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Toward a Sustainable More Electrified Future: The Role of Electrical Machines and Drives

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Toward a Sustainable More Electrified Future: The Role of Electrical Machines and Drives

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Abstract:
This article provided an overview of the broad range of applications in which advanced electrical machines and drives play a key role. There are many applications that require steep change in the performance of electrical machines and drives. In addition to novel topologies and design optimization, a broad range of enabling technologies, including advanced materials and thermal management, will play a key role in meeting the ever-growing requirements of the aforementioned applications. Judging by the breadth of the applications and the very demanding requirements in terms of system footprint, efficiency cost, and reliability R&D efforts in the area of advanced electrical machines and drives are expected to rise significantly.
In the past few decades, electrical machines and drives have played a key role in electrification across a wide range of applications. Several initiatives have been introduced to supplant mechanical and hydraulic systems with electrical systems and move toward advanced variable-speed drives (VSDs) when necessary. In terms of performance, reliability, efficiency, and robustness, electrical systems offer significant advantages, while “more electric” systems have become an industry trend for many applications, e.g., traction, aerospace, actuation, mining, oil and gas, and industrial applications. The broad topic of renewables and how to integrate them into the grid ties into the deployment of smart grids, microgrids, and distributed generation. This shift toward more electrification presents significant challenges, especially to the performance requirements of electrical machines and drives. It is now clear that there is a critical need for state-of-the-art electrical machines and drives to meet the demands of various applications including harsh environments, high power density, high efficiency, and fault tolerance in safety-critical applications.

This article provides a comprehensive overview of the key drivers for electrification, various application spaces, and several examples of advanced electrical machines and drives that either have been developed or are currently under development. A discussion about enabling technologies and R&D trends is presented.

Past and Future Trends

The terms “electrification” and “more electric” are used extensively in a wide range of applications. The different ways electrification can be defined are as

- expanding the adoption of electrical systems to replace mechanical and hydraulic systems
- higher penetration and integration of renewable energy sources
- replacing legacy fixed-speed electrical drives with advanced higher-performance VSDs.

A centerpiece of electrification is the use of advanced electrical machines and drives.
There are several megatrends that have contributed to the growing electrification wave. These include 1) transportation electrification, 2) more penetration and integration of renewables into the grid, 3) the need for electrical machines and drives that can operate in harsh environments (especially mining and oil and gas applications), and 4) the increasing demand on the grid and the growing role of distributed generation and microgrids.

A centerpiece of electrification is the use of advanced electrical machines and drives.

The evolution of power electronics and the transition toward VSDs has been a significant paradigm shift in technology. As seen in Figures 1 and 2, traditionally, systems consisted of an electrical machine (generator/motor) that was directly connected to the grid and operates at the grid frequency (i.e., 50/60 Hz, depending on the country). The system would also include either a prime mover in the case of a generator or a load in the case of a motor. The prime mover/load was usually designed/optimized based on a certain operating speed that was usually different from the optimum operating speed of the generator/motor. Traditionally, gearboxes were used to address this speed mismatch. Two of the main challenges presented by this approach was that of gearboxes that posed significant reliability and maintenance problems. The evolution of VSDs enabled the frequency converter to effectively act as an “electronic gear box,” as shown in Figures 3 and 4. This allowed for more optimized systems with higher efficiency, better control, high reliability, and reduced maintenance. This article will present an overview of the various applications where advanced electrical machines and drives are playing a key role in the electrification process.

Figure 1. A conventional generator connected to a prime mover via a gearbox.

Figure 2. A conventional motor connected to a load/process via a gearbox.

Figure 3. A variable-frequency generator directly coupled to a prime mover.
Light-Duty Hybrid/Electric Vehicles

As previously mentioned, one of the key megatrends that has inspired the current electrification wave is transportation electrification. There has been considerable focus on light-duty vehicles because they represent the biggest market in the transportation sector in terms of volume. There has been a sustained global effort over the past several decades to continue advancing state-of-the-art electric and light-duty hybrid/electric vehicles (HEVs/EVs). The centerpiece of this endeavor was the development of advanced electrical machines, power converters, and energy storage. The U.S. Department of Energy (DoE) has played an important role by setting aggressive targets for the performance standards of hybrid and electric drivetrains to surpass the machines (i.e., liquid-cooled variable-speed IPMs) that have long been considered state of the art in this sector. The DoE requirements are usually referred to as the *FreedomCar 2020 specifications* and summarized in Figure 5 and Table 1.

![Figure 4](image)

**Figure 4.** A variable-frequency motor directly coupled to a load.

![Figure 5](image)

**Figure 5.** (a) The FreedomCar 2020 motor-specified torque-speed curve and (b) an efficiency map.
Table 1. FreedomCAR 2020 advanced motor performance requirements.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum top speed</td>
<td>14,000 r/min</td>
<td></td>
</tr>
<tr>
<td>Peak output power</td>
<td>55 kW for 18 s</td>
<td>At 20% speed and nominal voltage</td>
</tr>
<tr>
<td>Continuous output power</td>
<td>30 kW</td>
<td>At ~20-100% speed and nominal voltage</td>
</tr>
<tr>
<td>Weight</td>
<td>Δ 35 kg</td>
<td></td>
</tr>
<tr>
<td>Operating dc bus voltage</td>
<td>~200-450 V, 325 V nominal</td>
<td></td>
</tr>
<tr>
<td>Maximum phase current</td>
<td>400 arms</td>
<td></td>
</tr>
<tr>
<td>Line-to-line back EMF</td>
<td>&lt;600-V peak</td>
<td>At 100% speed</td>
</tr>
<tr>
<td>Torque pulsation</td>
<td>&lt;5% peak torque</td>
<td>At any speed</td>
</tr>
<tr>
<td>Coolant inlet temperature</td>
<td>105 °C</td>
<td></td>
</tr>
</tbody>
</table>

Initial attempts focused on developing new concepts that meet this set of requirements. Several novel machine topologies in conjunction with advanced thermal management have been developed. One example is a novel spoke design with a modular rotor structure that eliminates the need for bridges or center posts, as shown in Figure 6. The design also featured a segmented stator structure with tooth windings. An advanced inner-bore rotor cooling was also incorporated. This design used rare neodymium iron boron (NdFeB) magnets and was state of the art in terms of specific power density efficiency.

Figure 6. A spoke design with a segmented stator structure.

There is considerable interest in reducing or eliminating rare-earth materials in next-generation traction motors.

Several years ago, this focus shifted toward developing high-performance motors that can meet the FreedomCar2020 requirements and reduce or eliminate rare-earth materials. This was mainly triggered by the nearly 70% spike in the price of rare-earth magnets that occurred a few years ago. Although the price of rare-earth magnets has decreased to its prespike levels, there remains much concern about their long-term sustainability and price stability. Because of this, there is considerable interest in reducing or eliminating rare-earth materials in next-generation traction motors. Recently, several motor topologies that incorporate advanced materials have been developed and evaluated to accomplish this goal. These topologies can be divided into three categories: 1) designs that reduce
rare-earth materials, 2) designs that use nonrare-earth permanent magnets, and 3) designs that do not use permanent magnets.

Designs That Reduce Rare-Earth Materials
Rare-earth materials are typically divided into light and heavy categories. Permanent magnets used in traction motors are typically NdFeB magnets, which include light rare-earth materials such as Nd and B. The real sustainability/price concern is with heavy rare-earth materials such as dysprosium (Dy), which is also included in these magnets (in small quantities). Dy has a significant impact on the coercivity of the magnets and hence their susceptibility to demagnetization. Several machine topologies using Dy-free magnets have been evaluated/developed, including multilayer IPM machines, IPM spoke machines, and flux-switching machines (FSMs). One of the topologies that emerged as an appealing candidate in this category is the Dy-free FSM. One of its main benefits is that, due to the nature of the magnetic circuit and the fact that the permanent magnets are located in the stator, the magnets are less susceptible to demagnetization, which makes Dy-free magnets a good fit for this topology. A prototype of a Dy-free FSM has been built and fully tested, as shown in Figure 7.

![Figure 7. (a) A Dy-free FSM stator and (b) a Dy-free FSM rotor.](image)

Induction machines represent an appealing option because they are inexpensive and simple and the technology is fairly mature.

Designs That Include Nonrare-Earth Permanent Magnets
Types of permanent magnets that do not contain rare-earth materials include ferrites and Alnico, among others. In addition to the lower energy product compared to that of rare-earth magnets, the use of ferrites and Alnico present additional challenges. In the case of ferrites, they have a negative coercivity thermal coefficient and tend to demagnetize at lower temperatures. In the case of Alnico, although it has fairly high remanence, its tendency to demagnetize is lower (less than half) than that of rare-earth magnets. Several machine topologies that use ferrites and Alnico have been evaluated, including multilayer IPM, spoke IPM, and FSMS. Because of limitations in terms of the magnetic properties of ferrites and Alnico, all of the designs in this category tended to be bigger in size when compared to designs that use rare-earth magnets. A spoke design using ferrite magnets emerged as the best option in terms of power density because of the flux concentration effect found in a spoke configuration as well as the elimination of bridges. It also has high efficiency, especially with light loads as well as at higher speeds. A prototype has been built and fully tested, as shown in Figure 8.
Designs That Do Not Include Permanent Magnets

Ideally, the solution that completely eliminates any risks associated with rare-earth materials is to develop topologies and designs that do not include any permanent magnets. This would lead to cheaper sustainable solutions, but a penalty in size and/or efficiency comparable to that of rare-earth designs is expected. Such topologies include induction machines, wound-field (WF) synchronous machines, WF flux-switching machines, and different variants of switched-reluctance machines (SRMs), including dc-biased SRMs and synchronous-reluctance machines.

*Induction Machines*

Similar to several other applications, induction machines represent an appealing option because they are inexpensive and simple and the technology is fairly mature. Although they are used in some commercial vehicles, e.g., Tesla, induction machines present a few challenges in the context of light-duty HEVs/EVs. These challenges include low power density [especially if the machine is designed for a wide constant power speed ratio (CPSR)], low efficiency at the machine-rated power envelope [when compared to phase-modulation (PM) machines] as well as a relatively low power factor. However, they have advantages in terms of partial-load efficiency, which can significantly improve driving-cycle efficiency.

*WF Synchronous Machines*

Another interesting option in terms of technological maturity as well as the ability to regulate the field is the use of WF synchronous machines, which enables machines to operate over a wide CPSR. The controllable field also allows for high partial-load efficiency and, hence, improved driving-cycle efficiency. The machine can have competitive torque/power density depending on how high the rotor-filed magnetomotive force (MMF) can be pushed (mainly from a thermal point of view). High-filed MMF can be achieved but this usually requires fairly aggressive and complicated cooling schemes. High reliability is another concern when either rotating diodes or sliprings/brushes are used, especially at higher speeds. WF synchronous machines are commercially available in the HEV/EV market through companies such as Continental.

*Synchronous-Reluctance Machines*

For many applications, synchronous-reluctance machines are viewed as potentially the best technology option, assuming that the well-known challenges associated with them can be addressed. The key advantage (in addition to not using permanent magnets) is the very simple and robust rotor structure. The main challenges of synchronous-reluctance machines include low power density, limited CPSR (mainly due to bridges and center posts and absence of magnets to saturate them), and low power.
factor. Several innovative designs have been used to address these challenges, one of which is a synchronous-reluctance rotor that uses a dual-phase magnetic material. This enables large bridges and/or center posts that can withstand mechanical stresses at high tip speeds while ensuring that these bridges and/or center posts are nonmagnetic, which eliminates or significantly reduces leakage flux in these regions. Another example is a carbon-fiber-wrapped synchronous-reluctance rotor, in which the bridges and/or center posts are minimized to a level that only maintains continuous rotor laminations while the carbon-fiber sleeve handles the mechanical stresses on the rotor. This type of approach leads to significant benefits in terms of power density and/or efficiency and expands the CPSR.

WF FSMs and SRMs

The permanent magnet version of the FSM has been previously discussed in the “Designs That Reduce Rare-Earth Materials” section. There are several variants of WF FSMs and different variants of SRMs, including doubly excited SRMs [Figure 9(a) and (b)]. WF FSMs and doubly excited SRMs address some of the key challenges with conventional SRMs mainly because they use a standard three-phase power converter to excite the armature winding and a small auxiliary power converter to excite the field winding. This is a key enabler for commercialization as it pertains to the unconventional power converter required for a conventional SRM to provide unipolar excitation. Moreover, torque ripple is much lower in both topologies than that of the conventional SRM. Another advantage is that they all have good flux-weakening capabilities. All salient pole-reluctance designs have the disadvantage of a very large effective airgap (and hence, high reluctance) as well as a high number of poles/frequency. Both of these factors have a significant impact on reducing machine power density and/or efficiency. A dc-biased doubly excited SRM prototype has been built and fully tested.

![Figure 9](image.png)

**Figure 9.** The (a) stator and (b) rotor of a doubly excited SRM.

Fuel Cell Applications

Hydrogen and fuel cells continue to generate interest. The DoE’s Hydrogen and Fuel Cells Program is a good example of such an initiative. Fuel cells are used in a broad range of applications including portable power, stationary power (e.g., combined heat and power, uninterruptable power supplies, and primary units), and transportation. The use of fuel cells in the transportation sector is a subset of the hybrid/electrical transportation sector. Considerable effort has been expended to use fuel cells for energy storage in different types of vehicles and in different hybrid/electrical system architectures. Fuel cells are considered the main source of energy storage and used to combine fuel cells with other types of energy storage (batteries, ultracapacitors, and so on). An article by Korane (2009) provides...
one example of novel electrical machines being used in conjunction with fuel cells. In his article, Korane discusses how axial-flux PM wheel motors can be used in a General Motors fuel cell truck, as shown in Figure 10.

![Figure 10. (a) The axial-flux motor and (b) the axial-flux motor integrated with the wheel motor for a General Motors fuel-cell truck (Rahman et al., 2006).](image)

**Aerospace**

In the past decade, aerospace applications have experienced a transformation in terms of their electrification and WF synchronous machines have been the workhorse of this movement. One popular way they are used is as starter alternators. However, the use of PM machines has been limited to nonmission critical small generators. One of the main reasons why WF synchronous machines are used more often than PM machines is fault tolerance. When working with WF synchronous machines, the field current can be reduced or completely interrupted in case of a fault. This is not an option with PM machines because the magnetic field generated by the permanent magnets is always there. Fault tolerance of PM machines is a more serious issue in generators, particularly those connected to the engine, because in the case of a fault, the engine/prime mover cannot be shut down, the PM rotor will continue to rotate, and the magnetic field generated by the permanent magnets will continue to feed the fault. WF synchronous machines have advantages in terms of voltage regulation (by adjusting field current) they can use passive power converters/rectifiers, and they do not need an active power converter (i.e., PM machines). However, PM machines are superior in terms of power density as well as efficiency.

With the steady increase in electrical loads in aircrafts and with key initiatives such as More Electric Aircraft, interest in PM machines (because of their size and efficiency advantages) for aerospace applications (e.g., primary generation) has been revived. A great deal of work has been performed to address fault tolerance in PM machines. A good understanding of what is needed from a machine design and control perspective to accomplish fault tolerance has been developed over the years.

Figure 11 shows an example of a liquid-cooled, fault-tolerant inside-out PM generator. This machine was designed specifically for primary generation. Using Samarium-Cobalt magnets, it is functional at a maximum operating temperature of 200°C. The machine’s characteristics include

- a 170-kW, three-phase electrical output
- a 3,000–12,000 r/min operating speed
- 500–2000 Hz, regulated to 230VphRMS
- a dc bus voltage of 700 V
- one was turn used to perform the turn-turn short test.
A turn-to-turn fault was introduced. As shown in Figure 12, the fault can be detected quickly enough (i.e., within 13 m/s) and a mitigation scheme then applied to reduce the fault current from 650 to 20 A. This machine is state of the art in terms of PM fault-tolerant machines, power density, and reliability. In addition to primary generation, there are other aerospace applications that require advanced high torque-density machines, e.g., electric motors for green taxiing.

A transformational emerging area that has the potential to revolutionize aerospace applications is the field of electric/hybrid propulsion systems. Recently, activities covering a wide range of applications have ranged from purely electrical propulsion systems for unmanned aerial vehicles and small planes to hybrid propulsion systems for large commercial planes. This is fundamentally different usage of electrical systems represents a departure from the traditional electrical systems that have focused on power distribution to the various loads within a plane. This area of study is essential for the development of advanced electrical machines and drives the current state of the art, particularly when it comes to specific power and efficiency. Very high specific power (and efficiency) is necessary for achieving reduced fuel consumption while minimizing the penalty of the additional mass of the electrical components. PM machines and electrical drives using wide-bandgap (WBG) devices are the best candidates in this arena.
Oil and Gas
The oil and gas industry is a good example of an application space that traditionally has not played a key role in advancing the state of the art of electrical machines and drives. This has changed over the past several years, and the electrification of the oil and gas industry became an important initiative. An important application within the oil and gas industry is using drivetrains for high-speed compressors. The traditional baseline system architecture that drives high-speed compressors comprises a power converter, a low-speed motor, a gearbox, and the compressor, as shown in Figure 13. This system architecture transitioned to a more advanced one that includes a high-frequency power converter and high-speed motor directly coupled to the compressor. In addition to replacing the system architecture, many attempts have been made to do the same with induction motors (which are still the dominant topology in this sector) that have PM machines. This transformation of the drivetrain in conjunction with PM machines leads to multiple benefits, including significant improvement in specific power and hence, a reduced system footprint, and better integration of the motor and compressor. Additionally, PM machines are more suitable for encapsulation than induction machines, which is important in acid/sour gas applications.

Figure 13. The transformation of electric drivetrains to drive high-speed compressors.

The traditional baseline system architecture that drives high-speed compressors comprises a power converter, a low-speed motor, a gearbox, and the compressor.

Designs ranging from 5 MW (at 20,000 r/min) to 20 MW (at 10,000 r/min) have been developed. Specific powers of approximately 2–3 kW/kg have been achieved. In addition to the PM topology adopted (i.e., typically surface PM machines with retaining sleeves; in some cases, magnet Halbach arrays have been utilized), other technologies such as active magnetic bearings are critical components of these advanced high-speed drivetrains. In addition to oil and gas, the same technology and drivetrain architecture can be leveraged for other synergistic spaces, including marine power generation and aerospace power generation.

Off-Highway Vehicle Propulsion Systems
In terms of transportation electrification, although the main focus has been on light-duty vehicles, medium- and heavy-duty vehicles have also experienced the electrification wave. One category of heavy-duty vehicles garnering interest is that of off-highway vehicles (OHVs) typically used in the construction and mining industries. Several of these vehicles have diesel-electric propulsion systems (Figure 14) in which a diesel engine drives an alternator that feeds the traction motor(s) (in many cases the traction motor is a wheel motor, as shown in Figure 14). Most of these vehicles use WF synchronous alternators and induction traction motors, although SRMs are also used. This application
space is suitable for SRMs because they are robust, while their potential drawbacks of acoustic noise, vibration, and torque ripple are not a concern because of the vehicle size and the nature of the application. IPM machines have also been evaluated for this application, but the level of vibration to which the vehicle is exposed must be carefully assessed because of the brittle nature of the permanent magnets.

Figure 14. (a) An exterior and (b) interior view of the wheel motor of a General Electric diesel-electric OHV.

The previous discussion focused on surface OHVs, which historically have been the center of attention in this category. In the past decade, interest has grown in underground mining vehicles. As shown in Figure 15, some of these vehicles are already battery powered. There are many underground vehicles (some that are diesel powered) used for various purposes in a mine (e.g., moving people, materials, and equipment), as shown in Figure 16. With mines getting deeper (some up to 10-km deep), the quality of air in a mine is an important consideration. Efforts have been taken to replace diesel-electric propulsion systems with either pure electrical or hybrid propulsion systems to reduce diesel emissions. This has led to the need for reliable, more compact, and, in some cases, explosion-proof electrical propulsion systems. Induction machines prevail in this field but PM machines are also being examined because of the limited space available to accommodate both energy storage and drives. In this case, the high torque density of PM machines is a key enabler.

Figure 15. A General Electric electric coal scoop with (a) traction- and (b) pump-induction motors.
Efforts have been taken to replace diesel-electric propulsion systems with either pure electrical or hybrid propulsion systems to reduce diesel emissions.

Wind Drivetrains
As previously mentioned, the use of renewables and the need to integrate them into the grid is one of the megatrends driving electrification and the accompanying interest in electrical machines and drives. Wind drivetrains are the main renewable energy application that utilize electrical machines and drives. Unlike earlier versions, the entire industry has transitioned to variable speed drives. The two main categories of wind are onshore and offshore wind turbines and drivetrains.

For onshore wind, typically, a geared solution is adopted in which a gearbox is placed between the wind turbine and the generator. Much work has been performed to optimize the overall drivetrain (i.e., the number of gear stages, gear ratio, and, therefore, generator speed) and minimize the system footprint while maintaining high efficiency. Double-fed induction generators have been instrumental for offshore wind drivetrains, especially those with lower power ratings. Their main advantage is that they require a partial power converter based on the slip power, which leads to significant reduction in the cost and size of power converters. PM generators are also used for onshore wind, and they become more appealing for higher power-ratings because of their higher torque density and efficiency (although they require a full power converter). A few years ago, the industry began to significantly shift toward PM generators. This shift was slowed because of a spike in the prices of rare-earth materials. Eventually, the prices of these materials went down again, although there is still long-term concern about their sustainability and price stability. To have a better feeling for how sensitive the wind industry is to this concern (at a very high level and as a rough guideline), wind generators use one metric ton of rare-earth magnets per MW of power. Because of this, any significant fluctuation in the price of rare-earth magnets can have a profound impact on the cost of wind generators.

Because of accessibility challenges, maintenance requirements should be minimized for offshore wind. This pushes the drivetrains to be direct drive, thereby eliminating the gearbox and all of the required maintenance that accompanies them. The direct-drive configuration, in addition to the high-power ratings of offshore wind turbines and the size of the generator, presents a challenge (i.e., for the same power and lower speed, the torque, which is what determines the physical size of electrical machine, is higher), especially because power ratings in excess of 10 MW are expected in the future. This is why
PM machines have clear advantages for offshore direct-drive wind drivetrains with regard to torque density and efficiency. As offshore wind continues to move toward higher power ratings, longer-term options such as superconducting generators can be considered. Figure 17 summarizes the various wind drivetrain options. As with different types of energy sources, the levelized cost of energy is a key factor that informs the decision of which drivetrain configuration to adopt for commercialization.

![Figure 17. Various examples of General Electric wind drivetrain architectures. (a) A scaled-up doubly fed induction generator (DFIG) with partial conversion, (b) PM direct drives, (c) a geared PM plus full conversion, and (d) a superconducting direct drive.]

There is some synergy between wind and other applications such as wave/tidal energy (these applications are even more challenging because the speeds are significantly lower compared to wind), so some of the technologies developed for wind, especially those that target high torque-density electrical machines, can be potentially leveraged for these other applications.

**Geothermal**

Although the focus has been on solar and wind, there are many other renewable sources of energy that will play a significant role in the future. Some of these other sources pose interesting challenges because of their mode of operation and system requirements. In one such application, i.e., geothermal, a motor-driven pump is required, as shown in Figure 18. In this case, the motor must operate in a very harsh environment (i.e., a well depth of up to 10 km, temperatures of up to 300°C, and pressures of up to 300 bar). Additionally, space is fairly limited. As shown in the figure, the motor section has multiple stages (the rotor stages are each supported by an independent set of bearings) and an extreme machine aspect ratio. Because of these factors, electrical machines with very high torque density are needed. Advanced insulation systems that can survive the very high temperatures are also necessary for meeting the reliability and life requirements.

![Figure 18. An example of a geothermal motor-driven pump.]

Industrial Applications

Industrial applications are one of the largest application areas where electrical machines and motors are used for various purposes. Historically, a significant portion of industrial motors are fixed speed, and induction machines are vitally important in this area. There continues to be a need for more advanced higher-efficiency and/or VSDs, and many regulations and initiatives have been introduced to accomplish this goal. Moving to higher-efficiency VSDs will have a significant impact on the amount of global energy consumed in industrial sectors. Several companies have introduced advanced higher-efficiency topologies to be used in small industrial motors, including Baldor's/ABB direct-drive IPM VSD for cooling tower applications, as shown in WEG, who also introduced an IPM VSD (Figure 19). ABB introduced the synchronous-reluctance VSD shown in Figure 20. Considering quality, the synchronous-reluctance drive surpassed the induction motor in terms of size and efficiency. Following these industry trends, companies like Yaskawa Electric Corporation are also offering PM drives that feature sensorless control.

![Figure 19. A WEG IPM VSD.](image)

![Figure 20. An ABB synchronous-reluctance VSD. (a) A traditional IE2 induction motor. (b) An IE4 SynRM motor.](image)

Special Machines

In addition to conventional rotating machines, special machines (e.g., linear machines) have played a role in electrification. They are used in many applications including linear compressors for refrigerators, actuators (i.e., for industrial and aerospace applications), and nontraditional applications, e.g., water desalination.

As offshore wind continues to move toward higher power ratings, longer-term options such as superconducting generators can be considered.
New Trends and Enabling Technologies

To reach the full potential of advanced electrical machines and drives and due to the multidisciplinary nature of this field, advancements in a wide range of enabling technologies will include different materials, systems, and processes.

Advanced Magnetic Materials
Like many other fields of science and technology, advanced new materials are key to making significant improvements in performance. Advanced magnetic materials will help enable breakthroughs in electrical machines in the future. There are several types of magnetic materials (both soft and hard) that have been developed or are currently being developed. The soft magnetic materials include low-loss magnetic materials that increase machine efficiency, high-strength magnetic materials with relatively low specific core losses (this will help increase machine torque/power density), and dual-phase magnetic materials that can open the design space for a wide range of machine topologies. Advanced hard magnetic materials include permanent magnets with a higher energy product as well as permanent magnets that reduce or eliminate rare-earth materials.

Advanced Insulation Systems
Of equal (if not of more) importance are advanced insulation systems. With the widespread use of VSDs in addition to electrical machines moving more to harsh environments and taking into consideration that bearings and insulation systems are the typical points of failure in electrical machines, there is a need for a variety of advanced insulation systems. Attempts have been made to develop high-temperature insulation, high-thermal conductivity insulation, and converter-duty insulation systems that can handle high dv/dt, particularly when WBG devices such as silicon carbide and gallium nitride are used.

Advanced Thermal Management
Thermal management is more critical than ever for meeting the increasingly demanding requirements of specific power, torque density, and reliability in harsh environments. There are continued efforts to incorporate air, gas, and liquid cooling as well. Several advanced concepts, including phase-changing materials, two-phase flow, and heat pipes are being researched and evaluated for various applications.

More Integrated Systems
Another key trend that will carry over into the future is more tightly integrated systems. One level of integration includes the electrical machine and drive. An additional level of integration includes the electrical machine, drive, and the transmission/gearing system in vehicles. Such integrated systems can have significant benefits in terms of overall system footprint, system cost, efficiency, and reduced electromagnetic interference.

Conclusions
This article provided an overview of the broad range of applications in which advanced electrical machines and drives play a key role. There are many applications that require steep change in the performance of electrical machines and drives. In addition to novel topologies and design optimization, a broad range of enabling technologies, including advanced materials and thermal management, will play a key role in meeting the ever-growing requirements of the aforementioned applications. Judging
by the breadth of the applications and the very demanding requirements in terms of system footprint, efficiency, cost, and reliability, R&D efforts in the area of advanced electrical machines and drives are expected to rise significantly.

References


