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# Opportunities and Challenges of Utilizing Additive Manufacturing Approaches in Thermal Management of Electrical Machines

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**ABSTRACT** The additive manufacturing approach is considered a new manufacturing technology method and is evolving dynamically in recent years. It is advancing and achieving as the key enabling technology in a wide range of applications, from medical sciences to the aerospace and automotive industries. This novel approach opens a new path to overcome the conventional manufacturing problems and challenges by providing more design freedom, new ranges of materials, lightweight and complex geometries. According to demands metrics such as lightweight and high power density motors. This offers clear motivation to develop the advanced thermal management method with new materials and a novel additive manufacturing (AM) approach. The paper aims to provide a comprehensive review of all the attempts in various electrical machines' thermal management methods using AM method. It considers the opportunities and challenges that designers are facing while implementing these approaches. Finally, the authors make some comments/forecasts on how the AM could improve the performance and manufacturability of the future thermal management system of electrical machines

**INDEX TERMS** Additive manufacturing (AM), cooling systems, electrical machine, manufacturing techniques, thermal management, three-dimensional (3-D) printing, traction motors.

## I. INTRODUCTION

The fundamental design procedure of the electrical machine has been developed over decades. The conventional manufacturing techniques of electrical machines already reach their desired level, and it seems there is less possibility to do the research and development of these techniques. As a result, the new design methods and manufacturing techniques are required to provide outstanding and profound impacts on electrical machines' evaluation process. In other words, requiring advanced modern techniques allow the electrical machine manufacturers to design the novel electrical machine with whatever complex shapes, structures, and advanced materials by implementing the modern computational electromagnetic, thermal, and material approaches. The demands for clean energy technologies for different applications, for instance, wind power, electric vehicle, and electric powertrain, are rising rapidly [1]. The demands metrics are mainly concentrated on high power density, high efficiency, and lightweight electrical machines [1].

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Additive Manufacturing (AM) method in less scientific word 3D printing technology, is the novel technique that absorbs the attention, as an alternative option for achieving the above ambitions. AM has a wide range of applications and generates complex three-dimensional shapes without any restriction. Besides, the wide range of materials used for the AM method, from metal alloys, plastic, ceramics to even bio-ink and biomaterial, is raising its attraction and has placed this technology among the pioneers of future manufacturing approach [2], [3]. The latest statistical reports also prove that the AM market, including all the sectors in 2018, faced an 18% growth and reached a $9.3 billion market value. Based on the forecasting, this value will be raised to $41.1 billion by 2027 [4], [5].

For the next generation of lightweight, high torque electric machines, thermal design, and heat transfer have the same importance as electromagnetic design, including the higher complexity and nonlinearity due to fluid flow nature. Selecting the appropriate cooling method has a significant effect on the machine's amount of heat extraction. The improvement in the amount of heat extraction directly impacts the machine's power rating and the reliability of temperature-sensitive components such as insulation materials and magnets.

Therefore, the paper aims to introduce the reader to the AM method's capability in the advanced thermal management design of electrical machines, review the current progress in implementing the thermal management methods, and outline areas that require further research and development. Moreover, the paper provides the reader with a picture of the state-of-the-art regarding the AM method and its various mechanisms. It describes the operating principle of AM and the progress and challenges of this method. Finally, it explores the evaluation of different cooling ways. It presents this technology's perspective to improve the weak points and drawbacks of the conventional cooling system of electrical machines by utilizing AM. For this purpose, this study's focus is, 1) consider the know-how of AM approaches in the thermal management system of electrical machines, which can replace conventional methods and overcome the drawbacks of these traditional manufacturing methods. 2) Investigate the potential achievement and benefits of AM technology in manufacturing advanced thermal management systems of electrical machines.

## II. ADDITIVE MANUFACTURING APPROACH

AM refers to the manufacturing of a three-dimensional component layer by layer material with printing technology. This method consists of several advantages such as fast prototyping, constructing the complex geometries or the geometries located in the hard to reach areas, building components including mixed materials, printing various components simultaneously, increasing performance, and improve the properties [6], [7]. However, due to the low manufacturing rate and high cost, the AM is implemented to build the low volume and small size components [6], [7]. As a result, further progress in this technology is needed to reach the desired level.

Today, there are several different types of printers and printing method for AM. Overall, the AM printers can be divided into three main categories based on how the material is formed into the object [6], [7]:

1. Fused filament fabrication (FFF)/fused deposition modeling (FDM) (Figure.1 a) [8];
2. Stereolithography (SLA) (Figure.1 b) [9],;
3. Selective laser sintering/melting (Figure.1 c) [10];

The first two AM methods (FFF/FDM and SLA) are most suitable to print polymers, ceramic and compound materials making them ideal for printing insulation components in an electrical machine. SLS/SLM printing uses a laser to heat the raw material, allowing a significantly higher temperature to be achieved. This makes it suitable to print different metals in an electrical machine; it is suitable for printing conductive sections (stator, rotor, and windings). The price of a 3D printer is on rising from FFF/FDM method to SLS/SLM [6], [7]; accordingly, the cost of a printer for FFF based on the performance varies between $ 100 and $ 2,000, but for SLM, the price of printer varies from $ 5000 to $ 600 k [6], [7]. From an accuracy point of view, the SLM has the highest accuracy and manufacturing speed among the three AM methods [6], [7]. Table 1 shows all the above contents and differences among the three AM methods.

3D printing is no longer just a laboratory tool but has found its place in the industry as well, and its usages are spreading [11], [12]. For instance, General Electric (GE) Aviation starts to produce 3-D fuel nozzle for airplane engines to run the liquid fuel and spray it into the engine. The fuel nozzle is a complex device including various sections (about 20 parts), Making it difficult and time-consuming to produce in a conventional manufacturing technique. Each piece must be made separately and then welded together [11]. However, AM technology provides this opportunity for GE Aviation to manufacture the entire structure (Figure. 2) with all the details, such as its twisting and interior chambers geometries in a single part [11]. GE Aviation announced the introduction of additive manufacturing for fuel nozzle production, as this production method significantly reduces labor costs and time, as well as producing a 25% lighter nozzle that is mechanically five times stronger [11]. According to all of those factors, they save $3 million per aircraft [11].

Contrary to the mechanical industry where the AM is used actively, AM manufacturing is making its first steps in electrical machine production. At the same time, all parts of the electrical machine can be produced with additive manufacturing. In principle, we can divide an electrical machine's design into five categories, as shown in Figure. 3: iron core – can be printed with SLM printing and can have several advantages like optimal shapes, less material, etc.; winding and insulations materials – can be printed with SLM and also FFF/FFD (for instance, Jassal *et al.* [13], proposed A novel

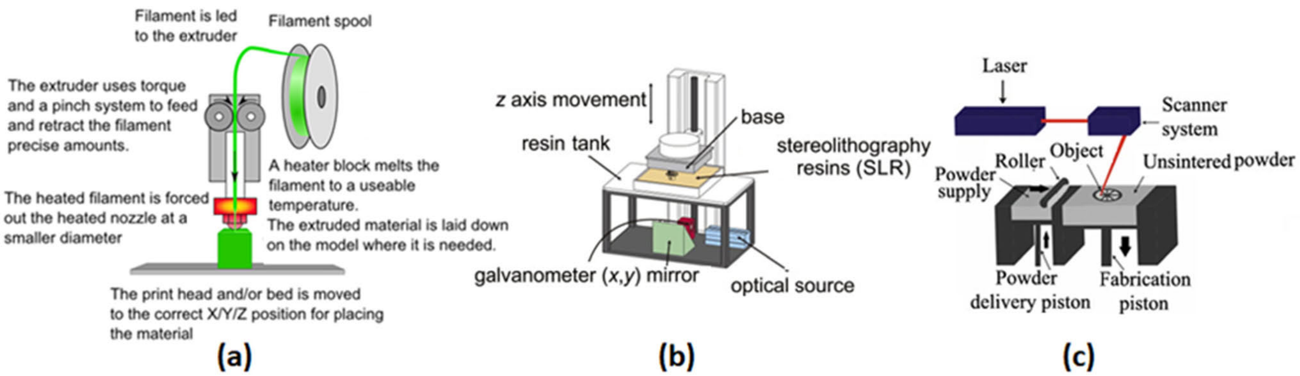


**FIGURE 1.** Various methods of additive manufacturing (a) FFF/FDM, (b) SLA, and (c) SLS/ SLM [8]–[10].

**TABLE 1.** Main features of three main AM methods [6].

| AM methods | Material | Printer Price | Accuracy and Maximum Build area | Applications |
|---|---|---|---|---|
| FFF/FDM | • Thermoplastic polymers (eg. ABS, PLA, ASA, nylon, etc.)<br>• Metal powder and Binder Mixture (eg .steel power mixed with polymer) | Low ($100 - $2 k depending on performances) | Layer thickness: 0.127-0.254 mm;<br>X/Y resolution: 0.607 mm<br>914.4×609.6×914.4 mm3 (F900) | Concept modeling;<br>Insulating parts;<br>Light structural parts;<br>Magnets and iron cores. |
| SLA | Clear, ABS-like, Polypropylene-like, heat resistant, ceramic reinforced resins (viscosity: 150-2000 cps) | Medium<br>$500-$3k: consumer<br>$3k-$200 k: industry | 0.025-0.05 mm per inch part of dimension<br>1500×750×550 $mm^3$ (Prox950) | Fast concept modeling;<br>Light structural parts. |
| SLS/SLM | Metal alloy in powder form (size: 10-100 um)<br>(eg. Copper, aluminum, stainless steel, cobalt chrome, titanium, etc.) | High ($5 k - $600 k depending on performances) | • SLS:<br>Layer thickness: 0.1-0.15 mm;<br>X/Y resolution: 0.76-1.27 mm<br>• SLM:<br>Layer thickness: 0.02-0.038 mm;<br>X/Y resolution: 0.30-0.41 mm<br>500×280×850 mm3 (SLM800) | Dense metal parts<br>(eg. Iron cores, magnets, structural parts, cooling jackets) |

**FIGURE 2.** 3D printed nozzles by GE aviation company [11].

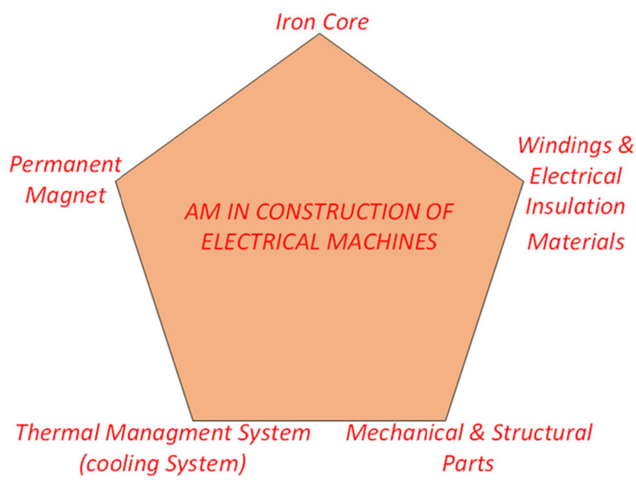


**FIGURE 3.** Various subjects of AM method in the construction of electrical machines.

approach to produce completely ceramic insulated copper coils for switched reluctance machines using an AM technique which was developed at the Chemnitz University of Technology (TUC)) and can have several benefits like higher filling factor, shorter end winding, etc.; Permanent magnet – will be printed with SLM and can have some advantages like special shapes, implementation in the construction, etc.; Mechanical and structural parts – can be printed with SLM, FFF/FFD, and SLA and can have advantages like optimal shapes, lighter construction, etc.; thermal managements - can take advantage from the additive manufacturing to produce better cooling.

As the main objective of this paper is to introduce the capability of the AM method in the advanced thermal management design of electrical machines; More information about the other subjects of additive manufacturing techniques in electrical machines can be found following literatures and references [1], [2], [6], [13]–[22].

## III. AM IN ADVANCED THERMAL MANAGEMENT DESIGN OF ELECTRICAL MACHINES

The electrical machine's thermal management is vital to ensure the reliability and longevity of the electrical machine. This means that better and more efficient cooling capability is always needed. The heat is extracted from an electrical machine by three phenomena; conduction, convection, and radiation [23]. Designers select a proper cooling system to mostly enhance the convection phenomenon's impact to achieve better heat extraction and reduce the temperature of the machine's key parameters. There are two main thermal management methods and several sub-methods used in electrical machines, as seen from Figure. 4. Passive cooling offers a highly reliable and relatively inexpensive solution, while active cooling offers significantly better cooling capability. The variety of choices makes it difficult for designers to choose the best solution. Due to advances in calculation tools and manufacturing capabilities, the existing solutions have become more efficient. Additive manufacturing creates an opportunity to improve electrical machines' cooling capability in several ways, such as reducing the weight, optimizing the cooling system's shape and geometries, and reducing the cooling systems' conventional drawbacks and constraints during conventional manufacturing.

### 1) ADDITIVE MANUFACTURING HEAT SINK

The finned housing and air-cooled heat sink are the primary thermal management methods for various electric and electronic devices to evacuate the heat from these devices to air. This air-cooled approach is the desired method according to a reliable, simple, and cost-effective design [24], [25]. This cooling method enhances heat extraction by increasing the heat transfer coefficient (HTC) or/ and raising the surface area in contact with air [26]. For active cooling finned structure and heat sink, the HTC can be increased by reduced hydraulic diameter or by enhancing the airflow rate [24], [27]. The reduced hydraulic diameter leads to higher flow resistances in the heat sink, and more electrical power is required to run the fan [24], [27]. Besides, increasing the airflow rate leads to a higher pressure drop, acoustic noise, and fan power consumption [24], [27]. Already, in most of the applications, the acoustic noise reaches its limits [24]. Consequently, these two ways are less applicable for increasing heat extraction due to the high acoustic noise and high-power consumption limits. The only feasible way to increase heat extraction is to fabricate the larger area heat sink.

**TABLE 2. Conventional manufacturing techniques constraints [28].**

| | Conventional Manufacturing Methods | | | |
|---|---|---|---|---|
| Parameters | Extrusion | Skiving | Di-casting | Machining |
| Min. fin thickness, $\delta$(mm) | 1 | 0.3 | 1.75 | 0.5 |
| Max. fin height $H$/ fin thickness $\delta$ | 8:1 | 25:1 | 6:1 | 50 |
| Min. inter-fin spacing, $s$ (mm) | 6.6 | 2 | 8.3 | 1 |
| Material | Al | Al | Al, Zn-alloy | Al, Cu, Mg |

Among various conventional manufacturing methods, extrusion, skiving, Di-casting, and machining are the most popular techniques to fabricate the heat sink [28]. Table 2 shows the limits of these conventional methods for constructing the heat sink. The aforementioned conventional methods, except the casting method, are utilized to produce the simple structure heat sinks. Besides, this heat sink's production cost by the casting technique is high, and this method's production has no economic justification.

To overcome these restrictions and manufacture the complex shape heat sink, several research studies start using the AM method as an alternative option to conventional manufacturing methods to fabricate the passive [29] and active heat sink [24], [27], and [30]. Figure. 5 shows the number of novel concept designs that benefit from AM method advantages in fabricating the complex heat sink for passive (Figure. 5. (a), and (c)) and active cooling (Figure.5. (b), (d)).

Figure 5. (a) shows the freeform-optimized shapes for passive cooling in which Wits *et al.* [29] have used a Bio-inspired (Biomimicry) design approach to design their heat sink based on the shape from brain coral. Moreover, they implemented the optimization process by numerical computational fluid dynamic (CFD) method. Then, they manufactured several heat sinks from aluminum alloy AlSi10Mg, using SLS and SLM techniques, and did experiments to validate the developed numerical models. Another research study, presented by Wong *et al.* [30], considered manufacturing the novel active heat sink by AM technology. They designed and manufactured three novel heat sinks (a staggered elliptical array, a lattice, and a rectangular fin array with rounded corners) and compared their performances with two conventional designs (the cylindrical pin and rectangular fin array). According to the significant impacts of the pressure drop and heat transfer coefficient on the heat sink design, as shown in Figure 6, they considered the performance of heat sinks based on the ratio of the modified heat transfer coefficient and the pressure losses. Based on their observation, the staggered elliptical array has a more significant performance from both heat transfer and pressure drop points of view. According to their findings, a heat sink with a lattice structure (Figure. 5 (b)) could not

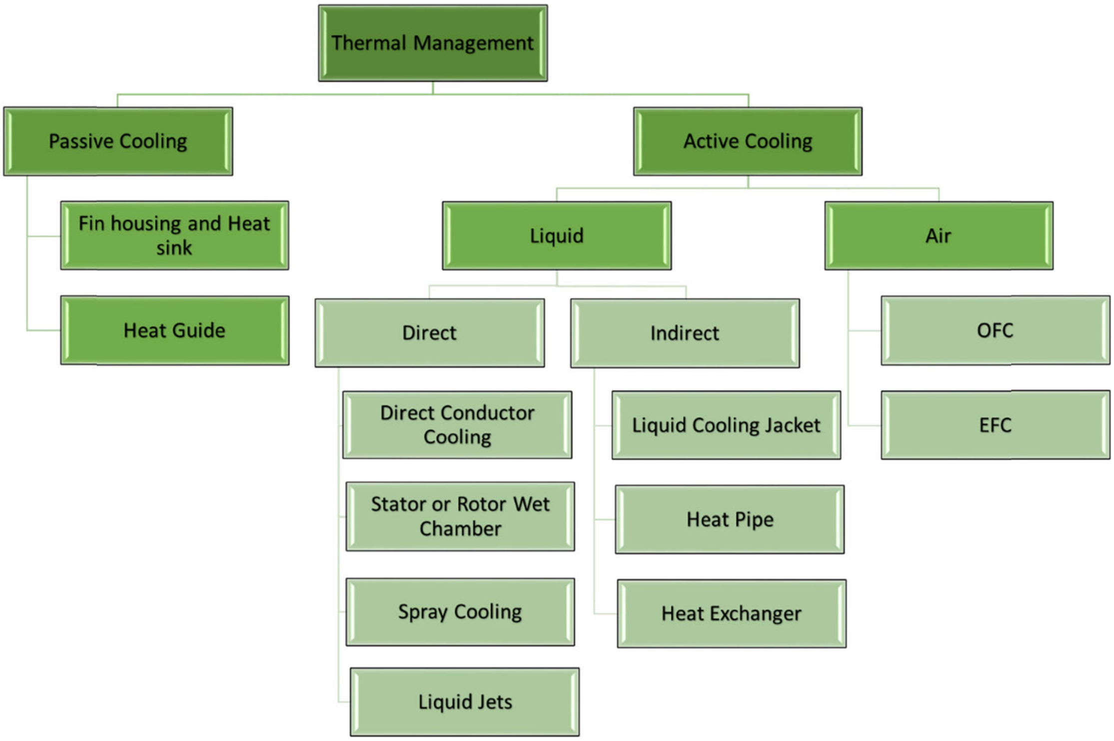


**FIGURE 4.** Various thermal management methods for electrical machines.

provide the proper heat transfer due to the lack of interaction between the cooling air and heat sink structure.

Another research study on designing a novel heat sink by rapid AM technology was presented by Fasano *et al.* [31]. As seen in Figure. 5 (c), they used the AM approach to manufacture an innovative passive heat sink based on the Pitot tube effect. They designed and fabricated two prototypes, a Pitot heat sink with open configuration and closed structure, and compared their performance with reference heat sine (rectangular heat sink made of copper and fabricated by traditional milling). Figure. 7 demonstrates convective thermal transmittance (*Tr*) of heat sinks in different Reynold numbers and the pitot heat sink with open configuration significantly improving the heat transfer by convection phenomenon and based on their preliminary test results, the thermal performance of the pitot heat sink compared to conventional rectangular heat sink enhances up to 95%.

Figure. 5 (d) shows the honeycomb (slotted hexagon) concept design of the air forced cooling heat sinks for the minimal pressure drop application, which is presented by Krishnan *et al.* [24], Lyons *et al.* [27]. They proposed three concept designs for heat sinks to enhance the heat transfer to a forced convection air stream by the honeycomb's title (slotted hexagon), finned-foam, and Schwartz configurations. Figure 8 shows the performance of their designs in comparison with the conventional parallel rectangular heat sink. As a result, all the designs show better thermal performance compared to the traditional rectangular heat sink. From application vision, the honeycomb design offers better thermal performance in applications with minimum pressure drops. Besides, for the applications with the pumping power importance, the fin foam, concept demonstrates the better performance. Finally, Schwartz configurations displayed better performance for the applications that the flow mass rate and velocity is vital.

### 2) AM HEAT EXCHANGERS

The electrical motors utilized for traction application, such as electric vehicles and hybrid electric vehicles, require a high torque density. In these types of machines, the majority of losses are generated in the stator slot and windings. Consequently, the thermal degradation of the stator slots and windings is one of the main constraint factors for developing a motor with high torque density [32]. One solution to overcome this problem is implementing the direct winding heat exchange (DWHX) as an advanced thermal management method. This cooling method's target is to cool the stator slot/ windings by significantly reducing the thermal path between the winding and ambient [33], leading to augment the machine's current density while maintaining the reliability of temperature-sensitive windings insulation materials (it achieved the continuous current densities of about 25 A/mm$^2$ and transient current densities around 40 A/mm$^2$ for class F insulation) [32]. This cooling technology can be implemented on the fractional-slot concentrated winding machines, as this

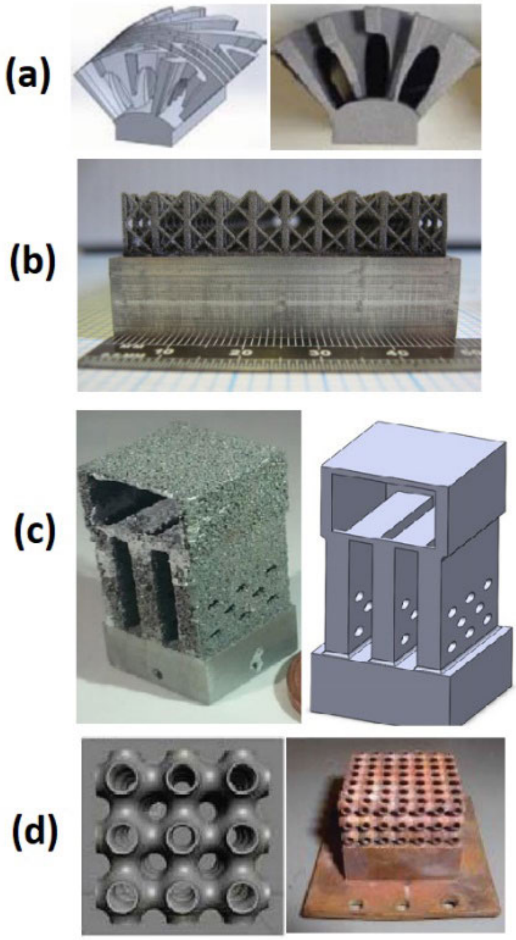


**FIGURE 5.** Additive manufacture heat sinks (a) brain coral shape heat sink [29], (b) lattice heat sink [30], (c) Pitot tube effect heat sink [31], and (d) honeycomb heat sink [24].

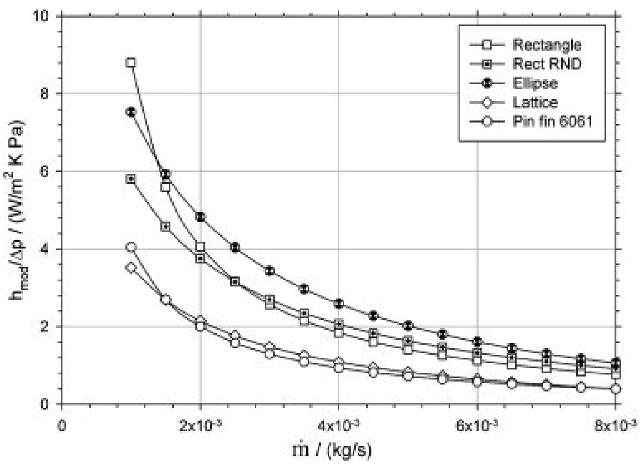


**FIGURE 6.** Heat sink efficiency [30].

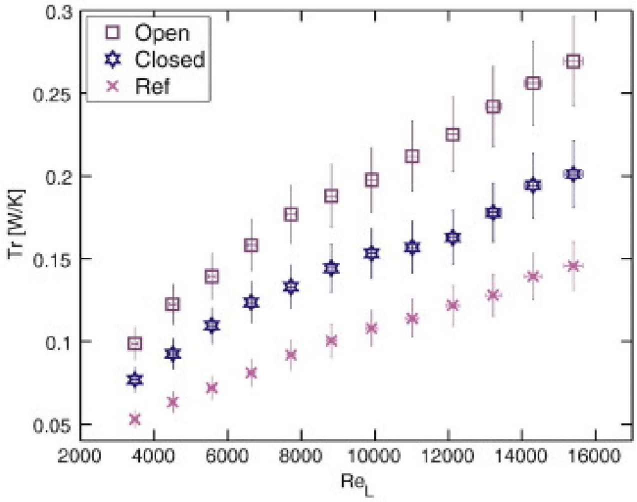


**FIGURE 7.** Convective thermal transmittance (Tr) of heat sinks in different Reynold numbers for open Pitot (purple squares), closed Pitot (blue stars), and reference (pink crosses) heat sinks [31].

winding topology provides shorter end turns compared to traditional distributed windings [34]. Reducing the end winding offers the opportunity to manage heat transfer by cooling the active length alone [35].

Several research studies [35]–[38], and [39] have investigated the effect of AM technology on the manufacturing of innovative HEs. Additive manufacturing provides the possibility of implementing more microfeature designs, intricate shapes, and producing the monolithic heat exchanger, reducing the components' counts. Hereafter, we divide the active HEs based on fluid coolant into two main groups, as liquid-cooled and air-cooled HEs, and consider thermal management evaluation in these devices by the AM approach.

The liquid-cooled heat exchanger is developed as an alternative option for the oil-cooled motor to reduce the thermal management system's weight, cost, and complexity [35]. In this technology, the glycol-water mixture is used as a coolant; this coolant has several advantages: low pumping losses, better thermal properties, improved thermal performance, and heat transfer for high-temperature applications [36]. Semidey and Mayor [32] offered a DWHX constructed from copper using the conventional manufacturing process. The copper is a conductive material and must be insulated from conductors inside slots where these electric insulation materials are also thermally insulated and have a negative impact on the thermal heat performance of liquid DWHX. Sixel *et al.* [35]–[37] proposed the 3D- DWHX by the dielectric structure. By selecting the dielectric materials and additive manufacturing approach, they improved the thermal performance by constructing the more complex flow geometry and adding an internal flow feature to their T shape design as well as eliminating the slot divider. Figure. 9 shows the concept designs of the liquid-cooled 3D printed DWHX (3D-DWHX). They used the FFF additive manufacturing method to manufacture their 3D-DWHX. They printed several prototypes with various dielectric materials: ABS, polycarbonate aluminum flake (PC-AL), CF-Nylon, and polylactic acid (PLA) and considered these prototypes' performance to select the proper dielectric material for DWHX. According to their studies,

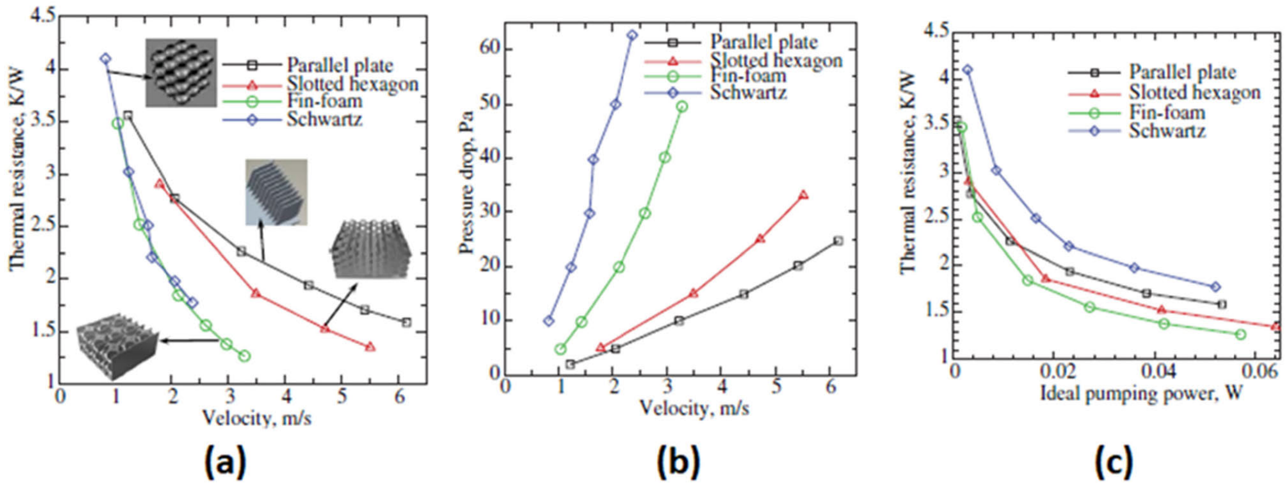


**FIGURE 8.** Experimental data of three novel heat sinks versus conventional rectangular heat sink (a) the thermal resistance via velocity (b) pressure drop via velocity, and (c) thermal resistance via ideal pumping power [24].

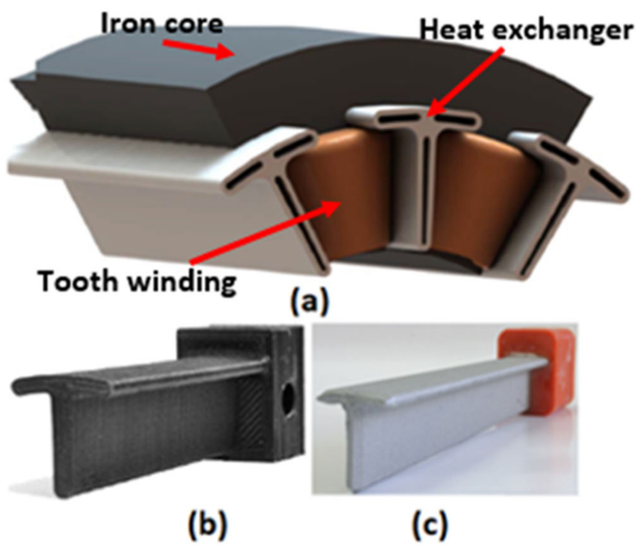


**FIGURE 9.** The concept designs of 3D-DWHX (a) the CAD design of stator and winding with the T shapes HEs, (b) CF-Nylon DWHX prototype (c) PC-AL DWHX prototype [35]–[37].

the PC-AL DWHX shown great performance. The Motorette (a small representative section of the stator) was tolerated with a continuous current density of about 20 A/mm$^2$ while maintain the maximum slot temperature around 148 °C. Moreover, the PLA DWHX is not the correct choice for high-temperature applications according to its low thermal conductivity and thermal performance of PLA.

The additive manufactured air-cooled HE was developed for uncrewed solar aircraft by Wroble *et al.* [38]. These aircraft types are manufactured for long-duration flights, and they consist of two performance modes [38]; the first one is the take-off mode, which needs high torque performance, and the second mode is high altitude cruise (continues operation mode)with high-efficiency performance. So, the motor structure must be lightweight and compact. In this application, the take-off mode's power losses are eight-times-larger than the continuous mode; accordingly, it is essential to implement the proper thermal management method to extract the motor's heat during this mode. Figure. 10 (a) shows the concept design of this air-cooled HE, made of AlSI10Mg by SLM printing technology to provide a light and robust body design. As most heat is generated inside the stator slots during the take-off, the HE has a bored stator core to give good heat transfer from the stator winding (Figure 10. (b)).

The passive heat guide (HG) is another method to remove the heat from active and/ or end parts of the stator windings. This thermal management way mainly concentrates on augmentation the thermal conductivity and improving the conduction phenomenon. In this method, the HG plates made of metal alloys are inserted into stator slots and installed between two windings for enhancing heat removal capability. These thermal conductive materials also have good electric performances, and placing them inside the magnetic fields (magnetic flux leakage due to current-carrying conductor) generates additional losses. Moreover, using solid metallic HG causes a rapidly rising amount of additional losses. These losses become even more significant in high-speed electrical applications, which neutralizes the effectiveness of this thermal management method. Wrobel and Hussein [39], [40] considered various concept designs of HGs using advanced Multiphasic and AM approaches to reach HG's optimized structure, balance the additional losses, and provide a good heat transfer. Figure. 11 shows the evaluation of their concept designs from solid metallic HGs to lattice with tamper structures. The AM approach allowed them to make the lattice structure, which is impossible to manufacture by conventional manufacturing methods, and to implement the full design details to enhance the heat transfer HG and minimize the additional losses. Finally, they achieved optimized HGs with a 30% improvement in the heat transfer.

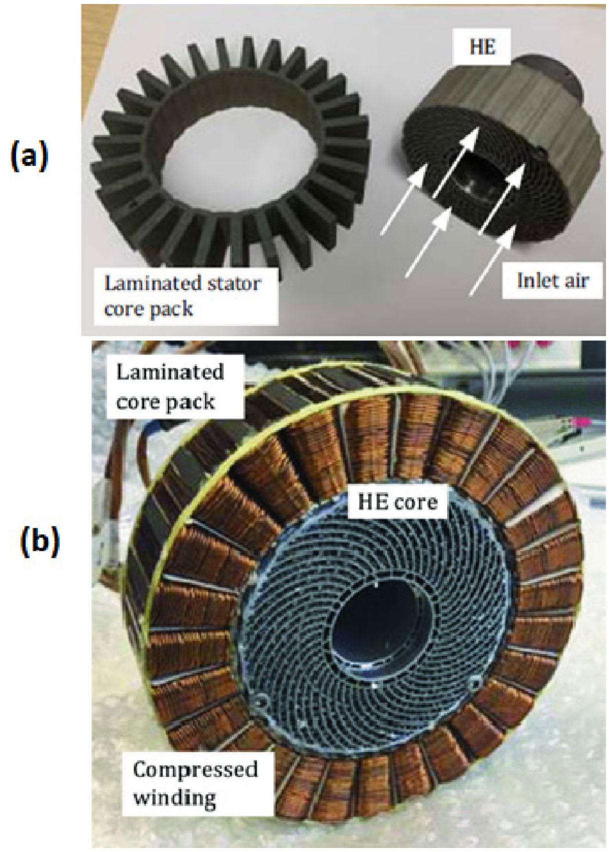


**FIGURE 10.** (a) prototype laminated stator core pack and HE-Newcastle University, (b) stator-winding assembly with integrated HE [38].

### 3) ADDITIVE MANUFACTURE HEAT PIPE

The heat pipe (HP) is the most straightforward phase change cooling schematic [26]. This cooling approach benefits from a two-phase working regime and at least some portions of the cooling fluid are transformed into vapor and increasing the amount of the heat transfer. Figure. 12 shows seven main concept application areas for this technique in electrical machines, 1- heat pipe inside shaft, 2and 5-rotational axial and radial HP (in the rotor), 3- HP in stator core or active winding, 4-HP in end winding, 6-HP in end region and 7- heat pipe in bearing [41], [42]. The implementation of the heat pipes has been investigated over decades, and considerable papers [41]–[49] available in utilizing and evaluating this technique in all the potential application areas of electrical machines.

The most conventional HPs for electrical machine applications is the wicked HPs. The wick-shaped body is located in HP's interior surface and works such as a capillary pump to transfer the condensate to the HP's evaporation portion. As seen in Figure. 13, the wicked body shape can be divided into three main categories: grooved, meshed, and sintered [41], [50]. The groove structure has the lowest price and high mass flow from a cost and performance point of view, but the drawback is a low liquid return against gravity. In contrast, the sintered structure has the highest cost and provides good pumping capability but reduced power transport. The meshed- -price and performance are located between these two structures.

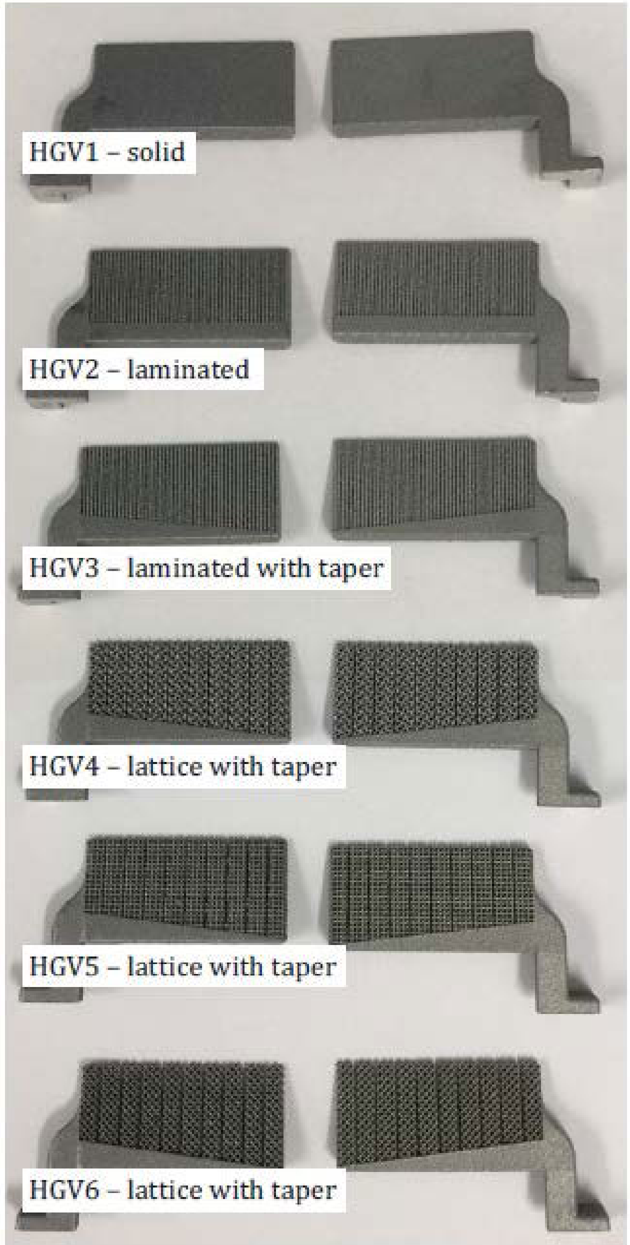


**FIGURE 11.** Evolution of the concept designs of HGs of Newcastle University [39].

Selecting the right materials in designing the HP for a particular application has a vital role in reliable HP operation. Generally, the type of material and the cooling fluid in HP appointed the heat transfer capability and the HP's temperature constraints. Table 3 demonstrates the typical mixture of materials, liquid fluids, and operating temperature range of HPs fabricating conventional methods utilizing electrical machines and power electronics. However, manufacturing HPs with complex geometries and functions for electrical

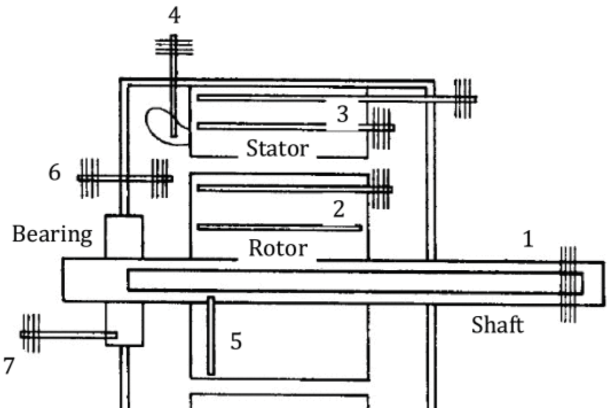


**FIGURE 12.** Various application areas of HP in electrical machines [42].

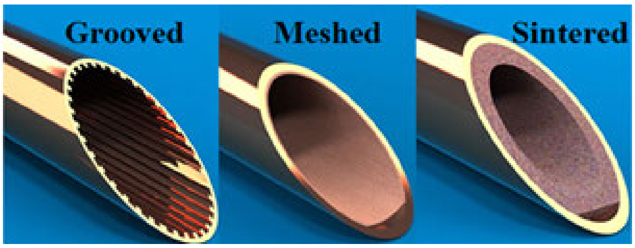


**FIGURE 13.** Various types of wicks in HPs [50].

**TABLE 3.** Conventional materials and working fluids of HPs.

| HP Structure Materials | Working Fluid | Temperature Range (°C) |
|---|---|---|
| Copper, Nickel, Titanium, Monel | Water | +5<Tem<+280 |
| Aluminum, Steel, Stainless Steel, Nickel | Ammonia | -65<Tem<+100 |
| Copper, Stainless Steel | Methanol | -60<Tem<+100 |
| Aluminum, Stainless Steel | Acento | -50<Tem<+100 |

machines' thermal management by conventional manufacturing ways is challenging and is not cost-effective.

Therefore, the research scientists consider fabricating the complex structure HPs with new materials, for instance, polymers [51], ceramics [52], [53], and metallic alloys [54], [55] using the AM approach. Figure. 14 shows aluminum alloys (AlSi12) HPs with two types of wick shapes manufactured by the SLM approach [56]. Figure. 15 presents another-interesting prototype, which is manufactured by the SLM method. This prototype is the multi-layered flat-plate oscillating HP constructed from Titanium alloy (Ti6Al4V), and it is able to work in multiple orientations. These figures show significant improvement in implementing the detailed design features using the AM approach, which is difficult or even impossible to produce by the conventional manufacturing methods.

### 4) ADDITIVE MANUFACTURING INDIRECT LIQUID JACKET

The liquid cooling jacket is the indirect cooling approach applied around the stator's outer circumferential to provide electrical machines' primary thermal management. Figure 16 presents various forms of cooling jackets manufactured by conventional methods [57]. As seen in the Figure, they have simplified liquid channels to reduce their production complexity; moreover, these liquid jackets do not have a monolithic structure, and they are at least made of two pieces.

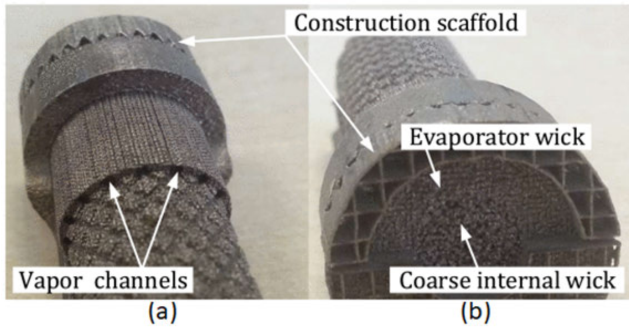


**FIGURE 14.** The HP's prototypes printed by SLM method (a) Sintered wick shape and b) grooved wick shape [41], [56].

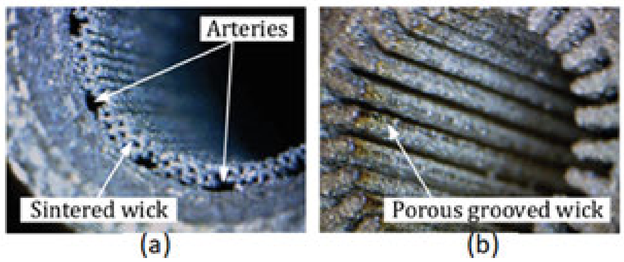


**FIGURE 15.** The multi-layered flat-plate oscillating HP [41].

AM provides a considerable effect on the fabrication of these cooling jackets by reducing the cost, production time, producing tools, weight, the total number of parts, and liquid leaking. This method provides the possibility to fabricate the cooling jacket and frame as a monolithic structure, and it becomes easier to locate the cooling jacket in its proper place. There are several research groups [58]–[61], and [62] that considered the possibility of fabricating the cooling jacket using AM technology. Two prototypes for EV applications are presented in Figure 17. Figure 17 (a) shows the latest concept design of TU fast racing team motor housing, with its cooling jacket to enhance its thermal management performance [58]. Accordingly, they designed the integrated structure, which consists of liquid jacket channels with optimized pin shapes. Manufacturing these cooling jackets in conventional ways is impossible, and they used the AM method (SLS). According to their reports, the boosting total mass flow and the cooling system efficiency are about 31% and 20%, respectively. Fig 17 (b) shows the Greenteam Stuttgart AM liquid jacket, in which they achieve a lighter structure (around 16% weight reduction) with enhancing by 37% the cooling performance [59] and [60].

### 5) ADDITIVE MANUFACTURE DIRECT LIQUID COOLING WINDING

One of the most efficient methods to dissipate the stator Joule losses is utilizing the winding's direct liquid cooling.

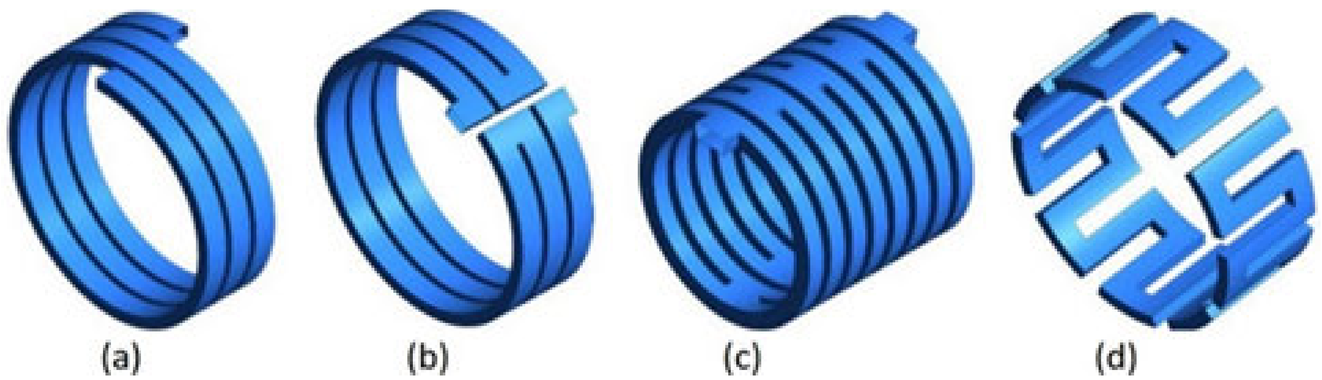


**FIGURE 16.** Various types of the liquid cooling jacket (a) spiral, (b) U-shape (one duct), (c) U-shape (bifurcated), and (d) axial water jacket [57].

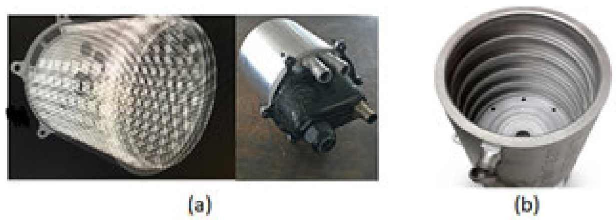


**FIGURE 17.** Two concept designs of liquid cooling jacket integrated into the housing and built by AM technology for racing car motor (a) TU fast racing team prototype [58], and (b) Greenteam Stuttgart prototype [59], and [60].

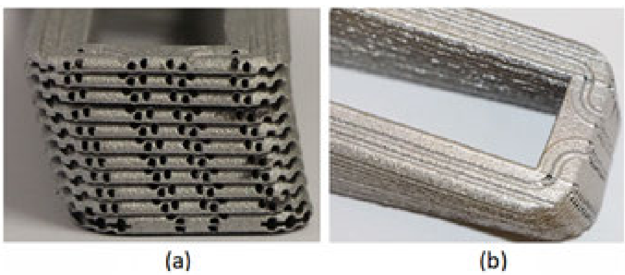


**FIGURE 18.** The aluminum tooth coil with integrated cooling passages (a) side view shows the cooling channels, and (b) top view of tooth coil [68].

This method consists of the hollow stator bars, phase connection rings, main leads, bushings, and neutral bus, that deionized water or oil past the hollow passages to remove the high temperature directly from the stator windings [63] and [64]. These types of cooling are mostly implemented on large synchronous machines [65], [66], and [67]. However, developing the AM method allows the designer to implement this thermal management system for small machines [68]. Figure. 18 shows an innovative concept design of a tooth-coil winding with its integrated cooling passages, using the SLM technology to construct the aluminum alloy coils (AlSi10Mg). They introduced novel coil geometry to reduce the AC copper losses with high heat loss dissipation capability to increase the conductor's current density to 100 A/mm$^2$.

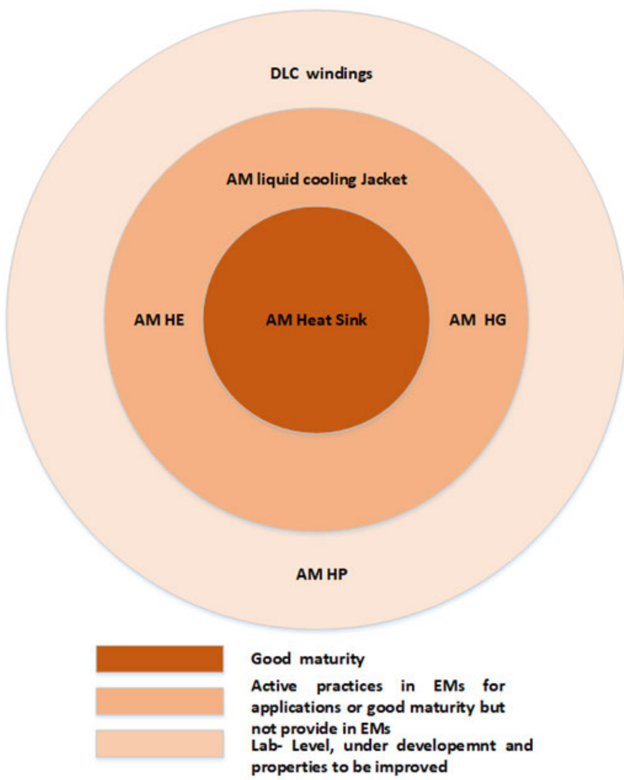


**FIGURE 19.** The level of growth and maturity of the AM thermal management system.

## IV. DISCUSSION AND CONCLUSION

The AM approach seems a promising solution to overcome conventional manufacturing problems and electrical machines' thermal management restrictions. However, more development and research work in various aspects such as the materials, the system development fully utilizing AM, and more new thermal management techniques (spray cooling) are needed.

The research studies present the different steps of growth and maturity for various thermal management approaches. Figure. 19 illustrates multiple levels of growth and maturity for the AM thermal management systems of electrical machines where AM thermal management methods with relatively good maturity are placed near the center of figure. Accordingly, thermal management methods are divided into three regimes based on their growth and maturity. The most significant development and maturity appear in the heat sinks and semi-open fin channels methods. These methods can also be used for power electronics devices, which opens the door for new and novel approaches called integrated electrical machines and drives (IMD) or integrated modular machines and drives (IMMD) [69]–[72], and [73]. The main aim of these new approaches is the augmentation of power density and heat extraction. Therefore, thermal management is one of the key considerations in these novel techniques. Several universities and R&D centers consider integrating drives and electrical machines such RWTH Aachen [72] (investigating the Si-diode chip with AM metallization to the vertical pin heat sink), Oak Ridge National Laboratory [73] (considering the AM SiC inverter with integrated cooling), and Rolls Royce central Technology [69] (integrated the DC rectifier with liquid heat sink cooling).

In contrast to the heat sink method, HEs, HGs, and liquid cooling jackets approaches are in electrical machines' active practice regime. But the HPs still need more development and improvement to reach the level of good maturity to be implemented in the electrical machines. However, some methods have not been considered by the AM method for electrical machines, such as oil spray cooling. The oil spray cooling has attracted attention in the recent decade. Several research studies consider it for electrical machines. It needs further development in both the cooling and system development to reach the desired maturity level. By inspiring GE aviation, the nozzles can be manufactured by AM technology, which reduces the numbers of parts with full details, and saves production time and cost.

Recent research and development in thermal management systems of the electrical machines with AM show a significant improvement in the heat removal capability without any considerable increase in weight and volume. However, the complex geometry design and saving the materials, weight, and volume are not the only advantages of this technology in thermal management systems. The most important feature of this technology in the thermal management system is the microstructural and material properties changes that significantly improved the thermal management system.

From the perspective and future work, the AM technology must move toward the multi-material systems to enable the fully additively manufactured electrical machines. This improves the heat transfer in the electrical machine in various ways, such as reducing the interfacial gaps created mainly due to the imperfections between solid materials' surfaces. Moreover, this feature will enable the printing of the conductors and insulation systems (an alternative option of resin insulated coils), which improve the thermal behavior of the winding and increasing the current loading capability of windings.

To conclude, AM technology will revolutionize the manufacturing of electrical machines. In our opinion, it is a matter of time to reach the same maturity level as conventional methods. This method allows the designer to more freely implement their creativity on the design using a wide range of materials to optimize the thermal management method that can support design with higher thermal loading from a geometrical perspective.

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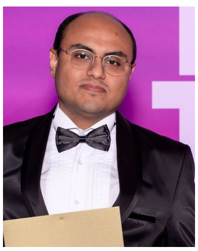

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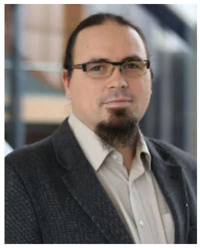

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