High Specific Power Electrical Machines: A System Perspective

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***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, and aerospace 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.**

***Index Terms*— Density, Electrical, High, Machines, Perspective, Power, Specific.**

I. INTRODUCTION

There has been growing and continued interest in high-speed 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, and aerospace applications.

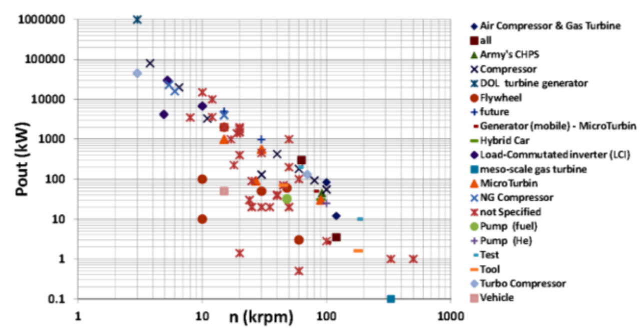

Fig. 1. Survey of high-speed machines by application[1].

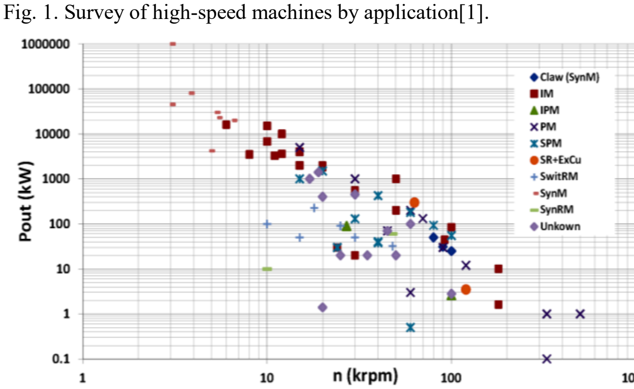

Fig. 2. Survey of high-speed machines by topology [1].

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,

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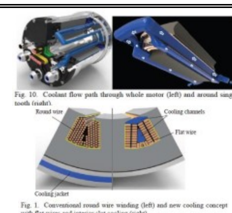
2012 Sonata generator, 2012 LEAF, 2013 LEAF charger, 2013 Camry PCU, 2014 Accord, 2016 BMW i3, and 2017 Prius. Those machines have “peak” specific power ranging from 1.1-3 kW/kg. The DC bus voltage ranges from 270-650V. Table I provides a summary of some of the salient examples in this space. (where 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 [5]. They target some specialized applications for example racing cars as in the case of McLaren motor. 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

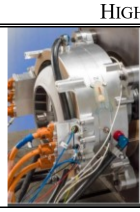
					
Manufacturer	McLaren	YASA	Protean	Karlsuhe Institute of Technology (KIT)	UQM
Reference #	[6]	[7]	[8]	[9]	[10]
Application	McLaren P1 Hybrid super car and Formula-E EV	2 direct drive motors for pure EV (Regera hyper car)	2 in-wheel motors for pure EV (VW Bora compact sedan)	Electric Vehicle (Audi race)	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
n_{rated} [rpm]	9545	1800	793	7400	2440
n_{peak} [rpm]	8815	2400	716		2122
n_{max} [rpm]	15000	3250	1600	15000	
Trated [Nm]	100	398	650	90	450
Tpeak [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/liter	3.81	5.2	2.13	9.93	2.97

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 [13-15] green taxiing [16], and UAVs and Vertical Takeoff and Landing (VTOL) [17]. All these machines are used for relatively new non-traditional applications. These include: (1) Generators as well as motors that drive propellers in the case of hybrid/electric propulsion, (2) 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 significant impact on specific fuel consumption). Tables II-IV 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 inlude 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 aigap 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 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 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). 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 ≤ 800V)
- 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

Efficiency [%]	≥ 95%	97%	≥ 95%	93%-98%	96%
Prated [kW]	260	1000 (only tested up to 540 kW)	170	100	100
Ppeak [kW]				200	150
kWrated/kg	5.2	7.9	7	4.9	4.4
kWpeak/kg				9.8	6.6
n_{rated} [rpm]	2500	19000	6250	4000	27000
n_{peak} [rpm]				4000	27000
n_{max} [rpm]		20000	6500	5000	27000
Trated [Nm]	993	110	260	250	35
Tpeak [Nm]				500	53
Nm_{rated}/kg	19.9	4	10.7	12.3	1.6
Nm_{peak}/kg				24.6	2.4
Kg/liter	1.21	2.09	2.18	4	3.02

TABLE III
HIGH-POWER DENSITY MACHINES FOR AEROSPACE APPLICATIONS ≥10 kW & <100 kW

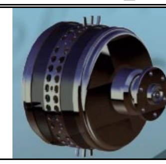
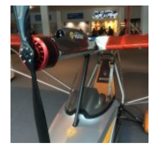
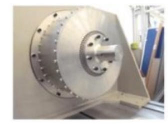
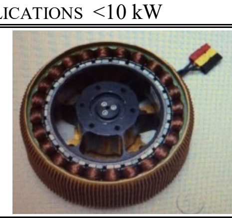
					
Manufacturer	Rotex-Czech Republic	Siemens and EADS-Germany	ACENTISS-Germany	Yuneec - China	University of Nottingham
Reference #	[22]	[23]	[24]	[25]	[26]
Application	Electric Powered small aircraft	Series hybrid electric drive for Diamond Aircraft 2-seater motor glider	Electric Powered small aircraft	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
n_{rated} [rpm]	2200	5000	2200	2400	
n_{peak} [rpm]	2200	5000	2200	2400	80.8
n_{max} [rpm]	2400	11000	2500		1800
Trated [Nm]	400	110	139	80	35
Tpeak [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/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
n_{rated} [rpm]		14900	6000	7987
n_{peak} [rpm]	8400	19800	6000	7987
Trated [Nm]		4.6	13	4.83
Tpeak [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/liter	1.8	3.78	3.78	1.44

IV. 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 towards hybrid/electrical propulsion applications with special focus on larger commercial planes which represents the most significant application space moving forward. These system tradeoffs 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.

V. Conclusions

Interest and need for high-specific power electrical machines especially for various aerospace applications will continue to grow. There are several new and un-conventional applications (especially in aerospace) that require completely new class of high-specific power electrical machines and drives. This paper attempted to provide a comprehensive review of the state-of-the art in these emerging areas. There is no other reference at the moment that provides such a comprehensive summary of overview of all these new applications/machines. The paper provides 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.

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Dr. Mohamed Osama is a Principal Engineer at GE Aviation with over 20 years of experience and with proven track record in leading projects and teams that develop electrical machines technologies. This includes extensive experience in the design and analysis of induction machines, wound-field synchronous machines and permanent magnet machine. His experience covers a broad range of electric machines applications that include aerospace applications, wind turbines, mining and traction applications, power generation and oil & gas applications.

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