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Review

Recent Trends in Additive Manufacturing and Topology Optimization of Reluctance Machines

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Abstract: Additive manufacturing (AM) or 3D printing has opened up new opportunities for researchers in the field of electrical machines, as it allows for more flexibility in design and faster prototyping, which can lead to more efficient and cost-effective production. An overview of the primary AM techniques utilized for designing electrical machines is presented in this paper. AM enables the creation of complex and intricate designs that are difficult or impossible to achieve using traditional methods. Topology Optimization (TO) can be used to optimize the design of parts for various purposes such as weight, thermal, material usage and structural performance. This paper primarily concentrates on the most recent studies of the AM and TO of the reluctance machines. The integration of AM with TO can enhance the design and fabrication process of magnetic components in electrical machines by overcoming current manufacturing limitations and enabling the exploration of new design possibilities. The technology of AM and TO both have limitations and challenges which are discussed in this paper. Overall, the paper offers a valuable resource for researchers and practitioners working in the field of AM and TO of electrical machines.

Keywords: additive manufacturing; topology optimization; level set; synchronous reluctance machine; switch reluctance machine; ON-OFF method; material density; genetic algorithm; power bed fusion; binder jetting; soft magnetic materials

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1. Introduction

The future goal of reducing carbon emissions in transportation can only be achieved by exploring and implementing new technologies and innovative designs for drive-train components. This will require a change in the traditional approach to electrification, as outlined in various roadmaps [1–3]. Additive Manufacturing (AM) or 3D printing technology is one of the developing technologies of the current contemporary era. AM is a technique for fabricating physical objects in which the substrate or powdered materials are deposited layer by layer to build the 3D object [4,5]. Compared to conventional manufacturing techniques, AM has several advantages over traditional manufacturing processes, such as the potential to decrease material waste and trash parts coupled with the conventional method [6].

In recent years, the use of additive manufacturing has grown in the field of electrical machines, providing new possibilities for design and production of these machines, although the technology is still maturing and has the potential to progress significantly. The manufacturers are able to save the vital resources that would be greatly wasted in the traditional subtraction-based production since AM allows for freeform limitless shape complexity. In addition, AM technology could provide the most affordable and frequent prompts to fabricate small volumes of extremely complicated shapes [7]. However, a fully assembled AM electrical machine is still a dream for large-scale manufacturing and industrial applications due to a number of challenges, including slow manufacturing speed, inner structural imperfections, constrained multi-material printing potential, and the requirement for postprocessing printed parts [8].

In order to maximize performance and efficiency while reducing size, weight, and losses, optimization is required in the design of electrical machines. The two primary sub parts in the design process for an electrical machine are design and preliminary design optimization [9,10]. By investigating several topologies and doing muti-disciplinary study of the machine, engineers use design optimization to determine the best essential performance parameters for a specific application [11,12]. The objective of conventional optimization techniques for the design of electric machines is to find the optimum values of the parameterized geometric variables by altering them within a defined range. However, conventional optimization is limited to optimizing shapes within predefined boundaries and cannot change the topology of the design. Topology optimization, on the other hand, overcomes these limitations by allowing the design of the structure to be changed during the optimization process, resulting in more optimal solutions [13].

Furthermore, the advantages of using AM for Topology Optimization (TO) include the ability to create complex geometries and internal structures that would be difficult or impossible to fabricate using traditional manufacturing techniques. TO is a design method that aims to find the optimal layout of a structure or system in order to meet certain design objectives, such as minimizing weight or maximizing average torque. Compared to the geometric parameterization and optimization of rotor flux barriers, TO provides a smoother barrier design by allowing for flexible material distribution within the design space [14]. However, the manufacturability level of the TO is lower than the conventional optimization, but thanks to the AM technique, it makes possible the fabrication of these complicated geometries.

Researchers work on the different techniques of AM and TO, but there is limited literature available on the integration of AM and TO. This paper reviews the use of TO and AM with regard to magnetic components for electrical machines. In order to provide background for further discussing the integration of TO in a later section of the paper, the paper initially highlights the primary AM techniques, with a particular focus on those pertaining to electrical machines. Additionally, various soft magnetic material types are examined for possible use in AM. The state-of-the-art current literature of AM and TO, particularly with regard to iron cores and windings in reluctance machines, is also covered in more detail. Some challenges and limitations in the AM and TO are also summarized in this paper. These case studies emphasize the innovative integration of these cutting-edge technologies and demonstrate their potential for use in electrical machine design in the future.

2. AM Technologies Suitable for Electrical Machines

Despite being designed for low-volume manufacturing with a low manufacturing rate (0.01–1 kg/h) and high cost (USD 0.1–10 per gram) [15], the potential for AM's application to expand exponentially is expected to grow. This is due to its rapid development in terms of material accessibility and process quality, which indicates a significant increase in the extent and diversity of its utilization. There are several printer types used for additive manufacturing; among these, the four AM technologies listed below are the most well-known and developed for commercial applications.

- Powder Bed Fusion (PBF)
- Binder Jetting Technology (BJT)
- Direct Energy Deposition (DED)
- Resistance Heat or Joule Printing (JP)

The Powder Bed Fusion (PBF) is also known as Selective Laser Melting (SLM) or Electron Beam Melting (EBM). The majority of current metal additive manufacturing systems use PBF technology [16]. For building full-density products, current PBF AM techniques often employ melting rather than sintering. However, rather than using a laser or other energy source to fuse the powder together, binder jetting uses a liquid binding agent to join the powder particles together [17]. Binder jetting is generally considered to be a more cost-effective method of fabricating parts compared to electron beam melting (EBM) and selective laser melting (SLM). However, binder jetting typically requires extensive post-processing after the 3D printing process is complete. The binder-bonded parts produced by binder jetting are typically weak and brittle and require additional processing steps to achieve the desired strength, hardness, and surface finish. In order to create high-performance superalloys, direct energy deposition (DED) has been developed. DED employs a laser or electron beam as an energy source that is simultaneously utilized to melt feedstock material (powder or wire) and is narrowly focused on a small area of the platform. The difference between DED and PBF technologies is that DED does not employ a powder bed and melts the feedstock layer by layer before deposition while using a much larger amount of energy to melt metals. This technique enables the simultaneous deposition of different materials and various axis [18]. When compared to PBF, it can construct less complicated components and has a lower precision, surface quality, and manufacturing capacity [19,19,20]. Joule heating uses direct electrical current with resistance heating for melting and layer bonding; it is somewhat comparable to other wire feed technologies like DED. Compared to other techniques, this method uses a single feed and melt process and a far more basic raw material. As a result, this simplicity reduces expenses and time saving [21–23].

Figure 1 shows the overall comparison of the aforementioned techniques. Both PBF and BJT provide higher resolution, which is needed in most applications, but are limited by printing speed. Further, DED and Joule printing are faster while having a lower resolution. On the other hand, EBM and SLM are typically more expensive 3D printing methods that use high-power lasers to melt metal, ceramic, or polymer powders into solid objects. However, EBM and SLM can produce high-quality, high-density parts with high mechanical strength and fine resolution, making them suitable for applications where high performance is required.

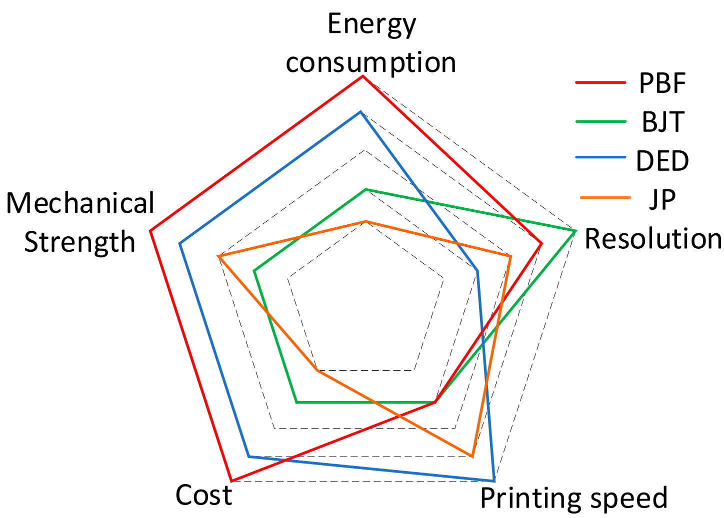


Figure 1. Different AM techniques comparison.

3. Soft Magnetic Materials for AM Machines

Iron cores for electrical machines are traditionally made from non-oriented electric steel laminations and these laminations are stacked together to form the core of the electrical machine [24]. However, the problem of low mechanical strength in thin sheets causes bending during stamping, which in turn reduces the ability to stack the laminations at a high stacking coefficient. Another problem is that electrical steel laminations can only be stacked in flat sheets and cannot be molded into intricate 3D patterns, which limits its application in 3D iron cores [25,26].

AM has the potential to bring advancements in the field of magnetic materials by allowing for the 3D printing of high-quality powdered soft magnetic materials, resulting in the creation of complex-shaped iron cores with improved control over the electromagnetic and mechanical properties [5,27]. Furthermore, these materials are typically iron-based alloys such as iron–nickel, iron–cobalt, and iron–silicon alloys can be printed. In [28] the author demonstrated that using Fe–6.5Si alloys in the AM process of the iron cores of electric machine components results in better magnetization properties compared to using Fe–3Si alloys with a lower silicon content. The use of Fe–6.5Si alloys also leads to a reduction of more than 50% in eddy current losses at 50 Hz frequency. Iron cores for electrical machine may be 3D-printed using Fe–Ni alloys with high nickel compositions (up to 80%). The magnetic characteristics of these alloys include low saturation magnetic flux density but exceptional properties regarding permeability and losses. Among soft magnetic materials, Fe–Co alloys have the greatest saturation magnetic flux density, with the 50–50% Fe–Co alloy having a saturation magnetic flux density of 2.45 T [29]. The magnetic properties of commonly used soft magnetic materials for AM is summarized in Table 1.

Table 1. Different soft magnetic material properties used for AM.

Material Compositions	Max. Saturation (T)	Relative Permeability (μ_r)	Resistivity $\rho(\mu\Omega cm)$	Density (g/cc)	AM Technique	Reference
Fe–Si6.5	1.8	10,700	82	7.3–7.7	BJT	[30]
Fe–Co-based alloy	2.4	20,000–66,000	40	8.12	SLM	[31,32]
Fe–49Co-2V	2.23	-	49.4	-	PBF	[33]
20%Fe–80%Ni	1.08	8000–120,000			SLM	[34]

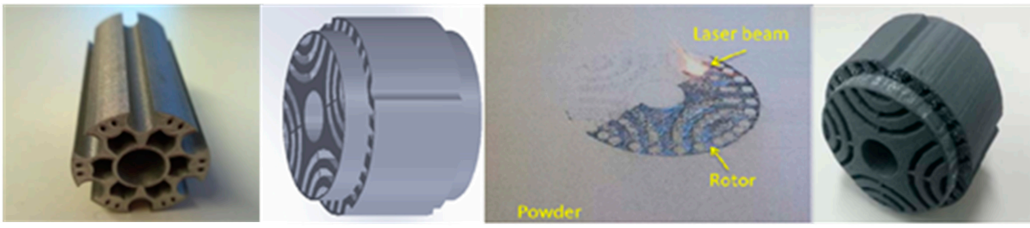
4. Electrical Machines Manufacturing Using AM Techniques

With the use of 3D computer-aided design, AM is rapidly developing a collection of new manufacturing technologies that allows for the direct manufacture of components from powder or wire filament. AM technology should make it unnecessary to do extra processing in order to produce intricate 3D geometries [35]. Furthermore, AM may reduce or even eliminate the material waste and scrap components that are common in many conventional manufacturing techniques. In general, the 3D printing process recycles wasted wire and powder to fully use the raw material [36]. Although some efforts have been made to bring a more holistic approach, where multiple parts are produced using AM, it is noteworthy that the majority of work linked to the AM of electrical machines is focused on the individual machine components and materials. In this section, the focus is on the electrical machine's active parts, and it includes the core and windings of the machine.

4.1. Stator and Rotor Core of Reluctance Machines

In order to build contemporary electrical machines with high specific output, magnetic materials are necessary. There are several electrical steels and soft magnetic composites (SMCs) used in the current procedures for creating magnetic cores. The most common method for producing a magnetic core is to stack a number of electrical steel profiles or lamination sheets that have been properly prepared, or to compress a mixture of metal powder and an insulating material [37]. However, these materials are often challenging to address using traditional methods because of their poor mechanical properties and limitations on the manufacturing of complex geometries.

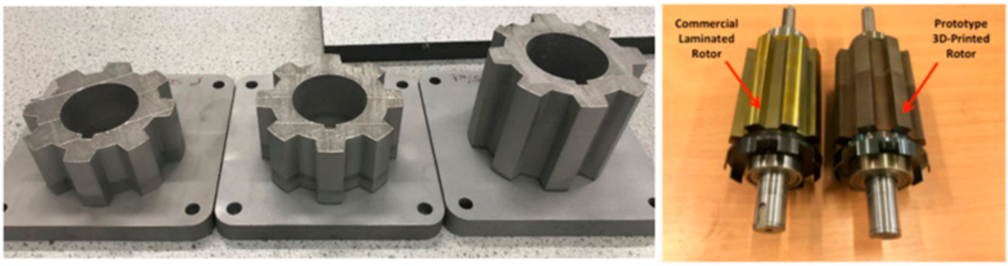
With respect to the fabrication of magnetic parts and components, AM offers a compelling alternative to the well-established methods. The optimized switch reluctance machine rotor, which has six poles of the salient type, is shown in Figure 2a. This rotor was constructed using the PBF technique from an iron–cobalt alloy with a magnetic flux density of 2.3T. The authors also indicate that to decrease the specific power loss, the electrical resistivity of the developed design might be further enhanced [29]. Moreover, Figure 2b depicts the synchronous reluctance machine's rotor, which was fabricated using the PBF AM approach [38].



(a) (b)

Figure 2. Electrical machine cores manufactured through AM techniques: (**a**) Rotor prototype of switched reluctance machine [37]; (**b**) Rotor core of synchronous reluctance machine [38].

In [39], the 3D-printed rotor of switched reluctance machine was compared with the benchmark machine. Due to the focus being on the material performance, both rotor prototypes' designs and dimensions were the same. Moreover, the rotor prototype was also manufactured in three segments owing to the height limitations of the 3D printer. The two segments' axial lengths are 25 mm each, the third segment is 54 mm long, and the rotor's total axial length is 104 mm, as shown in Figure 3a. Due to the segmentation, the 3D-printed rotor was also ensured to have lower eddy current losses than the solid component. In Figure 3b the fully assembled 3D-printed rotor is shown and was compared with the laminated benchmark rotor. This study demonstrates that the 3D-printed rotor produces results similar to those of the benchmark rotor while yet leaving a significant opportunities for performance improvement [40].



(a) (b)

Figure 3. 3D-printed SRM rotor: (**a**) 3D-printed segments of rotor; (**b**) Commercial and 3D-printed assembled rotor [39,40].

In order to lessen the torque ripples and windage loss, a novel skew rotor design for switched reluctance machines was proposed. It has 2 mm thick ribs with 0.4 mm diameter holes in a honeycomb structure as shown in Figure 4. Using the conventional process, it was challenging to construct this rotor design. The AM method of PBF is used to build the prototype for this rotor design. Additionally, the 45% decrease in the machine's torque ripples profile was shown by the experimental results [41].

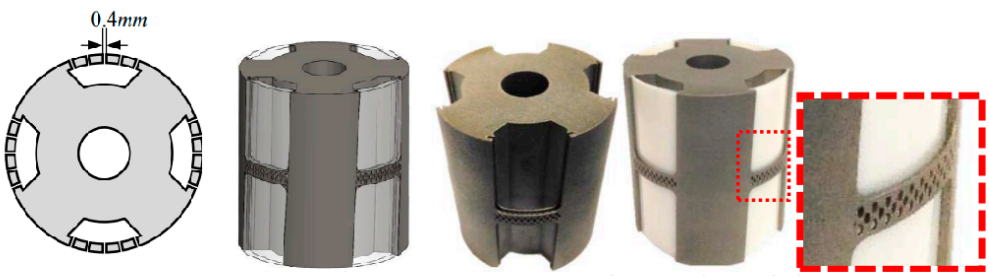


Figure 4. 3D-printed SRM rotor with honeycomb rib [41].

As the type of reluctance machine is most suited for PBF fabrication because it only needs one alloy powder, a fully assembled, fully functional axial flux switched reluctance was developed utilizing this technology. Other machine types, such as permanent magnet machines or induction machines, need several materials, making it challenging to print them using AM owing to the use of many materials. Due to the disparity in component sizes, the suggested machine was printed in five phases. For the whole machine with stator halves, the printing process takes 57 h. Figure 5 [42] depicts the different parts and fully assembled machine. Additionally, annealing was done to enhance the magnetic characteristics. In order to do this, the toroid was heated for one hour at a temperature of 1150 C with a heating rate of 300 K/h, and then gradually cooled [43].

Figure 5. Printed axial machine having stator halved embedded teeth [42].

In addition to emphasizing the internal design and manufacture of electrical machines, the author of [44] showed a prototype of an induction machine that was manufactured employing additive manufacturing. The author introduces airgaps in the core in the form of crack-like printed regions to enhance the internal resistance of the core, and these airgaps were placed perpendicular to the core axis. The rotor and stator core were manufactured using metal rods, and the author stated that it is the first 3D-printed machine in scientific literature whose performance has been assessed. Figure 6 depicts the stator and rotor of a printed induction machine. Despite the irregular airgaps between the thick material layers, the 3D-printed induction machine exhibited the nominal torque of 0.5 N-m at an efficiency of 34% when compared to the benchmark machine [45] whose efficiency was 52%.

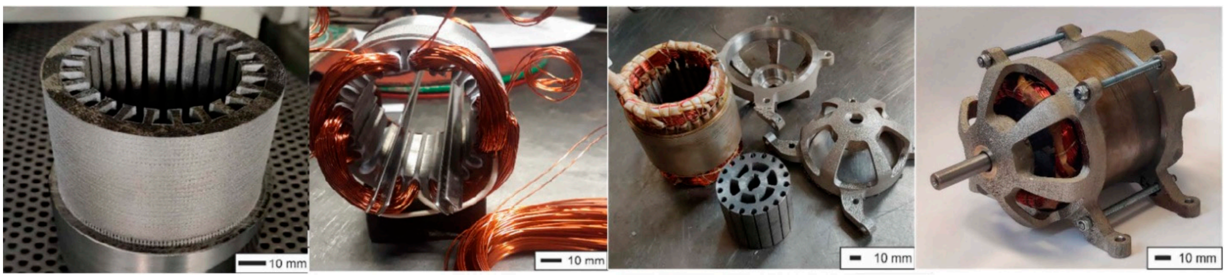


Figure 6. Fully assembled AM induction machine [44].

According to [46], a line start synchronous reluctance machine was designed with a novel, robust structure for less copper losses and vibration. As shown on the left side of Figure 7, the flux barriers include small ribs that go both in the xy and z directions to create a grid-like structure. Aluminum paste was placed within the cage of the line start synchronous reluctance machine, which was then heated to produce a solid aluminum cage as shown in Figure 7. The filling of the barriers lessens the machine's vibration, but this impact also lowers the saliency ratio, which reduces the torque.

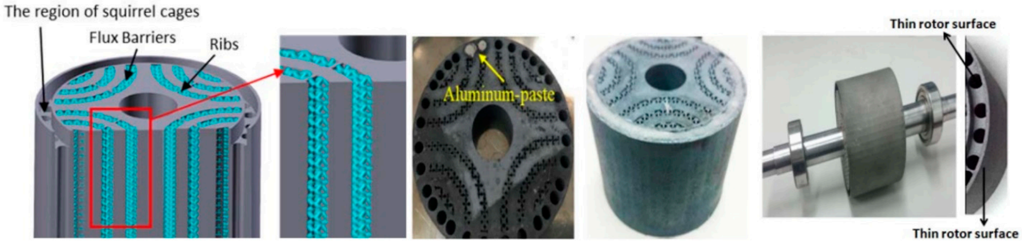


Figure 7. 3D-printed rotor of line start synchronous reluctance machine [46].

4.2. Windings

Electrical machine windings refer to the coils of wire that are used in electrical machines, to generate or utilize electromagnetic fields. These windings can be made of copper or aluminum and are typically wound around a core made of iron or other magnetic material. The development of modern electrical machine windings continues to be an active area of research and development, with the goal of creating more efficient and cost-effective electrical machines. In addition, AM is a promising technology for creating electrical machine windings, as it allows for the creation of complex geometries and can improve the performance and efficiency of the machine. It is important to note that the use of additive manufacturing for winding production is still in its early stages and there are not yet many examples in the industry, but it is considered a promising technology for the future.

In addition, the use of AM in electrical machines may serve a variety of goals, such as improving power density by improving the fill factor [47,48], optimizing end-winding [49,50], or integrating conductors with cooling channels [51]. The advancement in AM is the 3D multi-material printing which offers more design freedom and a faster and unique structure of fabricating different machines. Some examples of multi material printing are shown in Figure 8 [52–55]. This comprises ceramic materials that, in terms of various physical characteristics like heat resistance or thermal conductivity, outperform more traditional organic insulating materials composed of plastic. In this approach, electrical coils with much greater temperature resistance may be produced.

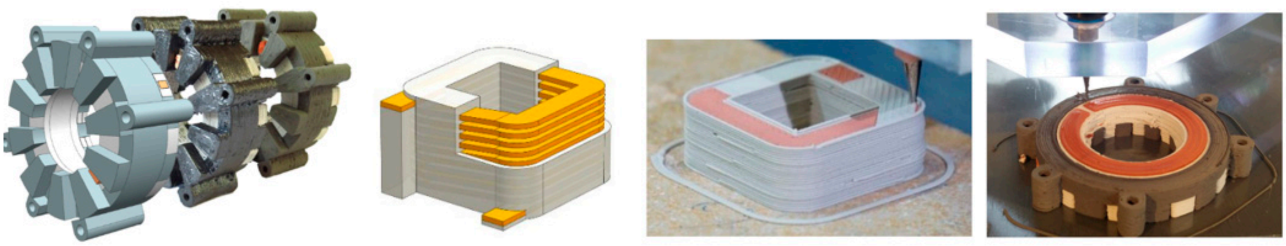


Figure 8. 3D-multi material printing technology [53–55].

The hybrid stranded concentrated winding of a high-speed traction machine is shown in Figure 9a, the resulted machine yields 60% reduction in the overall losses [56]. These improvements can be utilized to enhance the power density and reliability of the machine. The author in [57] demonstrated different types of AM coils prototype using different materials for low weight and low losses applications and was compared with the conventional manufactured coils. All four coils are shown in Figure 9b, which are then placed in the E-core. The performance comparison of different cores is illustrated in Table 2. The high fill factor and low AC losses were achieved as compared to the traditional one. Additionally, AM introduced new materials that gained attention in the enhanced thermal management method. In [58,59], the authors provide a detailed explanation about the advanced thermal management for AM machines.

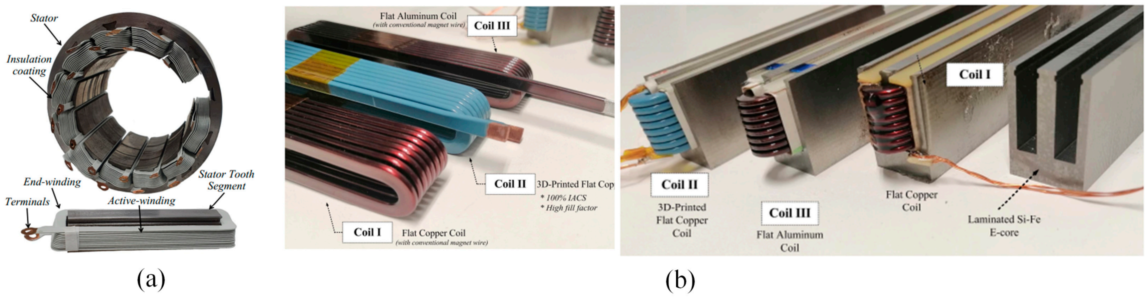


Figure 9. AM-based coils: (**a**) Concentrated AM copper coils [56]; (**b**) Solid flat shaped coils using different materials [57].

Table 2. Different coils comparison using different materials [57].

Type of Conductor	Flat Copper Coil	AM Shaped Copper Coil	Flat Aluminum Coil	AM Shaped Aluminum Coil
Material	Commercial copper	Pure copper powder	Commercial aluminum	Aluminum alloy powder
Insulation	Enameled	Class H-resin	Enameled	Class H-resin
Manufacturing	Commercial wire	3D printed	Commercial wire	3D printed
Fill factor	72.7%	77.96%	71.3%	62.4%
Cycle time	<one hour	9–10 h	<one hour	4–5 h
Mass density	8.96 g/cm^3	8.95 g/cm^3	2.7 g/cm^3	2.67 g/cm^3
Coil weight	171.2 gm	183.6 gm	55.2 gm	47.8 gm
DC losses	1 p.u	0.83 p.u	1.6 p.u	2.68 p.u
AC losses	81.6%	76.5%	64.5%	31.4%
Total losses	4.155 p.u	4.343 p.u	4.371 p.u	3.902 p.u
Efficiency	98.04%	97.76%	97.52%	98.71%
Frequency	Up to 900 Hz	Up to 900 Hz	Above 1.2 kHz	Above 900 Hz

5. Optimization of AM Electrical Machines

Optimization in electrical machine design refers to the process of making improvements to the design of an electrical machine in order to maximize its performance and/or cost-effectiveness. To examine and optimize several aspects of the machine, including various parameters such as the shape of the machine, mathematical models and algorithms are often used. The goal is to find the optimal trade-off between design objectives and constraints, such as power density, torque density, efficiency, size, weight, cost, and materials. Generally, optimization techniques can be classified as deterministic and stochastic optimization. Deterministic optimization techniques, such as gradient-based methods, use a specific mathematical formula to find the optimal solution. They are fast and reliable but may be trapped in a local minimum while stochastic optimization techniques, such as genetic algorithms and particle swarm optimization use random processes to explore the solution space. They are less likely to get trapped in a local minimum but may be slower and less reliable [60]. The choice of method depends on the specific problem and requirements of the application.

Moreover, commonly used machine geometry templates and mathematical models for optimization are used to shape magnetic structures in electrical machines. These methods are well established and have been used for many years in the design and optimization of electrical machines. The use of these methods can make the design process more efficient and manageable, but it also restricts the design options to the predefined parameters, limiting the possible shapes and forms that can be generated. On the other hand, topology optimization (TO) is a more recent technique that involves the optimization of the overall layout and structure of the magnetic components in an electrical machine, rather than just the shape of individual components. For example, in the design of electrical machines, flux barriers inside the rotor or stator design spaces can be added and optimized for performance improvement. If the geometry optimization is utilized for the flux barriers, it increases the optimization variables and is not flexible to get the optimal shape [61–64]. Nevertheless, the TO approach can lead to more efficient and lightweight designs, but it is generally more computationally intensive and requires specialized software [65–67]. The integration of TO and AM is demonstrated in the flowchart depicted in Figure 10.

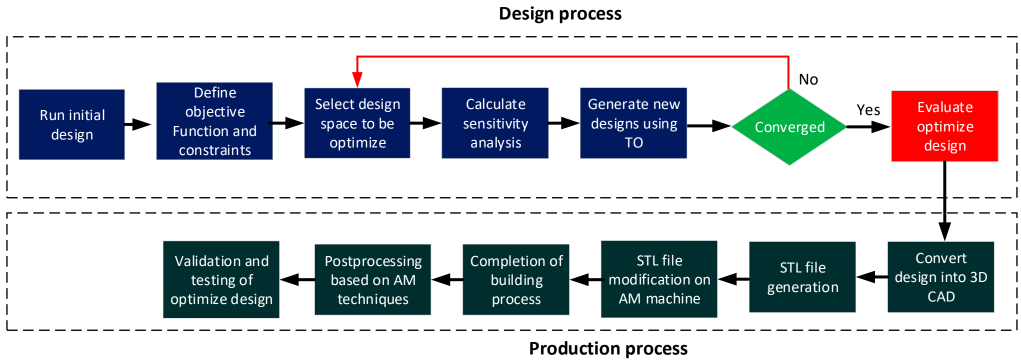


Figure 10. Steps involved for the TO and AM integration.

5.1. Topology Optimization of Reluctance Machines

The main objective of most TO studies for electric machines is to improve torque density and optimize the torque profile or cogging torque by adjusting the material distribution in the rotor. This can be achieved by using advanced optimization techniques and algorithms to find the optimal distribution of material in the rotor that results in the highest torque density or the desired torque profile [13]. Additionally, reluctance machines such as synchronous reluctance and switch reluctance machines have a simple construction compared to other types of electric machines, which makes them a good candidate for TO [13,68–71]. Despite receiving less attention, the TO of electric machine stator design has been reported in [72,73]. Different TO methods have been developed in the field of electrical machines during the last few years and these techniques may be broadly categorized into three groups: (i) the ON–OFF method, (ii) the Level set method, and (iii) the Material density method.

5.1.1. ON–OFF Method

The ON–OFF-based TO technique divides the design space into smaller cells and assigns each cell as either air (OFF) or iron (ON) through a discretization process using triangular or rectangular mesh structure [74]. This technique can be combined with various numerical optimization methods, such as evolutionary and gradient-based algorithms, to find approximate optimal solutions. In [75–78], evolutionary-based methods that do not require gradient information have been used. However, it may result in complex and non-intuitive shapes with isolated or disconnected regions of material, as shown in Figure 11a. This can lead to difficulties in fabrication or reduced performance of the final design. To overcome this issue, the author in [79–82] proposed the ON–OFF method with an immune algorithm to optimize the rotor of SRM, in which the filtering process is introduced to obtain the feasible shapes and improve the torque property as shown in Figure 11b.

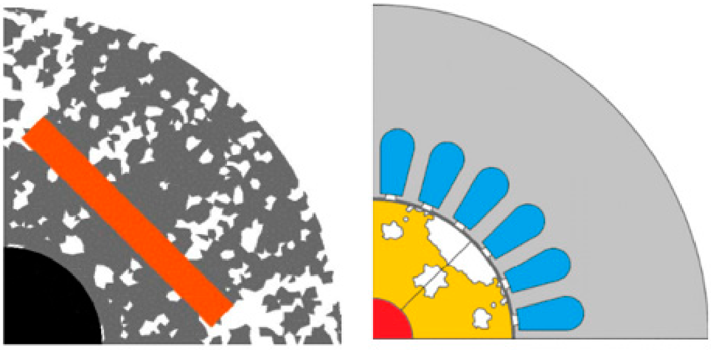
In [64,83], ON–OFF-based normalized Gaussian network (NGNet) is presented to improve the torque density and reduce the iron losses. The output of the NGNet is determined by:

$$y(x) = \sum_{i=1}^{N} w_i b_i(x) \tag{1}$$

$$b_i(x) = G_i(x) \Big/ \sum_{j=1}^{N} G_j(x) \tag{2}$$

where G_i is the Gaussian function, w_i and b_i are the weight coefficient and normalized function, respectively. N represents the number of Gaussian functions and i, j is the number of cells. The state of the cells can be determined by:

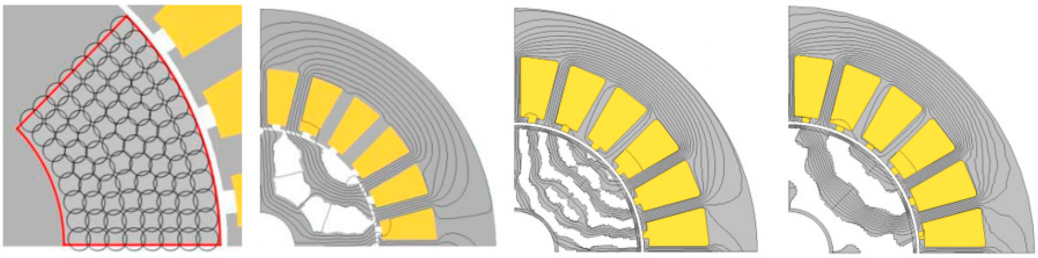
$$S_e = \begin{cases} on & y(x_e) \geq 0 \\ off & y(x_e) < 0 \end{cases} \tag{3}$$



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

Figure 11. ON–OFF TO results: (**a**) without filter; (**b**) with filter using immune algorithm.

The material is configured to iron when the cell is in the on state, whereas it is configured to air when the cell is in the off state. Three different optimization problems were studied to improve the performance of the machine: (i) maximize torque; (ii) minimize iron losses with constraint of average torque; (iii) maximize average torque with constraint of iron losses. Furthermore, the Gaussian function distribution and the optimized design is shown in Figure 12a. There should be a tradeoff between the average torque and the iron losses because the wider rotor surface increases the torque, but also, the latter should be made smaller to reduce the iron losses. Another filtering technique, Gabor filter combined with ON–OFF method based on NGNet, is presented in [84]. The authors concluded that the proposed filter provided lower torque ripples as compared to the conventional NGNet, and the optimized design using filter gives the thinner flux barriers as depicted in Figure 12b. The main disadvantage of the abovementioned methods is the high computational cost because the FEA computation is needed at each generation [85].



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

Figure 12. (**a**) Gaussian function distribution and optimized resulted shape; (**b**) Gabor filter and without filter [84].

The gradient based ON–OFF TO solves the problem of high computational cost but has the probability that it may stop on a local optimal solution. In [86], the gradient-based TO are applied to a 6/14 SRM to enhance the dynamic torque of the machine. The stator tooth is selected for the design space of the TO, then utilizes the method of adjoint gradients with respect to the material properties to optimize the material distribution for the reduction of torque ripples. The main drawback of this method is the difficulty in the evaluation of the non-differentiable functions [64].

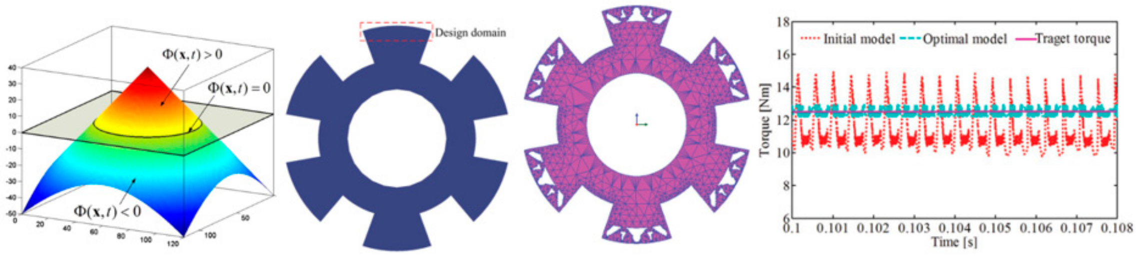
5.1.2. Level Set Method

The level set method uses an implicit function known as the "level set function" to handle interfaces and shapes numerically. The level set method was first introduced in [87] for the purpose of using it in TO to represent material boundaries. They demonstrated that this method can be used to design a cantilever beam with distinct boundaries without being dependent on a mesh or grayscale elements. Furthermore, the level set technique, which is based on gradients, produces a solution that is more practical for the given problem but lower convergence rate. In the level set TO, the material boundaries are shown in Figure 13a and computationally it can be defined as [88]:

$$\varphi(x,t) = \begin{cases} \varphi(x,t) > 0 & ferromagnetic\ material \\ \varphi(x,t) = 0 & boundary\ edge \\ \varphi(x,t) < 0 & Air \end{cases} \tag{4}$$

The objective of level set topology optimization is to find the optimal distribution of material in a design space to meet specific design objectives, by determining the value of $\varphi(x,t)$ at each location (x,t). In [89], the rotor of the synchronous reluctance machine was optimized using the level set method combined with the continuum sensitivity analysis. The objective function of the problem was to improve the torque of the machine by redistributing the magnetic material throughout the rotor design. The torque ripples profile of 8/6 pole SRM is enhanced by using the level set method, and sensitivity analysis having the adjoint variable method is utilized in [90]. In the optimized design, the average torque is improved by 12% with also the reduction in the torque ripples. The initial and optimized model with the torque waveform comparison is shown in Figure 13b. For reducing the iron losses and improving the torque of the synchronous reluctance machine, the level set method with sensitivity analysis of adjoint variable method is employed [91].

Additionally, this technique does not need the creation of intermediary materials or rely on the mesh that is used to discretize the design domain [92]. The level set approach for TO of EM devices has become quite well-liked as a result of these benefits [93]. However, this approach has certain limitations, including the need for an initial definition for the level set representation, convergence to local optima, and difficulties in computing the form gradients necessary to develop the interface [94].



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

Figure 13. Level set TO: (**a**) Different domain of level set method [90]; (**b**) Initial and optimized model with torque waveform.

5.1.3. Material Density Method

The density method is a technique that was originally developed for solid mechanics TO [14]. It is a simple method that has recently gained popularity for electromagnetic TO, even for multi-material problems. This method is based on the idea of using a density function to represent the material distribution in the design domain, then using optimization algorithms to find the optimal density distribution that satisfies certain design constraints and objectives. This method has been found to be effective for a wide range of electromagnetic optimization problems and has been applied to a variety of different types of electromagnetic structures [70,73,95–98]. It is based on interpolation, filtering, and projection schemes, and originally used the simple power-law as the material penalization function. This leads to the SIMP (Solid Isotropic Material with Penalization) approach [99]. A schematic flowchart of procedures in the material density method is presented in Figure 14.

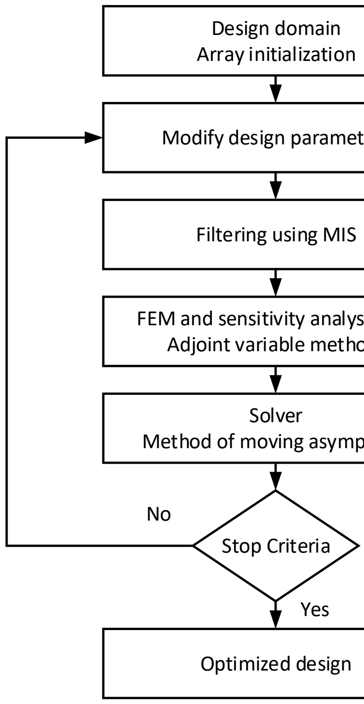


Figure 14. Flowchart of the TO using the material density-based method.

By solving the magnetic flux density and integrating the Maxwell tensor stress using (5) to determine torque, the material density approach is used to optimize the 8/6 pole rotor of the SRM [100].

$$T = \iint dAr \times (S.n) \tag{5}$$

The objective of the optimization problem is to determine the function density and is defined as:

$$\rho(x) = \begin{cases} 1 & x\epsilon\Omega_m \\ 0 & x\epsilon\Omega_a \end{cases} \tag{6}$$

where Ω_m and Ω_a represents the ferromagnetic region and air region, respectively. In the material density method, the $\rho(x)$ gives the values between 0 and 1 but practically, the distribution of the material is either 0 or 1, due to which the discontinuity exists in the final shape. To make the material distribution feasible, the magnetic reluctivity is defined by the smooth heaviside function [101]:

$$\rho(\psi) = \frac{3}{16}\left(\frac{\psi}{h}\right)^5 - \frac{5}{8}\left(\frac{\psi}{h}\right)^3 + \frac{3}{16}\left(\frac{\psi}{h}\right) + \frac{1}{2} \quad (-h \le \psi \le h) \tag{7}$$

where h represents the one half of the transition width between $\rho(-h) = 0$ and $\rho(h) = 1$. The magnetic reluctivity is defined as:

$$v_i\left(\psi_i, \left|B^2\right|\right) = (1 - \rho(\psi_i))^p * v_{air} + (\rho(\psi_i))^p \times v_F\left(\left|B^2\right|\right) \tag{8}$$

where $v_F(|B^2|)$ is the magnetic reluctivity and is a function of the mgnetic flux density and v_i, v_{air} is the reluctivity of the i^{th} element and reluctivity of air, respectively. The penalization coefficient is represented by the variable p. By choosing the proper value of p, the gray elements can be eliminated. In [102], the material density-based TO was utilized for the torque ripple minimization and the design space include the stator teeth and rotor poles. The optimized design showed a significant amount of reduction in the profile of torque ripple with the cost of a slight reduction of 7.22% in the average torque. In addition, the initial and optimized design of 6/4 pole SRM is depicted in Figure 15a. The TO of material density was applied in [103] to minimize the torque ripple and the final design reach to the target torque value. The design space includes the half of the rotor pole as shown in Figure 15b, and after optimization, the torque reached the target value. The overview of TO applied to the reluctance machine for performance enhancement is shown in Table 3.

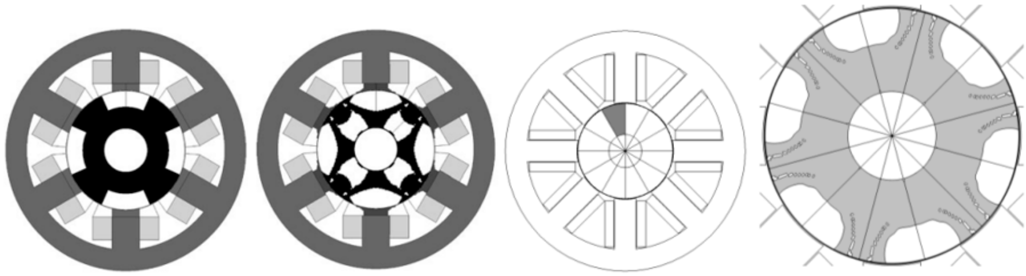


Figure 15. (**a**) Initial and optimized design of 6/4 SRM; (**b**) Initial design geometry and optimized design.

Table 3. Summary of TO used in reluctance machines for performance improvement.

Machine Type	Optimization Method	Design Space	Objective Function	Prototype Fabrication	Reference
SRM	Material density method	Stator teeth and rotor poles	Min. torque ripples	Yes	[101]
SRM	Level set method	Rotor poles	Max. average torque and min. torque ripples	No	[89]
SynRM	Level set method	The rotor	Max. average torque	No	[88]
SynRM	ON-OFF	The rotor	Max. torque	No	[63]
SRM	NGNet	Stator teeth	Min. iron losses	No	[85]
SRM	Gradient based ON-OFF	The rotor	Min. torque ripples	No	[99]
SRM	Material density + GCMMA	The rotor	Max. torque	No	[102]
SynRM	Material density + GCMMA	The rotor	Max. torque	No	[83]
SRM	ON-OFF NGNet	The rotor	Max. torque	No	[78]
SynRM	Using Gabor filter	The rotor	Min. torque ripples	No	[74]

6. Challenges and Opportunities

AM and TO have the potential to revolutionize the way electrical machines are designed and manufactured. However, there are several challenges associated with the AM and TO of electrical machines, including:

Simulation Time and Geometry Complexity

The use of AM technology in the manufacturing of electrical machines is now facing significant challenges due to simulation time and geometric complexity. Additionally, the design of electrical machines is a non-convex optimization problem, meaning that gradient-based optimization techniques may not always produce the global optimal solution. In order to confront these challenges, researchers have come up with methods that utilize machine learning and deep learning to reduce simulation time and improve the accuracy of the global optimal solution. These techniques utilize the power of machine learning algorithms and deep neural networks to improve the simulation process and reduce the time required to find the optimal solution [85,104–107]. However, while these techniques have shown promise in reducing simulation time and improving the accuracy of the solution, they also require significant computational resources and specialized expertise to implement effectively.

Manufacturability

AM offers a solution to the challenges posed by TO designs with unpredictable characteristics, rough faces, and uneven material distribution that are difficult to manufacture using traditional methods. However, the current state of AM technology presents a challenge in achieving the desired performance, especially when it comes to magnetic materials, which have low magnetic properties. Therefore, further development and improvement of AM technology is necessary to fully realize its potential in overcoming the limitations of optimized designs in traditional manufacturing methods.

Structural Integrity

TO is an important tool in the design of electromagnetic performance, but it has a significant limitation. It focuses primarily on improving electromagnetic performance and may result in designs that are not mechanically robust. Especially when it comes to synchronous reluctance machines, where the optimum design may have excessively thin ribs that are not practical from a structural integrity perspective. To overcome this limitation, it is necessary to perform a TO with structure analysis, which takes into account the mechanical restrictions of the machine. This will ensure that the optimized design is not only optimal in terms of electromagnetic performance but also has sufficient structural integrity.

Multi-Materials

To optimize different materials and manufacture multi-material machines, AM and TO are still in their early stages of development. As in case of reluctance machines, the materials are homogenous and the optimization process may be simplified. However, TO can become more difficult when dealing with multi-material machines, such as permanent magnet machines, since it is necessary to take into account various materials and their interactions. The usage of several materials may also lead to additional possible design alternatives and better performance characteristics, making it a desirable challenge for TO efforts. Despite notable developments in the area of AM, it is still very difficult for researchers to fabricate whole machines using this technology. Even while multi-material AM has been the subject of a few reports, it has not lived up to expectations. Future growth of this technology depends on the development of AM for manufacturing multi-material electrical machines.

To enhance the implementation of AM and TO in the design of electrical machines, research should focus on addressing these challenges. This could include developing new manufacturing techniques to produce the optimized designs, exploring new materials and designs to achieve the desired properties, and developing new optimization algorithms to reduce simulation time and complexity. Additionally, guidelines and design rules for the AM-based electric machine TO should be developed to assist designers in applying these techniques.

7. Conclusions

The paper reviewed various techniques used in modern AM and compared them, with a focus on the application of AM in the manufacturing of electric machines. In addition to highlighting examples of multi-material AM, also covered were various core and winding types that can be produced using AM. The paper also presented a detailed discussion on TO and how it can be used to optimize the design of electric machines for improved performance and reduced weight. Both gradient- and non-gradient-based TO methods are discussed, with an emphasis on reluctance machines. The ON–OFF TO produces complex geometries that are impossible to manufacture. To address these problems, various filtering techniques were used, and these were discussed in the study. The paper concluded that while the combination of AM and TO has the potential to fundamentally change the design of electrical machines, certain challenges such as manufacturability, geometric complexity, and structural integrity must be addressed before this technique can be feasibly adopted in practical machine designs. Overall, the paper suggests that there are many opportunities for future research in AM and TO to improve the design and manufacture of electric machines.

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