already demonstrates, not all technologies are suitable for all topologies and the possible manufacturing technologies must be considered separately for each topology.

VI. Conclusion and Outlook

With this paper, the authors want to examine the fundamental differences in the production process chains of AFMs and RFMs as well as to outline the influence of different motor topologies and architectures on the respective characteristics of the used processes and process chains. Although the production steps required for manufacturing an AFM do not appear to differ drastically from those of an RFM, the actual technologies for the production of AFMs are still largely uncharted. Due to the many different design options and topologies, a more in-depth consideration is required in the future.

The comparative study carried out in this thesis is based on a defined AFM topology. Process alternatives for the six most important process technologies are presented, discussed, and evaluated. Due to the dependency on one AFM topology, in some cases, it is not possible to select the best-evaluated process alternatives for the final process chain as they are not applicable. Since the selected topology is rather simple and increasingly complex topologies emerge in the course of AFM development (e.g. a combined radial and axial flux [24]), the manufacturing technologies used must also be continuously further developed, checked for their suitability, and re-evaluated. The procedure for determining the final process chain can and should serve as a methodical example for the future selection of AFM manufacturing processes.

This study aims to identify optimal manufacturing strategies that improve the production quality and performance of AFM. The knowledge gained from this study will be used to improve the development and production processes of high-performance AFM technology.

References

[1] International Energy Agency. "Tracking Electric Vehicles." Accessed: Apr. 30, 2024. [Online]. Available: https://www.iea.org/energy-system/transport/electric-vehicles

[2] J. Zhao, X. Liu, S. Wang, and L. Zheng, "Review of Design and Control Optimization of Axial Flux PMSM in Renewable-energy Applications," *Chin. J. Mech. Eng.*, vol. 36, no. 1, 2023, doi: 10.1186/s10033-023-00868-8.

[3] Z. Hao, Y. Ma, P. Wang, G. Luo, and Y. Chen, "A Review of Axial-Flux Permanent-Magnet Motors: Topological Structures, Design, Optimization and Control Techniques," *Machines*, vol. 10, no. 12, p. 1178, 2022, doi: 10.3390/machines10121178.

[4] S. Kahourzade, A. Mahmoudi, H. W. Ping, and M. N. Uddin, "A Comprehensive Review of Axial-Flux Permanent-Magnet Machines," *Can. J. Electr. Comput. Eng.*, vol. 37, no. 1, pp. 19–33, 2014, doi: 10.1109/CJECE.2014.2309322.

[5] A. Kampker, *Elektromobilproduktion*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[6] A. Echle, A. Neubauer, and N. Parspour, "Design and Comparison of Radial Flux and Axial Flux Brushless DC Motors for Power Tool Applications," in *Proceedings, 2018 XIII International Conference on Electrical Machines (ICEM): Ramada Plaza Thraki, Alexandroupoli, Greece, 03-06 September, 2018*, Alexandroupoli, 2018, pp. 125–130, doi: 10.1109/ICELMACH.2018.8507221.

[7] A. Kampker, P. Treichel, K. Kreiskother, R. Pandey, M. K. Buning, and T. Backes, "Alternative Fabrication Strategies for the Production of Axial Flux Permanent Magnet Synchronous Motors for Enhanced Performance Characteristics," in *2018 8th International Electric Drives Production Conference (EDPC): Proceedings : 4 and 5 December 2018, Schweinfurt, Germany*, Schweinfurt, Germany, 2018, pp. 1–7, doi: 10.1109/EDPC.2018.8658341.

[8] M. Ziegler, M. Biburger, A. Kuehl, and J. Franke, "Influences of Joining Process Parameters on Stator and Rotor Cores for Electric Drives," in *2019 16th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Varna, Bulgaria, 62019, pp. 1–6, doi: 10.1109/ELMA.2019.8771687.

[9] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical Insulation for Rotating Machines*. Wiley, 2003.

[10] J. Fleischer, *Handbook of coil winding - technologies for efficient electrical wound prod*. Berlin, Heidelberg: Springer Fachmedien Wiesbaden, 2017.

[11] J. Seefried, A. Mahr, M. Weigelt, A. Kuhl, and J. Franke, "Challenges of Contacting Processes for Thin Copper Flat Wires in the Context of Electromechanical Engineering," in *2021 11th International Electric Drives Production Conference (EDPC)*, Erlangen, Germany, Dec. 2021 - Dec. 2021, pp. 1–8, doi: 10.1109/EDPC53547.2021.9684202.

[12] J. Richnow, P. Stenzel, A. Renner, D. Gerling, and C. Endisch, "Influence of different impregnation methods and resins on thermal behavior and lifetime of electrical stators," in *2014 4th International Electric Drives Production Conference (EDPC 2014): Nuremberg, Germany, 30 September - 1 October 2014 ; [including related conferences: E-Motive Forum of the German Machine Builders Association (VDMA), the Energy Transfer for Electric Vehicles Conference (E|TEV) ...]*, Nuremberg, Germany, 2014, pp. 1–7, doi: 10.1109/EDPC.2014.6984406.

[13] A. Kampker, H. H. Heimes, S. Kawollek, P.-E. Treichel, and A. Kraus, *Production process of a hairpin stator*, 2019. Accessed: Apr. 30, 2024. [Online]. Available: https://publications.rwth-aachen.de/record/792200/files/792200.pdf

[14] J. Franke, B. Hofmann, J. Tremel, and A. Meyer, "Innovative Methods for Automated Assembly and Fixation of Permanent Magnets in Electrical Machines," *Procedia CIRP*, vol. 26, pp. 724–728, 2015, doi: 10.1016/j.procir.2014.07.066.

[15] M. Masuch *et al.*, "Comparison of Additive Balancing Processes for Rotors in the Context of High Speed Electric Traction Motors," in *2019 9th International Electric Drives Production Conference (EDPC)*, Esslingen, Germany, pp. 1–8, doi: 10.1109/EDPC48408.2019.9012036.

[16] T. Wu, Q. Wang, Y. Yang, and Y. Lv, "Magnetization and Demagnetization Characteristics of NdFeB Blocks in Pulsed Magnetic Field," in *2020 IEEE 1st China International Youth Conference on Electrical Engineering (CIYCEE)*, Wuhan, China, 1112020, pp. 1–5, doi: 10.1109/CIYCEE49808.2020.9332761.

[17] Ş. Bayraktar and Y. Turgut, "Effects of different cutting methods for electrical steel sheets on performance of induction motors," *Proceedings of the Institution of Mechanical Engineers, Part B:*

Journal of Engineering Manufacture, vol. 232, no. 7, pp. 1287–1294, 2018, doi: 10.1177/0954405416666899.

[18] M. Dems, K. Komeza, W. Kubiak, and J. Szulakowski, "Impact of Core Sheet Cutting Method on Parameters of Induction Motors," *Energies*, vol. 13, no. 8, p. 1960, 2020, doi: 10.3390/en13081960.

[19] S. Steentjes *et al.,* "Effect of the Interdependence of Cold Rolling Strategies and Subsequent Punching on Magnetic Properties of NO Steel Sheets," *IEEE Trans. Magn.*, vol. 52, no. 5, pp. 1–4, 2016, doi: 10.1109/TMAG.2016.2516340.

[20] B. Schauerte, S. Steentjes, N. Leuning, and K. Hameyer, "A continuous parameter-based approach to model the effect of mechanical stress on the electromagnetic hysteresis characteristic," in *2018 IEEE International Magnetic Conference (INTERMAG)*, Singapore, Apr. 2018 - Apr. 2018, pp. 1–5, doi: 10.1109/INTMAG.2018.8508359.

[21] A. Binder, T. Schneider, and M. Klohr, "Fixation of buried and surface mounted magnets in high-speed permanent magnet synchronous motors," in *Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005*, Hong Kong, China, 2005, pp. 2843–2848, doi: 10.1109/IAS.2005.1518863.

[22] J.-Y. Lee, J.-H. Lee, and T. K. Nguyen, "Axial-Flux Permanent-Magnet Generator Design for Hybrid Electric Propulsion Drone Applications," *Energies*, vol. 14, no. 24, p. 8509, 2021, doi: 10.3390/en14248509.

[23] J. Lee, B. Park, and D. Koo, "Analysis of Mechanical Fixation Made of Aluminum Alloy in an Axial Flux Permanent Magnet Machine," *Journal of Magnetics*, vol. 19, no. 3, pp. 309–313, 2014, doi: 10.4283/JMAG.2014.19.3.309.

[24] R. Huang, C. Liu, Z. Song, and H. Zhao, "Design and Analysis of a Novel Axial-Radial Flux Permanent Magnet Machine with Halbach-Array Permanent Magnets," *Energies*, vol. 14, no. 12, p. 3639, 2021, doi: 10.3390/en14123639.