WEMPEC

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Electrification of Aircraft and Vehicles
Current Status and Future Trends

Dr. Bulent Sarlioglu
Associate Professor, University of Wisconsin-Madison
Associate Director of WEMPEC
sarlioglu@wisc.edu
(608) 262 2703

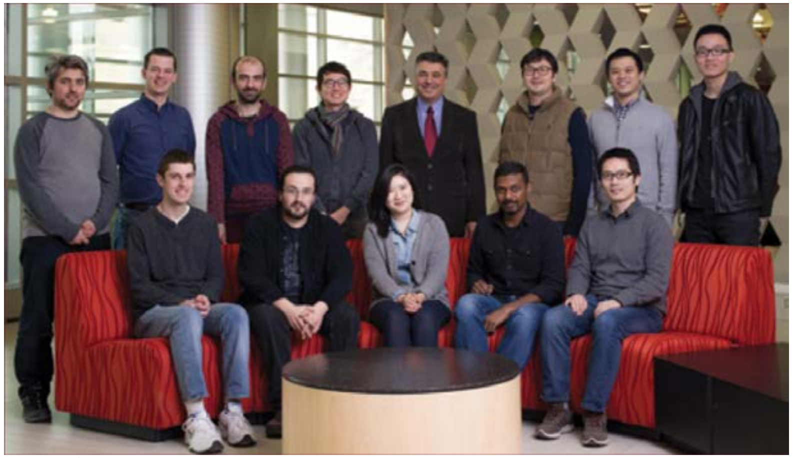
WEMPEC
Wisconsin Electric Machines and Power Electronics Consortium

My research is on innovative electric motors and power electronics.

- Conventional and Novel Electric Machines
- Power Electronics with SiC and GaN Devices

Tesla Model 3 Electric Power Train with SiC Inverter

Efficient Motors and Drives Research



Chuo Shinkansen (Maglev)

Transportation

Electric aircraft (Efan-X)

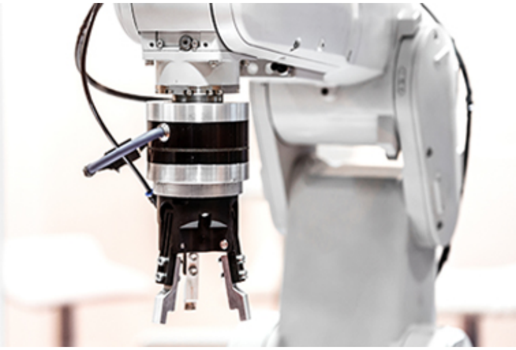
Electric and Autonomous vehicles

Daily life

Vacuum cleaners

HVAC units

Industrial

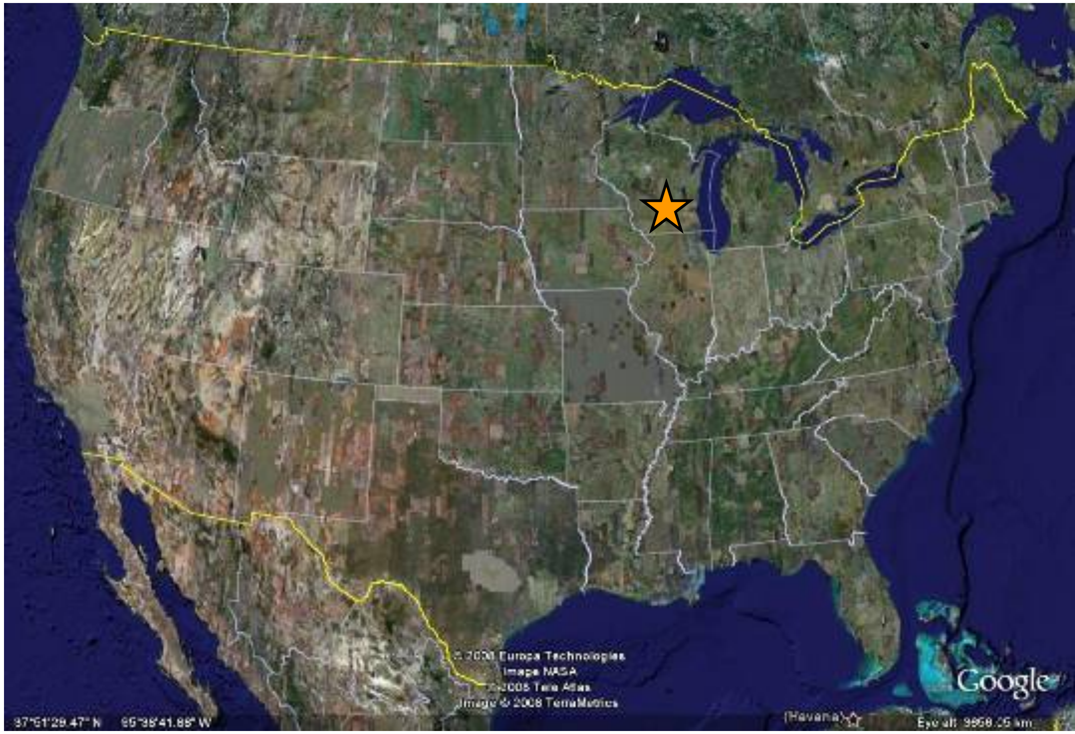


Robotics

Actuators

University of Wisconsin-Madison

- 2017 student enrollment: 43,820
- 2016-17 degrees awarded: 10,515
- 2017 research expenditure ranking (U.S.A.): 6th
- 2nd most for Federally Funded research



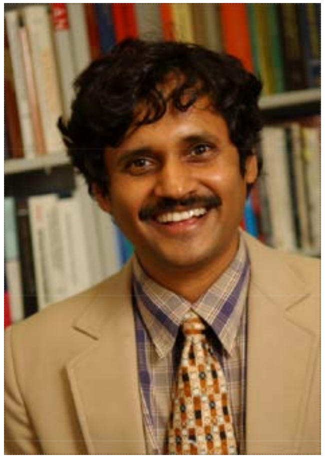
Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC)

- Innovative research for 37 years
  - Power electronics
  - Electric machines
  - Controls
- 87 sponsoring companies
- 4 tenured faculty
- 2 tenure-track faculty

- 60 on-campus students
- 70 off-campus students
- Degrees granted:
  - 425 MS Degrees
  - 160 PhD Degrees
- More than 510 alumni

WEMPEC Faculty

Prof. Tom Jahns



Prof. Giri Venkataramanan

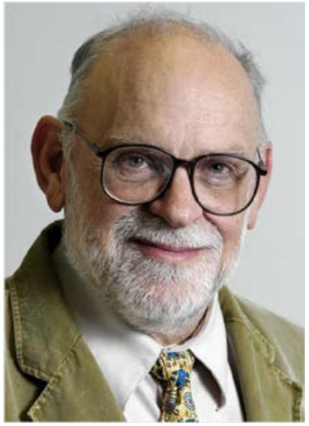
Prof. Bulent Sarlioglu

Prof. Dan Ludois

Prof. Eric Severson

WEMPEC Faculty, cont'd

Prof. Don Novotny
(Emeritus)



Prof. Tom Lipo
(Emeritus)

Prof. Bob Lasseter
(Emeritus)

WEMPEC Sponsors

ABB Inc., Drives and Power Products Division
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BAE Systems E&IS
Boeing Company
BorgWarner PowerDrive Systems
Carrier Corporation
CRRC Zhuzhou Institute Co., Ltd.
Daikin Industries
Danfoss Power Electronics
Delta Electronics, Inc.
DRS Power & Control Technologies, Inc.
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Eaton Corporation Research and Technology
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JSOL Corporation, Engr. Technology Div.
Kohler Company, Power Systems Div.
L-3 Communications Electronic Devices
L-3 Power Paragon, Inc.
LEM USA, Inc.
Lenze Americas
LG Electronics – Korea
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Nidec Motor Corp.
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Regal-Beloit Enabling Technologies Div
ResMed Motor Technologies
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Rockwell Automation - Standard Drives
Rolls-Royce Corp. N.A.
S & C Electric Company
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Smart Wires, Inc.
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Teledyne LeCroy
Texas Instruments Motor Control Kilby Lab
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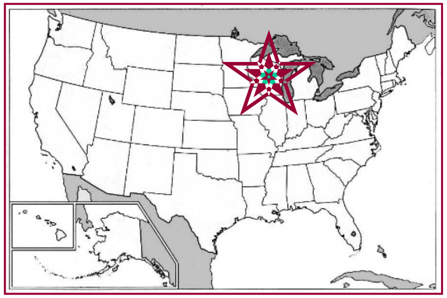
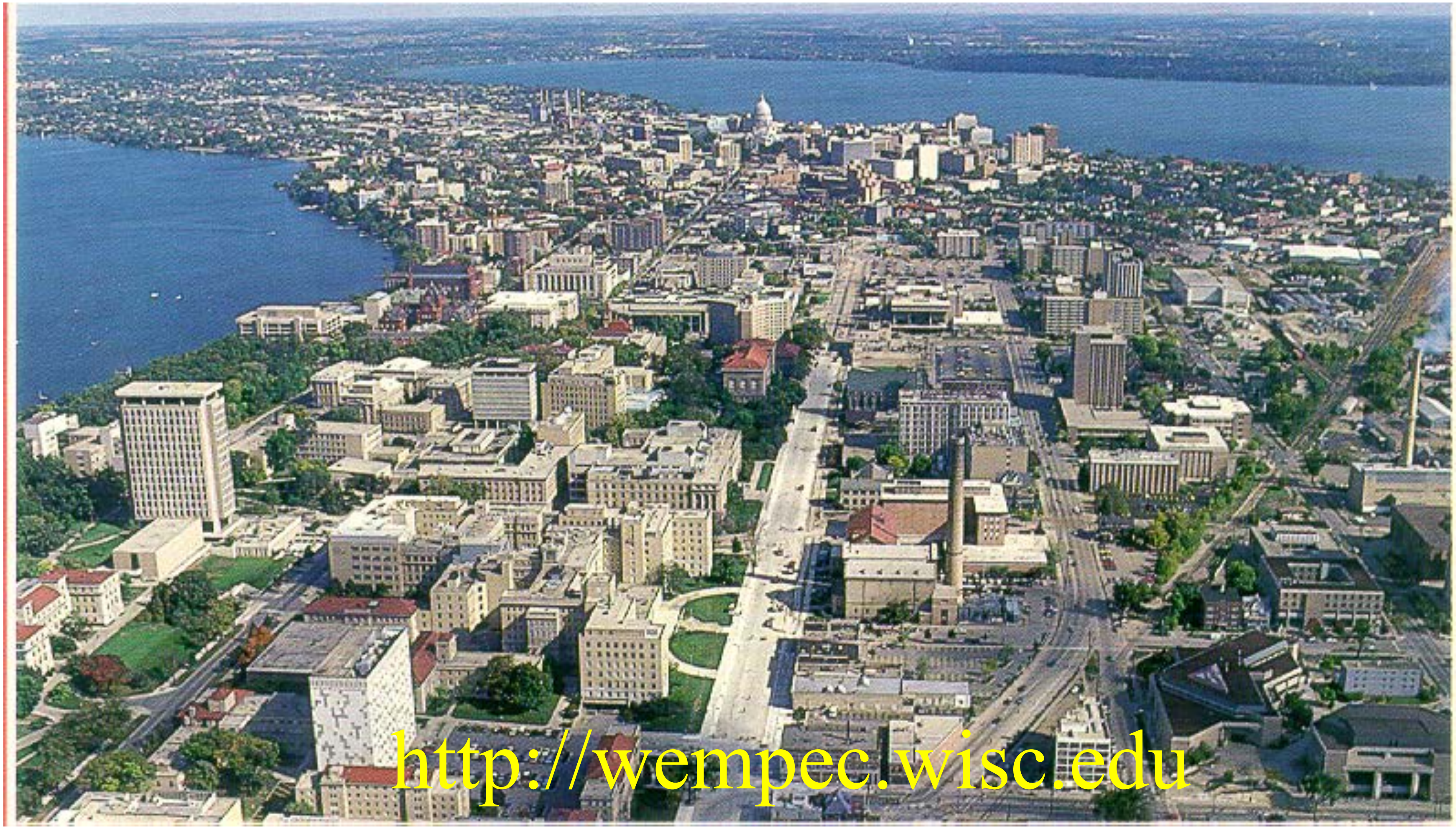
TMEIC Corporation
TMNA – Toyota Motor N.A. R&D
Toro Company
Trane Company Div. of Ingersoll Rand
Triumph Aerospace Systems
TRW Automotive
UNICO, Inc. Div. of Regal Corp.
UT Aerospace Systems
United Technologies Research Center
Wolong Electric Group Co., Ltd
Woodward
Yaskawa Electric America Inc.

University of Wisconsin - Madison





http://wempec.wisc.edu

Electrification of Aircraft

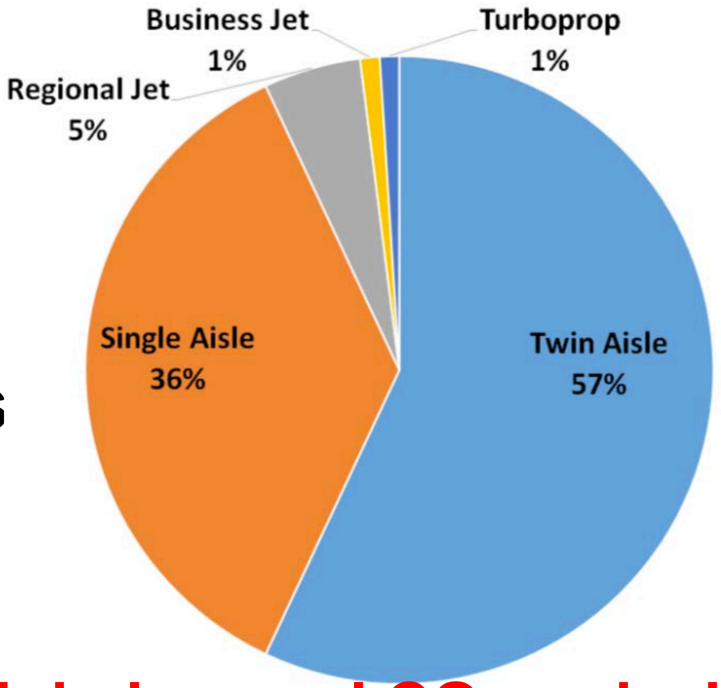
Current Status and Future Trends

Outline

1. Introduction and Motivations
2. Current Trends: power system, MES, etc.
3. Future Trends: e-taxi, e-propulsion
4. Enabling Technologies and Considerations
5. Conclusions

Potential Benefits of Electrification

- Benefits of Electrification
  - Reduced fuel consumption
  - **Reduced carbon emissions (highest priority)**
  - Increased reliability



2.0 - 2.5% of total global annual CO_2 emission

Electrification can potentially enable reduced fuel consumption and provide means to meet various requirements, such as environmental concerns, etc.

National Academies Press 2016 Commercial aircraft propulsion and energy systems research: reducing global carbon emissions
https://nap.edu/catalog/23490/ commercial-aircraft-propulsion-and-energy-systems- research-reducing-global-carbon

Outline

1. Introduction and Motivations
2. Current state-of-the art
3. Future Trends: e-taxi, e-propulsion
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More Electric Aircraft


B787

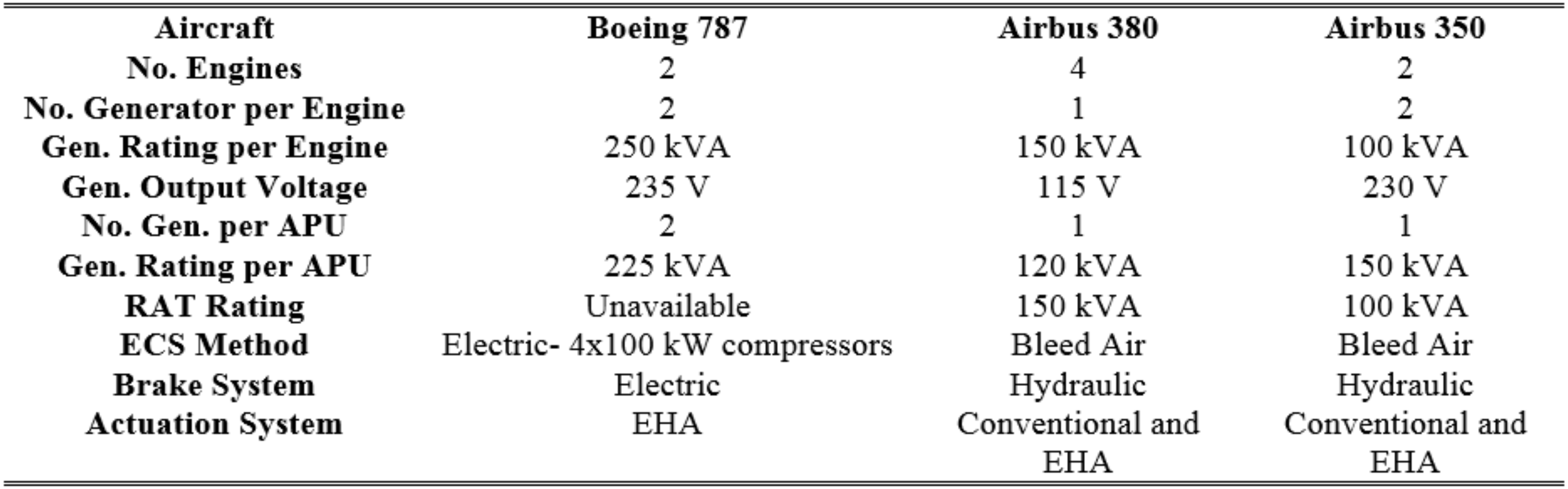

A350


A380

Trend is to use more electrical power for various subsystems

Comparison of Most Recent Commercial Aircraft Designs

Comparison of current MEA



Aircraft	Boeing 787	Airbus 380	Airbus 350
No. Engines	2	4	2
No. Generator per Engine	2	1	2
Gen. Rating per Engine	250 kVA	150 kVA	100 kVA
Gen. Output Voltage	235 V	115 V	230 V
No. Gen. per APU	2	1	1
Gen. Rating per APU	225 kVA	120 kVA	150 kVA
RAT Rating	Unavailable	150 kVA	100 kVA
ECS Method	Electric- 4x100 kW compressors	Bleed Air	Bleed Air
Brake System	Electric	Hydraulic	Hydraulic
Actuation System	EHA	Conventional and EHA	Conventional and EHA

All Electric Aircraft

Transitioning into using all electric propulsion systems

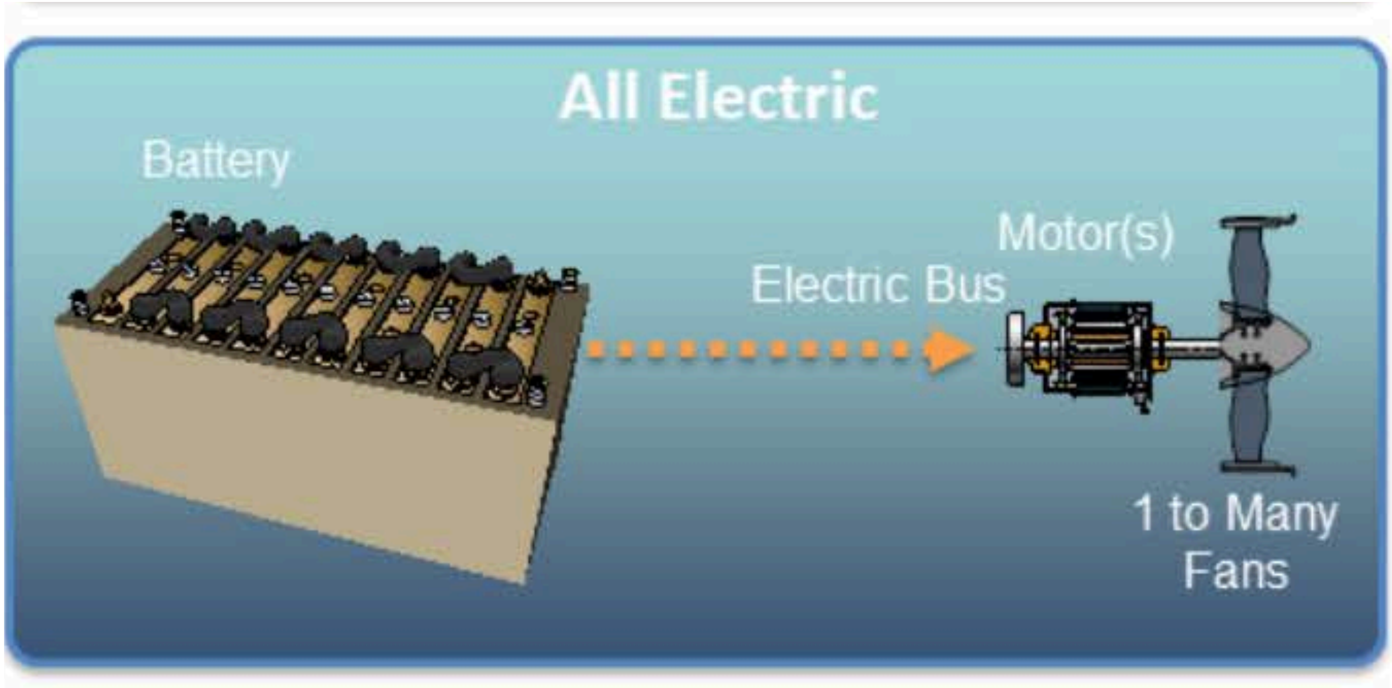
Outline

1. Introduction and Motivations
2. Current state-of-the art
3. **Future Trends: e-propulsion**
4. Enabling Technologies and Considerations
5. Conclusions

Future Trends: Electric Propulsion

- All Electric Propulsion (AEP)
  - Uses Battery and/or Fuel Cell
- Hybrid Electric Propulsion (HEP)
  - Series
  - Parallel
  - Series/parallel
- Turboelectric Propulsion (TEP)
  - Full
  - Partial

All Electric Propulsion (AEP)



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Airbus E-FAN All Electric

- Efan 2.0 with two seat trainer
- Weighs 500 kg
- **All electric using dual electric motors with total 60 kW (2 of 30kW)**
- : Lithium-ion 18650, with 207 Wh/kg per cel, total of 29 kWh

- Efan 4.0 with four seats, touring aircraft
- Engine used as range extender for Efan 4.0

www.airbusgroup.com

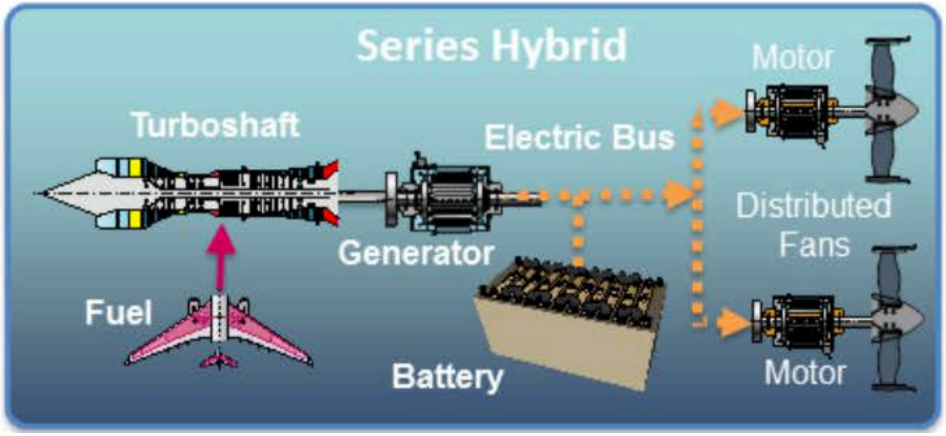
All electric using dual electric motors with total 60 kW (2 of 30kW)

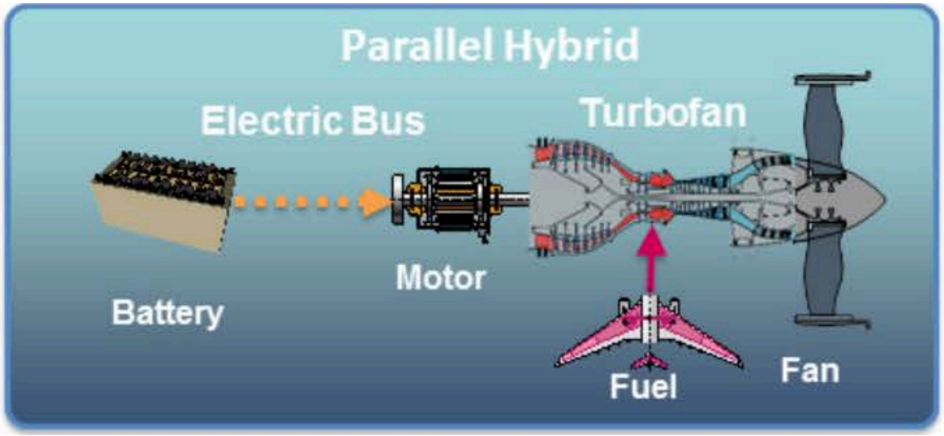
330 LE Siemens All-electric

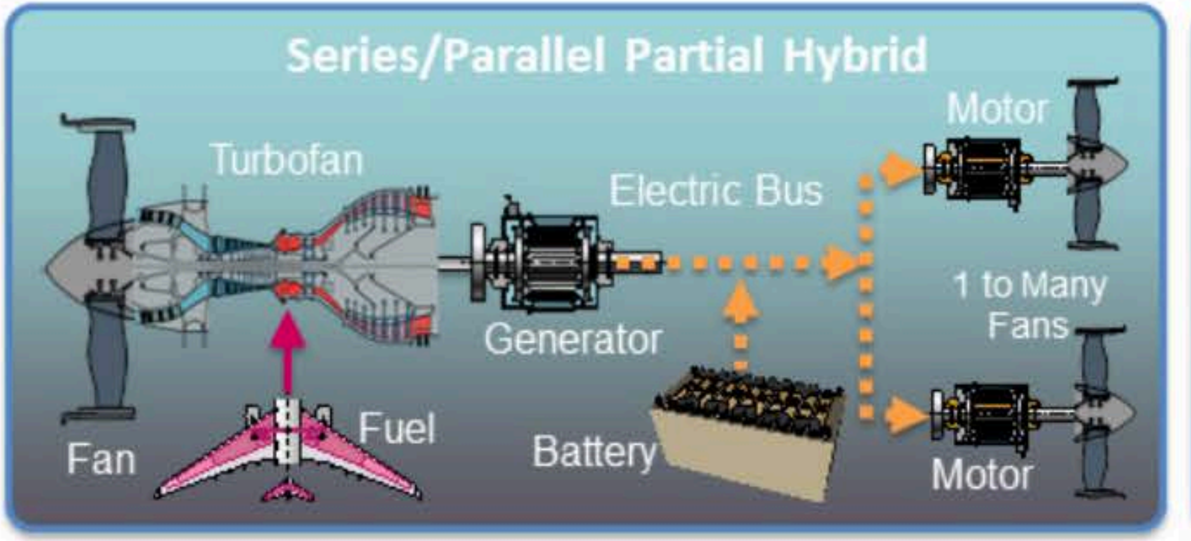
- Two passenger aircraft weighing approx. 1000 kg
- Single electric motor producing 260 kW and weighing only 50 kg
- 14 Li-Ion battery packs totaling 18.6 kWh.
- Target of 100 passenger craft with 1000 km range by 2030.

https://www.siemens.com

Hybrid Electric Propulsion (HEP)







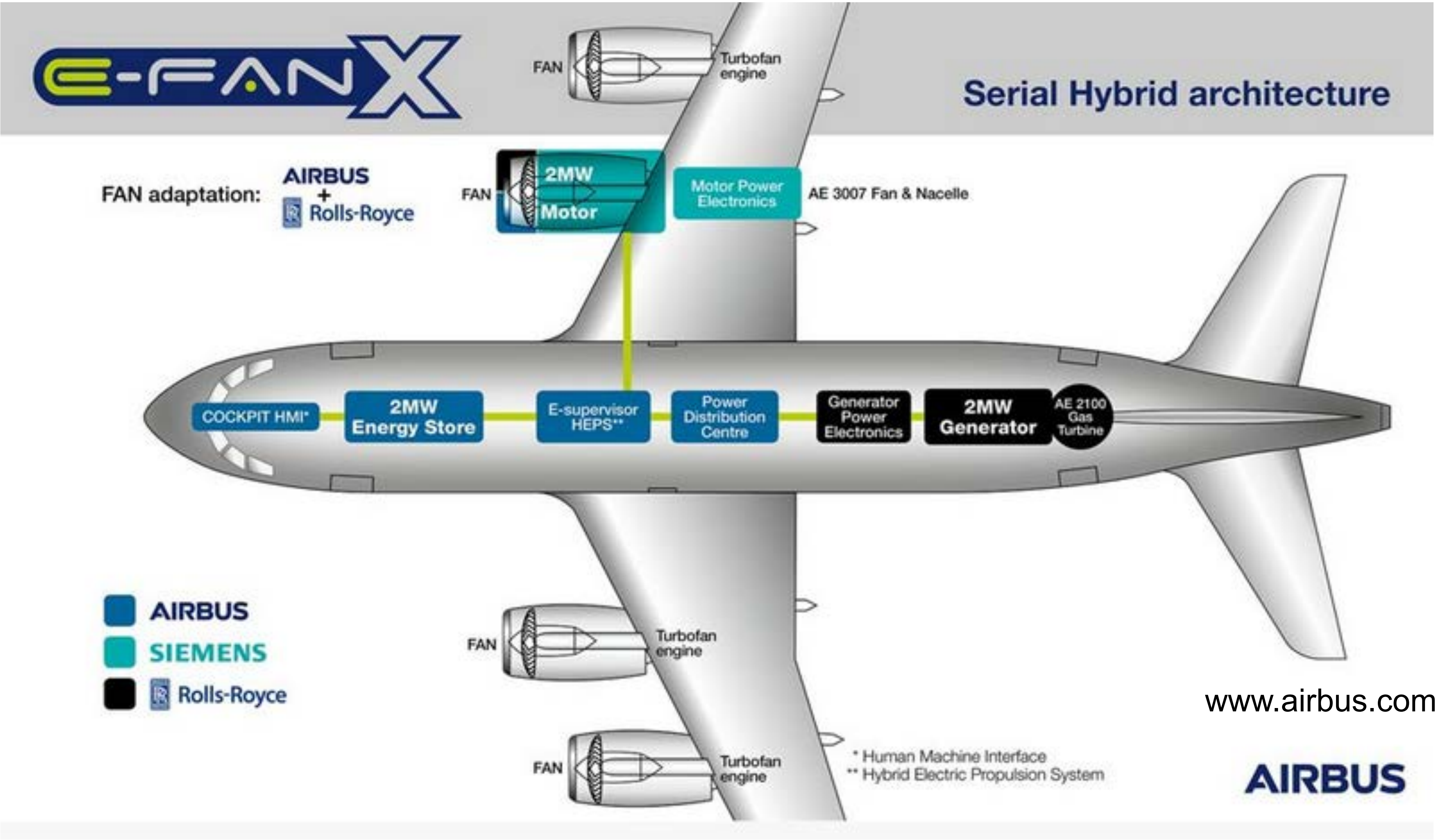
Batteries provide power to fans during one or more flight phases

Airbus E-FAN X Hybrid-electric propulsion

- Collaboration among Airbus, Rolls-Royce, Siemens
- Based on a 100-seat airplane
- One gas turbine replaced by a 2 MW electric motor
- Announced in November 2018, anticipate to fly in 2020

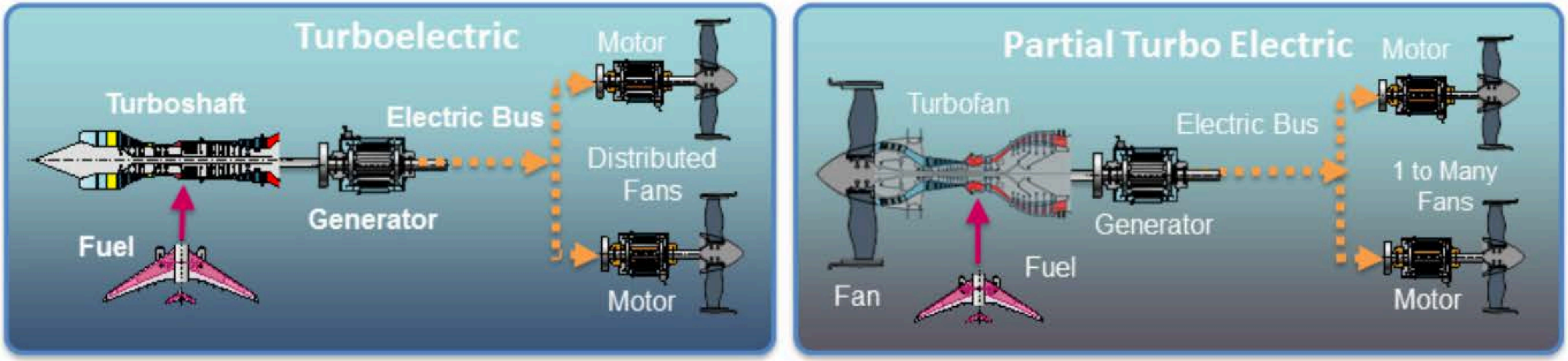
www.airbus.com

Future Trends: Hybrid-electric propulsion



www.airbus.com

Turbo Electric Propulsion (TEP)



No batteries are used in TEP.
Partial topology uses both fan connected to turbo engine and individual fans run by motors

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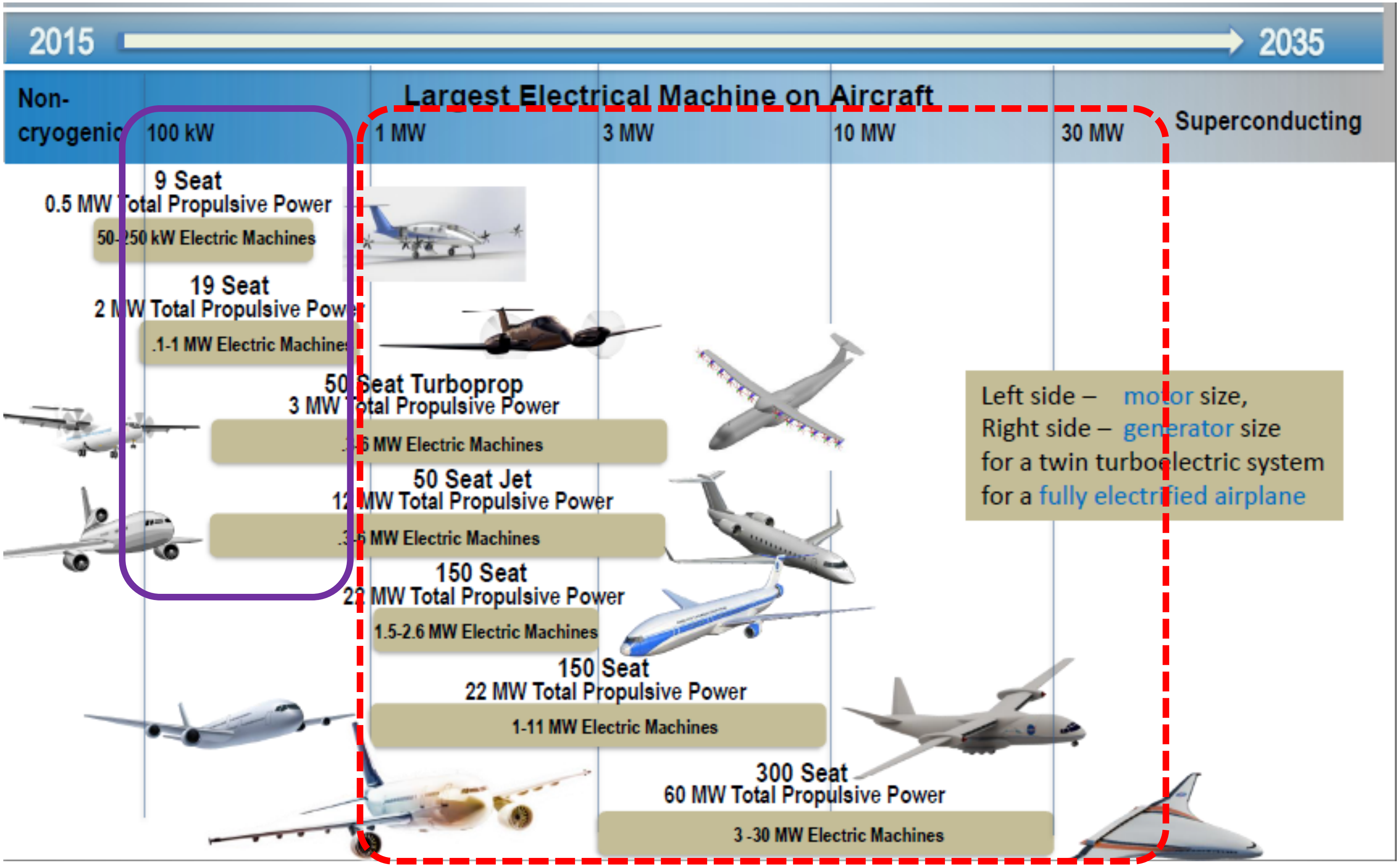
MW Class Motors

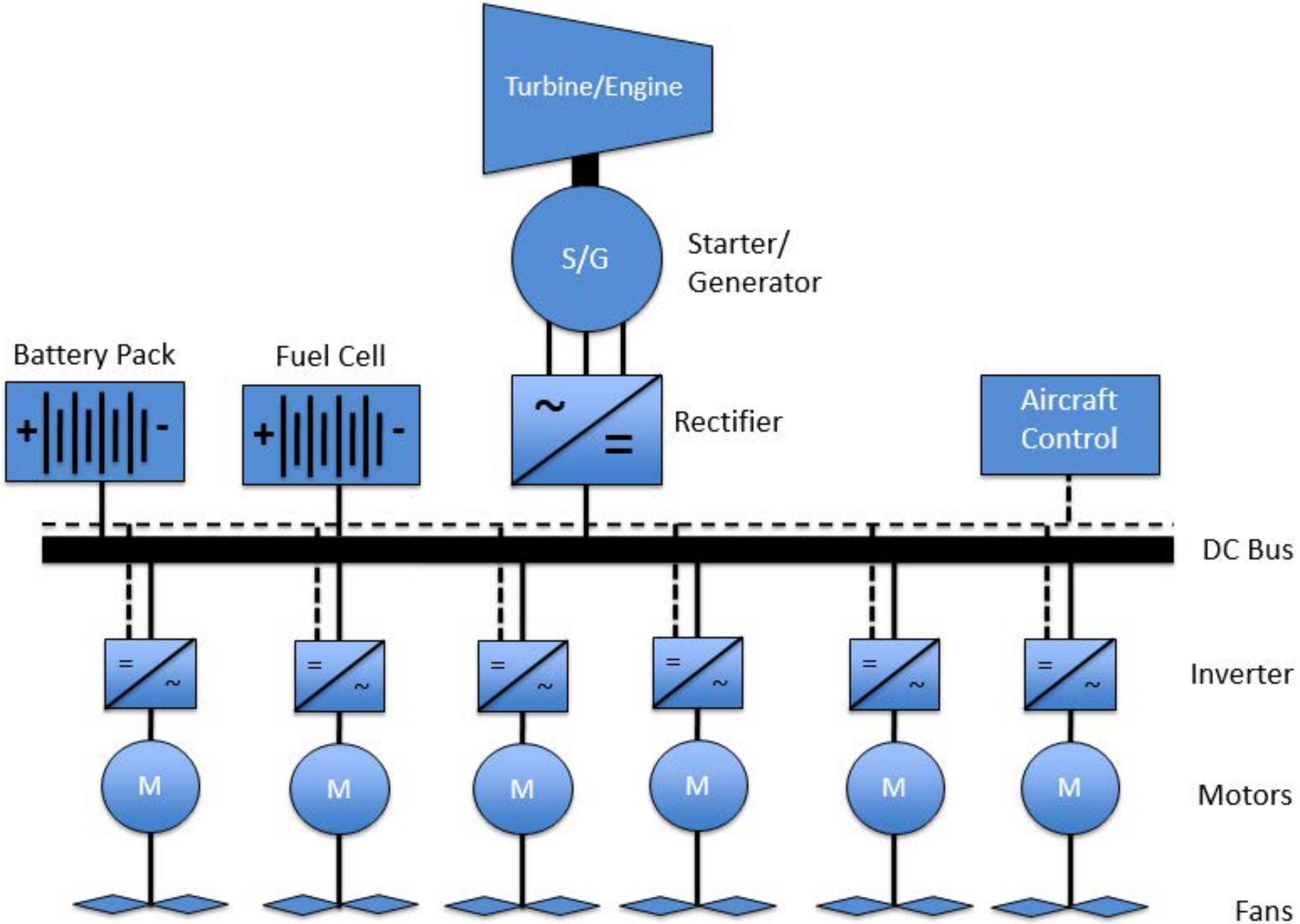
Papathakis, K. V.   https://ntrs.nasa.gov/search.jsp?R=20170009874



Left side – motor size,
Right side – generator size
for a twin turboelectric system
for a fully electrified airplane

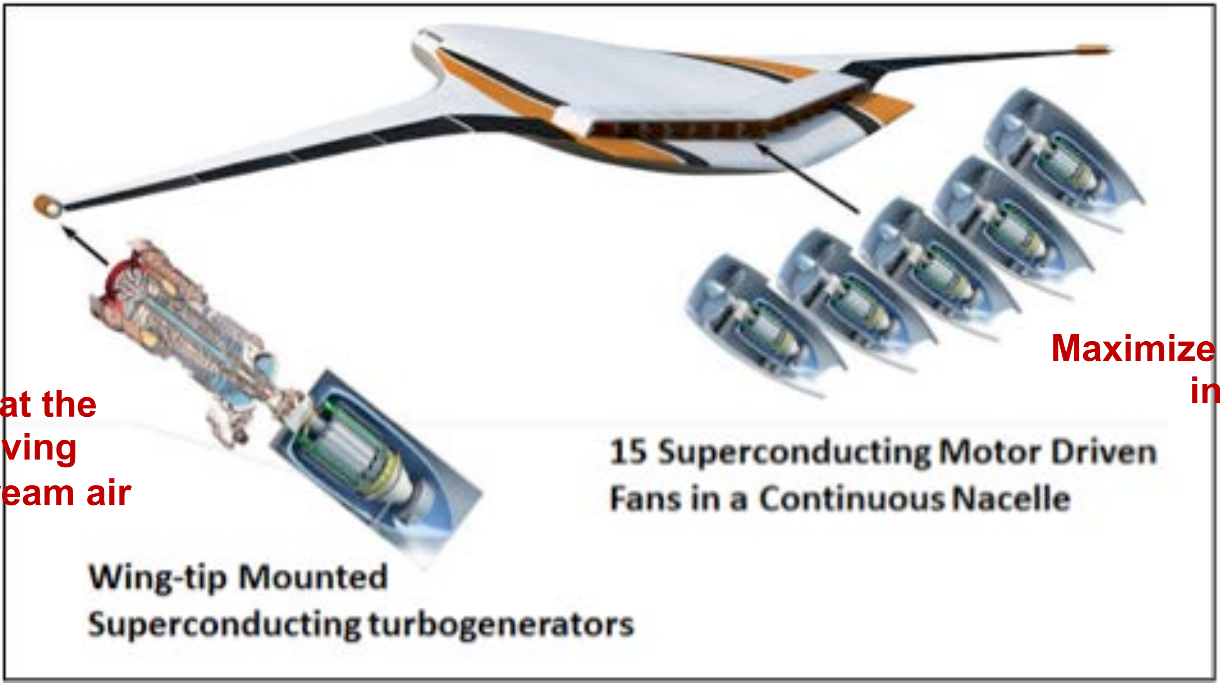
High power (MW class) machines are necessary for commercial aviation

Example: Series Hybrid Electric Propulsion Systems Architecture



NASA's Turbo Electric Propulsion

- Turboelectric Propulsion
  - NASA has proposed Turboelectric Distributed Propulsion (TeDP)
  - ~15 2-3 MW motors to propel machine from 2 massive engine/generator (~20 MW each)



Generator placed at the wing-tip for receiving undisturbed free-stream air

Maximize boundary layer ingestion

Future Trends: Distributed Propulsion

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Enabling Technologies and Considerations

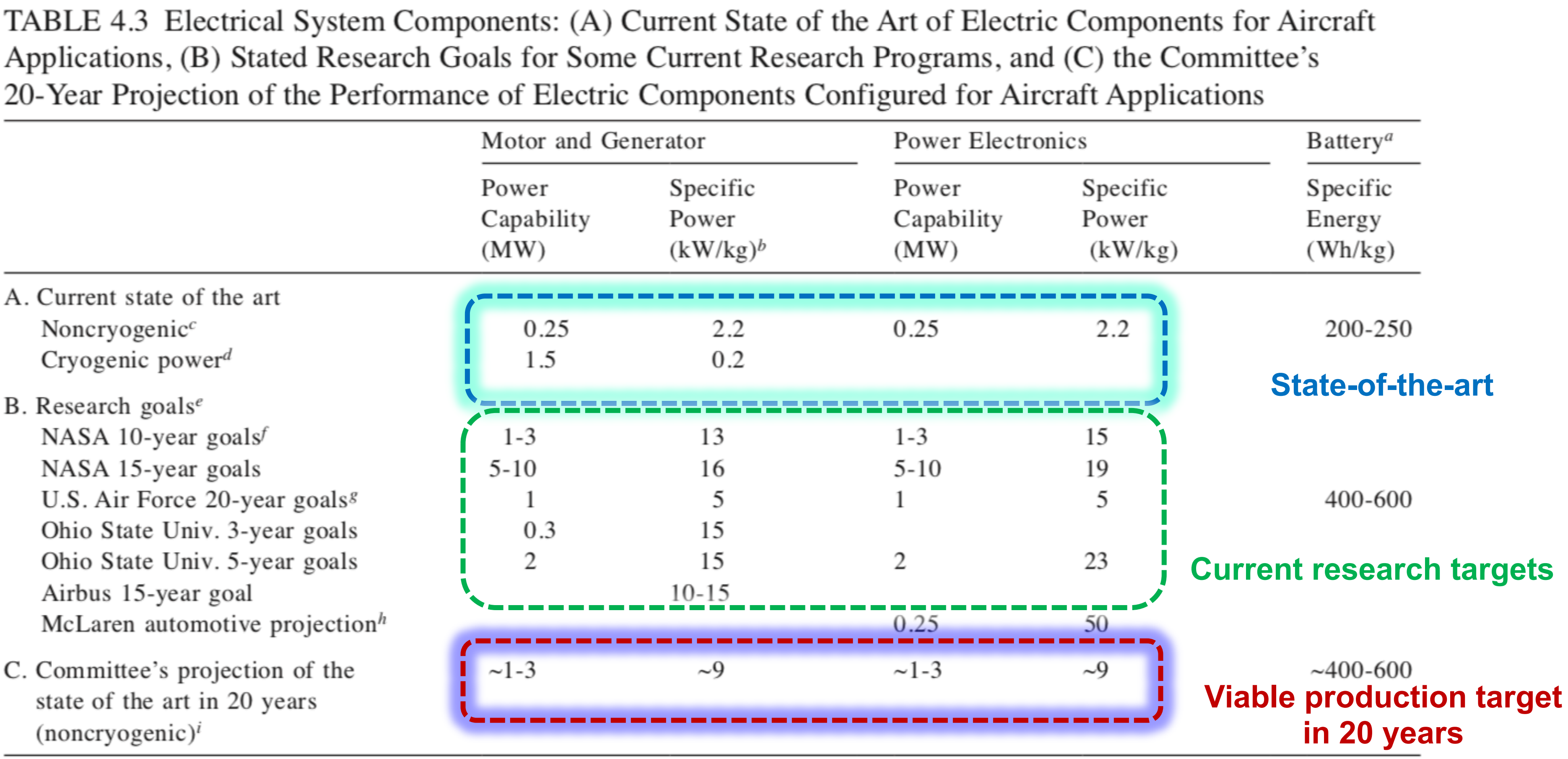

TABLE 4.3 Electrical System Components: (A) Current State of the Art of Electric Components for Aircraft Applications, (B) Stated Research Goals for Some Current Research Programs, and (C) the Committee's 20-Year Projection of the Performance of Electric Components Configured for Aircraft Applications

	Motor and Generator		Power Electronics		Battery[a]
	Power Capability (MW)	Specific Power (kW/kg)[b]	Power Capability (MW)	Specific Power (kW/kg)	Specific Energy (Wh/kg)
A. Current state of the art					
Noncryogenic[c]	0.25	2.2	0.25	2.2	200-250
Cryogenic power[d]	1.5	0.2			
B. Research goals[e]					
NASA 10-year goals[f]	1-3	13	1-3	15	
NASA 15-year goals	5-10	16	5-10	19	
U.S. Air Force 20-year goals[g]	1	5	1	5	400-600
Ohio State Univ. 3-year goals	0.3	15			
Ohio State Univ. 5-year goals	2	15	2	23	
Airbus 15-year goal		10-15			
McLaren automotive projection[h]			0.25	50	
C. Committee's projection of the state of the art in 20 years (noncryogenic)[i]	~1-3	~9	~1-3	~9	~400-600

State-of-the-art

Current research targets

Viable production target in 20 years

Research goal is set to achieve ~9 kW/kg specific power in both motor and power electronics

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Enabling Technologies and Considerations

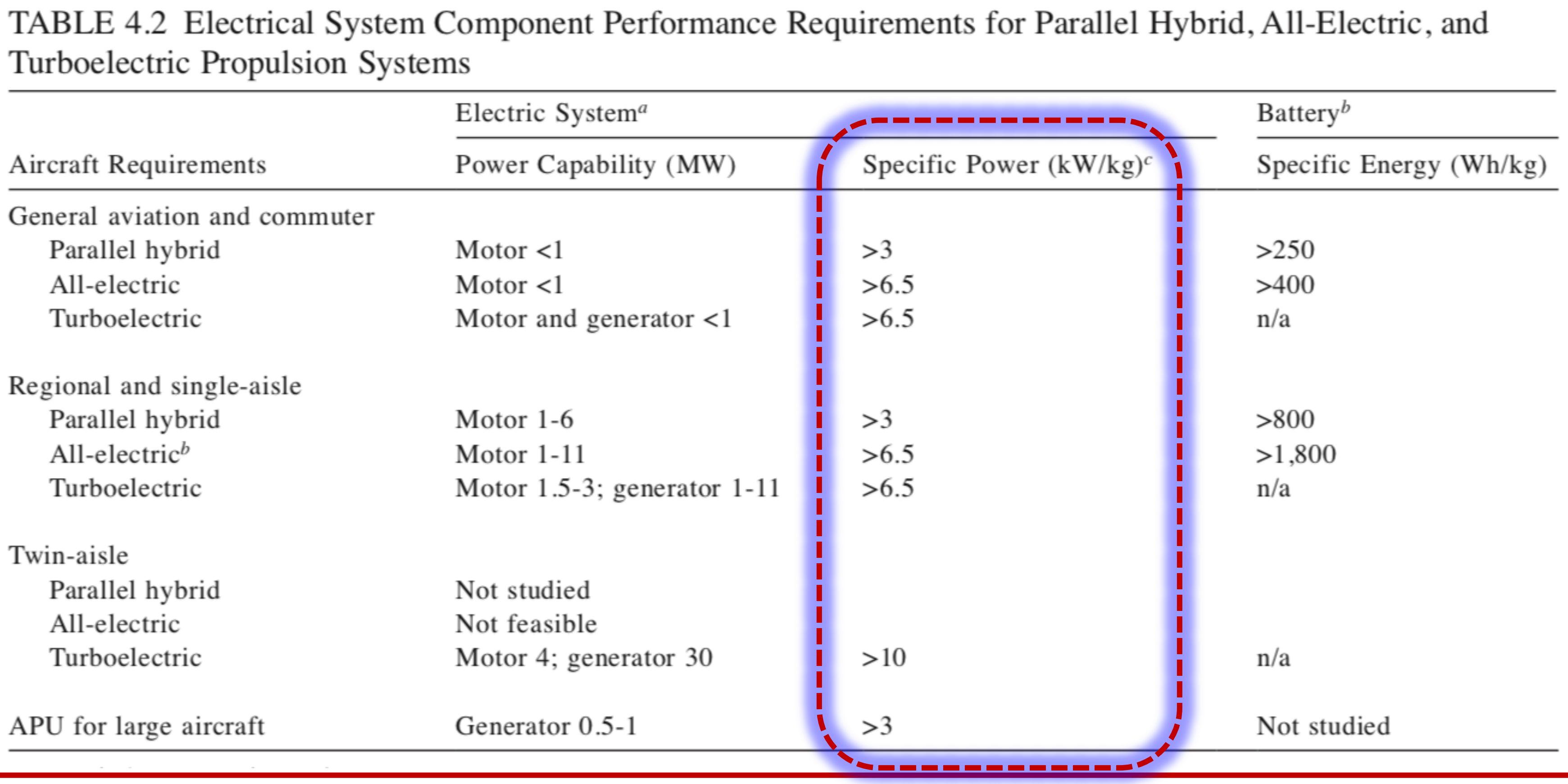

TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

	Electric System[a]		Battery[b]
Aircraft Requirements	Power Capability (MW)	Specific Power (kW/kg)[c]	Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator <1	>6.5	n/a
Regional and single-aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric[b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for large aircraft	Generator 0.5-1	>3	Not studied

Specific power for electric motor and power electronics needs to be higher than ~ 2.2 kW/kg state-of-the-art

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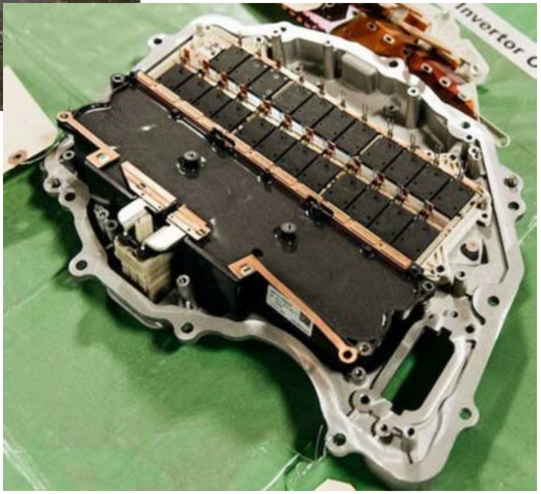
Needed Technologies

- Electric Machines
  - Particularly high speed, high power density and fault tolerant machines
  - MW level
  - Larger Voltage
- Power Electronics
  - High efficiency and high reliability
  - MW Level
  - Larger Voltage
- Batteries
  - Replacement of APUs
- Fuel Cells
  - Replacement of APUs

Electrification of Vehicles

Current Status and Future Trends

Application of WBG-based Motor Drive



- ~200 kW IPM machine replaces induction machine used in Roadster and Model S
- First production passenger vehicle to adopt SiC power switches in inverter

Tesla was the first to adopt SiC-based motor drive for EVs

DOE VTO
Electric Drive Technologies Consortium
FY20 Meeting

Integrated Motor and Drive for Traction Applications

Dr. Bulent Sarlioglu (PI) **Dr. Thomas Jahns (Co-PI)**

Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC)

University of Wisconsin-Madison

Jan 27, 2020

Major Goals and Objectives

The objective of the project is to design and test a high-performance traction motor and a high-efficiency traction inverter, and then to combine them into a state-of-the-art integrated motor drive (IMD) that requires only a single housing for electric vehicle applications.

The machine targets from DOE are:

1) Volumetric power density ≥ 50 kW/L for 100 kW peak power rating.

2) Machine cost ≤ 3.3 \$/kW.

The inverter targets from DOE are:

1) Volumetric power density ≥ 100 kW/L for 100 kW system peak power.

2) Inverter cost ≤ 2.7 \$/kW.

US DRIVE Roadmap Requirement

Requirement	AEMD
Peak power (kW)	100
Continuous power (kW)	55
Torque (N)	300
Maximum speed (rpm)	≤20,000
Battery voltage (V)	650 (525 - 775)
Switching frequency (kHz)	30 - 50
Power factor	>0.8
Maximum efficiency (%)	>97
Torque ripple (%)	5
Output current ripple – peak to peak (%)	≤5
Input voltage & current ripple (%)	≤5
Current loop bandwidth (kHz)	2
Maximum fundamental electrical frequency (kHz)	2
Mass (@ 5kW/kg)	20 kg

US DRIVE Roadmap Requirement

Cooling requirement	**AEMD**
Ambient operating temperature (℃)	-40 to +125
Storage temperature (℃)	-50 to +125
Cooling system flow rate, max (lpm)	10
Maximum partial size for liquid cooled (mm)	1
Maximum coolant inlet temperature (℃)	85

Peak torque requirement

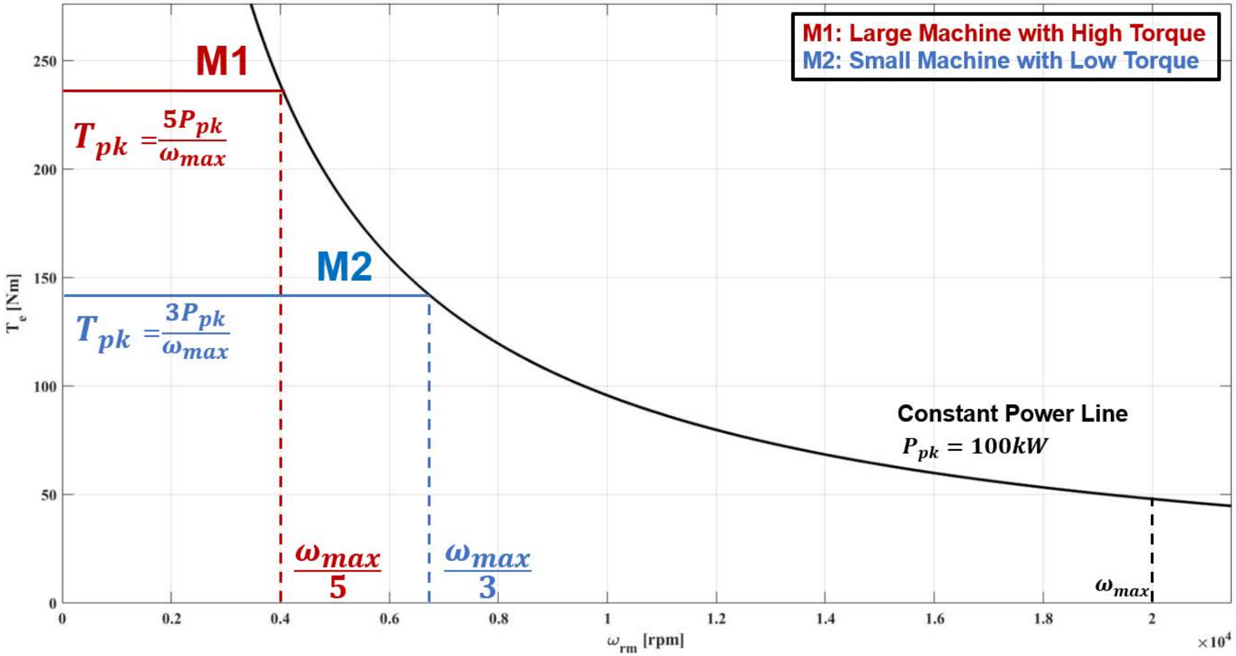
Torque (T_{pk}) Requirement From the US DRIVE Roadmap is 300 Nm

Maximum Speed (w_{max}) From the US DRIVE Roadmap is 20,000 rpm

- Peak power (P_{pk})is 100 kW
- Corner speed (w_{cn})
- $w_{cn} = \frac{P_{pk}}{T_{pk}} = \frac{100\ kW}{300\ Nm} = 333.33 \frac{rad}{s} \approx 3{,}200\ rpm$
- *Should we stay with peak torque of 300 Nm? What speed should we have the maximum torque?*
- *Should we stay with Maximum speed of 20,000 rpm?*

CPSR

- Peak power (P_{pk})is 100 kW
- Corner speed $w_{cn} = \frac{P_{pk}}{T_{pk}} = \frac{100\ kW}{300\ Nm} = 333.33\frac{rad}{s} \approx 3{,}200\ rpm$
- Constant power speed ratio CPSR = $\frac{w_{max}}{w_{cn}} = \frac{20{,}000\ rpm}{3{,}200\ rpm} = 6.25$
- Machine size is determined by the peak torque requirement.
- CPSR is relatively high. Average CPSR for commercialized vehicle is around 3.



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CPSR

Source	Manufacturer's manual/brochure	⬛
	Secondary resource	🟧
	Technical paper	🟦
	Caculation	🟥

Manufacturer	Name	Year	Ppk [kW]	Tpk [Nm]	Axle Ratio	Motor Corner Speed [rpm]	Motor Peak Speed [rpm]	CPSR
Hyundai	IONIQ Electric	2020	100	295	7.412	3237	10015	3.09
Hyundai	Kona Electric 39kWh Standard Battery	2018	100	395	7.981	2418	9826	4.06
Hyundai	Kona Electric SEL	2019	150	395	7.981	3626	10587	2.92
BMW	i3	2019	125	250	9.665	4775	11500	2.41
BMW	i3 S	2019	135	270	9.665	4500	12000	2.67
Jaguar	I-Pace	2019	147	348	9.04	4036	12723	3.15
Nissan	Leaf S	2019	110	320	8.19	3283	9908	3.02
Nissan	Leaf S PLUS	2019	160	339	8.19	4508	10856	2.41
Nissan	Leaf 2012	2012	80	280	8.19	2100	10000	4.76
Audi	E-tron 55 Quattro (Front)	2019	125	247	9.205	4833	12815	2.65
Audi	E-tron 55 Quattro (Rear)	2019	140	314	9.083	4258	12645	2.97
Chevrolet	Bolt EV	2019	150	360	7.05	3979	8201	2.06
Chevrolet	Bolt EV	2017	150	360	7.05	3979	8810	2.21
Chevrolet	Spark EV 2016	2016	105	444	3.87	2258	4500	1.99
KIA	Niro EV	2019	150	395	8.206	3626	10889	3.00
Volkswagon	E-Golf	2019	100	214	3.61	4459	12000	2.69
Tesla	Model X 100D (Front PM)	2019	193	330	9.325	5585	18000	3.22
Tesla	Model X 100D (Rear IM)	2019	193	330	9.325	5585	18000	3.22
Tesla	Model X P100D (Rear IM)	2019	375	660	9.734	5426	18300	3.37
Tesla	Model S, Non performance (Front PM)	2019	193	330	9.325	5585	18000	3.22
Tesla	Model S, Performance (Rear IM)	2019	375	650	9.734	5509	16000	2.90
							CPSR Avg	**2.95**

Switching Frequency Limit

Switching Frequency From the US DRIVE Roadmap

- **30 kHz ~ 50 kHz** switching frequency is in the US DRIVE Roadmap
- Is it ok to use 100 kHz switching frequency or even higher ?
- We are using dc/dc converter, should the given switching frequency be applied to the dc/dc converter also or just for the inverter?
- Normally dc/dc converter has higher switching frequency than the inverter

EMI Requirement ?

No Specified EMI Regulation in the US DRIVE Roadmap

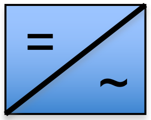
- Is there an EMI regulation that we need to meet?
- If so, which regulation should be considered?

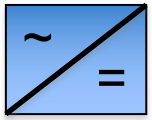
Enabling Technologies and Considerations

- Perhaps the most fundamental piece to enabling electrification:

Power Converters

- Key Requirements:
  - High Efficiency
  - High power density
  - Reliable
  - Long Lifetime





But, HOW?

Design Options for WBG

Option 1. Same Frequency of Si Design

- Reduced on-state and switching losses, i.e. increased efficiency
- Energy usage savings achieved over the life of the product
- Increased Power Density

Option 2. Increased Frequency Design

- Smaller filter, i.e. C and L and packaging
- Increased Power Density

Opportunities - WBG Devices

- Smaller Thermal Design
  - Smaller cooling components (fans, pumps, heatsinks, baseplates)
- Optimization of Converter Design
  - Use a combination of increased frequency, reduced cooling, reduced filtering
- Weight Reduction Savings
  - Mechanical packaging (less housing material, machining, etc.)
  - Less weight is less specific fuel consumption for vehicle applications (air, sea, and land)

Even though cost of WBG devices is currently high, there are systems benefits to consider

Challenges with WBG Devices

- Manufacturing
  - Substrate Cost
  - Defect Density - Reliability
    - No field data
- Low Ratings
  - Voltage and Current Rating of GaN devices
  - Current Rating of SiC devices
- Cost
- Knowledge base
  - Do we fully understand these devices for implementation to real products?

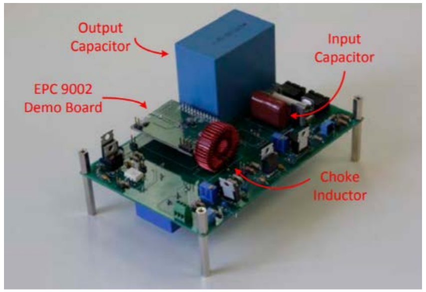
A Manufacturing Institute recently formed by DOE to solve device level issues

Design Considerations

- Gate Drive
  - Si IGBT requires 15 V gate drive
  - SiC requires ~20 V gate drive
  - GaN requires ~5 V gate drive
- Parasitic Inductances
  - Due to high dv/dt and di/dt, SiC and GaN design requires more knowledge on parasitic effects
  - Circuit layout important to minimize parasitic elements
- EMI
- Thermal

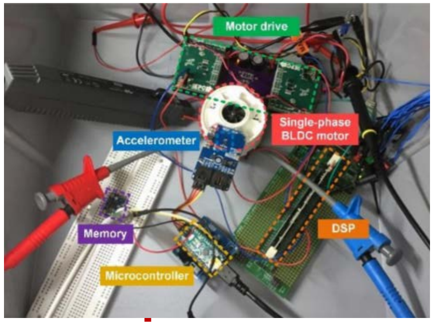
Some of these areas are our research focus to develop future technologies

WBG Research at WEMPEC



GaN-based boost Converter

- 24V to 80V
- 400 kHz with > 95% efficiency
- **Analysis on deadtime effect**



High-speed GaN motor drive

- Single-phase BLDC motor
- Speed > 60,000 rpm
- Vibration measurement
- Switching frequency > 100 kHz
- **Torque ripple minimization technique**

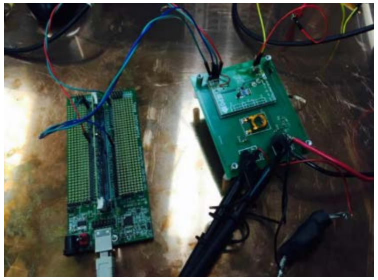
2011

2015

2017

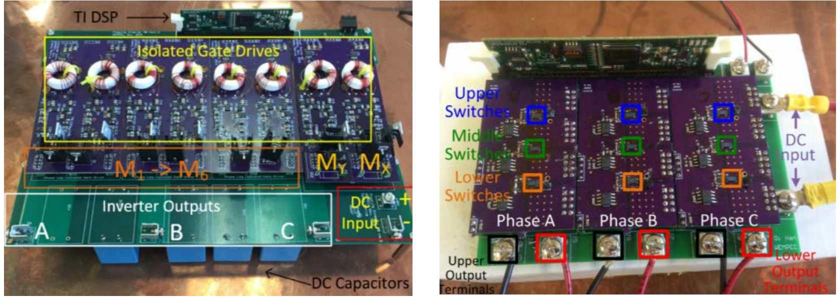
SiC-based Buck Converter

- 1200V / 24A SiC device
- **Turn-off overvoltage analysis**



GaN-based ZVS POL Converter

- 24V to 3.3V
- 2.7 MHz with > 91% efficiency
- **Zero-voltage switching**



WBG EMI/EMC Analysis

- GaN-based motor drive tested up to 200 kHz
- **Two new motor drive topologies are proposed**

Early research work on WBG

- **DC/DC converter**
- **Performance analysis**
- **Efficiency compassion with Si counterparts**
- **Gate drive and deadtime analysis**

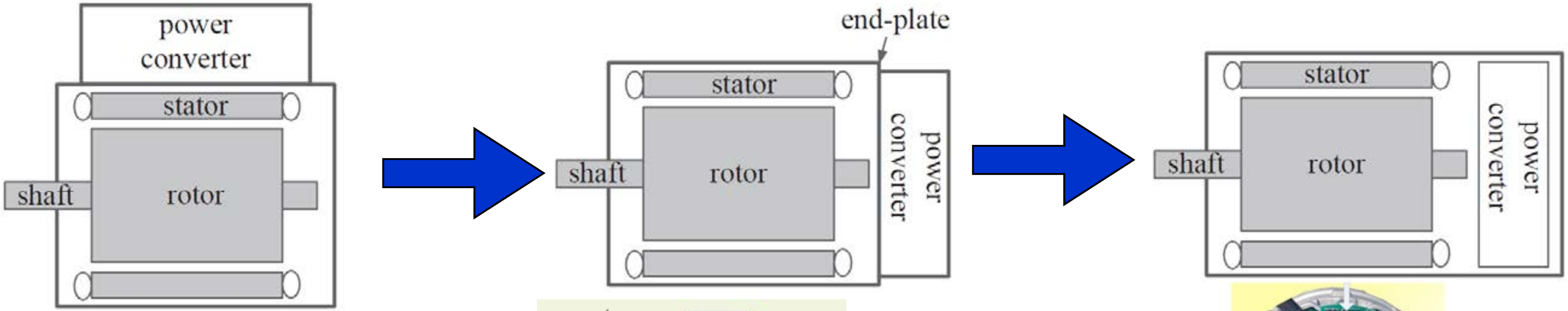
Current research work on WBG

- **High-switching frequency (>100kHz)**
- **High-speed motor drive (>60,000rpm)**
- **EMI/EMC analysis**
- **Novel topologies**

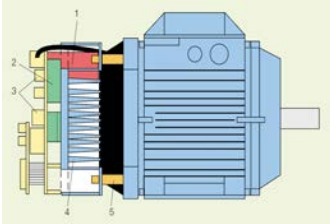
Future research work on WBG

- **Integrated motor drive with WBG**
- **VSI / CSI**
- **EMI/EMC analysis**
- **Thermal analysis**

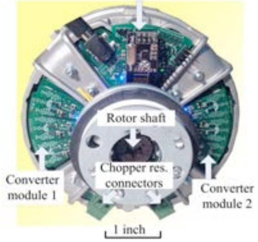
Motor Drive Trends: Integrated Motor Drive



Commercial Danfoss drive



ABB, 1996



GaN-based VSI IMD, 2015

External radial mount [71-75]

External axial mount [76-79]

Internal axial mount [81-86]

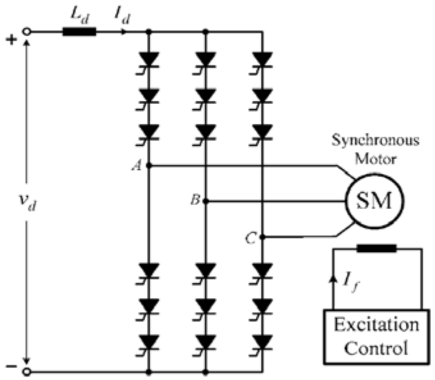
- IMD **promotes** the adoption of motor drive for electric machines
  - Easier installation, higher power density, low cable cost, etc.
- IMD **relieves** some major issues with WBG-VSI
  - Overvoltage due to very short cables
  - EMI by containment within IMD housing
- IMD **does not** solve some issues with WBG-VSI
  - Challenging short-circuit overcurrent protection
  - High winding *dv/dt* stress
- IMD **exacerbates** some issues with WBG-VSI
  - Temperature limitation and mechanical reliability of dc-link capacitor
  - Drive electronics electromagnetics susceptibility

IMD using VSI-topology cannot solve many of the issues with conventional motor drives using long cables. In addition, it can result in other more significant issues that make IMD unappealing.

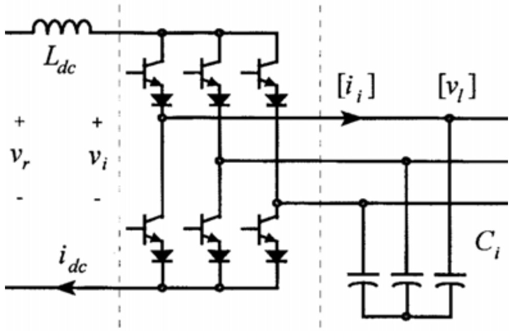
Question: Is VSI the only choice?

Alternative Topology: Current-Source Inverter

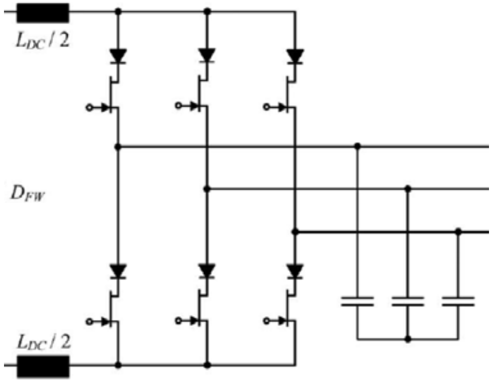
CSI requires switches of RVB capability



50/60 Hz
Thyristor-based CSI [101]



f_{sw}=10 kHz
Si-IGBT + Diode CSI [24]



f_{sw}=200 kHz
SiC-JFET + Diode CSI [25]

- The use of non-latching devices with gate-turn-off capability **simplifies** CSI commutation
- Increasing the switching frequency **significantly reduces** the CSI passive component size, enabling CSI to be **competitive** in low-voltage motor drive applications
- WBG-CSI's high-quality output voltage/current waveforms, use of rugged dc-link inductor, and inherent fault-tolerance make it **possible to relieve** many issues associated with WBG-VSI
- However, CSIs require reverse voltage blocking (RVB) power switches

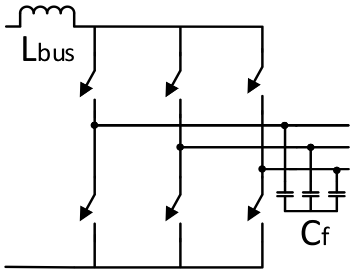
WBG devices open enticing opportunities for higher performance CSIs but RVB switch requirement poses a technical challenge

CSI-IMD for HVAC Application

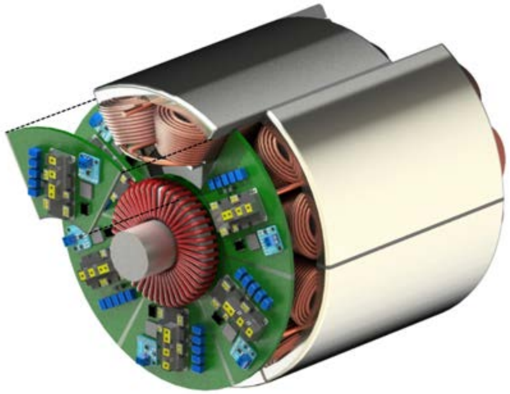
PM Motor Drive

WBG Switches

CSI



Next-Generation Integrated Motor Drive (IMD)



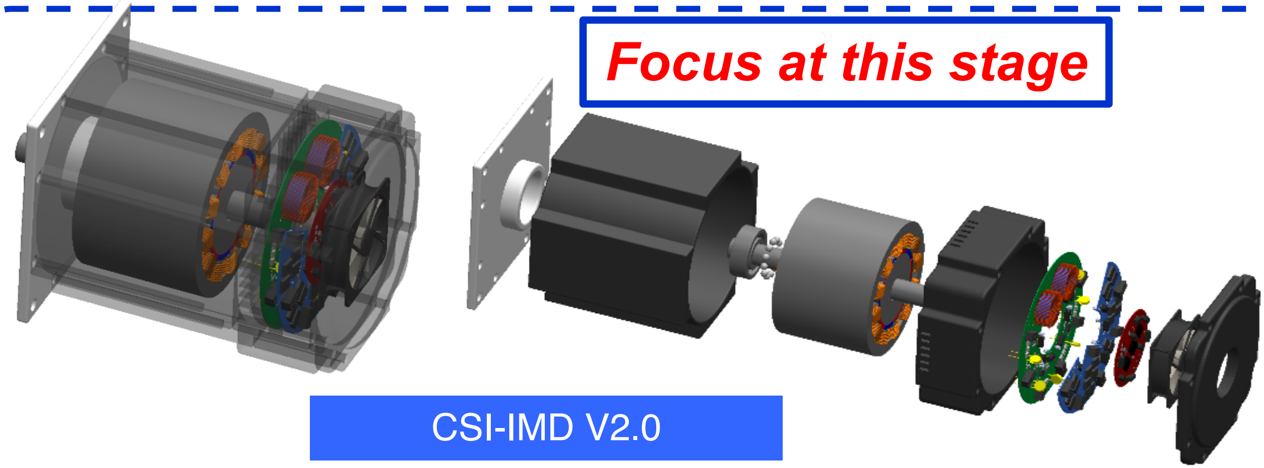
- WBG-CSI-IMD provides several powerful advantages
  - High-freq. switching shrinks passives
  - Eliminates temp.-sensitive capacitors
  - CSI suppresses EMI and cable voltage overshoot
  - Higher fault-tolerance, etc.
- Opens door to impressive increases in key performance metrics

CSI-IMD Performance Metrics

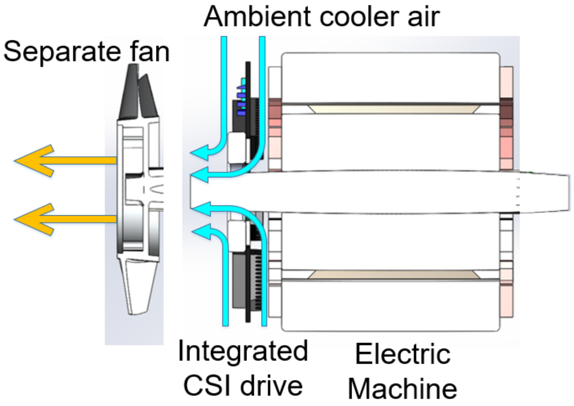
Metric	State-of-the- Art VSI	Proposed CSI-IMD	Improvement
Inverter Power density @ 3 kW, 230V-3ph	*1.6 kW/L*	*8 kW/L*	*5.0x*
Specific Power @ 3 kW	*2.72 kW/kg*	*7 kW/kg*	*2.5x*

Two Versions of CSI-IMD

Focus at this stage

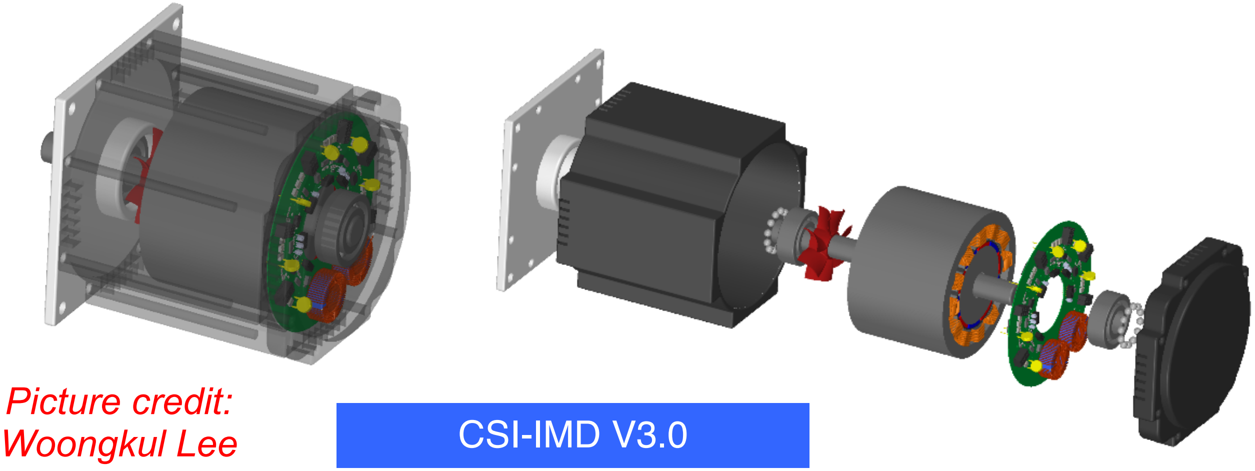


CSI-IMD V2.0



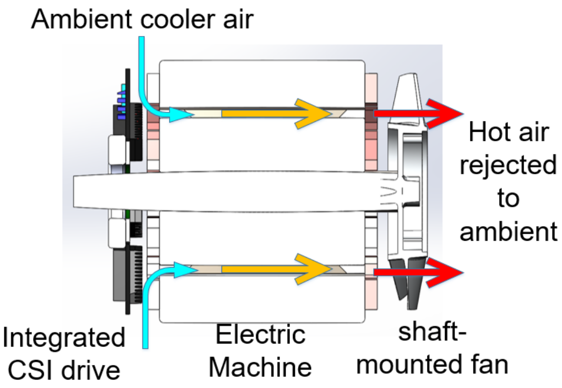
External fan

- Mother-daughterboard configuration for power stage
- CSI mounted in adjacent axial chamber with external fan



Picture credit: Woongkul Lee

CSI-IMD V3.0

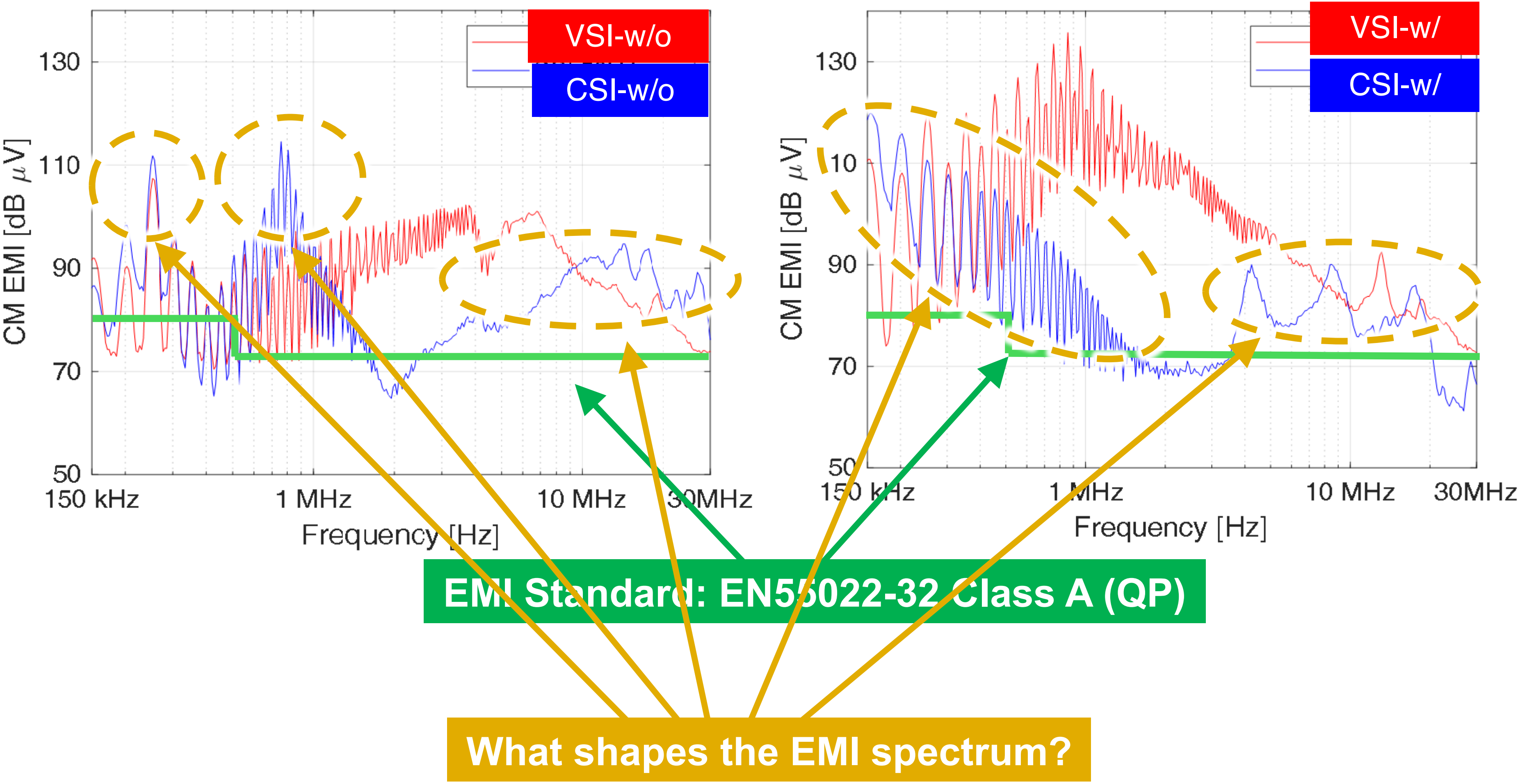


Shaft-mounted fan

- Single-board design for power stages
- Internal axial mounted CSI with shaft-mounted fan

Conducted CM EMI of WBG-CSI

Measured WBG-CSI/VSI CM EMI w/ and w/o shielded cable



EMI Standard: EN55022-32 Class A (QP)

What shapes the EMI spectrum?

How can the EMI spectrum be accurately estimated?
How can the EMI spectrum be reduced to comply with EMI standards?

Conducted CM EMI of WBG-CSI needs to be further investigated

Enabling Technologies and Considerations

- Machine Design Considerations
  - Material limitations/innovations
    - Improved steel saturation characteristics to reduce core weight /volume
    - Better PM material to increase airgap flux density and avoid demagnetization
    - Innovative winding configurations/material to increase current density and reduce losses/heat
  - Others?
    - Insulation material to handle higher voltages without partial discharge
    - Novel machine designs using existing materials

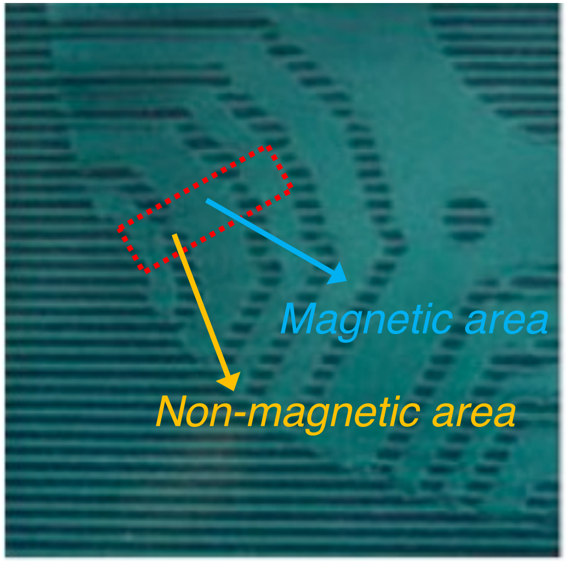
Leaps in development of new materials is key in enabling high power density traction motors for MEA

Materials – Dual Phase

- Dual phase material with both magnetic and non-magnetic properties in one material
  - Local heat treatment to change magnetic properties
- Eliminates electromagnetic bridges in IPM or Synchronous reluctance machines and enhances structural strength
- Suitable for high-speed operation

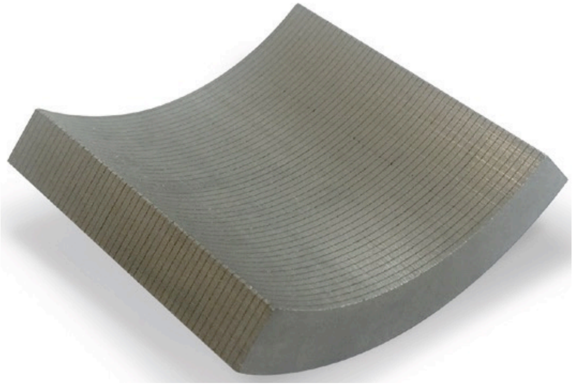
Decoupled electromagnetic and mechanical rotor design

US Patent: 9,634,549 B2 - GE



Materials – Laminated Magnets

- Laminated magnets
  - Each lamination can be reduced up to 0.5 mm thick
  - Insulation thickness < 20 μm
  - Eddy current loss reducing of up to 300% reported compared to conventional magnet



http://www.arnoldmagnetics.com

.5mm L20
96% magnet fill fraction

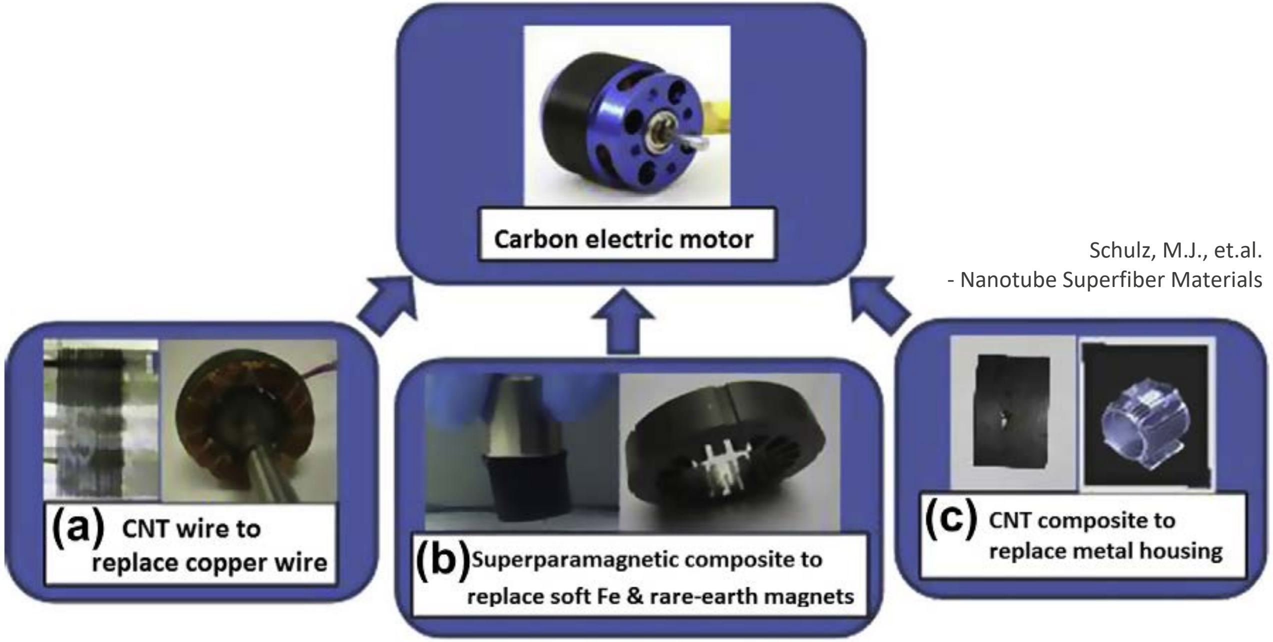
1mm L20
98% magnet fill fraction

1mm L40
96% magnet fill fraction

Low joule losses, suitable for high frequency, high efficiency applications

Materials – Carbon Composite

- Carbon composite material can substitute many components in machines
  - Winding – Carbon nanotube wire
  - Steel, Magnets – Superparamagnetic nano-particle polymer matrix
  - Stator Housing, rotor sleeve – Carbon Fiber Composite



Schulz, M.J., et.al.
- Nanotube Superfiber Materials

Ferromagnetic behavior of hybrid magnetite–CNT nano-fillers

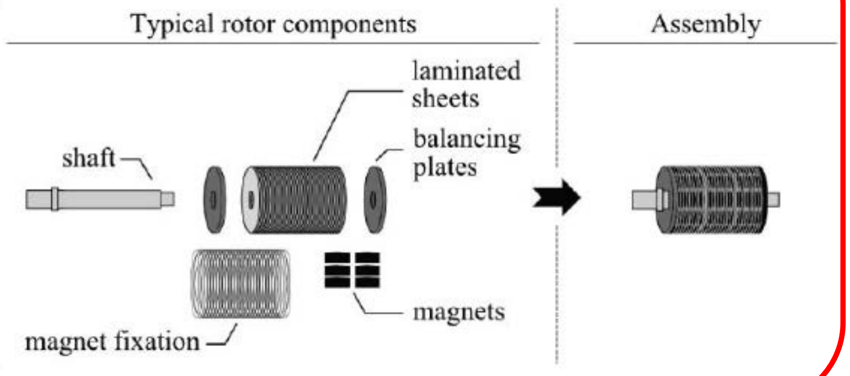
S.G. Prolongo et. al. , Karlsruhe Institute of Technology
Proc. Composites Part B: Engineering

Low EM losses, light weight, high structural strength

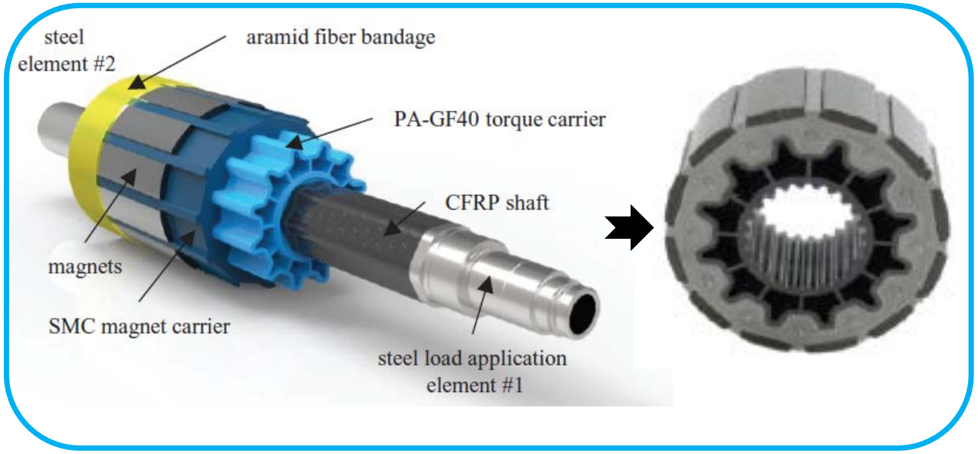
Advanced Manufacturing

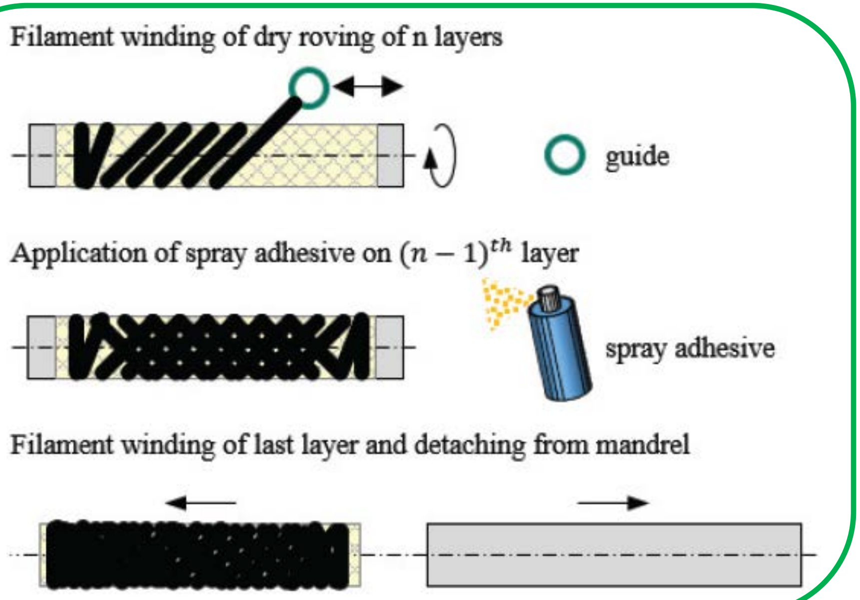
- Rotor core must address two functionalities – structural, magnetic
- Separating the functionalities and can produce light weight motors

Conventional Manufacturing



- ➢ Light weight polyamide (PA) plastic and carbon fiber (CF) combination for structural
- ➢ PA infused SMC for magnetic

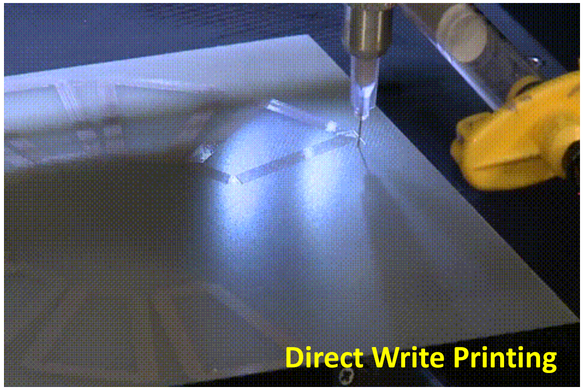


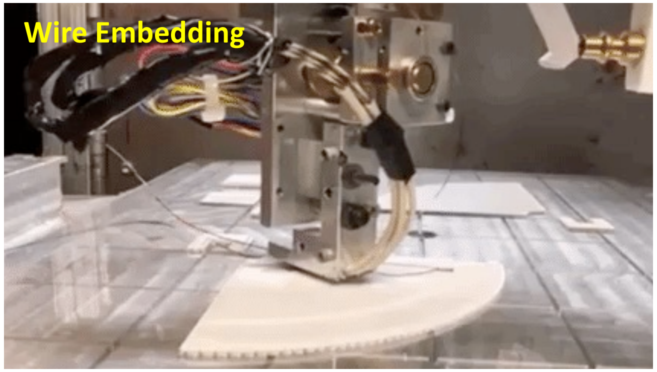


Simon-Frederik Koch et.al. – Procedia CIRP 66 (2017)

Advanced Manufacturing

- Additive manufacturing technologies can eliminate extensive machining, expensive tooling and structural weight reduction
- Facilitates innovative designs that can be compact and robust
- Produce high fill factors with embedding coils into multi material
- Allows rapid prototyping

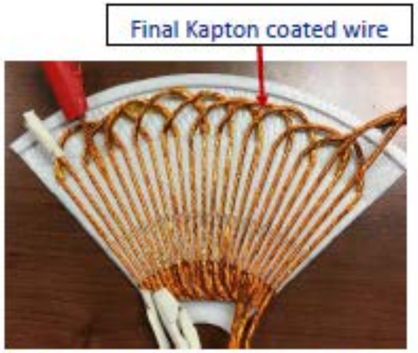




Papathakis, K. V. https://ntrs.nasa.gov/search.jsp?R=20170009874

Stator design: Launch Point & UTEP

3 coils embedded and printed over



Quarter stator with cavities placing 0.06" Kapton coated Litz wire.

MW Scale Machine Research at WEMPEC

NASA - University Leadership Initiative (ULI)

Objectives and Challenge

- ***Problem Statement:*** Develop advanced technology required for high-performance aviation electric propulsion machine suitable for integration with its drive power inverter and operation at a high bus voltage >2000 Vdc
- While development of a high-power-density, high-speed 1 MW machine will be challenging, inverter integration and high-voltage operation raises the challenge level
- ***Objectives:*** Develop, build, and test a 1 MW machine that demonstrates its suitability for power electronics integration and operation at voltages >2000 Vdc while achieving a specific power density >14 kW/kg (active mass)

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

MARQUETTE
UNIVERSITY

THE OHIO STATE
UNIVERSITY

UNIVERSITY OF MARYLAND
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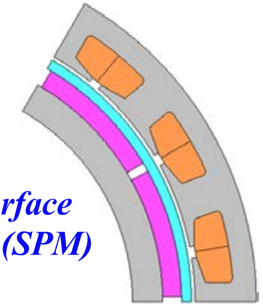
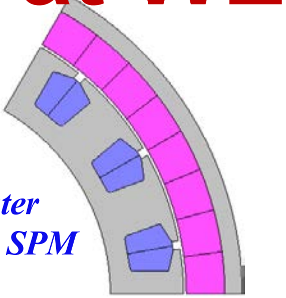
MAGNETIC TECHNOLOGIES

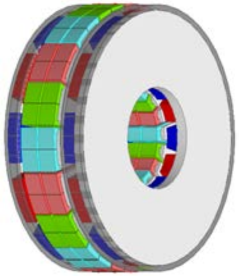
MW Scale Machine Research at WEMPEC



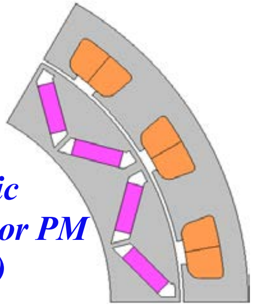
Surface PM (SPM)



Outer Rotor SPM

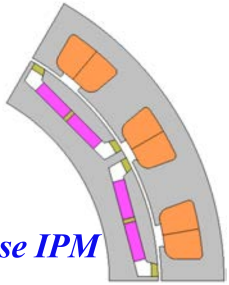


Axial Flux SPM

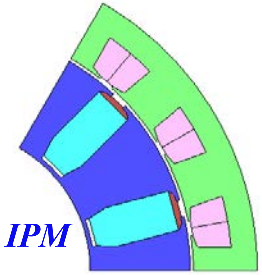


Classic Interior PM (IPM)

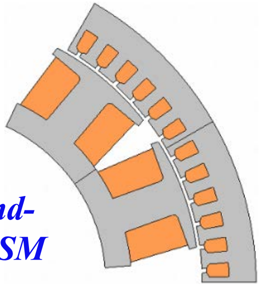
Merits	- Simple electromagnetic configuration - Concentrated windings	- No magnet containment issue	- No rotor yokes required, reducing mass and core losses - Add stator/rotor stacks to increase power	- Magnets inside rotor simplify containment - Reluctance torque
Challenges	- Magnet containment reduces power density - Risk of high losses in rotor magnets	- Cantilevered rotor leads to complex bearing design - Poor access to stator windings for cooling	- Mechanical alignment critical with multi-stator/rotor - Magnet containment and leakage at both inner and outer rotor diameter	- High speed complicates structural/electromagnetic design tradeoffs



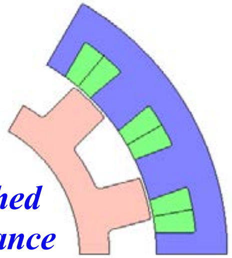
Dual Phase IPM



Spoke IPM



Wound-Field SM



Switched Reluctance

Merits	- Decouples structural and electromagnetic design issues	- High magnet flux concentration	- Freedom from magnet demag. & temp. limits - Adjustable field control	- No magnets - Simple, robust rotor structure - Appealing fault tolerance
Challenges	- Low saturation flux density - Material availability is uncertain	- Complicated structural/electromagnetic design tradeoffs - Demagnetization concerns	- High rotor winding losses - Rotor excitation adds mass and volume	- High torque ripple - High core losses - More complicated control

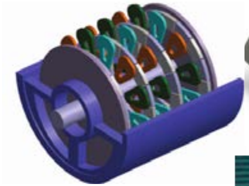
MW Scale Machine Research at WEMPEC

State of the Art

- Investigate past and active work on MW scale machines
- Novel and innovative developments in material and designs
- **Establish technology and manufacturability readiness level**

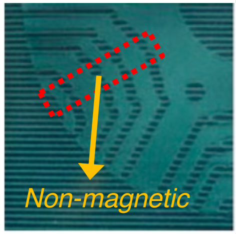
2017

Multi Stage axial flux machine



0.5 mm Laminated Permanent Magnet

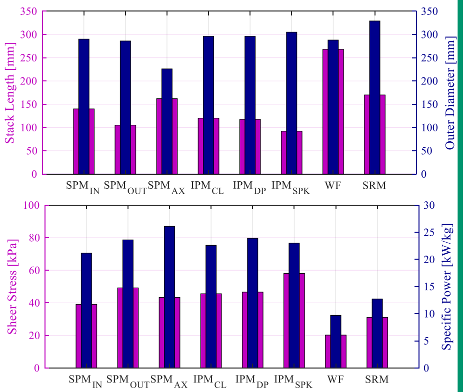
Direct Cooled windings



Dual-Phase Lamination Steel

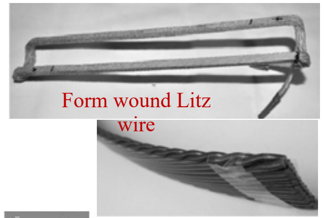
Tradeoff Study for IMMD

- Develop multiple candidate IMMD designs
- 1 MW at 20,000 RPM
- **Targeting 25 kW/kg active mass power density**

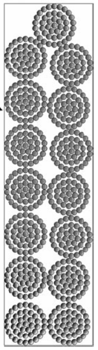


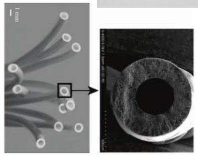
2018

1MW IMMD Concept | **State of the Art** | **Tradeoff Study**

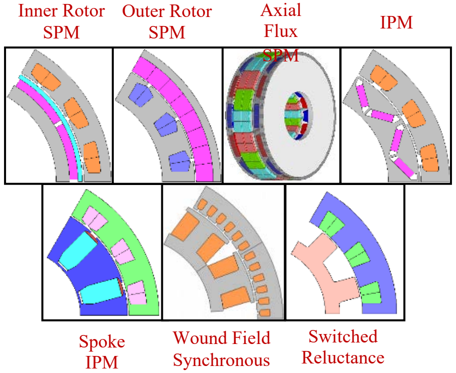


Form wound Litz wire





Carbon Nanotube winding



Parameter Sensitivity Analysis of IMMD

- Variation of power density with speed and current density
- **Structural limitations and safety margins of the material**

Early research work on IMMD

- **Integrated Modular Motor Drive (IMMD) concept**
- **Manufacturability and risk factors**
- **Efficiency and power density improvement**

Current research work

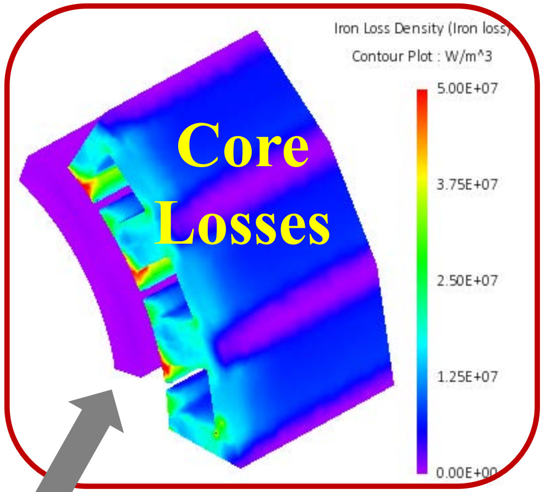
- **High active power density of components**
- **2000 V_{DC}, 10,000 – 20,000 RPM**
- **Scalability analysis of IMMD**
- **Modularity and fault tolerance**

Future research work on IMMD

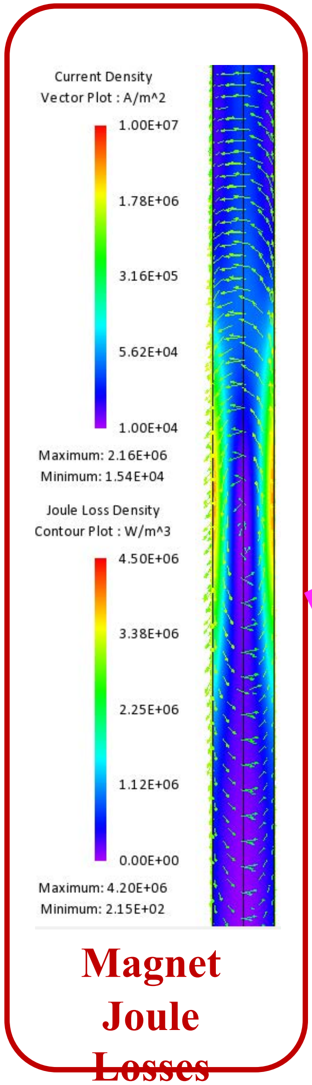
- **Integrated motor drive with WBG**
- **System level modeling and analysis**
- **Thermal analysis**

MW Scale Machine Research at WEMPEC

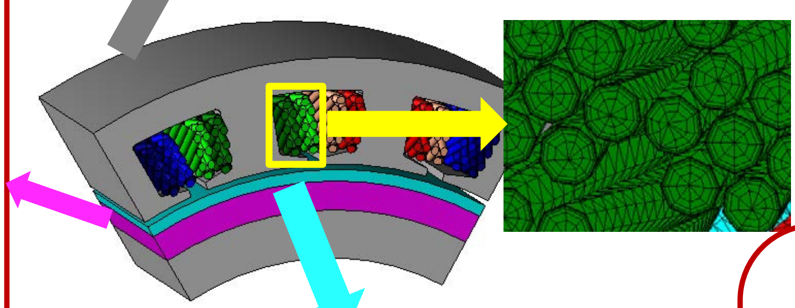
- In depth analysis of individual electromagnetic aspects of the design performed



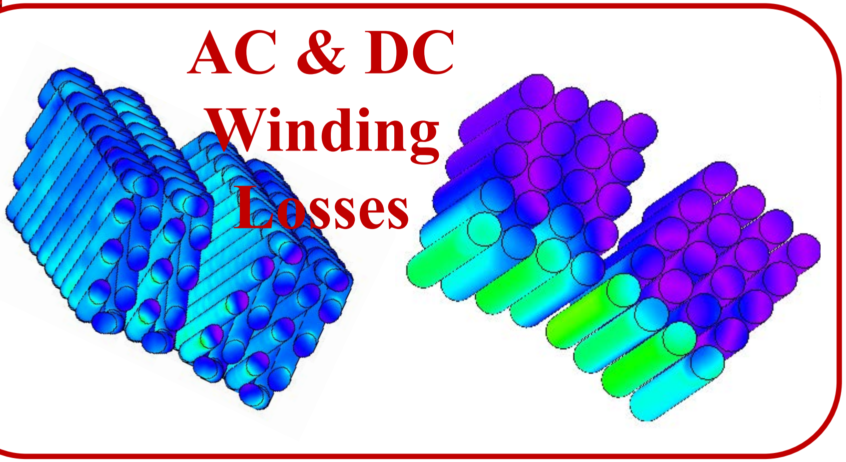
Core Losses



Magnet Joule Losses



Sleeve Joule Losses



AC & DC Winding Losses

Outline

1. Introduction and Motivations
2. Current Trends: power system, MES, etc.
3. Future Trends: e-taxi, e-propulsion
4. Enabling Technologies and Considerations
5. **Conclusions**

Conclusions

- New motor technology needed
  - High specific power density
  - High efficiency
  - Partial discharge issue solved
  - Fault tolerant
- New Power Electronic Technologies
  - SiC based - High specific power density and high efficiency
  - Partial discharge issue solved
  - Fault tolerant
- Integrate the motor and power electronic drive
  - Reduced EMI, integrated thermal design, reduced cable and connectors

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Questions?

Thank You!

For more info please see our paper
B. Sarlioglu and C. Morris, “More Electric Aircraft – Review, Challenges and Opportunities for Commercial Transport Aircraft”, Transactions on Transportation Electrification, available in IEEE Xplorer