IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 12, 2020, accepted November 18, 2020, date of publication November 24, 2020, date of current version December 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3040045

An Overview of Modern Thermo-Conductive Materials for Heat Extraction in Electrical Machines

MEHMET CAGLAR KULAN[1], (Member, IEEE), **SAMET ŞAHIN**[2], AND **NICK J. BAKER**[1]
[1]School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, U.K.
[2]Department of Bioengineering, Faculty of Engineering, Bilecik Seyh Edebali University, 11230 Bilecik, Turkey
Corresponding author: Mehmet Caglar Kulan (mehmet.kulan@newcastle.ac.uk)

ABSTRACT This article presents a comprehensive review of the modern thermo-conductive materials that have potential to improve the heat extraction in electrical machines by conduction. Currently, there is a significant interest in thermal design and analysis of electrical machines as the demand for high power/torque density is substantially raised in applications such as marine, aerospace, e-mobility and rail. Thermal design engineering has become very important to develop smaller and more efficient electric motors, therefore electrical machine designers need to be more informed with the recent development in novel thermo-conductive (insulation) materials. Such developments can provide enhanced thermal characteristics for high power dense electrical machines. It is reported that high voltage electrical insulations can have more sophisticated thermal properties with the recent advancements in materials science. This study aims to inform electrical machine designers with and without a thermal background about recent thermo-conductive materials. Thus, a profound understanding can be gained in thermally conductive materials for the use of numerous applications in electrical machines for which thermal management is a crucial aspect of the overall multi-physics design and optimization process.

INDEX TERMS Electrical machines, heat extraction, insulation materials, rotating machines, thermal analysis, thermal design, thermal conduction, and thermal materials.

I. INTRODUCTION

An optimal electrical machine performance is based on electromagnetic and thermal design. Thermal management and its impact on electrical machine manufacture has grown significantly with the recent developments in computing, manufacturing and materials science. Thermal behavior is of paramount importance for electrical machine reliability. Recently, it is common practice that electrical machine designers carry out traditional electromagnetic design and thermal analysis in parallel [1], [2]. The dramatic rise in awareness of the importance of thermal issues and associated cooling methods in electric motors/generators lead to an increased thermal analysis in the early design stage of the machines [3]. In the literature, the published papers to date focus on how to conduct a thermal analysis of an electric motor by using a variety of thermal modelling approaches such as analytical, experimental and numerical methods [4]–[13].

The associate editor coordinating the review of this manuscript and approving it for publication was Xiaodong Liang.

Several review papers with the main concern of cooling technologies, modern heat extraction systems and electrical insulation systems in electric motors have been reported in the literature [3], [14]–[23]. The structure of published review papers is based on the common cooling technologies such as passive cooling and forced cooling [6], [21]; heat extraction methods with a brief overview of heat transfer by conduction, convection and radiation [6], [20], [22]; machine topology-specific cooling technologies such as thermal management in switched reluctance or axial machines [10], [16]; and finally application-specific thermal review papers including automotive, traction and transportation [17], [18], [20], [21].

Regarding review papers focusing on the thermal aspects, the main discussions include loss generation principles in electrical machines; analysis techniques including experiment informed finite element method (FEM) and computational fluid dynamics (CFD) investigations and cooling schemes/instruments such as natural and forced cooling with numerous application examples. Furthermore, another review paper concentrates on insulation systems in modern electrical machines with a principal objective in electrical aspects including dielectric properties, and partial discharge [23]. However, a comprehensive study of thermally conductive (i.e. thermo-conductive) insulation systems for modern electrical machines has not been presented in the literature with a focus on heat transfer by conduction.

Therefore, this review paper is structured in such a way that machine designers and industry professionals in the electrical motor/generator sector can access recent advancements in thermo-conductive insulation materials especially for use of high power/torque dense electrical machines, providing thermal management by conduction.

A thermo-conductive material can be defined as a stable material for use in removing or transferring thermal energy [24]. More specifically, thermo-conductive materials in rotating machines are mostly electrical insulating materials with a certain thermal conductivity (Watts/meter-Kelvin) and they help dissipating thermal energy since a buildup of heat (Watts or Joules per second) adversely affects the performance and life-time of active electromagnetic components in electrical machines. Numerous examples can be given for thermo-conductive materials in rotating machines. Insulating varnishes for motor conductors, impregnating epoxy resins, the interface materials between windings and laminations, structural bonding materials, and adhesives can all be adopted as thermo-conductive materials owing to their duty regarding heat transfer in electrical machines. From the point of view of thermal management, the principal insulating materials/systems and their physical interfaces within an electrical machine structure are illustrated in Fig. 1 [25].

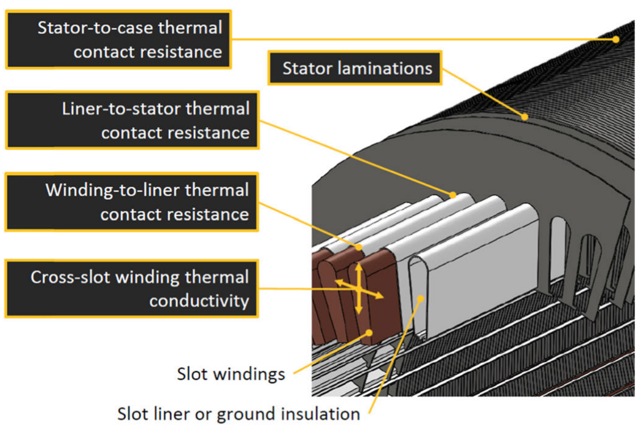


FIGURE 1. Material interfaces requiring thermal management in an electrical machine assembly [25].

It is worth emphasizing that heat extraction by conduction is the principal element of all heat extraction systems as the thermal performance of all rotating machinery is fundamentally dependent upon the thermal properties of the materials within their structure. Electrical insulation systems under the perspective of thermal management can be considered to be thermal materials since thermal conductivity, specific heat capacity and density are the only material properties of interest. Therefore, in the last decade, significant research efforts have been made leading to the development of novel insulation materials with higher thermal conductivity.

According to a technical roadmap of the U.S. Department of Energy, specific research is needed in many areas including thermal materials as depicted in Fig. 2 [26] to carry out the electric motor strategy for meeting the 2025 targets as planned in the roadmap.

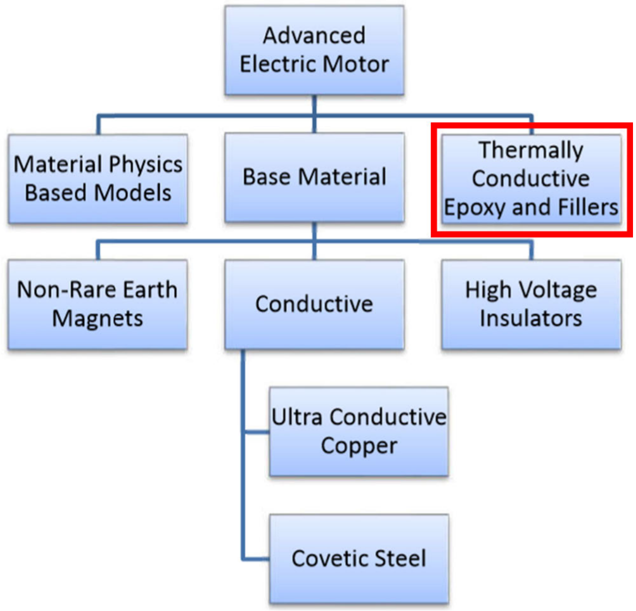


FIGURE 2. Electric motor research and development (R&D) areas according to U.S. Drive Electrical and Electronics Technical Team Roadmap [26].

This review paper aims to discuss thermally conductive insulation materials recently being used in industry and academia. Furthermore, novel materials that have potential applications in electrical machines to improve heat transfer by conduction have been compiled.

The paper is outlined as follows; Section II gives a brief thermal materials market information, Section III contains heat transfer by conduction and material data, Section IV covers key insulation materials used in modern electrical machines with their possible advantages in thermal management, Section V shows some real-life examples and applications of thermally conductive insulation materials reported previously in the literature, Section VI presents novel thermo-conductive materials developed in material science having potential for use in electrical machines to improve the extraction of heat. In Section VII, the authors give a brief discussion of this review.

II. THERMAL MANAGEMENT MATERIALS MARKET

As electrical traction motors and generators technology evolves globally, the thermal management market grows dramatically. According to Global Market Insights (GMI), the market size was over USD 4.5 billion in 2018 and is anticipated to hit USD 8.7 billion in 2026 [27]. The market covers various products such as pastes, gap fillers, tapes, and thermal gels/greases for the industries including consumer electronics, automotive, aerospace, healthcare and telecommunication.

Similarly, according to GMI, thermally conductive paste is the most predominant product in the thermal management and phase change materials (PCM), which might find some applications in electrical machines in near future, are mostly offered in high power electronic applications [27]. Furthermore, some important thermal management companies such as 3M, Parker Chomerics, Boyd, European Thermodynamics, Dr Dietrich Muller Gmbh, Lord Corporation, Henkel AG & Company, Honeywell International Inc. and Dupont have been highlighted in the recently published, GMI report [27]. The report also covers the pitfalls of the market since the product volume demand and high prices are the main challenges in long term. Therefore, high product prices might also be a limitation in the use of thermal management materials in electrical machines industry.

III. HEAT EXTRACTION THROUGH CONDUCTION

In electrical machines, conduction heat transfer is the principal element of heat extraction as heat is generated in various components of electrical machines due to electromagnetic and mechanical power losses. The conduction heat transfer is achieved by molecule vibration within a certain material [22].

Thermal performance is linked with the thermal properties of the active and passive materials within the structure of electric machines. Active materials contribute to electromagnetic torque generation and they are vital components of the operation. However, insulation materials are passive components of rotating machines as they do not contribute electromagnetic torque production, but they usually limit thermal class (i.e. maximum allowable temperature), manufacturing techniques and life expectancy [20], [23]. Therefore, insulating materials are critical as their thermal properties are directly related to the thermal performance and reliability of electric machines.

Electrically insulating materials with high thermal conductivity are very important to reduce the size and packaging of electric motors. Thermal conductivity is a material data that needs to be known for an accurate thermal model of electric motors. For better understanding, the thermal conductivity of air at 25 °C is 0.026 W/mK which is very low in comparison to highly conductive copper with thermal conductivity of 400 W/mK at room temperature. Similarly, the thermal conductivity of electric steels typically ranges between 15-55 W/mK, although steel manufacturers usually do not provide thermal conductivity data [11].

However, thermoset and thermoplastic polymers which constitute the majority of insulation materials in rotating machines, mostly do not possess a high thermal conductivity and hence prevent good heat dissipation inside the machine components [23]. This causes accelerated aging, lower life expectancy, increased Joule losses and lower efficiency. Therefore, recently there has been a significant effort put forward in the literature to improve heat conduction in polymer-based insulation materials including polymer coatings, impregnation materials, slot liners, sealants and thermally conductive adhesives.

IV. INSULATION MATERIALS IN ROTATING ELECTRIC MACHINES WITH IMPORTANT THERMAL PROPERTIES

A classification has been made in this section for all insulation materials used in rotating machines. The main objective is to introduce thermo-conductive insulating materials which are electromagnetically inactive components of electrical machines yet crucial in terms of long term reliability and efficiency. Thermal aspects of these materials are also explored here as they are on principal heat extraction paths. Turn to turn, winding slot to tooth, stator laminations to housing and winding to housing are some of the important heat extraction paths and electrical insulation materials in these particular regions determine the amount of the heat flux flow (W/m^2) which is a function of effective thermal conductivity. Therefore, the common materials currently in use and novel materials under the light of materials science will be described thoroughly later in this section.

The main insulation materials in electrical machines have been classified in Fig. 3. [23], [28]. The majority of these insulating materials will be reviewed here in terms of their thermo-conductive aspects.

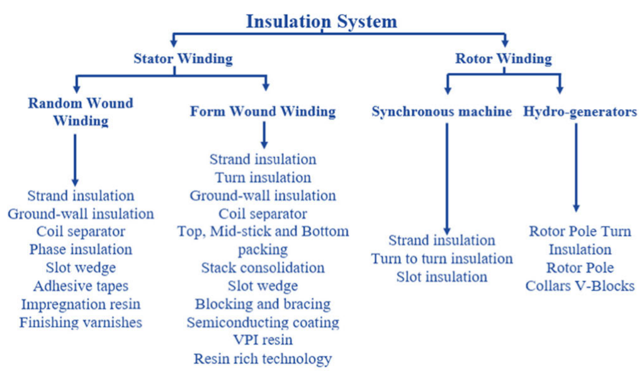


FIGURE 3. Main insulation materials in rotating electrical machines (©2019 IEEE) [23].

A. POLYMER-BASED WIRE INSULATION MATERIALS

A polymer can be defined as a large molecule composed of repeated subunits. Polymers range from common synthetic plastics including nylon, rubber, resins, etc. to some bio-molecules. The classification scheme could be fulfilled according to the behavior of polymers with rising temperature. In this context, polymers can be studied under two titles: thermoplastic and thermosetting polymers. A thermosetting polymer is one that becomes irreversibly cured (permanently hard) and does not soften upon heating [29], [30].

The thermoset polymer-based insulation layer usually called coating or enamel in copper or aluminum magnet wires (i.e. rotor and stator windings) constitutes the principal insulation system of rotating machines. Thermoset materials such as polyurethane, polyamide, polyimide, etc. are types of organic resins and usually determine resistance to chemicals, solder-ability and a thermal class of magnet wires. The standardized magnet wire coatings and their corresponding thermal classes are given in Table 1 [20], [31]. Thermal class of an insulation system such as thermal class 'F', 'H' is determined by testing according to international standards [17], [32], [33].

TABLE 1. Magnet wire insulations and standardized thermal classes ANSI/NEMA MW1000-2015 [20], [31].

Magnet wire thermal class	*Standard*	*Insulation*	
		Underlying coating	*Superimposed coating*
105	MW15-C	polyvinyl acetal-phenolic	
130	MW28-C	polyurethane	polyamide
155	MW79-C	polyurethane	
155	MW80-C	polyurethane	polyamide
155	MW41-C	glass fibre covered	
180	MW76-C	polyester (amide) (imide)	polyamide
180	MW77-C	polyester (imide)	
180	MW78-C	polyester (imide)	polyamide
180	MW82-C	polyurethane	
180	MW83-C	polyurethane	polyamide
180	MW50-C	glass fibre covered	
200	MW74-C	polyamide (amide) (imide)	
200	MW35-C	polyester (amide) (imide)	polyamide-imide
200	MW44-C	glass fibre covered	
220	MW61-C	aromatic polyamide	
220	MW37-C	polyester (amide) (imide)	polyamide-imide
220	MW81-C	polyamide-imide	
240	MW16-C	aromatic polyimide	

Since the insulation films/enamels are the most sensitive to thermal overloads, the selection of the insulation film is critical for long service life. If magnet wires are subjected to higher temperature overloads, life expectancy will be greatly reduced. Most notably, 10 °C temperature rise in windings reduces the life expectancy by half according to Hendershot and Miller [40]. Regarding thermal properties of thermoset based magnet wire coatings, their thermal conductivity is within the range 0.1 – 0.5 W/mK which is very low compared to active materials in the machine structure. While the thermal conductivity of primary insulating materials is very low compared to the steel and conductors, the relative length scales differ by orders of magnitude. The selection of magnet wire insulating materials and their thermal conductivity is reported in Table 2.

According to Seilmayer and Katepally [41], there is less information in general thermal performance and quality of

TABLE 2. Selected insulating materials as magnet wire enamels.

Material	*Thermal conductivity (W/mK)*	*Maximum temperature (°C)*	*Remarks*	*References*
Polyurethane	0.25 – 0.5	95	Raw material	[34]
Polyamid/ imide	0.26 – 0.54	200 – 260	Raw material	[35, 36]
Kapton MT+	0.78	>200	Polyimide film	[37, 38]
Kapton 150PRN411 polyimide film	0.12	>200	Fluoro-polymer in both sides	[37]
Kapton 200FN919	0.12	>200	Fluoro-polymer in both sides	[37]
Kapton 100FCRN019	0.38	>200	-	[37, 39]
Teflon	0.19 – 0.24	150 – 200	-	[36]

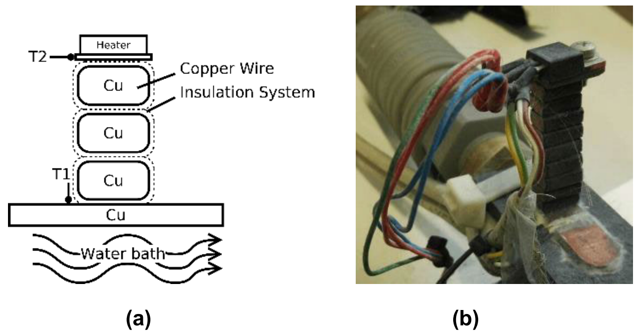


FIGURE 4. (a) The principle of direct thermal conductivity measurement, (b) a segment of winding to measure thermal conductivity with a transistor as a heater element [41].

manufactured multilayer insulation systems. Therefore, they have tested several magnet wire samples and have estimated the thermal conductivity of some commercial magnet wire segments (Magnetemp CA 200, Magnebond AB 220 by Essex Inc.) by using one dimensional Fourier Law of Heat as described in Fig.4 [41], [42]. They have measured the thermal conductivity of Magnetemp CA-200 and Magnebond AB-220 in a range between 0.11-0.19 and 0.22-0.27, respectively through different measurement setups.

PEEK insulated wires, an alternative to magnet wires given in Table 1, are also available in various AWG (America Wire Gauge) sizes shown in Fig. 5, produced by, for example, ZEUS Industrial Products Inc. They are particularly designed for challenging environments with improved thermal properties [43]. PEEK insulated magnet wires are rated up to 260 °C with a coating thermal conductivity of 0.29 W/mK, higher than those enameled with more conventional thermoset insulations.

FIGURE 5. PEEK insulated magnet wires rated up to 260 °C as reported by Zeus Inc. [43].

B. WIRE IMPREGNATION MATERIALS

According to Liu *et al.*, bare windings in electrical machines tend to vibrate and bend during operation which might cause a failure [44]. Therefore, stator windings are traditionally impregnated by varnish or epoxy to reduce any vibration caused during operation. Impregnation of windings also offers higher average thermal conductivity for the coils as it reduces air gaps, voids between the strands. Vacuum impregnation is a more sophisticated way of doing that as it can significantly reduce air voids leading to higher efficiency and a smaller temperature gradient in the windings.

Epoxy resins are alternative impregnation materials offering higher thermal conductivity at the cost of lower resistivity and lower dielectric strength. In Table 3, a set of impregnation materials are given to compare their key parameters [44], [45].

TABLE 3. Various winding impregnation materials [44], [45], [47].

Material	*Thermal Conductivity (W/mK)*	*Dielectric Strength (kV/mm)*
Varnish	0.25	80
Epoxylite (different ranges)	0.2 - 0.85	20
CoolTherm ® SC-320 (Silicone encapsulant)	3.2	10
U2002T	0.22	120
U2050R	0.4	20
U2002L	0.22	104

Varnish has low thermal conductivity but traditionally very popular as an impregnation material owing to its high dielectric strength. Silicone-based encapsulant (CoolTherm ® SC-320 by Lord Corp. [46]) has relatively very high thermal conductivity with low dielectric strength. It is worth mentioning that silicone-based encapsulants might not be suitable for wire impregnation due to their high viscosity. Ultimeg series epoxy resins specifically produced for motor/generator applications, offer some advantages such as low viscosity, high dielectric strength, etc. as stated in [47].

Guo *et al.* [45] reported the application of vacuum pressure impregnation (VPI) for stator windings by using U2050L&R epoxy resins for stator windings. The study highlights that impregnation goodness, varying between 0 and 1 depending on the perfection of impregnation, is key to improve the electro-thermal performance of a machine. It was also shown that a gap between the winding and the tooth lamination is an important parameter affecting thermal conductance. The VPI impregnated coils are illustrated in Fig. 6 [45].

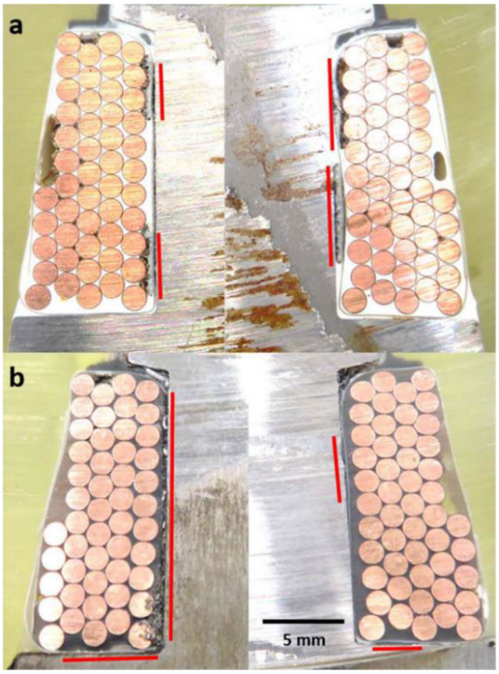


FIGURE 6. Comparison between cross-sections of segments: a) a segment filled with resin U2050R, b) a segment filled with resin U2050L (©2019 IEEE) [45].

Recently, polymer nanocomposites have drawn attention from researchers to be used in the insulation system in electrical machines [23]. They are epoxy resins with some thermally conductive micro- or nano-fillers such as aluminum-oxide, boron-nitride, graphene-oxide, etc. These materials and their potentials in electrical machines will be presented later in Section VI.

C. SLOT LINERS

Slot liners constitute primary insulation systems of electrical machines as they are an electrical insulation barrier between winding and tooth laminations. In terms of electrical aspects, slot liners aim to prevent turn to ground wall insulation faults with their high dielectric strengths. Nonetheless, slot liners are also a thermal barrier between the winding and tooth and they are always desired to exhibit high thermal conductance as it is on the principal heat paths.

The thermal performance of slot liners depends on the material, manufacturing, and impregnation. Table 4 shows the electrical and thermal properties of different commercially available slot liners.

TABLE 4. Slot liner properties [44], [45], [49].

Material	*Thickness*	*Thermal conductivity (W/mK)*	*Dielectric Breakdown Strength (kV/mm)*
Nomex 410	0.25 mm	0.139 at 180 °C	33
ThermaVolt (3M)	0.25 mm	0.23 at 180 °C	36
CeQuin I (3M)	0.25 mm	0.195 at 180 °C	27
PEEK APTIV™ film	25 – 250 μm	0.32 – 1.30	70 -270

According to research conducted by Yin *et al.*, a novel and high-performance ceramic composite dielectric coating is developed as an alternative to Nomex or PEEK slot liners. The coating results in significantly higher thermal conductivity and temperature stability than conventional insulation systems and can be applied directly onto the magnetic core as slot insulation and onto the copper conductor as winding insulation by electrophoretic deposition (EPD) [48].

In Fig. 7(a), a stator core which is deposited by Aluminum Nitride (AlN) and polymer by implementing EPD, is shown. The final coating is an electrical insulation with superior thermal properties. The thermal conductivity comparison is illustrated in Fig. 7(b).

D. POTTING MATERIALS BETWEEN WINDINGS AND HOUSING

Potting materials are considered to be secondary insulation systems. Epoxy resins and silicone-based high thermal conductivity polymers are the most common potting materials which might provide a compact and low-cost alternative to direct cooling. Potting materials between windings and housing create additional heat extraction paths as illustrated in Fig. 8 and previously researchers suggested that potting the stator end windings reduce winding hot spot temperature up to 50 °C at given power output and increase the power output by 15-25% in comparison to the un-potted machine [17], [50]–[52].

Similarly, researchers have investigated the quantitative effect of a silicone-based potting material on heat extraction [13]. They claim that that the axial heat flow is improved by 5.6% by potting end windings for an aerospace alternator. This in turn reduced the winding temperature by around 10.5% during standstill DC thermal tests. Potting materials might usually have high thermal conductivity up to 3.5 W/mK. Higher thermal conductivity can be achieved by metal-based nano or micro powders. However, it should be noted that potting materials are part of insulation and

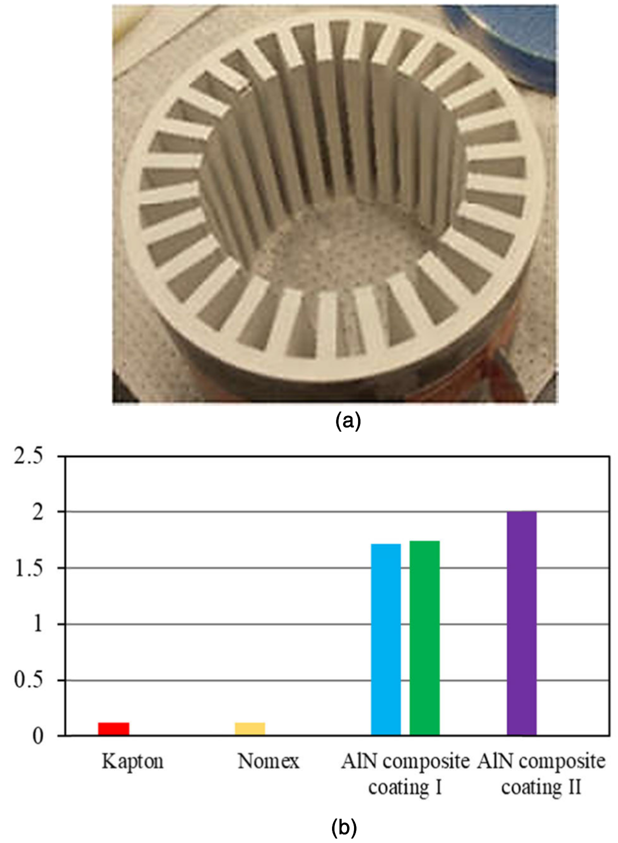


FIGURE 7. A novel highly thermally conductive, electrical insulation approach for stator core; (a) AlN deposited stator core, (b) thermal conductivity comparison (©2019 IEEE) [48].

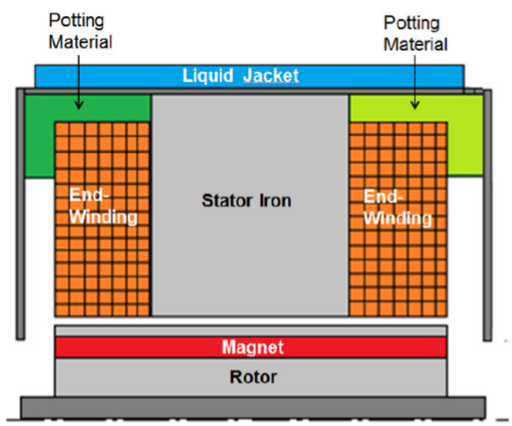


FIGURE 8. Potting material on end windings as previously reported in [44], [53] (©2019 IEEE).

should possess high enough dielectric strength to prevent any insulation related faults.

A good comparison table related to the performance of potting materials including silicone, epoxy and urethane based materials was suggested by Nategh *et al.* [17]. It is shown that silicone has the best material characteristics in terms of temperature range, electrical insulation and processing.

Epoxy is the best in terms of chemical resistance, stiffness and adhesive strength. They also found urethane to be the best moisture barrier but not good regarding the material's temperature range. The electrical and thermal properties of some new potting materials are given in Table 5.

TABLE 5. Electrical and thermal properties of selected potting materials [44], [53], [54].

Material	*Density (kg/m^3)*	*Thermal Conductivity (W/mK)*	*Volume Resistivity (Ohm.m)*
Ceramacast 675N	3260	100	10^{11}
Epoxy 2315	1800	58	10^{14}
Alumina filled epoxy	-	20-25	10^{15}
AlN filled epoxy	2470	3.8	10^{16}
Silicone	1960	2	10^{16}

Another study [23] has investigated the most common encapsulation materials as shown in Table 6, used for the potting of electrical machines to enhance average thermal conductivity and so heat flow rate, as part of passive cooling.

TABLE 6. The most common encapsulation materials for electrical machines [23], [55].

Encapsulation Material	*Dielectric Strength (kV/mm)*	*Thermal Conductivity (W/mK)*
E88 epoxy C89 hardener	30.7	1.049 (at 23°C) 1.069 (at 50°C)
Aradur CW 229-3 Hardener HW-229	20	0.75
Altherm XB-2710 Aradur XB-2711	20	1.5
Araldite XB-2252 Aradur XB-2253	20	0.7
Araldite CW-1312 Aradur HY-1300	15	1.1
Arathane CW-5631 Arathane HY-5610	20	0.6
Aratherm CW-2731	-	3
Catalyst-11	15	1.28
Epoxy-234	16.3	3.77
Epoxy-1121	17.3	0.14
Epoxy-1282	17.3	0.14
Epoxy-1285	14.4-15.7	1-1.27
Thermoset SC 320	-	3.2
Epoxylite® 6203	22	0.25
Epoxylite® 8628	23.6	0.25
Dolphon® CC-1105	-	0.2-0.25

E. THERMALLY CONDUCTIVE SEALANTS, ADHESIVES AND GREASES

Thermally conductive adhesives have some applications in electrical machines such as bonding thermocouples onto a surface for more precise measurements which require high thermal conductivity. Omegatherm^{TM}is a material with a thermal conductivity of 2.3 W/mK from Omega for encapsulating the thermal sensors operating up to 200 °C [56].

Silicone-based thermal gap fillers might be of interest to electric motor designers as the mechanical clearance between the machine components causes lower thermal contact conductance (TCC). Low viscosity thermal gap fillers for electronics might find an application in electrical machines to enhance thermal conductance. Fig. 9 shows a material with a thermal conductivity of 4.2 W/mK (TIS420C) from Momentive to improve heat extraction by improving thermal contact conductance between components [57].

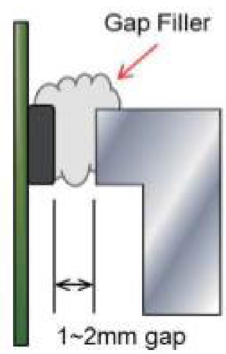


FIGURE 9. Thermally conductive gap filler from Momentive (non-adhesive curing) with a thermal conductivity of 4.2 W/mK [57].

Electrically and thermally conductive greases also offer a very high thermal conductivity as these materials have metal or semi-metal based fillers such as silver, boron, etc. For the machine parts where electrical insulation is not usually necessary, such as bearings, this type of greases might be used to achieve higher thermal conductivity as bearings are part of the rotor cooling mechanism. Silver-based conductive grease, boron nitride heat sink grease and non-silicone based grease (i.e. lubricators) with superior thermal conductivity up to 5.6 W/mK are commercially available and they are produced by several chemical companies such as Intertronics, MG Chemicals, Shin-Etsu Silicone and CHT, etc. [58]–[61].

Integrated motor drives [62], [63] where power electronics and machine are in a single package can be considered to be a good miniaturization example in electrical energy conversion and heat extraction by thermo-conductive materials is vital for reliability. To achieve a certain amount of life expectancy in integrated motor drives, thermal stress, causing the aging of components needs to be reduced. In this case, thermo-conductive materials such as greases and sealants have the potentials to keep the temperature within an acceptable range and can be applied between components where heat extraction is critical. Fig. 10 [57] illustrates how thermal performance can be improved in power electronics devices and integrated motor drive packaging by using thermo-conductive materials. They are usually introduced as thermal interface materials (TIM) in the literature as previously investigated in [64], [65]. These materials are likely to find more applications in the electrical machine industry soon due to sophisticated cooling schemes, requiring more thermo-conductive materials.

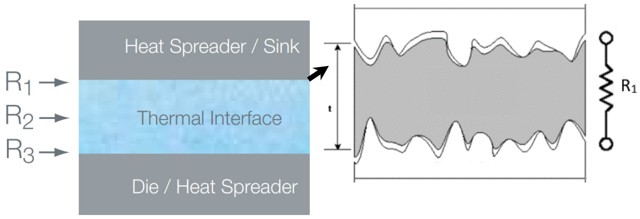


FIGURE 10. Thermo-conductive interface between the surfaces where heat management is critical by Momentive Inc. [57].

It can be noted in Fig. 10 that greasy, non-slumping and wetting properties of the thermo-conductive material fill the majority of microscopic gaps and so enhance the thermal contact conductance between the components.

V. APPLICATION OF THERMO-CONDUCTIVE MATERIALS IN ELECTRIC MOTORS AND SOME EXAMPLES

Thermo-conductive materials can be used in many interfaces in an electrical machine assembly to provide better thermal performance. The key thermal interfaces are as follows:

- Stator to housing interface
- Winding to liner interface
- Liner to stator laminations interface
- Lamination to lamination interface
- End-windings to housing interface
- Magnet to rotor core back interface for permanent magnet (PM) machines
- Magnetic or non-magnetic slot wedges to stator/rotor interface
- Housing to finned heat exchanger interface
- The mounting interface between 3D printed heat exchangers and the machine cooling channels
- Ball bearings to housing clearance interfaces

All material interfaces highlighted above might cause thermal management issues in electrical machines as they constitute thermal contact resistance between the material interfaces. Thermo-conductive materials such as adhesives, epoxy resins, silicon-based paste, etc. therefore find many applications in electrical machine design. Some thermal management examples via thermo-conductive materials are given in this section.

In Fig. 11 [66], a vacuum pressure impregnated (VPI) rotor and stator are shown. The aim of global potting is to reduce vibration, noise, moisture and thermal shock. In addition to these, high thermal conductivity encapsulation materials such as silicone-based paste, epoxy resins result in lower temperature rise. In addition to enhanced heat conduction paths due to lower thermal resistance, global potting also assists the heat transfer by convection via solid potting compound surfaces, and thus it allows the machine to operate in overload without exceeding the thermal limit. Penrose and Wittmuss [66] claim that the encapsulated machine maintains 10°C lower temperature in comparison to the machine without global potting while operating in similar conditions.

FIGURE 11. Encapsulated rotor and stator as previously studied by [66] (©2011 IEEE).

In [67], Nategh *et al.* investigated end winding potting and global winding potting. They claim that both potting approaches significantly reduce the winding temperature. Furthermore, it is stated that global potting with low thermal conductivity resins gives the same thermal performance as end winding potting. The performance results are plotted in Fig. 12 when the injected power is 500 Watts [67].

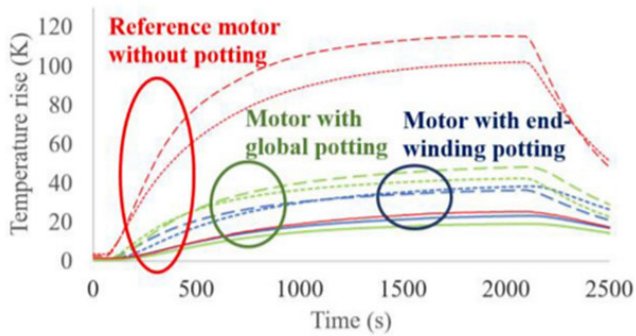


FIGURE 12. Temperature measurements on the motors without potting, with end winding potting (Resin with thermal conductivity of 3.5 W/mK) and global potting (Resin with thermal conductivity of 1.1 W/mK) (©2020 IEEE) [67].

Yao *et al.* [68] used a composite potting material containing aluminum-nitride inside (AlN). They predict the thermal conductivity of the silicon-based encapsulation material to be 40 W/mK after adding AlN. Authors have experienced some challenges during the application as the liquidity of the potting compound was an issue. The composite material was flowing along the wall of the stator during the curing process. The potential cause of the liquidity is perhaps the 'binder' separating from the filler during the curing/drying process. The photograph of the encapsulated machine is given in Fig. 13 [68].

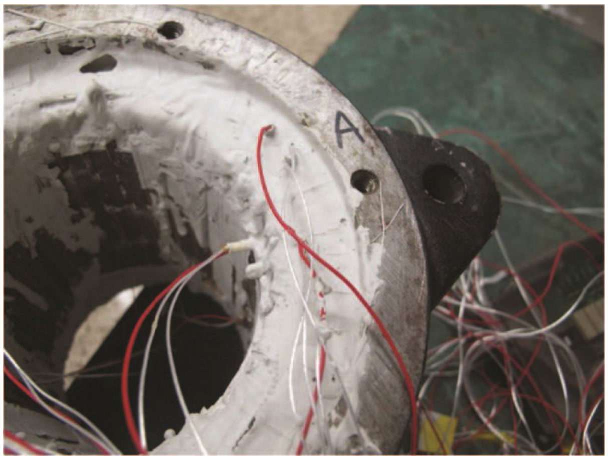


FIGURE 13. Composite material encapsulation containing AlN for 7 kW PMSM for electric vehicles (EVs) (©2011 IEEE) [68].

The authors conducted thermal experiments at 400 Hz to see the temperature rise in the original machine and the machine with encapsulation material while injecting 1000 Watts. The global temperature rise was reduced by 20 °C as reported.

VI. NOVEL THERMO-CONDUCTIVE MATERIALS AND THEIR POTENTIAL APPLICATIONS IN ELECTRIC MOTORS

Recent advancements in material science enable novel thermo-conductive materials that can be used as high thermal performance insulation materials in high power density electrical machines to improve heat extraction. There are many studies on thermo-conductive insulating materials in the literature, aiming to explore the potentials of dielectric polymer composites. Polymeric materials are the most common insulating materials in electrical machines due to their high breakdown strength, high electrical resistivity and low cost [69]. Xiao *et al.* state that the common polymers used in electrical engineering are epoxy, silicone rubber, polyimide (PI), polypropylene (PP), low-density PE (LDPE), etc. [70]. However, most polymers such as epoxy resins exhibit relatively low thermal conductivity between 0.1 – 0.5 W/mK. Furthermore, according to Wang *et al.*, a conventional epoxy resin having a thermal conductivity range of 0.17-0.21 W/mK cannot fulfil the thermal management requirements [71].

High thermal conductivity fillers such as aluminium oxide, aluminium nitride, boron nitride, silicon nitride, beryllium oxide, graphene oxide or diamond are usually introduced to increase the average thermal conductivity of epoxy resins. Wong *et al.* reveal that heat could be conducted through the fillers instead of the polymer when they are added in the polymer as these fillers usually have high thermal conductivity [72]. Xiao *et al.* confirm that many factors affect the thermal conductivity of composite material (epoxy + inorganic fillers) including thermal conductivity of particles, shape and size of the particle, particle dispersion and orientation, preparation process, etc. [70]. Thermal conductivity of various materials including the most common fillers at room temperature is given in Table 7. [69].

TABLE 7. Thermal conductivity of various materials including inorganic fillers [69], [73]–[76].

Material	***Thermal Conductivity (W/mK)***
Epoxy	0.17 – 0.21
Nylon 6,6	0.25
Nylon 1,1	0.36
Silicone elastomer	0.17 – 0.26
Fused SiO_{2}·	1.5 – 1.6
Crystalline silica	3
Al_2O_3	38 – 42
BeO	300
ZnO	60
Si_4N_3	86 – 120
BN	29 – 300
AlN	150 – 220
SiC	85
$BaTiO_3$	6.2
Diamond	2000
Graphite [74]	25 - 470
Graphene (single layer) [75]	3080 – 5150
Graphene-Oxide [76]	2 – 1000

So far, several methods have been proposed to calculate the thermal conductivity of a two-phase composite system (usually epoxy and inorganic fillers) [77], [78]. According to Miyazaki *et al.* [79], the Bruggeman model [80], which is a popular model to determine the thermal conductivity, states that the thermal conductivity of the composite monotonically increases with filler content or thermal conductivity of fillers.

A. EPOXY RESIN WITH ALUMINUM–OXIDE, ALUMINUM–NITRIDE AND SILICON–DIOXIDE FILLERS

Kochetov *et al.* [81] attempt to find out the thermal properties of epoxy resins filled with microparticles of aluminium-oxide (Al_2O_3) and silicon dioxide (SiO_2·). They claim that thermal conductivity and the relative permittivity of the epoxy composites were significantly influenced by the filler loading as depicted in Fig. 14 [81].

It can be noted in Fig. 14 that pure epoxy resin (ER) has around 0.17 W/mK thermal conductivity and when Al_2O_3

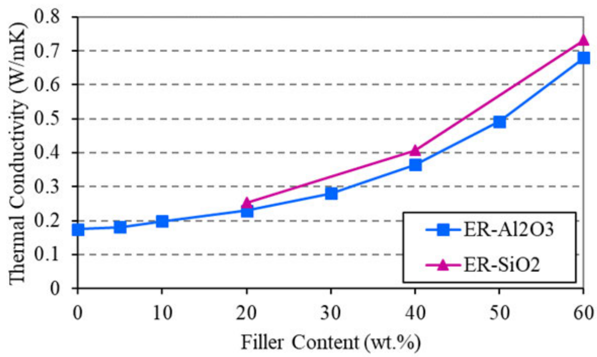


FIGURE 14. Thermal conductivity variations of ER composites filled with Al2O3 and SiO2 by weight (%)(©2010 IEEE) [81].

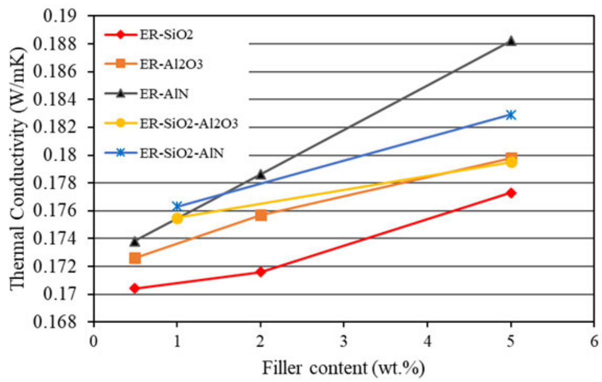


FIGURE 16. Thermal conductivity variations of ER with 'nano' particles of Al2O3, SiO2, AlN (©2009 IEEE) [83].

and SiO_2· are added to form a composite material, its thermal conductivity increased up to 0.74 W/mK.

In a similar research [82], the authors investigated the effect of Al_2O_3 micro fillers in ER in lower quantities. They obtained slightly increased thermal conductivity for the composites compared with neat epoxy as shown in Fig. 15 [82].

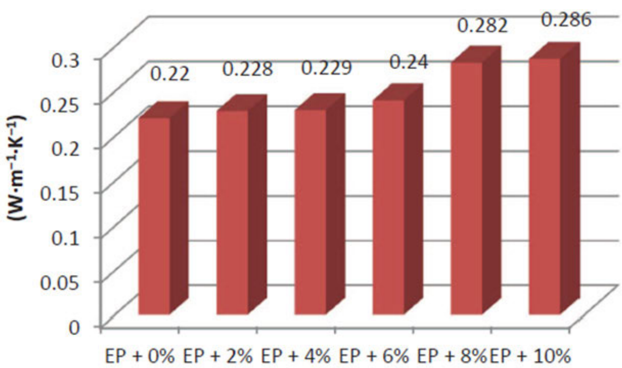


FIGURE 15. Thermal conductivity variations of ER with lower concentrations of Al2O3 (©2016 IEEE) [82].

Some research was also conducted on nano-fillers rather than micro-filler to form epoxy composites. Authors use up to 50-70 % fillers when they form composite materials with microparticles. Nonetheless, a study [83] focuses on nanofillers of silica, alumina or aluminum nitride with a lower volume fraction to obtain thermo-conductive materials. It is shown that nano-fillers improve the thermal conductivity but not significantly as given in Fig. 16 [83].

The authors in [84] focus on the thermal conductivity of ER with Al_2O_3 and its dissipation factor (tan δ). For dielectric materials, the higher the value of tan δ means the greater the dielectric loss. In Table 8 [84], the effect of Al_2O_3 micro-particles on the composite performance is summarized.

Researchers in [85], state that the impregnation process of superconducting power equipment, low thermal expansion, high dielectric strength and high thermal conductivity

TABLE 8. The effect of $Al_2\ O_3$ micro-particles on the composite thermal and dielectric performance (©2015 IEEE) [84].

Material	*Thermal conductivity (W/mK)*	*Dissipation factor (tan δ)*
Pure Epoxy	0.22	0.0023
Epoxy + Al_2O_3 2%	0.22	0.0022
Epoxy + Al_2O_3 4%	0.23	0.0021
Epoxy + Al_2O_3 6%	0.24	0.0028
Epoxy + Al_2O_3 8%	0.28	0.0025
Epoxy + Al_2O_3 10%	0.29	0.0027

are all factors that need to be considered. Therefore, they investigated thermo-conductive epoxy with aluminum-nitride (AlN) fillers. Their experimental results demonstrated that the maximum thermal conductivity is 1.13W/mK from the sample obtained at 60% filler content of AlN-2 μm and AlN-600 nm (50%/50%) with curing temperature of 0 °C by using a method described in their study in [85].

In [86], the authors measured the volume resistivity of thermo-conductive epoxy resins with Al_2O_3 fillers. The results are plotted in Fig. 17 [86] which might be of interest to realize the dielectric properties of thermo-conductive epoxy composites with alumina (Al_2O_3) fillers.

B. BORON NITRIDE (BN) BASED EPOXY COMPOSITES

Huang *et al.* [69] suggest that Boron nitride (BN) is suitable as a filler to achieve thermo-conductive composites. BN also has high electrical resistivity, low dielectric constant and low density which makes it ideal for the packaging of electrical and electronic devices [87]. Commercially BN is available in three forms: amorphous BN, hexagonal BN (h-BN) and cubic BN. The structure of h-BN is similar to graphite as shown previously in [69]. Moreover, BN nanotubes and nano-sheets have recently attracted researchers in material science [88].

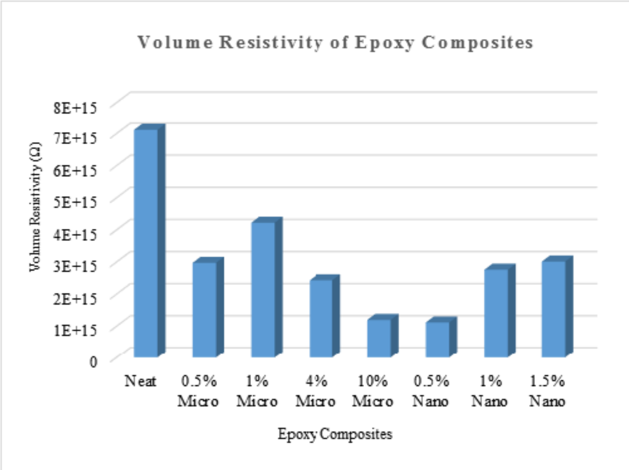


FIGURE 17. Volume resistivity measurement of epoxy composites with micro and nano-particles of Al2O3 fillers as reported in [86] (©2018 IEEE).

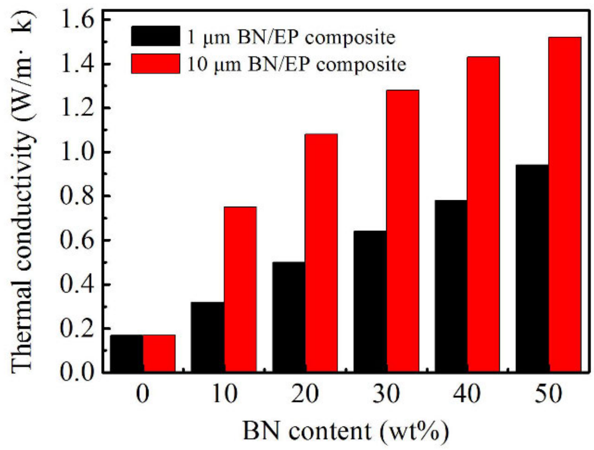


FIGURE 18. Thermal conductivity of BN/EP composites in various BN content by weight (©2018 IEEE) [71].

In the literature, several studies focus on epoxy resins with BN fillers, as the polymer composites with BN fillers have enhanced thermal conductivity and acceptable dielectric strength for use as an electrical insulator. Authors in the literature propose BN fillers for epoxy resins in different weights/volumes, sizes and structures. Many authors suggest novel methodologies to prepare the material samples. In this article, details of material preparation and characterization for epoxy resins with BN fillers are avoided as the main scope here is to give an insight about high-performance thermo-conductive materials for electrical machine designers rather than describing the scientific approaches, pursued to propose a material with a novel methodology in material science. Readers who are interested in specific material preparation/characterisation might refer to references given after Section VIII.

Wang *et al.* [71] propose two types of composites with an average BN particle size of 1 μm and 10 μm and a filler concentration of 20, 30, 40, and 50 percent by weight. The particles are modified with a coupling agent to improve compatibility with epoxy resin. The results are given in Fig. 18 [71]. They obtained a thermo-conductive insulating material with a maximum thermal conductivity of 1.52 W/mK.

Tuo *et al.* [89] state that compatibility of BN with the polymer matrix is low and the improvement of thermal conductivity is limited. Therefore, BN filler was modified by an agent called KH-560 and designated as f-BN. Epoxy resins with fillers of BN and f-BN were prepared. The improvement of thermal conductivity with different BN fillers is demonstrated in Fig. 19 [89].

Kochetov *et al.* [90] investigate the effect of BN nanoparticles with different filler contents on the thermal conductivity of epoxy resin. They used BN nanopowders to enhance the thermal conductivity by adding 0.5 to 10% fillers by weight. The results were compared with AlN-epoxy mesocomposites as given in Table 9 [90].

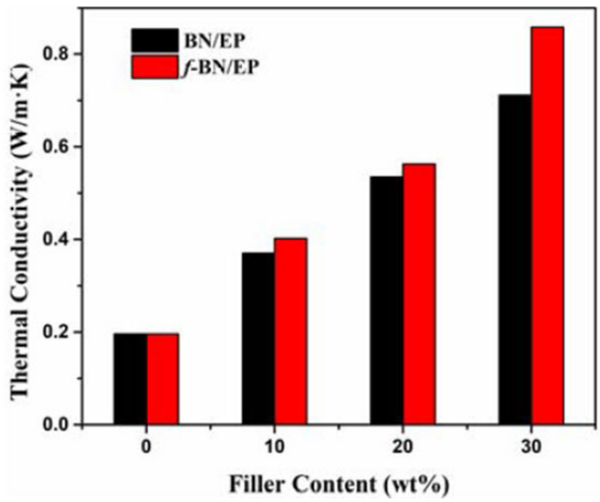


FIGURE 19. Thermal conductivity of BN/Epoxy and f-BN/Epoxy in different mass fractions of filler content (©2019 IEEE) [89].

TABLE 9. Thermal conductivities of obtained composites (©2009 IEEE) [90].

Sample Material (filler by weight)	*Thermal conductivity (W/mK)*
Pure Epoxy	0.168
Epoxy + BN (0.5%)	0.1718
Epoxy + BN (2%)	0.1722
Epoxy + BN (5%)	0.1797
Epoxy + BN (10%)	0.191
Epoxy + AlN (0.5%)	0.1728
Epoxy + AlN (2%)	0.1768
Epoxy + AlN (5%)	0.1851
Epoxy + AlN (10%)	0.1987

In Table 9, the thermal conductivities of AlN filled composites are higher than for composites filled with BN when nano-powders are used for the preparation of the composites. This implies that the size of the BN particles is a factor in thermal conductivity improvement in epoxy resins.

According to Yung *et al.*, the mixture of hexagonal BN and cubic BN is considered to improve the thermal conductivity of epoxy resins [91]. In a study [92], researchers prepared 25 types of epoxy/BN composites by using an approach called the hot press method. The BN fillers were surface modified with some coupling agents and thermal conductivity values of 2.91 W/mK, 3.95 W/mK and 10.1 W/mK were obtained for the composites that were single loaded with h-BN (hexagonal boron nitride), c-BN (cubic boron nitride) and conglomerated h-BN, respectively. They were further improved to 5.26 W/mK, 5.94 W/mK and 12.3 W/mK, respectively, by adding extra smaller AlN particles to fill the voids in the epoxy composites. However, the authors state in [93] that the material with a thermal conductivity of 12.3 W/mK has 75.1 kVpeak/mm in breakdown dielectric strength which is 260% of breakdown dielectric time for neat epoxy [93]. This enhancement in thermal conductivity comes with low dielectric strength in this case.

Similarly, authors studied novel epoxy nanocomposites that are fabricated by using 3D interconnected Boron Nitride Nanosheets (BNNSs) [94]. A novel strategy for the fabrication of 3D BNNS network is suggested by self- assembly of BNNS on a 3D CNF (cellulose nanofiber) skeleton employing sol-gel and freeze-drying methods. The results show that the obtained materials exhibit ultrahigh thermal conductivity and suppressed dielectric loss at low BNNS loading. Furthermore, the authors report high electrical insulation performance as tabulated in Table 10 [94].

TABLE 10. **Properties of novel epoxy nanocomposites with BN nanosheets (©2017 IEEE) [94].**

Material Sample	*BNNS Loading (Volume %)*	*Thermal Conductivity (W/mK)*	*Volume resistivity (Ohm.cm)*
Epoxy	0	0.180	4.45×10^{16}
Epoxy/BNNS	9.6	0.404	9.68×10^{16}
EP/CNF	0	0.184	1.71×10^{15}
EP/CNF/BNNS	9.6	3.13	3.51×10^{16}

C. GRAPHENE, GRAPHENE-OXIDE AND DIAMOND POWDERS FOR THERMO-CONDUCTIVE EPOXY COMPOSITES

Graphene is an electrical conductor and is inappropriate as a filler in insulating polymer-based composites [69]. Oxidized graphene (graphene-oxide) is electrically insulating and therefore can be an appropriate filler for thermo-conductive insulating materials since it exhibits high thermal conductivity, given in Table 9. Huang *et al.* [69] and Wang *et al.* [75] reported that 5.0 wt% graphene oxide epoxy composites show about a 4-fold increase in thermal conductivity and a low coefficient of thermal expansion compared to pure epoxy. Nevertheless, the authors did not include any electrical property of the composites.

Li *et al.* [95] investigate epoxy nanocomposites with multilayer graphene sheets, which are fabricated by solution blended processes. The results indicate that at 25 °C, the thermal conductivity of nanocomposite increases to 0.227 W/(mK) with 0.5 wt.% filler, which is 34.59 % larger than that of a neat epoxy composite. The variation of thermal conductivity with respect to temperature is given in Fig. 20 [95].

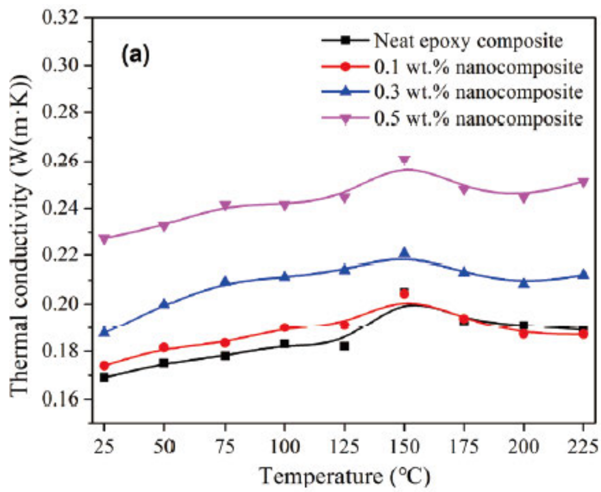


FIGURE 20. **Thermal conductivity variation with respect to temperature for epoxy/graphene composites (©2017 IEEE) [95].**

Zhang *et al.* achieved a thermal conductivity of 4.1 W/mK in epoxy composites by adding diamond powder with a size of 9 μm [97]. However, diamond powder is rarely used as a filler material due to its cost. Moreover, the study demonstrates that cheaper fillers with high concentrations such as AlN (70% by volume) can result in the same thermal performance as epoxy resins with a diamond powder [97].

Oxidized nano-diamond (OND) has been preferred to improve the thermal conductivity yet keeping the electrical insulation properties in an acceptable range in a study given in [96]. A simple oxidization strategy was used to obtain oxidized nano-diamond powder. Fig. 21 [96] shows the electrical and thermal properties of the obtained composite materials. It can be noted that thermal conductivity improvement is limited in this case, with a maximum increase of 36% in comparison to pure epoxy. Besides, the volume resistance of composites was nearly the same as the original epoxy resin, implying that the composite mostly preserves its dielectric strength.

VII. DISCUSSION

Although there are several, but not necessarily enough, studies in the literature, there are very important points that need to be clarified for the use of thermo-conductive materials in electrical machines. Such points involve theoretical and

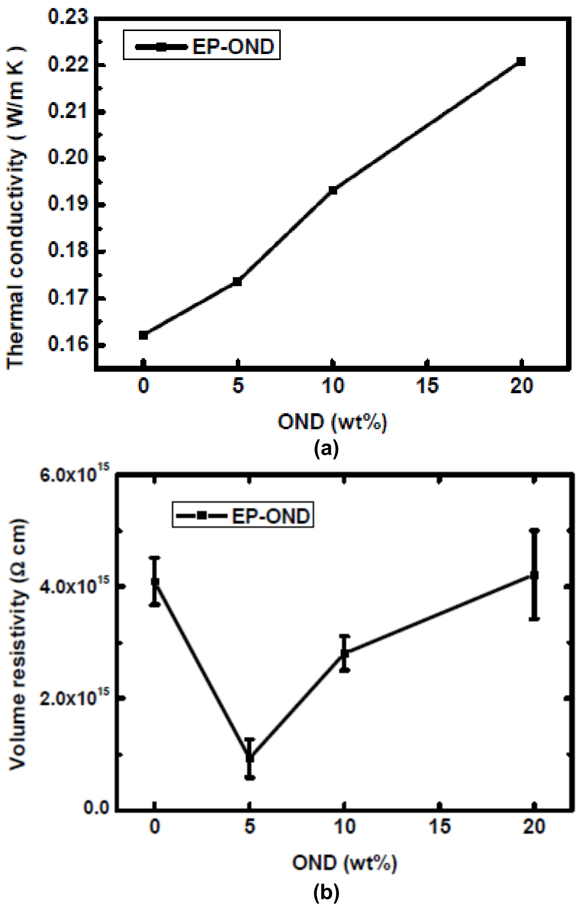


FIGURE 21. **Epoxy + oxidized nano-diamond (OND) properties: (a) thermal conductivity variation by weight; (b) volume resistivity variation by weight (©2016 IEEE) [96].**

practical aspects. First of all, it is hard to classify thermal materials in terms of their overall thermo-electric performance. We highlighted many materials in this review article but it is not straightforward to classify the materials under similar topics. For example, some thermal materials have superior thermal properties, but this usually comes with a reduced volume resistivity, which is not desired in rotating machines. Secondly, the studies mainly focusing on material science usually assess the material without presenting results in a practical application, especially rarely in an electrical machine application. The experimental work in material science is mostly limited to material characterization without the consideration of an application. Material scientists usually conduct thermal property measurements on thin films. However, thermal conductivity predictions on bulk materials might diverge in comparison to thermal measurements obtained on the fabricated thin films.

It is therefore hard to comment on whether the novel thermo-conductive materials developed can replace the traditional insulating materials such as varnish and neat epoxy in the short term.

There are many criterions need to be considered to choose the best thermo-conductive insulation for an electrical machine since application, cost-effectiveness and dielectric properties are all important aspects to choose the optimal material in a certain thermal class. Furthermore, engineers might encounter several difficulties during the application of thermo-conductive materials as the material's viscosity, density and impregnation goodness are all key factors affecting the overall performance.

Thermal material manufacturers usually market their commercial products by highlighting a single thermal and/or electrical property of the material. For instance, a highly thermally conductive insulating material might have a very high viscosity, making the application very difficult even unsuccessful. Another example can be the curing conditions of the material. Some thermo-conductive materials are of two components or curing temperature is very high and it takes a remarkable amount of time to cure. These are all potential issues that cannot be addressed by a unique thermo-conductive material. Cost-effectiveness of the material is another problem as this affects the overall cost of an electric machine. For example, some of the widely used thermally conductive nanomaterials such as graphene oxide could enhance the heat transfer rates significantly, however, researchers might end up having very expensive composite material at hand that may be impossible to commercialize.

Besides, the authors would like to mention that high thermal conductivity values reported in the literature do not necessarily lead to higher thermal performance in some circumstances in electrical machines. Therefore, electrical machine designers need to utilize modern computational methods (i.e. FEM) to simulate the thermal performance of an electrical machine under different scenarios, with thermal sensitivity studies. Hence, theoretical work becomes as important as the practical work.

Lastly, the reported thermal conductivity values in the literature might show anisotropic properties (i.e. directional rather than uniform) and they might have been assessed under certain physical/ambient conditions, implying that the performance of the given material might diverge significantly in real-life applications. Therefore, more quantitative studies on electrical machines with various thermo-conductive materials are necessary for the literature to make a fair performance comparison among the thermal materials. Furthermore, a consistent methodology practice should be followed for presenting thermal performance data regarding the effect of thermo-conductive material used, such as the theoretical and experimental conditions hand calculations.

VIII. CONCLUSION

In this article, a comprehensive review of thermo-conductive insulation materials is presented. The authors highlight that advanced, high torque dense electric machine for various applications such as aerospace, marine, railway etc., targeted by many countries until 2025, requires thermally conductive advanced materials. However, electrical machine designers usually have limited background on these materials and their electro-thermal properties. This article aims to inform the readers about the recent developments in material science regarding thermo-conductive insulating materials which are part of advanced thermal management in electrical machines.

It is explicit that recent developments in materials result in several new thermo-conductive materials, some of which are commercially available but the majority of these materials are only available in the literature. High thermal conductivity is a very important material property for the materials used in electrical machines. Nonetheless, these materials must have sufficient dielectric strength to be able used as insulation materials.

The authors would like to summarize the key points of this article as follows:

- There is significant research on thermo-conductive material as miniaturization of electrical devices including electrical machine components and power electronics packaging push the researchers towards novel material investigation with improved thermal conductance.
- Electric machine designers need more knowledge and understanding of the selection of thermal materials as part of the design and optimization process. Therefore, this article overviews almost all potential insulating materials that might be used in electrical propulsion in the near future with superior thermal properties.
- The authors give several application examples from the literature to highlight the importance of thermo-conductive materials.
- In Section VI, the authors summarized the novel thermo-conductive insulating materials including micro and nano-sized thermally conductive fillers such as boron nitride, aluminum oxide, diamond nano-powders, etc. Authors believe that most of these materials will have strong potentials for an application in electrical machines in the future.

REFERENCES

[1] P. Pescetto, S. Ferrari, G. Pellegrino, E. Carpaneto, and A. Boglietti, "Short-time transient thermal model identification of multiple three-phase machines," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2018, pp. 222–228.

[2] A. Boglietti, A. Cavagnino, and D. A. Staton, "TEFC induction motors thermal models: A parameter sensitivity analysis," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 756–763, May 2005.

[3] R. Wrobel, P. H. Mellor, M. Popescu, and D. A. Staton, "Power loss analysis in thermal design of permanent-magnet machines—A review," *IEEE Trans. Ind. Appl.*, vol. 52, no. 2, pp. 1359–1368, Apr. 2016.

[4] A. Boglietti, A. Cavagnino, M. Lazzari, and M. Pastorelli, "A simplified thermal model for variable-speed self-cooled industrial induction motor," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 945–952, Jul. 2003.

[5] A. Boglietti, A. Cavagnino, and D. Staton, "Determination of critical parameters in electrical machine thermal models," *IEEE Trans. Ind. Appl.*, vol. 44, no. 4, pp. 1150–1159, Jul./Aug. 2008.

[6] A. Boglietti, A. Cavagnino, D. Staton, M. Shanel, M. Mueller, and C. Mejuto, "Evolution and modern approaches for thermal analysis of electrical machines," *IEEE Trans. Ind. Electron.*, vol. 56, no. 3, pp. 871–882, Mar. 2009.

[7] T. Huber, W. Peters, and J. Bocker, "A low-order thermal model for monitoring critical temperatures in permanent magnet synchronous motors," in *Proc. IET Conf.* London, U.K.: Institution of Engineering & Technology, 2014.

[8] C. Sciascera, P. Giangrande, L. Papini, C. Gerada, and M. Galea, "Analytical thermal model for fast stator winding temperature prediction," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6116–6126, Aug. 2017.

[9] S. Ayat, R. Wrobel, J. Goss, and D. Drury, "Experimental calibration in thermal analysis of PM electrical machines," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2016, pp. 1–8.

[10] D. A. Howey, A. S. Holmes, and K. R. Pullen, "Measurement and CFD prediction of heat transfer in air-cooled disc-type electrical machines," *IEEE Trans. Ind. Appl.*, vol. 47, no. 4, pp. 1716–1723, Jul. 2011.

[11] D. Staton, A. Boglietti, and A. Cavagnino, "Solving the more difficult aspects of electric motor thermal analysis in small and medium size industrial induction motors," *IEEE Trans. Energy Convers.*, vol. 20, no. 3, pp. 620–628, Sep. 2005.

[12] G. D. Demetriades, H. Zelaya de la Parra, E. Andersson, and H. Olsson, "A real-time thermal model of a permanent-magnet synchronous motor," *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 463–474, Feb. 2010.

[13] M. C. Kulan and N. J. Baker, "Development of a thermal equivalent circuit to quantify the effect of thermal paste on heat flow through a permanent magnet alternator," *IEEE Trans. Ind. Appl.*, vol. 55, no. 2, pp. 1261–1271, Mar. 2019.

[14] A. Adouni and A. J. M. Cardoso, "Thermal Analysis of Synchronous Reluctance Machines-A Review," *Electr. Power Compon. Syst.*, vol. 47, nos. 6–7, pp. 471–485, 2019.

[15] F. Chauvicourt, P. Romanazzi, D. Howey, A. Dziechciarz, C. Martis, and C. T. Faria, "Review of multidisciplinary homogenization techniques applied to electric machines," in *Proc. 11th Int. Conf. Ecol. Vehicles Renew. Energies (EVER)*, Apr. 2016, pp. 1–9.

[16] P. S. Ghahfarokhi, A. Kallaste, A. Belahcen, T. Vaimann, and A. Rassolkin, "Review of thermal analysis of permanent magnet assisted synchronous reluctance machines," in *Proc. Electr. Power Qual. Supply Rel. (PQ)*, Aug. 2016, pp. 219–224.

[17] S. Nategh, D. Barber, D. Lindberg, A. Boglietti, and O. Aglen, "Review and trends in traction motor design: Primary and secondary insulation systems," in *Proc. 13th Int. Conf. Electr. Mach. (ICEM)*, Sep. 2018, pp. 2607–2612.

[18] S. Ramarathnam, A. K. Mohammed, B. Bilgin, A. Sathyan, H. Dadkhah, and A. Emadi, "A review of structural and thermal analysis of traction motors," *IEEE Trans. Transport. Electrific.*, vol. 1, no. 3, pp. 255–265, Oct. 2015.

[19] W. Sixel, M. Liu, and B. Sarlioglu, "Rotor thermal design for electric machines: Challenges and opportunities," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2018, pp. 821–826.

[20] Y. Yang, B. Bilgin, M. Kasprzak, S. Nalakath, H. Sadek, M. Preindl, J. Cotton, N. Schofield, and A. Emadi, "Thermal management of electric machines," *IET Elect. Syst. Transp.*, vol. 7, no. 2, pp. 104–116, Jun. 2017.

[21] Y. Gai, M. Kimiabeigi, Y. Chuan Chong, J. D. Widmer, X. Deng, M. Popescu, J. Goss, D. A. Staton, and A. Steven, "Cooling of automotive traction motors: Schemes, examples, and computation methods," *IEEE Trans. Ind. Electron.*, vol. 66, no. 3, pp. 1681–1692, Mar. 2019.

[22] M. Popescu, D. Staton, A. Boglietti, A. Cavagnino, D. Hawkins, and J. Goss, "Modern heat extraction systems for electrical machines—A review," in *Proc. IEEE Workshop Electr. Mach. Design, Control Diagnosis (WEMDCD)*, Mar. 2015, pp. 289–296.

[23] R. Hemmati, F. Wu, and A. El-Refaie, "Survey of insulation systems in electrical machines," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2019, pp. 2069–2076.

[24] V. Squitieri, "Thermally conductive materials," U.S. Patent 4 869 954, Sep. 26, 1989.

[25] K. Bennion, "Electric motor thermal management R&D. Annual report," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep. NREL/MP-5400-64944, 2016.

[26] Roadmap. *U.S. Drive Electrical and Electronics Technical Team Roadmap*. Accessed: May 12, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

[27] K. Pulidindi and H. Pandey, "Electronic thermal management materials market size by product, industry analysis report," Global Market Insights, Selbyville, DE, USA, Tech. Rep. GMI3780, 2020. Accessed: Nov. 9, 2020. [Online]. Available: https://www.gminsights.com/industry-analysis/electronic-thermal-management-materials-market

[28] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair*. Hoboken, NJ, USA: Wiley, 2004.

[29] Q. Guo, *Thermosets: Structure, Properties and Applications*. Amsterdam, The Netherlands: Elsevier, 2012.
[30] M. Kulan, "Analysis of the influence of different manufacturing methods on the thermal aspects of permanent magnet electrical machines," Ph.D. dissertation, School Eng., Newcastle Univ., Newcastle upon Tyne, 2018.
[31] *National Electrical Manufacturers Association Standard*, Standard ANSI/NEMA MW 1000-2015, 2015.
[32] *IEEE Recommended Practice for Thermal Evaluation of Unsealed or Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Pre-Insulated Stator Coils for Machines Rated 15000 V and Below*, IEEE Std 1776-2008, vol. C1-15, Feb. 2009.
[33] *Part 18-31: Functional Evaluation of Insulation Systems-Test Procedures for Form-Wound Windings-Thermal Evaluation and Classification of Insulation Systems Used in Rotating Machines*, Standard IEC 60034-18-312012, R. E. Machines-Part, 2012.
[34] Ghaziabad, India. (2017). *Properties of PTFE and Some Other Insulating Materials*. [Online]. Available: http://www.druflon.com/ptfeprop.html
[35] *Specifications for Particular Types of Winding Wires*, Standard Deutsche Norm DIN EN 60317, 2011.
[36] *Thermal Properties of Plastic Materials*, Professional Plastics Inc and Kietzke C, Fullertron, CA, USA, 2008.
[37] *Kapton-Summary of Properties, Datasheet*, DuPont, Wilmington, Delaware, USA, 2020.
[38] *Kapton MT+ Thermally Conductive Polyimide Film, Datasheet*, DuPont, Wilmington, DE, USA, 2020.
[39] *Corona Resistant Kapton CR Takes Electrical Insulation Design and Reliability to New Levels*, DuPont, Wilmington, DE, USA, 2010.
[40] J. R. Hendershot and T. J. E. Miller, *Design of Brushless Permanent-Magnet Motors*. Oxford, U.K.: Magna Physics Oxford Science Publications, 1994.
[41] M. Seilmayer and V. K. Katepally, "Thermal conductivity survey of different manufactured insulation systems of rectangular copper wires," *AIMS Electron. Electr. Eng.*, vol. 2, no. 1, p. 27, 2018.
[42] *Magnetemp CA-200*, Superior Essex Inc., Atlanta, GA, USA, 2010.
[43] (May 18, 2020). *PEEK Insulated Wire*. [Online]. Available: https://www.zeusinc.com/products/insulated-wire/peek-insulated-wire/
[44] M. Liu, Y. Li, H. Ding, and B. Sarlioglu, "Thermal management and cooling of windings in electrical machines for electric vehicle and traction application," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2017, pp. 668–673.
[45] Y. Guo, J. Soulard, and D. Greenwood, "Challenges in electric machine stator manufacturing and their influences on thermal performance," in *Proc. 9th Int. Electr. Drives Prod. Conf. (EDPC)*, Dec. 2019, pp. 1–9.
[46] *Potting and Encapsulation Products, Datasheet*. Accessed: May 14, 2020. [Online]. Available: https://www.lord.com/products-and-solutions/electronic-materials/potting-and-encapsulation
[47] *Electrical Insulating Epoxy Resins—Ultimeg Range, Datasheet*. Accessed: May 14, 2020. [Online]. Available: https://www.aev.co.uk/userfiles/files/Ultimeg_Epoxy_GTS_2019-v1_4.pdf
[48] W. Yin, A. Yakimov, H. Comanzo, O. Siclovan, P. Smigelski, K. Bodla, and A. Duggal, "Highly thermally conductive insulation for high power density electric machines," in *Proc. AIAA Propuls. Energy Forum*, Aug. 2019, p. 4510.
[49] *Victrex Aptiv Films, Datasheet*. Accessed: May 14, 2020. [Online]. Available: https://www.victrex.com/en/datasheets
[50] J. Cao, W. Li, Y. Zhang, X. Zhang, Y. Jiang, and Y. He, "Analyses on heat transfer and fluid flowing in a traction motor used in high-speed CRH," in *Proc. Int. Conf. Electr. Syst. Aircr., Railway, Ship Propuls. Road Vehicles (ESARS)*, Mar. 2015, pp. 1–8.
[51] S. Nategh, A. Krings, O. Wallmark, and M. Leksell, "Evaluation of impregnation materials for thermal management of liquid-cooled electric machines," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 5956–5965, Nov. 2014.
[52] D. Yu, X. Y. Huang, Y. T. Fang, and J. Zhang, "Design and comparison of interior permanent magnet synchronous traction motors for high speed railway applications," in *Proc. IEEE Workshop Electr. Mach. Design, Control Diagnosis (WEMDCD)*, Apr. 2017, pp. 58–62.
[53] M. Polikarpova, P. M. Lindh, J. A. Tapia, and J. J. Pyrhonen, "Application of potting material for a 100 kW radial flux PMSM," in *Proc. Int. Conf. Electr. Mach. (ICEM)*, Sep. 2014, pp. 2146–2151.
[54] J. H. Davis, D. W. Rees, and I. H. Riley, "Silicone encapsulating and potting materials," *Proc. IEE-Part B, Electron. Commun. Eng.*, vol. 109, no. 21S, pp. 266–270, 1962.
[55] J. Faiz, H. Nejadi-Koti, and Z. Valipour, "Comprehensive review on inter-turn fault indexes in permanent magnet motors," *IET Electr. Power Appl.*, vol. 11, no. 1, pp. 142–156, Jan. 2017.
[56] *OMEGATHERM High Temperature and High heat Conductive Paste*. Accessed: May 15, 2020. [Online]. Available: https://www.omega.co.uk/pptst/ot-201.html
[57] *Thermal Management Silicones for Electronics*. Accessed: May 15, 2020. [Online]. Available: https://www.silicone-solutions.co.uk/wp-content/uploads/2019/02/Thermal_Management_Silicones_for_Electronics_Brochure_2018.pdf
[58] *Silver Conductive Grease, Boron Nitride Heat Sink Grease, Silicone Free Heat Sink Grease*. Accessed: May 15, 2020. [Online]. Available: https://www.intertronics.co.uk/product/silver-conductive-grease-boron-nitride-heat-sink-grease-silicone-free-heat-sink-grease/
[59] *MG Chemicals Thermal Greases*. Accessed: May 15, 2020. [Online]. Available: https://www.mgchemicals.com/downloads/comparison-tables/Thermally%20Conductive%20Greases%20Comparison%20Chart.pdf
[60] *Thermal Interface Materials*. Accessed: May 15, 2020. [Online]. Available: https://www.shinetsusilicone-global.com/products/function/heat/index.shtml
[61] *SILCOTHERM Materials Brochure*. Accessed: May 16, 2020. [Online]. Available: https://www.cht.com/cht/medien.nsf/gfx/med_MJOS-BBHJYX_4F7EF0/$file/CHT-SILCOTHERM-Silicones-Brochure.pdf
[62] F. Farina, D. Rossi, A. Tenconi, F. Profumo, and S. E. Bauer, "Thermal design of integrated motor drives for traction applications," in *Proc. Eur. Conf. Power Electron. Appl.*, Sep. 2005, p. 10.
[63] R. Abebe, G. Lo Calzo, G. Vakil, B. Mecrow, S. Lambert, C. Gerada, T. Cox, and M. Johnson, "Integrated motor drives: State of the art and future trends," *IET Electr. Power Appl.*, vol. 10, no. 8, pp. 757–771, Sep. 2016.
[64] M. T. Demko, J. E. Yourey, A. Wong, P.-Y. Lin, G. S. Blackman, G. C. Catlin, and M. Yahyazadehfar, "Thermal and mechanical properties of electrically insulating thermal interface materials," in *Proc. 16th IEEE Intersoc. Conf. Thermal Thermomech. Phenomena Electron. Syst. (ITherm)*, May 2017, pp. 237–242.
[65] N. Wang, Y. Liu, S. Chen, L. Ye, and J. Liu, "Highly thermal conductive and electrically insulated graphene based thermal interface material with long-term reliability," in *Proc. IEEE 69th Electron. Compon. Technol. Conf. (ECTC)*, May 2019, pp. 1564–1568.
[66] H. W. Penrose and D. Wittmuss, "Evaluation of vacuum encapsulation systems for integral motors," in *Proc. Electr. Insul. Conf. (EIC).*, Jun. 2011, pp. 180–183.
[67] S. Nategh, A. Boglietti, D. Barber, Y. Liu, and R. Brammer, "Thermal and manufacturing aspects of traction motors potting: A deep experimental evaluation," *IEEE Trans. Energy Convers.*, vol. 35, no. 2, pp. 1026–1035, Jun. 2020.
[68] Y. Yao, L. Gu, T. Fan, W. Sun, and J. Luo, "Evaluation of heat transfer characteristic of aluminum nitride (AlN) potting compound for the end windings of permanent magnet synchronous machines," in *Proc. Int. Conf. Electr. Control Eng.*, Sep. 2011, pp. 4498–4501.
[69] X. Huang, P. Jiang, and T. Tanaka, "A review of dielectric polymer composites with high thermal conductivity," *IEEE Elect. Insul. Mag.*, vol. 27, no. 4, pp. 8–16, Jul./Aug. 2011.
[70] M. Xiao and B. X. Du, "Review of high thermal conductivity polymer dielectrics for electrical insulation," *High Voltage*, vol. 1, no. 1, pp. 34–42, Apr. 2016.
[71] S.-J. Wang, S.-L. Zhong, Z.-M. Dang, J.-W. Zha, and M.-S. Zheng, "The thermal conductivity and electrical properties of EP composite with different size BN," in *Proc. IEEE 2nd Int. Conf. Dielectr. (ICD)*, Jul. 2018, pp. 1–4.
[72] C. P. Wong and R. S. Bollampally, "Thermal conductivity, elastic modulus, and coefficient of thermal expansion of polymer composites filled with ceramic particles for electronic packaging," *J. Appl. Polym. Sci.*, vol. 74, no. 14, pp. 3396–3403, Dec. 1999.
[73] A. A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao, and C. N. Lau, "Superior thermal conductivity of single-layer graphene," *Nano Lett.*, vol. 8, no. 3, pp. 902–907, Mar. 2008.
[74] T. C. Mokhena, M. J. Mochane, J. S. Sefadi, S. V. Motloung, and D. M. Andala, "Thermal conductivity of graphite-based polymer composites," in *Impact of Thermal Conductivity on Energy Technologies*. London, U.K.: IntechOpen, 2018, p. 181.
[75] S. Wang, M. Tambraparni, J. Qiu, J. Tipton, and D. Dean, "Thermal expansion of graphene composites," *Macromolecules*, vol. 42, no. 14, pp. 5251–5255, Jul. 2009.

[76] Y. Yang, J. Cao, N. Wei, D. Meng, L. Wang, G. Ren, R. Yan, and N. Zhang, ''Thermal conductivity of defective graphene oxide: A molecular dynamic study,'' *Molecules*, vol. 24, no. 6, p. 1103, Mar. 2019.

[77] D. Bigg, ''Thermal conductivity of heterophase polymer compositions,'' in *Thermal and Electrical Conductivity of Polymer Materials*. Berlin, Germany: Springer, 1995, pp. 1–30.

[78] J. Z. Liang and G. S. Liu, ''A new heat transfer model of inorganic particulate-filled polymer composites,'' *J. Mater. Sci.*, vol. 44, no. 17, pp. 4715–4720, Sep. 2009.

[79] Y. Miyazaki, T. Nishiyama, H. Takahashi, J.-I. Katagiri, and Y. Takezawa, ''Development of highly thermoconductive epoxy composites,'' in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Aug. 2009, pp. 638–641.

[80] D. A. G. Bruggeman, ''Berechnung verschiedener physikalischer konstanten von heterogenen Substanzen. II. Dielektrizitätskonstanten und Leitfähigkeiten von vielkristallen der nichtregulären systeme,'' *Annalen der Physik*, vol. 417, no. 7, pp. 645–672, 1936.

[81] R. Kochetov, T. Andritsch, P. H. F. Morshuis, and J. J. Smit, ''Thermal and electrical behaviour of epoxy-based microcomposites filled with Al_2O_3 and SiO_2 particles,'' in *Proc. IEEE Int. Symp. Electr. Insul.*, Jun. 2010, pp. 1–5.

[82] T. Tomaskova, S. Blaha, A. Shlykevich, P. Trnka, and M. Gutten, ''Effect of micro-filler of aluminium oxide on the mechanical, electrical and thermal properties of electrical insulation systems,'' in *Proc. 18th Eur. Conf. Power Electron. Appl. (EPE ECCE Eur.)*, Sep. 2016, pp. 1–10.

[83] R. Kochetov, T. Andritsch, U. Lafont, P. H. F. Morshuis, and J. J. Smit, ''Thermal conductivity of nano-filled epoxy systems,'' in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena*, Aug. 2009, pp. 658–661.

[84] T. Tomaskova, M. Svoboda, A. Shlykevich, and P. Trnka, ''Increase the thermal conductivity of high voltage electrical insulation systems,'' in *Proc. 17th Eur. Conf. Power Electron. Appl. (EPE ECCE-Eur.)*, Sep. 2015, pp. 1–6.

[85] S. Dai, T. Zhang, S. Mo, Y. Cai, W. Yuan, T. Ma, L. Hu, and B. Wang, ''Study on preparation, thermal conductivity, and electrical insulation properties of Epoxy/AlN,'' *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, pp. 1–6, Mar. 2019.

[86] A. K. Parmar and R. R. Patel, ''Dielectric properties of alumina based epoxy composites for electrical insulation,'' in *Proc. 2nd Int. Conf. Electron., Mater. Eng. Nano-Technol. (IEMENTech)*, May 2018, pp. 1–4.

[87] K. Sato, H. Horibe, T. Shirai, Y. Hotta, H. Nakano, H. Nagai, K. Mitsuishi, and K. Watari, ''Thermally conductive composite films of hexagonal boron nitride and polyimide with affinity-enhanced interfaces,'' *J. Mater. Chem.*, vol. 20, no. 14, pp. 2749–2752, 2010.

[88] T. Terao, Y. Bando, M. Mitome, C. Zhi, C. Tang, and D. Golberg, ''Thermal conductivity improvement of polymer films by catechin-modified boron nitride nanotubes,'' *J. Phys. Chem. C*, vol. 113, no. 31, pp. 13605–13609, Aug. 2009.

[89] R. Tuo, Y. Zhang, W. Yang, S. He, Q. Xie, J. Lin, and X. Bian, ''Effect of micron thermal conductive filler on thermal conductivity and electrical properties of epoxy composites,'' in *Proc. IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP)*, Oct. 2019, pp. 717–720.

[90] R. Kochetov, T. Andritsch, U. Lafont, P. H. F. Morshuis, S. J. Picken, and J. J. Smit, ''Thermal behaviour of epoxy resin filled with high thermal conductivity nanopowders,'' in *Proc. IEEE Electr. Insul. Conf.*, May 2009, pp. 524–528.

[91] K. C. Yung and H. Liem, ''Enhanced thermal conductivity of boron nitride epoxy-matrix composite through multi-modal particle size mixing,'' *J. Appl. Polym. Sci.*, vol. 106, no. 6, pp. 3587–3591, Dec. 2007.

[92] Z. Wang, T. Iizuka, M. Kozako, Y. Ohki, and T. Tanaka, ''Development of epoxy/BN composites with high thermal conductivity and sufficient dielectric breakdown strength partI–sample preparations and thermal conductivity,'' *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 6, pp. 1963–1972, Dec. 2011.

[93] Z. Wang, T. Iizuka, M. Kozako, Y. Ohki, and T. Tanaka, ''Development of epoxy/BN composites with high thermal conductivity and sufficient dielectric breakdown strength part II-breakdown strength,'' *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 6, pp. 1973–1983, Dec. 2011.

[94] X. Huang, J. Chen, Y. Zhu, and P. Jiang, ''Ultrahigh thermal conductivity enhancement in polymer insulating materials by constructing 3D BN nanosheet networks,'' in *Proc. 1st Int. Conf. Electr. Mater. Power Equip. (ICEMPE)*, May 2017, pp. 10–13.

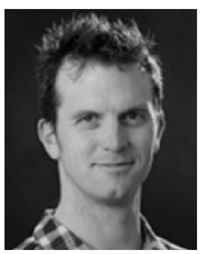
[95] H. Li, H. Tian, M. Cai, A. Gong, Z. Zhou, C. Wang, and Z. Peng, ''Dielectric properties of graphene-filled epoxy nanocomposite with enhanced thermal conductivity,'' in *Proc. Int. Symp. Electr. Insulating Mater. (ISEIM)*, Sep. 2017, pp. 149–152.

[96] W. Wang, W. Bian, and Y. Yang, ''Incorporation of nanodiamond into an epoxy polymer network with high thermal conductivity for electrical insulations,'' in *Proc. IEEE Int. Conf. Dielectrics (ICD)*, vol. 2, Jul. 2016, pp. 868–871.

[97] Y. Zhang, X. Hu, J. H. Zhao, K. Sheng, W. R. Cannon, X. Wang, and L. Fursin, ''Rheology and thermal conductivity of diamond powder-filled liquid epoxy encapsulants for electronic packaging,'' *IEEE Trans. Compon. Packag. Technol.*, vol. 32, no. 4, pp. 716–723, Dec. 2009.

MEHMET CAGLAR KULAN (Member, IEEE) received the B.Sc. degree in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2011, and the M.Sc. and Ph.D. degrees from the Electrical Power Research Group, School of Engineering, Newcastle University, Newcastle upon Tyne, U.K., in 2013 and 2018, respectively. He is currently with the Electrical Power Research Group, Newcastle University, working on fault-tolerant aerospace alternators. His research interests include thermal management of electrical machines and finite element modeling of electric motors and alternators.

SAMET ŞAHIN received the B.Sc. and M.Sc. degrees in chemical engineering from Hacettepe University, Ankara, Turkey, in 2009 and 2011, respectively, and the Ph.D. degree in chemical engineering from Newcastle University, U.K., in 2017. He was a Research Assistant and a Research Associate with the School of Chemical Engineering and Advanced Materials, Newcastle University, from 2016 to 2017. He is currently an Assistant Professor with the Department of Bioengineering, Bilecik Seyh Edebali University, Turkey, and also a Fulbright Scholar with Northwestern University, Chicago, USA. His research interests include biosensors, bioelectronics, and advanced materials.



NICK J. BAKER received the M.Eng. degree in mechanical engineering from Birmingham University, Birmingham, U.K., in 1999, and the Ph.D. degree in electrical machine design for marine renewable energy devices from Durham University, Durham, U.K., in 2003. He was a Researcher of machine design with Durham University, in addition to academic posts within the Lancaster University's Renewable Energy Group, from 2005 to 2008, and currently with the Newcastle University's Electrical Power Group. He has spent a period in industry as a Senior Consultant for energy consultancy TNEI Services, Ltd., Newcastle, U.K., from 2008 to 2010. He is a Senior Lecturer and also working on machines across the renewable, automotive, and aerospace sectors.