3-2019

High Specific Power Electrical Machines: A System Perspective

Ayman M. EL-Refaie

Mohamed Osama

CES Transactions on Electrical Machines and Systems, Vol. 3, No. 1 (March 2019) : 88-93. DOI.

High Specific Power Electrical Machines: A System Perspective

Ayman El-Refaie
Marquette University, Milwaukee, WI
Mohamed Osama
GE Global Research Center, Munich, Germany

Abstract:

There has been a growing need for high specific power electrical machines for a wide range of applications. These include hybrid/electric traction applications, aerospace applications and Oil and Gas applications. A lot of work has been done to accomplish significantly higher specific power electrical machines especially for aerospace applications. Several machine topologies as well as thermal management schemes have been proposed. Even though there has been a few publications that provided an overview of high-speed and high specific power electrical machines [1-3], the goal of this paper is to provide a more comprehensive review of high specific power electrical machines with special focus on machines that have been built and tested and are considered the leading candidates defining the state-of-the art. Another key objective of this paper is to highlight the key "system-level" tradeoffs involved in pushing electrical machines to higher specific power. Focusing solely on the machine specific power can lead to a sub-optimal solution at the system-level.

Keywords

Density, Electrical, High, Machines, Perspective, Power, Specific

SECTION I. Introduction

There has been growing and continued interest in highspeed and high specific power electrical machines. In [1], a survey of high-speed machines based on various application and machine topologies is reported as shown in Fig 1 and 2. Another survey has been presented in [2] highlighting the key technologies that go into high-speed machines, as well as some performance figure-of-merit (FoM). For example, RPM$\sqrt{kW}$ is used to identify the safe limits for tip speeds to avoid running into mechanical and rotor dynamics issues. In [3], a survey of high high-specific power electrical machines is disclosed. The focus in [3] is on the electric machine specific power and a general comparison between different machine topologies is presented. This paper 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 paper will mainly focus on electrical machines for land vehicles, aerospace application and to a lesser extent on oil & gas applications.

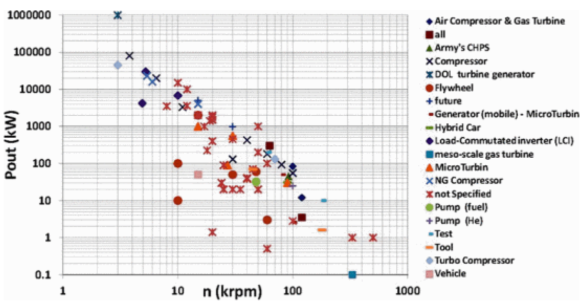


Fig. 1: Survey of high-speed machines by application [1]

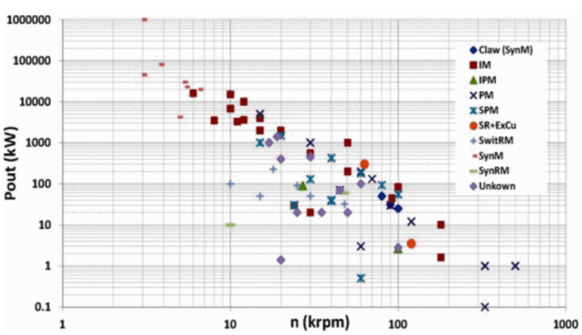


Fig. 2: Survey of high-speed machines by topology [1]

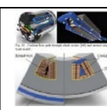
SECTION II. Machines for Land Vehicles

In this section, high-specific power electrical machines designed for hybrid/electric vehicles is covered. The focus will be on machines that stand out in terms of having significantly higher power density and/or torque density compared to many other machines in that crowded space. In this paper, 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 [4]. In [5] a comprehensive summary of the teardown and test results of several mainstream central traction motors in light duty vehicles was disclosed. These include: 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600h, 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-

650V. Table I provides a summary of some of the salient examples in this space. 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 (McClaren is a mature product while KIT targets a 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 motors 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 important than specific power. This is why kg/liter (which is effectively the ratio of power density and specific power) is included in Table I.
- The DC bus voltage varies from 400-800V which is considered low voltage. This is suitable for the power ratings of these machines.

Table I: High-power density machines for land vehicles

					
Manufacturer	McLaren	YASA	Protean	Karlsuhe Institute of Technology (KIT)	UQM
Reference #	[6]	[7]	[8]	[9]	[10]
Application	McLaren P1 Hybrid super car and Formula-E EV	2 direct drive motors for pure EV (Regera hyper car)	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 & 13krpm)	≥95%	≥93% (including inverter)	97% (max eff.)	94% (max eff.)
Prated [kW]	100	75	54	70	115
Ppeak [kW]	120	199	75		200
kWrated/kg	3.8	2.3	1.6	5	1.2
kWpeak/kg	4.6	6	2.2		2.1

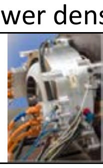
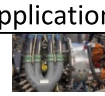
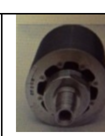
nrated [rpm]	9545	1800	793	7400	2440
npeak [rpm]	8815	2400	716		2122
nmax [rpm]	15000	3250	1600	15000	
Trated [Nm]	100	398	650	90	450
Tpeak [Nm]	130	792	1000		900
Nmrated/kg	3.8	12	19.1	6.4	4.7
Nmpeak/kg	5	24	29.4		9.5
Kg/liter	3.81	5.2	2.13	9.93	2.97

SECTION III. 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 include More Electric Aircraft (MEA) [11], [12], hybrid/electric propulsion [13]–[14][15] green taxiing [16], and UAVs and Vertical Takeoff and Landing (VTOL) [17]. Tables II–IV provide a detailed summary of various electrical machines broken down by power ratings. The general trends include:

- Higher power (> 100 kW) electrical machines cover applications ranging from small aircrafts (4 seats or more) all the way up to large commercial aircrafts (Honeywell machine). Electrical machines between 10–100 kW mainly cover smaller planes. Electrical machines <10 kW mainly cover UAV s and remote-controlled small planes.
- All machines are PM (radial inner rotor, radial outer rotor, and axial flux)
- Higher power machines $\geq 100\text{kW}$ are largely liquid-cooled. Lower power machines $< 100\text{kW}$ 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). 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 $\leq 800\text{V}$)
- Lower-speed machines (< 3000 rpm) tend to have higher specific torque while higher speed machines (8000–24000 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/liter values.
- Key system tradeoffs and considerations will be discussed in section V.

Table II: High-Power density machines for aerospace applications ≥100 KW

					
Manufacturer	Siemens	Honeywell	Siemens	ENSTROJ - Slovenia	Rolls Royce-University of Sheffield
Reference #	[18]	[19]	[18]	[20]	[21]
Application	4 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	Direct cooled conductors.	Engine oil cooling, conduction and end-winding spray	Direct 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

Table III: High-Power density machines for aerospace applications >10 KW & <100 KW

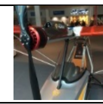
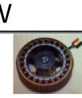
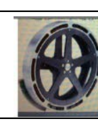
					
Manufacturer	Rotex-Czech Republic	Siemens and EADS-Germany	ACENTISS-Germany	Yuneec - China	University of Nottingham
Reference #	[22]	[23]	[24]	[25]	[26]
Application	Electric Powered small aircraft	Series hybrid electric drive for Diamond Aircraft 2-seater motor glider	Electric Powered small aircraft	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%			
Prated [kW]	50	65	32	20	
Ppeak [kW]	80	80	40		59.1
kWrated/kg	2.5	5	2.9		2.4
kWpeak/kg	4	6.2	3.6		0.5
nrated [rpm]	2200	5000	2200	2400	
npeak [rpm]	2200	5000	2200	2400	80.8
nmax [rpm]	2400	11000	2500		1800
Trated [Nm]	400	110	139	80	35
Tpeak [Nm]	790	130	174		6979
Nmrated/kg	10.9	9.5	12.6	9.7	
Nmpeak/kg	17.4	11.8	15.8		64.6
Kg/liter	3.17			1.96	4.25

Table IV: High-Power density machines for aerospace applications <10 KW

				
Manufacturer	Launchpoint	KDE Direct	Joby Motors	ThinGap
Reference #	[27]	[28]	[29]	[30]

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
Ppeak [kW]	5.22	12.9	12.6	11.3
kWrated/kg		10.4	4.6	2.5
kWpeak/kg	8.2	18.5	7	7.1
nrated [rpm]		14900	6000	7987
npeak [rpm]	8400	19800	6000	7987
Trated [Nm]		4.6	13	4.83
Tpeak [Nm]	6	6.2	20	13.55
Nmrated/kg		6.6	7.3	3
Nmpeak/kg	9.3	8.9	11.1	8.5
Kg/liter	1.8	3.78	3.78	1.44

SECTION IV. Machines for Oil and Gas Applications

Even though the main focus of the paper are traction/propulsion applications which are the key drivers for high-specific power electrical machines, it is important to keep in mind that there other applications Oil &Gas applications that would benefit significantly from high-speed/high-specific power electrical machines that can lead to significant reduction in system footprint. A key area is high-speed machines for driving compressors. One example is shown in Fig. 3 [31], [32]. This machine is a surface PM machine with Halbach array. It has a specific power of ~*1* kW /kg. Even though this is fairly low compared to traction/propulsion applications, it is fairly high for MW -class oil & gas machines.

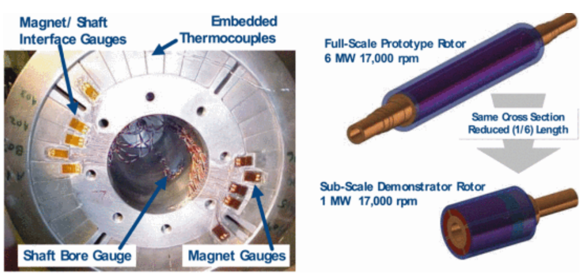


Fig 3: GE 6 MW PM machine

SECTION V. 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. These include:

(a) 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.

(b) Fault-Tolerance

As shown in the paper, 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. Some of the propose 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.

(c) 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). 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).

(d) 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, 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.

SECTION VI. Conclusions

Interest and need for high-specific power electrical machines especially for various aerospace applications will continue to grow. This paper attempted to provide a comprehensive review of the state-of-the art in this area. The paper provide full details about specific examples. The paper also attempts to highlight the need for a “system-perspective” instead of just focusing on electrical machines in isolation. Hopefully the paper will serve as a useful reference for engineers and researchers working in this field.

References

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

2. D. Gerada, A. Mebarki, N. L. Brown, C. Gerada, A. Cavagnino, A. Boglietti, "High-Speed Electrical Machines: Technologies Trends and Developments", *IEEE Transactions on Industrial Electronics*, vol. 61, no. 6, pp. 2946-2959, June 2014.

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

4. A. M. El-Refaie, "Motors/generators for traction/propulsion applications: A review", *IEEE Vehicular Technology Magazine*, vol. 8, no. 1, pp. 90-99, March 2013.
5. https://energy.gov/sites/prod/files/2017/06/f34/edt087_burress_2017_o.pdf.
6. http://www.mclaren.com/appliedtechnologies/products/item/e-motor-120kw-130nm/.
7. http://www.yasamotors.com/products/yasa-750/.
8. http://www.proteanelectric.com/en/specifications/.
9. Markus Schiefer, Martin Doppelbauer, "Indirect Slot Cooling for High-Power-Density machine with Concentrated Winding", *# Presentaiton by M. Doppelbauer in Airbus Symposium*, March 11, 2016.
10. https://www.neweagle.net/support/wiki/ProductDocumentation/EV_Software_and_Hardware/Electric_Motors/UQM/PowerPhase%20HD%20250%20web.pdf.
11. X. Roboam, B. Sareni, A. D. Andrade, "More Electricity in the Air: Toward Optimized Electrical Networks Embedded in More-Electrical Aircraft", *IEEE Industrial Electronics Magazine*, vol. 6, no. 4, pp. 6-17, Dec. 2012.
12. W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett, D. J. Atkinson, "Overview of Electric Motor Technologies Used for More Electric Aircraft (MEA)", *IEEE Transactions on Industrial Electronics*, vol. 59, no. 9, pp. 3523-3531, Sept. 2012.
13. T. Neuman, "Fly the electric skies", *IEEE Spectrum*, vol. 53, no. 6, pp. 44-48, June 2016.
14. https://aerospaceamerica.aiaa.org/features/fly-the-electric-skiesl.
15. A. Yoon, Xuan Yi, J. Martin, Yuanshan Chen, K. Haran, "A high-speed high-frequency air-core PM machine for aircraft application", *2016 IEEE Power and Energy Conference at Illinois (PECI)*, pp. 1-4, 2016.
16. M. Galea, Z. Xu, C. Tighe, T. Hamiti, C. Gerada, S. Pickering, "Development of an aircraft wheel actuator for green taxiing", *2014 International Conference on Electrical Machines (ICEM)*, pp. 2492-2498, 2014.
17. https://www.theguardian.com/business/2017/apr/21/electric-flying-car-lilium-google-uber-vtol-jet-taxi.
18. https://nari.arc.nasa.gov/sites/default/files/attachments/Korbinian-TVFW-Aug2015.pdf.
19. Cristian Anghel, "High-efficiency and high-power-density generator rated for 1MW", *Electric & Hybrid Aerospace Technology Symposium*, Nov. 2015.
20. http://www.enstroj.si/Electric-products/emrax-motorsgenerators.html.
21. Eddie Orr, *Keynote presentation by Rolls Royce at More Electric Aircraft MEA*, 2017.
22. http://www.rotexelectric.eu/rotexen/index.php/template-infolbldcmotors/2012-01-30-22-30-21.
23. 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.
24. http://www.acentiss.de/de/produkte/produkte-duplexmotor.
25. https://en.wikipedia.org/wiki/Yuneec_Power_Drive_20https://youtu.be/sKOJ8UzUnYs.
26. M. Galea et al., "Development of an aircraft wheel actuator for Green Taxiing", *ICEM*, 2014.
27. http://www.launchpnt.com/portfolio/transportation/electric-vehicle-propulsion/.
28. https://www.kdedirect.com/collections/xf-brushless-motors/products/kde700xf-295-g3.
29. http://www.jobymotors.com/public/public/views/pages/prodcuts.php.
30. http://www.thingap.com/standard-products/.
31. K. R. Weeber et al., "Advanced permanent magnet machines for a wide range of industrial applications", *2010 IEEE Power and Energy Society General Meeting*, pp. 1-6, Jul. 25–29, 2010.

32. A. El-Refaie et al., "Testing of advanced permanent magnet machines for a wide range of applications", *2012 International Conference on Electrical Machines*, pp. 1860-1867, 2012.