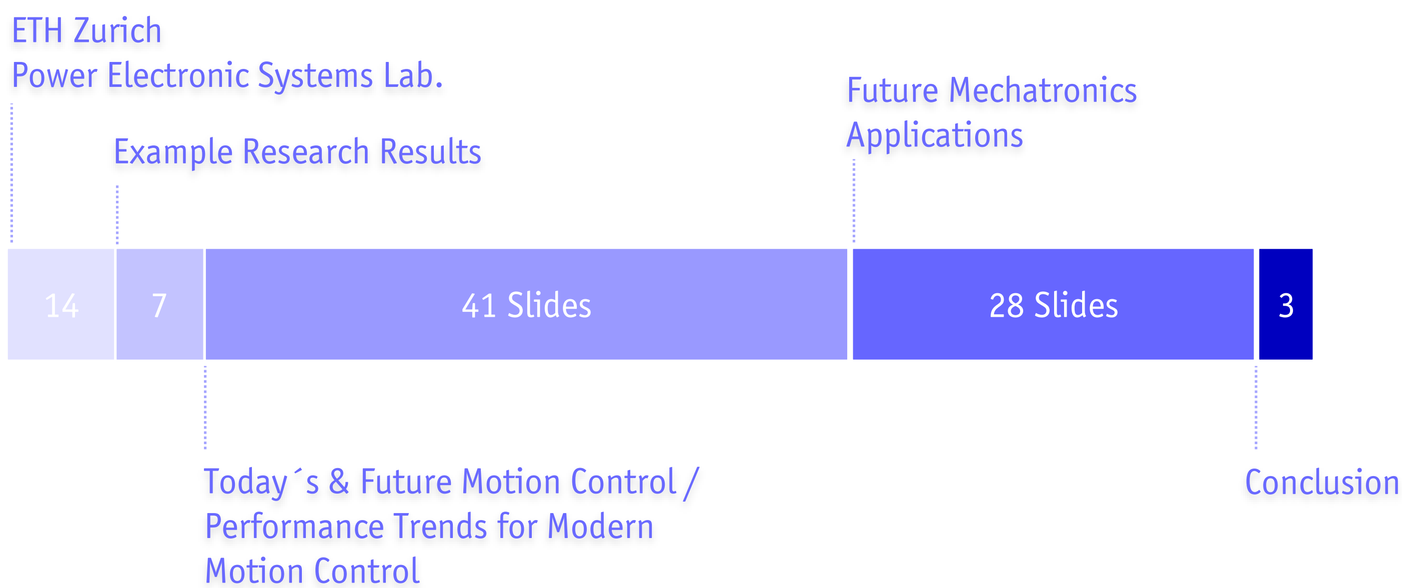
ETH zürich

Power Electronic Systems Laboratory

Research Vectors in Power Electronics and Motion Control

Johann W. Kolar
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

Agenda


ETH Zurich
Power Electronic Systems Lab.
Example Research Results
Future Mechatronics Applications
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41 Slides
28 Slides
3
Today´s & Future Motion Control / Performance Trends for Modern Motion Control
Conclusion

ETH Zurich

Dept. of Inform. Tech. and Electrical Eng.
Power Electronic Systems Lab.

► ETH Zurich

■ Founded 1855

- Driving Force of Industrialization in Switzerland

■ ETH Zurich Today

- One of the Leading International Universities for technology and the Natural Sciences
- Place of Study, Research and Employment for Approximately **29,000** People from over **110** Different Countries

■ ETH Research and Education

- Excellent Education
- Ground-Breaking Fundamental Research
- Putting New Findings into Practice

ETH Zurich

- **Two Main Locations in Zurich**
  - Historic Main Building in the Heart of Zurich, Built by Gottfried Semper
  - Modern Campus on the Outskirts of the City, in Hönggerberg, which Links Science, the Business World and the General Public
- **Additional Locations in Switzerland**
  - Basel: Department of Biosystems Science and Engineering (D-BSSE)
  - Lugano: Swiss National Supercomputing Center (CSCS)
  - Other Decentralized Entities
- **Research Facility in Singapore**
  - Singapore ETH Centre for Global Environmental Sustainability (SEC)

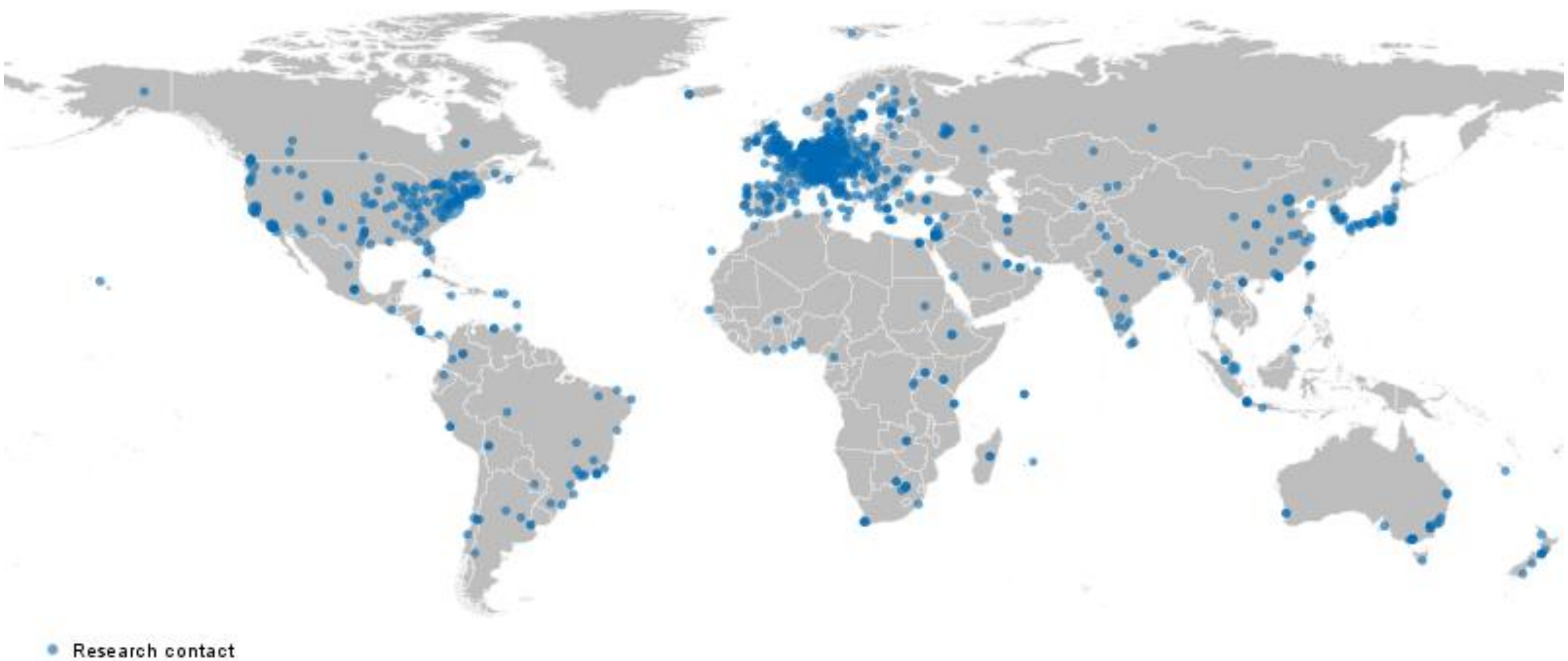
ETH Zurich, Zentrum

ETH Zurich, Hönggerberg

▶ ETH Zurich

■ Globally Networked with Leading Universities

- International Cooperation in Research and Education
- Partnerships with Leading Universities
  (IDEA League, IARU, GlobalTech, UNITECH etc.)



Departments of ETH Zurich

ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	**Information Technology and Electrical Eng.**
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

21	Nobel Prizes
413	Professors
6240	T&R Staff
2	Campuses
136	Labs
35%	Int. Students
110	Nationalities
36	Languages
150th	Anniv. in 2005

► Research @ D-ITET

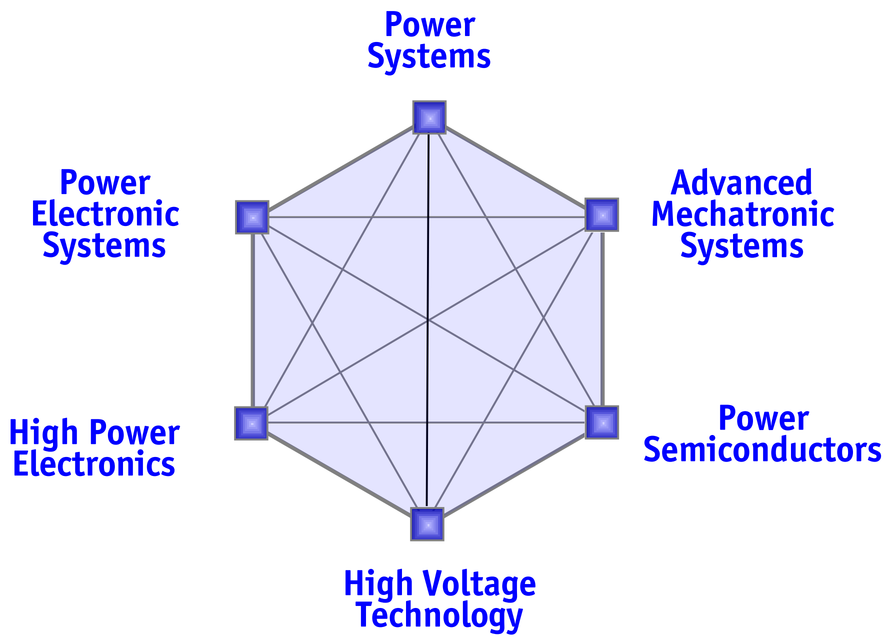
Four Core Research Areas

Energy
Electronics and Photonics
Information and Communication
Biomedical Engineering

Students & Staff

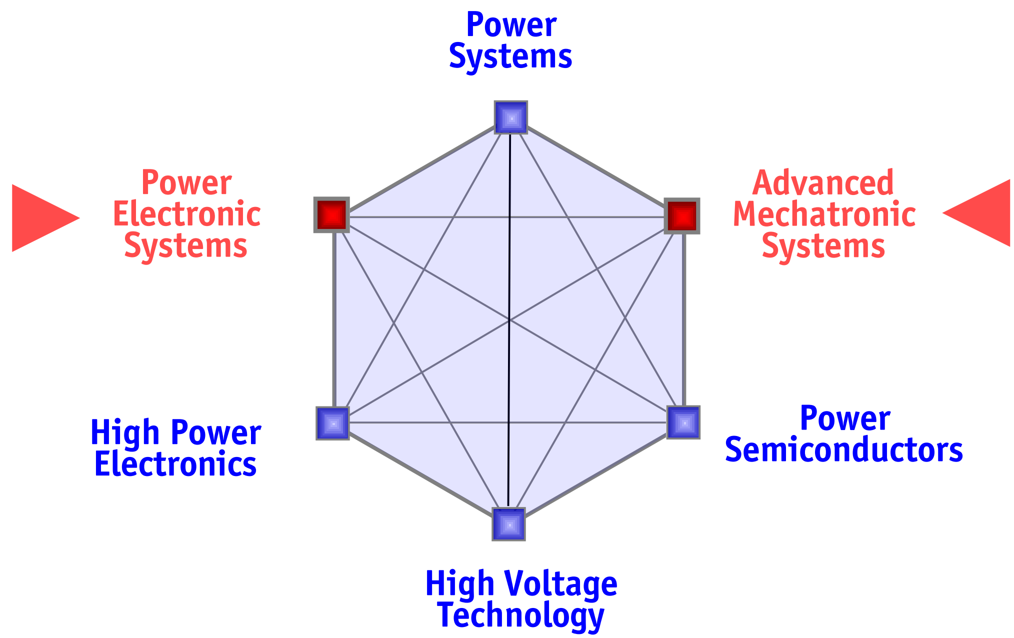
650 B.Sc. Students
300 M.Sc. Students
400 Ph.D. Students
27 Professors

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory (PES)

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Wireless Power	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	**D. Bortis**		**R. Bosshard**	**A. Tüysüz**	
M. Leibl D. Neumayr D. Rothmund L. Schrittwieser	D. Boillat Th. Guillod J. Huber H. Uemura	P. Bezerra M. Kasper	Ch. Gammeter	R. Burkart	O. Knecht	M. Flankl M. Mauerer M. Kaufmann	Th. Holenstein P. Püntener D. Steinert M. Schuck T. Wellerdieck

Secretariat
M. Kohn / D. Egger

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

22 Ph.D. Students
4 Post Docs → *1:5 PostDoc/Doc - Ratio*

ECPE Competence Centre

EPSMA

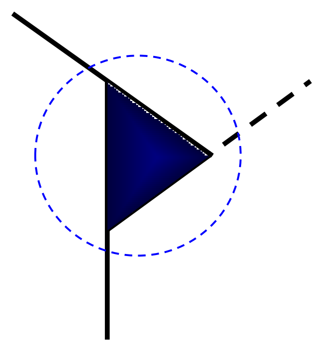
Leading Univ. in Europe

PES Research Scope

Power Electronics

Cross-Departmental

Mechanical Eng., e.g. Turbomachinery, Robotics
Microsystems
Medical Systems
Economics / Society

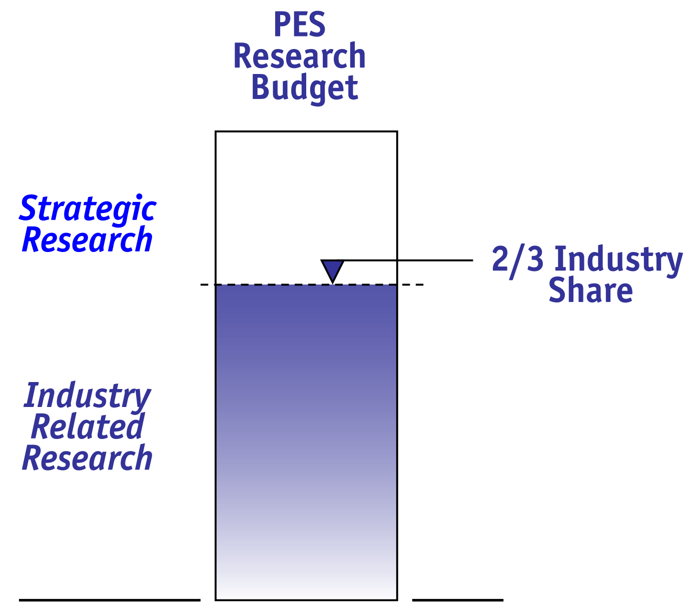


Actuators / EL. Machines

- *Airborne Wind Turbines*
- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Hybrid Systems*
- *Pulsed Power*

PES Industry Collaboration

- Core Application Areas
  - Renewable Energy
  - UPS
  - Smart Grid
  - Automotive Systems
  - More-Electric Aircraft
  - Medical Systems
  - Industry Automation
  - Semiconductor Process Technology
  - Etc.
- *16 International Industry Partners*



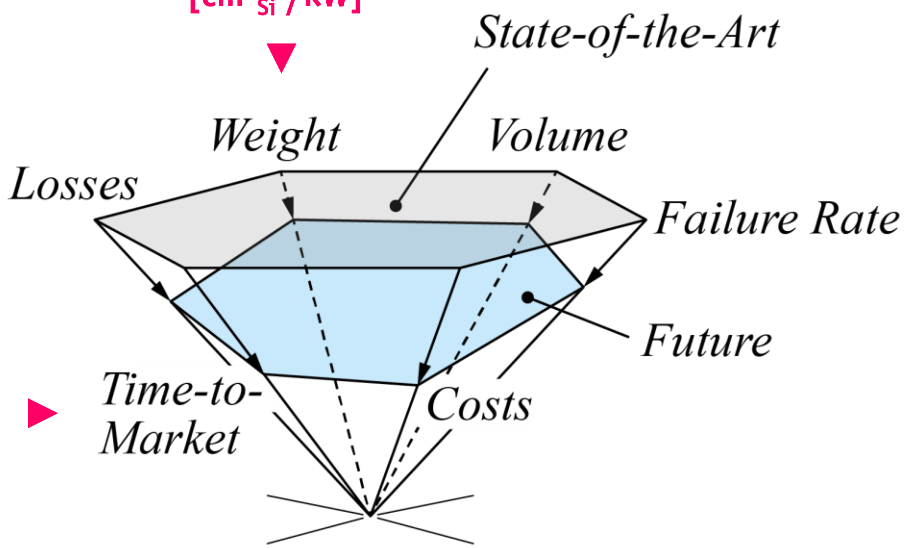
General Research Approach

▶ Power Electronics Converters Performance Trends

Environmental Impact... [kg_{Fe} /kW]
[kg_{Cu} /kW]
[kg_{Al} /kW]
[cm^2_{Si} /kW]

■ Performance Indices

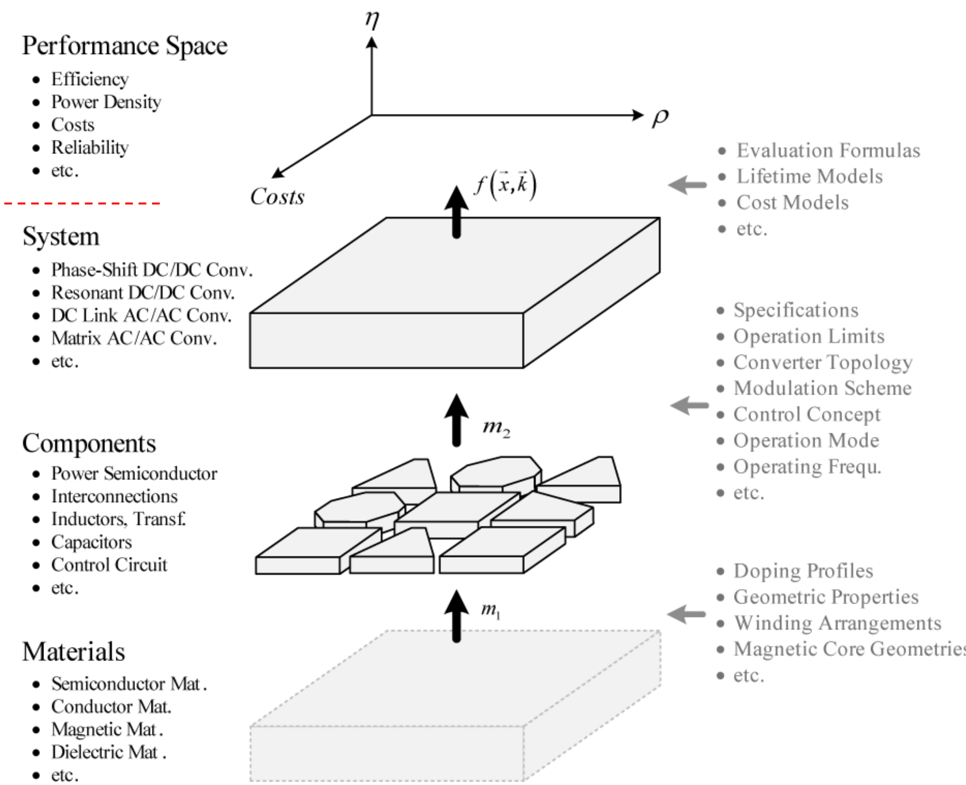
- Power Density [kW/dm^3]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h^{-1}]



Abstraction of Power Converter Design

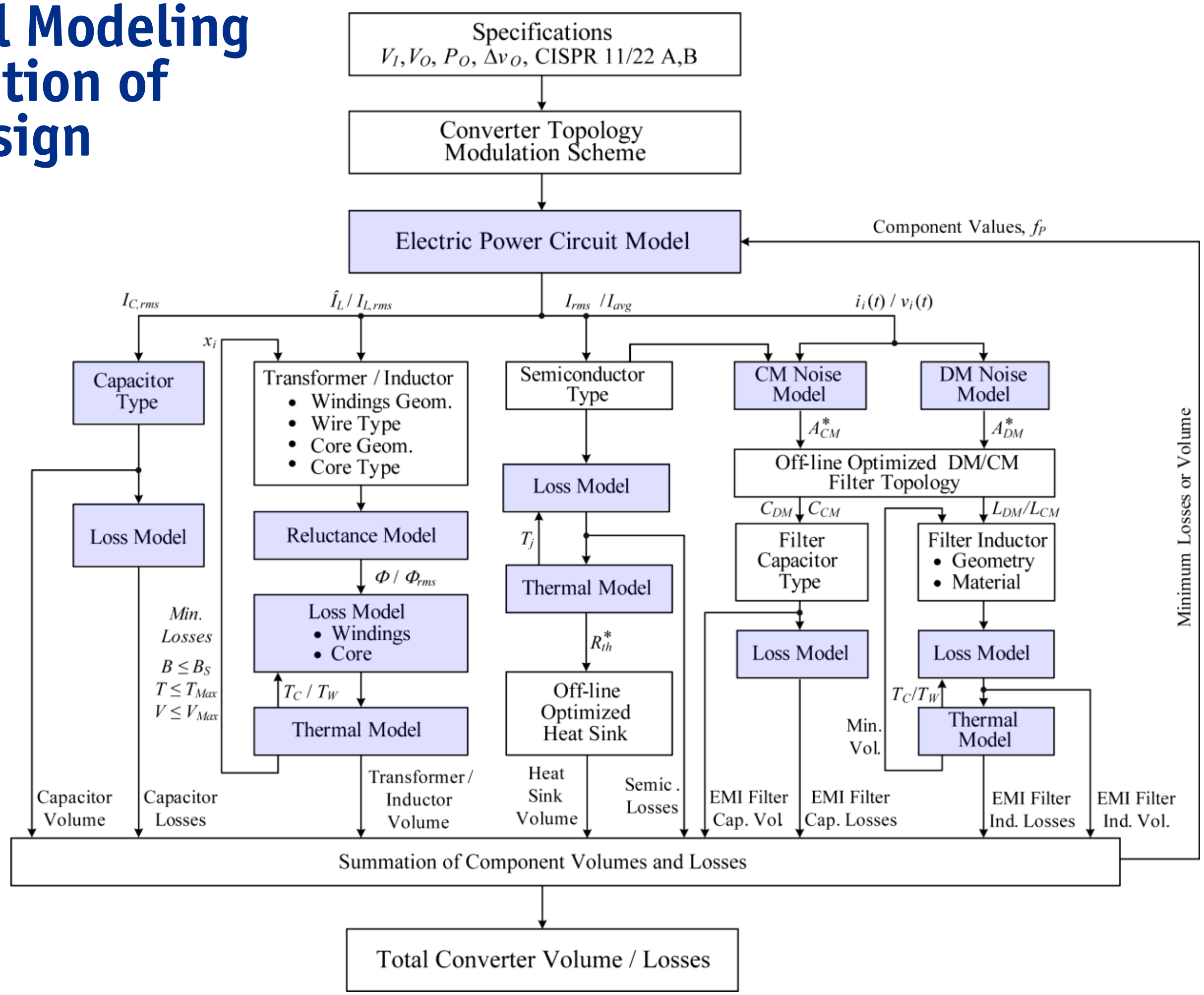
Performance Space

Design Space



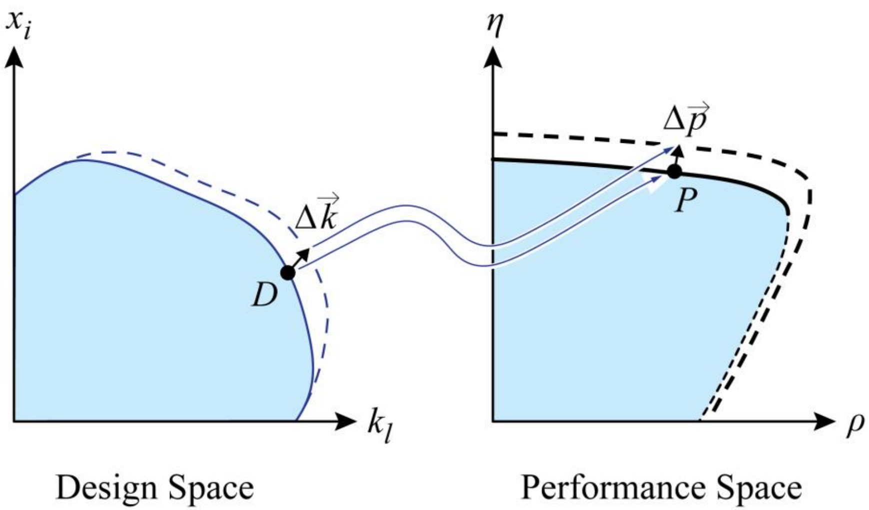
► **Mapping of *Design Space* into System *Performance Space***

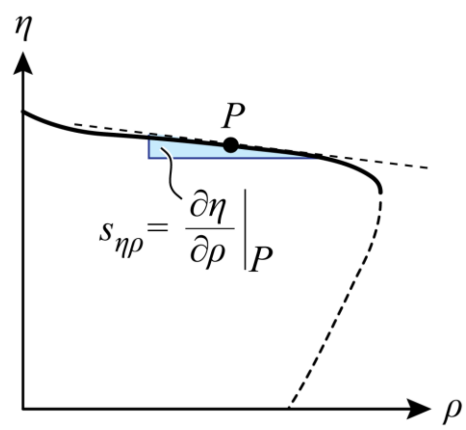
Mathematical Modeling and Optimization of Converter Design



Technology Sensitivity Analysis Based on η-ρ-Pareto Front

- ▶ Sensitivity to Technology Advancements
- ▶ Trade-off Analysis





▶ Example of Recent Research Results in Power Electronics

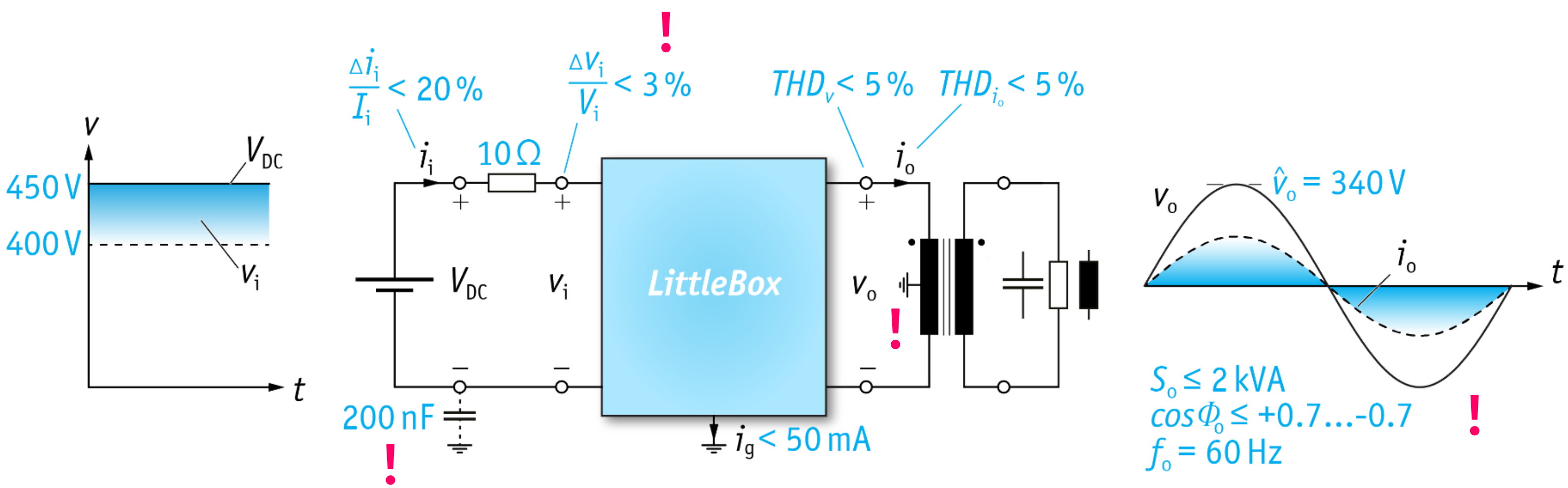
The Google Little Box Challenge

Requirements
Grand Prize
System →

LiTTLE BOX CHALLENGE

Google | IEEE

- Design / Build the 2kW 1-Φ Solar Inverter with the Highest Power Density in the World
- Power Density > 3kW/dm³ (50W/in³)
- Efficiency > 95%
- Case Temp. < 60°C
- EMI FCC Part 15 B



- Push the Forefront of New Technologies in R&D of High Power Density Inverters

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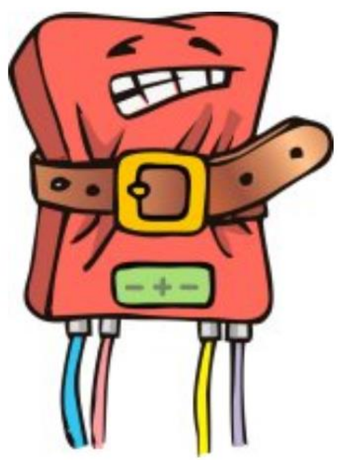

- Push the Forefront of New Technologies in R&D of High Power Density Inverters

The Grand Prize

- Highest Power Density (> 50W/in^3)
- Highest Level of Innovation

$1,000,000

- **Timeline**
  - Challenge Announced in Summer 2014
  - 650 Teams Worldwide
  - 100+ Teams Submitted a Technical Description until July 22, 2015
  - 15 Finalists / Presentation @ NREL on Oct. 21, 2015, Golden, Colorado, USA
  - Testing @ NREL, Colorado, USA / Winner will be Announced in Early 2016

Inverter

■ Compliant to All Specifications (!)

14.8in^3 (243 cm^3)
96,3% Efficiency @ 2kW
95.07% Weighted Efficiency
T_c=58°C @ 2kW

Δu_{DC}= 1.1%
Δi_{DC}= 2.8%
$THD+N_U$ = 2.6%
$THD+N_I$ = 1.9%

88.7mm x 88.4mm x 31mm

★ 135 W/in^3

New Technologies

- Cascaded Control for Active Power Pulsation Buffer
- TCM Modulation → Active ZVS in Whole Operating Range
- 4D Interleaving of 2 Bridge Legs per Phase
- 20ns Delay / 500kV/us Gate Drive for 600V IFX Norm.-Off GaN GIT
- Q=800 / Multi-Micro-Airgap HF Inductor w. Multi-Layer Foil Winding
- *CSPI*=34W/(dm^{3}K) Heatsink also Employed as EMI Shield

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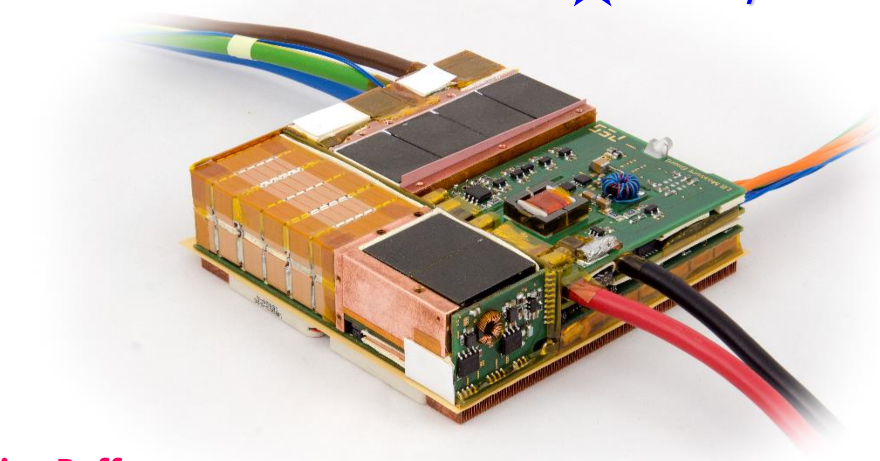

New Technologies

- Cascaded Control for Active Power Pulsation Buffer
- TCM Modulation → Active ZVS in Whole Operating Range
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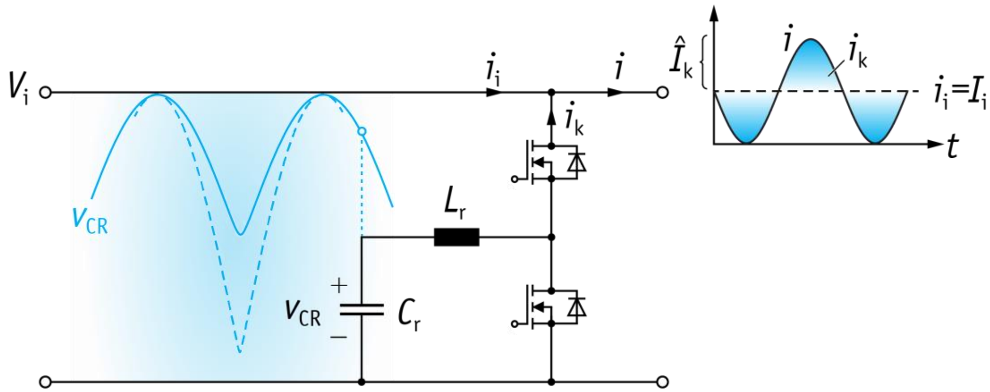
- Q=800 / Multi-Micro-Airgap HF Inductor w. Multi-Layer Foil Winding
- *CSPI*=34W/(dm^{3}K) Heatsink also Employed as EMI Shield

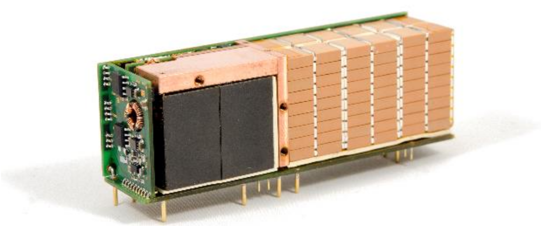
Power Pulsation Buffer

- Employs Large Voltage Fluctuation Capacitor & DC/DC Buck Converter Stage
- High Energy Density Ceramic Capacitors (CeraLink)
- New Multi-Loop Cascaded Control Structure



5 x 493µF/450 V
C = 2.46 mF

V = 48 cm^3



V = 166 cm^3

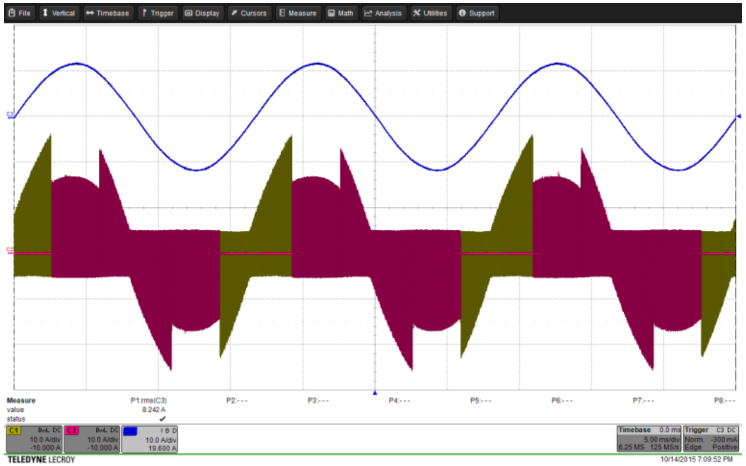
- Significantly Lower Volume Compared to Electrolytic Capacitors

Measurement Results

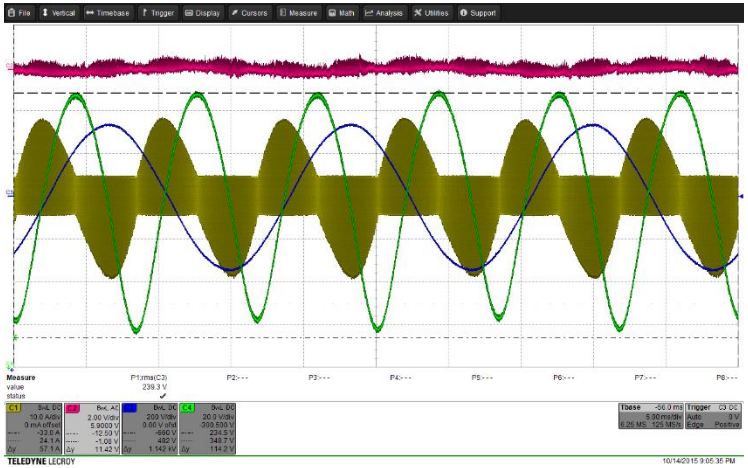
- System Complies to All Specifications (!)

- Ohmic Load / 2kW

Output Current
Inductor Current Bridge Leg 1-1
Inductor Current Bridge Leg 1-2

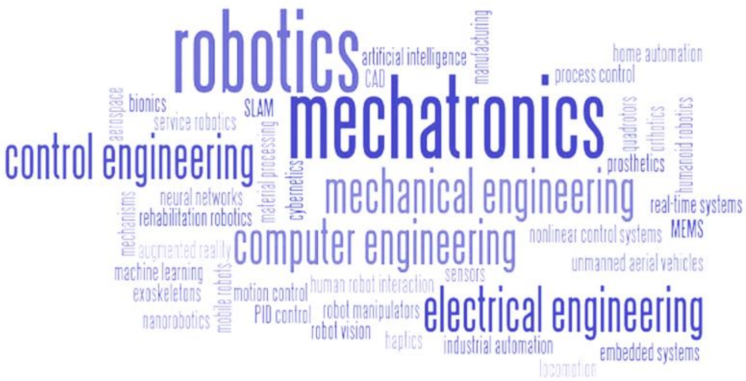


DC Link Voltage (AC-Coupl.)
Buffer Cap. Voltage
Buffer Cap. Current
Output Voltage

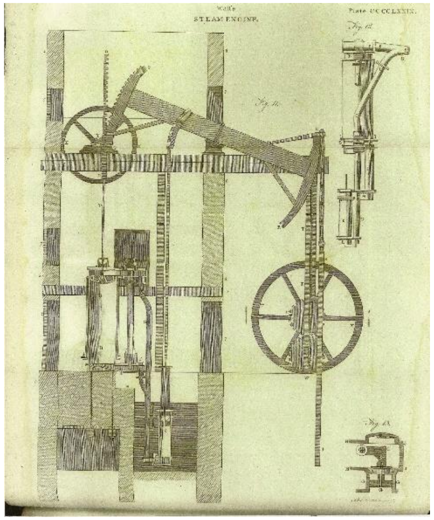


- New 4D Interleaving Combined with Active ZVS TCM Modulation

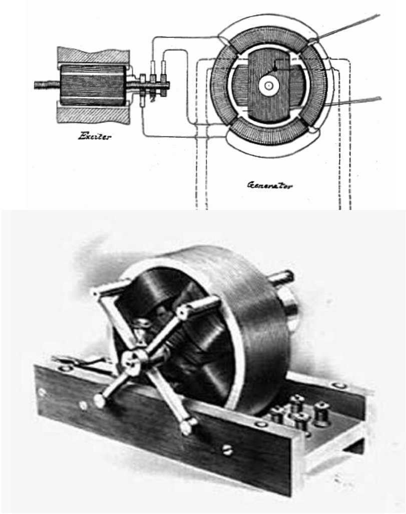
Today's and Future Motion Control Systems



▶ Development of Motion Control Systems



James Watt's Steam Engine



Nikola Tesla's AC Induction Machine

Integrated Drive System (AC Motor + SkiN IGBT Power Electronics) for Today's Electric Vehicles

■ Exponential Development

< 1900 Mechanical
1900 Mechanical + Electrical
1950 Mechanical + Electrical + Electronic → **Electronic Motion Control**
1975 Mechanical + Electrical + Electronic + Computation → **MECHATRONICS**
1985 Mechanical + Electrical + Electronic + Computation + Information/Communication

▶ Future Innovation in Motion Control Systems

■ Key Components are Today Available with High Performance


Ultra-Compact & Efficient
Power Converter


High-Performance
Mechanical Actuators

Precision Sensors



Ultra-Compact & Efficient
Electrical Machines


High-Speed Digital
Signal Processing

■ Extremely Wide Application Areas

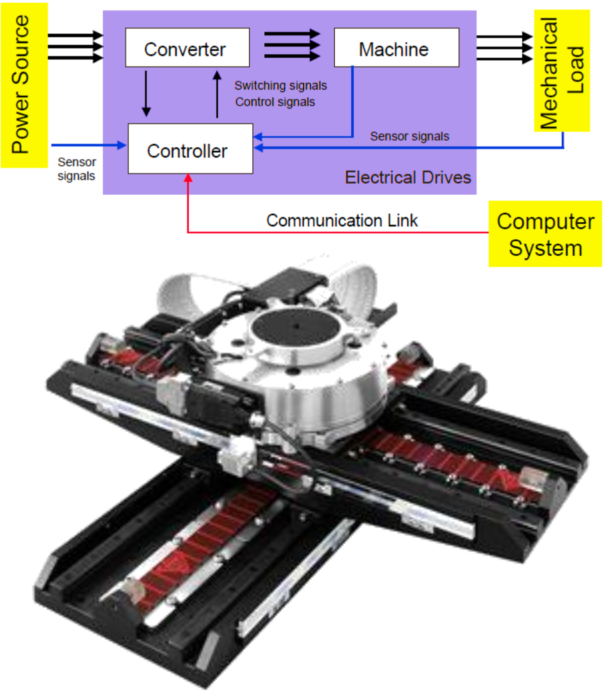
- Machining
- Handling and Assembly
- Transportation (land, sea, air)
- Gas, Oil and Mining
- Water, Wastewater
- Consumer Electronics
- Computers
- Home Appliances
- Defense
- Medical
- Space Exploration

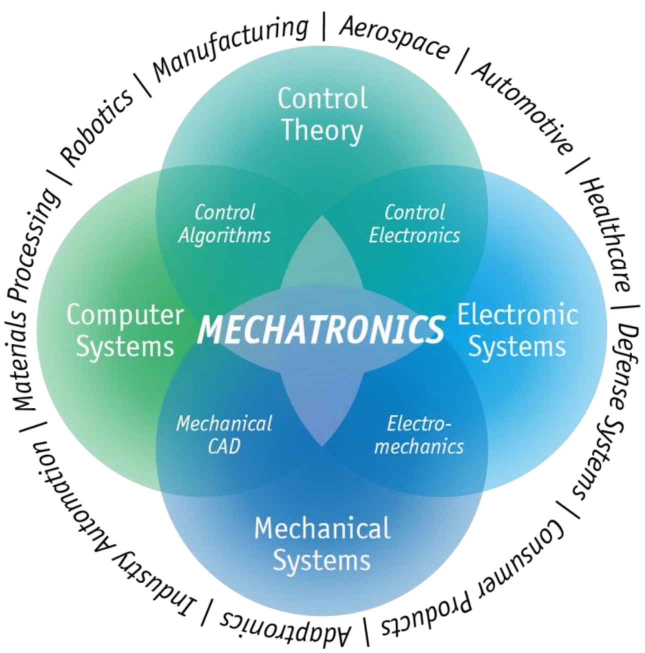
▶ 1st Option for Gaining Competitive Advantage: *Further Optimize the «Component»*

e.g. Ultra-High Speed Machines, Ultra-Efficient Converter, ...

▶ 2nd Option for Gaining Competitive Advantage: *Target Future Mechatronic Systems*

- Target «System Level» and have Competences to Bridge the Boundaries between > 3 Key Areas
- Opens Path to Endless Product Innovation → «Multiplication by Infinity»





Electrical Drives: Performance Trends

Compact & Lightweight Drives
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

Electrical Drives: Performance Trends

Compact & Lightweight Drives
Power Electronics & Integration
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Extreme Ambient Conditions

▶ Requirements for Electric Transportation Systems

- **In-Wheel Drives for Electric Vehicles**
  - High Controllability
  - Better Vehicle Response
  - More Free Space in the Vehicle
  - Very Tight Space Constraints

- P_{nom} 54 kW
- n_{max} 1400 r/min
- D_{out} 420 mm
- l_{ax} 56 mm
- m_{tot} 31 kg (incl. Inverter)

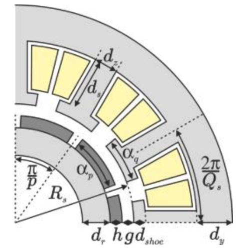
- **More Electric, Hybrid, All Electric Aircraft**
  - Reduced Fuel Costs
  - Silent Propulsion
  - Low-Weight Electrical Machines (Propulsion Motor, Gas Turbine Driven Generator)

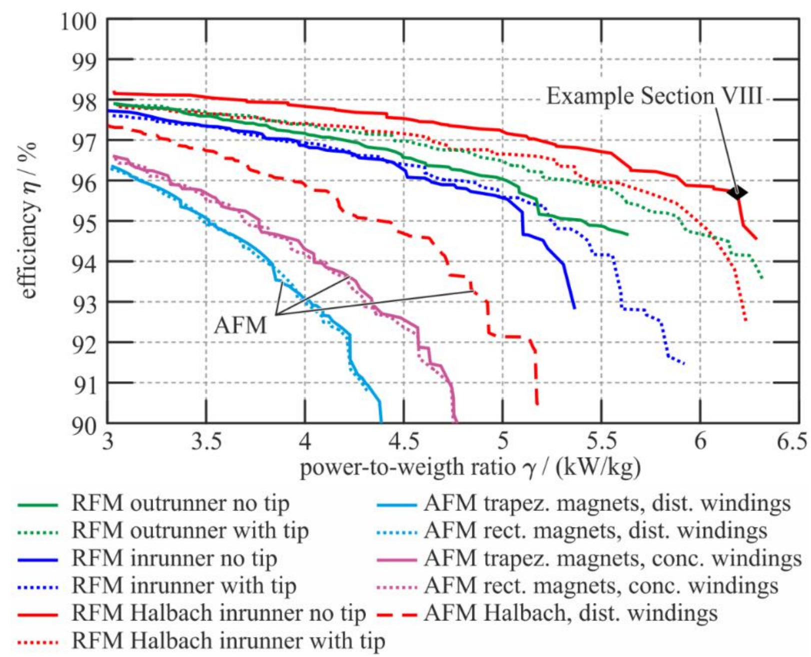
- P_{nom} 260 kW (η = 95%)
- n_{max} 2500 r/min
- D_{out} 418 mm
- l_{ax} 300 mm
- m_{tot} 50 kg (incl. Prop. Bearing)

► Pushing Conventional Motors to the Limit

- **Analysis & Optimization of Advanced Machine Topologies**
- **Comprehensive Multiphysics Machine Models**
  (Electromagnetic, Mechanical, Thermal)

- **Multi-Objective Pareto-Optimization to find Optimal Design Parameters**





▶ Increasing Power/Torque Density

■ **Esson's Scaling Law for Electrical Machines**

Machine Torque

Machine Speed

1) Mechanical Power $P_m = \omega T$

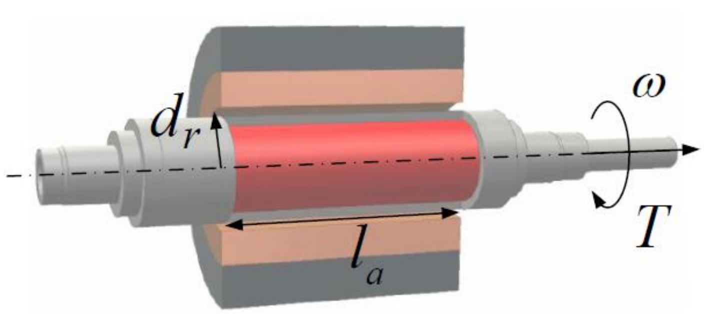
2) Machine Torque $T = c\, l_a d_r^2$

Rotor Diameter

Axial Length of Machine

Machine Size

Utilization Factor
- Machine topology
- Materials
- Manufacturing methods
- Cooling



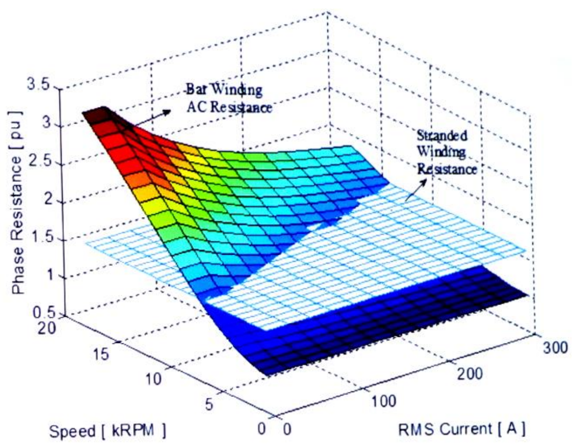
▶ Increasing the Machine Utilization Factor (1)

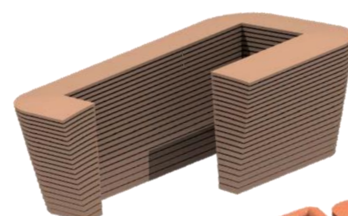
■ Degrees-of-Freedom for Improved Utilization

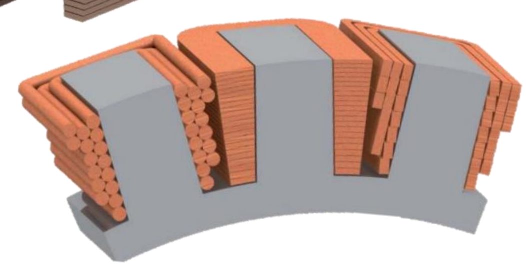
- Manufacturing Methods
- Materials
- Cooling

– **Cast coils:**
  + Very High Filling Factor
  + Low-Cost
  + Aluminum or Copper
  + High Power Densities
  - High-Frequency Losses

Source: GM
Cevrolet Volt 2016







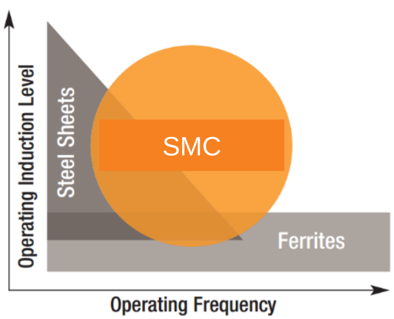
▶ Increasing the Machine Utilization Factor (2)

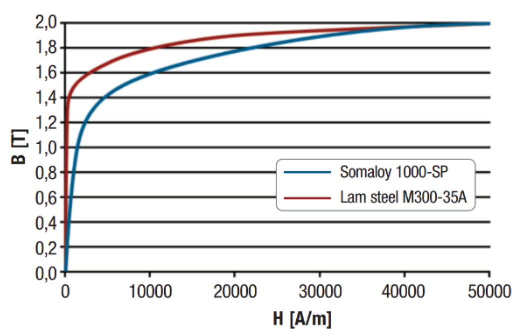
■ Degrees-of-Freedom for Improved Utilization

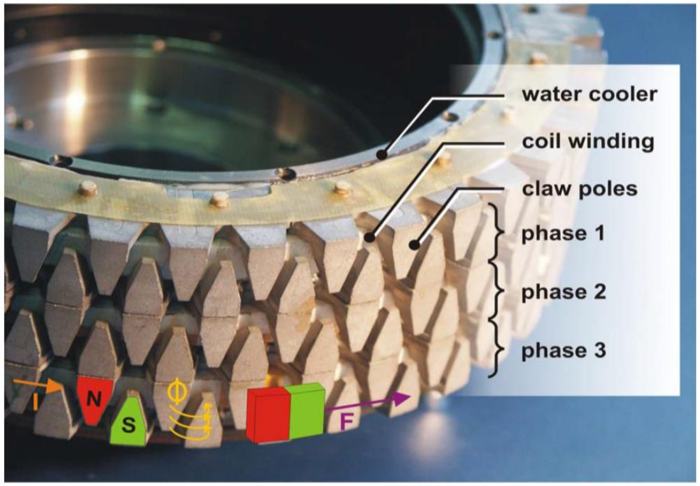
- Manufacturing Methods
- Materials
- Cooling

– **Soft magnetic composites (SMC):**
+ 3-D Electrical Insulation
+ Low Eddy-Current Losses
+ Transversal- or Axial-Flux Machines
- Mechanical Strength
- Low Magnetic Permeability

Source: gkn.com







Source: Bauer, Kleimaier
Observer Based Sensorless Predictive Hysteresis Control of a Transverse Flux Machine

▶ Increasing the Machine Utilization Factor (2)

■ Degrees-of-Freedom for Improved Utilization

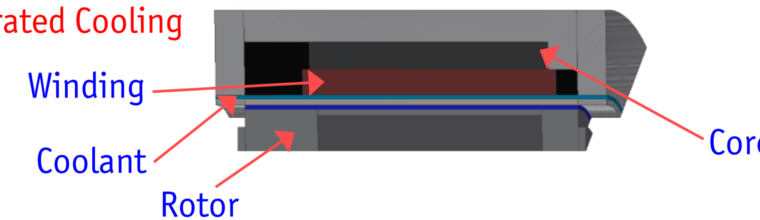
- Manufacturing methods
- Materials
- Cooling

– **Integrated cooling (slotless machines)**

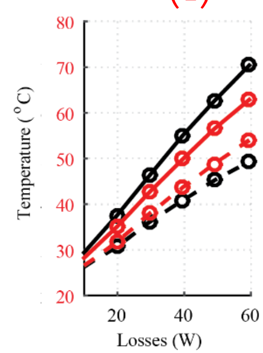
+ Smart Design:
  Fast Empirical Models for Cooling
  Magnetic ↔ Mechanical ↔ Thermal
+ > 40 °C Hotspot Temp. Reduction

(1) Jacket Cooling
(State of the Art)

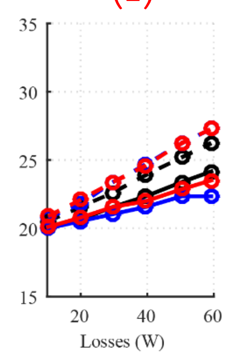
(2) Integrated Cooling



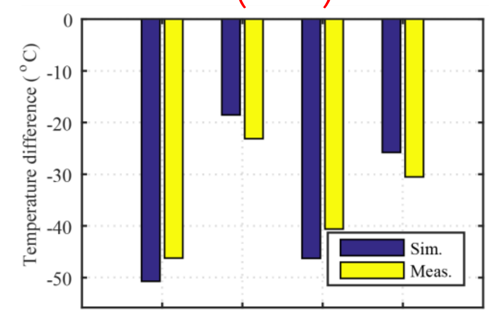
(1)

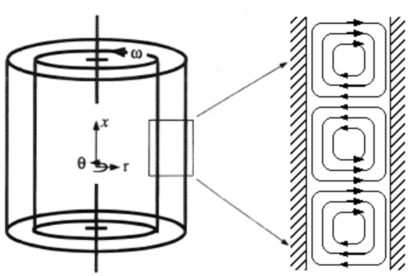


(2)



(1 – 2)



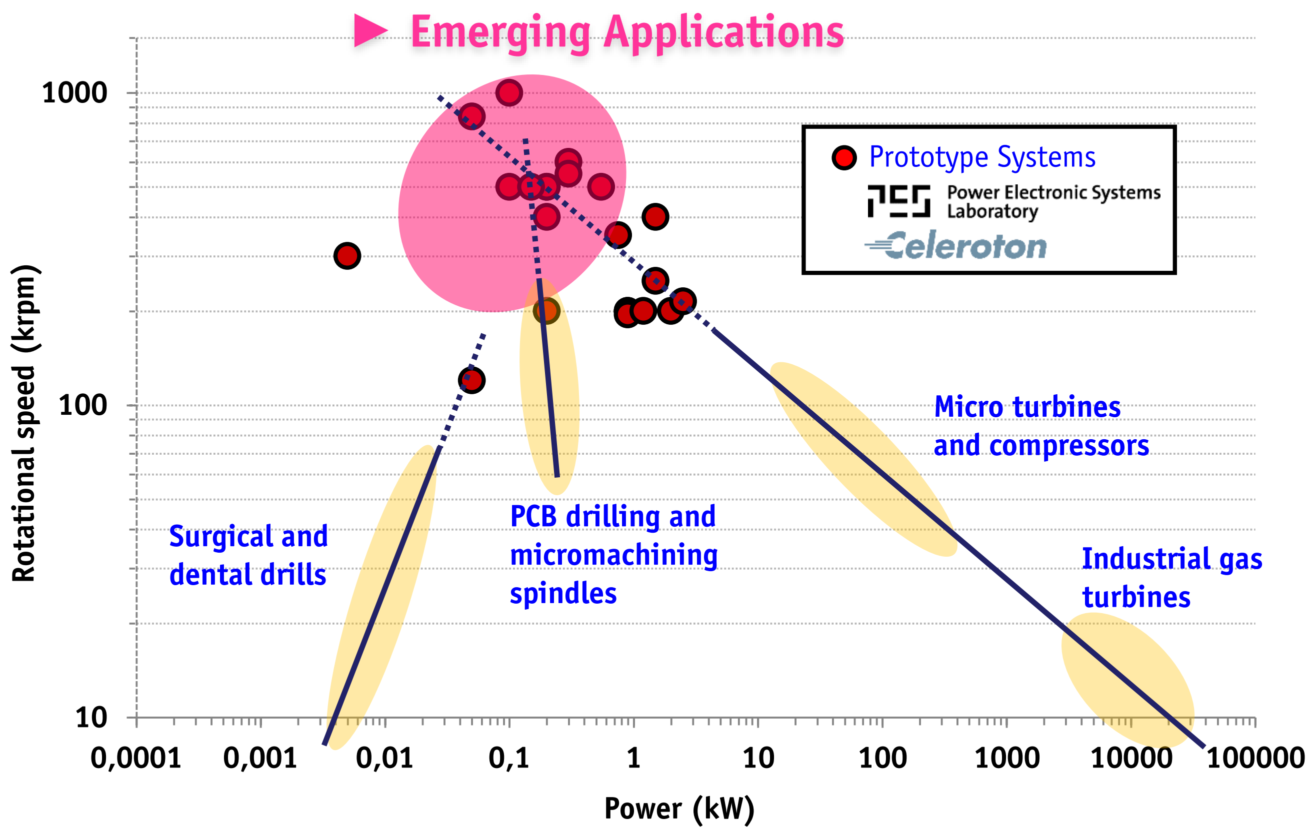


$$Nu_d = f\left(3.66^3 + 0.7^3 + \left(1.615\left(RePr\frac{d}{l_d}\right)^{1/3} - 0.7\right)^3 + \left(\left(\frac{2}{1+22Pr}\right)^{\frac{1}{6}}\left(RePr\frac{d}{l}\right)^{\frac{1}{2}}\right)^3\right)^{\frac{1}{3}}$$

▶ Industry Trend: High Rotational Speed for High Compactness

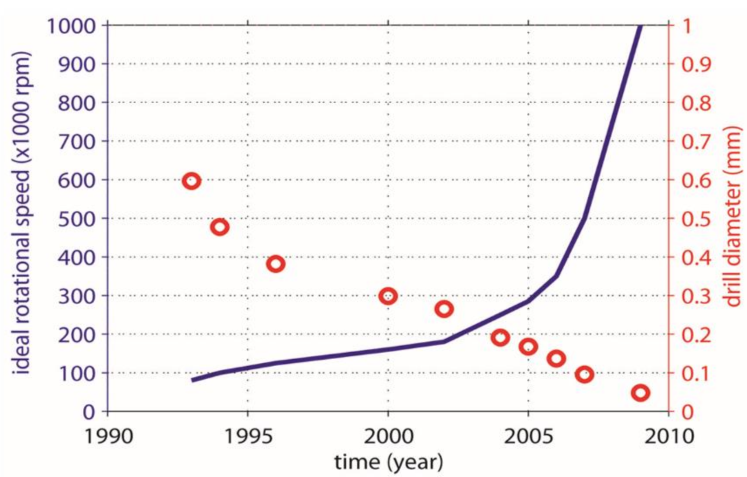
■ Ultra-High-Speed Drives have Numerous Applications Across Industries

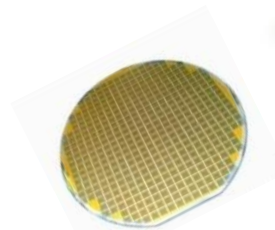
1) Mechanical Power $P_m = \omega T$
2) Machine Torque $T = C\,L\,D^2$



►Ultra-High-Speed Micro-Machining Applications

- **Rotational Speed: 250’000 – 1’000’000 r/min**
  - Smaller Feature Size (µ-vias for Consumer Electronics)
  - Higher Precision in Manufacturing
  - Accelerated Manufacturing Process
  - Higher Productivity





Wafer notch grinding

Dental crowns

µ- vias in PCBs

Watchmaking

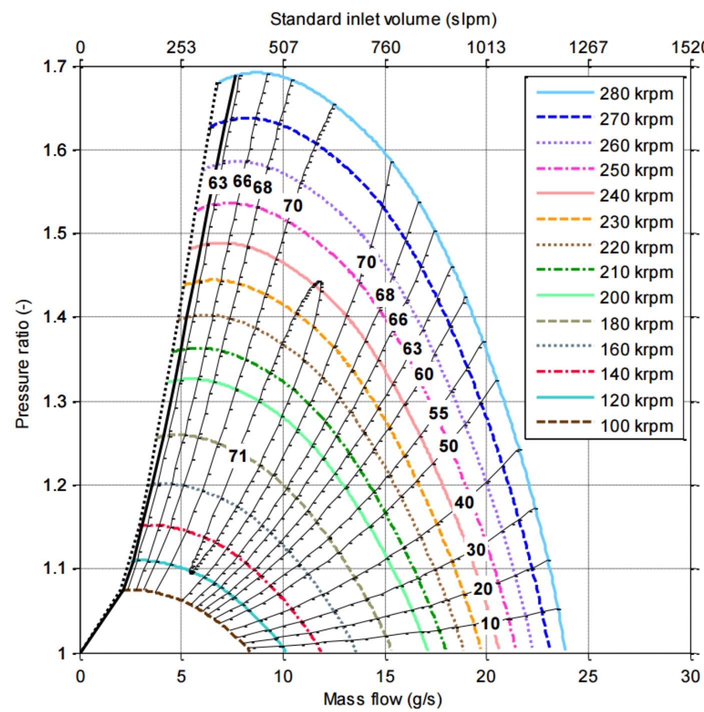
Dental/surgical drills

► High-Speed Turbocompressor for Portable Fuel Cell

- Reduced Weight/Volume
- Increased Pressure Ratio

Fuel Cell

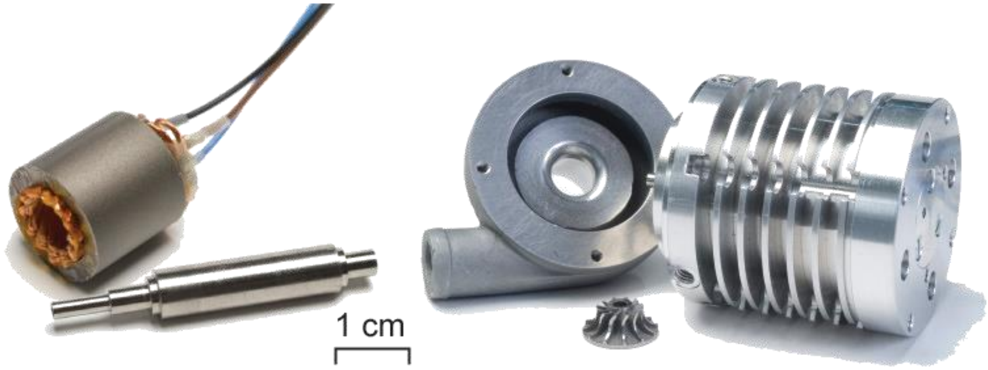
Commercially available compressors		
Speed (r/min)	280 000	18 000
Pressure Ratio	1.6	1.4
Mass Flow (g/s)	15	15
Weight (kg)	0.6	4



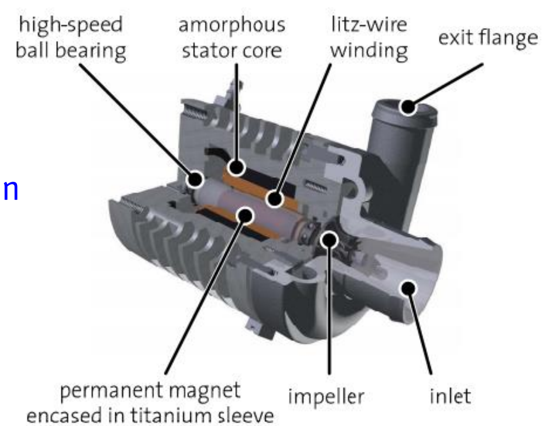
► Ultra-Compact Turbocompressor for *«Solar Impulse»*

■ Cabin Pressurization in Solar-Powered All-Electric Aircraft

- Compact Machine Design with 150 W, 150’000 r/min



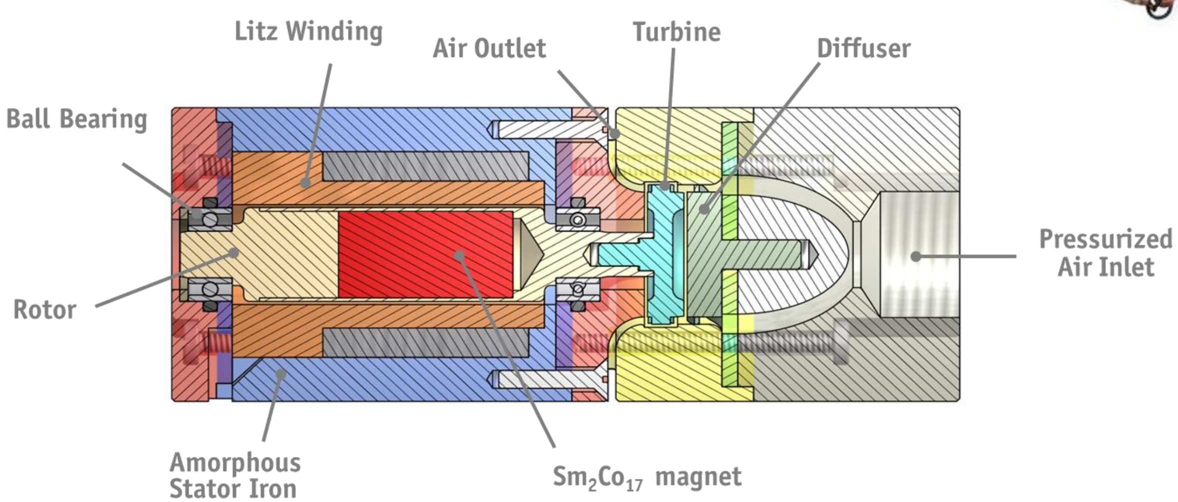
Rotational Speed	500’000 r/min
Machine Power	150 W
Mass Flow	1.2 g/s
Compression Ratio	1.8

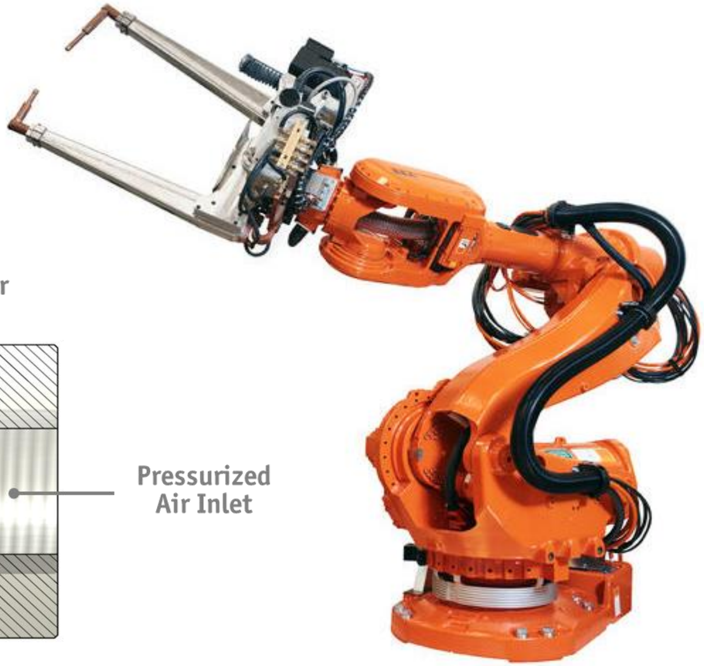


► High-Speed Air-to-Power Systems

- **Local Electric Power Generation from Compressed Air of Pneumatic Supply**
  - Supply of Compressed Air Already in Place for Pneumatic Components
  - Robust Air Hose Instead of Electrical Wiring

  – Compressed Air Input 3..8 bar
  – Electrical Power Output 100 W
  – Ultra Compact Design 20 x 50 mm



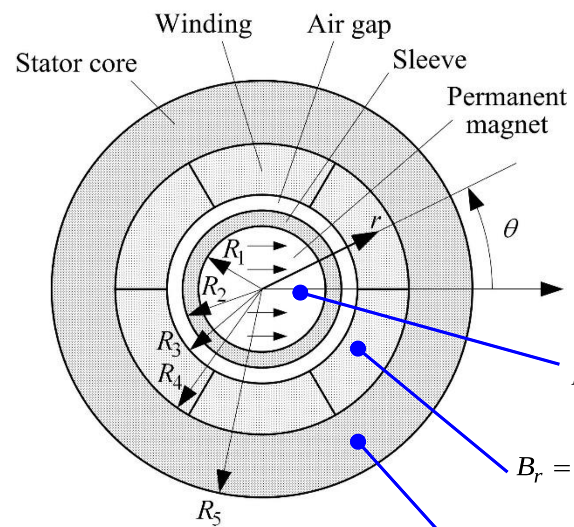


▶ Magnetic Design of Ultra-High-Speed Drives

■ Magnetic Design is Key Challenge at High Rotational Speed

■ 1-Pole Pair Slotless PM Machine
- Low Armature Reaction: Low Rotor Losses
- Litz Wire Stator Windings
- Amorphous Iron Stator Core

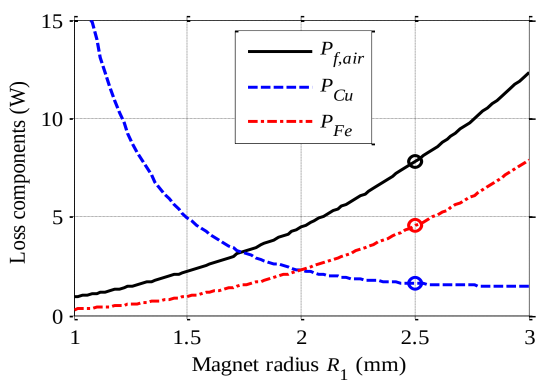
■ Optimization of Machine Geometry
- Analytical Field Models
- Skin and Proximity Losses
- Air Friction Loss in Air Gap
- Strand Packing Fill Factor vs. Wire Diameter

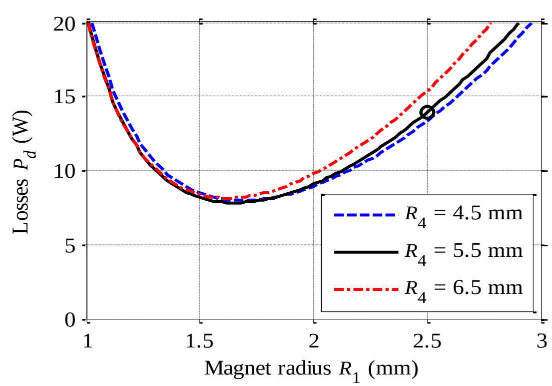


$$B_r = K_{B1}\cos\theta$$

$$B_r = K_{B2}\left[1+\left(\frac{R_4}{r}\right)^2\right]\cos\theta$$

$$B_r = K_{B3}\left[-1+\left(\frac{R_5}{r}\right)^2\right]\cos\theta$$





$$P_{f,air} = c_f \pi \rho_{air} \omega^3 R_2^4 L$$

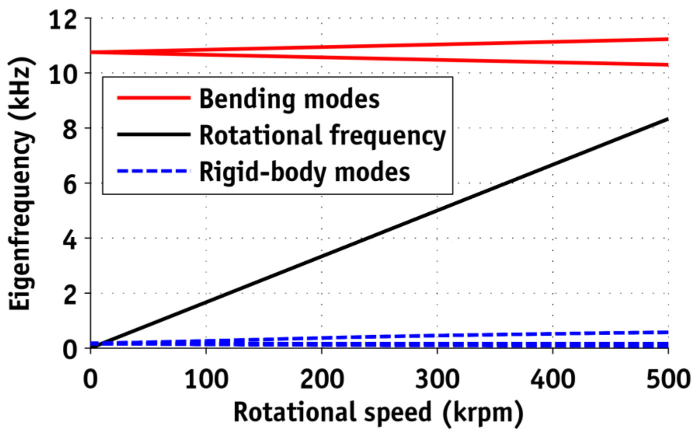
$$P_{Cu} = P_{Cu,s} + P_{Cu,p} = I^2 F + G\frac{\hat{H}^2}{\sigma}$$

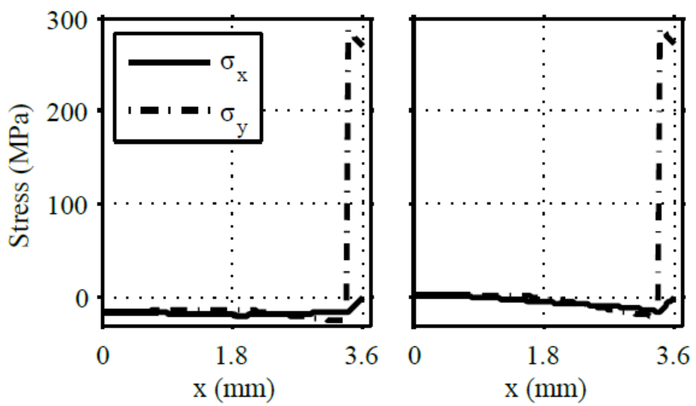
$$P_{Fe} = \int_{V_{Fe}} C_m \cdot f^{\alpha} \cdot \hat{B}^{\beta} dV$$

► Rotor Design Challenges at Ultra-High-Speeds

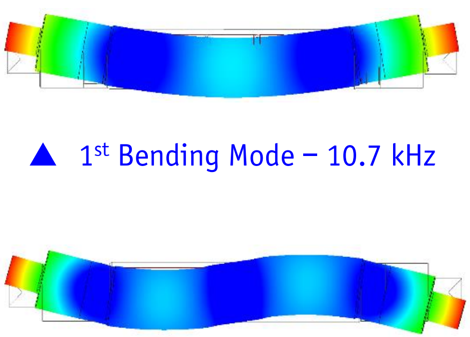
- **Rotor Dynamics**
  - Bending Modes Limit Maximum Speed
  - Rigid-Body Modes Within Operation

- **Stresses due to Centrifugal Force**
  - Metallic or Composite Sleeve Needed
  - Tight Tolerances for Interference Fit





▲ Rotor Stresses due to Rotation



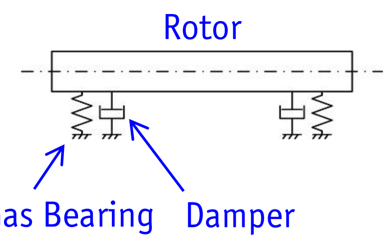
▲ 1st Bending Mode – 10.7 kHz

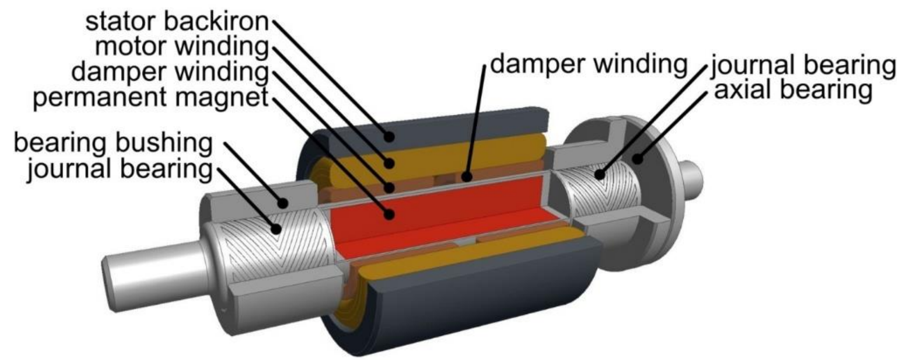
▲ 2nd Bending Mode – 25 kHz

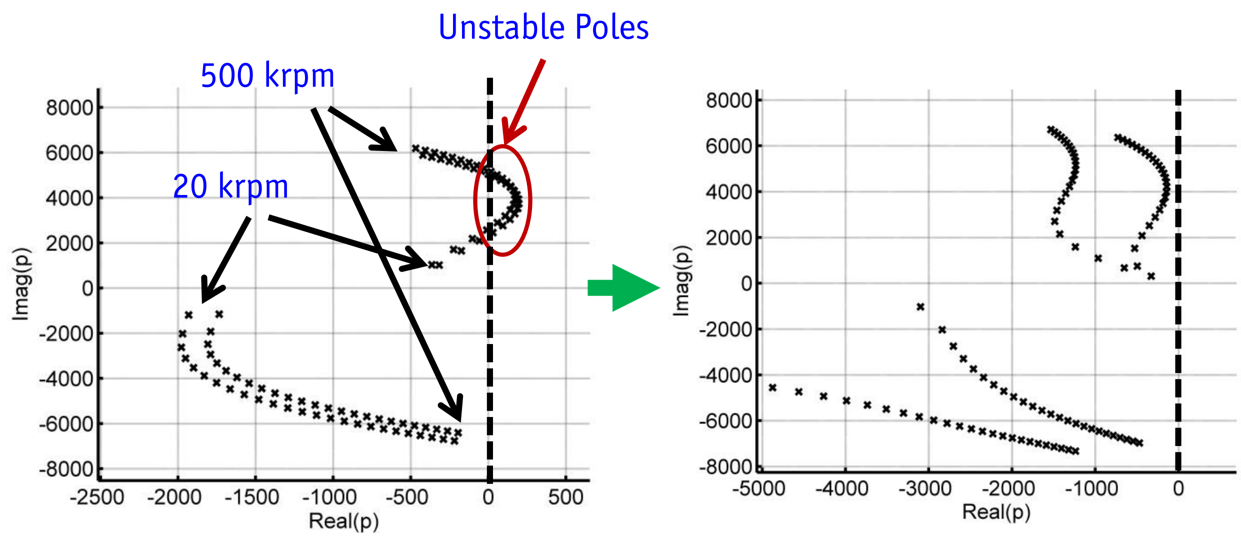
▶ Advanced Bearing Systems for Ultra-High-Speed-Drives (1)

- **Lifetime of Ball Bearings Limits Rotational Speed of Electric Machine**

- **Gas Bearings**
  - \+ No Wear, Long Lifetime
  - \+ High Stiffness, Load Capacity
  - \- Self-Excited Whirl / Damping





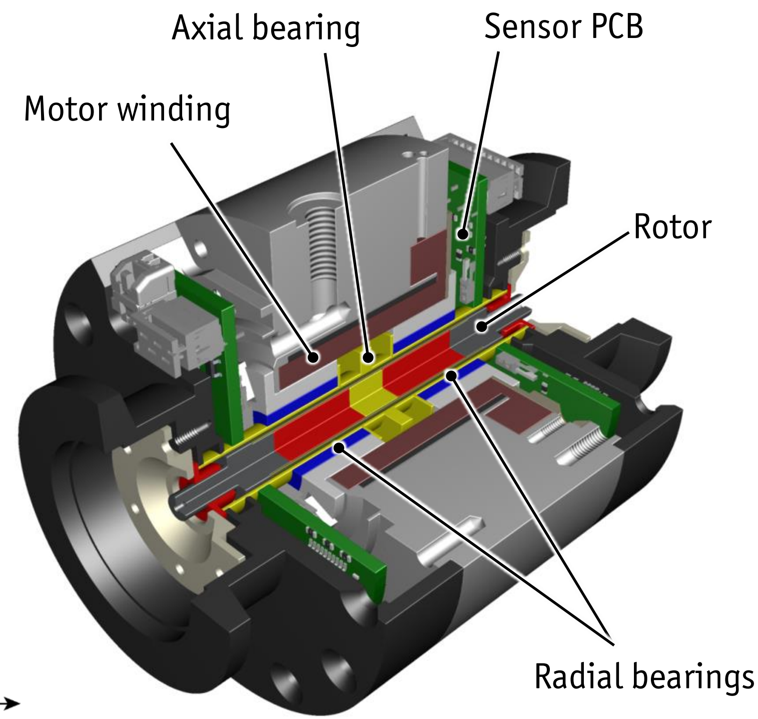


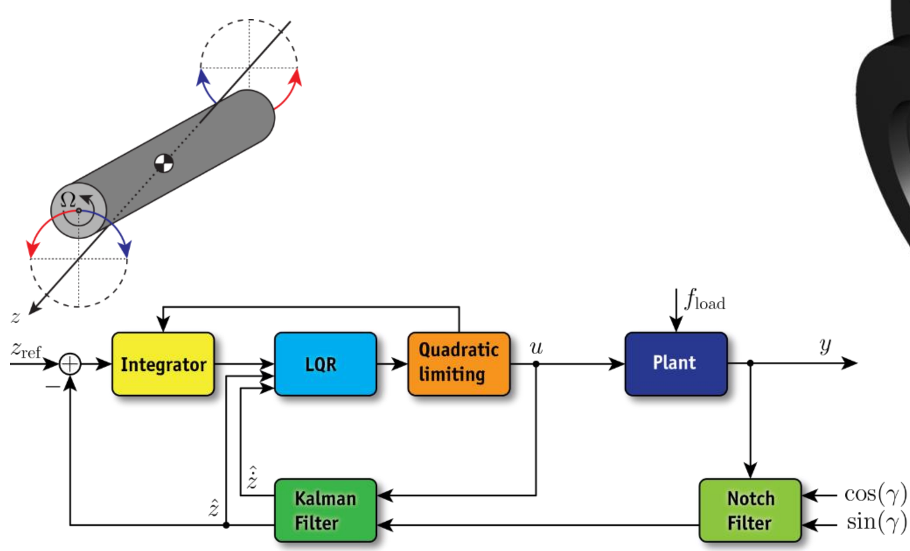
▶ Advanced Bearing Systems for Ultra-High-Speed-Drives (2)

■ Lifetime of Ball Bearings Limits Rotational Speed of Electric Machine

■ Active Magnetic Bearings

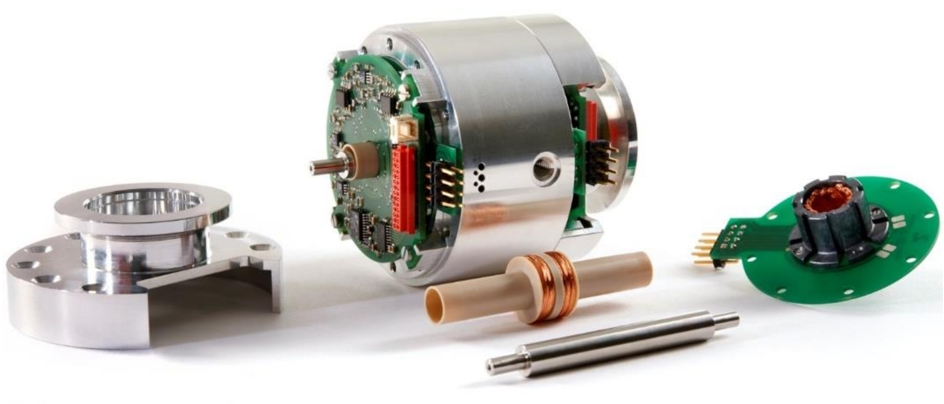
- \+ No Wear, Long Lifetime
- \+ Control of Rotor Dynamics
- \- Limited Load Capacity
- \- High Bandwidth / Complex Control
- \- Accurate Displacement Sensing

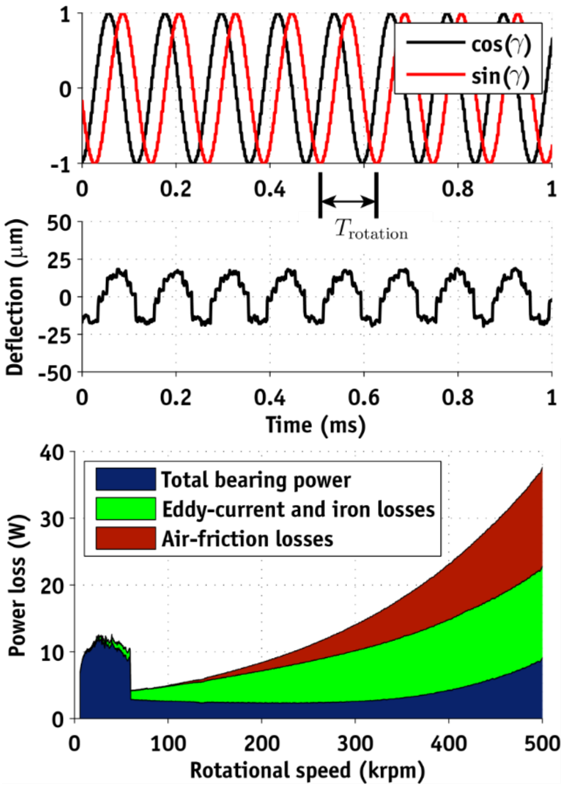




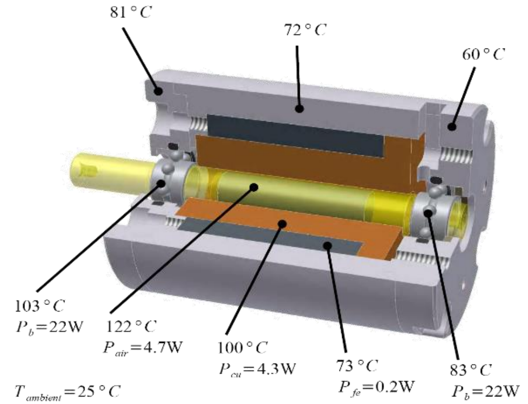
▶ World Record Magnetic Bearing with 500’000 r/min

- Demonstration of Active Magnetic Bearing Concept at World-Record Speed of 500’000 r/min

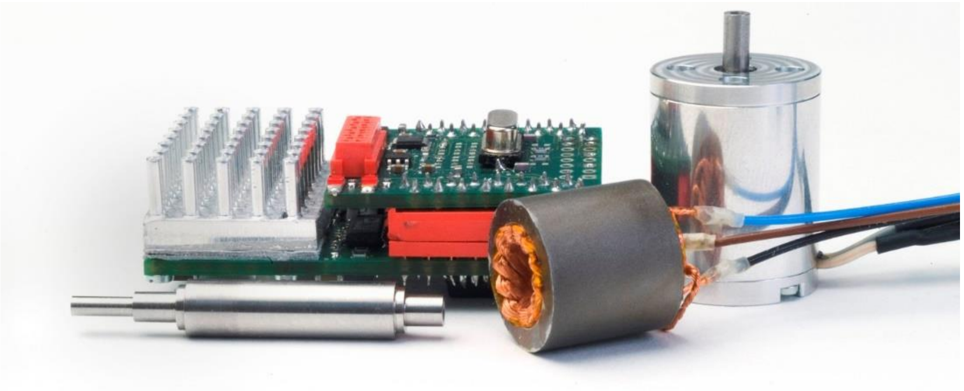


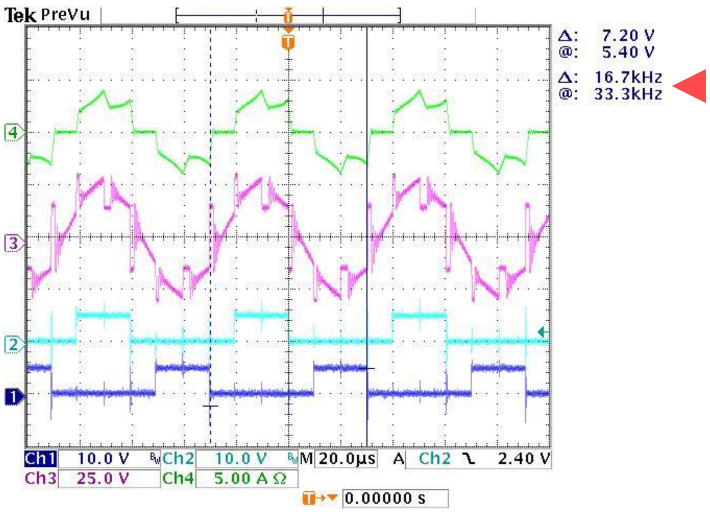


▶ 1’000’000 r/min- World Record Drive System



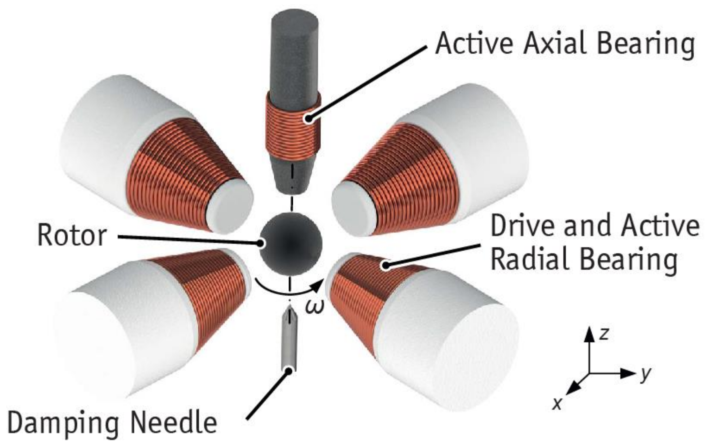
- **Demonstration of Machine Design Principles by 100 W / 1’000’000 r/min Drive System**
  - P_{loss} 9 W (excl. Bearings)
  - D_{rotor} 3 mm

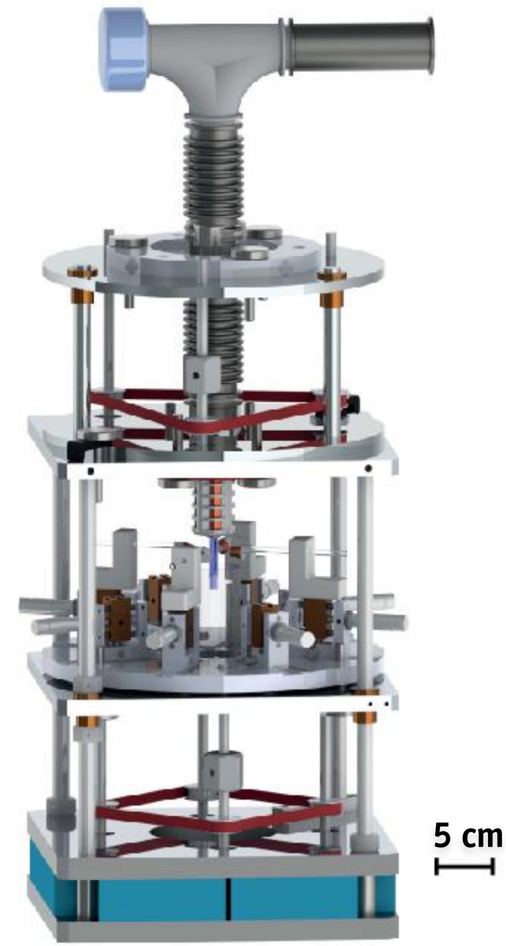




► Exploring the Limits: 29’000’000 r/min Electric Drive

- **Demonstrator System for Highest Recorded Rotational Speed for Electric Machines**
  - Development of Novel Control Concepts for Ultra-High Speed
  - Material Testing at Highest Centrifugal Acceleration

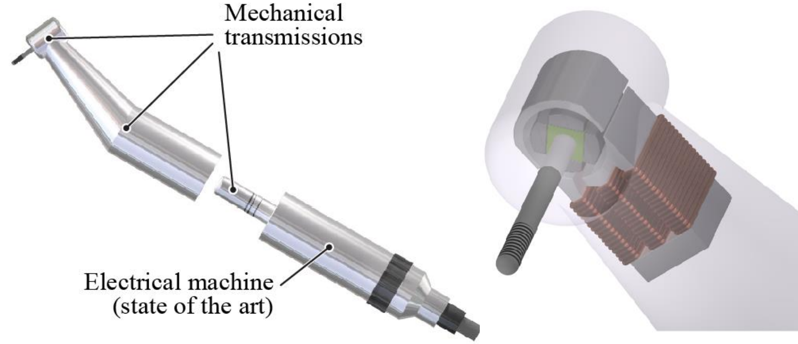




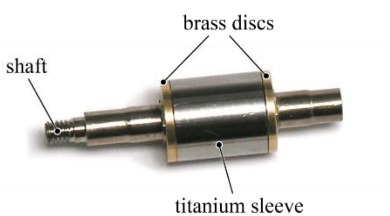
▶ Application-Specific Machine Concepts (1)

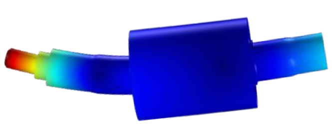
■ **Optimization of Machine Design for Application Specific Requirements**

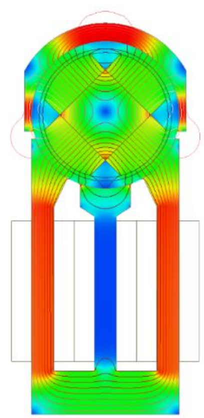
■ **Lateral-Stator Machine Concept**
- Novel Actuator Topology
- Direct Drive
- 3 x Higher Local Torque Density

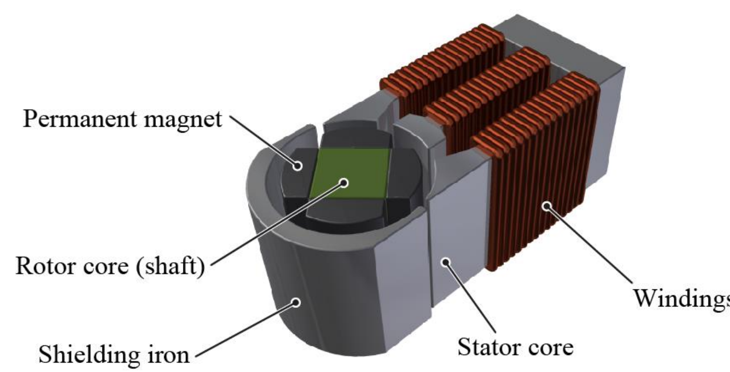


■ **2/3-D Numeric Analysis and Optimization**





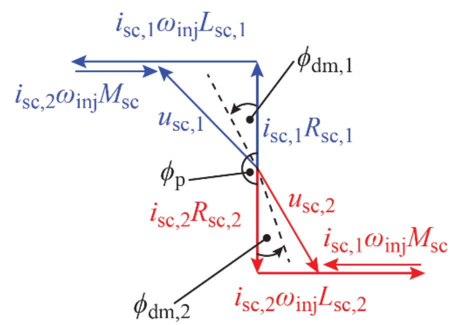


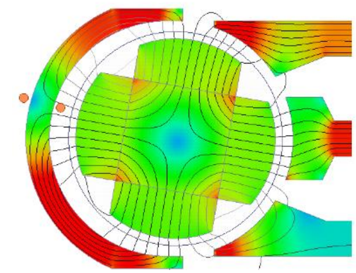


▶ Application-Specific Machine Concepts (2)

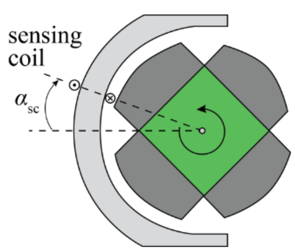
■ Optimization of Machine Design for Application Specific Requirements

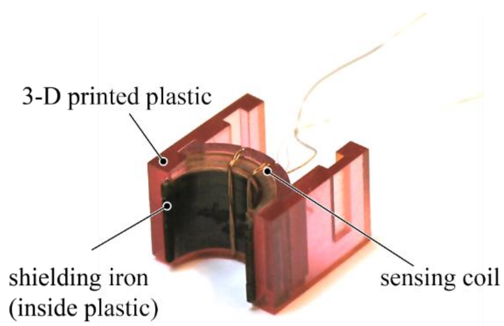
■ Lateral-Stator Machine Concept
- Novel Actuator Topology
- Direct Drive
- 3 x Higher Local Torque Density

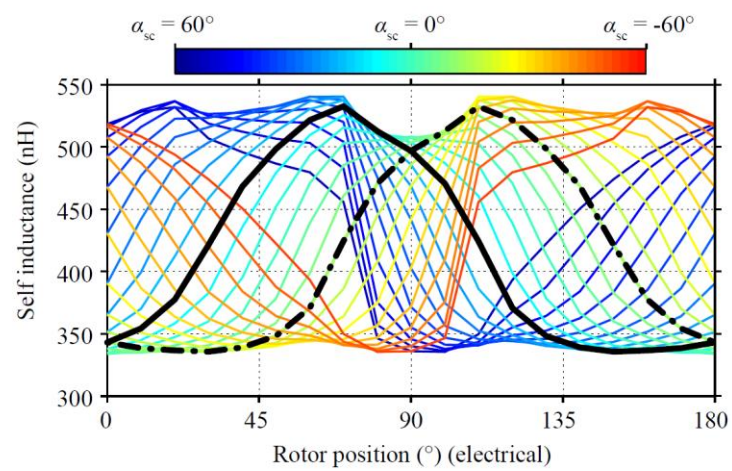




■ Topology-Specific Integrated Position Sensor
- Compact Realization
- Load Independent



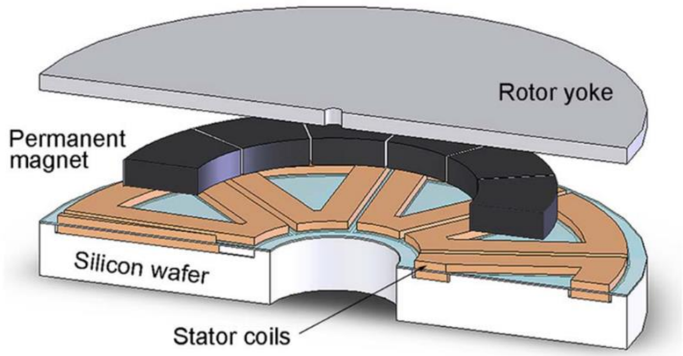


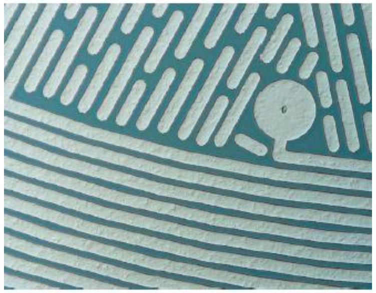


► MEMS Brushless-DC Micromotor

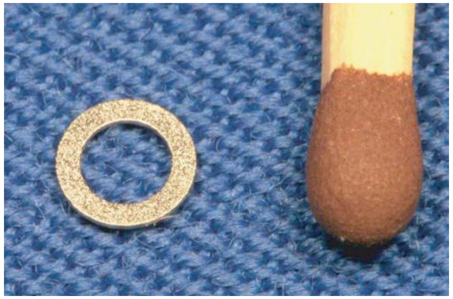
- **Main Application: Watch Industry**

- **Stator Manufactured in Clean Room** (CMOS Technology)
- **310 nW at 300 r/min**
- **42% Efficiency (Open-Loop Drive)**

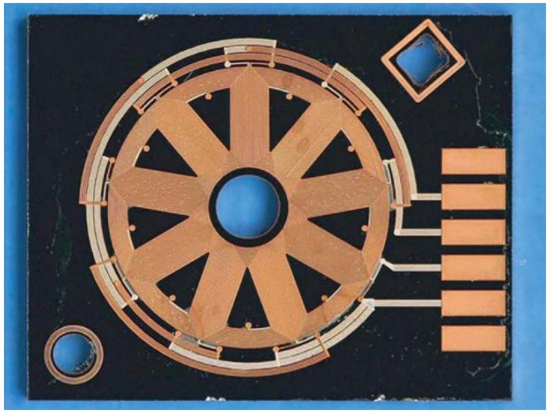




Stator Coil Structure



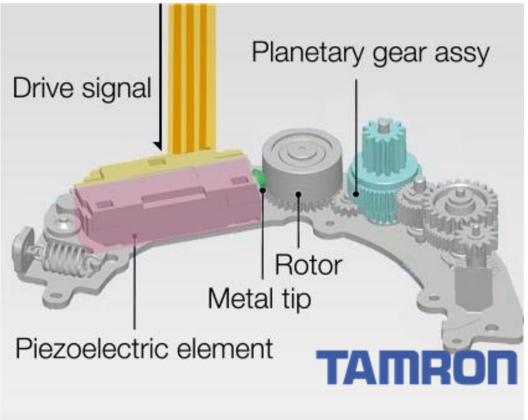
Permanent Magnet



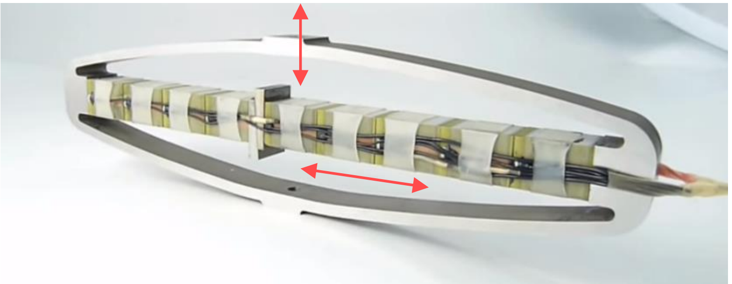
MEMS BLDC (Top View)

► Piezoelectric Positioning for Optical Systems

- High-Precision Positioning and/or Sensing
- High-Frequency (Ultrasonic) Vibration Control



- Nano-Meter Position Control with Piezo-Stack



cedrat-technologies.com

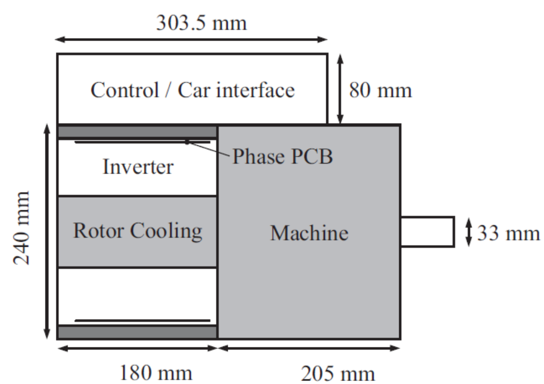
Electrical Drives: Performance Trends

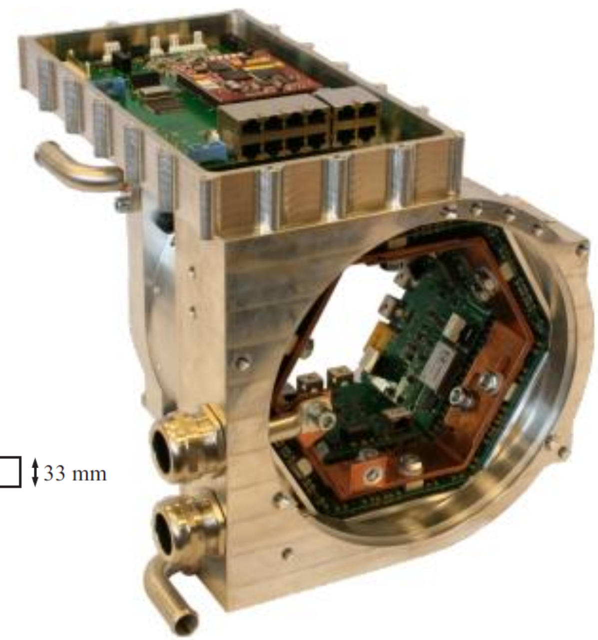
Compact & Lightweight Drives
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

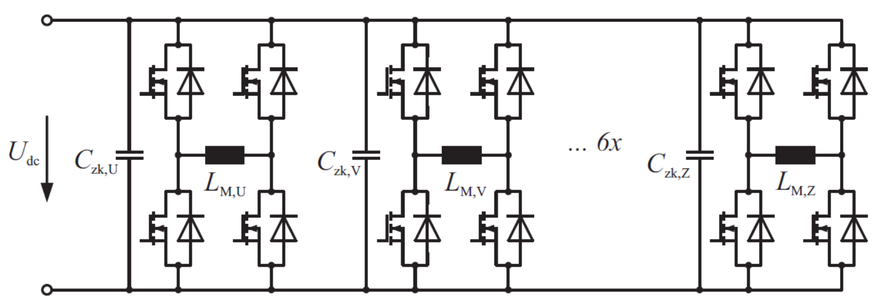
▶ Integration of Power Electronics & Electrical Machine (1)

- **Highest Compactness by Integration**
  - Shorter Connections betw. Components
  - Common Housing and Cooling System for Motor & Inverter

- **6-Phase Open-Windings Machine with Full Bridges using DirectFET**
  - P_{nom} 30 kW
  - V_{DC} 125 V
  - f_{out} 0 - 500 Hz
  - f_{sw} 50 kHz





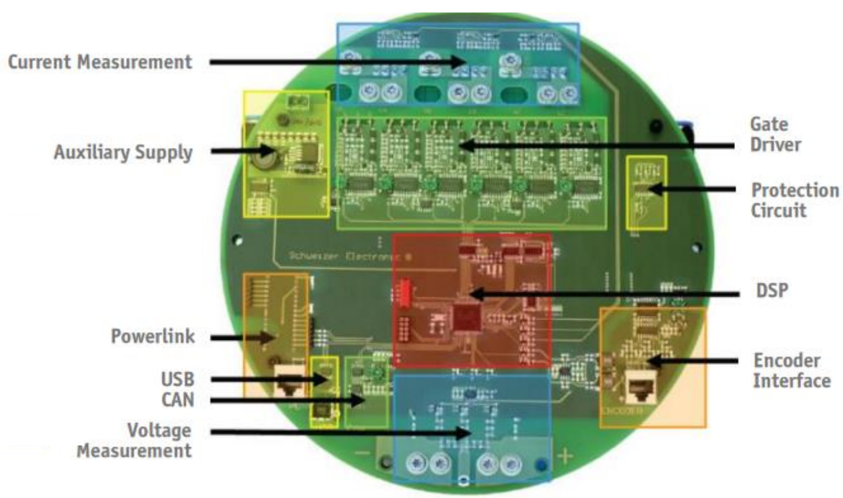


+ Fault Tolerant Design
- Number of Power Switches

▶ Integration of Power Electronics & Electrical Machine (2)

- **Highest Compactness by Integration**
  - Shorter Connections betw. Components
  - Common Housing and Cooling System for Motor & Inverter

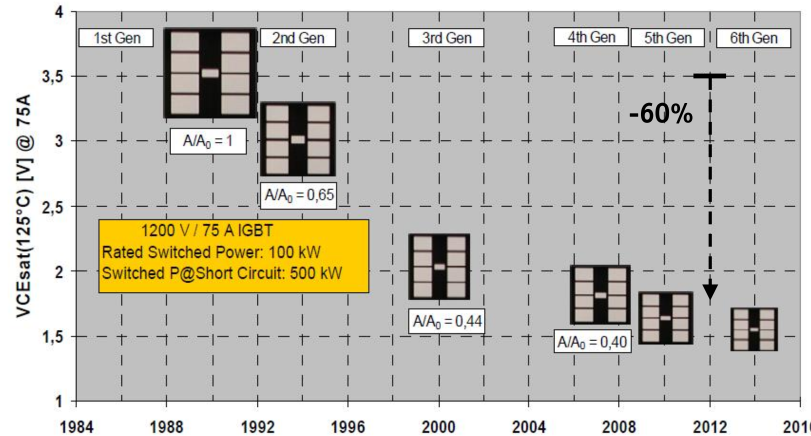
- **3-Phase Si-IGBT Inverter in p²pack-Technology**
  - S_{nom} 32 kVA
  - V_{in} 700 V
  - f_{out} 0 - 800 Hz
  - f_{sw} 20 kHz



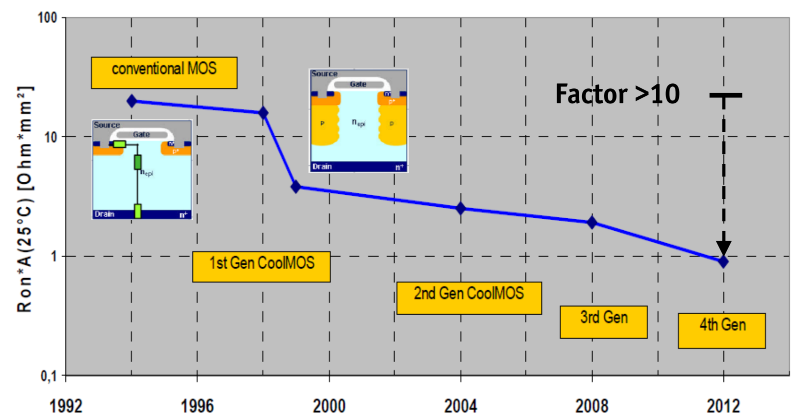
SCHWEIZER ELECTRONIC
enertronics

▶ Si Power Semiconductors

Source: Dr. Miller / Infineon / CIPS 2010



600V Devices

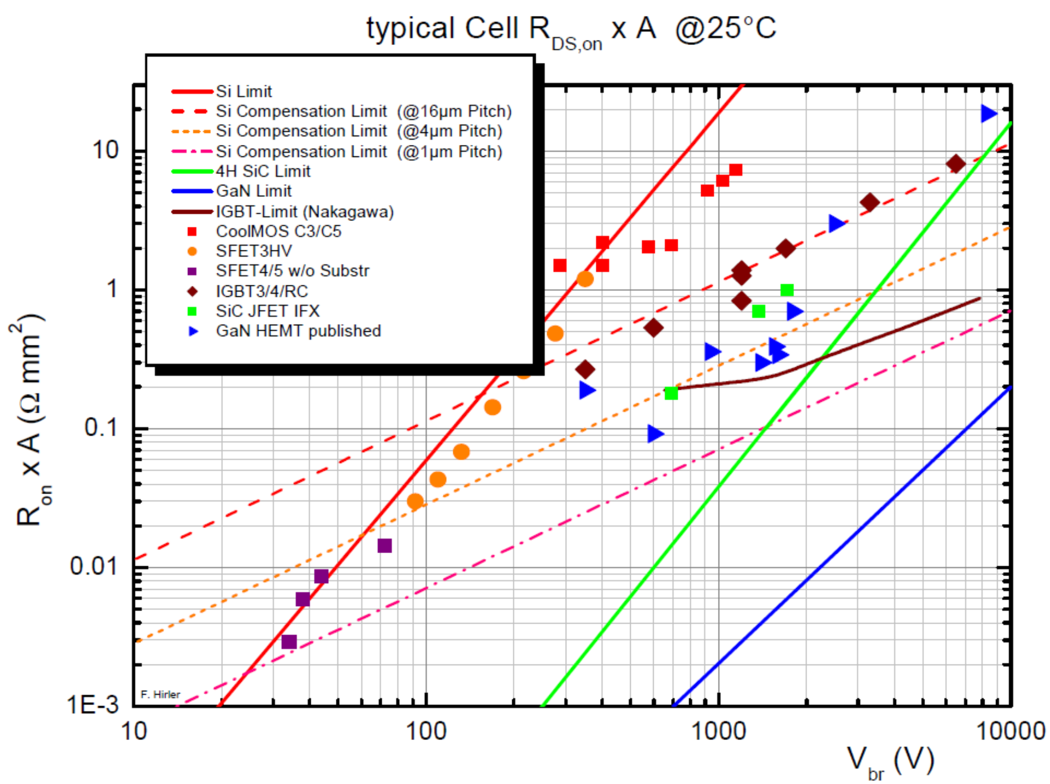


- **Past Disruptive Changes**

— **IGBT** **Trench & Field-Stop**
— **MOSFET** **Superjunction Technology**

▶ WBG Power Semiconductors

Source: Dr. Miller Infineon CIPS 2010

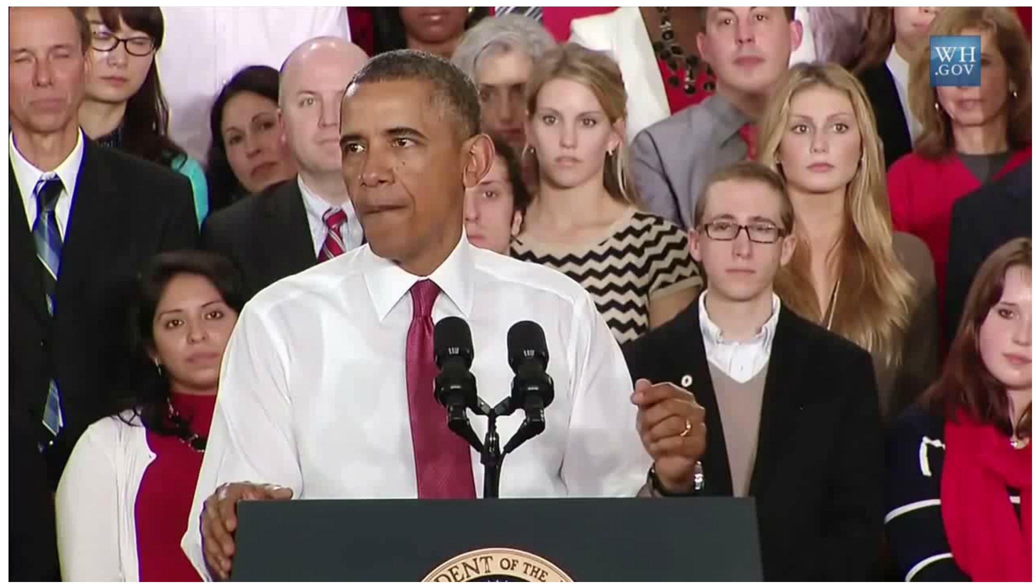


- **Disruptive Change**

  — Extremely Low $R_{DS(on)}$
  — Very High $T_{j,max}$
  — Extreme Sw. Speed

- **Utilization of Excellent Properties → Main Challenges in Packaging (!)**

▶ WBG Power Semiconductors



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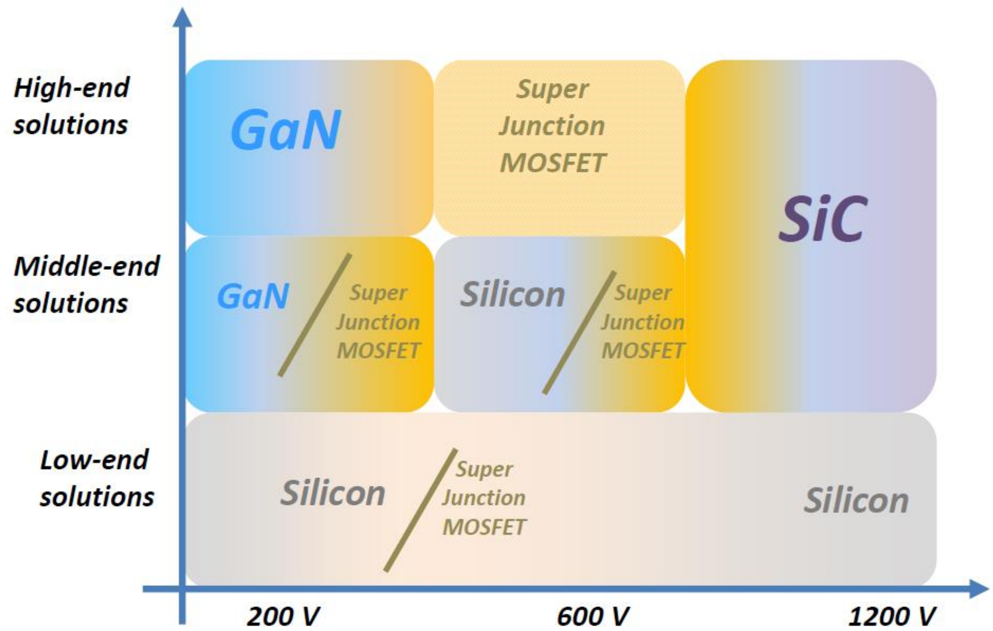
▶ WBG Power Semiconductors

■ Application Perspectives



Source: Dr. Honea
PEDG 2013
transphorm

What Yole Developement showed in 2011 as future view

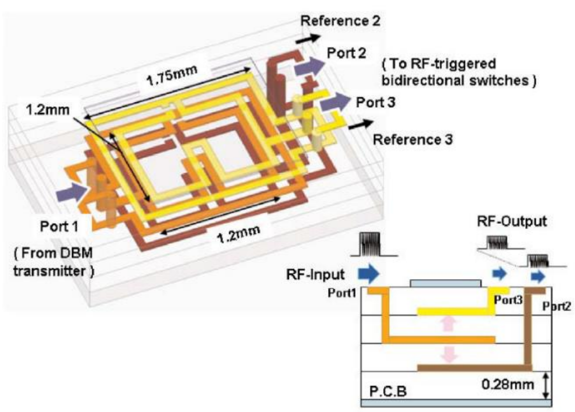
▶ Latest Systems Using WBG Devices → GaN

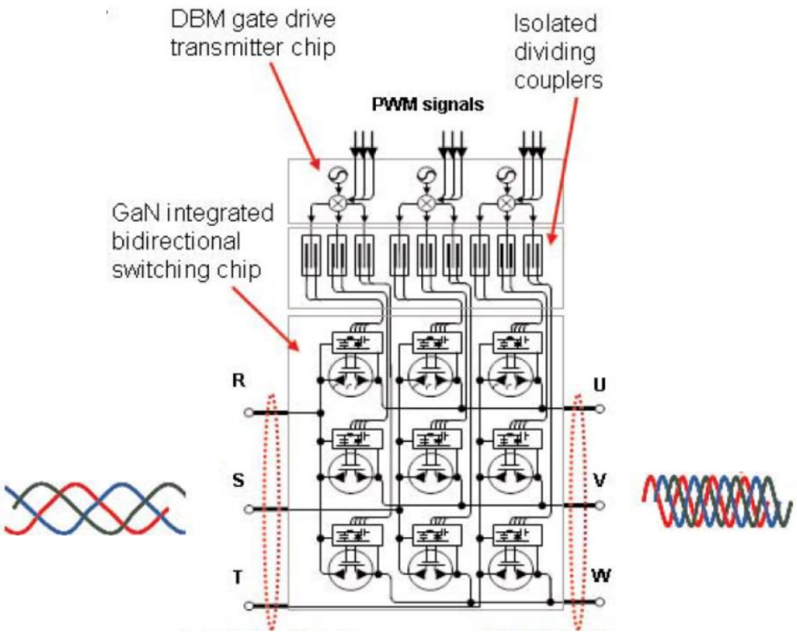
Source: Panasonic ISSCC 2014

■ GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology

- 9 Dual-Gate Normally-Off Gate-Injection Bidirectional Switches
- DBM Gate Drive Transmitter Chip & Isolating Dividing Couplers
- Extremely Small Overall Footprint - 25 x 18 mm^2 (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler

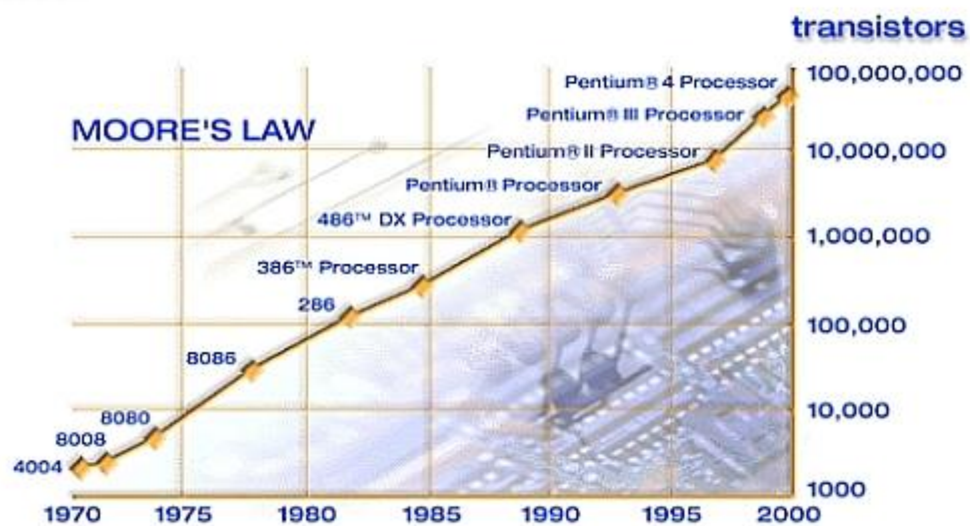




► Moore's Law: Key Enabler for Advanced Mechatronics

- **Micro-Controllers with Ever-Higher Signal Processing Capability**
  - Advanced Control Algorithms (e.g. Model Predictive Control)
  - Image Recognition in Robotic Applications
  - Fast-Closed Loop Control for High-Bandwidth Systems

- **Improved Computer-Aided Design Methods**
  - Finite-Element-Method Evaluation of Designs
  - Fully Virtual Prototyping and Multi-Physics Evaluation before Hardware Realization



Electrical Drives: Performance Trends

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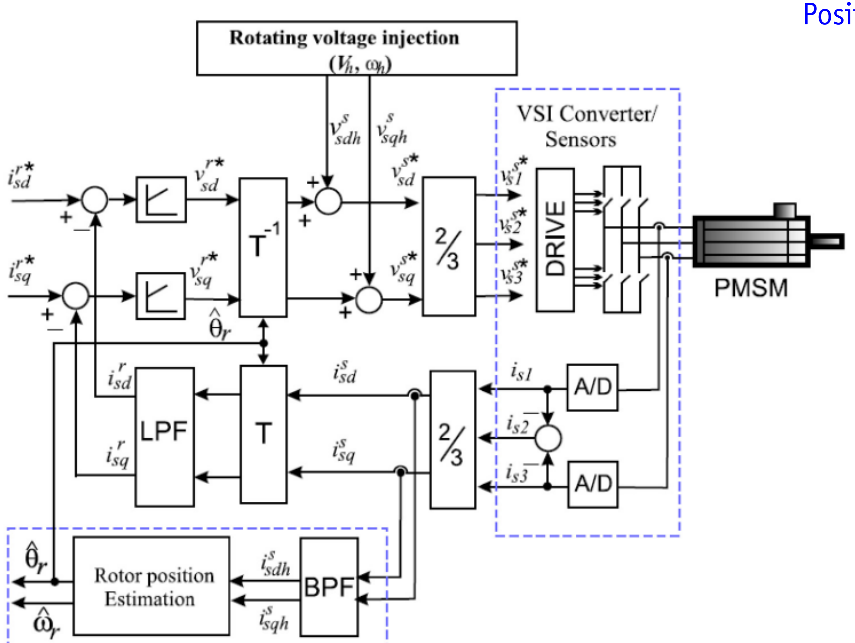
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

► Self-Sensing High-Reliability Drive Systems

■ Elimination of the Position Sensor

- Increased Reliability
- Compact & Cost Effective
- Additional Signal Processing
- Challenging for Certain Machine Types



Sensor Cable

Position Sensor

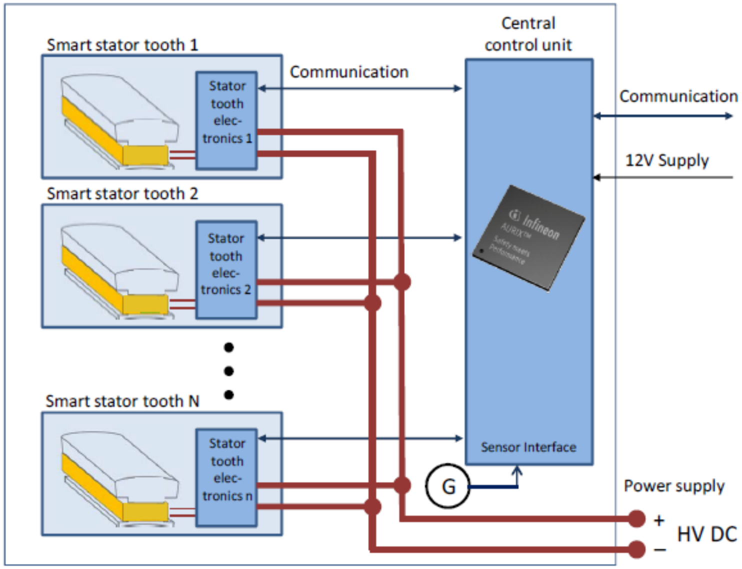
Source: galilmc.com

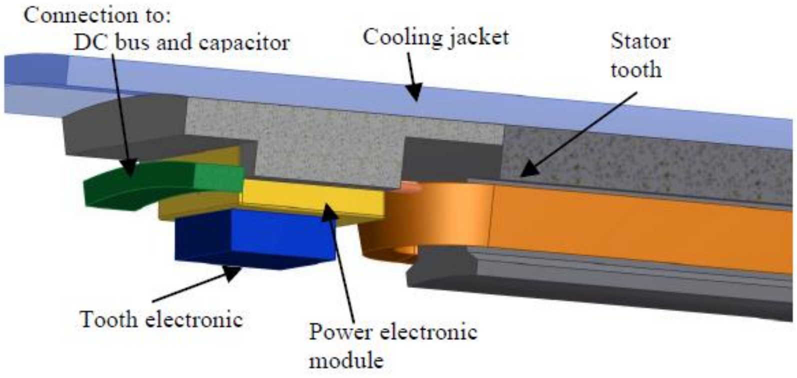
▶ Smart Tooth Concept for Fault Tolerant Machines

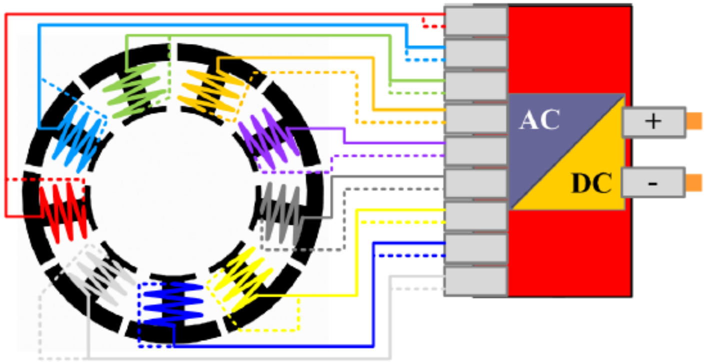
Source: Brockerhoff et. al.
Highly integrated drivetrain solution:
Integration of motor, inverter and gearing

- **Smart Tooth Concept**
  - Stator Segment
  - Power Electronics
  - Control Electronics

- **Higher Power Density**
- **Fault Tolerance**
- **Higher Efficiency**
- **Lower Cost**







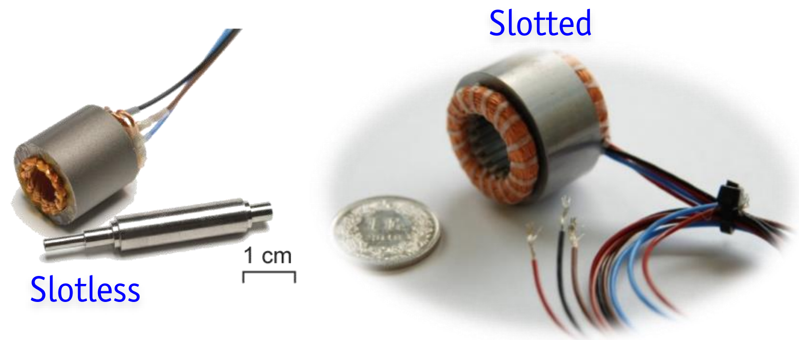
Electrical Drives: Performance Trends

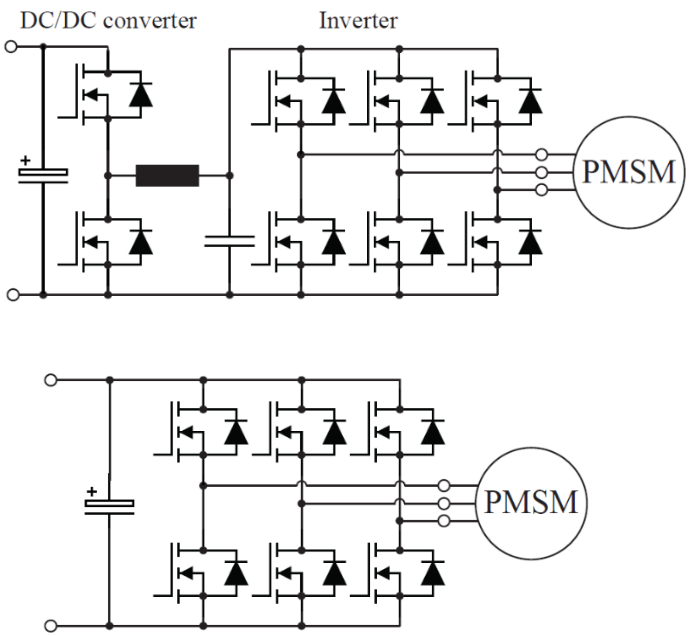
Compact & Lightweight Drives
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

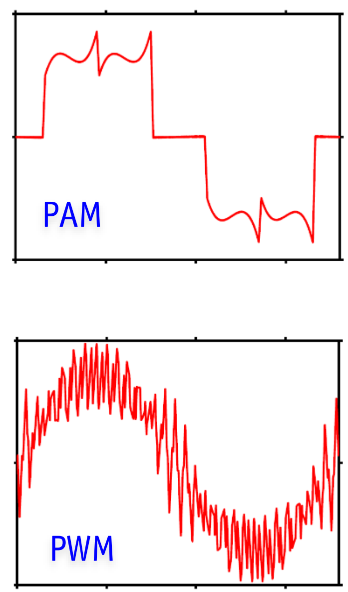
▶ Optimized Modulation Scheme for High Efficiency

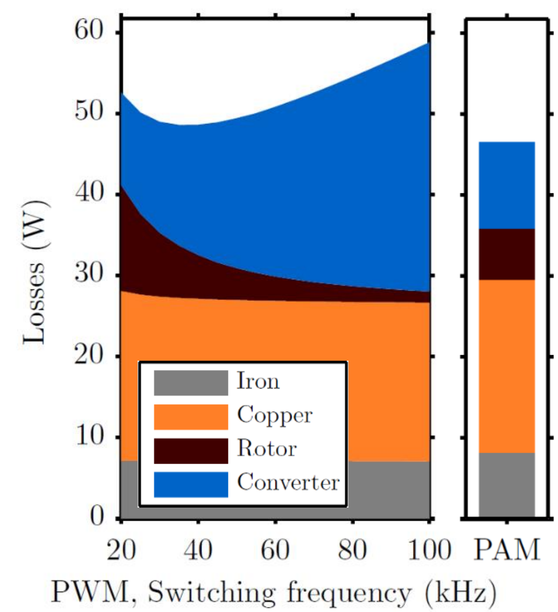
■ Modulation Scheme as a Degree-of-Freedom

- Optimum Selection Depends on
  - Machine Type
  - Rotational Speed
  - Loss Distribution
  - Power Level





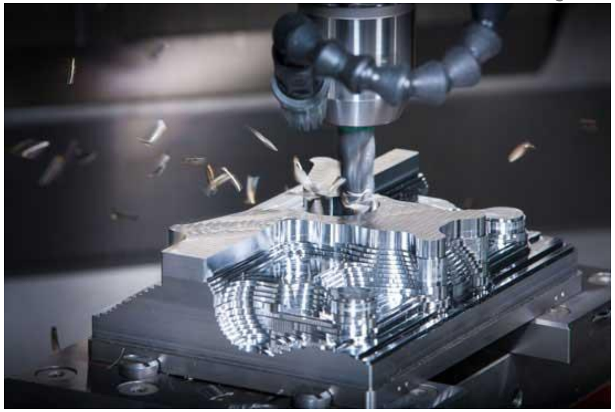




▶ Increased Productivity in Manufacturing

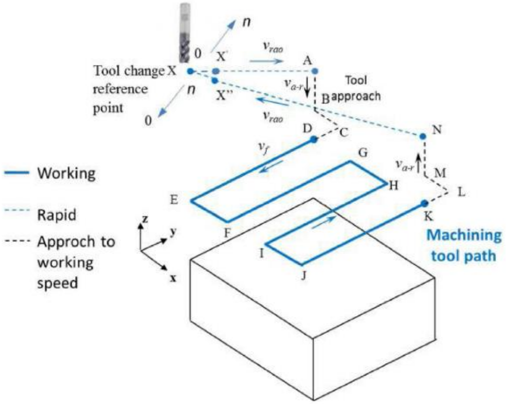
- **Industry Consumes 43% of the Electricity Production Globally**
  - In Germany as much as 47%
  - Machining is a Major Energy Consumer
  - Metal Cutting has Largest Share in Automotive Industry

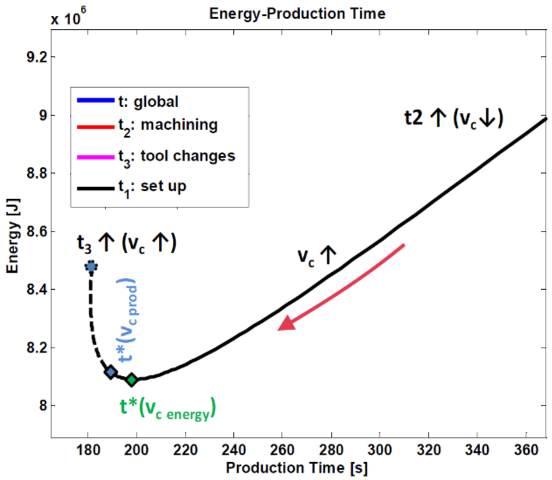
Source: ut-machining.com



- **High Motivation for Sustainable Manufacturing**
  - Legislative Initiatives: 2009/125/EC and 2012/27/EU
  - Cost Savings from Reduced Energy Consumption

- **Multi-Objective Optimization for Competing Design Goals**
  - Low Energy Consumption, Low Wear, Short Manufacturing Time
  - What is Optimum Cutting Trajectory & Speed, Feed Rate, ...





Source: Calvanese et.al.
Analysis of Energy Consumption in CNC Machining Centers and Determination of Optimal Cutting Conditions

Electrical Drives: Performance Trends

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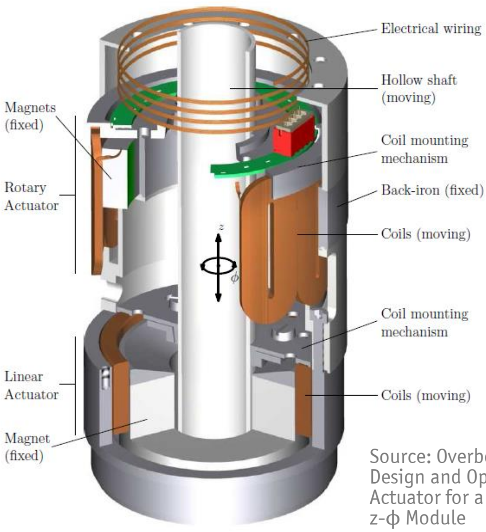
High Accuracy & Dynamics
Extreme Ambient Conditions

▶ Motion Control with Extreme Accuracy & Dynamics

Source: etel.ch



Source: Overboom et. al
Design and Optimization of a Rotary Actuator for a Two Degree-of-Freedom z-ϕ Module

High Positioning Accuracy

- Wafer Processing/Inspection
- Air Bearings
- Active Isolation System for Vibration Decoupling

- $S_{X,Y}/S_Z$ 320/12 mm
- $a_{X,Y}/a_Z$ 1.2/0.2 g
- a_ϕ 1 000 rpm/s

- Position Stability: ±25 nm, ±1 µrad
- Bidirectional Repeatability: ±0.4 µm, ±10 µrad

Highly Dynamic Operation

- High Throughput Pick & Place: 10 000 pcs/hr
- Integrated Linear and Rotational Actuator

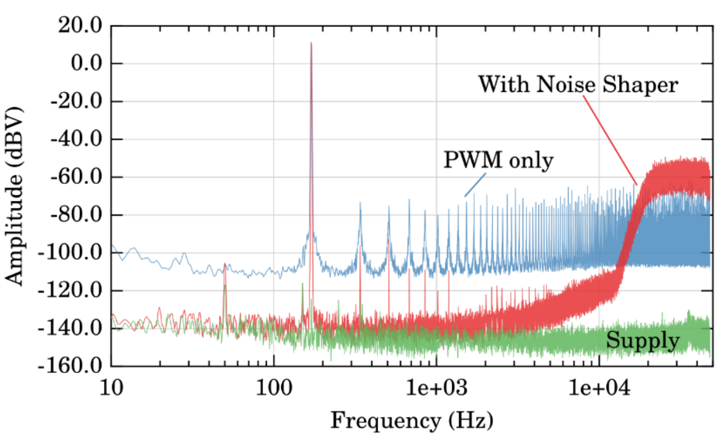
- S_ϕ 1 turn
- S_Z 10 mm
- a_Z 15 g
- a_ϕ 73 500 rpm/s

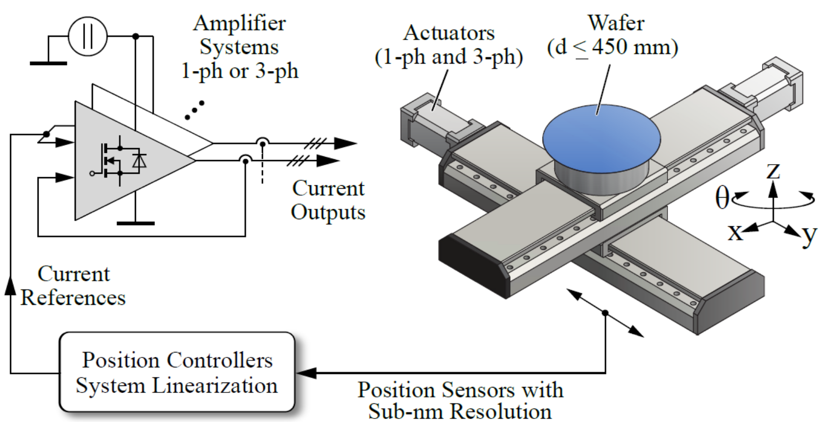
- Linear Accuracy: 5 µm
- Rotational Accuracy: 3 mrad

▶ High-Precision Amplifiers for Mechatronic Applications

- **1 or 3-Phase nm-Precision Positioning System**
  - Linear/Rotational Permanent Magnet Machine
  - Magnetic Bearing System to Avoid Friction
  - Ultra-Low Noise/Distortion of Output Current
    → SNR & THD > 100 dB Required

- **In-Depth Analysis of Noise/Distortion Sources in all System Components (Power Stage, Control, etc.)**
- **High-Quality Current Shaping with Fast-Switching WBG Power Semiconductors (GaN, SiC)**





Electrical Drives: Performance Trends

Compact & Lightweight Drives
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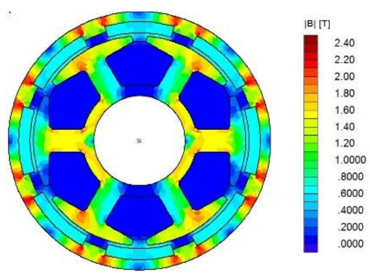
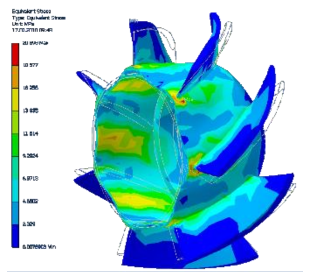
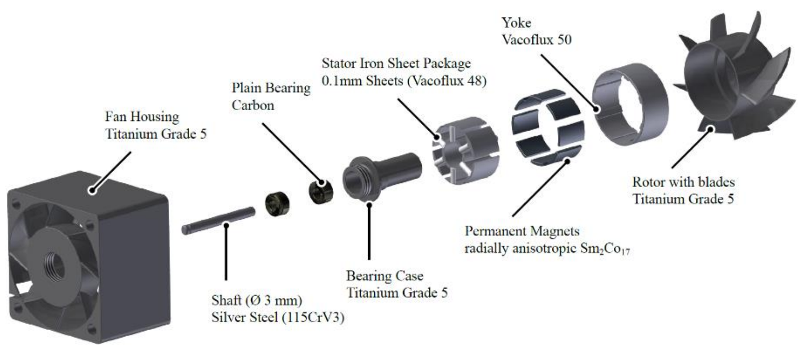
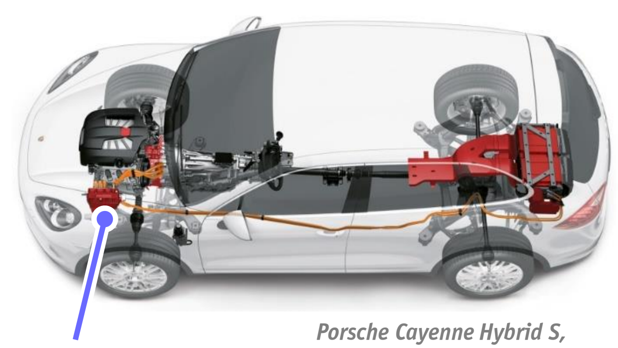
▶ Extreme Temperature Drive System

- **Extreme Ambient Temperatures Common in Automotive Applications (e.g. Hybrid EV)**
  - Cooling of Power Electronics Critical
  - High Complexity of Liquid Cooling System
  - Dedicated High Temp. Fan Required for Forced-Air Cooling



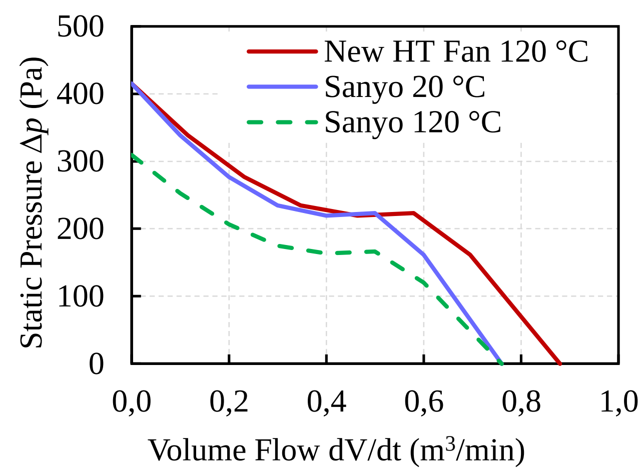






$T_A \approx 120\ ^\circ C$

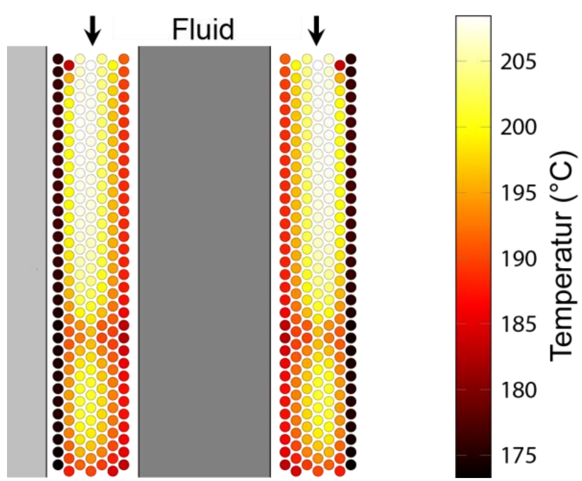
Porsche Cayenne Hybrid S,
www.porsche.de

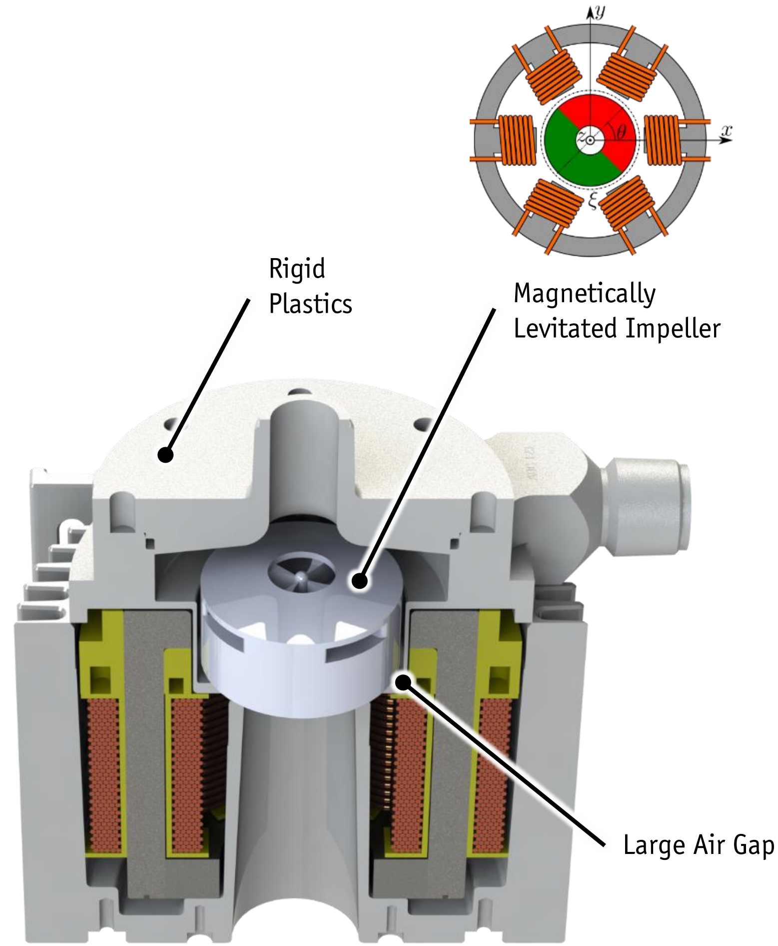


▶ High-Temperature Pump for Acidic Environment

- **Pumping of Sulfuric Acid at up to 280°C**
  - Magnetic Levitation to Avoid Mech. Shaft
  - No Particle Generation/Fluid Contamination

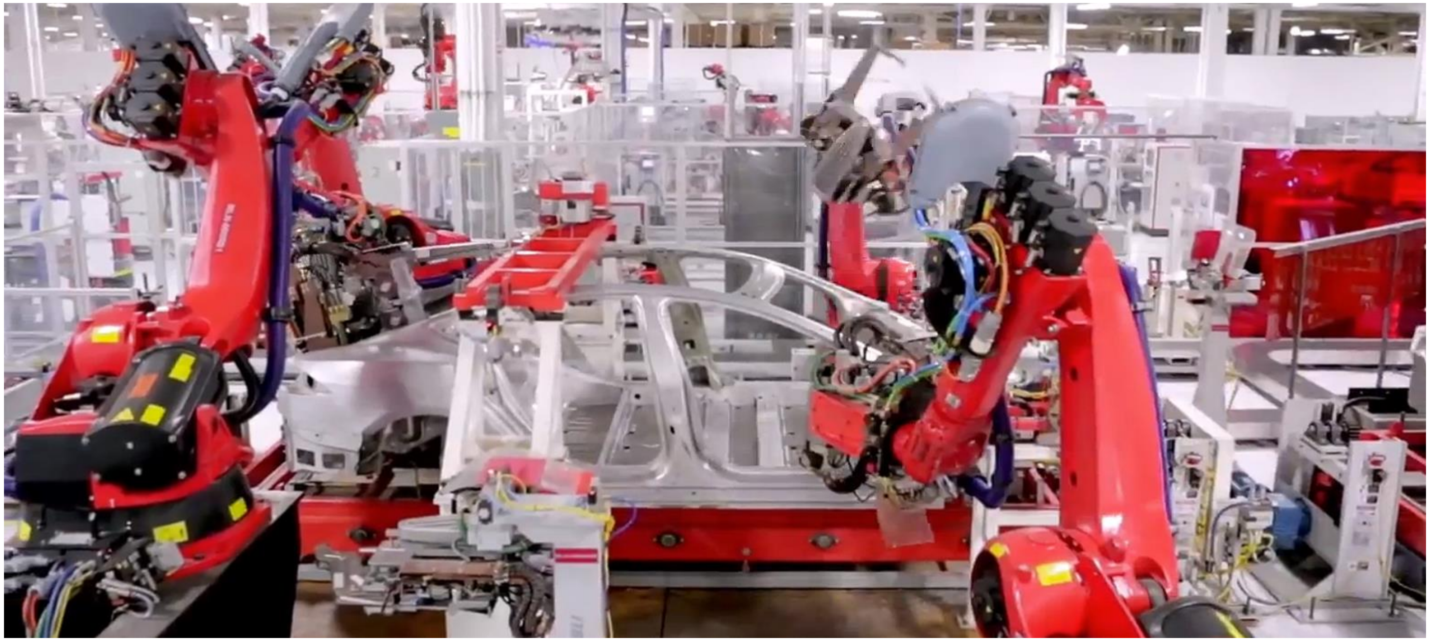
- **Key Design Challenges**
  - Mechanical Stability Despite Thermal Expansion
  - Chemical & Thermal Resistance
  - High-Temperature Eddy-Current Sensor
  - Self-sensing for Rotor Angle Detection





► Selected Applications in Future Mechatronics

Source: TESLA MOTORS



Selected Applications in Future Mechatronics

Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

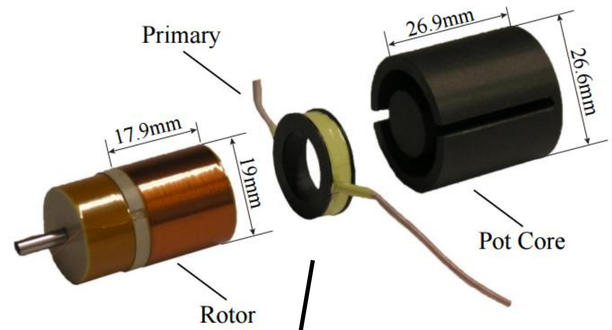
Selected Applications in Future Mechatronics

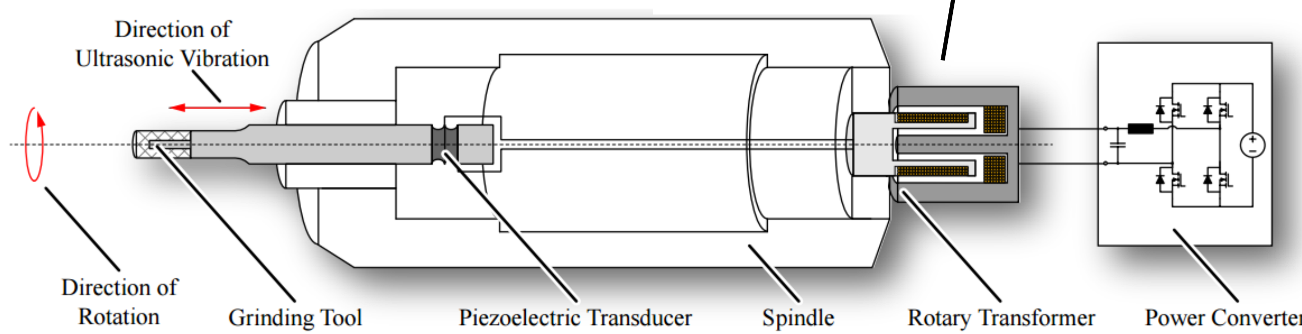
Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

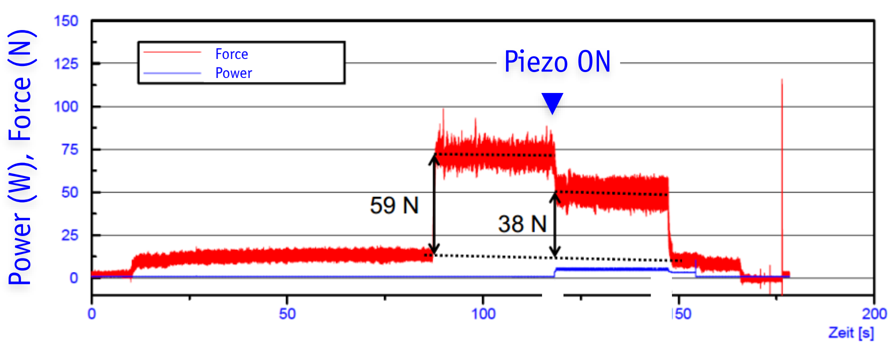
▶ Grinding Tool with Piezoelectric Actuator

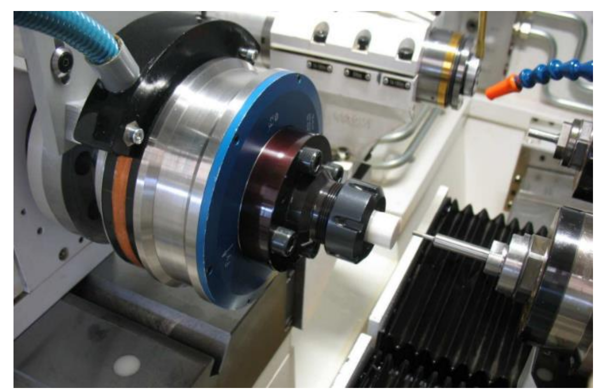
■ Ultrasonic Vibrations to Grinding Tool

- Reduced Stress & Wear on Cutting Tool
- Cost Reduction for Grinding Process
- Contactless Power Supply of Piezoelectric Transducer
- Wireless Supply to Rotor





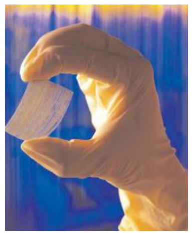


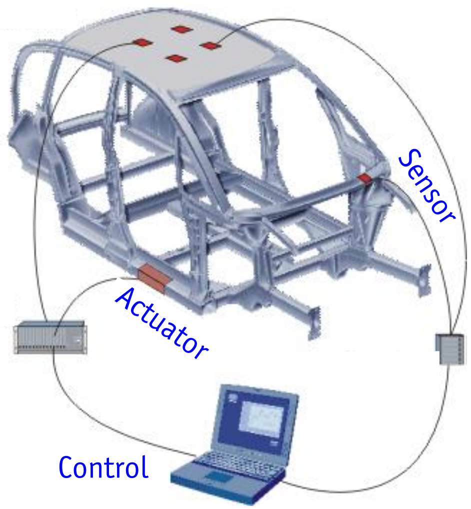


▶ Adaptronics: Adaptive Mechanical Structures

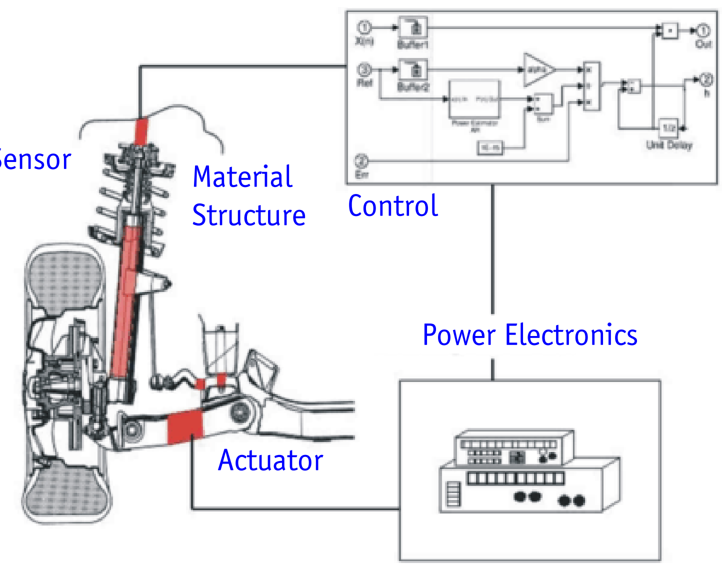
■ Lightweight Mechanical Structures with Active Piezoelectric Vibration Damping

Flexible Piezoelectric Fibers Incorporated in Material Layers



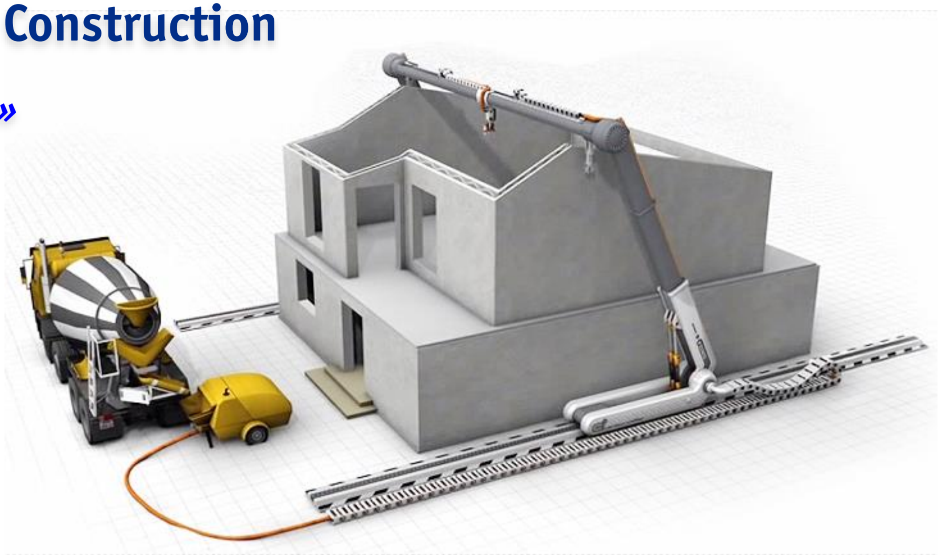


Fraunhofer ADAPTRONIK



▶ Robots for Autonomous Construction

- **Contour Crafting: Large *«3D Printer»***
  - 185 m^2 House in Under 24 Hours
  - Low Cost / Low Waste



- **Fast Brick Laying Robots**
  - Faster Construction

http://spectrum.ieee.org/automation/robotics/industrial-robots/robots-do-construction-with-brick-and-concrete

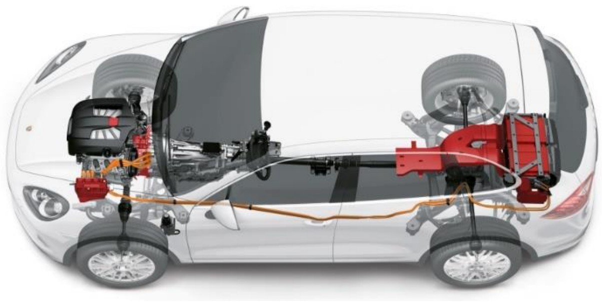
Selected Applications in Future Mechatronics

Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

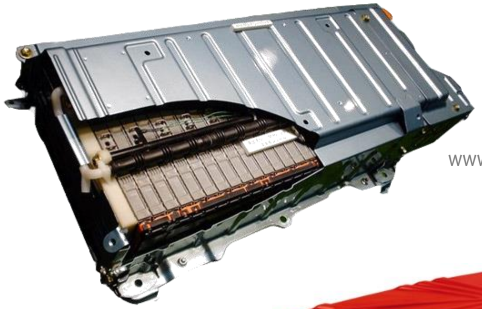
► Hybrid & Battery Electric Vehicles

- **25% of Global CO_2-Emissions Caused by Transportation Sector**
  - Replace Fossil Fuels by *Renewable* Electrical Power
  - Smaller CO_2-Footprint and Lower Total Cost of Ownership

- **Main Technology Enablers/Drivers**
  - Battery Energy/Power Density & Cost
  - Charging Technology & Infrastructure
  - (Cost) Optimization & Integration of Powertrain and Power Electronics



Porsche Cayenne Hybrid S,
www.porsche.de



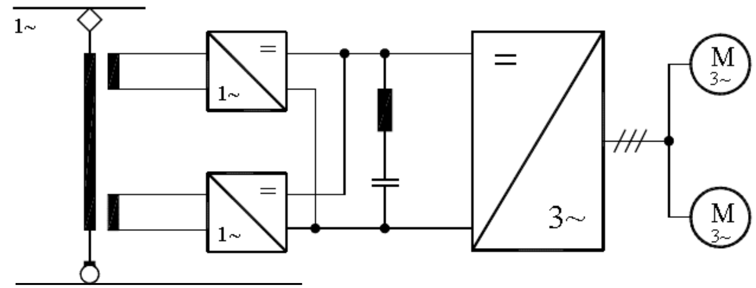
UNIST,
www.unist.ac.kr

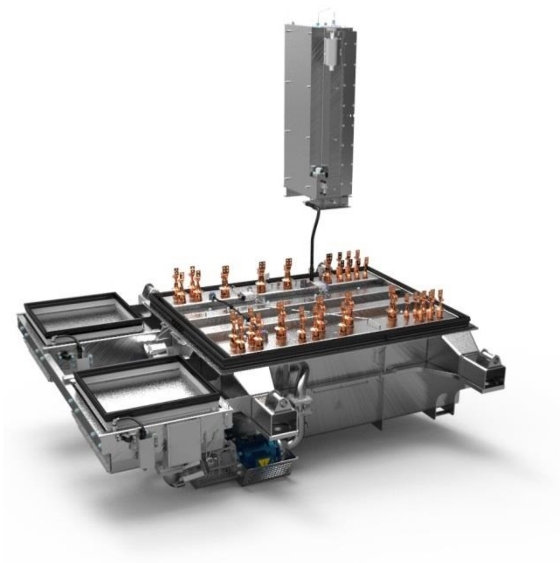
BRUSA 22kW Charger,
www.brusa.biz

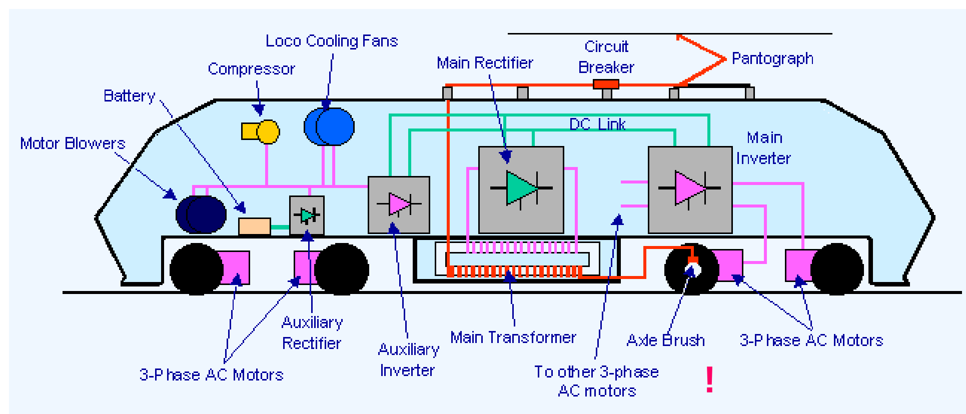
Honda Accord Hybrid,
www.honda.com

▶ Classical Locomotives

- Catenary Voltage 15kV or 25kV
- Frequency $16\,^{2}/_{3}$Hz or 50Hz
- Power Level 1...10MW typ.







Transformer:

Efficiency	90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
Power Density	2...4 kg/kVA

▶ Next Generation Locomotives

- **Trends:**
  - Distributed Propulsion System → Volume Reduction (Decreases Efficiency)
  - Energy Efficient Rail Vehicles → Loss Reduction (Requires Higher Volume)
  - Red. of Mech. Stress on Track → Mass Reduction

Source: ABB

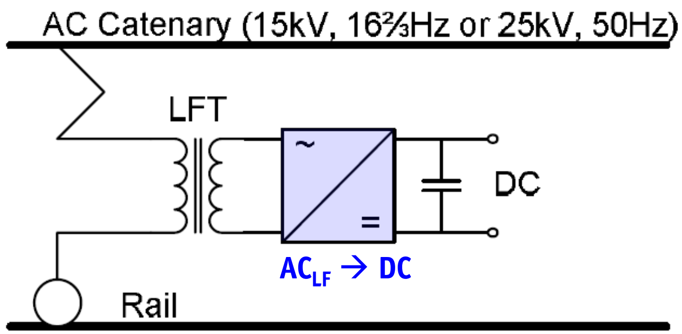


Fig. 1. *Conventional AC-DC conversion with a line frequency transformer (LFT).*

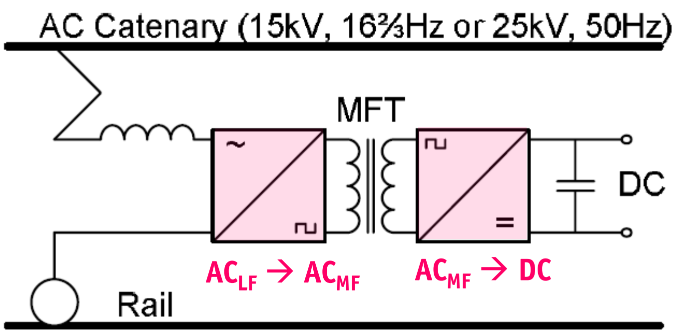


Fig. 2. *AC-DC conversion with medium frequency transformer (MFT).*

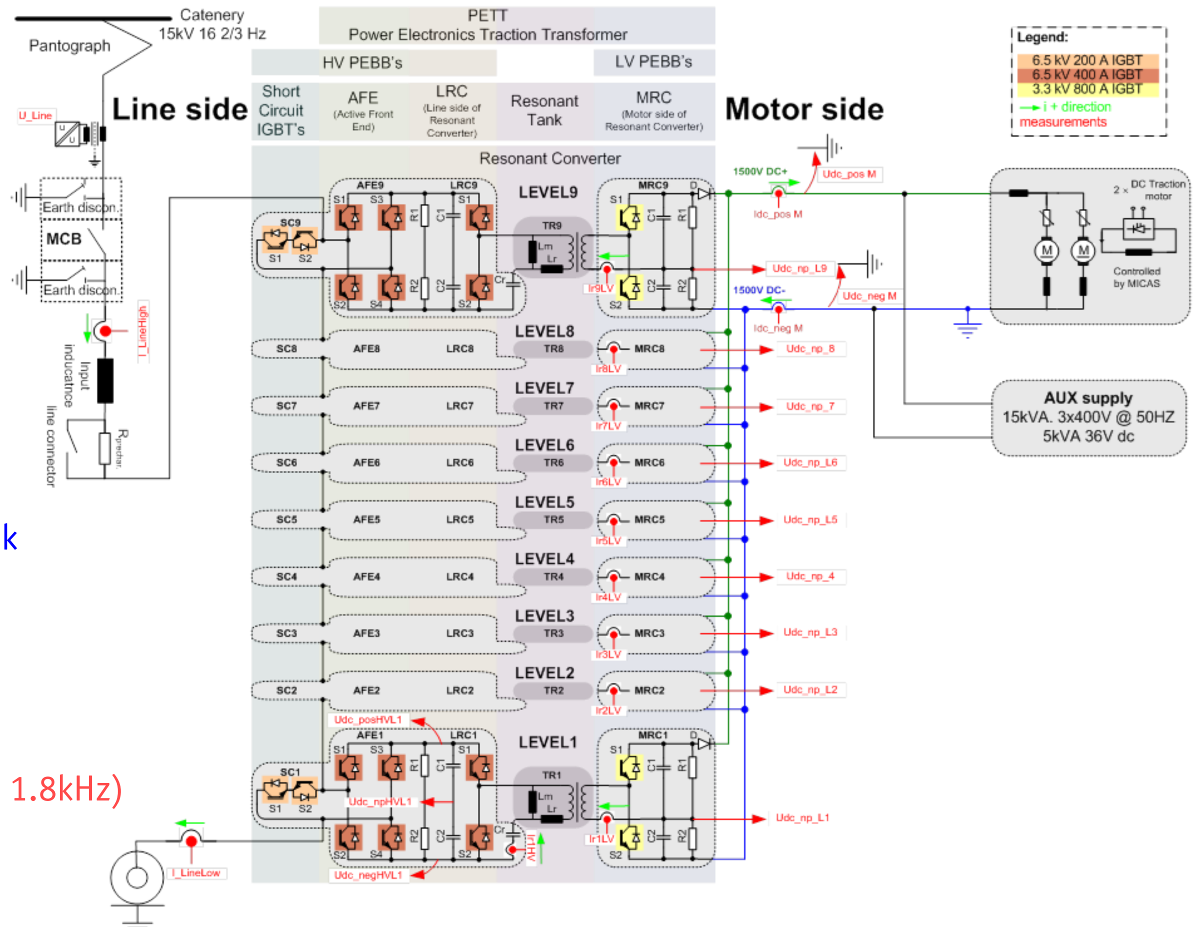
- Replace LF Transformer by Medium Frequency Power Electronics Transformer → **SST**
- Medium Frequency Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction

▶ 1ph. AC/DC Power Electronic Transformer - PET

ABB

- Dujic et al. (2011)

- Rufer (1996)
- Steiner (1997)
- Heinemann (2002)



P = 1.2 MVA, 1.8 MVA pk
9 Cells (Modular)

54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

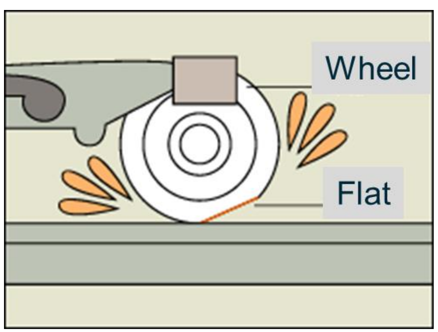
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

► Energy Harvesting in Railway Applications (1)

- **Wheel Lock During Braking**
  - Cost of Repair
  - Downtimes
  - Replacement Costs

- **Anti-lock Braking System (ABS)**
  - Electrical Power Not Available for Controller on Freight Wagons

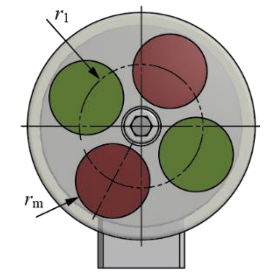
- **Local Electrical Energy Harvesting**
  - Non-Contact
  - Modular
  - Robust
  - 5 ... 10 W @ 10 mm Air Gap
  - Self-starting

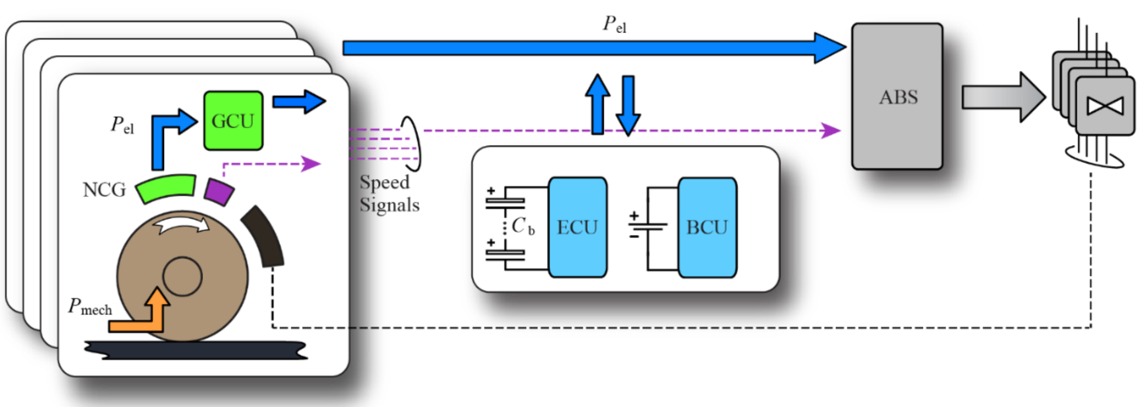


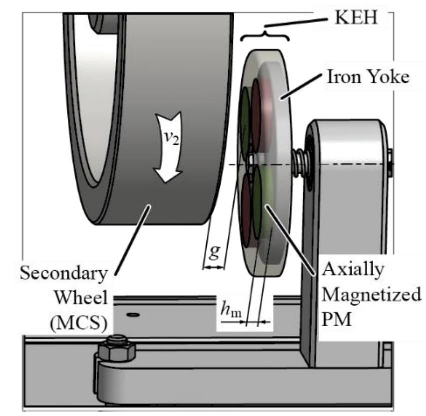
▶ Energy Harvesting in Railway Applications (2)

- **Novel Axial-Flux Non-Contact Energy Harvester**
  - High Magnet Utilization
  - Generator can be Integrated

- **Energy Management**
  - Energy Storage
  - Line Voltage Regulation
  - Maximum Power Tracking







▶ Energy Harvesting in Railway Applications (2)

■ Novel Axial-Flux Non-Contact Energy Harvester

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■ Energy Management

- Energy Storage
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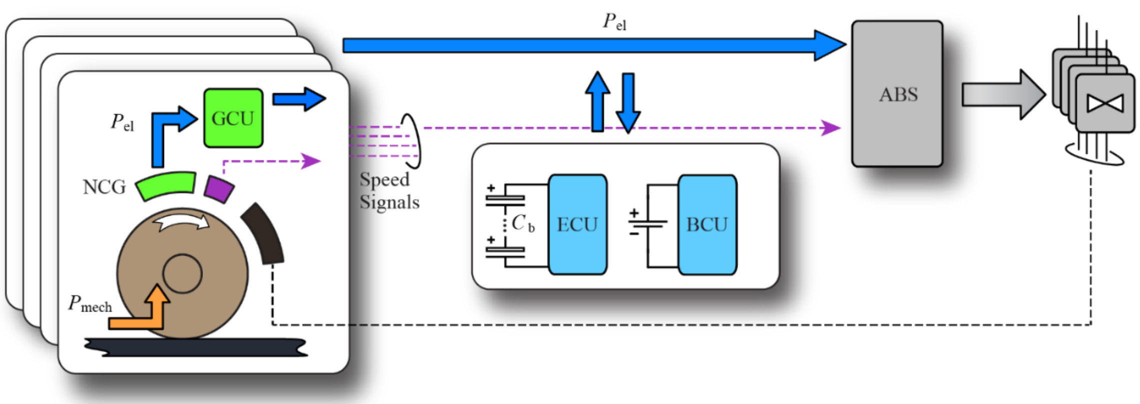
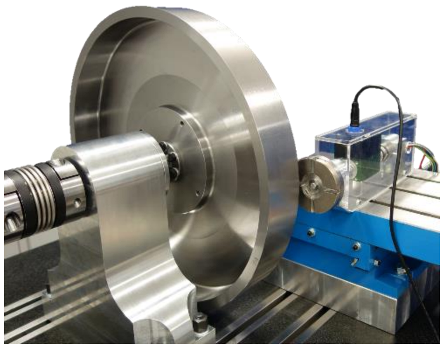


1/2 Scale Test Bench

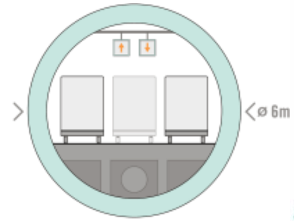
- Close to Real Application
- Dynamic Measurements
- Speed Sensing Development

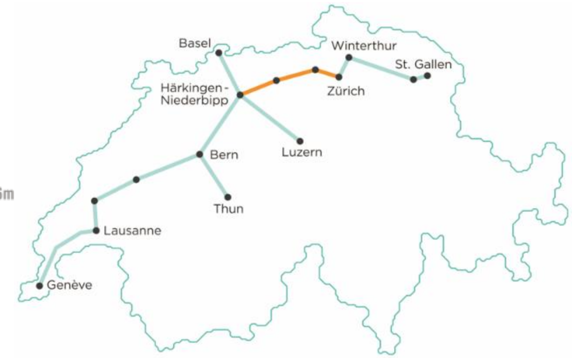


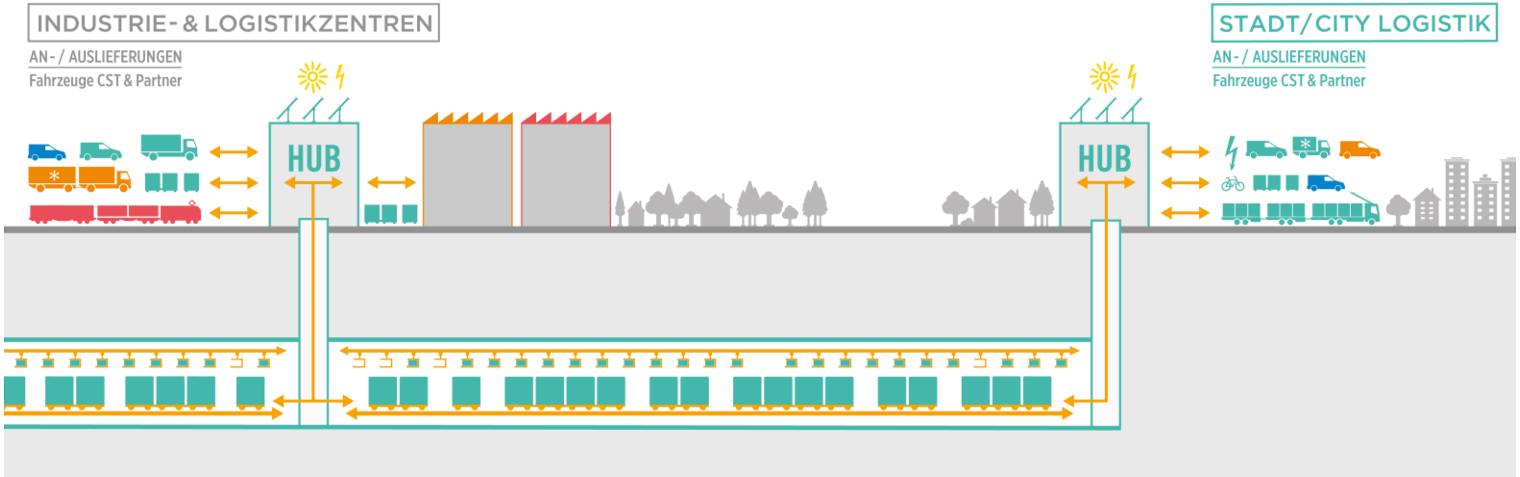
▶ Cargo Sous Terrain in Switzerland

- **Project in Switzerland for Novel Logistics System**
  Developed and Fully Financed by Industry

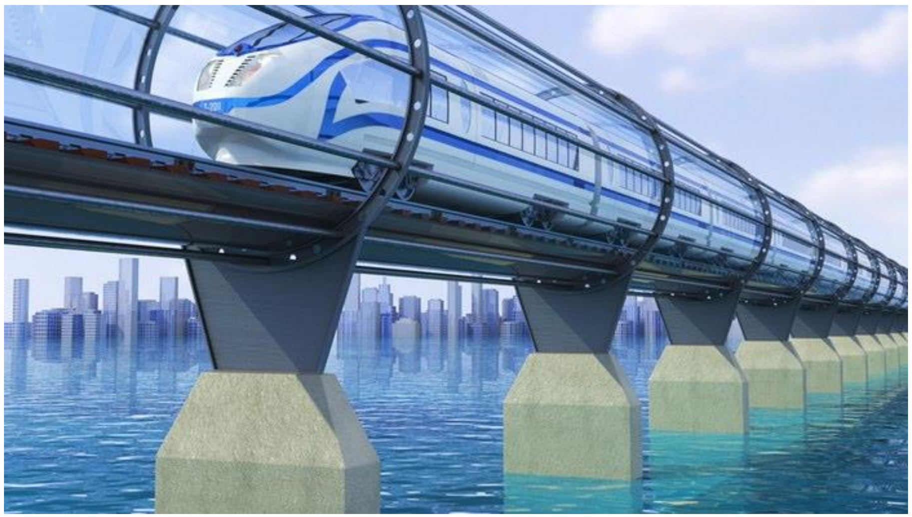
- **Overground Transportation of People**
- **Underground Transportation of Goods**





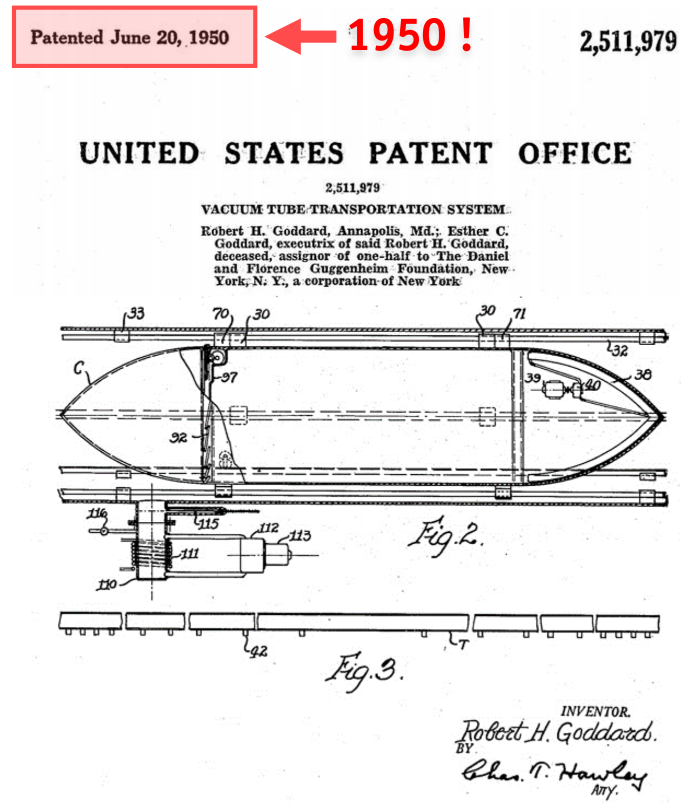


▶ Futuristic (!) Transportation: Hyperloop



Source: gizmag.com

1950 !



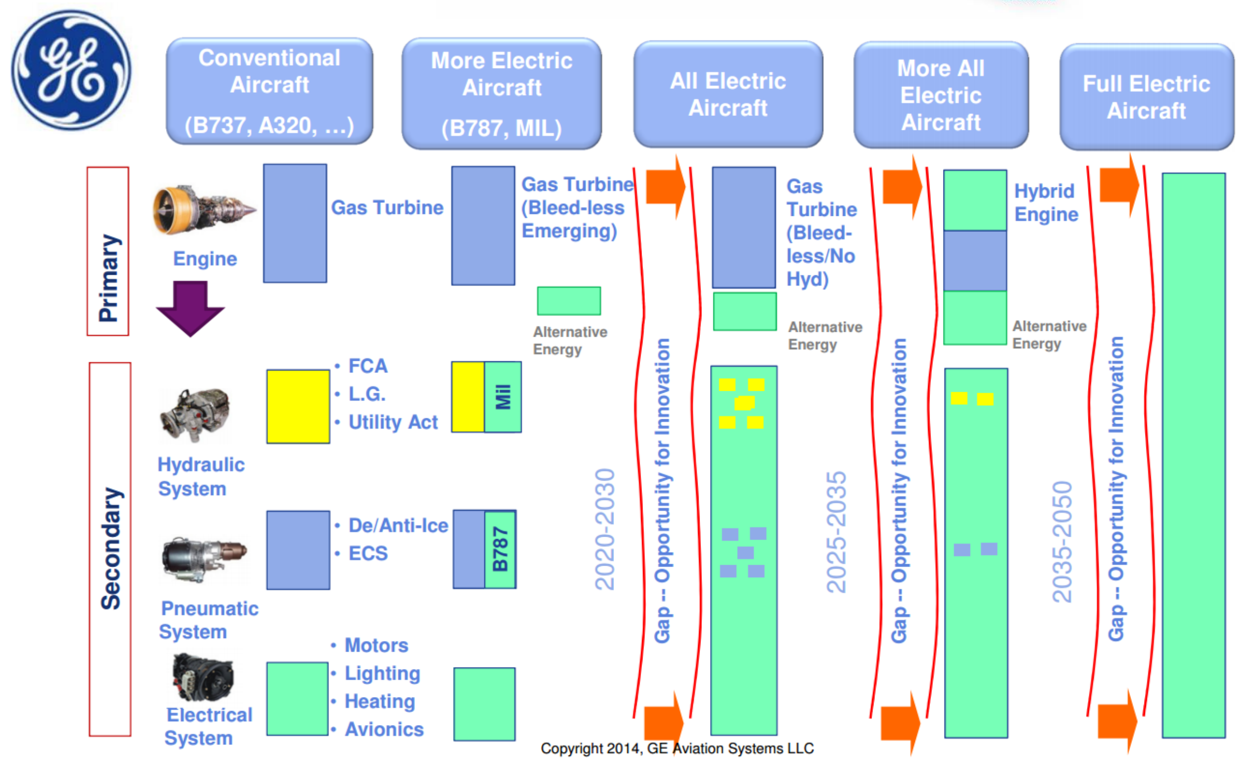
- High Speed Train in Evacuated Tube
- Los Angeles → San Francisco in 30 Minutes
- Low Friction: Low Energy Costs
- Maglev or Hovercraft Technology

▶ Towards the Full Electric Aircraft (1)

- **Reduction of Fuel Consumption and CO_2-Footprint**
  - Lower Noise Emissions and Environmental Impact

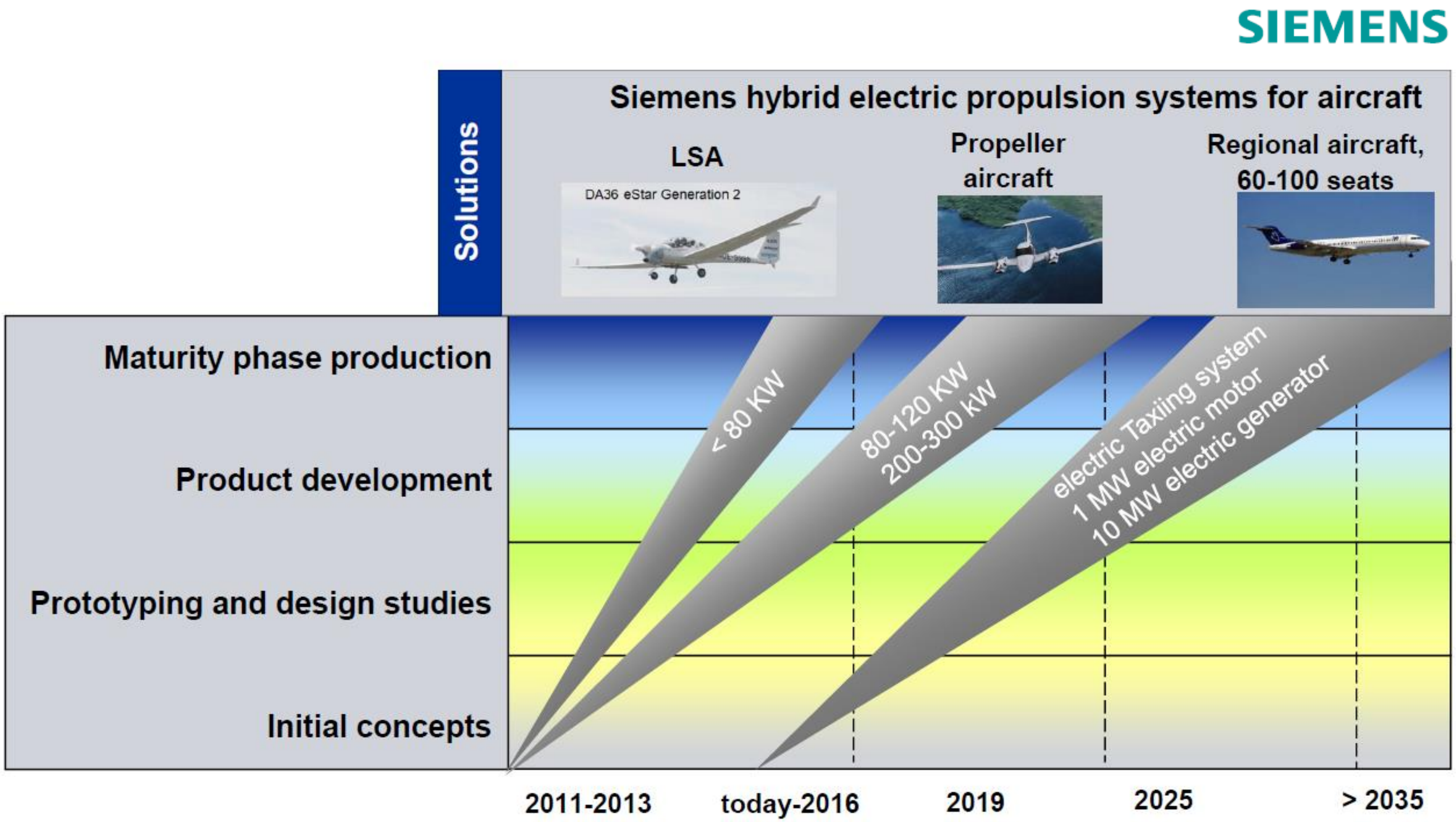
- **Multi-Disciplinary Innovation Opportunities!**

labinal-power.com



▶ Towards the Full Electric Aircraft (2)

- **Today:** Full Electric 2-Seater Planes for Pilot Training
- **Near Future:** Electric Propulsion for Regional Transportation



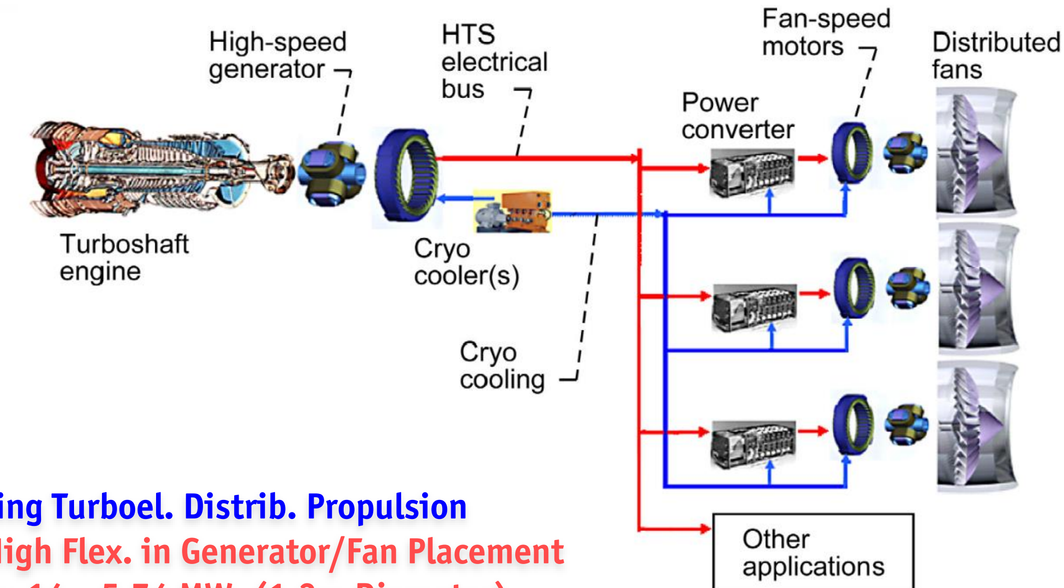
► Future Hybrid or All-Electric Aircraft

Source: EADS

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- Until 2050: Cut CO_2 Emissions by 75%, NO_x by 90%, Noise Level by 65%

▶ Future Hybrid Aircraft

Source: NASA



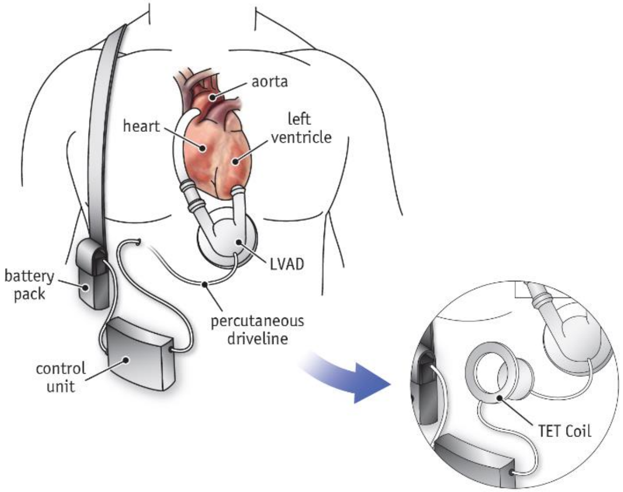
- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

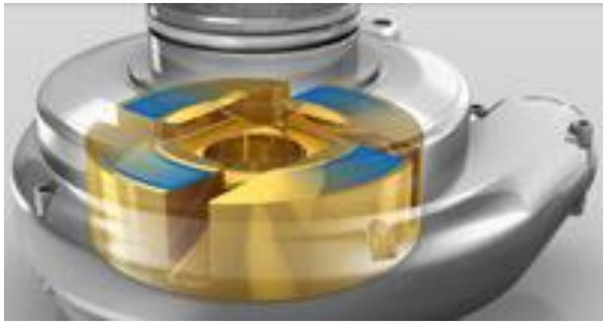
Selected Applications in Future Mechatronics

Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

► Implantable Left-Ventricular Assist Device

■ **Highly Compact Electrical Drive for Implantable Blood Pump**





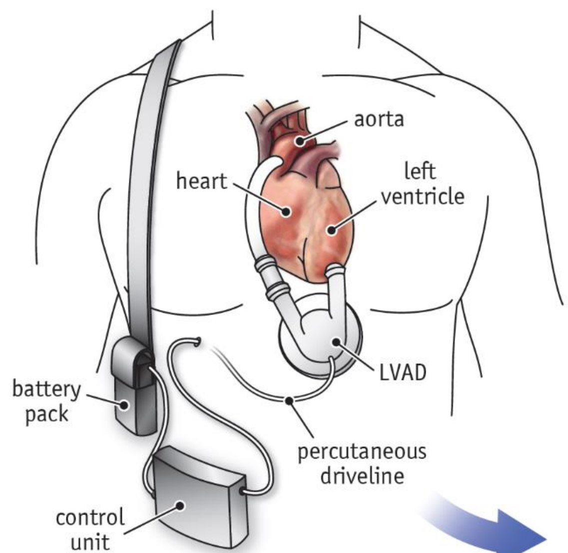
- Elimination of Ball Bearings for High Purity
- Hydrodynamic Thrust Bearing (Blood as Fluid)
- Passive Magnetic Bearings

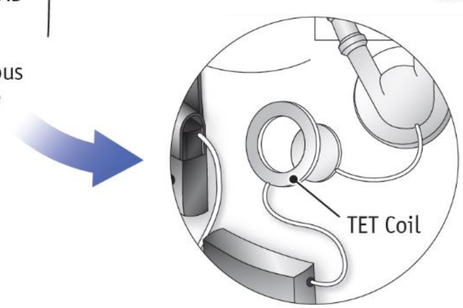
Source: heartware.com

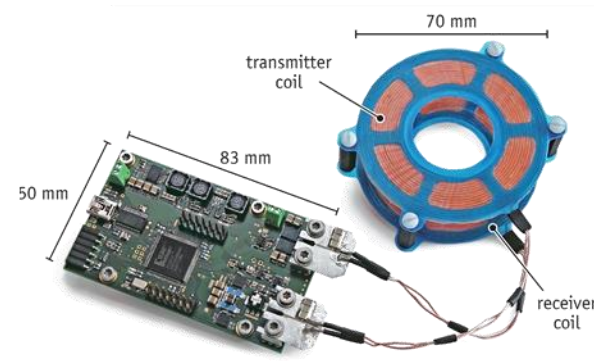
► Transcutaneous Power Supply

■ Implanted Devices with Ever-Higher Energy Demand (e.g. Heart-Assist Devices)
- High Risk of Severe Infections due to Conductive Connection

■ Fully-Implantable LVAD
- Wireless Power Transfer
- Wireless Communication
- Implated Battery Backup
- Implanted Motor Inverter & Electrical Blood Pump







► Zurich Heart Project:

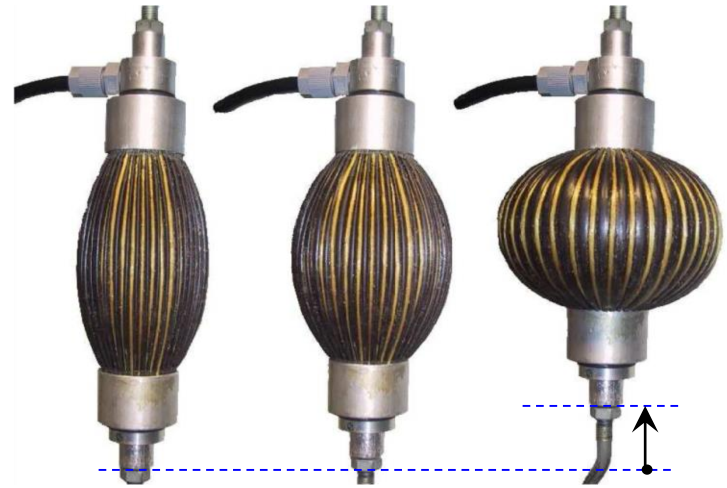
ETH zürich

University of Zurich UZH

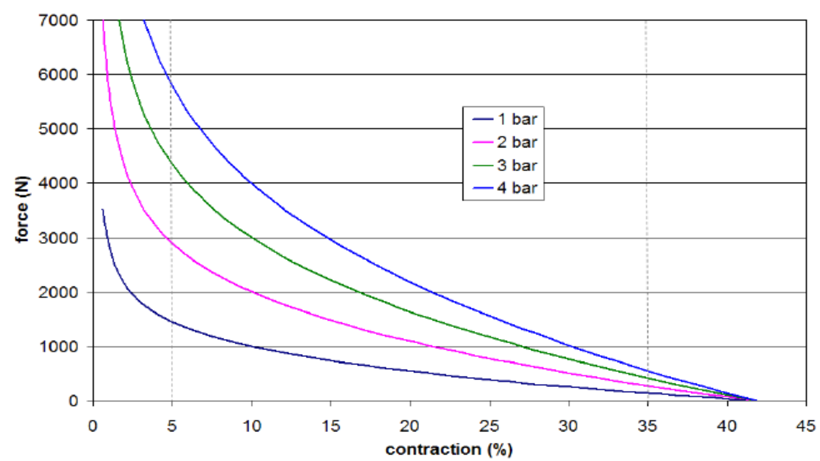
UniversityHospital Zurich

▶ Pneumatic Artificial Muscles

- **Lightweight Pneumatic Actuators**
  - Expands Radially & Contracts Axially when Inflated
  - Generates High Pulling Forces
  - Low Working Pressures (0 – 7 bar)



6000 N @ 4 bar for a Device with 10 cm Initial Length, Weighing only 100 g!



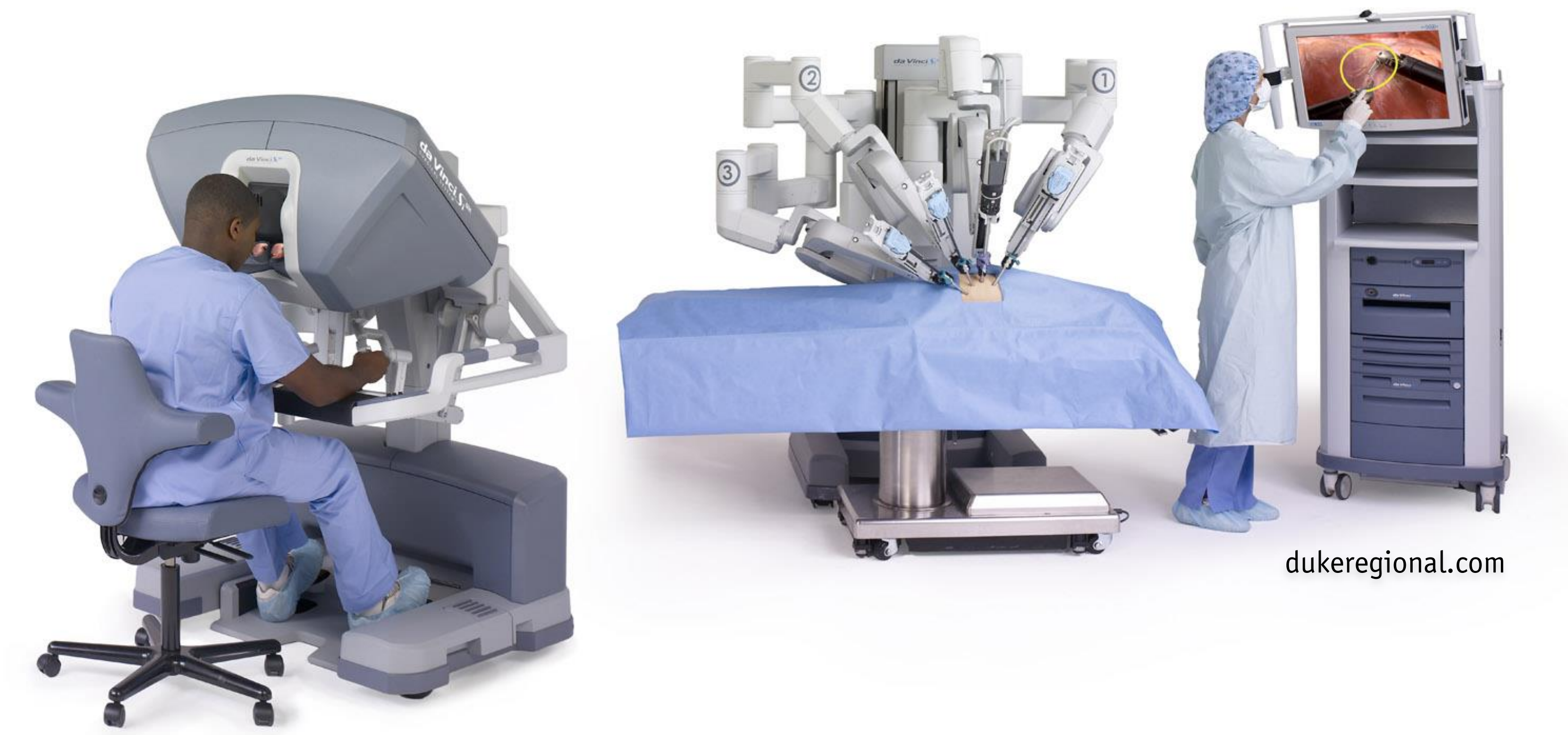
Mobile Applications →
Small and Light Weight High Speed Turbo Compressor

► Bionic Systems

- Innovative Way to Convey Future Orientation and Technolog Leadership
- Life Form Guarantees Emotional Relation

FESTO

► Robotically Assisted Surgical Systems



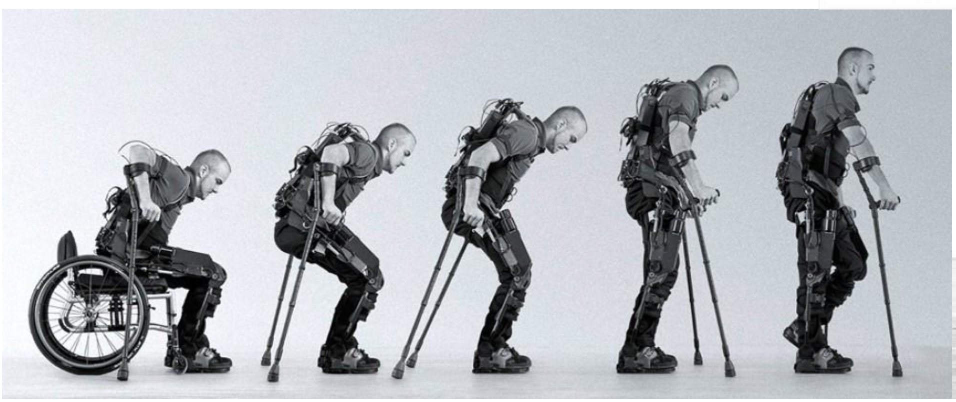
dukeregional.com

- Four Robotic Arms Holding a Camera and Surgical Instruments
- Complex Procedures with Minimum Invasion due to Small Incisions
- Quicker Recovery Time and Shorter Hospital Stay

► Robotic Exoskeleton for Humans

- Helping Patients with Partial Paralysis or for Rehabilitation After Injury
- Assist Workers with Heavy Lifting or Other Manual Tasks
- Protection of Firefighters/Soldiers in Harsh Environments

ekso BIONICS

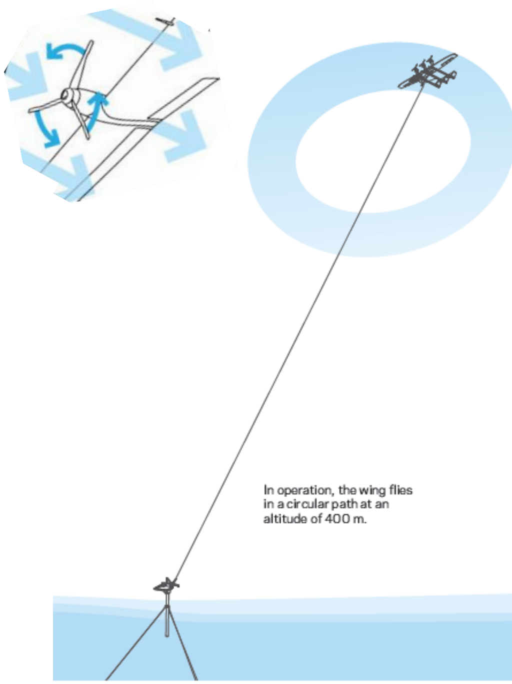


Selected Applications in Future Mechatronics

- *Advanced Manufacturing*
- *Future Mobility*
- *Healthcare & Medical*
- *Renewable Energy*
- *Space Applications*
- *Developing World*

▶ Airborne Wind Turbines

- Power Kite Equipped with Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanically Supporting Parts

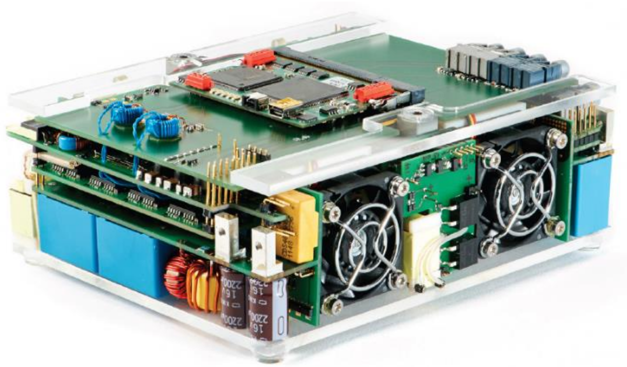


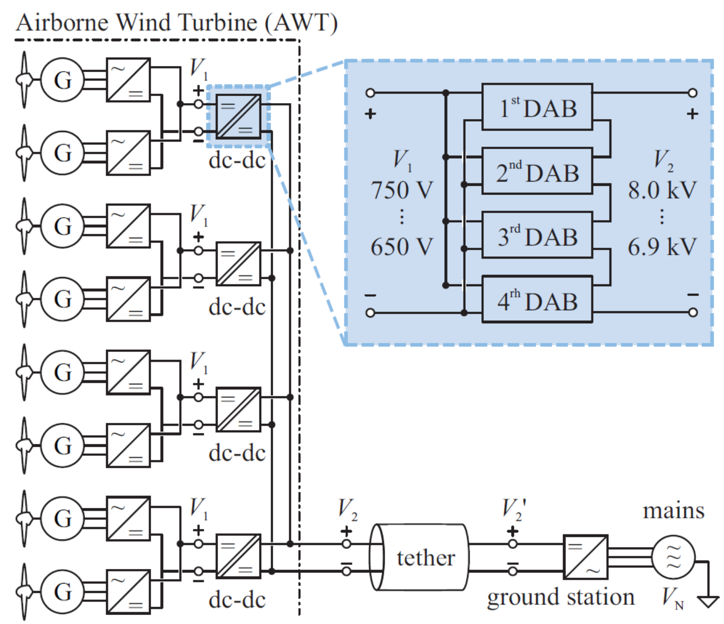
MAKANI POWER Google X

▶ 100 kW Airborne Wind Turbine

■ Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer – 8kV$_{DC}$ → 700V$_{DC}$

• Medium Voltage Port	1750 … 2000	VDC
• Switching Frequency	100	kHz
• Low Voltage Port	650 … 750	VDC
• Cell Rated Power	6.25	kW
• Power Density	5.2	kW/dm^3
• Specific Weight	4.4	kW/kg

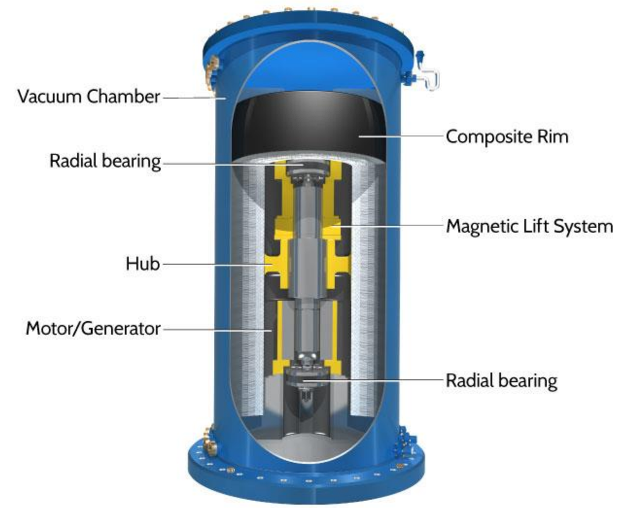


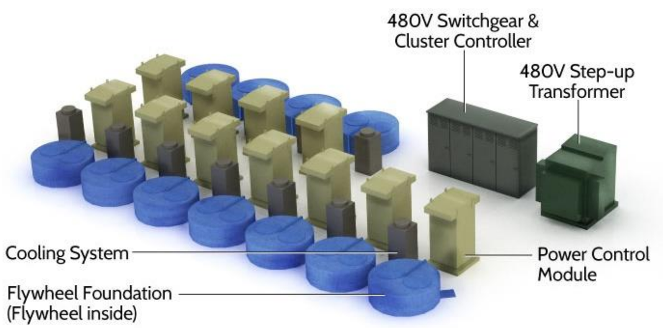


► Renewable Energy

- **Grid Balancing**
- **Renewable Integration**
- **Islands/Isolated Grids**

- **Market Competition**
  - Cost (vs. Batteries)
  - Power Density (vs. Supercaps)
  - Niche Applications: Space etc.





→ 200 Flywheels/20 MW, Stephentown NY

beaconpower.com

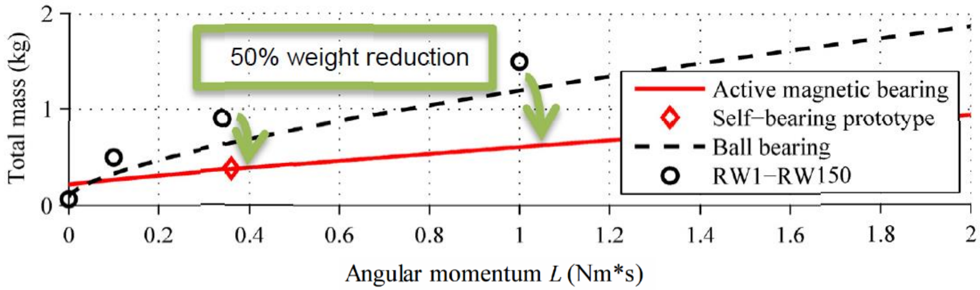
Selected Applications in Future Mechatronics

Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

▶ Space Application: Satelite Attitude Control

- **Reaction Wheels are Widely Used for Satellite Attitude Control**
- **Currently Ball Bearings are Used Despite Disadvantages**

- **Magnetic Bearings Allow for**
  - Less Microvibrations
  - Higher Speed: Smaller Reaction Wheel Size



Source: nasa.gov

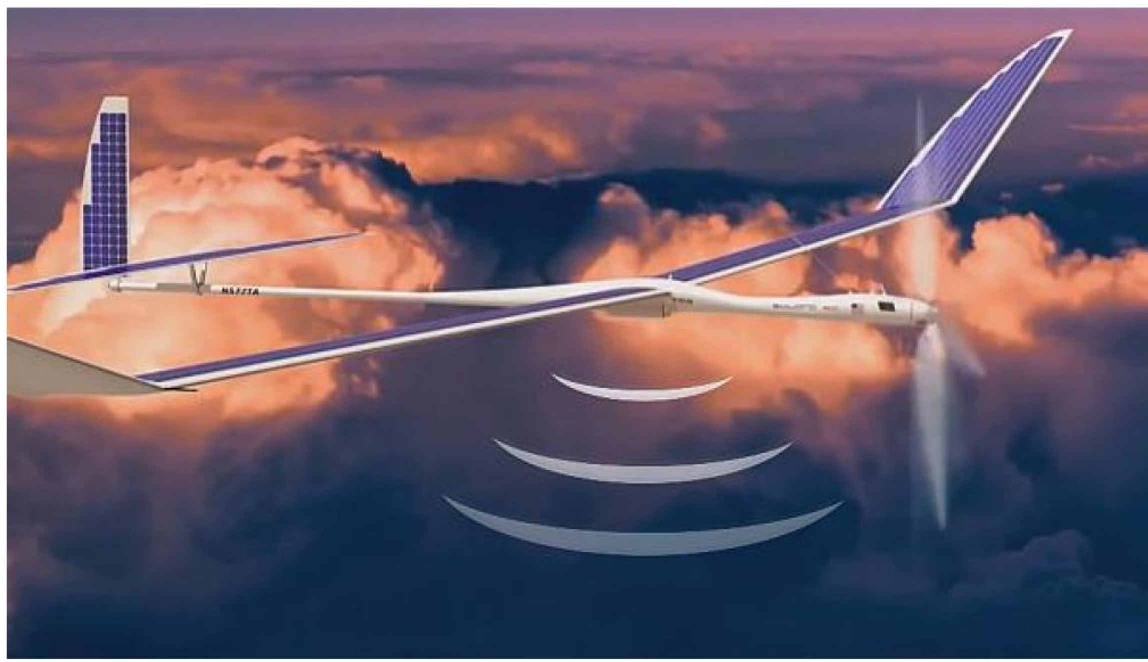
Selected Applications in Future Mechatronics

Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

► High-Altitude Drones

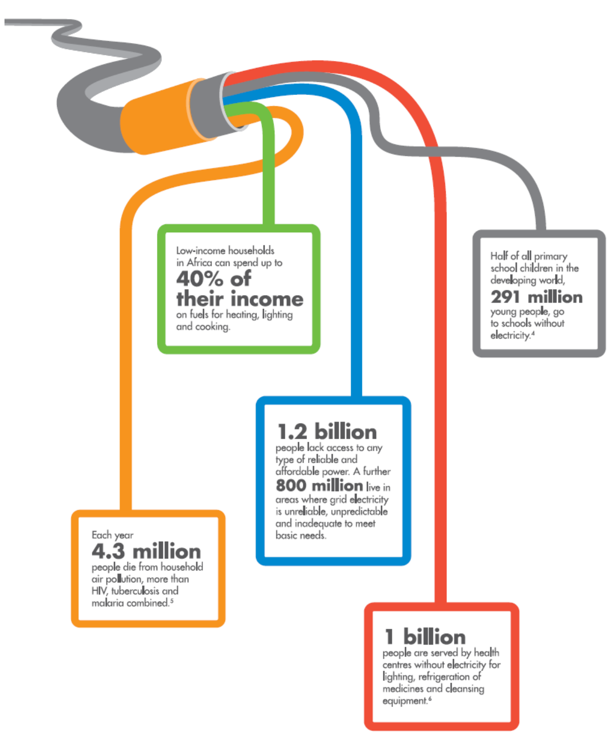
- **Provide Internet Access to Large Underdeveloped Areas**
- **Facebook Drone Research**
  - Solar Powered Drones
  - Stratospheric Flight
  - Can Stay Aloft for 90 days
  - High-Speed Laser Communication Between Drones

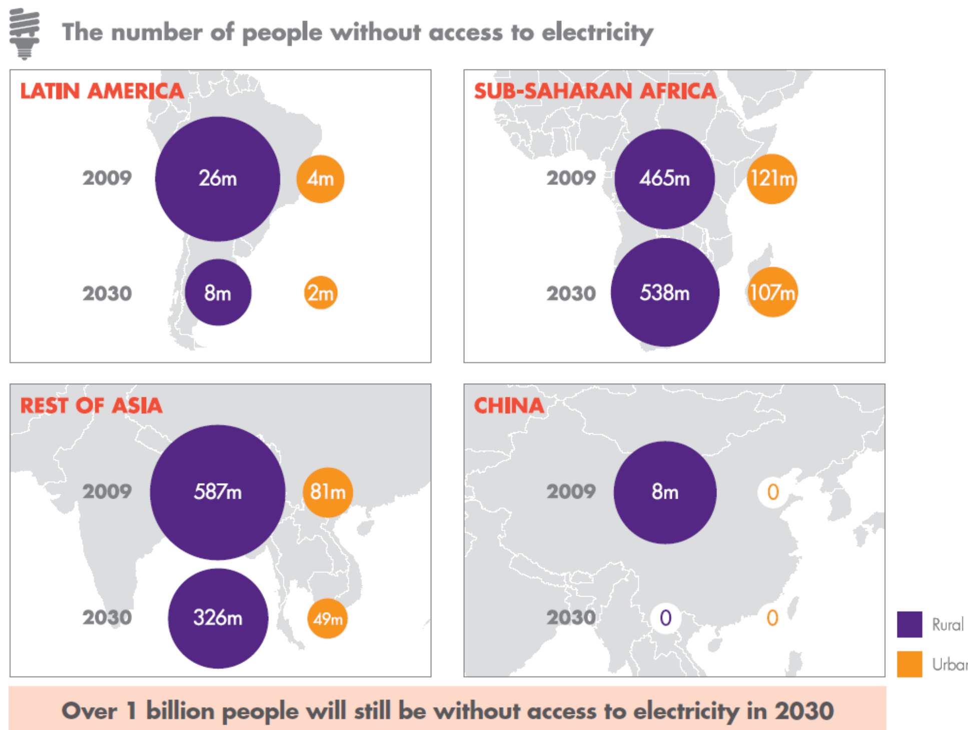
Like



Rural Electrification in the Developing World

2 Billion "Bottom-of-the-Pyramid People" Lack Access to Clean Energy





Source: IEA, Dalberg Analysis, IFC

→ Urgent Need for Village-Scale Solar DC Mirogrids etc.
→ 2 US$ for 2 LED Lights + Mobile-Phone Charging / Household / Month (!)

Conclusions

► Summary

Future Perspectives for Motion Control

► **Possible Ways for *«Component»* Performance Improvement**
- Miniaturization of Electric Machines
- Integration of Power Electronics
- System Optimization (Converter & Actuator)
- Application Specific Design
- etc.

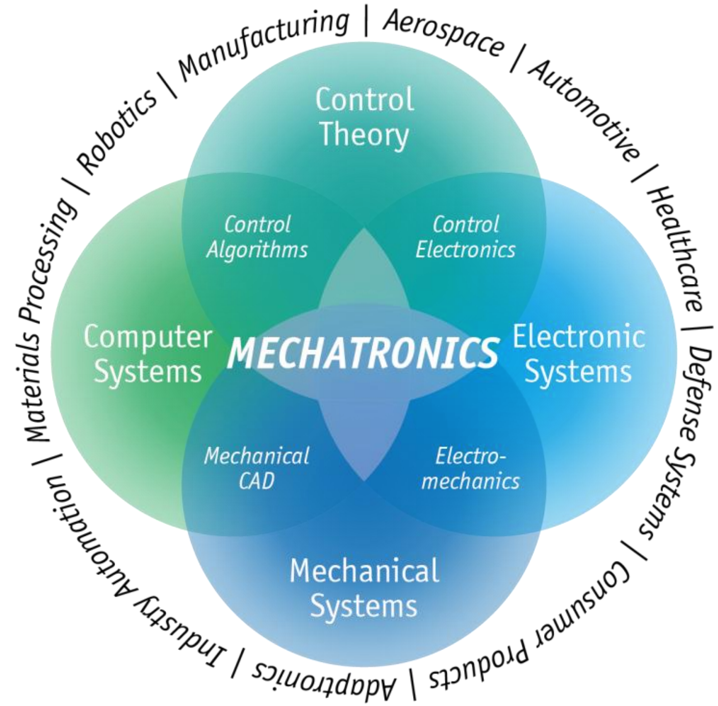
► **Today's and Future High-Performance Systems Enable Countless Novel Application Areas**
- Healthcare & Medical Systems
- Industry Automation & Robotics
- Renewable Energy & Smart Grid
- Mobility on Land/Air/Sea
- etc.

► Mechatronic Systems

- **Target *«System Level»* and Cover Core Competences in Mechatronic Areas**
  - Interdisciplinary Engineering Knowledge
  - Application-Specific Combination of High-Performance Components

  - Characteristics
    → ***Smart***
    → ***Integrated***
    → ***Hybrid***
    → ***Ubiquitous***

  - Future
    → ***Automatization (Machine Learning)***
    → ***Modularization***
    → ***Links to Internet***
    → ***Society of Devices***



► Endless Product Innovation Possible by Combination of Core Elements

Bounded only by

- Laws of Physics
- Material Properties
- Imagination / Vision

«Multiplication by Infinity»

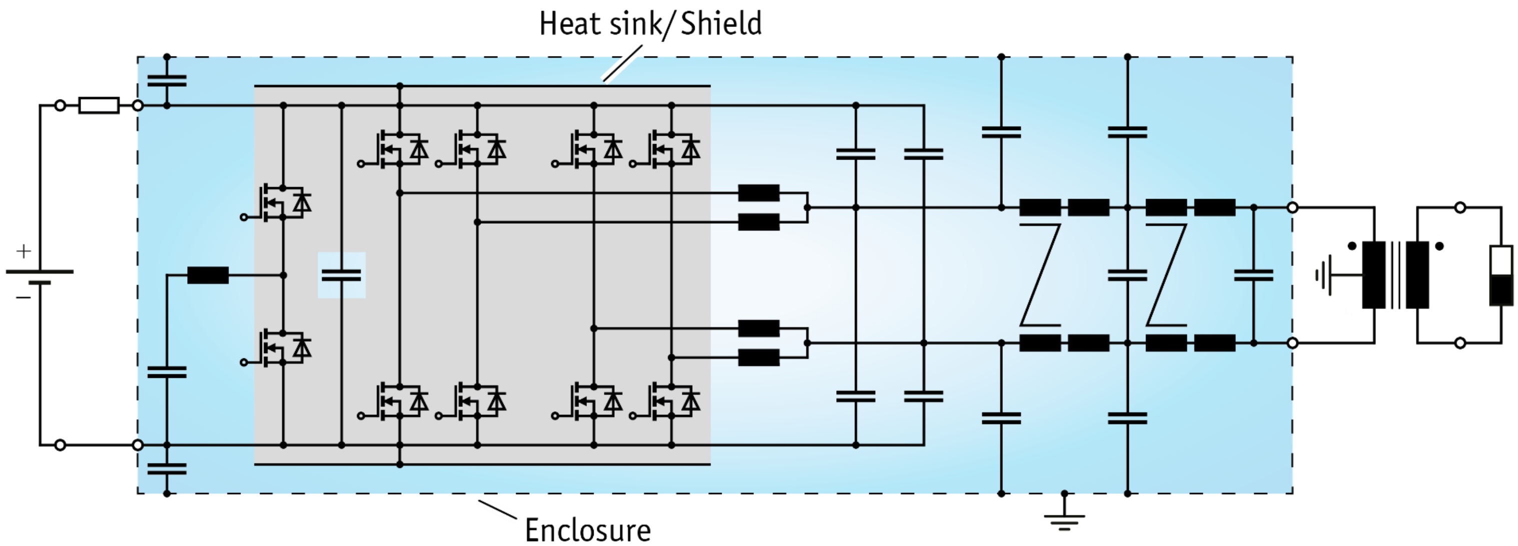
Thank You!

Questions?

Backup Slides

Selected Converter Topology

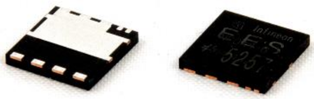
- Interleaving of 2 Bridge Legs per Phase - Volume / Filtering / Efficiency Optimum
- Active 1-Φ Output Power Pulsation Buffer



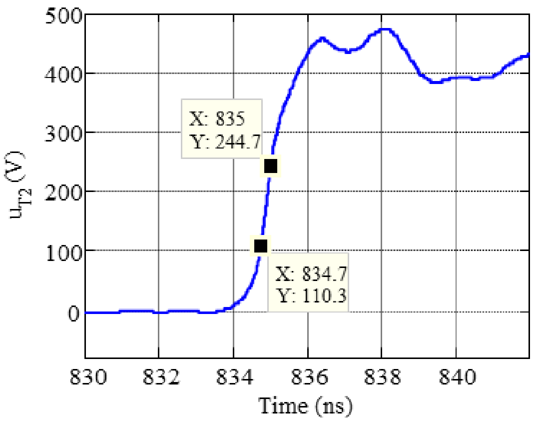
- ZVS of All Bridge Legs @ Turn-On/Turn-Off in Whole Operating Range – 4D TCM Interleaving
- Heatsinks Connected to DC bus / Shield to Prevent Capacitive Coupling to Grounded Enclosure

Power Semiconductors

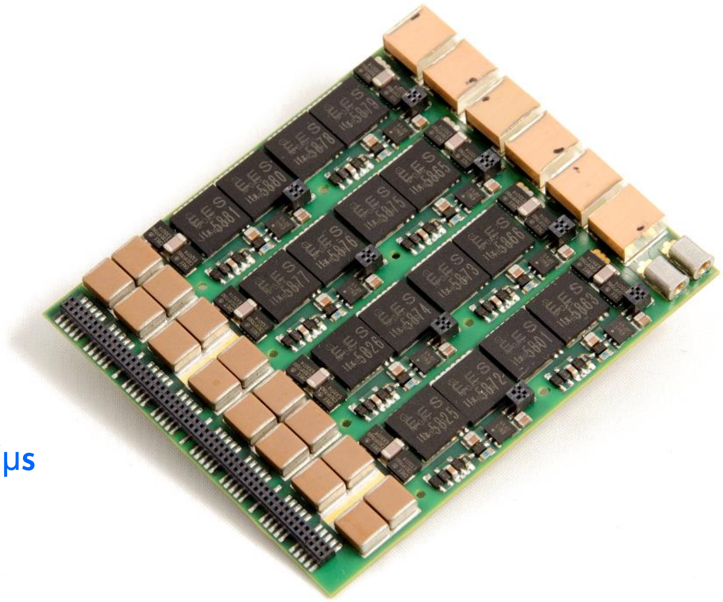
- 600V IFX Normally-Off GaN GIT - ThinPAK8x8
- 2 Parallel Transistors / Switch
- Antiparallel CREE SiC Schottky Diodes



- 1.2V typ. Gate Threshold Voltage
- 55 mΩ $R_{DS,on}$ @ 25°C, 120mΩ @ 150°C
- 5Ω Internal Gate Resistance



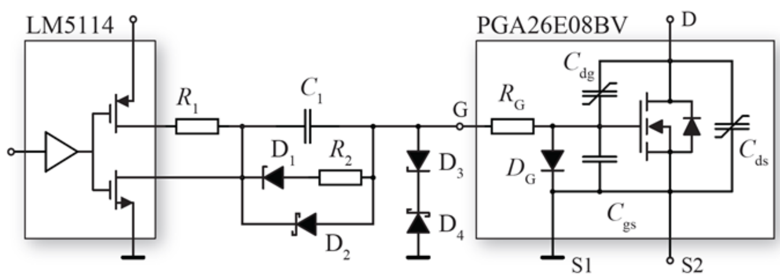
dv/dt = 500kV/μs

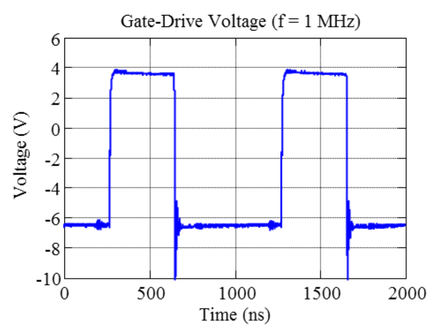


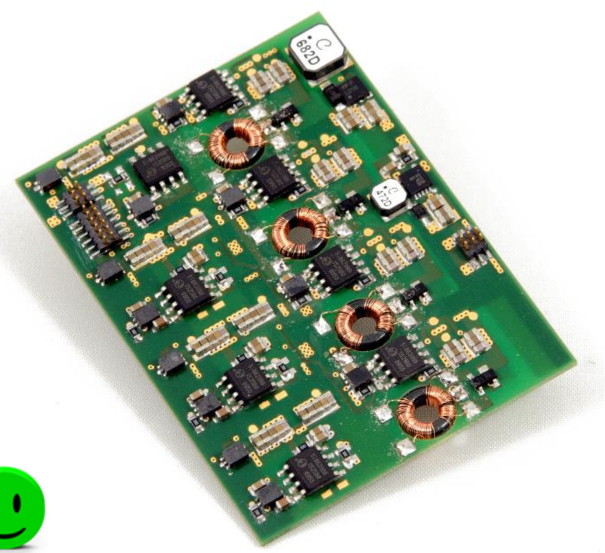
■ CeraLink Capacitors for DC Voltage Buffering

Advanced Gate Drive

- Fixed Negative Turn-off Gate Voltage Independent of Sw. Frequency and Duty Cycle
- Extreme dv/dt Immunity (500 kV/μs) Due to CM Choke at Signal Isolator Input





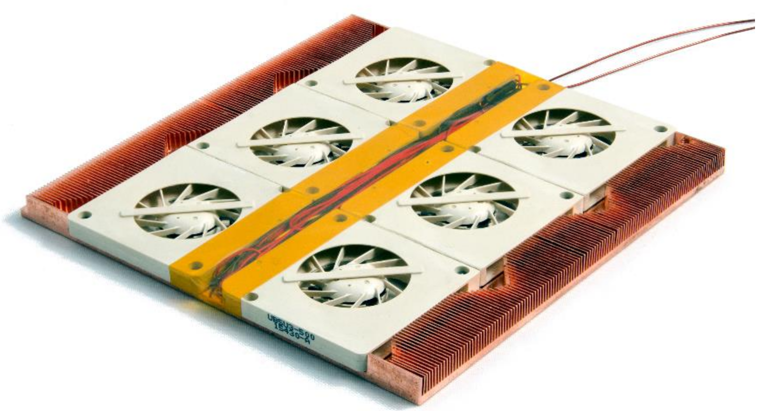


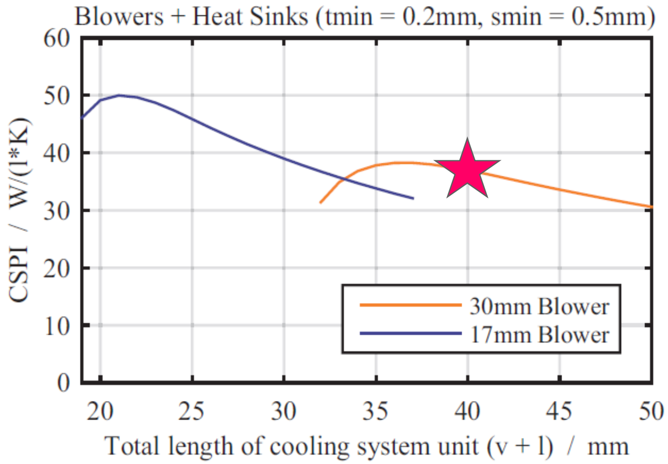
- Total Prop. Delay < 30ns incl. Signal Isolator, Gate Drive, and Switch Turn-On Delay

Thermal Management

- 30mm Blowers with Axial Air Intake / Radial Outlet
- Full Optimization of the Heatsink Parameters
- Outstanding Cooling Syst. Performance Index

- 200um Fin Thickness
- 500um Fin Spacing
- 3mm Fin Height
- 10mm Fin Length
- CSPI = 37 W/(dm^3.K)
- 1.5mm Baseplate

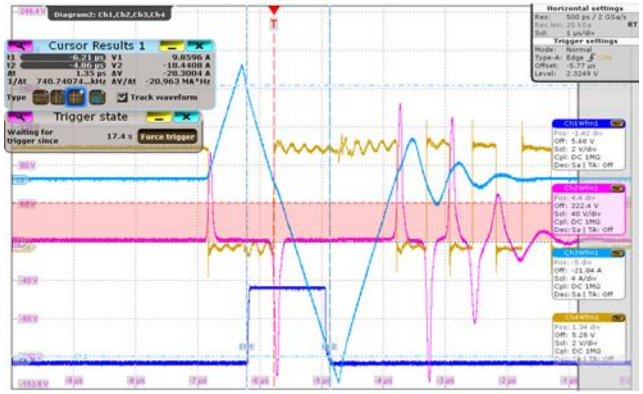


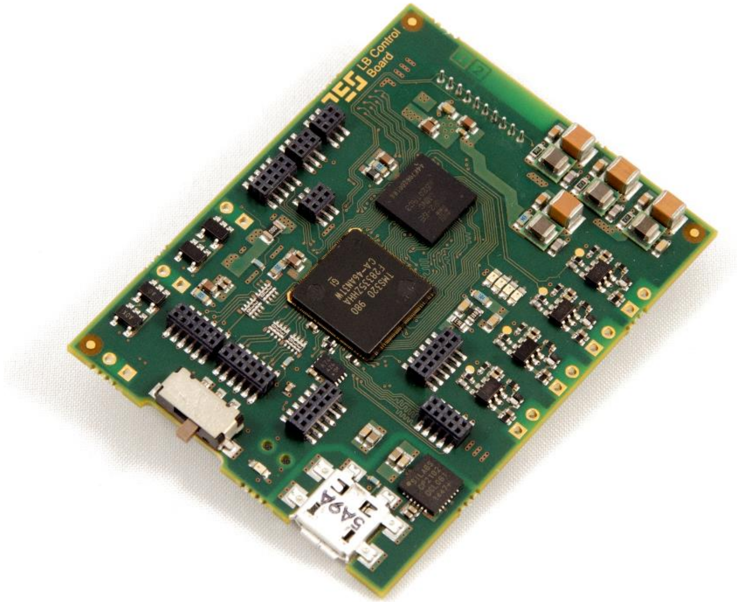


Control Board & i=0 Detection

- Fully Digital Control - Overall Control Sampling Frequency of 25kHz
- TI DSC TMS320F28335 / 150MHz / 179-pin BGA / 12mmx12mm
- Lattice FPGA LFXP2-5E / 200MHz / 86-pin BGA / 8mmx8mm

- TCM Current / Induced Voltage / Comparator Output

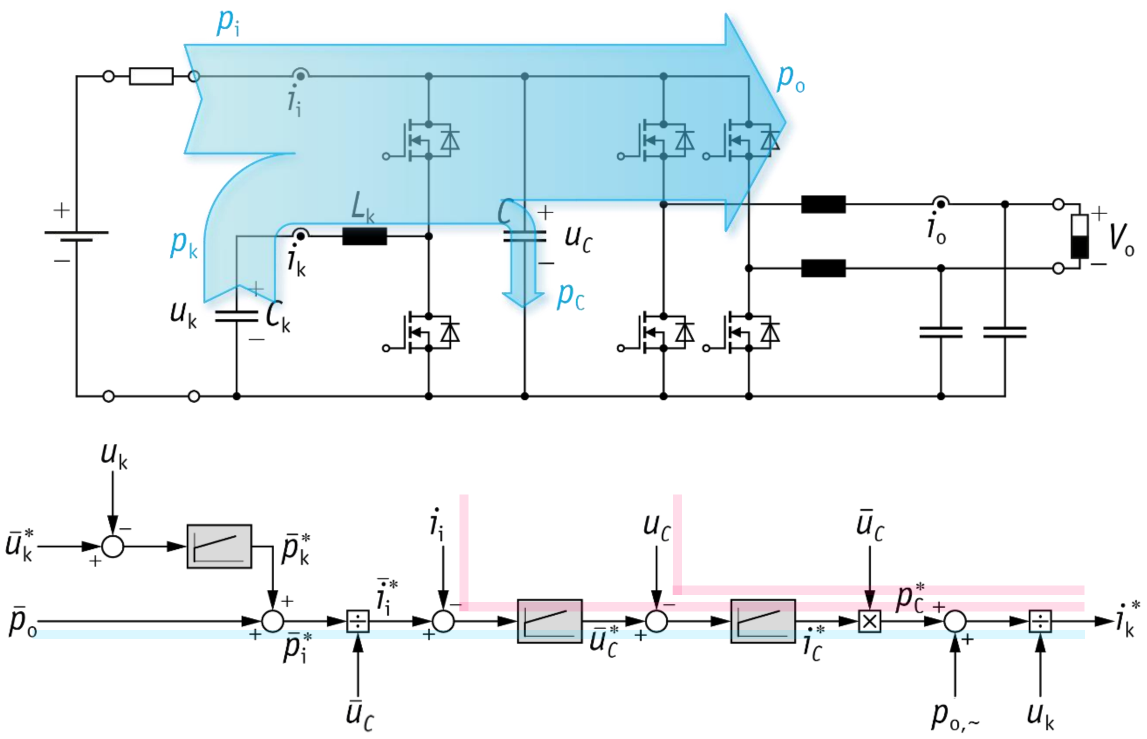




- i=0 Detection of TCM Currents Using R4/N30 Saturable Inductors
- Galv. Isolated / Operates up to 2.5MHz Switching Frequency / <10ns Delay

Control of Power Pulsation Buffer

- Cascaded Control Structure

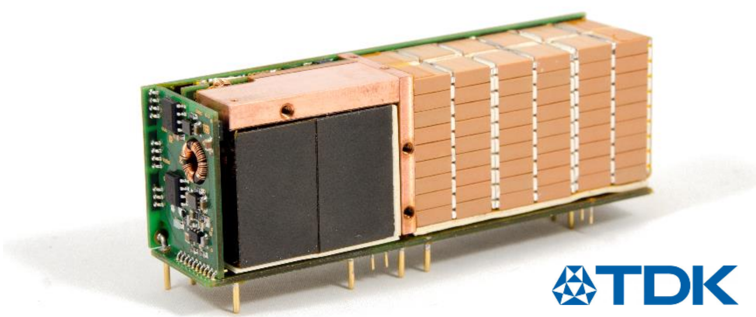


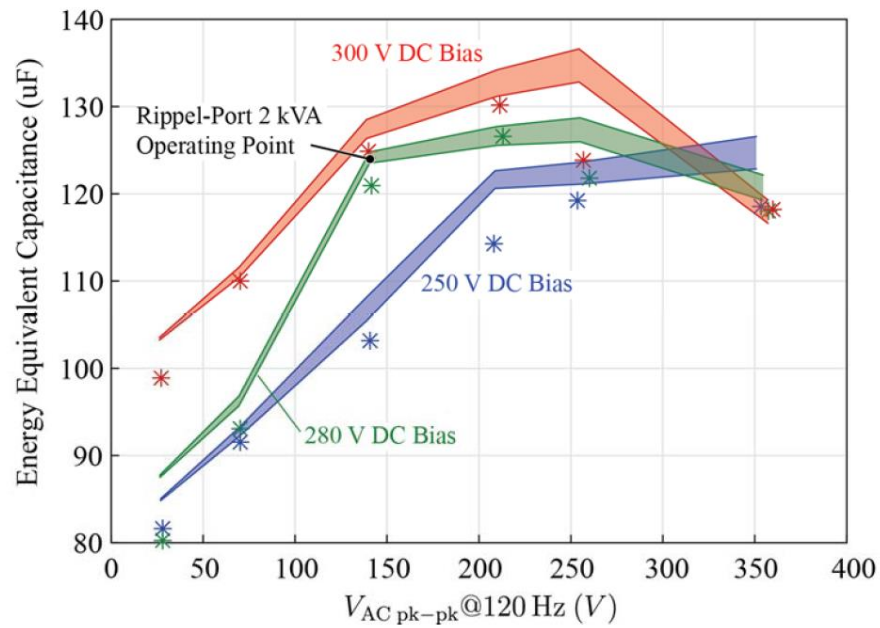
- Feedforward of Output Power Fluctuation
- Underlying Input Current / DC Link Voltage Control

Power Pulsation Buffer Capacitor

- High Energy Density 2nd Gen. 400VDC CeraLink Capacitors Utilized as Energy Storage
- Highly Non-Linear Behavior → Opt. DC Bias Voltage of 280VDC
- Losses of 6W @ 2kVA Output Power

- 108 x 1.2µF /400 V
- 23.7cm^3 Capacitor Volume

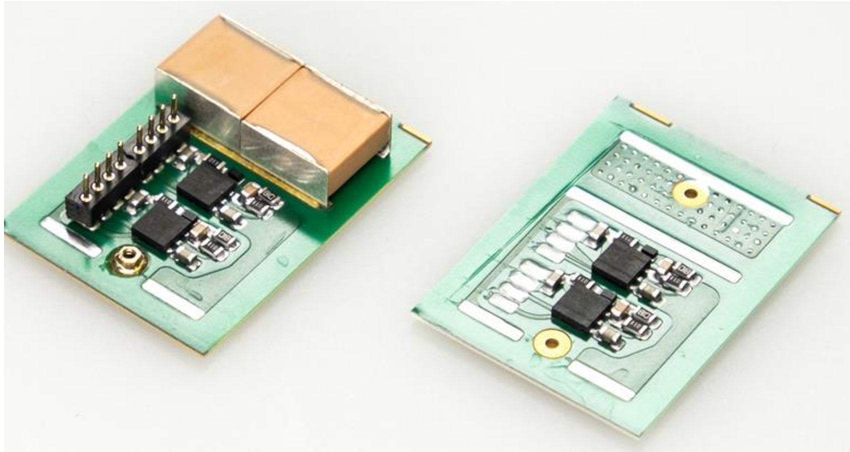




- Effective Large Signal Capacitance of C ≈140µF

Outlook

- Embedded Switching Cell Package for Further Size Reduction
- Integr. Half Bridge Module incl. DC Link Caps and Drivers



- 2 Parallel Chips / Switch
- Embedded in PCB

- 8 mm Smaller than Conv. Design
- Extremely Low DC Link Indutance
- Driver Directly on Top of Switches
- Very Low Gate Inductance

▶ Highly Versatile Signal Processing Platform

Controller: TMS320F28335 (TI)
- **150 MHz** Clock Frequency
- Multitude of Peripheral Units:
  - **12 PWM** Channels
  - **16 A/D** Channels (12-Bit)
  - General Purpose I/O Pins
  - On-Chip Memory: Flash and RAM
  - Communication Interfaces

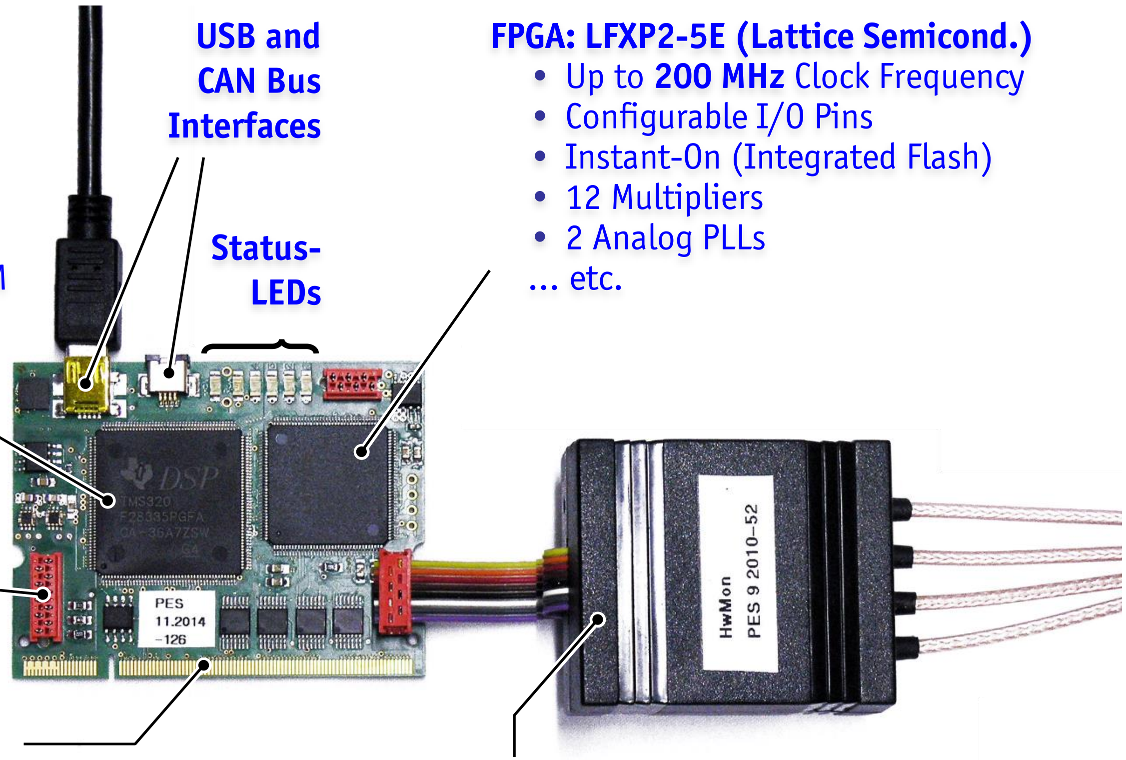
  … and More

USB and CAN Bus Interfaces

Status-LEDs

FPGA: LFXP2-5E (Lattice Semicond.)
- Up to **200 MHz** Clock Frequency
- Configurable I/O Pins
- Instant-On (Integrated Flash)
- 12 Multipliers
- 2 Analog PLLs

… etc.



JTAG Connectors
(DSP & FPGA)
- Programming
- Debugging

High density external interface:
- Suitable for Low Profile DIMM Connector
- 46 General Purpose I/O Pins
- 16 A/D Channels
- External Memory Interface (16-Bit)
- SPI bus, Encoder Interface, etc.

Hardware Monitor:
- For Real-Time Visualization of Control Variables
- 4 Channels
- Employs SPI Interface of Controller

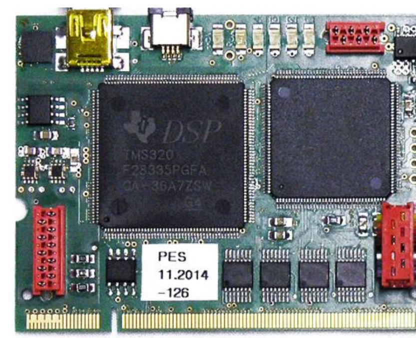
▶ Highly Versatile Signal Processing Platform

■ Modern Controller and FPGA ICs

- Controller and FPGA Communicate via High Speed Memory Interface

- **Controller**: TMS320F28335 (TI)
  - **Fast implementation** of User Programs, High-level Software Libraries available
  - Multitude of Peripheral Inits Readily available: **PWM, ADC**, etc.

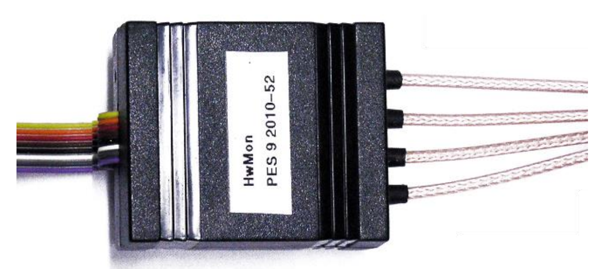
- **FPGA**: LFXP2-5E (Lattice Semiconductor)
  - **True parallelizing** of Processes
  - High Flexibility regarding Implementation Needs
  - High Speed Digital Control
  - High Number of Configurable I/O Pins



■ Real-time debugging: Hardware Monitor

- Converts Values of up to **4 Selected Control Variables** into Analog Voltages ⟶ Displayed on Oscilloscope

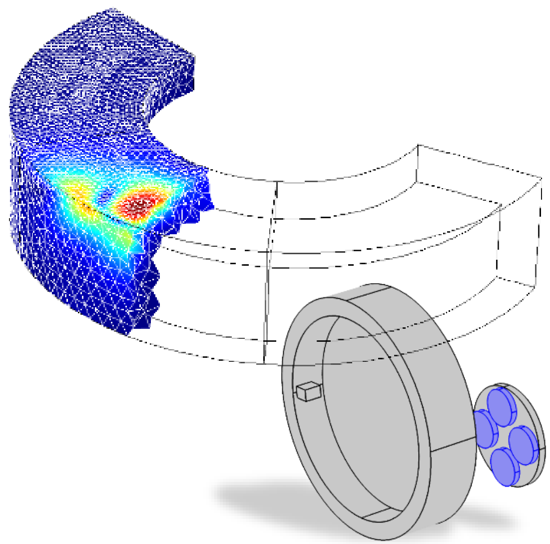
- Non-Invasive and Real-Time Debugging of Operating Power Converter



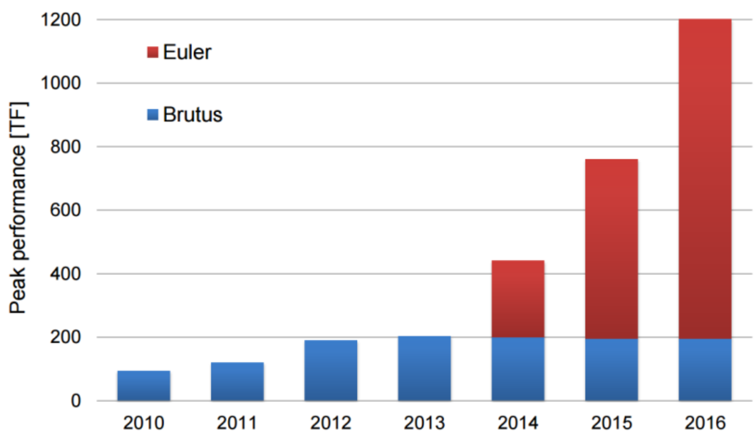
► Fully Virtual Optimization and Prototyping

■ Advanced Finite-Element-Analysis of Designs

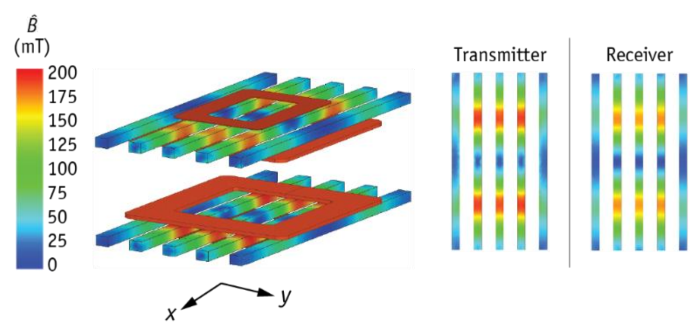
- 3-D Geometries, Moving Mesh (True Rotation)
- Time-Transient Numeric Solvers
- Skin Depth Resolution at High Frequency
- Non-Linear Magnetic Materials
- Coupled Multi-Physics Simulations



■ Multi-Core Parallel and Distributed Computing



Source: ETHZ HPC Group



► Increasing the Machine Utilization Factor

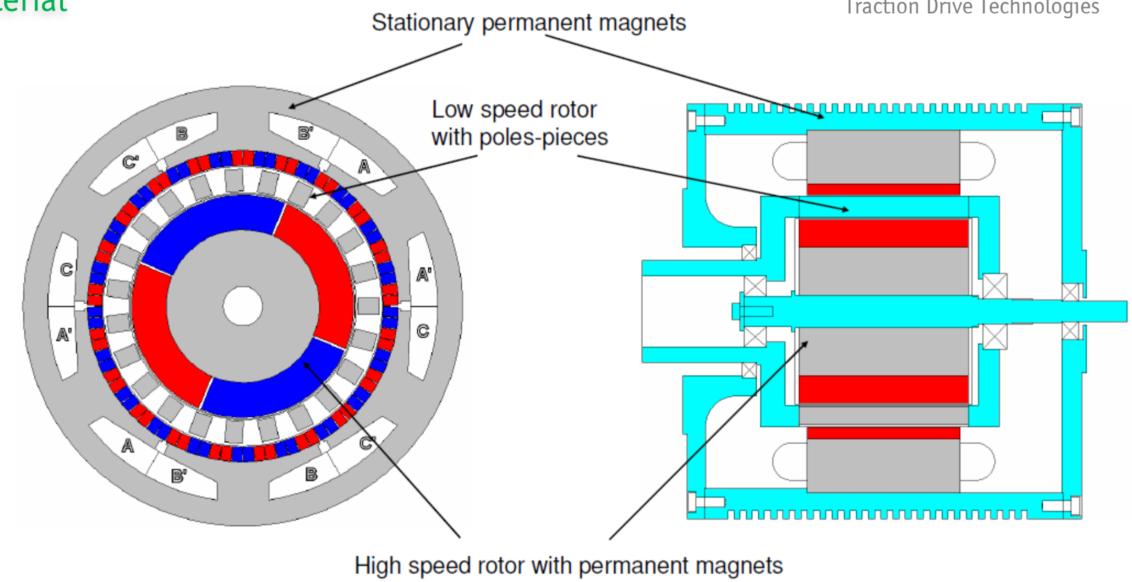
■ Degrees-of-Freedom for Improved Utilization

- Manufacturing Methods
- Materials
- Cooling
- Machine Topology

– **Integration of Magnetic Gears (Pseudo Direct Drive)**

+ Higher Torque per Magnetic Material
+ Low Current Density
- More Structural Mass
- More Complicated Design

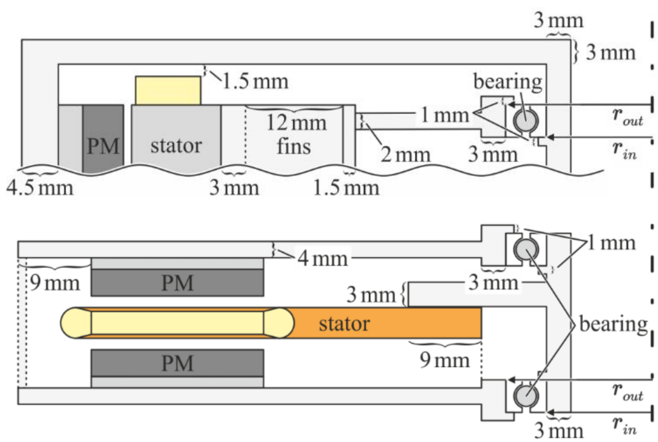
Source: Wang
Recent Development in Electric
Traction Drive Technologies



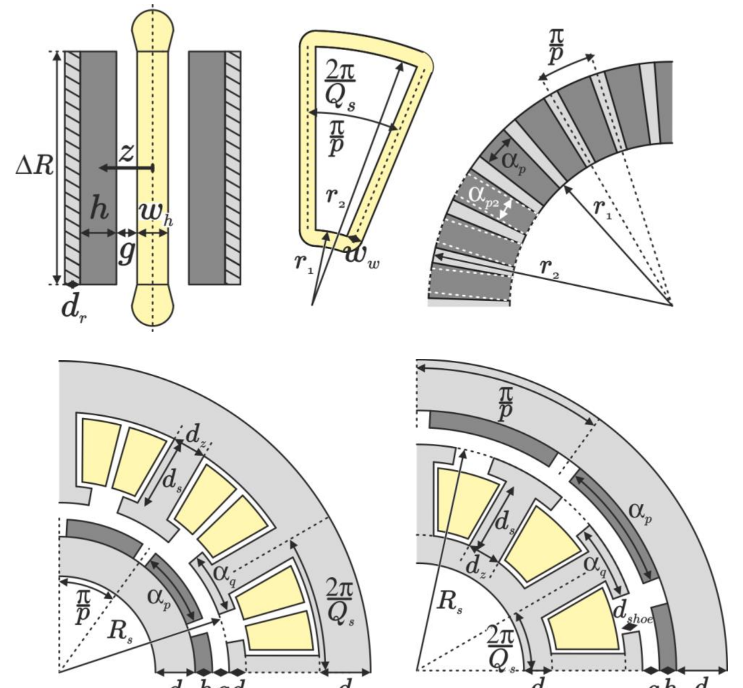
► Pushing the Performance of Conventional Systems to the Limit (1)

■ Comprehensive Machine Models
- Magnetic Field, Torque, Losses
- Structural Mass
- Thermal Behavior

■ Advanced Machine Topologies
- Hallbach Array
- Cobalt-Iron Alloy or Air Core
- Copper or Aluminum Coils



▲ Structural Mass Model

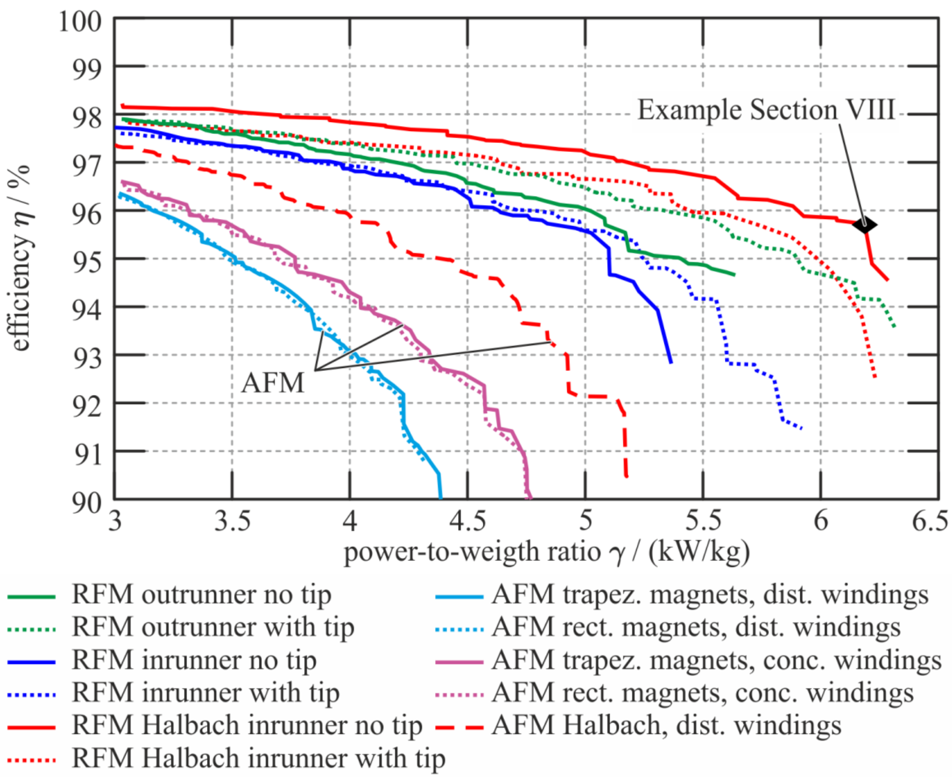


$$\Psi_{\mathrm{ph,A}}(\theta) = 4p \int_{0}^{\frac{w_\mathrm{h}}{2}} \int_{r_1}^{r_2} \int_{\phi_\mathrm{s}}^{\phi_\mathrm{e}} r \cdot B_\mathrm{z}(r,\phi,z)\,\mathrm{d}\phi\,\mathrm{d}r\,\mathrm{d}z$$

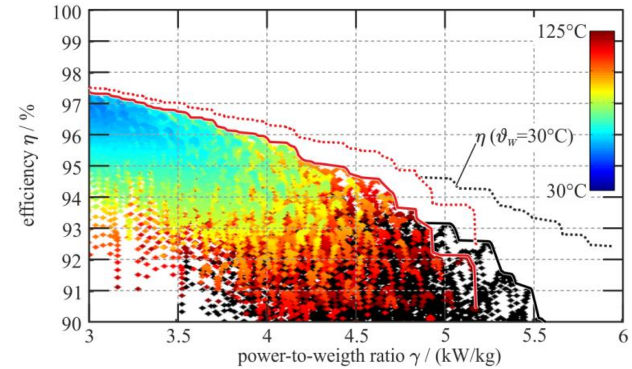
$$u_{\mathrm{ph,A}} = -\frac{\mathrm{d}}{\mathrm{d}t}\Psi_{\mathrm{ph,A}}$$

▲ Electromagnetic Models

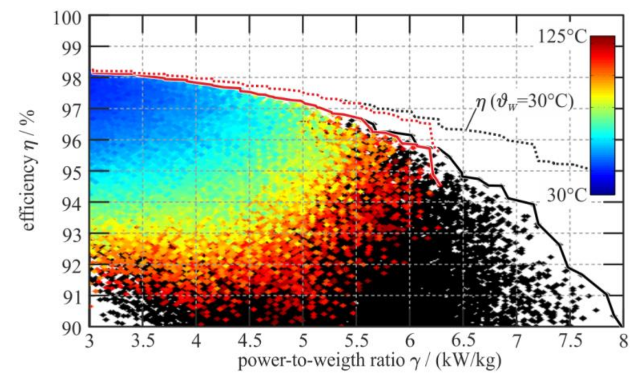
► Pushing the Performance of Conventional Systems to the Limit (2)



▲ Pareto Fronts of all Considered Machine Topologies



▲ Pareto Space of AFM with Distributed Windings and Halbach Magnetization



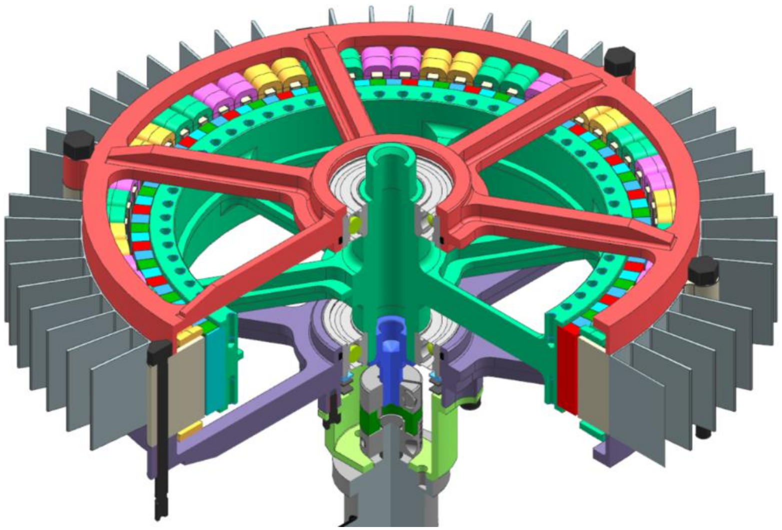
▲ Pareto Space of Internal Rotor RFM with Segmented Halbach Magnetization

► Weight-Optimized Machine Prototype

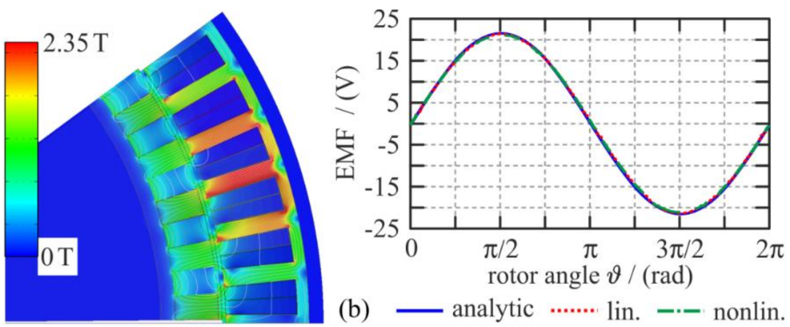
- **Internal rotor RFM**
  - 25 Pole Pairs / 60 slots
  - CoFe Stator Iron
  - Segmented Halbach Magnetization
  - NdFeB Magnets

- **Outer Dimensions: 200 mm x 65 mm**
- **Bore radius: 67 mm**
- **Active length: 25mm**

- **Weight: 2.1 kg → 6.1 kW/kg**



▲ **CAD Drawing of AWT Motor Prototype**

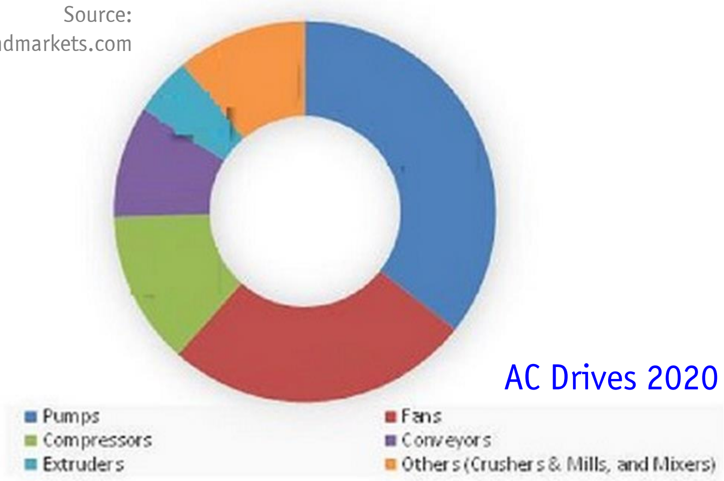


▶ Motion Control: Global Market Size

- **Global AC Drives Market**
(Pumps, Fans, Compressors, Conveyors, Extruders,...)
  - USD 13.7 Billion in 2014
  - USD 21 Billion in 2020

- **Main drivers**
  - Energy Savings in Manufacturing
  - Government Regulations in Carbon Emissions
  - Infrastructural Development especially in Asia-Pacific Region

Source: marketsandmarkets.com



AC Drives 2020

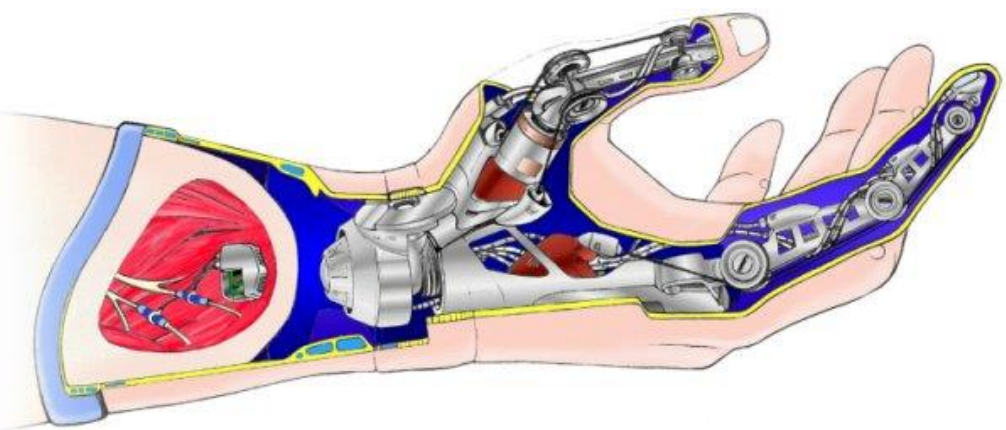
- **Global Servo Motors and Drives Market**
(Motors, Amplifiers, Sensors, Controller Modules)
  - USD 8.6 Billion in 2014
  - USD 12.5 Billion in 2020

- **Main drivers**
  - Rapid Growth in the Automation Market
  - Demand for Energy Efficient Processes
  - Increasing Production Capacity

- **Fastest growth**
  1. Asia-Pacific
  2. Europe

► Biomimetic Systems in Healthcare

- **Biologically Inspired Actuators Replacing (Human) Body Parts**
- **Neural Stimulation: Sensory Feedback to the Patient**
  - Interaction with the Patient´s Neurons
  - Detection of Patient’s Intention



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