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Perspective

Additive Manufacturing of Electrical Machines—Towards the Industrial Use of a Novel Technology

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Abstract: For several decades, the design and manufacture of electrical machines has been considered a technically mature area and, as a result, research and development in the area has been extremely limited, even though this is a crucial technology in the application of electrical energy. Electrical machines are used in over 80% of the world's energy conversion processes—first to create electrical energy, which can be easily transmitted, and second to convert that energy into mechanical form for applications ranging from dishwashers to transportation, and from medical devices to those used for industrial processes. Today, two technologies are changing this. The first is the development of power electronic drives and the second is the introduction of additive manufacturing technology. The latter technology has opened up new areas for innovation and research, and many conventional processes are likely to become obsolete. Considering the overall consumption of electricity by electrical machines, the design freedom granted by the novel production technology gives the opportunity for even more efficient, object-oriented machines to be built, with a lower environmental impact and less raw material consumption. If this technology can be developed to maturity, it would have a significant positive impact on the desired green transition that is being pursued all over the world.

Keywords: additive manufacturing; construction; design; diagnostics; electric machines; materials; motors; optimization; thermal management

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1. Introduction

Additive manufacturing is an all-encompassing terminology in which manufacturing is done in layers and is rendered from a digital model. It emerged in the last few years as an alternative for conventional manufacturing techniques, offering virtually unlimited possibilities for a wide range of industrial and special-purpose applications, involving complex geometrical-shape realization and rapid prototyping. With the forecasted potential of what it has to offer, it will surely change the production industry's dynamics.

In the field of electrical machines, currently, applications are majorly modified/customized according to a rather small amount of generic machine types. The customization of these machines according to application requirements is hindered primarily due to the limitations and constraints offered by conventional manufacturing techniques. However, by means of maturity and advancement in the field of additive manufacturing of electrical machines, the dynamics will reverse towards the customization of electrical machines according to the application requirements. This means a new era for application possibilities. Considering the immaturity of the additive manufacturing of electrical machines, the possibilities cannot be utilized to their full potential, as methodologies and typical solutions for using the novel opportunities in all of the aspects are non-existent, including research on the material properties, design, construction, and whole manufacturing process.

2. Material Properties

The primary material properties that affect the electrical machine performance include magnetic, electrical, mechanical, and thermal properties. The limitations set by conventional manufacturing techniques in terms of material composition and processing possibilities hinder achieving the maximum limits of these properties. When considering additive manufacturing, it offers virtually unrestricted control over the following:

- Material composition;
- Selective anisotropy;
- Hysteresis and eddy current losses;
- Material electrical and thermal conductivity;
- Selective resistivity of layers;
- The grain structure of printed material;
- Topologies for enhanced mechanical strength and structural integrity;
- Complex geometry realization;
- Material density.

Various crucial and application-specific combinations of material properties that are otherwise impossible can be realized with additive manufacturing. For instance, a variation in only the powder mix composition [1] can yield a wide range of magnetic properties and densities with the added advantage of reducing the reliance on rare-earth magnetic materials. Additive manufacturing also lifts the constraints associated with mechanical processing requirements, as it does not involve mechanical steps for specific dimensioning and shape realization. Yet, accounting for the specific usage of metal alloys and their respective processing methods, there is a lack of research and developed methodologies.

With conventional manufacturing techniques, attaining a specific combination of material properties requires several unique manufacturing processes in a sequential order. It necessitates separate manufacturing resources and facilities for each individual component category. However, with additive manufacturing, by having control over material properties, the requirements of different or individual functional components can be achieved within a single manufacturing facility.

The research and development work in this field is currently being done in a segregated manner, with research regarding the mechanical and thermal properties at a relatively more advanced level than magnetic and electrical properties [1]. A more systematic approach is needed, as the specific solutions and universal approaches to utilize the advantages regarding the additive manufacturing of electrical machines do not exist. Most of the work has to be done regarding the mapping and standardization of the following:

- Material compositions for additive manufacturing processes;
- Grain structure yield for various additive manufacturing techniques;
- Material density;
- Electrical, magnetic, and thermal property yields for various powder-mix compositions;
- Effects and need for post-processing;
- Effect of topology optimization on material properties.

In conclusion, the development of novel compound and anisotropic materials, applicable to the additive manufacturing of electrical machines; additive manufacturing materials thermal treatment methods, to adjust the material properties for use in electrical machines; and novel methods considering how to isolate materials between each other, resulting in a comprehensive database for additive manufacturing materials to be performed with the above-mentioned parameters of interest. Additionally, a methodology regarding the optimization of losses connected with lattice structure possibilities also needs to be developed.

3. Design and Construction

The design and construction of electrical machines is a generally well-established area, in both the technical and process related questions. However, with the growth of even more energy-dense electrical machines, the conventional manufacturing process possesses significant limitations, leading to a small variety of technical solutions for design and construction. The following section describes the technical and process challenges for electrical machine design and construction using conventional manufacturing, and lists the possibilities for solutions to these challenges when using additive manufacturing as the manufacturing technique.

3.1. Technical Challenges Using Conventional Manufacturing

Although the decades of research in the field of design and construction has made electrical machines very efficient, reliable, robust, and economical, considerable work still needs to be done in the fields such as:

- Magnetic losses reduction [2,3];
- Reduction in the skinning and proximity and fringing effects [4];
- Local magnetic stress in the form of magnetic saturation [5];
- Thermal losses mitigation [6];
- Local thermal effect reduction for reliability improvement [7,8];
- Reduction of the probability of insulation failure [9,10];
- Smoothening of air gap magnetomotive force distribution [11];
- Reduction in the speed and torque ripples [12,13];
- Improvement in the power density of the machine (torque-to-weight ratio) [14];
- Optimization of the leakage fluxes for controlling the transient interval of the machine [15];
- Effective utilization of the machine geometry by controlling filling factors [16,17];
- Exploitation of the benefits produced by complex stator and rotor winding distributions [18];
- Complex optimized skews in the stator and rotor winding distributions [19];
- Reduction in the air gap friction by optimized stator and rotor slot openings [20];
- Reduction in the effects due to cutting and welding phenomena in the conventional approaches [21];
- Exploitation of complex non-symmetrical stator and rotor structure and windings [22];
- Meeting the consumer and standard specifications.

There are several examples of different aspects in electrical machine design possibilities regarding additive manufacturing. Yet, it has to be stressed that most of the reported individual results have been achieved through trial and error, as the technology is still relatively immature and not widely available. Hence, there is the utmost need for developing a typical procedure and methodology regarding different aspects, in order to reach the best possible results.

3.2. Process Challenges Using Conventional Manufacturing

Considerable work has already been done in the fields using conventional design and fabrication methods, but these approaches have already reached their maximum limit because of the associated technical limitations. As these machines are constructed in a part-wise manner, different parts are produced by different companies and are assembled later somewhere else, resulting in final assemblies. Regarding these aspects, the following challenges are prominent:

- Dependency of different manufacturers with different constraints on each other;
- Excessive logistic costs;
- Involvement of several steps depending on several organizations among design and fabrication;
- Time-consuming prototyping;
- Resource dense development of application-based specific machines;
- Impossibility to manufacture complex non-symmetrical machines.

All of these technical and operational issues can potentially be handled by exploiting cutting-edge additive manufacturing technology; however, the immaturity of the technology and infrastructure, as well as the current technology readiness level, do not allow for the full exploitation of additive manufacturing in electrical machines.

3.3. Solution for Technical Challenges Using Additive Manufacturing

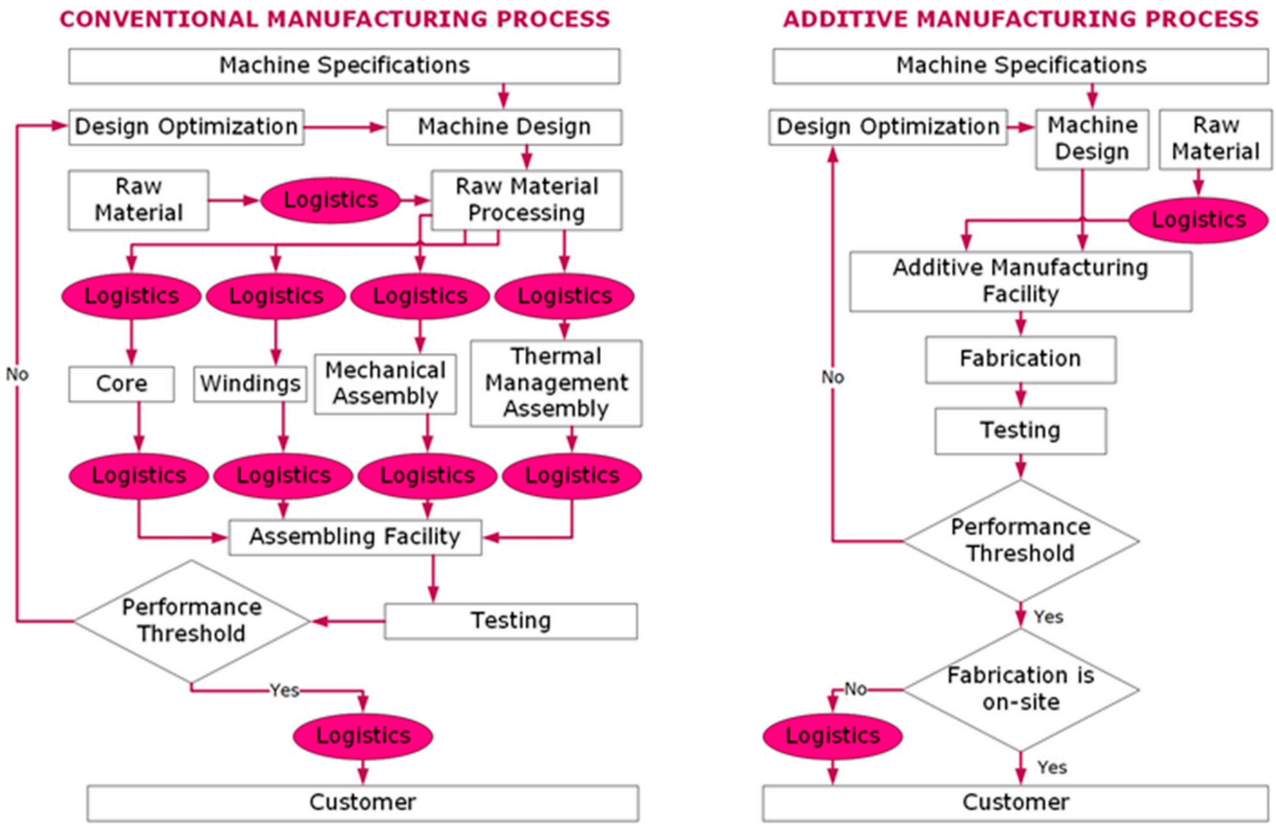
To give the overview on how the traditional manufacturing related technical challenges would potentially benefit from using additive manufacturing, a bullet list has been composed:

- As additive manufacturing allows for handling different compound materials, the machine's magnetic properties can be optimized by changing its percentage composition. It can also be achieved by designing complex non-symmetrical magnetic cores of the machine.
- Skinning and proximity effects can be reduced by printing the current-carrying conductors with different sizes and shapes, such as hollow structures.
- The local magnetic saturation impact can be reduced by changing the stator and rotor tooth tips' shape.
- Thermal losses can be handled by adjusting the current density in parallel conductors. Moreover, various cooling ducts can be printed in the slots, which is not possible using conventional techniques.
- Because of uneven insulation and more heat at the slot's center, the local hot spots can burn the windings. This can be handled by novel cooling methods and deploying a uniformly distributed insulation layer.
- The probability of insulation failure can be reduced by changing its thickness in different regions with different current densities and temperature profiles.
- Air gap magnetomotive force distribution is full of higher-order harmonics due to varying air gaps, which can be reduced by customized printing of the slot openings.
- Poorly optimized slot openings lead to speed and torque ripples. Additive manufacturing gives freedom for printing those slots for minimal torque and speed ripples.
- The machine size can be reduced by effective utilization of the magnetic and conductive areas.
- A fill-factor of almost unity can be achieved, not only reducing the dimensions but also the higher-order harmonics of the machine.
- Various complex winding distributions can be printed, leading to a uniform air gap flux density.
- Different customized skewing approaches can be used.
- Air windage losses can be effectively optimized.
- Cutting and welding effects in the case of conventional machines are no longer a problem.
- Additive manufacturing provides the possibility of producing specific-purpose non-symmetrical machines.
- Special machines with a limited number of demands can be printed without any economic burden.

3.4. Solution for Process Challenges Using Additive Manufacturing

Development-related conventional issues are no longer a problem in the case of the additive manufacturing of electrical machines. As all parts can be fabricated simultaneously, the overall process becomes economically feasible, fast, and reliable. The availability of different powder form materials provides freedom to optimize the design, and print and test it within a limited time window. As the dependency on different companies is minimal, the logistic cost reduction reduces the overall cost significantly.

Figure 1 shows the flowcharts of conventional manufacturing and additive manufacturing processes. It lists the advantages and solutions that additive manufacturing would provide in the field of manufacturing of electrical machines, provided that further research and methodological development is enhanced. The full potential of the mentioned solutions lacks the deeper and universal knowledge, development strategies, and matured methodologies, making it, today, at best, a trial-and-error-based approach.



(**a**) (**b**)

Figure 1. Flowchart comparing (**a**) conventional manufacturing methods and (**b**) additive manufacturing with advantages and solutions still in need of further in-depth research.

4. Thermal Management Systems

Thermal management systems impose limitations on machine operating limits, the environment, and lifetime usefulness. With the increased demand for high-performance electrical machines in modern-day applications, thermal management systems for electrical machines must also be improved regarding their efficiency. Conventional manufacturing techniques do not offer the flexibility of integrated functionalities within the individual machine components. This is why the placement of heat-exchangers and heat management systems within the heat source's immediate vicinity is usually not possible. The benefits offered by additive manufacturing can be exploited the most in terms of thermal management in electrical machines, as follows:

- Production of lattice structures in heat exchangers;
- Realization of complex geometrical shapes;
- Wide range of material selection for heat exchangers such as plastics or ceramics.
- Increased contact area for heat exchange;
- Customized heat-sink production in accordance with application-specific design requirements;
- Integrated functionalities;
- Novel heat-exchange topologies for a higher cooling efficiency;
- Placement of the heat exchanger near the heat source;
- Weight and size reduction for compact-size requiring applications.

Currently, great emphasis has been placed on the development of novel heat-exchanging structures utilizing honeycomb, finned foam, and Schwartz configurations, etc. Furthermore, liquid cooling options in the form of hollow windings, liquid-cooled stator slots, and rotor surfaces have also been explored [23].

There are several additively manufactured thermal management solutions that have shown promising results for usage in electrical machines [24,25]. Yet, there are no prototypes presenting the whole system integration of additively manufactured heat exchangers to additively manufactured electrical machines. In order to take the next step, in-depth study in the field must be carried out, adapting and developing the calculation and modelling methods in order to mature the technology enough to be implemented in the manufacturing industry and at a wider scale production.

5. Machine Optimization

Machine design optimization is a crucial step in the development of electrical machines. It is necessary for efficiency improvement, cost reduction, reliability, and various other electrical machine performance parameters. Electrical machines are complex structures of several components with different material properties, all produced by different suppliers. Those components include the following:

- Magnetic cores;
- Permanent magnets;
- Copper and aluminum conductors;
- Insulators;
- Shafts;
- Housing;
- Cooling mechanisms;
- Bearings;
- Control systems.

A well-optimized machine depends on each part's optimal optimization, which becomes costly and time-consuming, not only process-wise, but also logistically. Moreover, the fully optimized system, today, depends on trial and error methods, where the problems in any single part can drastically increase the production time.

In additive manufacturing setups, as all components can be fabricated simultaneously, novel grounds for optimization methodology development are being considered. There is the necessity to work with methodologies and tools, allowing these advancements to be achieved. Through the results of such research material, any machine could be optimized according to the shape of the components, overall topology, applicable control methods, using appropriate software, and being printed at the spot for experimental validation or production quality purposes.

6. Diagnostics

During the development of a novel technology, there are several subfields that have to be considered. One of the aspects leading to a high-quality end product is the operation, condition, and production monitoring. This can be summed up as the diagnostic procedure. Regarding the additive manufacturing of electrical machines, one of the most critical stages is the ideal printing of the machine parts. During this phase, several inner defects of the elements can occur (porosity, cracks, and uneven distribution of the material), the control of which is generally a time consuming and expensive process. In order to speed this process up and diminish the potential costs, novel fast diagnostic procedures must be developed to diagnose the faults and failures at the earliest possible stage.

The benefits provided by the additive manufacturing technology allow for the manufacture of novel electrical machine topologies, which, again, are in need of novel diagnostic approaches, as the physical behavior of the machines and their subparts is highly likely to be changed compared with conventional topologies. In addition, additive manufacturing technology allows for improvement of the applied sensorics in electrical machines, meaning the necessary measurement sensors can be implemented in the machine construction to the places where their existence is most desired. This, again, improves the monitoring of the machine behavior and leads to more accurate decisions regarding the electrical machine condition and operation.

However, it has to be stressed that considering the novelty of using additive manufacturing in electrical machine manufacturing, there has been no published research on such novel diagnostic approaches. This is because there are a very small amount of additively manufactured electrical machines available and thus the data are lacking. Considering that the technology must mature enough to be applicable for the industry, the diagnostic part must be developed in hand with the technology itself, in order to guarantee the reliable performance of the devices in their application field.

7. Situation Today

The authors have been involved in the research of the additive manufacturing of electrical machines since 2018. The field has been developing since that time, from the first trials in the production of magnetic cores and electrical machine components, to an active field of research, where several research groups from all over the world are involved. The fact that the topic is of high interest can be seen from topical conferences, where, for example, IEEE International Conference on Electrical Machines received a number of presentations and papers for dedicated sessions [26–34].

Through the past few years, the basis for the methodical understanding has been laid, on which, in the future, the topologically optimized electrical machines and their components, produced by additive manufacturing, can be relied on. There has been significant progress made regarding conductive material printing, the maturity of which can be utilized for industrial use [35,36]. However, this can be applied, today, mainly to niche products, as the printing of insulation layers is still both complex and problematic to the conductive parts [37,38]. Similar problems can be found in the case of additively manufactured soft magnetic cores, where there is a problem with eddy-current suppression, leading to a decrease in energy efficiency [39–41].

Although these challenges persist, there are promising results in the production of magnetic cores from 3.7% silicon steel [42–44]. The publications on the topic show that the properties of the prototypes are not far from the standardized magnetic core materials [45]. The authors and their teams have also made attempts to manufacture functional electromagnetic devices with fully printed magnetic cores [42,46–48]. These attempts have been successful, although the devices' parameters are somewhat lower than in their industrial analogues. This can, however, be expected, as these are the first prototypes and first trials in the development stage.

The further steps in the applied research in the additive manufacturing of electrical machines must include optimization of the electrical machines in order to produce a sufficient magnetic flux, thermal flux, and electric current conductors, together with the fitting diagnostic and operational maintenance methods. Through this, the reliability of such devices can be mapped and improved.

8. Conclusions

In conclusion, additive manufacturing provides new possibilities as an emerging agile manufacturing industrial branch, which is nonexistent in the case of the electrical machine manufacturing industry. The biggest challenge providing enough developed methods and methodologies in all stages of electrical machine design, and to find typical appropriate solutions that can later be standardized. Only through these steps, will the technology be able to reach a readiness level where it can be utilized to its full potential and be usable for engineers in industry, in order to produce novel, efficient, and reliable 3D printed electrical machines. The flow, intended to tackle gaps in the existing research, is presented in Figure 2.

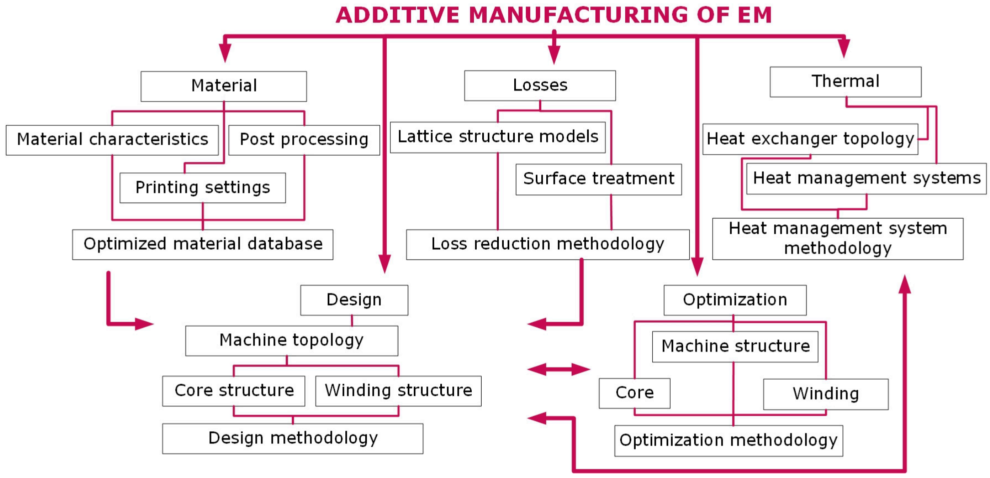


Figure 2. Interconnection of fields in need of methodological advancement and further research.

It is highly likely that the additive manufacturing of electrical machines will, at first, remain a niche product, until the multi-material printing technology becomes faster and more available for a larger community of engineers and researchers. However, it has to be considered that the development of additive manufacturing systems is very fast and it is only a question of time before the additive manufacturing of electrical machines will reach the mainstream. For this to happen, there must be significant effort and input made by the scientific community in order to mature the technologies and methodologies enough to meet industrial needs.

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