

# Role of Advanced Materials in Electrical Machines

Ayman EL-Refai, *Fellow, IEEE*

(Invited)

**Abstract**—There has been a revived and growing role for electrical machines and drives across a wide range of applications. Such applications include, hybrid/electrical traction applications, aerospace applications, and renewable energy. All these applications present different set of requirements and challenges. The common trend is that there is a need for higher-performance electrical machines in terms of higher power/torque density, and higher efficiency while keeping cost under control. There has been a lot of work done around coming up with novel machine topologies, optimizing more conventional topologies as well as improved thermal management schemes. Like many other areas of engineering/research, advanced materials can play a key role in opening up the design space for electrical machines leading to a step improvement in their performance. This paper will present an overview of some of the key advanced materials that are either recently developed or are currently under development and their potential impact on electrical machines.

**Index Terms**— Advanced, electrical, materials, machines.

## I. INTRODUCTION

THE goal of the paper is to provide researchers and practicing engineers of a comprehensive overview of the potential of advanced materials in enhancing the performance of electrical machines across a wide range of applications.

The paper will cover the various categories of materials that go into an electrical machine. The focus will be on the most promising materials as well as highlighting general trends.

The paper is arranged as follows:

- Section II will cover advancements in soft magnetic materials.
- Section III will cover advancements in permanent magnets
- Section IV will cover advancements in conductors
- Section V will cover advancements in insulation systems
- Section VI will cover advancements in composite materials
- Section VII will provide some conclusions.

The main focus of the paper is non-cryogenic electrical

machines. Superconducting machines is a broad topic and will not be covered in this paper.

Since most of the discussed materials are fairly new and several are still under development, it is very difficult to assume realistic costs at this point.

## II. ADVANCED SOFT MAGNETIC MATERIALS

In this section, advanced soft magnetic materials for stator and/or rotor laminations will be covered. These include:

### A. Dual-phase magnetic materials

These are materials where the permeability of selective regions with the lamination can be controlled [1]. Fig. 1 shows a dual-phase magnetic material that has been developed by GE. The ability to selectively control the magnetic properties of certain locations within the lamination opens up the design space for several machine topologies. This involves a nitriding process at high temperature and a material composition that enables higher absorption of nitrogen. The treatment is done on a lamination-by-lamination basis as well as masking of the regions that are intended to retain their magnetic properties while regions that are intended to become non-magnetic are exposed to the nitriding process. The details of the material composition and the process to achieve the local non-magnetic regions are included in [2]. Table I compares the properties of silicon steel M19 material to the magnetic and the non-magnetic phases of the novel dual-phase material.

The more obvious and significant benefits of using such materials is in interior permanent magnet (IPM) and synchronous reluctance machines. In this case, the bridges and center pots in the rotor laminations can become non-magnetic as shown in Fig. 1. This enables having thick bridges and center posts to be able to handle mechanical stresses while minimizing the magnet flux shunted in those regions. This can have significant impact on improving the power density and/or efficiency. Also this can lead to improvements in power factor which leads to reduction in power converter KVA rating and reduction in cable sizing. Also the ability to selectively introduce variable-permeability regions can be used to reduce torque ripple as well as introduce salient features that can be used for sensorless control. Similar benefits can be achieved with induction machines by introducing non-magnetic regions that effectively represent stator/rotor slot opening areas as shown in Fig. 4. This can have significant impact on the machine leakage inductance. In case of switched reluctance machines (SRM), the rotor can be made using complete discs and non-magnetic regions are introduced in the inter-polar

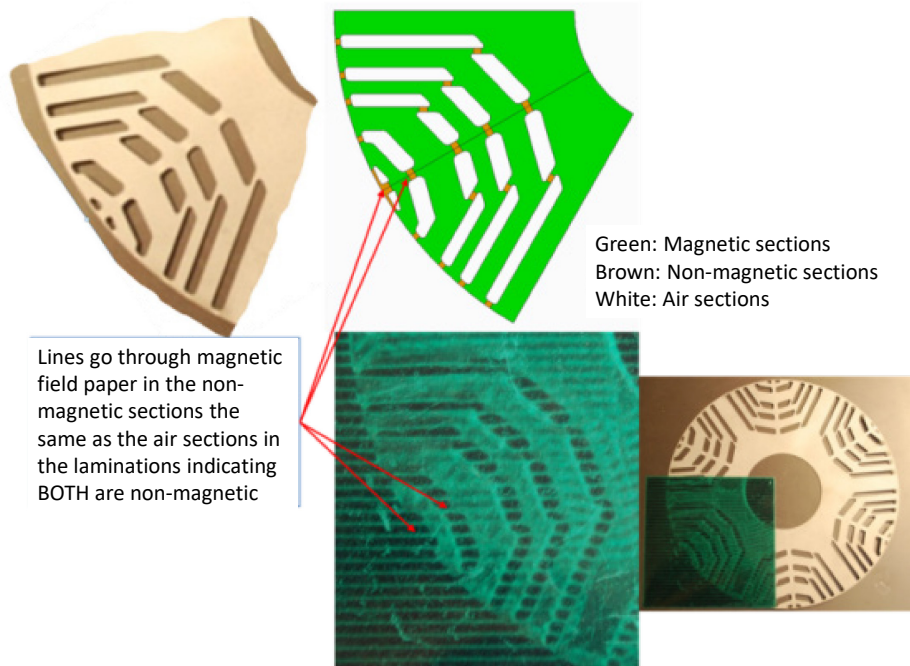


Fig. 1: Proof-of-concept lamination showing the magnetic and non-magnetic regions

TABLE I:  
COMPARISON OF KEY PROPERTIES OF M19 AND THE DUAL-PHASE MATERIAL

	M19 3% Si	Dual-phase Material (Magnetic phase)	Dual-phase Material (Non-Magnetic phase)
Max relative permeability	Up to 2100	~1100	~1
Magnetization Saturation [T] @ room temperature (represents saturation level of B-H curve)	1.8-2	1.56	0.25 (could be further reduced with better control of the processes)
Intrinsic coercivity [Oe] @ room temperature	0.66	0.752	N/A
Electrical resistivity [ $\mu\Omega\text{m}$ ]	0.5	0.49	
Thermal Conductivity (W/m/K)	22	22.6	
Yield strength [MPa]	344.7	275.8	565.4

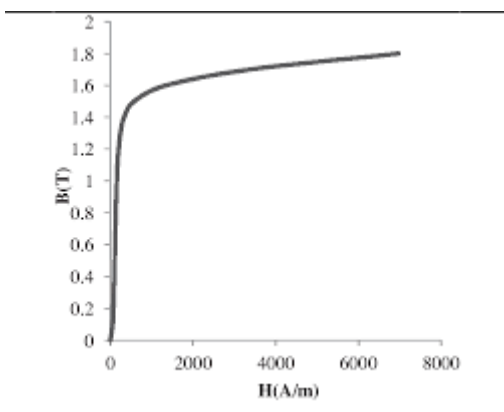


Fig. 2. Sample B-H curve of M19 silicon steel.

regions creating what is effectively a salient pole rotor from a magnetic perspective but with a smooth rotor as shown in Fig.5. This can have a significant impact on reducing windage losses as well torque ripple.

Table I summarizes the potential impact of using dual-phase magnetic materials on various machine topologies. In [1], it was shown that a synchronous reluctance machine using

dual-phase magnetic material can be competitive with an IPM for traction applications especially in terms of achieving a wide constant power speed ratio (CPSR) of 4:1

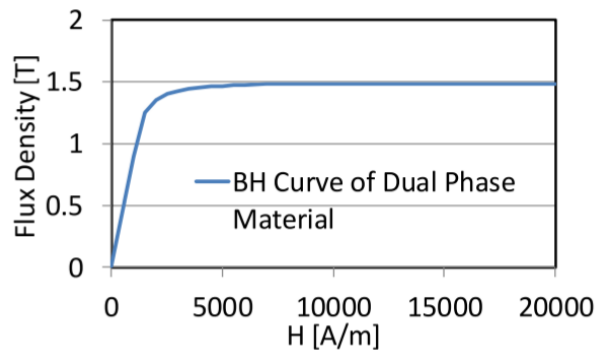


Fig. 3. B-H curve of magnetic regions of dual-phase magnetic material.

which cannot be typically achieved in conventional synchronous reluctance machines without significant penalty in terms of machine size. In [3], a 5 HP proof-of concept synchronous reluctance motor using dual-phase magnetic material has been built and tested. This helped confirm some of

the performance improvements as well as highlight some of the scaling challenges to be able to build full-scale machines using such materials. The best estimate so far is that this material will cost ~ 2X the cost of conventional silicon steel laminations.

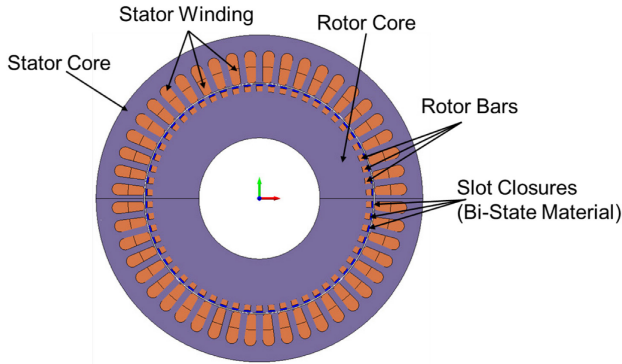


Fig 4. Induction machine using dual-phase magnetic material.

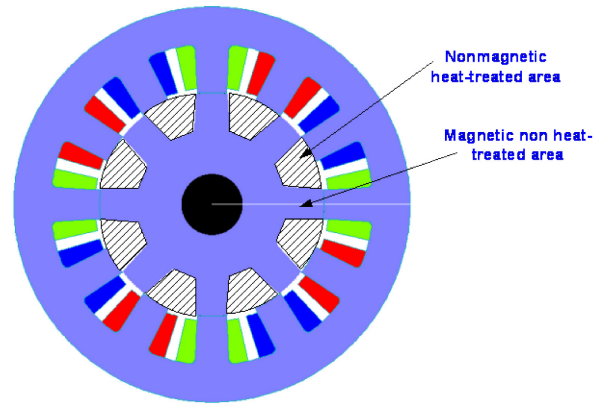


Fig 5: Switched reluctance machine using dual-phase magnetic material

TABLE II  
SUMMARY OF POTENTIAL IMPACT OF USING DUAL-PHASE MAGNETIC MATERIALS ON DIFFERENT MACHINE TOPOLOGIE

Machine Topology	IPM	Induction	Synchronous Reluctance	Switched Reluctance
Non-magnetic regions	Bridges and centerposts	Stator/rotor slot openings areas	Bridges and centerposts	Inter-polar spaces
Performance benefits	<ul style="list-style-type: none"> <li>Higher power density</li> <li>Improved power factor</li> <li>Pole shaping-&gt; torque ripple reduction</li> <li>Sensorless control</li> </ul>	<ul style="list-style-type: none"> <li>Improved power density (ability to go to higher tip speeds)</li> <li>Improved power factor-&gt; Reduction in converter VA rating</li> <li>Reduction in cable sizing/cost</li> <li>Sensorless control</li> </ul>	<ul style="list-style-type: none"> <li>Higher power density</li> <li>Improved power factor</li> <li>Wider constant power speed range (CPSR)</li> <li>Pole shaping-&gt; torque ripple reduction</li> <li>Sensorless control</li> </ul>	<ul style="list-style-type: none"> <li>Lower windage losses at high speeds</li> <li>Torque ripple reduction</li> </ul>

*B. Low-loss magnetic materials*

Low-loss magnetic materials are key enablers to achieve higher efficiencies. One leading candidate in this category is the 6.5% silicon materials [4]. Currently the 6.5% silicon is mainly used for high-frequency inductors and transformers. It has significantly lower specific core losses compared to conventional silicon steel while maintaining comparable magnetic properties. In [5] an SRM was built and tested (using 6.5% silicon) and it was shown that an efficiency higher than 95% could be achieved. The key challenge with the 6.5% silicon in terms of mass production is that the laminations are difficult to stamp due to its brittleness and it also comes in fairly thin thicknesses. Another challenge is that the currently available strip sizes are limited which means that for physically large machines, they have to be made out of segmented laminations. Currently the production base is very limited. JFE Steel in Japan is the only commercial producer [4]. In addition to the 6.5% silicon, there has been development efforts to produce conventional silicon steel in thinner gauges.

Another category of materials that has great potential as low-loss materials are nickel-iron alloys [6]. They have very high permeability and significantly low losses even compared to 6.5% silicon. They have the advantage that they are much easier to work with compared to 6.5% silicon. They have lower saturation level but are slightly lower compared to 6.5% silicon. The other challenge with these materials is cost but alloys with

48% nickel have comparable prices to 6.5% silicon.

Any machine topology would benefit from lower specific core losses. In addition to rotating electrical machines, these materials especially the 6.5% silicon is used in high frequency transformers and cores of inductors used as filters in power converters.

Table II summarizes the key properties of the low-loss magnetic materials in comparison to conventional silicon-steel laminations.

TABLE III  
SUMMARY OF KEY PROPERTIES OF LOW-LOSS MAGNETIC MATERIALS

	6.5% Silicon	Conventional Silicon	Nickel-iron
Thickness [mm]	0.1	0.1	0.1
Saturation magnetization [T]	1.8	2	1.6
Resistivity [ $\mu\Omega\text{m}$ ]	0.82	0.57	0.48
Specific core loss @ 1T and 1 kHz [W/kg]	18.7	27.1	6-10
Yield strength [MPa]	275.8-344.7	344.7	248.2

*C. High-strength magnetic materials*

These are materials that have significantly higher yield/ultimate strength compared to regular silicon-steel laminations. The key tradeoff is how to accomplish this while keeping specific core losses at an acceptable level [7]. The

benefit of such materials is that they enable high-speed machines (with high rotor tip speeds) which enable achieving high specific power without a significant penalty in efficiency. There are materials like iron-cobalt that have significantly higher strength and moderately higher core losses, but cost is prohibitive for many applications except for applications like aerospace where performance is more important than cost. High-strength grades of iron-cobalt laminations can reach yield strength around 100 ksi (690 MPa).

Nippon Steel and Sumitomo Metal have high-strength magnetic materials some of which have comparable specific core losses to conventional silicon steel laminations as shown in Fig. 4 [8] with up to 60% increase in ultimate tensile strength. There are two categories of materials: (a) Cu-precipitate hardened steel (b) Dislocation strengthened steel. These materials are currently not globally available and still require further assessments in actual machine designs that are built and tested. These materials have the potential of significantly opening the design space for almost all machine topologies for high-speed/high-specific power applications. Table III summarizes the potential impact of these materials on various machine topologies.

So far, there has been nothing reported in literature indicating that the properties of these materials will be significantly impacted by manufacturing processes for example stamping, laser cutting, interlocking etc.

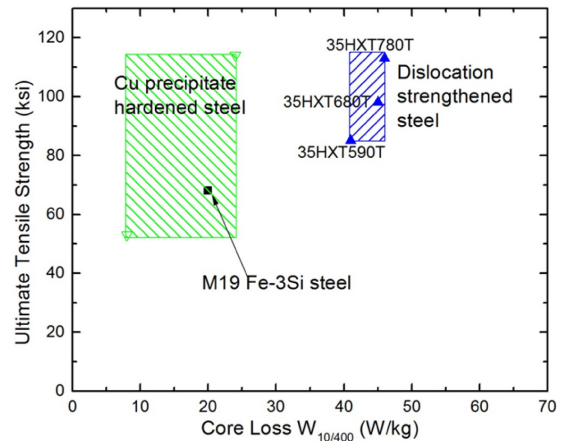


Fig 6. High-strength magnetic materials by Nippon Steel and Sumitomo Metal.

TABLE IV  
SUMMARY OF POTENTIAL IMPACT OF USING HIGH-STRENGTH MAGNETIC MATERIALS ON DIFFERENT MACHINE TOPOLOGIES

Machine Topology	IPM	Induction	Synchronous Reluctance	Switched Reluctance
Design benefits	Higher tip speed and/or reduced bridges and centerposts	Higher tip speed and/or reduced rotor bridges	Higher tip speed and/or reduced bridges and centerposts	Higher tip speed
Performance benefits	<ul style="list-style-type: none"> <li>Higher power density</li> <li>Improved power factor</li> </ul>	<ul style="list-style-type: none"> <li>Improved power density</li> <li>Improved power factor-&gt;</li> <li>a) Reduction in converter VA rating</li> <li>b) Reduction in cable sizing/cost</li> </ul>	<ul style="list-style-type: none"> <li>Higher power density</li> <li>Improved power factor</li> <li>Wider constant power speed range (CPSR)</li> </ul>	<ul style="list-style-type: none"> <li>Higher power density</li> </ul>

D. Soft Magnetic Composites

Soft magnetic composites (SMC) which are pressed Fe powder parts continue to be an appealing option in machine design [9]. This is mainly because the enable 3D flux path, low losses at high speeds/frequencies and advantages in terms of size and weight reduction. One of the earlier and more established materials in this category, is Somaloy by Höganäs. There are various grades of Somaloy Table IV summarizes the properties of some of these grades [9]. These grades have electrical resistivity in the range of 400-1000  $\mu\Omega\text{m}$ , saturation magnetization in the range of 1.4-1.57 T, relative permeability in the range of 290-850 and specific core losses @ 1T and 1 kHz in the range of 104-145 W/kg. The key challenge is the low permeability and saturation level compared to silicon steel laminations. That is why SMCs require novel machine topologies that would utilize the benefits they offer while minimizing the penalty of poorer magnetic properties. There has been large number of publications around the proper characterization of SMCs and as well as their potential applications in electrical machines. A couple of examples are [10, 11]. Over the years, there has been several attempts to address these challenges. One of those attempts was by

IMFINE Inc. to develop sintered lamellar SMC [12]. They were able to achieve improvements in relative permeability and saturation level:  $W 1.0/60 < 2 \text{ W/kg}$ ,  $\mu > 2,000$ ,  $B_{\text{max}} 1.7$ . Another more recent effort is by Persimmon Technologies (acquired by Sumitomo) to develop spray-formed SMC [13]. They are targeting saturation levels comparable to conventional silicon steel laminations. It is not clear (from what is available in the public domain), the type of properties achieved. Ultimately for SMC to reach its full potential in terms of opening the design space for electrical machines, improved permeabilities and saturation levels will be required. If SMCs with better magnetic properties can be achieved, this can open the design space for several machine topologies especially if coupled with advanced manufacturing especially additive manufacturing.

Amorphous metals are a synergistic area that is also gaining interest. The key challenges include low saturation levels. Also there are still manufacturing and scalability challenges. One of the key advantages includes low losses at high frequencies. This is one of the reasons, such materials have been explored/targeted for high-speed/high-frequency electrical machines. A recently reported amorphous material has been

shown to have a saturation flux density of 1.3 T with a power loss of 0.9 W/kg at 1 T and 400 Hz and 2.4 W/kg at 1 T and 1 kHz [14]. This material has been evaluated for high power density, rare earth free electrical machines [15].

TABLE V  
PROPERTIES OF SOMALOY FROM HÖGANÄS [9]

Somaloy Material	Resistivity [ $\mu\Omega\cdot\text{m}$ ]	TRS [MPa]	B@10000 A/m [T]	$\mu_{\text{max}}$	Core Losses @ 1T [W/kg]			
					5x5 mm*			15x15 mm
					100 Hz	400 Hz	1000 Hz	1000 Hz
<b>Baseline</b>								
1P Somaloy 130i	8000	35	1.40	290	12	54	145	147
1P Somaloy 700	400	40	1.56	540	10	44	131	158
1P Somaloy 700 HR	1000	35	1.53	440	10	46	134	145
<b>High strength, high permeability</b>								
3P Somaloy 700	200	125	1.61	750	10	46	137	189
3P Somaloy 700 HR	600	120	1.57	630	11	48	137	157
3P Somaloy 1000	70	140	1.63	850	10	46	144	287
<b>Lowest losses</b>								
5P** Somaloy 700 HR	700	60	1.57	600	6	32	104	115

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### III. ADVANCED PERMANENT MAGNETS

In this section, advanced permanent magnets will be covered. These include: (a) High-energy product magnets (b) Dysprosium (Dy)-free magnets and (c) Higher coercivity Alnico.

Over the years, there has been a lot of effort towards developing different types of advanced permanent magnets. The first category includes high-energy product magnets. As an example, GE worked on developing nano-structured composite magnets under ARPA-E funding [16]. The concept is shown in Fig. 5. The goal was to develop magnets with energy products up to 85 MGOe. The other alternative was to develop magnets with more conventional energy product (around 60 MGOe) but using lower content of rare-earth materials. Both approaches lead to lower cost and/or improved performance of electrical machines. The higher energy product can lead to higher power density due to the higher magnetic loading of the machine (ultimately limited by the flux-carrying capability of the lamination material) as well as due to reduced magnet retention requirements due to lower magnet content. The details of the process are included in [17]. It was claimed in [17] that an energy product of 80 MGOe could be reached. It was also claimed in [17] that up to 80% reduction of rare-earth materials compared to other commercial magnets could be achieved.

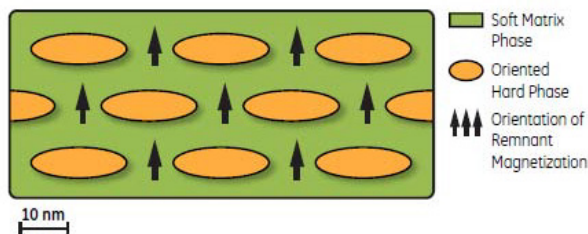


Fig. 7. Nano-structured composite magnets [16].

Another category is permanent magnets that include lower content of the heavy rare-earth components (mainly Dysprosium (Dy) and Terbium (Tb)). This was triggered by spikes in prices and concerns about sustainability of rare-earth

materials especially the heavy ones like Dy and Tb. Several companies and suppliers developed various versions of Dy-free magnets using different techniques. Usually the main concern with Dy-free magnets is demagnetization since magnet coercivity and hence susceptibility to demagnetization is dependent on Dy content. In [18, 19], a flux-switching machine (FSM) was built using Dy-free magnets developed by GE. The magnet properties are shown in Fig. 8. The machine was tested under high temperatures as well as deep flux-weakening and there was no sign of demagnetization.

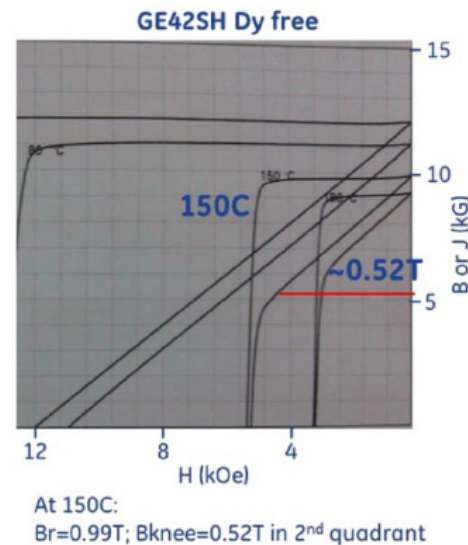


Fig. 8. Dy-free permanent magnets by GE [18].

Within the same category of trying to reduce or eliminate dependence on rare-earth materials, there has been several efforts to develop higher-coercivity Alnico magnets [20, 21].

There has been good progress towards achieving this goal, but these efforts are still under way to address remaining technical challenges and scalability. So far Coercivity  $> 2700$  Oe (commercially available alnico 8H  $\sim 2170$  Oe) has been demonstrated as well as remanence of  $\sim 0.79$ T. Still there is the need for improved microstructural alignment for maximum



energy product and improved remanence. In parallel, there have been some machine designs proposed based on Alnico that would benefit from the higher-coercivity Alnico. One such example is the machine topology developed by UQM [21]

#### IV. ADVANCED CONDUCTORS

In this section, advanced materials for conductors will be covered. There is an increased level of activities to find higher performance conductors as replacements for Cu. One key area where there is significant activity is Carbon Nano Tubes (CNT). In [22], CNT-Cu conductors are presented as replacement for Cu. The basic concept of combining CNT and CU is shown in Fig. 9. There are several different approaches of how to combine CNT and CU currently being pursued. Most of the effort so far has been on the small sample scale and scalability remains the key challenge. It was shown that the conductivity of CNT-Cu composite conductors is much less sensitive to temperature compared to Cu which is a significant advantage in terms of maintaining high efficiency at higher temperatures (Fig.10). It was also shown that CNT-Cu conductors have ~100 times higher current-carrying capacity compared to Cu (Fig.11). This can have a significant impact on electrical machines power density and/or efficiency. Considering that in many electrical machines, conductor losses can be as high as 50% of the losses, one can easily see the significant potential of CNT-Cu conductors in terms of reducing losses and increasing efficiency. Unlike other discussed materials, all machine topologies will benefit from these properties both in terms of efficiency as well as power density. In addition, CNT-Cu conductors have significantly lower density compared to Cu which further improves power density. Aside from using CNT-Cu conductors for machine windings, they are also being considered for cables. From a system perspective, this can have significant advantages in terms of overall system power density and efficiency especially for specialized applications that demand high-performance. A prime application example is hybrid propulsion for aerospace where the electrical system power density is a key performance metrics and where cables represent a big portion of the overall system mass. There has been some effort to assess CNT-Cu conductors in electrical machines [23, 24]. In [23], a proof-of-principle motor using CNT yarn was built and tested which is a significant step towards understanding the benefits and challenges of using such conductors in electrical machines. Even though this area is at an early development stage and a lot effort is required to address manufacturing and scaling challenges, it is an area of great potential and is expected to continue gaining interest moving forward.

For large-scale electrical machines like off-shore wind generators, large industrial motors, and electrical machines for aerospace hybrid propulsion, superconducting machines are being considered. Still the key challenges of cost and reliability need to be addressed. As previously mentioned, the topic of superconducting electrical machines is not the main focus of this paper and advancements in superconducting conductors is a fairly broad topic and warrants a standalone dedicated

publication.

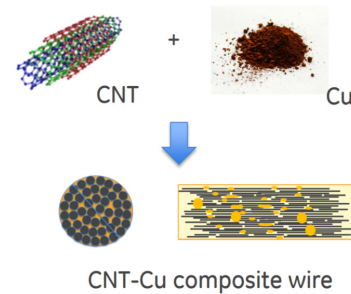


Fig. 9. Concept of CNT-Cu composite conductor.

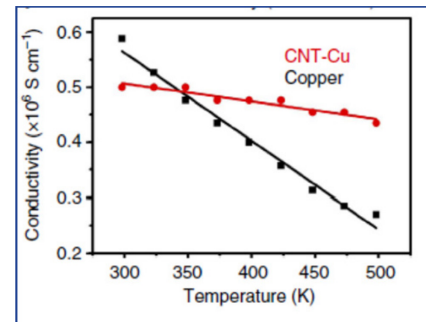


Fig. 10. Electrical conductivity as a function of temperature [22].

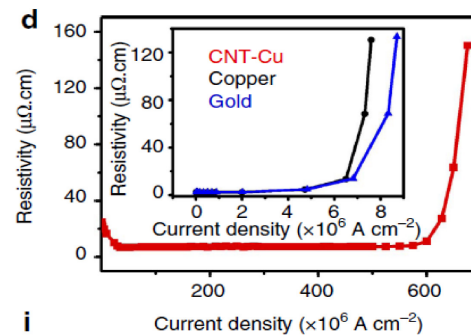


Fig. 11. Resistivity as a function of current density [22]

#### V. ADVANCED INSULATION SYSTEMS

The two key sources of failures in electrical machines are bearings and insulation systems. A reliable insulation system is a key to meeting the performance and life requirements of electrical machines. There are ever-growing requirements on insulation systems due to the more demanding performance of electrical machines (in terms of power density and efficiency) as well as the fact that more electrical machines are required to operate in harsh environments. There have been development efforts covering several advanced insulation systems. These include high temperature insulation system, high-thermal conductivity, and high-frequency insulation systems.

There is a need for high-temperature insulation systems for a wide range of applications as shown in Fig.12. The high operating temperatures enable significant increase in machine's power density. For example, in [26], a high temperature DC biased reluctance machine which is structurally like a conventional switched reluctance machine has been presented. This non-permanent magnet machine has a DC field winding and an AC three phase armature winding. The machine is

equipped with a high temperature 280°C rated insulation system. This high temperature prototype features high temperature slot liners, wire coating and VPI varnish as described in Fig. 13. Test results showing machine performance under continuous operation against the FreedomCar 2020 specifications as well as at high temperature up to 280°C are presented. A 43% improvement in power density was achieved by going to high temperature.

There are also ongoing efforts to develop high-thermal conductivity insulation systems. This will enable better heat removal out of the machines and hence an increase in power density and/or reduction/simplification of thermal management schemes. This is specially more critical in medium-voltage inverter-driven applications where the insulation thickness becomes a challenge in terms of pulling heat out of the machine using conventional thermal management schemes.

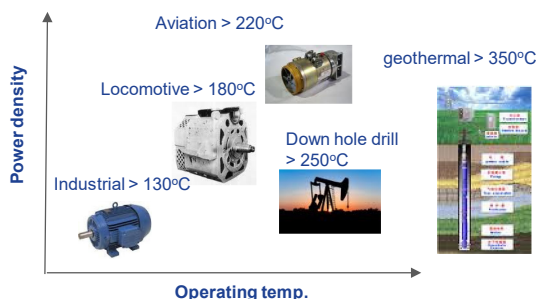


Fig. 12. Applications requiring high-temperature insulation systems [25].

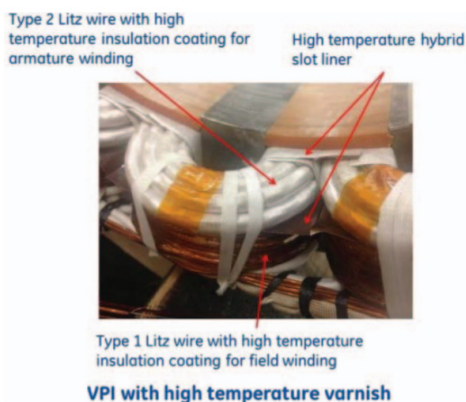


Fig. 13. High-temperature insulation system rated for 280°C [26].

Inverter-duty insulation systems continue to be an area of interest especially as electrical machines continue to move towards high frequencies and voltages in several applications. A prime example is aerospace hybrid propulsion systems. Electrical machines are high speed/frequency to achieve high power density. Higher voltages are needed to reduce the cables mass especially for MW-class systems. The challenge is even bigger at altitude due to increased corona effects. Based on all of this, there is a need for advanced inverter-duty insulation systems.

VI. COMPOSITE MATERIALS

In addition to “active” materials, non-active material like composite materials are expected to play a significant role in developing high-performance electrical machines. The more

conventional use of composite materials is for retention of high-speed rotors. Carbon-fiber rings are typically used as retaining sleeves for high-speed permanent magnet (PM) machines [27]. This section will cover the potential and advantages of using composite materials especially for structural components. This can have significant impact on increasing the overall machine power density.

There has been increasing interest in high power-density electrical machines specially for aerospace applications especially in the context of electrical/hybrid propulsion [28]. Typically, the “total” machine power density is roughly around 50% of the “active” machine power density to account for all the structural and non-active components including machine enclosure. If these components can be made from light-weight composites, this can have a significant impact on increasing the “total” machine power density. Fig. 14 shows a state-of-the art motor by Siemens designed for aerospace propulsion applications. This motor achieves record power (since the speed is only 2500 rpm) and torque densities [29]. A big factor contributing to this is the use of composites for structural components as shown in Fig. 14. In this case, it is estimated that the mass of non-active structural components is in the range of 10-20% of the total mass, a significant reduction compared to the typical 50%. This is an area that is expected to continue to grow and gain more interest. Some of the challenges will be to develop composite materials that can be sued for the non-active structural components of electrical machines that are capable of meeting the machine’s mechanical and thermal requirements especially in harsh environments.

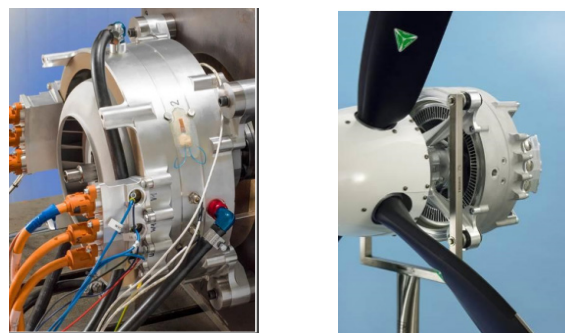


Fig 14. Siemens 250 kW PM motor [28].

VII. ADVANCED MANUFACTURING

In addition to advanced materials, advanced manufacturing is expected to have a significant impact on improving the performance of electrical machines. One key area is additive manufacturing (AM). In [30], a feasibility study of the impact of AM of electrical machines in the context of electrical machines in the context of the More Electric Aircraft (MEA) initiative has been presented. It was concluded that AM can open the design space for some machine topologies especially synchronous reluctance machines.

In [31-33], the concept of using AM to develop high slot-fill factor winding for an induction machine (IM) and the corresponding machine thermal performance has been presented. This work was done by United Technologies under

funding from ARPA-E.

Another area where AM might help open the design space for electrical machines is very high-power density electrical machines especially for aerospace applications. There is growing interest in this area to support electrical/hybrid propulsion for aerospace. For MW-class propulsion systems (for large commercial aircrafts), higher system voltage is expected, and hence much thicker insulation build will be required specially to avoid corona effects at altitude. This will make the thermal management of electrical machines more challenging. One approach to achieve high-power density as well as effective thermal management is using hollow conductors as shown in Fig. 15 [34]. Even though these hollow conductors can be used to form stator windings, the process might become complicated depending on the available conductor sizes and the required bend radii. AM can help simplify forming the windings as well as the end connections. In general, AM is a fast-growing area and as the technology keeps evolving and more materials can be additively-manufactured, this know-how can be more leveraged in electrical machines.

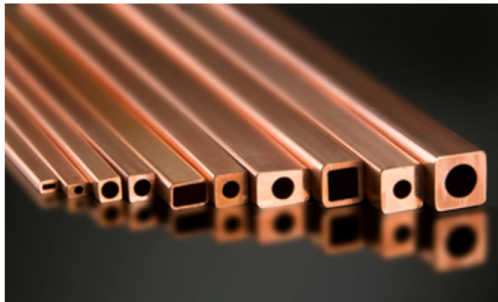


Fig.15. Samples of hollow conductors [34].

### VIII. CONCLUSIONS

This paper provided an overview of the potential role of advanced materials in electrical machines. Advanced magnetic materials, advanced permanent magnets, advanced conductors, advanced insulation systems and advanced manufacturing have been discussed. Based on the wide variety of advanced materials, it can be seen that such materials are key enablers to achieve a step change in performance of electrical machines. They will also have a significant impact on opening the design space for electrical machines across a broad range of applications. Some materials like CNT/Cu conductors, advanced insulation systems and composite materials would benefit all machine topologies. Dual-phase magnetic materials would mainly benefit IPM and synchronous reluctance machines due to the elimination of bridges and center posts. High strength magnetic materials and low-loss magnetic materials would benefit all machine topologies in terms of power density and efficiency. Even though these materials and manufacturing techniques are at different development stages, there is enough information to focus research efforts on assessing the potential impact of these materials. Some studies have shown that cumulative impact of the discussed materials can lead to 2X increase in power density in the context of

hybrid propulsion aerospace applications. The quantitative details of the design(s) and the impact of the various materials will be the subject of a dedicated paper.

The hope is that this paper will serve as a good reference in terms of highlighting the key advanced materials as well as advanced manufacturing and will trigger more effort in terms of considering these materials in novel machine designs as well as quantitatively assessing their impact on performance.

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**Ayman M. EL-Refae** (S'95-M'05-SM'07-F'13) received the B.S and M.S degrees in electrical power engineering from Cairo University in 1995 and 1998 respectively. He received the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin Madison on 2002, and 2005 respectively. Since 2005 he has been with the Electrical Machines and Drives Lab at General Electric Global Research Center. Since January 2017, he became the Thomas and Suzanne Werner Endowed Chair in Secure and Sustainable Energy at Marquette University. His interests include electrical machines and drives. He is a fellow of the IEEE. He has over 100 publications and 40 issued US patents.