1

Electrical Machines for Traction and Propulsion Applications

Ayman M. EL-Refaie

Marquette University, Electrical and Computer Engineering Department, Milwaukee, WI 53233, USA

COPYRIGHTED MATERIAL

1.1 Introduction

Over the past few decades, there has been growing interest in electrification. This led to growing interest in hybrid/electrical traction applications. Many hybrid/electrical vehicles have been commercially introduced. Even though the main focus has been on areas like energy storage and power electronics, there is growing recognition of the importance of traction motors and generators. Various technologies for traction motors/generators have been developed. There is wide recognition of the need for advanced motors and generators in order to meet the aggressive targets (in terms of power density, efficiency, and cost) of the electric drive train. This recognition led several of the main Original Equipment Manufacturer (OEMs) like General Motors (GM) to decide to make large investments in developing and producing their own traction motors and generators [1]. In addition, over the past decade, hybrid/electric propulsion for aerospace applications became a big initiative as a part of the overall transportation electrification efforts. This chapter will provide a comprehensive review of the state of the art highlighting the key global trends and tradeoffs of various technologies. The chapter will also discuss future trends and potential areas of research. The chapter will cover light-duty vehicles (with more focus), medium- and heavy-duty vehicles, off-highway vehicles (OHVs), locomotives, and ship propulsion. In addition, the chapter will cover the fast-growing area of hybrid/electric propulsion for aerospace applications. Most of the material for Sections 1.2–1.6 come from [2] while most of the material for Section 1.7 comes from [3]. The goal of the chapter is to serve as a comprehensive reference for engineers working in the traction/propulsion area (Figure 1.1).

1.2 Light-Duty Vehicles

The light-duty vehicle market has been leading the way in terms of hybrid and electric vehicles. Companies like Toyota and Honda have been pioneers in commercializing hybrid vehicles. The Toyota machines have been viewed for many years as the state of the art. A lot of effort went into trying to /benchmark the motors/generators in the various vehicles. A lot of this work has been done at Oak Ridge National Lab (ORNL) and Argonne National Lab (ANL). Table 1.1 provides a summary of the various motors/generators used in the various vehicles, as well the technology used in each machine as well as the machine rating [4–7].

Transportation Electrification: Breakthroughs in Electrified Vehicles, Aircraft, Rolling Stock, and Watercraft,
First Edition. Edited by Ahmed A. Mohamed, Ahmad Arshan Khan, Ahmed T. Elsayed, and Mohamed A. Elshaer.
© 2023 The Institute of Electrical and Electronics Engineers, Inc. Published 2023 by John Wiley & Sons, Inc.

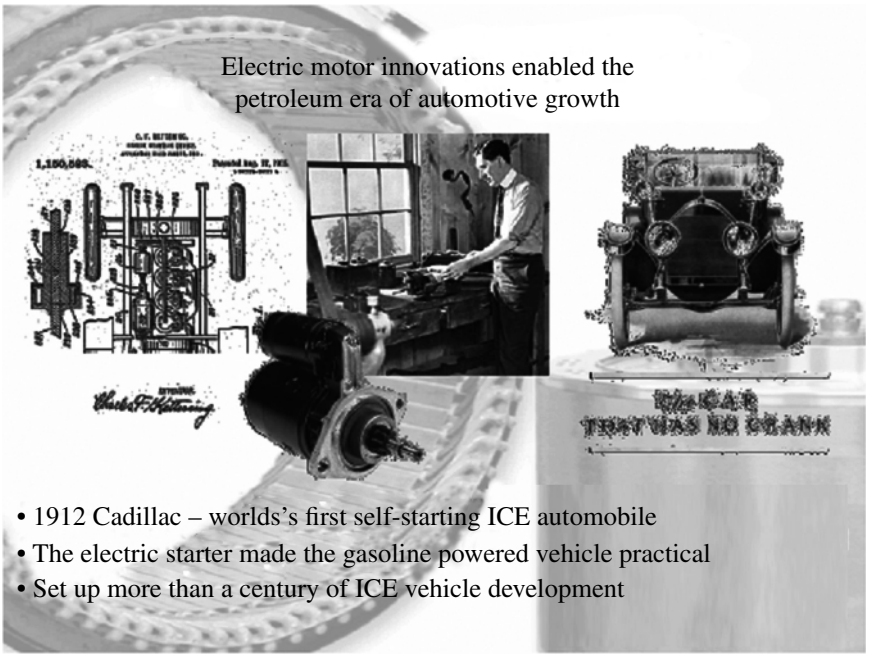
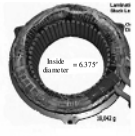
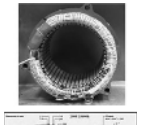


Figure 1.1 Historical importance of electric traction motors. *Source:* Savagian [1]/IEEE.

Several key observations come out of looking at this table:

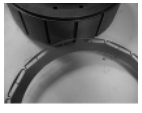
- Almost the entire light-duty hybrid vehicle industry has shifted to PM machines in order to meet the increasing power density and efficiency requirements. GM's EV1 was one of the very first vehicles to use induction machines in the early 1990s. Tesla was one of the few companies that used induction machines for a number of years but shifted to IPM machines in the newer models (Model 3 followed by Models S and X).[1]
- The Honda vehicles (as well as Hyundai which can be classified as mild hybrid) focused on surface PM (SPM) and Inset PM machines with segmented stator structures and fractional-slot concentrated windings. Segmented structures have the potential of increasing copper slot factor and reducing manufacturing costs. On the other hand, the segmented structures compromise the stator back iron rigidity. The Honda designs focused on 0.5 slot/pole/phase configurations, which tend to have low winding factor of 0.866. Also, it can be seen that the Honda designs utilize low DC bus voltage.
- The Toyota designs (which can be classified as full hybrid) focused on interior PM (IPM) machines with continuous laminations and regular integral-slot distributed windings. Relatively recently, Toyota is using fractional-slot concentrated windings in the Prius 2010 generator. Some of the Toyota designs have a single layer of magnets and some have multiple layers of magnets to increase reluctance torque contribution. Also, it can be seen that the more recent designs utilize higher DC bus voltage (by using a boost converter). This reduces the flux-weakening requirements, especially for higher-speed machines like the Toyota Camry and Lexus motors. Currently, there is a trend to explore higher DC bus voltages up to 800 V [8]. This will help further improve efficiency and reduce the size of electrical connections.

Table 1.1 Summary of the motors/generators in the key hybrid vehicles.

Motor/ generator					 
Vehicle	Honda Insight 2000 (mild hybrid)	Honda Civic 2003 (mild hybrid)	Honda Accord 2005 (mild hybrid)	Honda Civic 2006 (mild hybrid)	Toyota Camry 2007 (full hybrid)
Stator	Concentrated Wdg.	Concentrated Wdg.	Concentrated Wdg.	Concentrated Wdg.	Distributed Wdg.
Rotor	SPM	SPM	Inset PM	Inset PM	IPM
Rating	9.2 kW/83 Nm	12 kW/108 Nm	14 kW/136 Nm	15.5 kW/123 Nm	105 kW
DC bus voltage	144 V_{dc}	144 V_{dc}	156 V_{dc}	156 V_{dc}	244–650 V_{dc}
Motor/ generator	 		 	 	 
Vehicle	Lexus 2005 Rx400h (full hybrid)	Toyota Prius 1998 (full hybrid)	Toyota Prius 2002 (full hybrid)	Toyota Prius 2004 (full hybrid)	Toyota Prius 2010 (full hybrid)

(*Continued*)

Table 1.1 (Continued)

Stator	Distributed Wdg.	Distributed Wdg.	Distributed Wdg.	Distributed Wdg.	Distributed Wdg.
Rotor	IPM	IPM	IPM	IPM	IPM
Rating	123 kW	30 kW	33 kW	50 kW	60 kW
DC bus voltage	650 V_{dc}	273 V_{dc}	274 V_{dc}	500 V_{dc}	650 V_{dc}
Motor/ generator	 	 	 	 	 
Vehicle	Toyota Prius 2017 (full hybrid)	BMW i3 2016 (plug-in hybrid)	Hyundai Sonata 2011 (mild hybrid)	Nissan Leaf 2012 (pure EV)	Tesla Model 3 (pure EV)
Stator	Hairpin Distributed Wdg.	Distributed Wdg.	Concentrated Wdg.	Distributed Wdg.	Distributed Wdg.
Rotor	IPM	IPM	Inset IPM	IPM	Carbon-wrapped IPM
Rating	53 kW	125 kW/250 Nm	30 kW/205 Nm	80 kW	211 kW/450 Nm
DC bus voltage	600 V_{dc}	300 V_{dc}	270 V_{dc}	375 V_{dc}	350 V_{dc}

- The Honda designs as well as the Prius have a top speed of around 6000 rpm. In more recent designs like the Camry and Lexus (as well as some of the GM and Ford designs), the machines are designed for higher top speeds up to 14,000 rpm, in order to increase the machine power density.
- IPM machines are becoming the dominant type.
- 30–70 kW ratings/machine for full hybrids (cars).
- >120 kW for full-hybrid SUVs.

In more recent electrified vehicles, the machine power ratings can go as high as 200 kW and even higher in some cases.

- Liquid cooling is becoming an industry common practice in order to meet higher performance requirements. The peak air gap shear stress for all these machines ranges from 8 psi up to 17 psi depending on how aggressive the cooling is and how long is the transient power requirement.
- Higher coolant inlet temperature up to 105 °C is still targeted for future designs (to eliminate additional cooling loop).
- Electric machines tightly integrated with ICE/drive train housing.
- GM as well as several other OEMs are pursuing IPM machines with bar-wound (hairpin) windings [1]. This winding has a higher fill factor (and hence power density) but the main concern is the AC losses in the windings, especially at higher speeds. The performance of the machine will rely heavily on the vehicle duty cycle and how long the motor can thermally operate at higher speeds, and also depends on the cooling mechanism implemented (Figure 1.2).

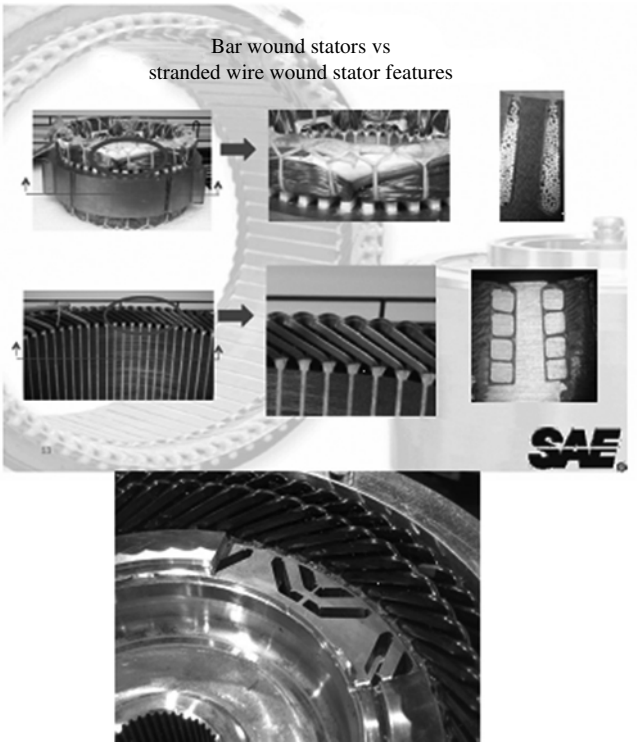


Figure 1.2 GM/Remy IPM motors with bar-wound (hairpin) windings. *Source:* Savagian [1]/IEEE.

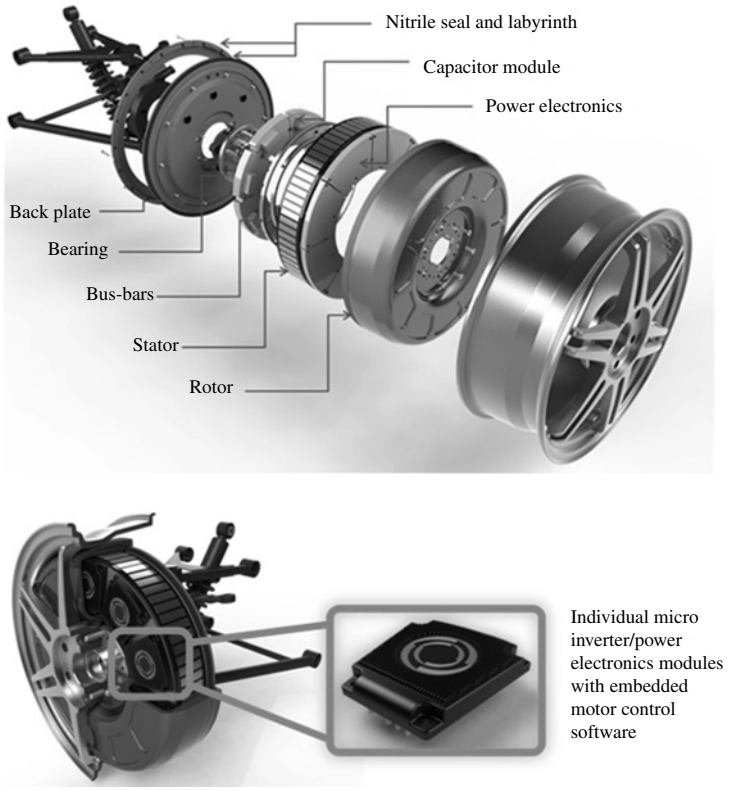


Figure 1.3 Protean electric wheel motor. *Source:* Protean electric wheel (http://www.proteanelectric.com/live/docs/PD18-3-LV1.2-Data-Sheet.pdf).



Figure 1.4 Mitsubishi wheel motor. *Source:* Mitsubishi Motors North America, Inc. (www.mitsubishimotors.com).

In addition to the regular central traction motors, numerous wheel-hub motor concepts have been developed (some were installed in a few vehicles) but no commercial autos yet. One of the main technical challenges of wheel motors is the un-sprung mass [9]. Many ideas have been developed to minimize this issue. Protean Electric[2] developed an inside-out radial-flux PM wheel motor (54 kW/83 kWpk) in which the power electronics and controls are distributed along the motor circumference as shown in Figure 1.3. Mitsubishi[3] (50 kW) and TM4[4] (80 kW) also developed inside-out radial-flux PM wheel motors as shown in Figures 1.4 and 1.5. GM developed a dual rotor axial-flux PM with an epoxy-based stator [10, 11]. The motor is shown in Figure 1.6. Despite all these concepts and the significant progress made, cost, fault tolerance, system complexity, and unsprung mass continue to be significant challenges for wheel motors.

1.3 Medium- and Heavy-Duty Vehicles

Even though the light-duty vehicle section has been dominated by liquid-cooled (as previously mentioned in Section 1.2), this is not the case with medium-, and heavy-duty vehicles for example delivery trucks, buses, and class 8 (super) trucks. In these vehicles, induction machines are still considered the main workhorse. This is probably due to the historical robustness and cost-effectiveness of induction machines. Table 1.2 summarizes some of the available traction systems for medium- and heavy-duty vehicles.[5–9] The majority are liquid-cooled induction machines. There is also growing interest in IPM machines. UQM is considered one of the leading companies in providing PM liquid-cooled traction systems for medium and heavy-duty vehicles[10] Switched reluctance (SR) machines are also used in some heavy-duty vehicles.[11] In these types of vehicles, the well-known issues of SR machines including acoustic noise as well as torque ripple and vibration might not be of great concern. SR Drives (part of Emerson) is a lead supplier of SR machines. PM machines have higher power density and efficiency at the machine torque–speed envelope. Induction machines have advantages in terms of partial load efficiency (also there are very low-drag losses if the machine is unloaded). Also, induction machines do not have the issues of fault tolerance[12]

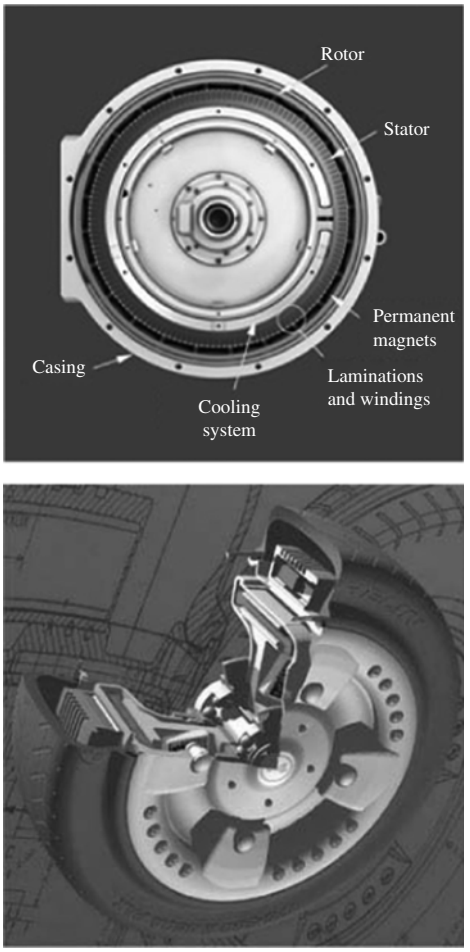


Figure 1.5 TM4 wheel motor. *Source:* DANA TM4 Inc. (http://www.tm4.com/moteurs_generateurs.aspx).

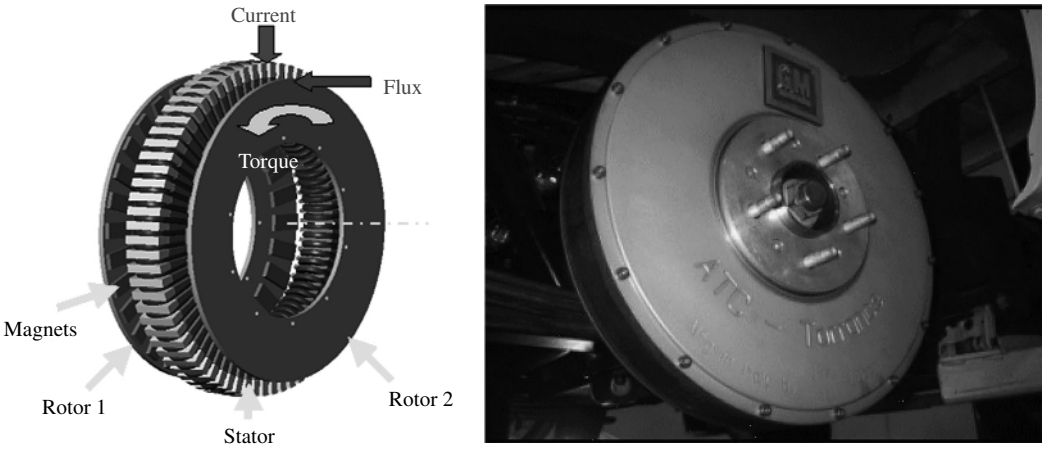


Figure 1.6 GM axial-flux PM wheel motor. *Source:* Rahman et al. [10]/IEEE.

Table 1.2 Summary of hybrid systems for medium and heavy-duty vehicles.

Allison transmission	BAE	Azure dynamics	Solectria	UQM	Oshkosh
• Allison EP-50/40 • Motor/ generator • 75 kW nominal 150 kW peak • Induction machine by Remy	• HybriDrive® propulsion systems • Induction machine traction motor 160 kW (215 hp) Continuous • 200 kW (268 hp) peak	• 50 kW Continuous shaft power at 1000–2500 rpm • 97 kW peak shaft power • Induction machine air-cooled • AC90 Motor with DMOC645 Controller	• AC55 is a single output, 78 kW 3-phase AC induction motor • Nominal speed of 2.5 krpm and a maximum speed of 8 krpm	• PM liquid cooling • 200 kW peak, 115 kW continuous motor power • 200 kW peak, 120 kW continuous generator power/regenerative braking • 150 kW peak, 100 kW continuous motor power • 150 kW peak, 100 kW continuous generator power	• The ProPulse system combines a 300 hp. diesel engine with a 225 kW induction generator and ultracapacitors (1.4 MJ) to drive two 140 hp induction traction motors

(and the braking torque produced in case of a fault) or uncontrolled generation mode (UCG) as in the case of a PM machine [12, 13].

1.4 Off-Highway Vehicles

There is growing interest in hybrid-electric drive systems in construction and OHVs to replace existing mechanical and hydraulic systems to achieve higher performance.[13] Table 1.3 provides a summary of these examples. As can be seen, Siemens Motors (as well as GE) and advanced AC control systems are very popular, especially in big mining trucks. It can also be seen that induction machines are the dominant type. Also SR machines are being used due to their robustness and as previously mentioned, acoustic noise, and vibrations are not key issues in such applications. PM machines are also being evaluated but there are concerns about the shock/vibration levels that the machine can tolerate mainly due to the brittleness of PMs [14]

1.5 Locomotives

Historically, induction machines are the dominant type of traction motors in locomotives. This can be seen in Table 1.4, which summarizes the traction motors used in various locomotives [15]. The typical maximum speeds for these motors are in the range of 3000–6000 rpm. All these motors are air-cooled. More recently, PM motors have been developed for high-speed rail,[14] for example, the AGV PM traction motor developed by Alstom and shown in Figure 1.7. This motor is closed and self-ventilated and has a maximum speed of 4500 rpm. The next step in order to meet the demand-

Table 1.3 Examples of OHV motors and generators.

Application	Company	Machine type and rating
Tractor	Caterpillar (CAT D7E with electric drive train)	2∗110 HP induction motors
Loader	Volvo (Volvo L220F hybrid wheel loader)	700 Nm and 50 kW peak induction motors
	LeTourneaue Technologies (50-Series for loaders and dozers, e.g. new hybrid wheel loader L-1150)	1050 HP switched reluctance motors and an SR generator
Mining trucks	Caterpillar 795F-AC Rear axle mounted	3400 HP wheel induction motor
	Hitachi EH5000AC	3000 HP induction motor
	Liebherr TI 274	3000 HP Siemens induction wheel motors
	Komatsu 860E	2400 HP Siemens induction motors

Source: Adapted from http://machinedesign.com/article/hybrid-drives-for-construction-equipment-0707.

Table 1.4 Summary of the motors/generators in various locomotives.

Locomotive	Motor type and rating	Locomotive	Motor type and rating
Italian Pendolino ETR 460 tilting train generation, max. Speed 250 km/h, in operation since 1992.	12∗500 kW induction motors traction motors made by Alstom	German DB 152 electrical locomotive, max. speed 170 km/h, in operation since 2001	4∗1600 kW induction machines made by Siemens
German DB ICE 3 high-speed train, max. speed 330 km/h, traction motors, power 16 × 500 kW, in operation since 1999	16∗500 kW induction motors made by Siemens max speed of 6000 rpm	German DB-Railion 189 electrical freight locomotive, max. speed 140 km/h, in operation since 2003	4∗1600 kW induction machines made by Siemens
Swiss Railways SBB FLIRT RABe 521/523, max. speed 160 km/h, in operation since 2004	4∗500 kW Induction motors made by TSA Traktionssysteme	Swiss SBB Re 460 electrical locomotive, max. speed 230 km/h, in operation since 1992	4∗1525 kW induction machines made by ABB
Spanish Talgo 350 high-speed train, max. speed 350 km/h, traction motors, in operation since 2005	8∗1000 kW Induction motors made by Siemens	Indian 3-phase electric freight locomotive WAG-9, max. speed 100 km/h, in operation since 1996	6∗850 kW induction motors made by ABB
Korean KTX high-speed train, operational speed 300 km/h, in operation since 2004	12∗1130 kW self-commutated synchronous machines (replaced by induction machines in KTX-II) made by Rotem, power	USA – Houston TX, MetroRail, Avanto light rail vehicle, max. Speed 105 km/h, in operation since 2001	4∗200 kW at 2500 rpm induction machines made by Siemens
Austrian ÖBB Taurus electrical locomotive 1016/1116, max. speed 230 km/h, in operation since 2000	4∗1600 kW induction machines made by Siemens	Czech Republic – Prague 15 T low floor tramway, max. speed 60 km/h	16∗60 kW induction motors made by ŠKODA ELECTRIC
Chinese Railways DJ4 electrical locomotive, max. speed 120 km/h, in operation since 2006	8∗1200 kW induction machines made by Siemens and Zhuzhou Electric Locomotives Works	Austria – Graz, Cityrunner, low floor tramway, max. speed 70 km/h, in operation since 2001	8∗50 kW induction motors made by ŠKODA ELECTRIC

Source: Adapted from SKF [15].

ing requirements for light-weight high-speed rail is to move toward a liquid cooling of both the power converter and traction motors. This is currently under investigation and development.

1.6 Ship Propulsion

Historically: DC and synchronous machines have been the dominant type of ship propulsion.[15] Figures 1.8 and 1.9 show examples of such machines by LDW. More recently, PM machines have been developed for ship propulsion.[16] Figure 1.10 shows an example of a

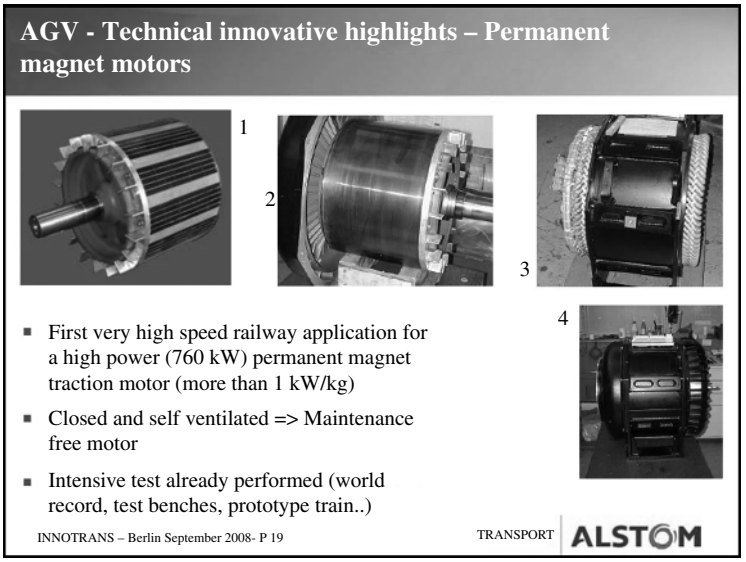


Figure 1.7 AGV high-speed PM traction motor by Alstom.

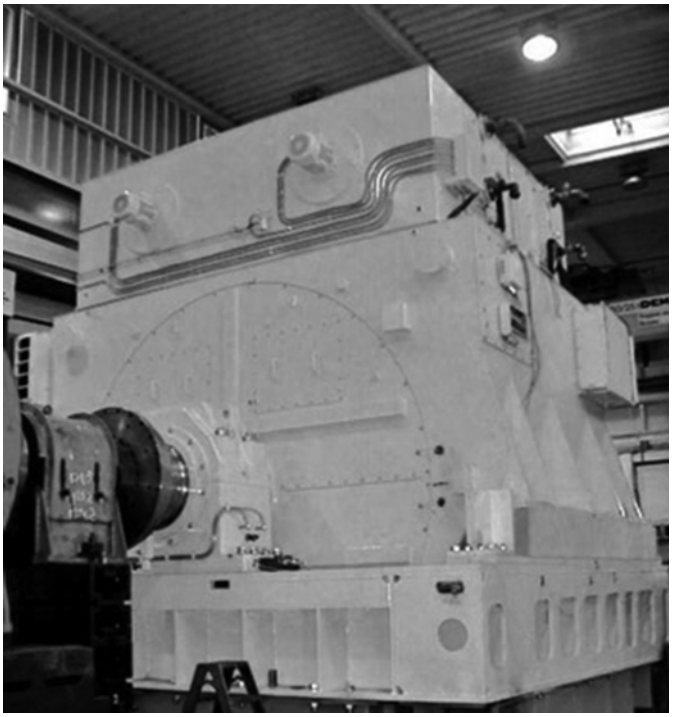
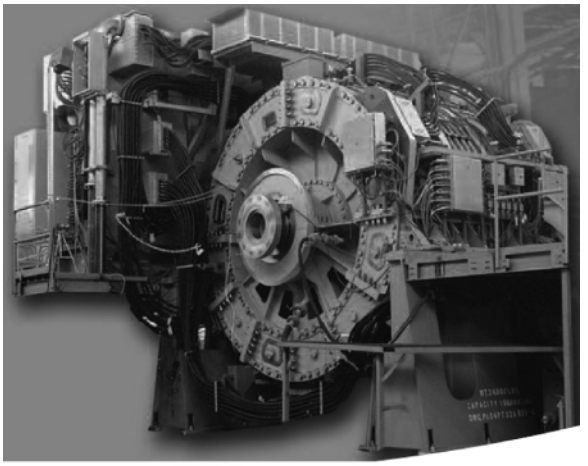


Figure 1.8 21 000-kW variable speed synchronous propulsion motor for cruise liner. *Source:* http://www.ship-technology.com/contractors/propulsion/ldw.



Figure 1.9 950 kW DC motor, delivered by LDW, as main drive for the research vessel "Solea."

shipboard propulsion high-speed 36.5 MW PM motor developed by DRS. Some companies are also working on superconducting machines for marine propulsion applications.[17] Figure 1.11 shows the potentially significant increase in power density by replacing conventional machines with high-temperature superconducting machines by American superconductors. Table 1.5 summarizes some of the key motors used in podded ship propulsion. As can be seen, there are a mix of wound field synchronous machines, induction machines, and PM machines.[18,19] Also there have been several rim-driven machines proposed.[20] Few examples are shown in Figures 1.12–1.14 [16].[21,22]



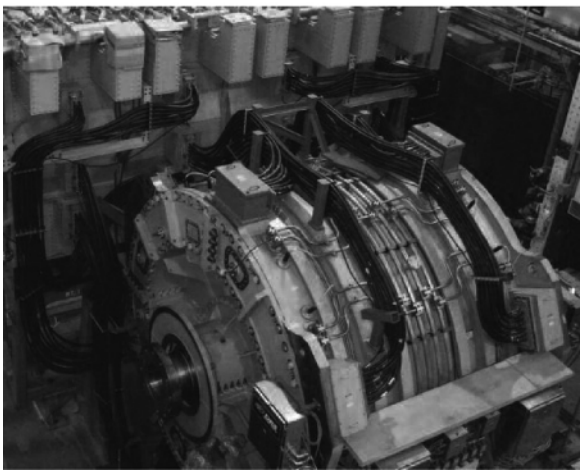


Figure 1.10 36.5 MW permanent magnet motor systems (PMMS) by DRS. *Source:* http://www.drs.com/Products/PESG/PDF/PMMS.pdf.

1.7 High Specific Torque/ Power Electrical Machines

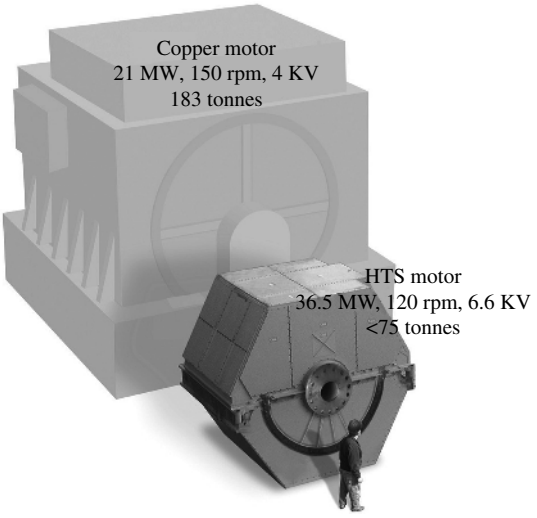


Figure 1.11 Comparison of conventional 21 MW motor and HTS 36.5 MW motor by American Superconductor. *Source:* http://www.amsc.com/products/motorsgenerators/documents/MP_DS_365_1007_A4_r3.pdf.

There has been growing and continued interest in high-speed and high specific power electrical machines. In [17], a survey of high-speed machines based on various application and machine topologies is reported as shown in Figures 1.15 and 1.16. Another survey has been presented in [18] highlighting the key technologies that go into high-speed machines, as well as some performance figure-of-merit (FoM). For example, RPM$\sqrt{\text{kW}}$ is used to identify the safe limits for tip speeds to avoid running into mechanical and rotor dynamics issues. In [19], a survey of high specific power electrical machines is disclosed. The focus in [19] is on the electric machine-specific power and a general comparison between different machine topologies is presented. This section will provide a more comprehensive survey of high specific power machines in terms of highlighting specific examples that are considered the state of the art. More performance details for these specific examples will be reported. Key "system" tradeoffs and considerations will also be discussed. The section will mainly focus on electrical machines for land vehicles, and aerospace applications.

1.7.1 Electrical Machines for Land Vehicles

In this section, high specific power electrical machines designed for hybrid/electric vehicles are covered. The focus will be on machines that stand out in terms of having significantly higher power

Table 1.5 Summary of the motors used in podded ship propulsion.

Company	Mermaid (RR)	Azipod (ABB)	Azipod compact (ABB)	SSP (Siemens)	Converteam
Machine type	Wound field synchronous	Wound field synchronous and induction	PM synchronous	PM synchronous	Induction
Power rating	5–25 MW[a]	Induction <5 MW[b] Synchronous 5–25 MW	1.3–4.5 MW[c]	5–30 MW[d]	1–12 MW[e]

[a] http://www.rollsroyce.com/Images/Product%20Range_tcm92-8658.pdf.
[b] http://www05.abb.com/global/scot/scot293.nsf/veritydisplay/9eccbc669a5fcff1c125768f004a9bc9/$file/azipod%20project%20guide%206-3.pdf.
[c] http://www05.abb.com/global/scot/scot293.nsf/veritydisplay/d77d9ac59ba74cb7c12576d3004cfe3f/$file/azipod%20co%20brochure_2010.pdf.
[d] http://www.industrysolutions.siemens.com/marine/en/.
[e] http://www.converteam.de/majic/dl/4/doc/Markets/Navy/Final_NAVAL.pdf.



Figure 1.12 110 kW, 4100 rpm rim-driven PM motor by SatCon. *Source:* Nichols et al. [20]/ Synapticon GmbH.

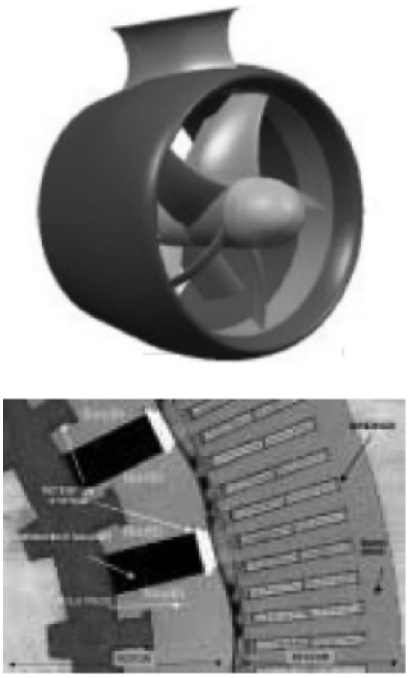


Figure 1.13 4.47 MW rim-driven IPM motor by GDEB. *Source:* Kane et al. [21]/IEEE.

density and/or torque density compared to many other machines in that crowded space. In this section, the focus will be on electrical machines used in light-duty vehicles (since they usually target the highest specific power) while a comprehensive review of electrical machines used in other types of vehicles has been presented in [2]. Also, a comprehensive summary of the teardown and test results of several mainstream central traction motors in light-duty vehicles was disclosed.[23] These include 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600 h, 2010 Prius, 2011 Sonata, 2012 Sonata generator, 2012 LEAF, 2013 LEAF charger, 2013 Camry PCU, 2014 Accord, 2016 BMW i3, and 2017 Prius. Those machines have "peak" specific power ranging from 1.1–3 kW/kg. The DC bus voltage ranges from 270 to 650 V. Table 1.6 provides a summary of some of the salient examples in this space (where n_{peak} is the peak power speed while n_{max} is the maximum speed). These machines are mainly traction motors (some are central traction motors and others are wheel motors). They have significantly higher specific power and/or specific torque compared to other mainstream traction motors covered in previous references.[23] They target some specialized applications, for example, racing cars as in the case of McLaren motor. Also, YASA Motors have been used in some high-performance cars like Ferrari and the company has been acquired by Mercedes Benz. The following points can be observed:

- All high-performance machines in this space are PM machines. In addition to the high specific power, maximum efficiency of 94% or higher could be achieved.
- Central traction motors are mainly radial-flux inner-rotor PM machines.
- Wheel motors use other topologies including axial-flux PM (YASA) as well outer-rotor PM (Protean), which lend themselves to better integration with wheels as hub motors.
- All machines are liquid-cooled (masses listed are based on dry machines, the cooling liquid mass is not included).
- The McLaren and KIT machines have the highest corner speeds and achieve the highest specific power density. Both are targeting racing vehicles (McLaren is a mature product while KIT targets university racing and not a commercial product).

Racing applications are not cost-sensitive and hence there is room to come up with higher-performance designs.

- The wheel motors are lower-speed motors so their specific power is not as high but they have significantly higher specific torque. Usually, there is a tradeoff between specific power and specific torque.
- The UQM is a central traction motor and its performance falls within the performance of other mainstream central traction motors.
- For automotive applications, it is important to remember that available space comes at a premium. So, power density/volume is of equal if not more importance than specific power. Therefore, kg/l (which is effectively the ratio of power density and specific power) is included in Table 1.6.
- The DC bus voltage varies from 400 to 800 V, which is considered low voltage. This is suitable for the power ratings of these machines.



Figure 1.14 100 kW rim-driven PM motor by Brunvoll. *Source:* [22] and http://www.norpropeller.no.

1.7.2 Electrical Machines for Aerospace Applications

In this section, high specific power electrical machines designed for aerospace applications will be covered. Aerospace is the key area that requires substantial improvement in power density. This includes More Electric Aircraft (MEA) [23, 24], hybrid/electric propulsion[24] [25, 26] green taxiing [27], and UAVs and Vertical Takeoff and Landing (VTOL).[25] All these machines are used for relatively new non-traditional applications. These include:

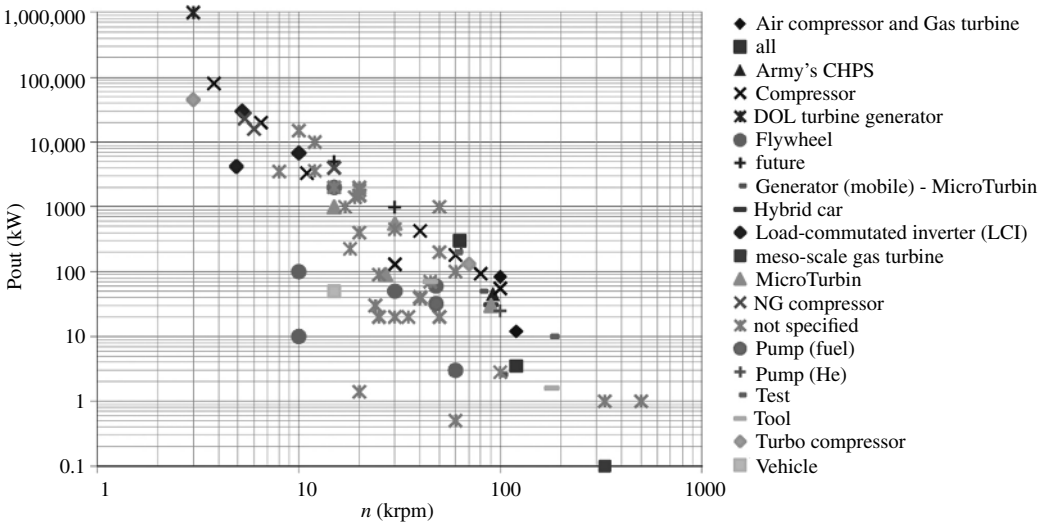


Figure 1.15 Survey of high-speed machines by application [17].

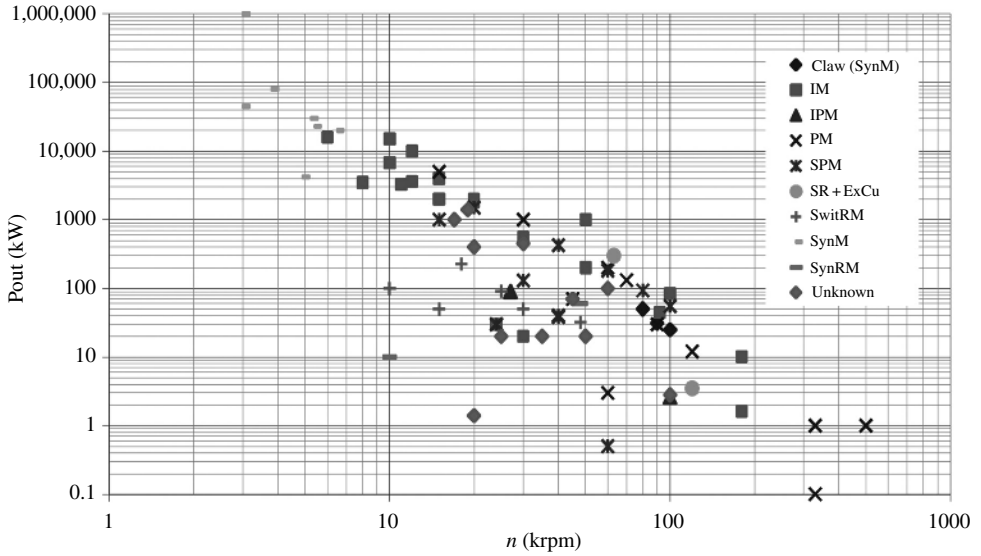


Figure 1.16 Survey of high-speed machines by topology [17].

(i) generators as well as motors that drive propellers in the case of hybrid/electric propulsion, (ii) wheel motors for green taxiing, and (3) motors that provide both vertical lift as well as propulsion in the case of UAVs and VTOL. These applications are very different from the conventional role of electrical machines in aerospace applications which mainly included generators (connected to the engine vis power takeoff (PTO) shafts, small motors driving various loads as well as electrical actuators. These new applications have significantly higher demands when it comes to specific power and efficiency (since both have a significant impact on specific fuel consumption). Tables 1.7–1.9 provide a detailed summary of various electrical machines broken down by power ratings. Since the previously mentioned applications are fairly new, the amount of information about these high specific power machines available in the public domain is still relatively limited. These tables include the main bulk of information that is available. Most of the internal dimensions of the various machines are not readily available and hence it is difficult to calculate useful quantities like air gap shear stress, torque per airgap volume and rotor tip speed. Still, the information included in these tables should be very useful for engineers and researchers working in this field in terms of understanding and establishing technology trends. The general trends include:

- Higher power (>100 kW) electrical machines cover applications ranging from small aircraft (four seats or more) all the way up to large commercial aircrafts (Honeywell machine). Electrical machines between 10 and 100 kW mainly cover smaller planes. Electrical machines <10 kW mainly cover UAVs and remote-controlled small planes.
- All machines are PM (radial inner rotor, radial outer rotor, and axial flux).
- Higher power machines ≥100 kW are largely liquid-cooled. Lower power machines <100 kW are largely forced air-cooled.
- Lower-speed machines lend themselves better to tooth windings (due to the lower frequency, which is typically 10s–100s Hz) as well as direct-conductor cooling (due to larger fewer slots).

Table 1.6 High-power density machines for land vehicles.

					
Manufacturer	McLaren	YASA	Protean	Karlsuhe Institute of Technology (KIT)	UQM
Reference	http://www.mclaren.com/appliedtechnologies/products/item/e-motor-120kw-130nm	http://www.yasamotors.com/products/yasa-750	http://www.proteanelectric.com/en/specifications	[28]	https://www.neweagle.net/support/wiki/ProductDocumentation/EV_Software_and_Hardware/Electric_Motors/UQM/PowerPhase%20HD%20250%20web.pdf
Application	McLaren P1 Hybrid supercar and Formula-E EV	2 direct drive motors for pure EV (Regera hypercar)	2 in-wheel motors for pure EV (VW Bora compact sedan)	Electric vehicle (Audi race)	EV/HEV
Machine topology	Surface PM (SPM)	Axial flux PM	Outer rotor SPM	Interior PM (IPM)	SPM
Cooling method	50/50 water/glycol	Oil cooling	Liquid cooling jacket	50/50 water/glycol indirect slot cooling	Water jacket cooling
Mass (kg)	26	33	34	14	95
DC bus voltage (V)	545	800	400	450	360–440
Efficiency (%)	96 (@120 kW and 13 krpm)	≥95	≥93 (including inverter)	97 (max eff.)	94 (max eff.)
P_{rated} (kW)	100	75	54	70	115
P_{peak} (kW)	120	199	75		200
kW_{rated}/kg	3.8	2.3	1.6	5	1.2
kW_{peak}/kg	4.6	6	2.2		2.1
n_{rated} (rpm)	9545	1800	793	7400	2440
n_{peak} (rpm)	8815	2400	716		2122
n_{max} (rpm)	15 000	3250	1600	15,000	
T_{rated} (Nm)	100	398	650	90	450
T_{peak} (Nm)	130	792	1000		900
Nm_{rated}/kg	3.8	12	19.1	6.4	4.7
Nm_{peak}/kg	5	24	29.4		9.5
kg/l	3.81	5.2	2.13	9.93	2.97

Table 1.7 High-power density machines for aerospace applications ≥100 kW.

					
Manufacturer	Siemens	Honeywell	Siemens	ENSTROJ – Slovenia	Rolls Royce-University of Sheffield
Reference	https://nari.arc.nasa.gov/sites/default/files/attachments/Korbinian-TVFW-Aug2015.pdf	[29]	https://nari.arc.nasa.gov/sites/default/files/attachments/Korbinian-TVFW-Aug2015.pdf	http://www.enstroj.si/Electric-products/emrax-motorsgenerators.html	[30]
Application	Four or more seats' plane	Hybrid electric aircraft propulsion	Generator lab approval for series hybrid propulsion	Electric glider Apis EA2	Starter-generator for small civil turbofan
Machine topology	Halbach array SPM	Wound-field synchronous (2 sets of 3-ph windings)	SPM	Axial-flux PM	SPM
Cooling method	Directly cooled conductors	Engine oil cooling, conduction and end-winding spray	Directly cooled conductors	Combined cooling; indirect cooling: air + water	Water jacket cooling
Mass (kg)	50	126.5	24.4	20.3	22.7
DC bus voltage (V)	580	300–600 (2 3-ph diode rectifiers in series or in parallel)	580	700	540
Efficiency (%)	≥95	97	≥95	93–98	96
P_{rated} (kW)	260	1000 (only tested up to 540 kW)	170	100	100
P_{peak} (kW)				200	150
kW_{rated}/kg	5.2	7.9	7	4.9	4.4
kW_{peak}/kg				9.8	6.6
n_{rated} (rpm)	2500	19,000	6250	4000	27,000
n_{peak} (rpm)				4000	27,000
n_{max} (rpm)		20,000	6500	5000	27,000
T_{rated} (Nm)	993	110	260	250	35
T_{peak} (Nm)				500	53
Nm_{rated}/kg	19.9	4	10.7	12.3	1.6
Nm_{peak}/kg				24.6	2.4
kg/l	1.21	2.09	2.18	4	3.02

Table 1.8 High-power density machines for aerospace applications ≥10 kW and <100 kW.

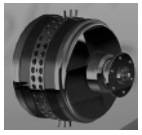
					
Manufacturer	Rotex – Czech Republic	Siemens and EADS – Germany	ACENTISS – Germany	Yuneec – China	University of Nottingham
Reference	http://www.rotexelectric.eu/rotexen/index.php/template-info/bldcmotors/2012-01-30-22-30-21	http://www.siemens.com/press/en/feature/2013/corporate/2013-06-airshow.php?content%5b%5d=CC&content%5b%5d=I&content%5b%5d=IDT&_sm_au_=iMVts5DMjPZ7RNvM	http://www.acentiss.de/de/produkte/produkte-duplexmotor	https://en.wikipedia.org/wiki/Yuneec_Power_Drive_20 https://youtu.be/sKOJ8UzUnYs	[31]
Application	Electric Powered small aircraft	Series hybrid electric drive for Diamond Aircraft 2-seater motor glider	Electric Powered small aircraft	Ultralight aircraft (Espyder)	Green taxiing motor
Machine topology	Outer rotor SPM	Surface PM	Two electric motors on a common drive shaft of the propeller	Outer rotor SPM	Halbach array outer rotor SPM
Cooling method	Air or liquid cooling	Direct oil cooled winding	Air cooling	Air cooling	Air cooling
Mass (kg)	20	13	11	8.2	108 (active)
DC bus voltage (V)	800	545	58	67	
Efficiency (%)	≥95	95			
P_{rated} (kW)	50	65	32	20	
Ppeak (kW)	80	80	40		59.1
kW_{rated}/kg	2.5	5	2.9	2.4	
kW_{peak}/kg	4	6.2	3.6		0.5
n_{rated} (rpm)	2200	5000	2200	2400	
n_{peak} (rpm)	2200	5000	2200	2400	80.8
n_{max} (rpm)	2400	11,000	2500		1800
T_{rated} (Nm)	400	110	139	80	35
T_{peak} (Nm)	790	130	174		6979
Nm_{rated}/kg	10.9	9.5	12.6	9.7	
Nm_{peak}/kg	17.4	11.8	15.8		64.6
kg/l	3.17			1.96	4.25

Table 1.9 High-power density machines for aerospace applications <10 kW.

				
Manufacturer	Launchpoint	KDE Direct	Joby Motors	ThinGap
Reference	http://www.launchpnt.com/portfolio/transportation/electric-vehicle-propulsion	https://www.kdedirect.com/collections/xf-brushless-motors/products/kde700xf-295-g3	http://www.jobymotors.com/public/public/views/pages/prodcuts.php	http://www.thingap.com/standard-products
Application	Unmanned Aerial Vehicle (UAV)	Remote-controlled electric helicopter series	Remote-controlled model planes	UAV
Machine topology	Axial flux ironless SPM with dual Hallbach arrays	Outer rotor SPM	SPM	Outer rotor SPM
Cooling method	Air cooling	Air cooling	Air cooling	Air cooling
Mass (kg)	0.64	0.695	1.8	1.59
DC bus voltage (V)		50.4–67.2	40–450 (depending on winding connections)	
Efficiency (%)	95	93	85–95	91
Prated (kW)		7.2	8.2	4
P_{peak} (kW)	5.22	12.9	12.6	11.3
kW_{rated}/kg		10.4	4.6	2.5
kW_{peak}/kg	8.2	18.5	7	7.1
n_{rated} (rpm)		14,900	6000	7987
n_{peak} (rpm)	8400	19,800	6000	7987
T_{rated} (Nm)		4.6	13	4.83
*T*peak (Nm)	6	6.2	20	13.55
Nm_{rated}/kg		6.6	7.3	3
Nm_{peak}/kg	9.3	8.9	11.1	8.5
kg/l	1.8	3.78	3.78	1.44

Higher-speed machines (>1 kHz frequency) lend themselves better to distributed windings as well as indirect-conductor cooling (immersed stator, spray cooling, and cooling jacket).

- As previously noted, all the masses are "dry" masses not including the cooling liquid mass. If "wet" masses are included, the gap in specific power between liquid- and air-cooling will decrease.
- All machines are considered low-voltage machines (DC bus voltage ≤ 800 V).
- Lower-speed machines (<3000 rpm) tend to have higher specific torque while higher-speed machines (8000–24,000 rpm) tend to have higher specific power.
- Most of these machines have significantly higher specific power and/or specific torque compared to machines used in the automotive sector. The emphasis is more on specific power and not power density and this is reflected in the kg/l values.

1.7.3 Key System Tradeoffs and Considerations

Beyond the electrical machine, there are several system level tradeoffs and considerations that are equally or more important than the machine specific power. Even though the various applications previously discussed might have different system requirements, they might have some system tradeoffs in common. In general, the following discussion is more geared toward hybrid/electrical propulsion applications with special focus on larger commercial planes which represent the most significant application space moving forward. These system tradeoffs include.

1.7.3.1 Specific Power vs Efficiency

Even though typically the focus especially in aerospace applications is on specific power, efficiency is another key performance metrics. Typically, there is a tradeoff between specific power and efficiency. Specific fuel consumption (SFC) is dependent on both specific power and efficiency. Depending on the overall system architecture, sometimes it is better to design an electrical machine with lower specific power and higher efficiency.

1.7.3.2 Fault Tolerance

As shown, PM machines are really the dominant type since they have the entitlement in terms of high specific power and/or efficiency. For safety-critical applications, it is important to take fault tolerance into consideration. This can lead to a significant reduction in specific power (for example, back emf might need to be limited). Some of the proposed designs that are either ironless and/or have airgap windings usually have very low inductances. This leads to very high fault-currents which would not be acceptable from a system perspective.

1.7.3.3 System Voltage

System voltage is a key parameter. Even though all the machines presented in the paper are low voltage, for MW-class systems and depending on the aircraft size, there will be a need for higher system voltages in excess of 2 kV DC bus voltage. This is mainly to reduce the cables mass which can be the most dominant factor in the overall system specific power. The higher system voltage poses a challenge in terms of the insulation systems required to withstand such voltage levels at altitude (corona effects are more severe at higher altitudes and reduced pressure). This will lead to a different and much thicker insulation build which will make the thermal management of electrical machines much more challenging (depending on the machine aspect ratio and whether spray cooling can be effective or not).

1.7.3.4 Machine Controllability

Machine parameters affecting machine controllability are key factors that have to be considered while designing high specific power machines. Similar to the comments about fault tolerance, if a machine is designed with a low inductance (for example, designs that are ironless and/or have airgap windings), this poses control challenges to keep current ripple under control (to minimize its impact on losses and torque ripple) as well as the control stability. Another design parameter is the machine fundamental frequency. The higher the machine fundamental frequency, the higher the required switching frequency to maintain high quality current waveform. The higher switching frequency can have adverse effect on insulation system and/or sizing of filters. In addition, it can lead to higher switching losses in the power converter and hence reduction in overall system efficiency. A typical switching frequency of 15–20 kHz is used depending on the machine power rating.

1.8 How Does the Future Look Like?

This section will discuss how does the future look like as well as ongoing and potential areas of research. The main focus will be on light-duty vehicles and aerospace applications.

Short-term future, PM machines will continue to dominate the light-duty vehicle market. Also, they started to extend into medium and heavy-duty markets as well as high-speed rail, off – highway vehicles and ship propulsion as previously mentioned in Sections 1.4–1.6 [32, 33].

In terms of PM machines, there are several research areas of interest. These include developing concepts for integrated motor and drive. This can have a significant impact on reducing system cost as well as EMI issues. Couple of examples is shown in Figures 1.17 and 1.18 [34].[26] Another area of research is developing traction motors with 105 °C coolant inlet temperature as previously mentioned. This can have a significant impact on eliminating a separate cooling loop for the motor and inverter, which can cause significant reduction in system cost.

Long-term, there is a lot of concern about the prices, and availability of rare-earth permanent magnets in the future as discussed in the previous section. There is increased activity to try to develop non-rare earth PM traction motors that can have comparable performance to the rare-earth PM motors. Some of the key examples on the commercial side is in [35]. Continental announced that they are at the verge of commercializing wound-field synchronous traction motors as shown in Figure 1.19. Also, BMW is pursuing wound-field synchronous traction motors for their future vehicles.

Jaguar also recently released the plug-in electrical CX75 that has two SR generators provided by SR drives.[27]

Toyota also recently made an announcement that they are working on an advanced induction motor.[28] The concern about the sustainability of rare earth permanent magnets is also obvious

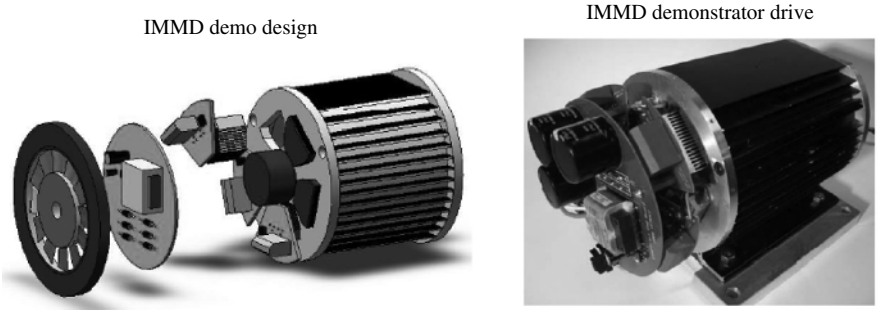


Figure 1.17 Modular integrated motor drive. *Source:* U.S. Department of Energy (https://energy.gov/sites/prod/files/2014/04/f15/2013_apeem_report.pdf (page 191)).

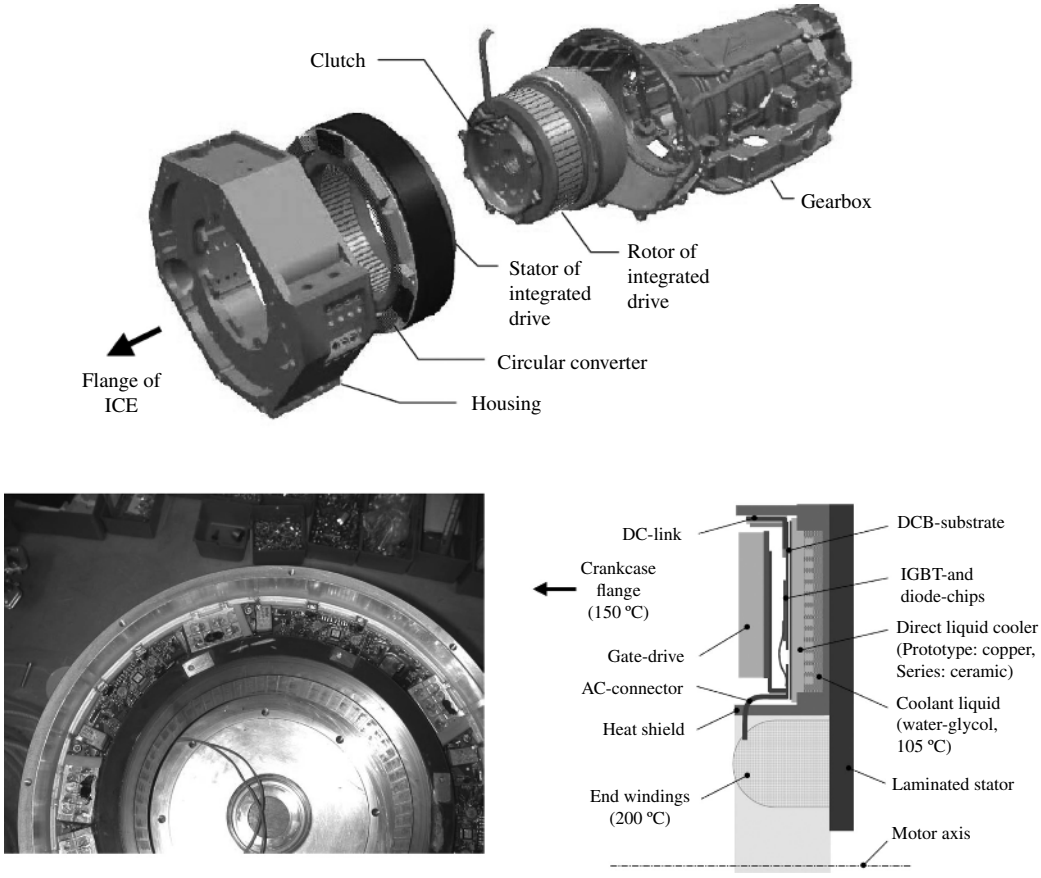


Figure 1.18 Daimler ring integrated motor drive. *Source:* Brown et al. [34].

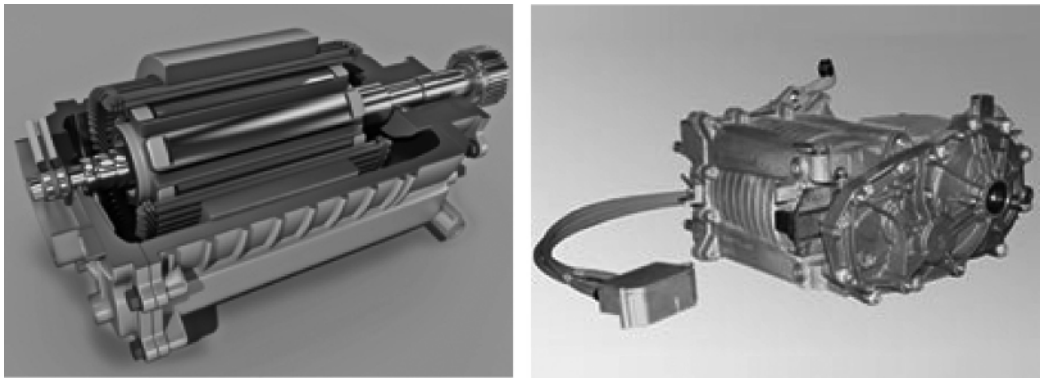


Figure 1.19 Continental wound-field synchronous traction motors 5–120 kW. *Source:* Tadros et al. [35].

in the fact that the US Department of Energy started funding research and development in the area of non-rare earth PM traction motors.[29] So far, the focus has been on light-duty vehicles, but there is a big market for medium and heavy-duty vehicles that needs to be properly addressed.

A critical area (especially for pure electrical traction applications) that needs to be properly addressed is fault tolerance and limp-home capability. Many of the concepts for safety-critical applications like aerospace applications can potentially leveraged in the traction sector [36].

In terms of the hybrid/electric propulsion for aerospace applications, an increased level of research and development to achieve very high specific powers will continue. This will include developing and optimizing novel machine topologies, develop advanced thermal management as well as developing and implementing advanced materials and manufacturing.

Notes

1 https://arstechnica.com/cars/2019/04/motor-technology-from-model-3-helps-tesla-boost-model-s-range-10/
2 www.proteanelectric.com/live/docs/PD18-3-LV1.2-Data-Sheet.pdf
3 www.mitsubishimotors.com
4 www.tm4.com/moteurs_generateurs.aspx
5 http://xoomer.virgilio.it/parimirco/Wheel%20Hub%20Motors%20-Nagashima-%20Session%20D2%20.ppt
6 www.atstransmission.com
7 www.baesystems.com/
8 www.azuredynamics.com/
9 http://metadope.com/Bus/pdf/AC55.pdf
10 www.oshkoshcorporation.com/
11 www.uqm.com/
12 www.srdrives.co.uk/
13 http://machinedesign.com/article/hybrid-drives-for-construction-equipment-0707
14 http://www.unife.org/uploads/2008/presentations%20innotrans/rs/01_Presentation%20Alstom.pdf
15 http://www.ship-technology.com/contractors/propulsion/ldw/
16 http://www.drs.com/Products/PESG/PDF/PMMS.pdf
17 http://www.amsc.com/products/motorsgenerators/documents/mp_ds_365_1007_a4_r3.pdf
18 http://www.rolls-royce.com/Images/Product%20Range_tcm92-8658.pdf
19 http://www05.abb.com/global/scot/scot293.nsf/veritydisplay/9eccbc669a5fcff1c125768f004a9bc9/$file/azipod%20project%20guide%206-3.pdf
20 http://www05.abb.com/global/scot/scot293.nsf/veritydisplay/d77d9ac59ba74cb7c12576d3004cfe3f/$file/azipod%20co%20brochure_2010.pdf
21 http://www.industrysolutions.siemens.com/marine/en/
22 http://www.converteam.de/majic/dl/4/doc/Markets/Navy/Final_NAVAL.pdf
23 https://energy.gov/sites/prod/files/2017/06/f34/edt087_burress_2017_o.pdf
24 https://aerospaceamerica.aiaa.org/features/fly-the-electric-skies/
25 https://www.theguardian.com/business/2017/apr/21/electric-flying-car-lilium-google-uber-vtol-jet-taxi
26 https://energy.gov/sites/prod/files/2014/04/f15/2013_apeem_report.pdf (page 191)
27 http://www.contionline.com/generator/www/com/en/continental/pressportal/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2010_04_29_elektromotoren_en.html
28 http://online.wsj.com/article/SB10001424052748703583404576080213245888864.html
29 http://www.cleancitieseastbay.org/DOE-Funding-opp-12-16-10.sflb.pdf

References

1 Savagian, P. (2010). Motors for automotive electrification: a GM perspective. *SAE Hybrid Vehicle Technologies 2010 Symposium*, February 2010, San Diego.

2 El-Refaie, A.M. (2013). Motors/generators for traction/propulsion applications: a review. *IEEE Veh. Technol. Mag.* 8 (1): 90–99.

3 El-Refaie, A. and Osama, M. (2019). High specific power electrical machines: a system perspective. *CES Trans. Electr. Machines Syst.* 3 (1): 88–93. https://doi.org/10.30941/CESTEMS.2019.00012.

4 Staunton, R.H., Burress, T.A., and Marlino, L.D. (2006). Evaluation of 2005 HONDA ACCORD hybrid electric drive system. ORNL/TM-2006/535.

5 Hsu, J.S., Ayers, C.W., Coomer, C.L. et al. (2007). Report on Toyota/Prius motor torque capability, torque property, no-load back EMF, and mechanical losses. ORNL/TM-2004/185.

6 Burress, T.A., Coomer, C.L., Campbell, S.L. et al. (2007). Evaluation of the 2007 Toyota Camry hybrid synergy drive system. ORNL/TM-2007/190.

7 Burress, T.A., Coomer, C.L., Campbell, S.L. et al. (2008). Evaluation of the 2008 Lexus LS 600H hybrid synergy drive system. ORNL/TM-2008/185.

8 Aghabali, I., Bauman, J., Kollmeyer, P.J. et al. (2021). 800-V electric vehicle powertrains: review and analysis of benefits, challenges, and future trends. *IEEE Trans. Transp. Electrification* 7 (3): 927–948. https://doi.org/10.1109/TTE.2020.3044938.

9 Mraz, S.J. (2010). Hub motors for all-electric vehicles still have some technological challenges to overcome. Machine http://Design.com (accessed 2021).

10 Rahman, K.M., Patel, N.R., Ward, T.G. et al. (2006). Application of direct-drive wheel motor for fuel cell electric and hybrid electric vehicle propulsion system. *IEE Trans. Industry Appl.* 42 (5): 1185–1192.

11 Nagashima, J. (2005). Wheel hub motors for automotive applications, EVS-21, Monaco.

12 Welchko, B.A., Jahns, T.M., Soong, W.L., and Nagashima, J.M. (2003). IPM synchronous machine drive response to symmetrical and asymmetrical short circuit faults. *IEE Trans. Energy Convers.* 18 (2): 291–298.

13 Han, S.-H., Jahns, T.M., Guven, M.K. et al. (2006). Impact of maximum back-EMF limits on the performance characteristics of interior permanent magnet synchronous machines. *Industry Applications Conference, 2006. 41st IAS Annual Meeting*. Conference Record of the 2006 IEEE, vol. 4, pp. 1962–1969, 8–12 October 2006.

14 Jahns, T.M., Han, S.-H., El-Refaic, A.M. et al. (2006). Design and experimental verification of a 50 kW interior permanent magnet synchronous machine. *Industry Applications Conference, 2006. 41st IAS Annual Meeting*. Conference Record of the 2006 IEEE, vol. 4, pp. 1941–1948, 8–12 October 2006.

15 SKF. Solutions for traction motors. https://www.skf.com/binaries/pub12/Images/0901d1968019754c-6815EN_tcm_12-57716.pdf.

16 Gieras, J. (2008). *Advancements in Electric Machines*. Springer.

17 Moghaddam, R.R. (2014). High speed operation of electrical machines, a review on technology, benefits and challenges. *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, pp. 5539–5546.

18 Gerada, D., Mebarki, A., Brown, N.L. et al. (2014). High-speed electrical machines: technologies, trends, and developments. *IEEE Trans. Ind. Electron.* 61 (6): 2946–2959.

19 Zhang, X. and Haran, K.S. (2016). High-specific-power electric machines for electrified transportation applications-technology options. *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, pp. 1–8.

20 Nichols, S., Foshage, J., and Lovelace, E. (2006). Integrated motor, propulsor (IMP) and drive electronics for high power density propulsion. *Electric Machine Technology Symposium EMTS06*, Philadelphia, PA: American Society of Naval Engineers (ASNE).

21 Kane, D.M. and Warburton, M.R. (2002). Integration of permanent magnet motor technology. *Power Engineering Society Summer Meeting*. IEEE, vol. 1, pp. 275–280; vol. 1, 25–25 July 2002.

22 Brunvoll presents a rim driven thruster RDT, 2005, Brunvoll AS, Molde, Norway. www.brunvoll.no; http://www.norpropeller.no

23 Roboam, X., Sareni, B., and Andrade, A.D. (2012). More electricity in the air: toward optimized electrical networks embedded in more-electrical aircraft. *IEEE Ind. Electron. Mag.* 6 (4): 6–17.

24 Cao, W., Mecrow, B.C., Atkinson, G.J. et al. (2012). Overview of electric motor technologies used for more electric aircraft (MEA). *IEEE Trans. Ind. Electron.* 59 (9): 3523–3531.

25 Neuman, T. (2016). Fly the electric skies. *IEEE Spectr.* 53 (6): 44–48.

26 Yoon, A., Xuan Yi, J. Martin, Y.C. and Haran, K. (2016) A high-speed, high-frequency, air-core PM machine for aircraft application. *2016 IEEE Power and Energy Conference at Illinois (PECI)*, Urbana, IL, pp. 1–4.

27 Galea, M., Xu, Z., Tighe, C. et al. (2014). Development of an aircraft wheel actuator for green taxiing. *2014 International Conference on Electrical Machines (ICEM)*, Berlin, pp. 2492–2498.

28 Schiefer, M. and Doppelbauer, M. (2016). Indirect slot cooling for high-power-density machine with concentrated winding. *# Presentation by M. Doppelbauer in Airbus Symposium*, Ottobrun (11 March 2016).

29 Anghel, C. (2015). High-efficiency and high-power-density generator rated for 1MW. *Electric & Hybrid Aerospace Technology Symposium*, Bremen, Germany.

30 Orr, E. (2017). Keynote presentation by Rolls Royce at More Electric Aircraft MEA.

31 Galea, M., Xu, Z., Tighe, C. et al. (2014). Development of an aircraft wheel actuator for green taxiing. *2014 International Conference on Electrical Machines (ICEM)*, pp. 2492–2498.

32 Weeber, K.R., Shah, M.R., Sivasubramaniam, K. et al. (2010). Advanced permanent magnet machines for a wide range of industrial applications. *2010 IEEE Power and Energy Society General Meeting*, pp. 1–6, 25–29 July 2010.

33 El-Refaie, A., Nold, R., Haran, K. et al. (2012). Testing of advanced permanent magnet machines for a wide range of applications. *2012 International Conference on Electrical Machines*, Marseille, pp. 1860–1867

34 Brown, N.R., Jahns, T.M., and Lorenz, R.D. (2007). Power converter design for an integrated modular motor drive. *Industry Applications Conference. 42nd IAS Annual Meeting*, New Orleans, LA. Conference Record of the 2007 IEEE, pp. 1322–1328, 23–27 September 2007.

35 Tadros, Y., Ranneberg, J., and Schäfer, U. (2003). Ring shaped motor-integrated electric drive for hybrid electric vehicles. EPE, Toulose.

36 EL-Refaie, A.M. (2009). Fault-tolerant PM machines: a review. *Electric Machines and Drives Conference*, Miami, FL. IEMDC '09. IEEE International, pp. 1700–1709, 3–6 May 2009.