Research Vectors in Power Electronics and Motion Control

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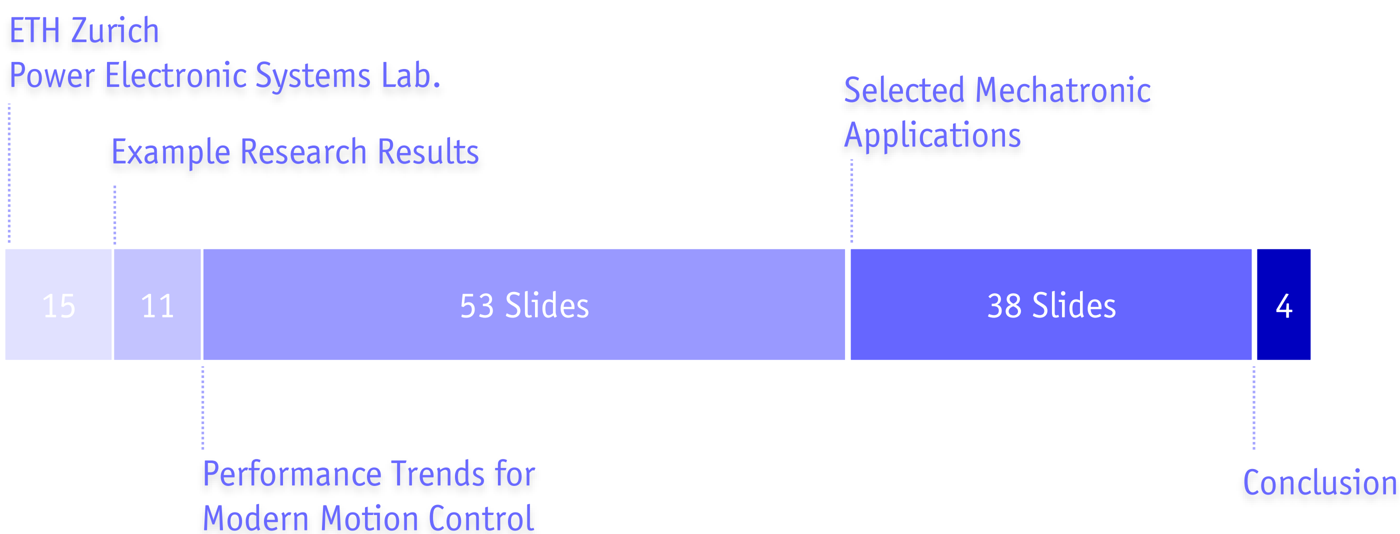
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

Agenda


ETH Zurich
Power Electronic Systems Lab.
Example Research Results
Selected Mechatronic Applications
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53 Slides
38 Slides
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Performance Trends for Modern Motion Control
Conclusion

ETH Zurich

Dept. of Information 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

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

150th Anniv. in 2005

▶ Research @ D-ITET

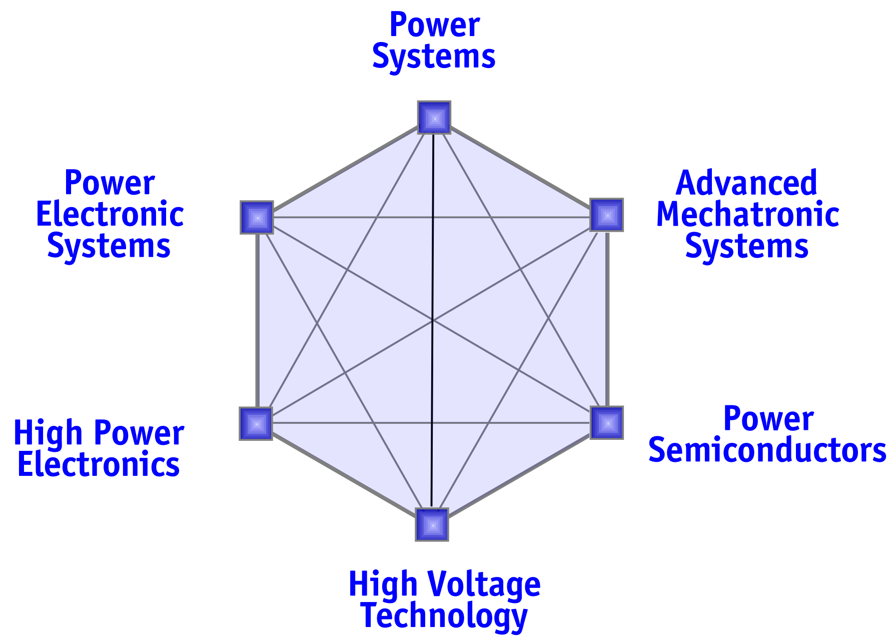
Four Core Research Areas

- Energy
- Electronics and Photonics
- Information and Communication
- Biomedical Engineering

Students & Staff

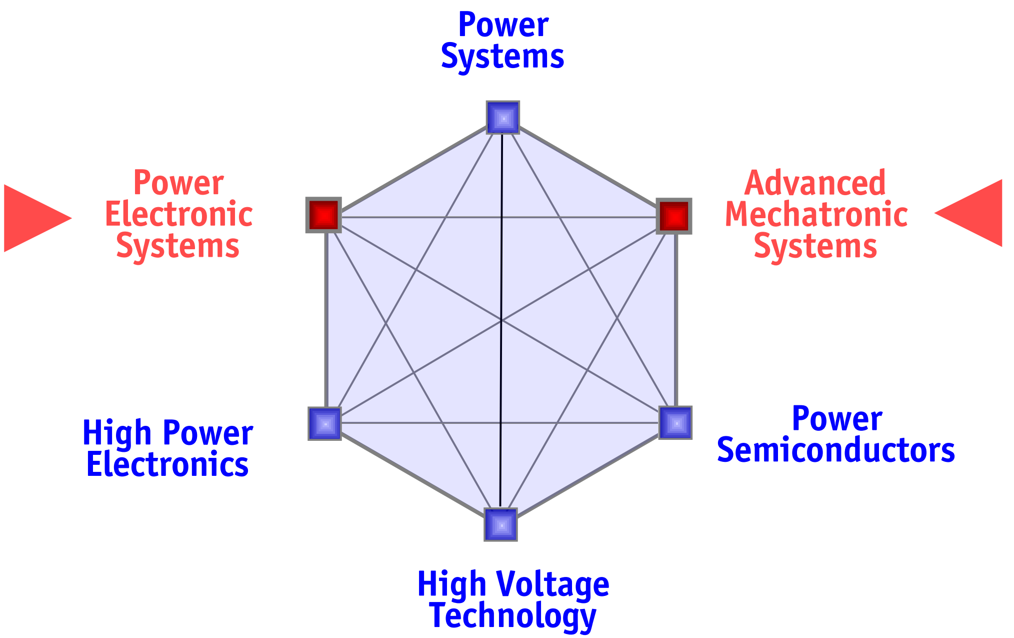
650 B.Sc. Students
300 M.Sc. Students
400 Ph.D. Students
27 Professors

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

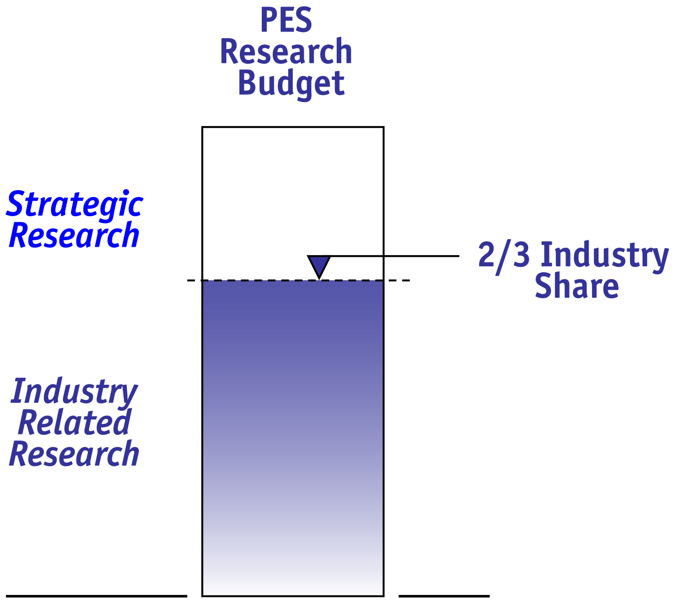
Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

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*



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

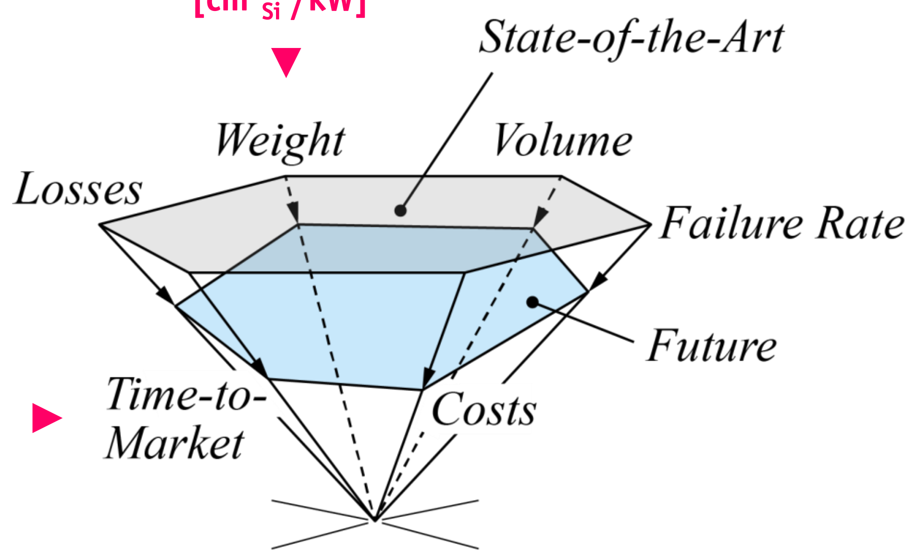
EPSMA

Leading Univ. in Europe

General Research Approach

Power Electronics Converters Performance Trends

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



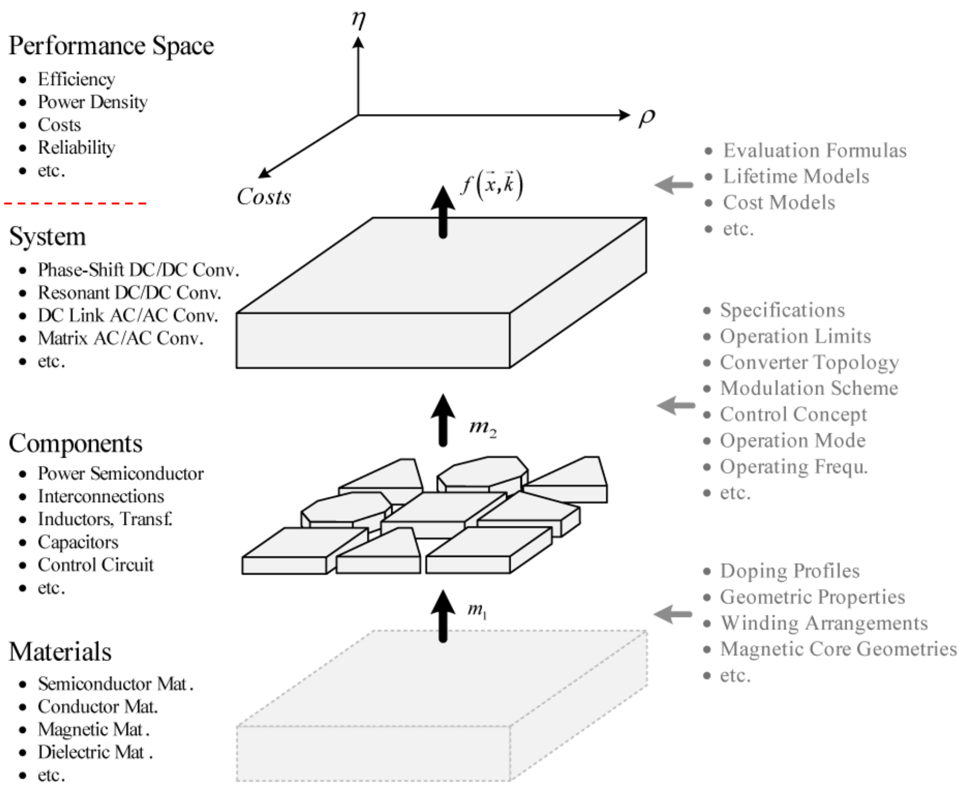
■ Performance Indices

- 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

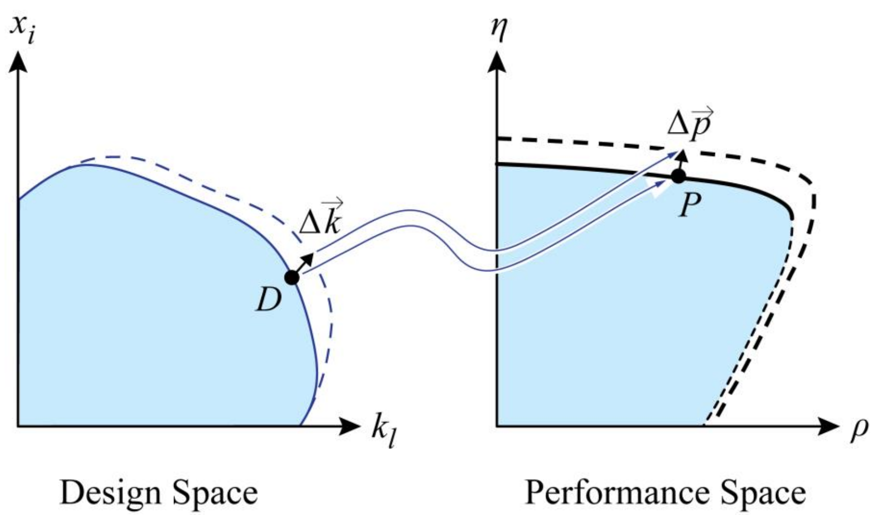
Design Space

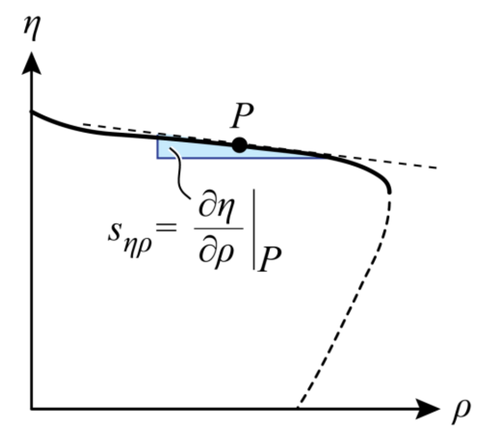


- ▶ **Mapping of *Design Space* into System *Performance Space***

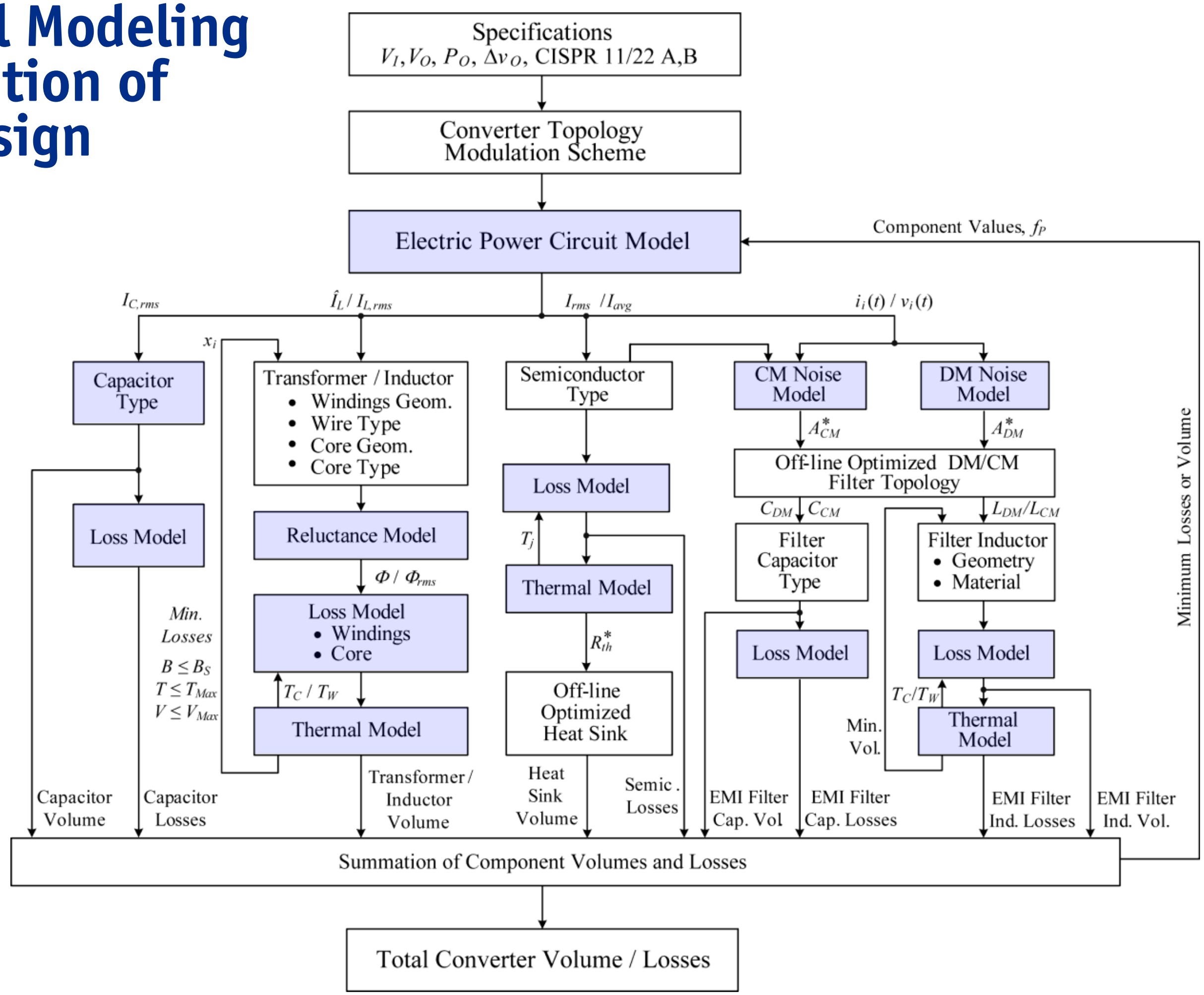
Technology Sensitivity Analysis Based on η-ρ-Pareto Front

► Sensitivity to Technology Advancements
► Trade-off Analysis





Mathematical Modeling and Optimization of Converter Design



Example of Recent Research Results in Power Electronics

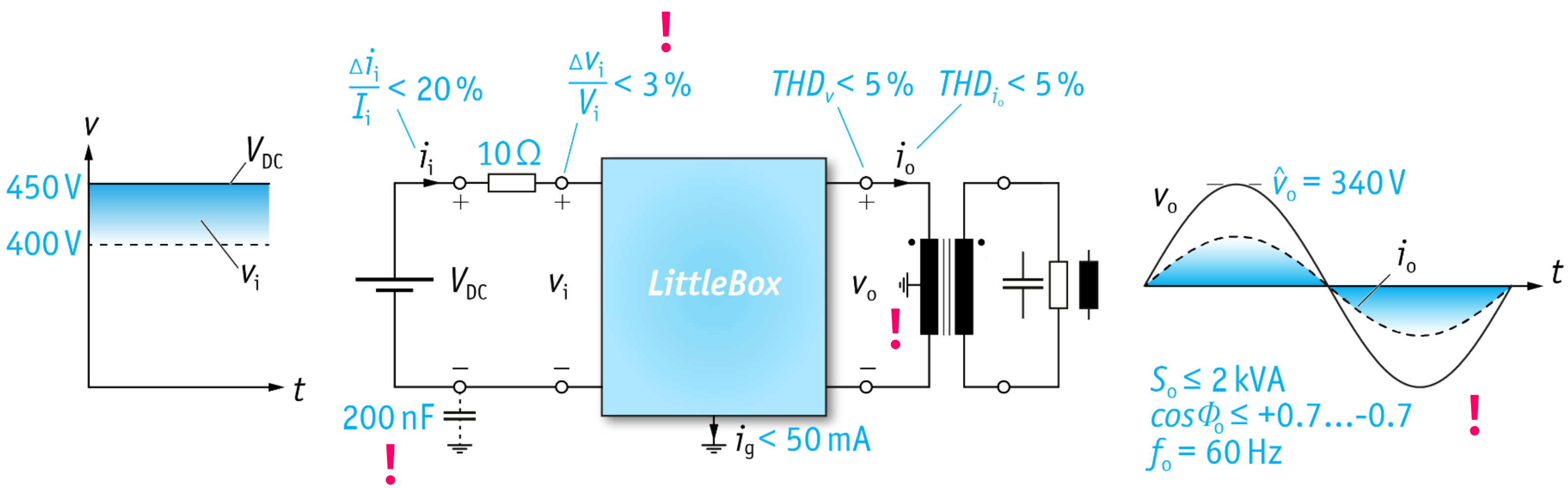
The Google Little Box Challenge

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**

Source: Kolar et. al., Little Box Challenge, CIPS 2016

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- EMI FCC Part 15 B

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

Source: Kolar et. al., Little Box Challenge, CIPS 2016

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

Source: Kolar et. al., Little Box Challenge, CIPS 2016

Inverter

■ Compliant to All Specifications (!)

14.8in³ (243 cm³)
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/in³

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/(dm³K) Heatsink also Employed as EMI Shield

Source: Kolar et. al., Little Box Challenge, CIPS 2016

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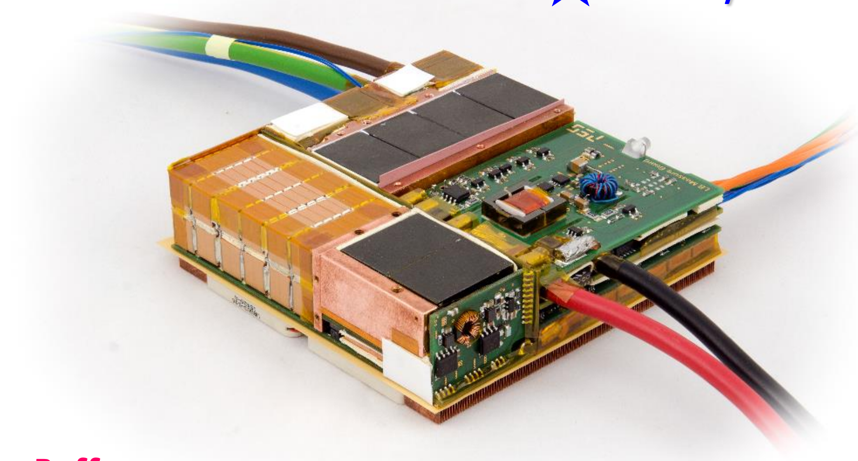


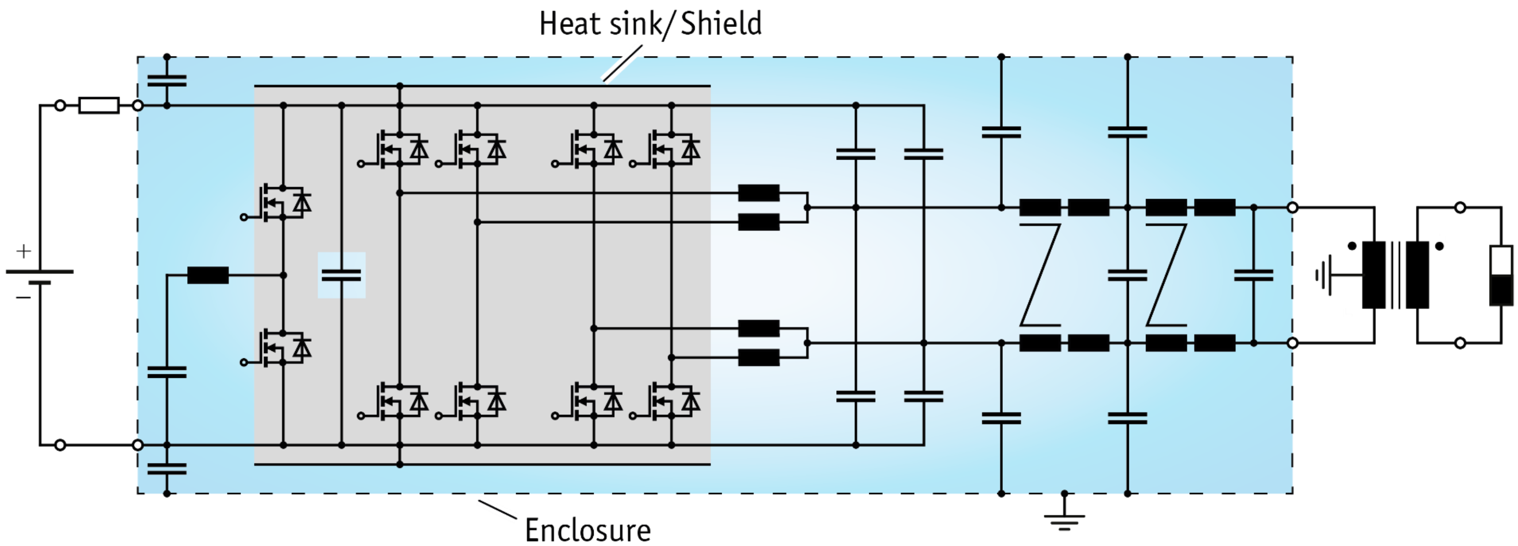
■ New Technologies

- 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^3K) Heatsink also Employed as EMI Shield

Source: Kolar et. al., Little Box Challenge, CIPS 2016

Selected Converter Topology

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

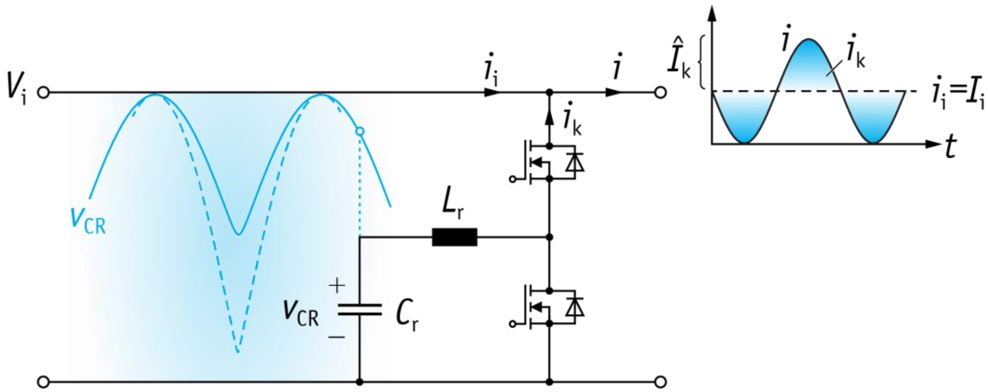


- ZVS of All Bridge Legs @ Turn-On/Turn-Off in Whole Operating Range – 4D TCM Interleaving
- Heatsinks Connected to DC bus / Shield to Prevent Capacitive Coupling to Grounded Enclosure

Source: Kolar et. al., Little Box Challenge, CIPS 2016

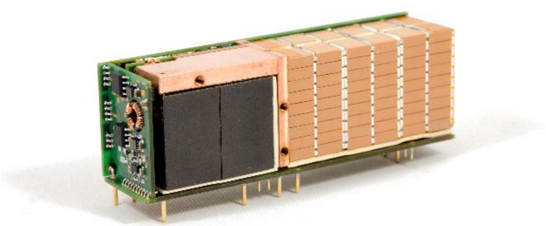
Power Pulsation Buffer

- 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

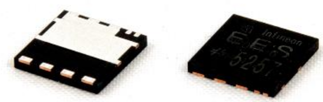


V = 166 cm^3

- Significantly Lower Volume Compared to Electrolytic Capacitors

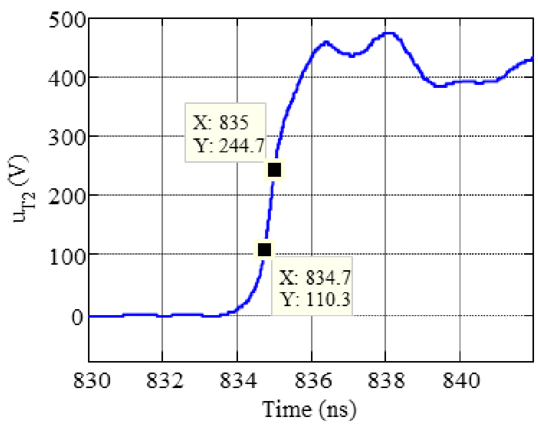
Source: Kolar et. al., Little Box Challenge, CIPS 2016

Power Semiconductors

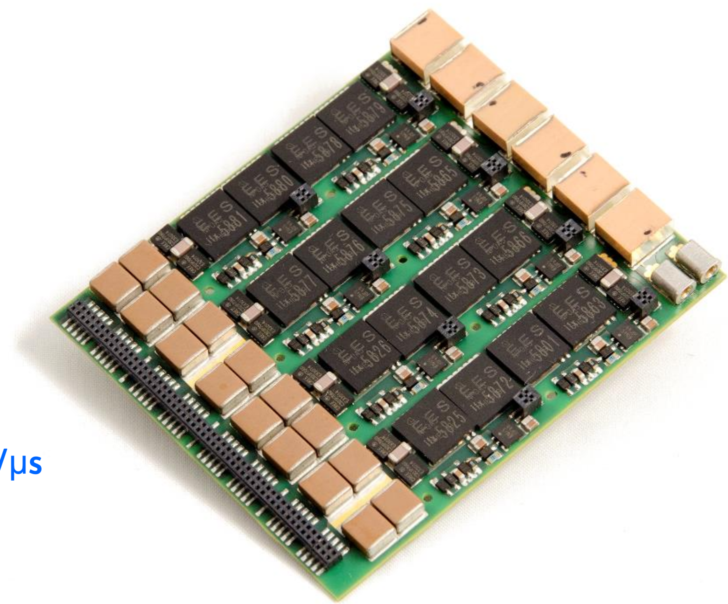


- 600V IFX Normally-Off GaN GIT - ThinPAK8x8
- 2 Parallel Transistors / Switch
- Antiparallel CREE SiC Schottky Diodes

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



dv/dt = 500kV/µs



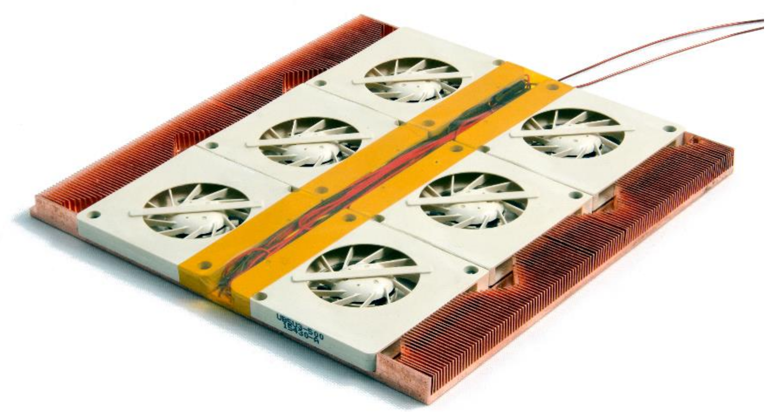
- CeraLink Capacitors for DC Voltage Buffering

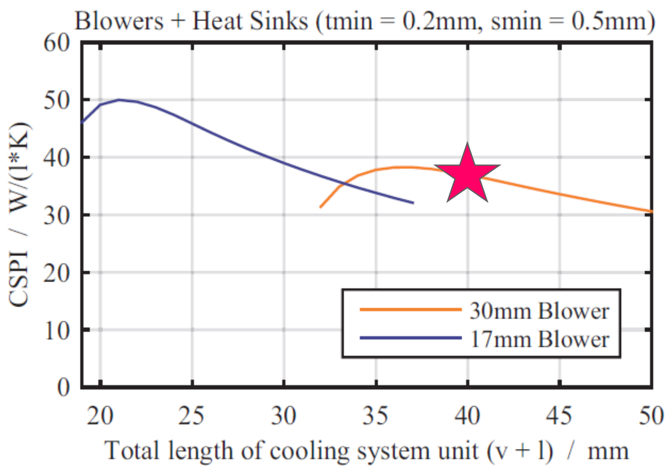
Source: Kolar et. al., Little Box Challenge, CIPS 2016

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





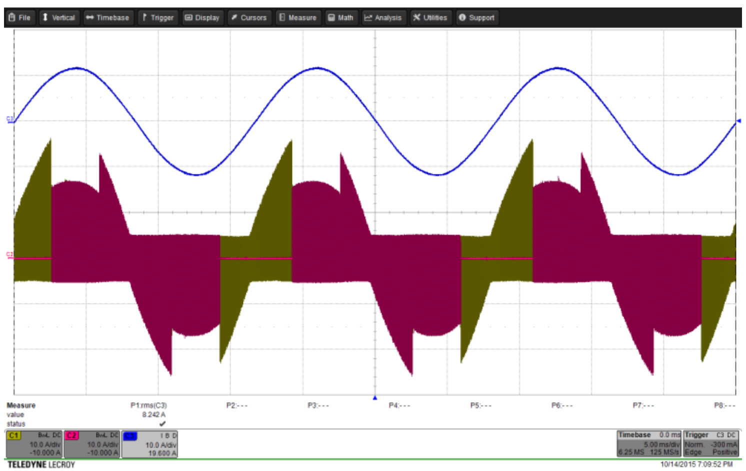
Source: Kolar et. al., Little Box Challenge, CIPS 2016

Measurement Results

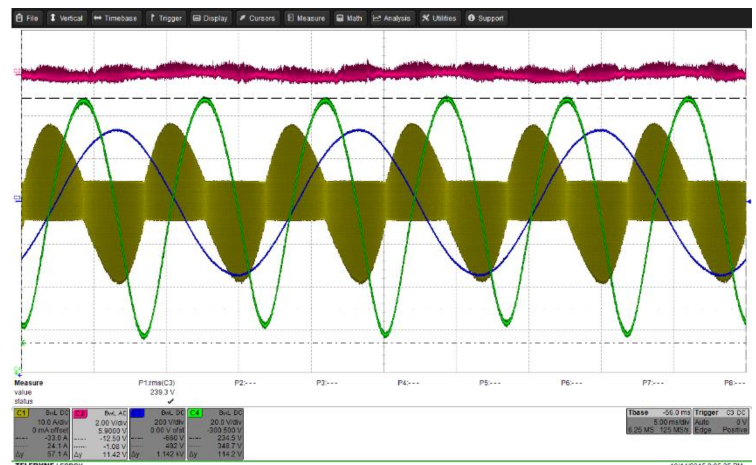
- System Complies to All Specifications (!)

- Ohmic Load / 2kW

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



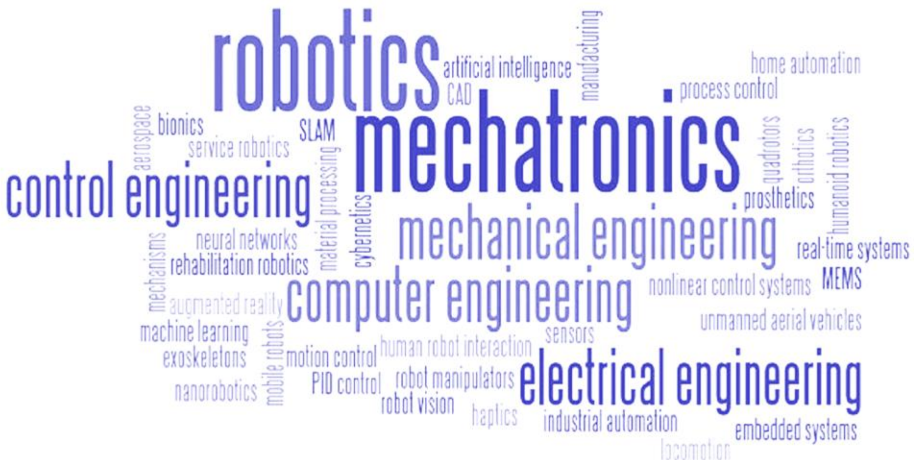
DC Link Voltage (AC-Coupl.)
Buffer Cap. Voltage
Buffer Cap. Current
Output Voltage



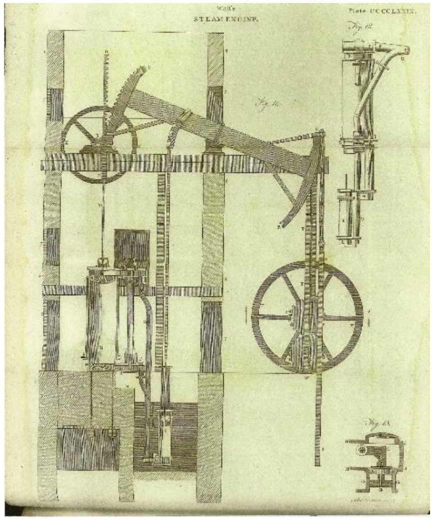
■ New 4D Interleaving Combined with Active ZVS TCM Modulation

Source: Kolar et. al., Little Box Challenge, CIPS 2016

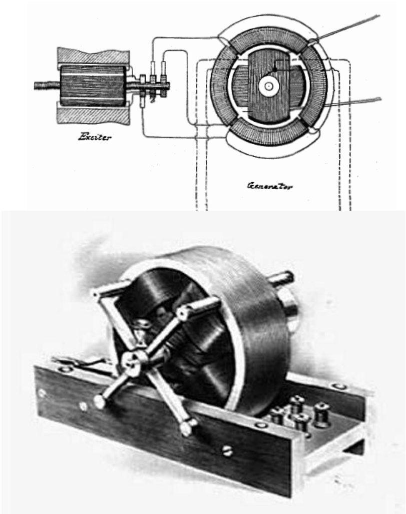
Today's and Future Motion Control Systems



▶ 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

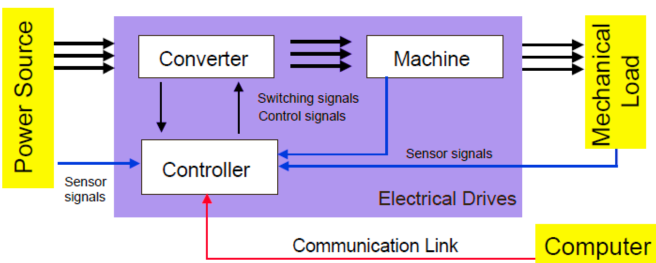
- Machining
- Handling and Assembly
- Transportation (land, sea, air)
- Gas, Oil and Mining
- Water, Wastewater
- Consumer Electronics
- Computers
- Home Appliances
- Defense
- Medical
- Space Exploration

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

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

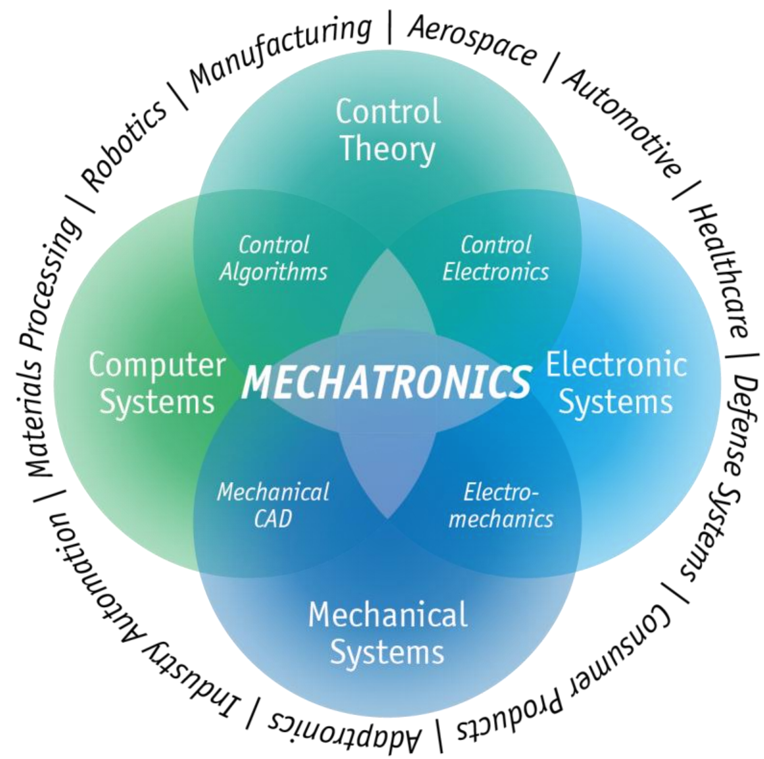
▶ 2nd Option for Gaining Competitive Advantage: *Target Future Mechatronic Systems*

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



Source: De Doncker, Modern Electrical Drives: Design and Future Trends, IPEMC 2006

Source: ETEL



Electrical Drives: Performance Trends

Compact & Lightweight Drives
Power Electronics Integration
Fault Tolerant Systems
High Energy and Cost Efficiency
High Accuracy & Dynamics
Extreme Ambient Conditions

Electrical Drives: Performance Trends

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

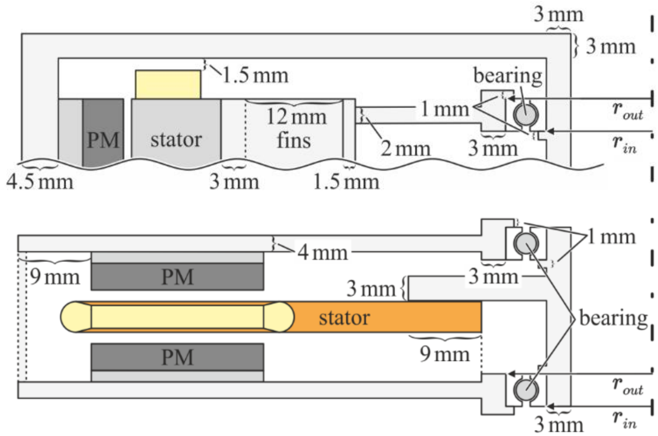
- P_{nom} 260 kW (η = 95%)
- n_{max} 2500 r/min
- D_{out} 418 mm
- l_{ax} 300 mm
- m_{tot} 50 kg (incl. Prop. Bearing)

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

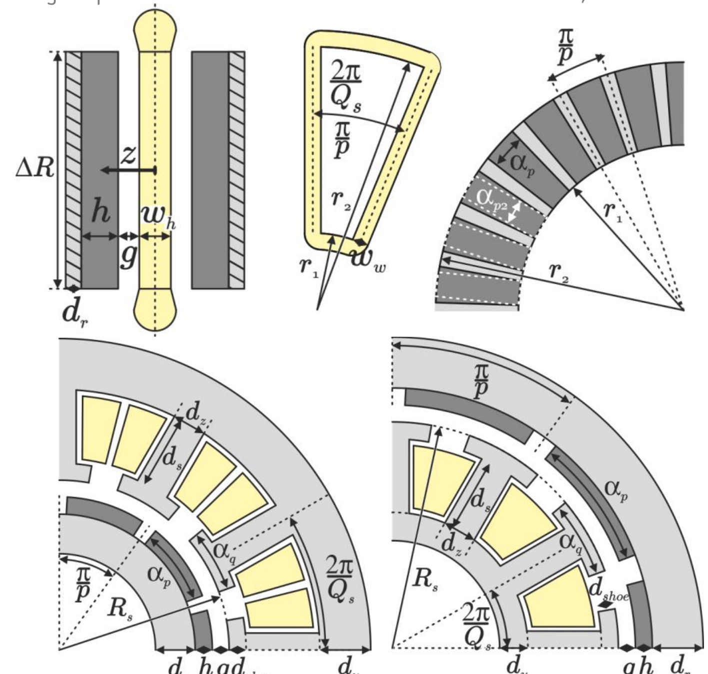
■ Comprehensive Machine Models
- Magnetic field, torque, losses
- Structural mass
- Thermal behavior

■ Advanced Machine Topologies
- Hallbach array
- Cobalt-iron alloy or air core
- Copper or aluminum coils

Source: Gammeter et. al., Weight Optimization of a Machine for Airborne Wind Turbines, IECON 2014



▲ Structural mass model

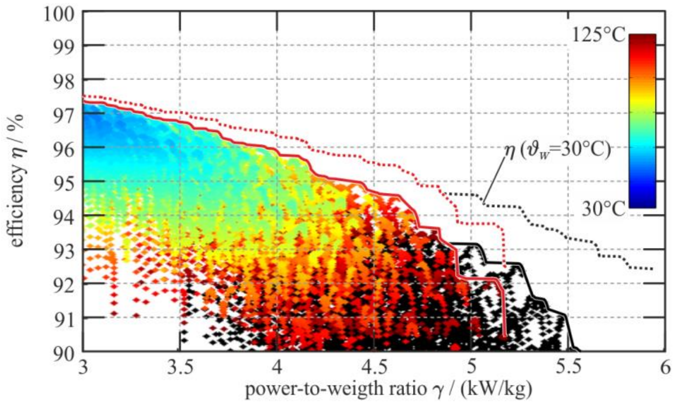


$$\Psi_{\mathrm{ph,A}}(\theta) = 4p \int_0^{\frac{w_h}{2}} \int_{r_1}^{r_2} \int_{\phi_s}^{\phi_e} r \cdot B_z(r,\phi,z)\, \mathrm{d}\phi\, \mathrm{d}r\, \mathrm{d}z$$

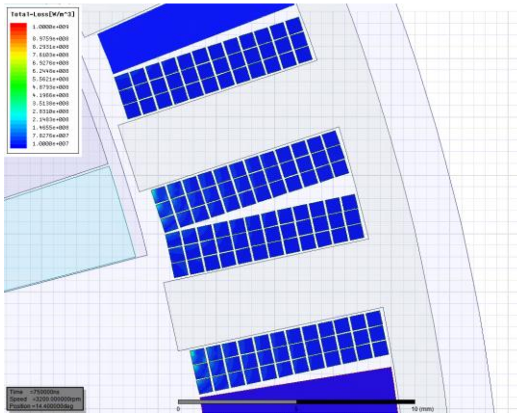
$$u_{\mathrm{ph,A}} = -\frac{\mathrm{d}}{\mathrm{d}t}\Psi_{\mathrm{ph,A}}$$

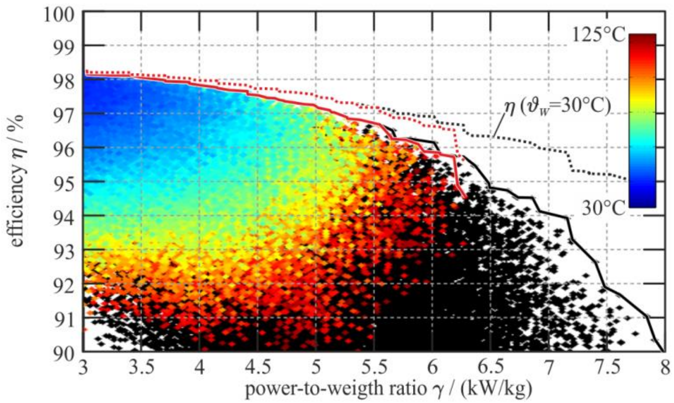
▲ Electromagnetic models

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

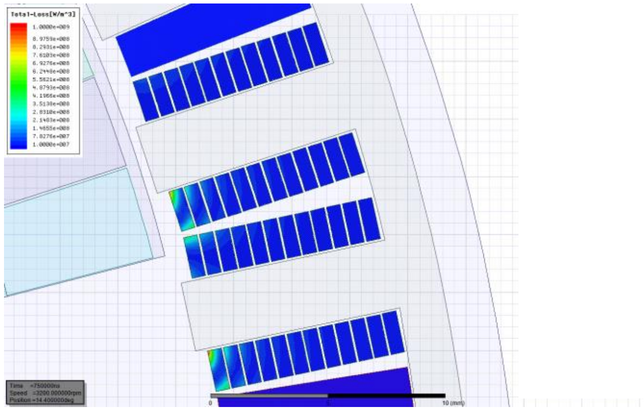


▲ AFM with distributed windings and Halbach magnetization





▲ Inrunner RFM with segmented Halbach magnetization

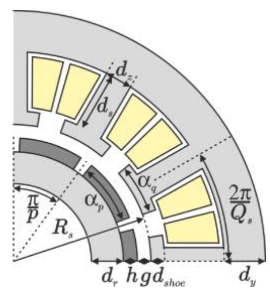


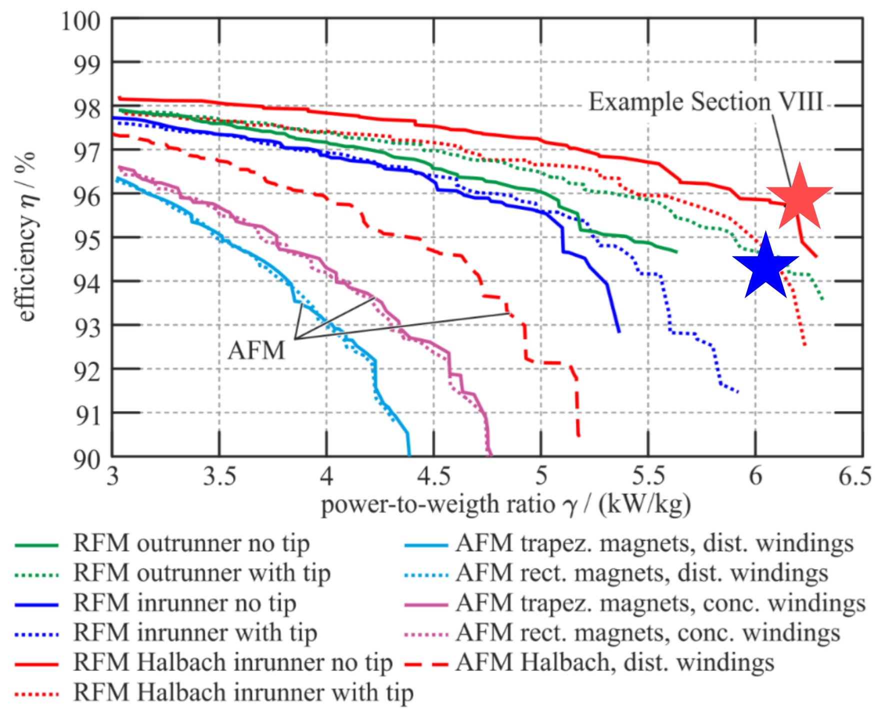
▲ 2-D FEM for Proximity Loss Calculation

► Reliable, Efficient and Compact Electrical Drives

- **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

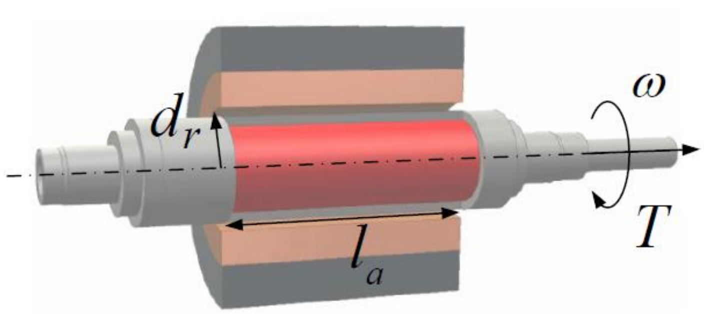
1) Mechanical Power $P_m = \omega T$

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

Rotor Diameter

Axial Length of Machine

Machine Size



Utilization Factor

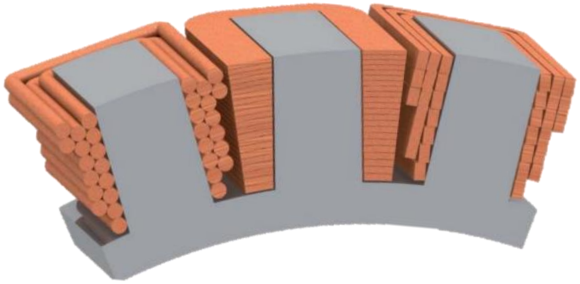
- Machine topology
- Materials
- Manufacturing methods
- Cooling

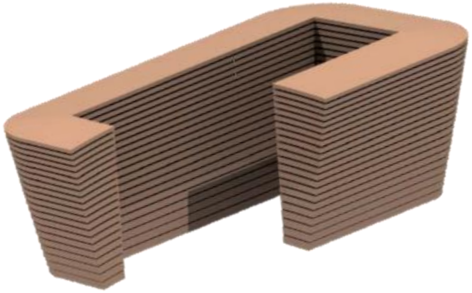
▶ Increasing the Machine Utilization Factor (1)

■ 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





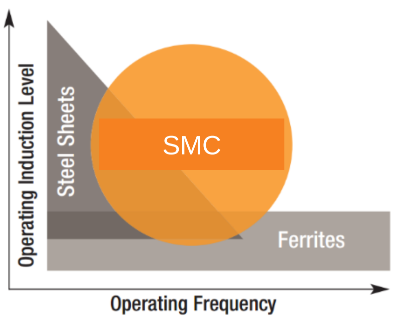
▶ Increasing the Machine Utilization Factor (2)

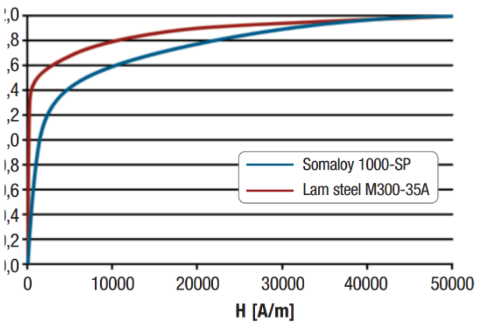
■ Degrees-of-Freedom for Improved Utilization

- Manufacturing methods
- Materials
- Cooling

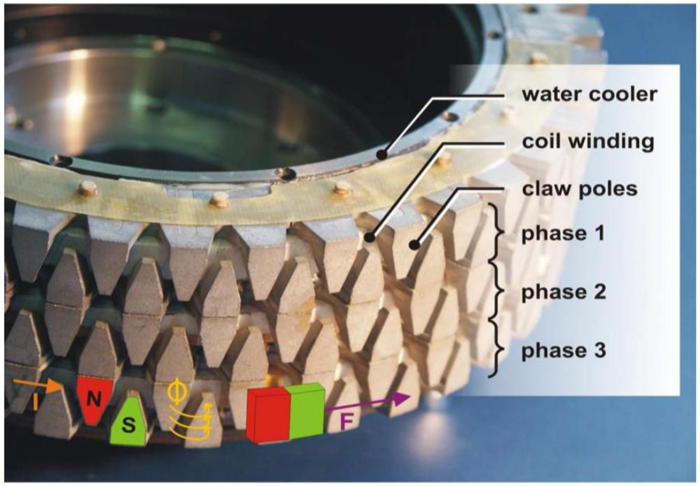
– **Soft magnetic composites (SMC):**
+ 3-D electrical insulation
+ Low eddy-current losses
+ Transversal- or Axial-Flux Machines
- Mechanical strength
- Low magnetic permeability

Source: gkn.com





Source: Höganäs



Source: Bauer, Kleimaier, Observer Based Sensorless Predictive Hysteresis Control of a Transverse Flux Machine, ICEMS 2014

▶ Increasing the Machine Utilization Factor (3)

■ Degrees-of-Freedom for Improved Utilization

- Manufacturing methods
- Materials
- Cooling

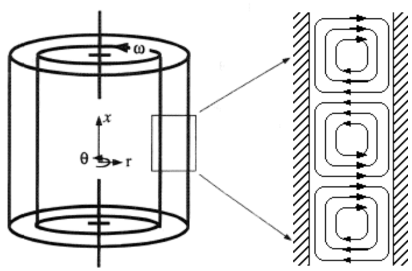
– **Integrated cooling (slotless machines)**

+ Smart design:
  Fast empirical models for cooling
  Magnetic ↔ Mechanical ↔ Thermal
+ > 40 °C hotspot temp. reduction

Source: integy.com

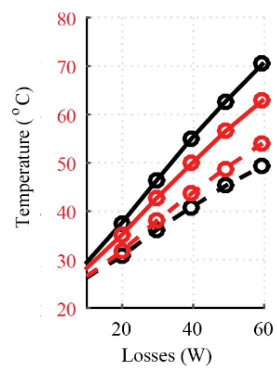
(1) Jacket cooling
(State of the art)

(2) Integrated cooling

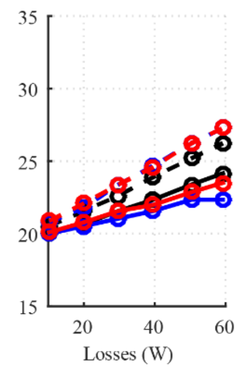


Source: Childs, Long, A Review of Forced Convective Heat Transfer in Stationary and Rotating Annuli, 1996

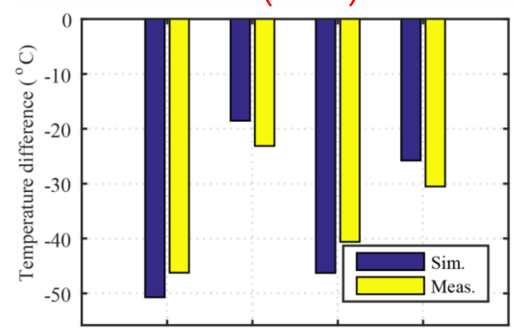
(1)



(2)



(1 − 2)

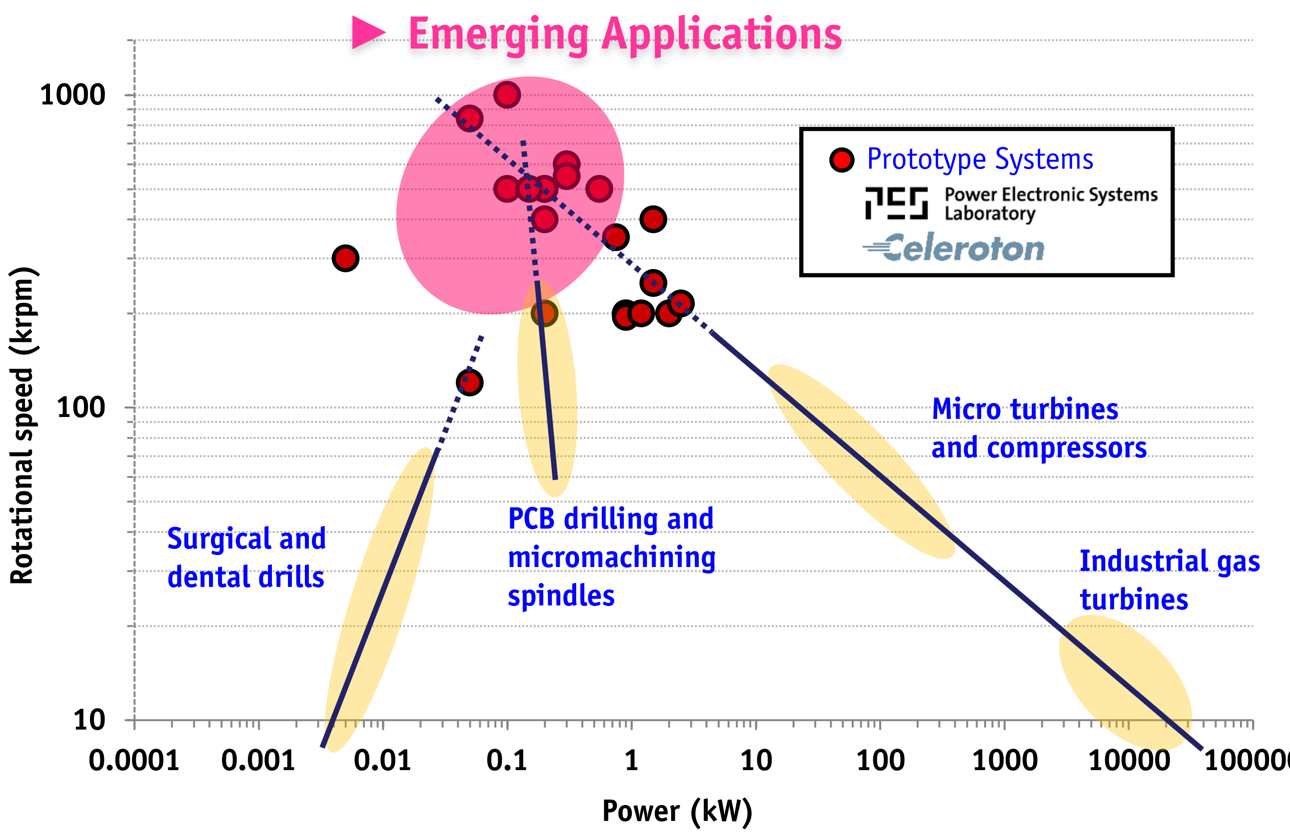


Source: Tüysüz et. al., Advanced Cooling Concepts for Ultra-High-Speed Machines, ICPE 2015

▶ Industry Trend: High Rotational Speed for High Compactness

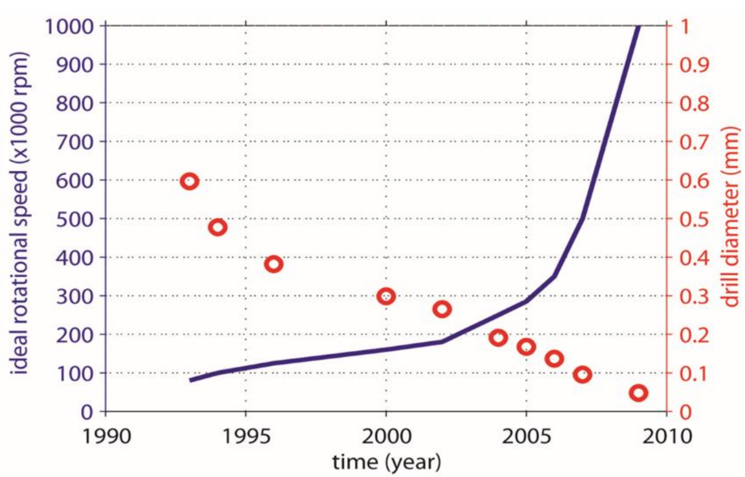
■ Ultra-High-Speed Drives have Numerous Applications Across Industries

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



►Ultra-High-Speed Micro-Machining Applications

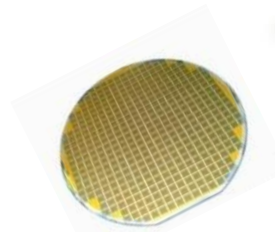
- **Rotational Speed: 250'000 – 1'000'000 r/min**
  - Smaller Feature Size (µ-vias for Consumer Electronics)
  - Higher Precision in Manufacturing
  - Accelerated Manufacturing Process
  - Higher Productivity



Source: Kolar et. al.,
Beyond 1 000 000 rpm Review of Research on Mega-Speed Drives, COBEP 2007

Dental crowns

µ- vias in PCBs



Wafer notch grinding

Dental/surgical drills

Watchmaking

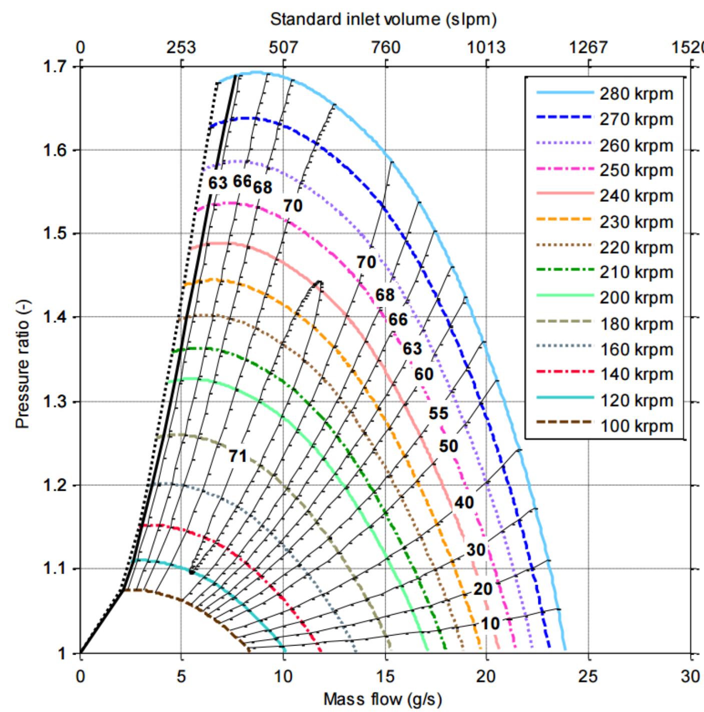
► High-Speed Turbocompressor for Portable Fuel Cell

- Reduced Weight/Volume
- Increased Pressure Ratio

Fuel cell

Celeroton

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

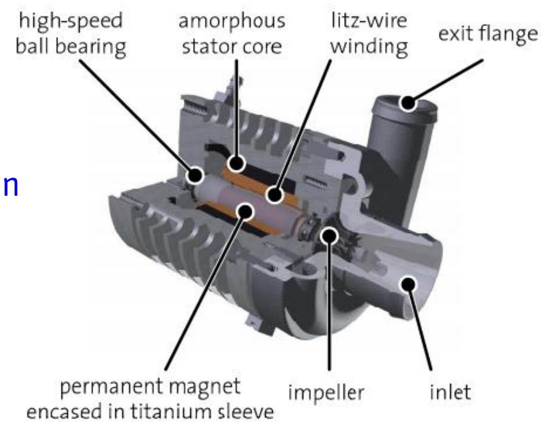


► Ultra-Compact Turbocompressor for *«Solar Impulse»*

- **Cabin Pressurization in Solar-Powered All-Electric Aircraft**
  - Compact machine design with 150 W, 150’000 r/min

Source: Zwyssig et. al., A Miniature Turbocompressor System, SES 2008

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

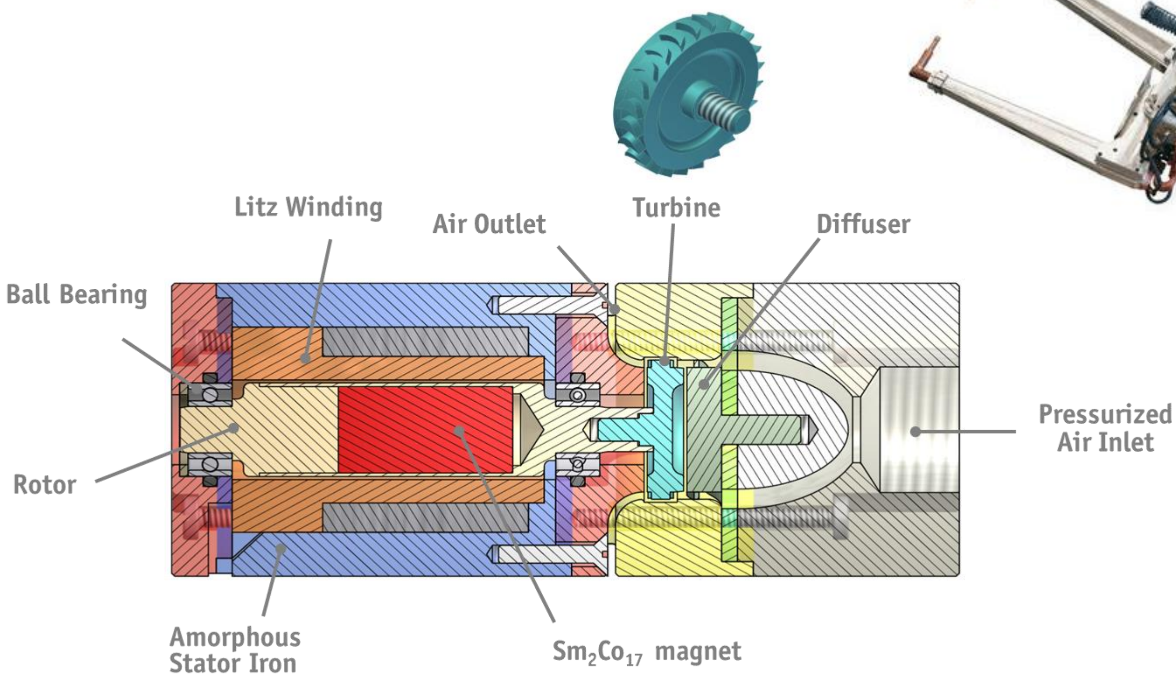


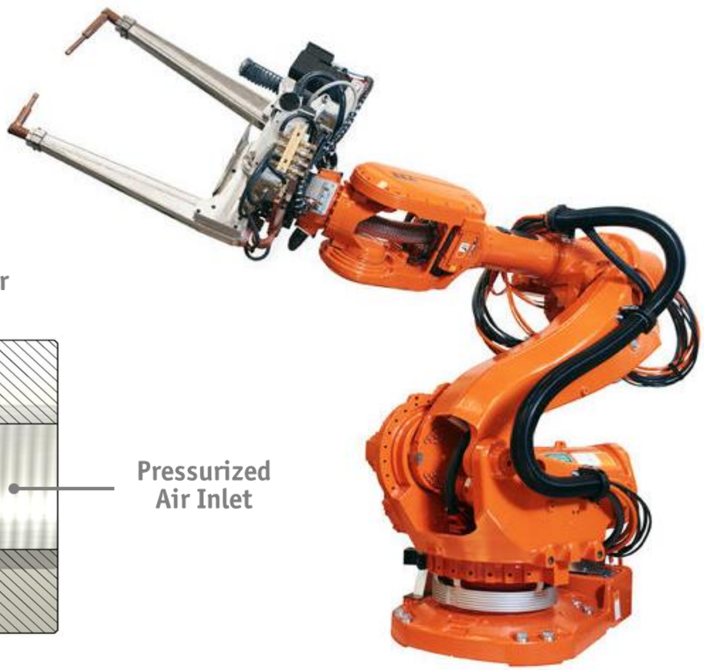
► High-Speed Air-to-Power Systems

■ 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





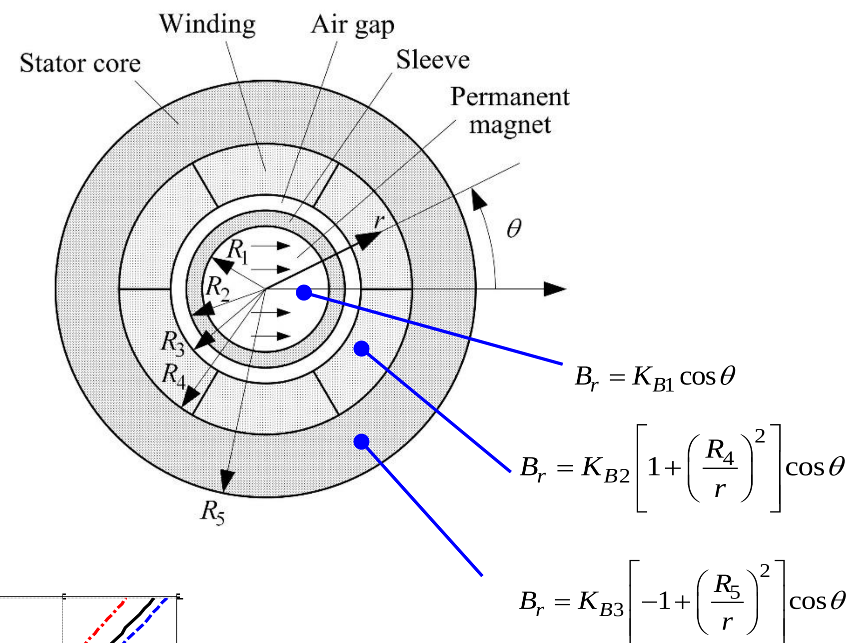
Source: Kolar et. al.,
Beyond 1 000 000 rpm Review of Research on Mega-Speed Drives, COBEP 2007

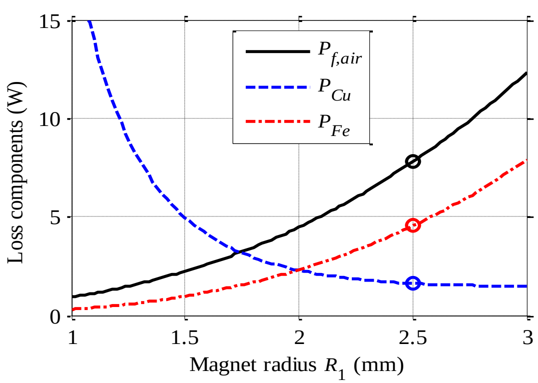
▶ Magnetic Design of Ultra-High-Speed Drives

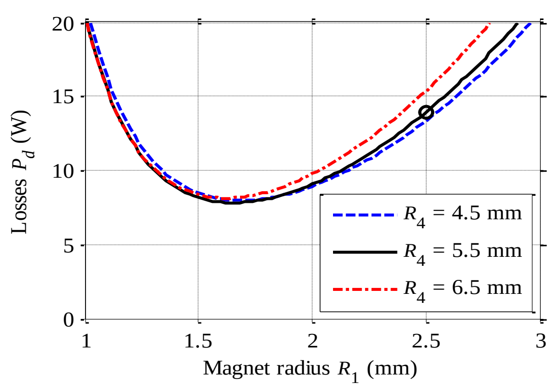
■ Magnetic Design is Key Challenge at High Rotational Speed

■ 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







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

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

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

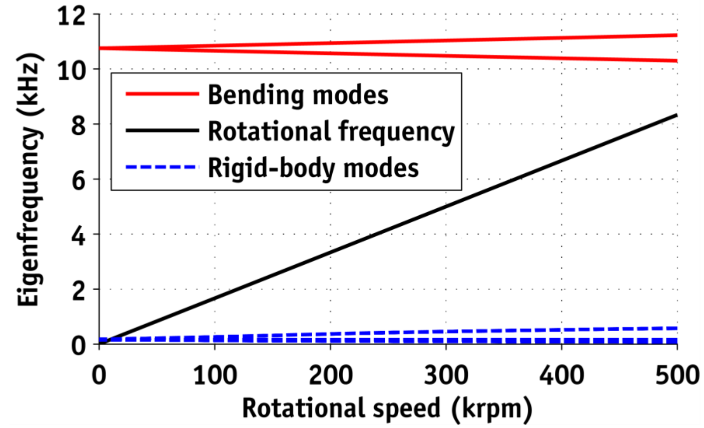
Source: Luomi et. al., Efficiency Optimization of a 100-W 500 000-r/min Permanent-Magnet Machine Including Air-Friction Losses, IEEE Trans. on Ind. App., 2009

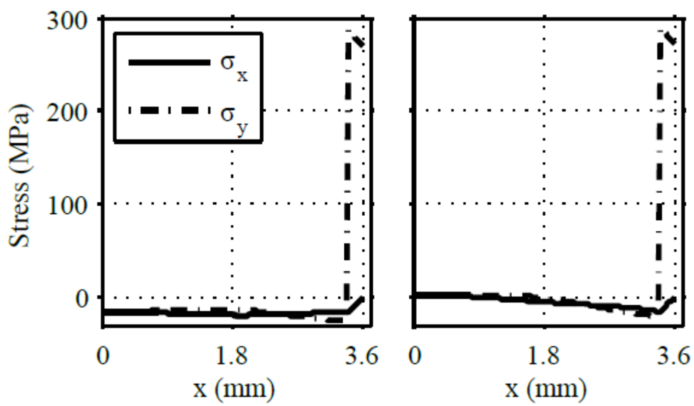
▶ Rotor Design Challenges at Ultra-High-Speeds

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

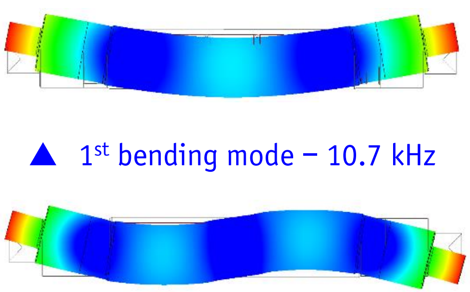
- **Stresses due to Centrifugal Force**
  - Metallic or Composite Sleeve Needed
  - Tight Tolerances for Interference Fit

Source: Baumgartner, Kolar, Multivariable State Feedback Control of a 500 000 rpm Self-Bearing Motor, IEMDC 2013





▲ Rotor stresses due to rotation

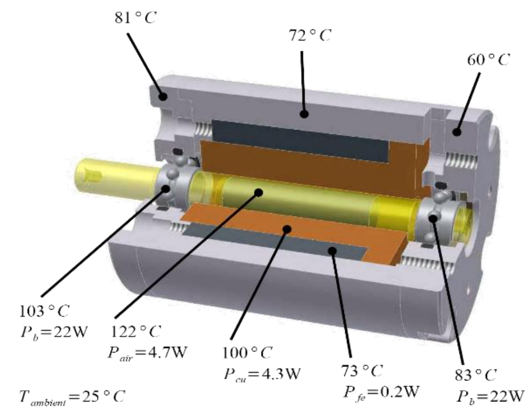


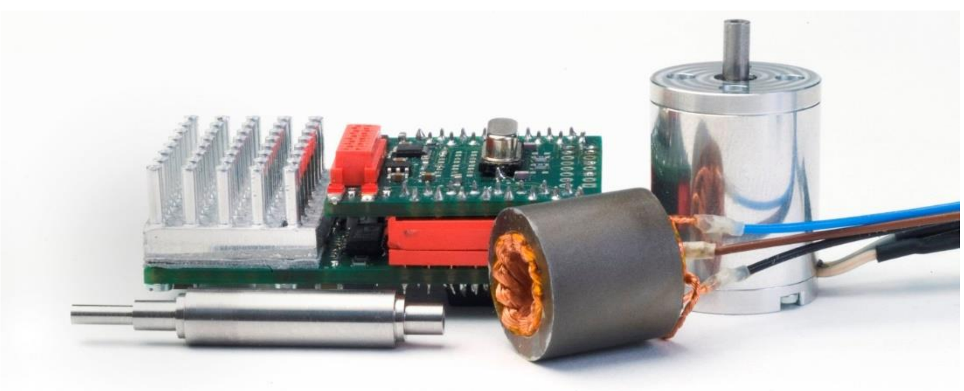
▲ 1st bending mode – 10.7 kHz

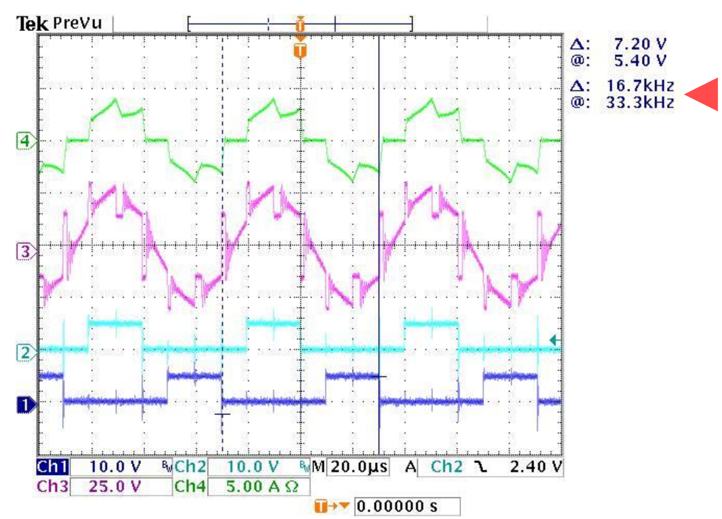
▲ 2nd bending mode – 25 kHz

▶ 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



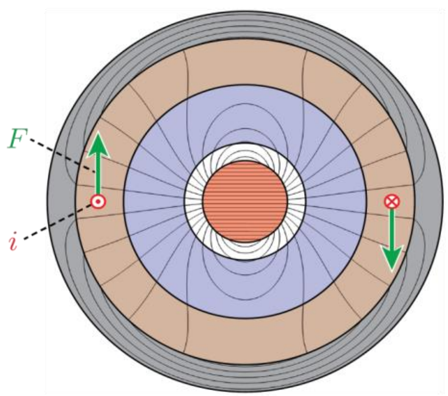




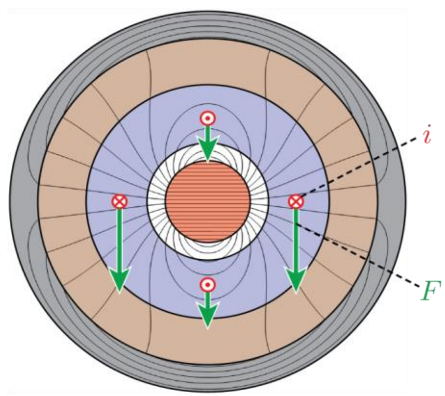
▶ Advanced Bearing Systems: Magnetic Bearings

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

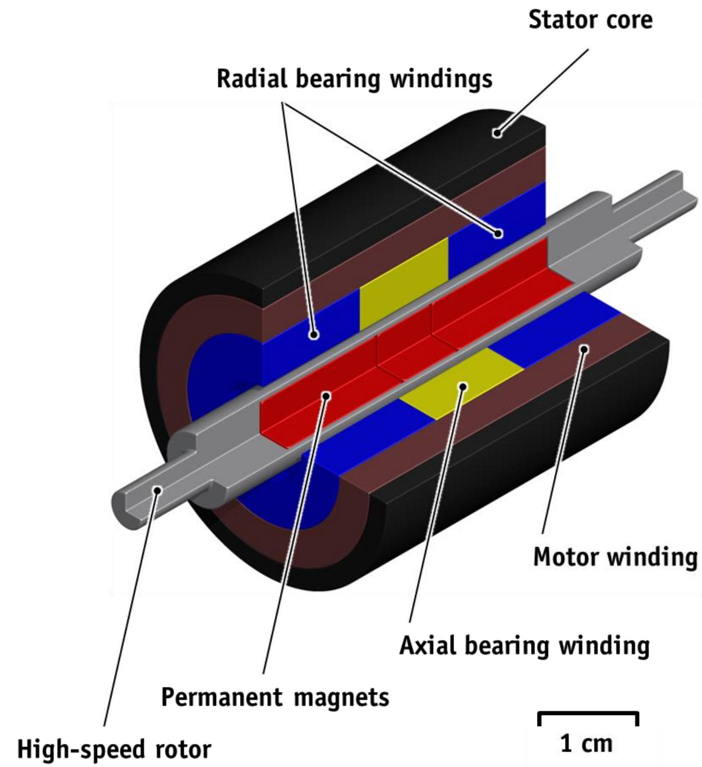
- **Active Magnetic Bearings**
  + No Wear, Long Lifetime
  + Control of Rotor Dynamics
  - Limited Load Capacity
  - High Bandwidth / Complex Control
  - Accurate Displacement Sensing



▲ Drive torque



▲ Radial bearing force



Source: Baumgartner, A Magnetically Levitated 500 000 RPM Electrical Drive System, ETH Zurich, 2013

► Advanced Bearing Systems: Magnetic Bearings

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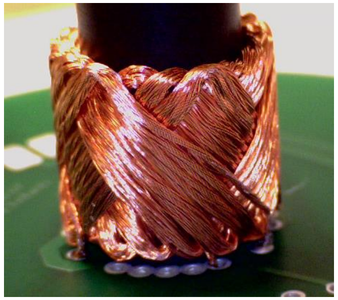
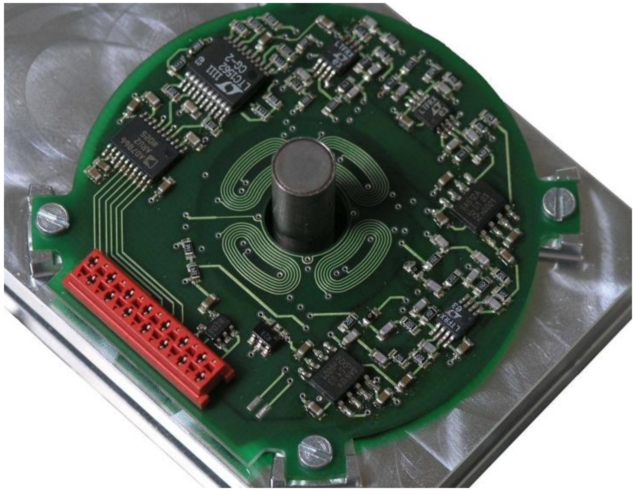
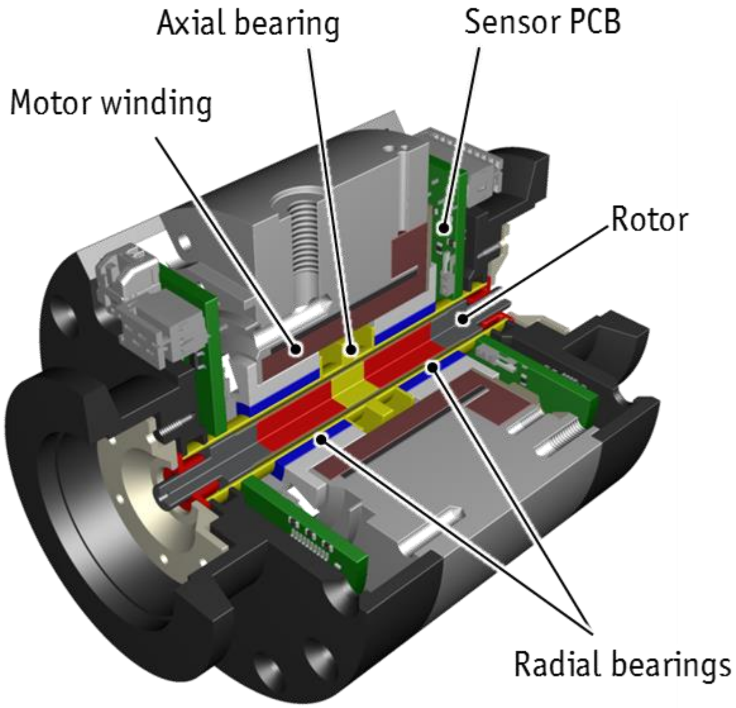


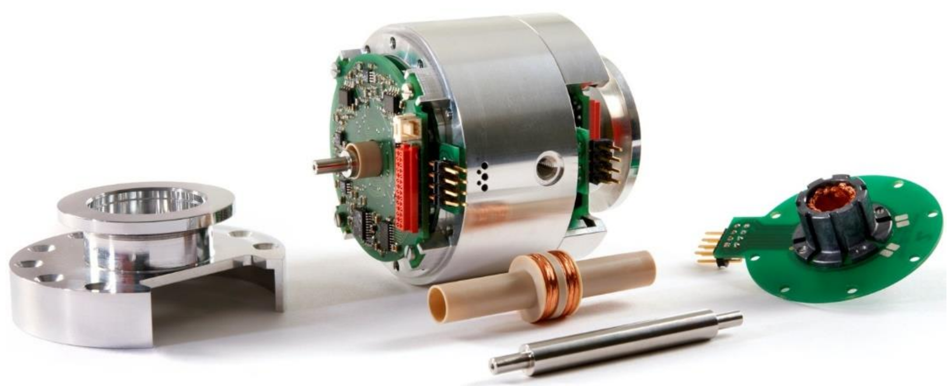




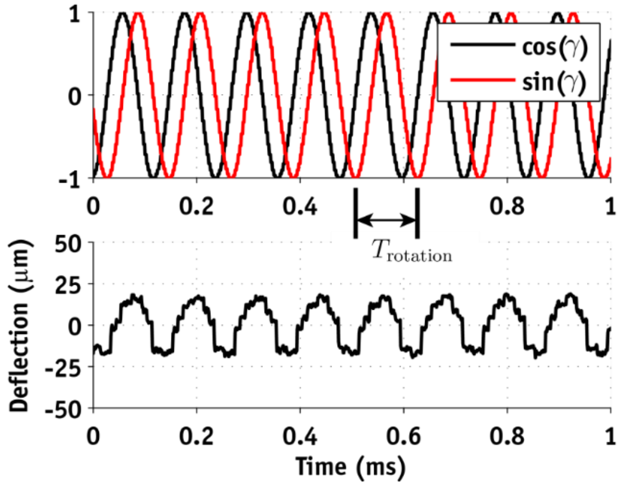
Source: Baumgartner, A Magnetically Levitated 500 000 RPM Electrical Drive System, ETH Zurich, 2013

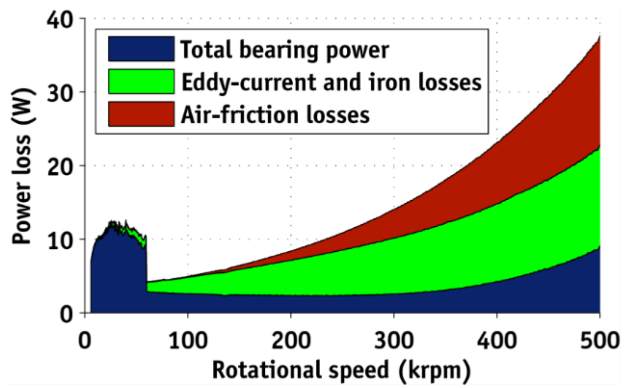
► World Record Magnetic Bearing with 500'000 r/min

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



Source: Baumgartner, Kolar, Multivariable State Feedback Control of a 500 000 rpm Self-Bearing Motor, IEMDC 2013



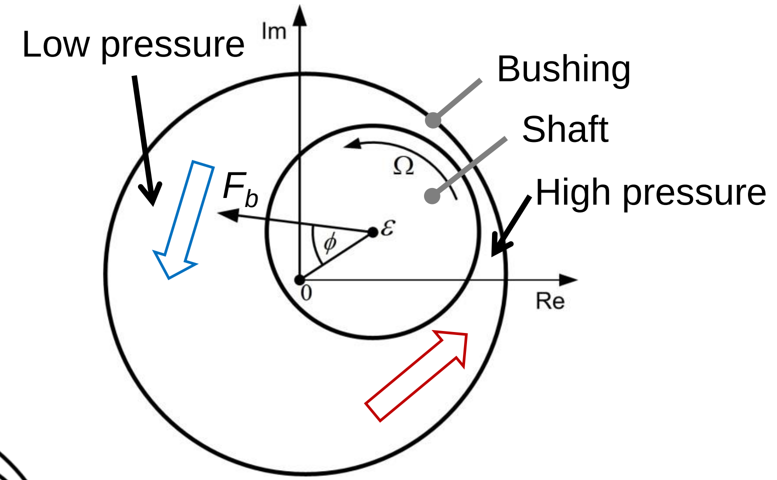


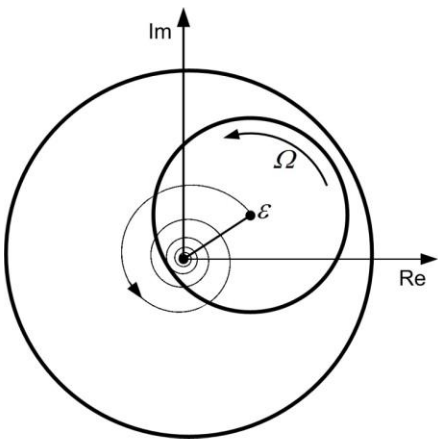
▶ Advanced Bearing Systems: Hybrid Bearings

■ Lifetime of Ball Bearings Limits Rotational Speed of Electric Machine

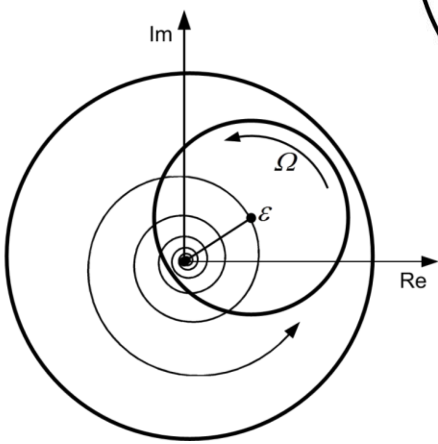
■ Gas Bearings

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





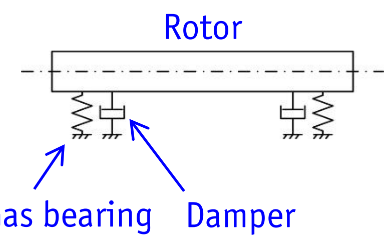
Stable orbit with sufficient internal damping (gas-film) usually at lower speeds

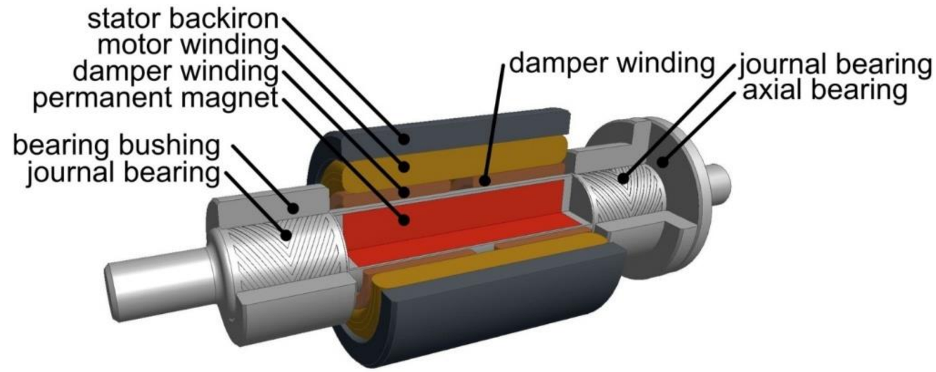


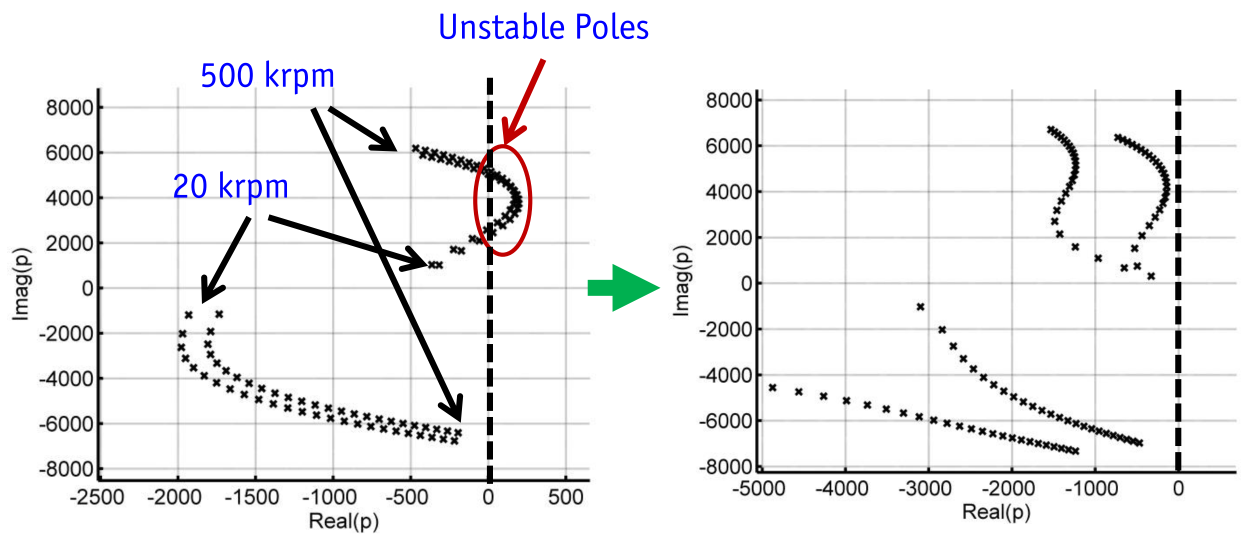
Unstable orbit with insufficient damping (usually at higher speeds)

▶ Advanced Bearing Systems: Hybrid Bearings

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



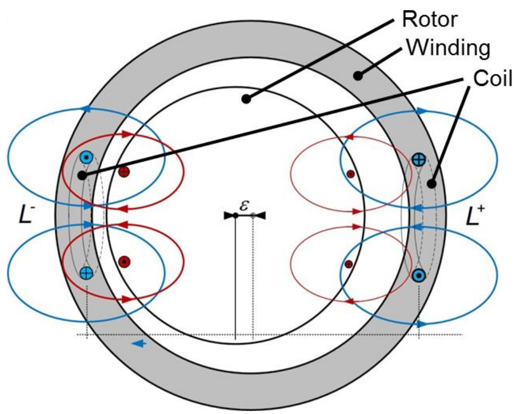


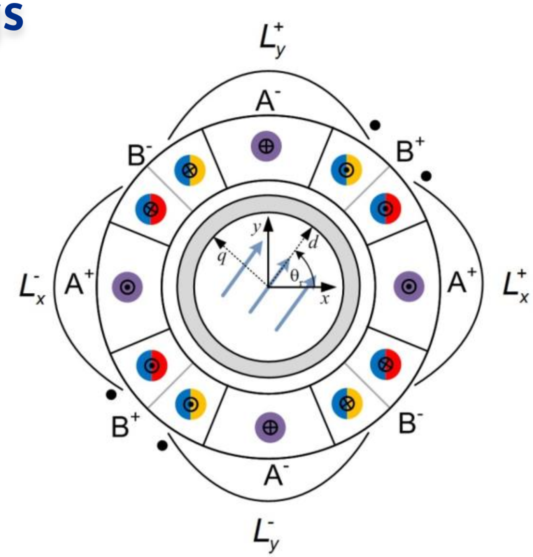


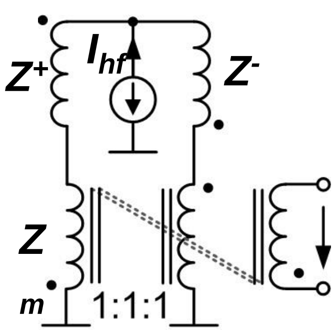
Source: Looser, Kolar, An Active Magnetic Damper Concept for Stabilization of Gas Bearings in High-Speed Permanent-Magnet Machines, IEEE Trans. on Ind. Elect., 2014

▶ Advanced Bearing Systems: Hybrid Bearings

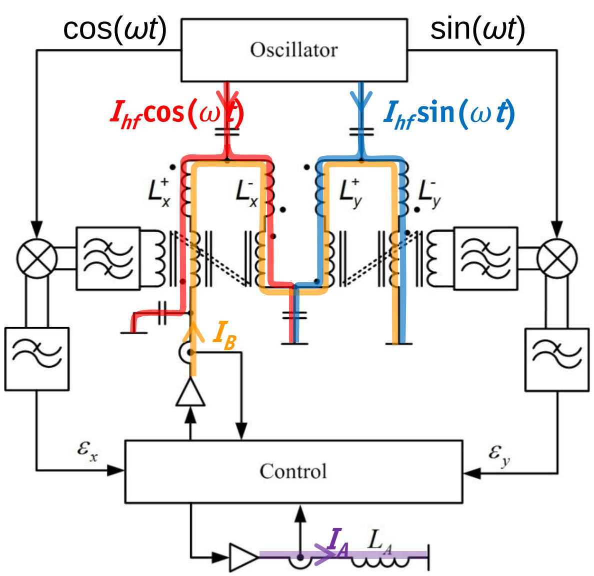
■ Accurate Self-Sensing Method using Damper Windings







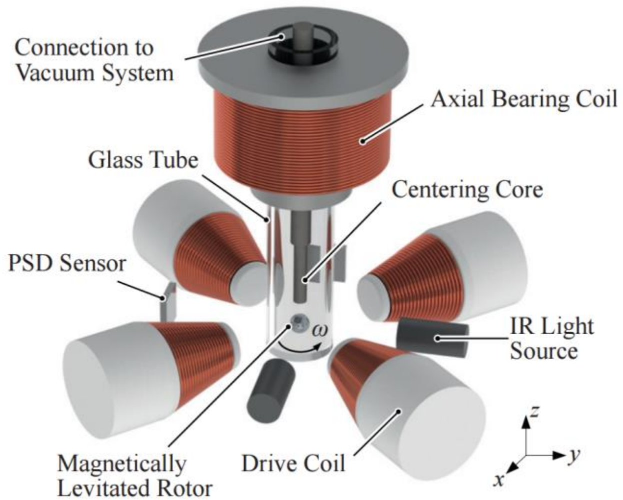
$$U_m = I_{hf} \cdot \frac{Z_m}{Z + 2 \cdot Z_m} \cdot \Delta Z(\varepsilon)$$

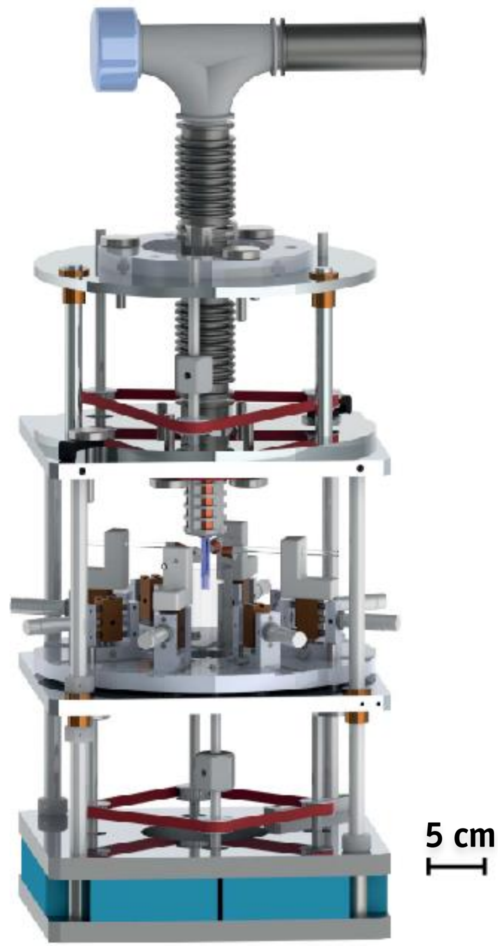


Source: Looser, Kolar, An Active Magnetic Damper Concept for Stabilization of Gas Bearings in High-Speed Permanent-Magnet Machines, IEEE Trans. on Ind. Elect., 2014

▶ Exploring the Limits: 40’000’000 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



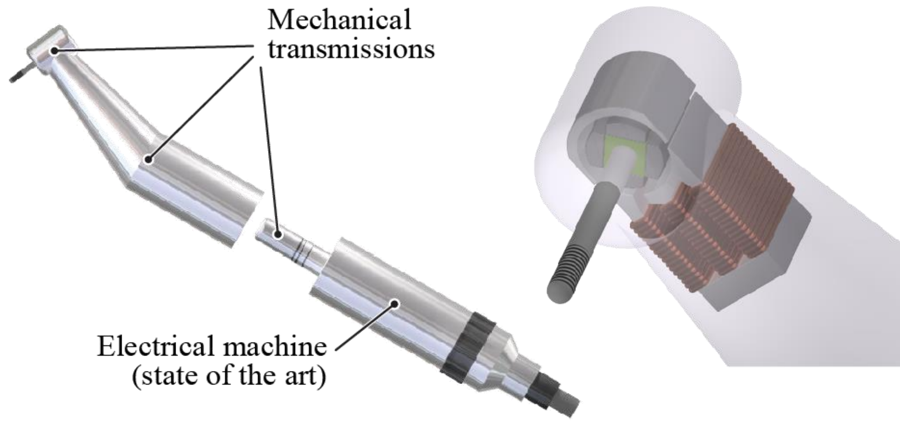


Source: Schuck et. al., Electromagnetic Suitability Analysis and Characterization of Ultra-High Speed Spherical Steel Rotors, INTERMAG 2016

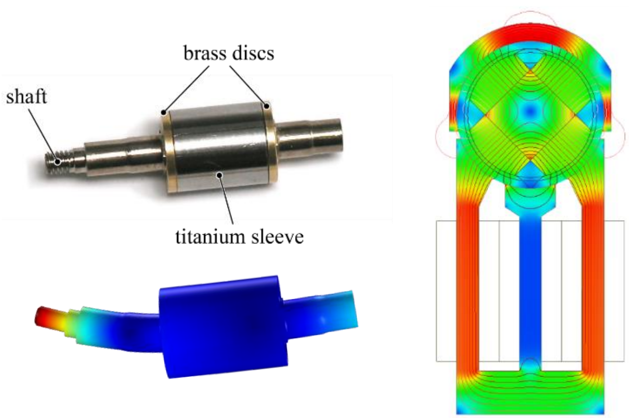
► Application-Specific Machine Concepts (1)

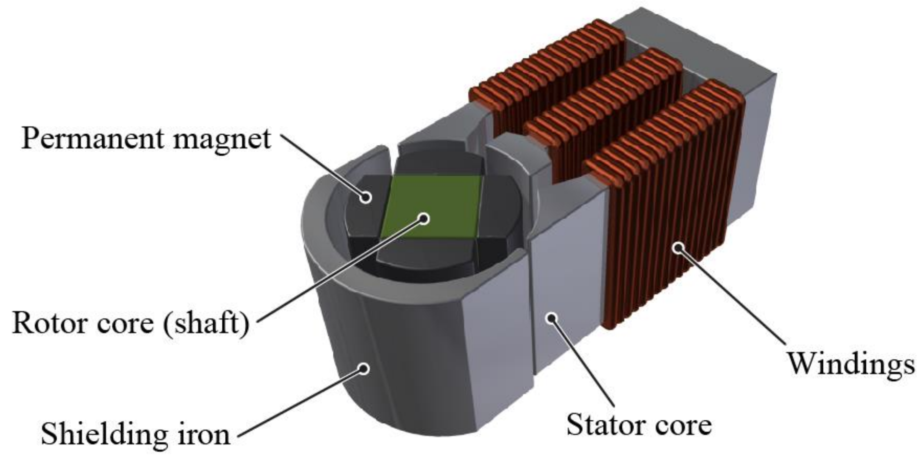
- **Optimization of Machine Design for Application Specific Requirements**

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



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



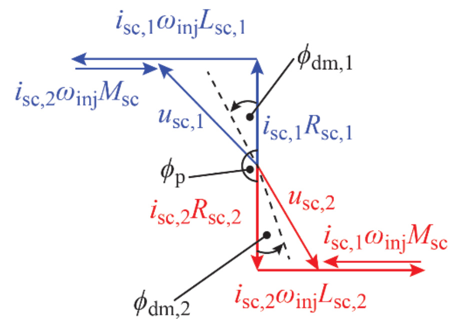


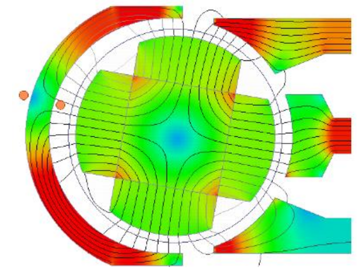
Tüysüz, Kolar, Comparison of lateral- and cylindrical-stator electrical machines for high-speed direct-drive applications in confined spaces, APEC 2016

▶ Application-Specific Machine Concepts (2)

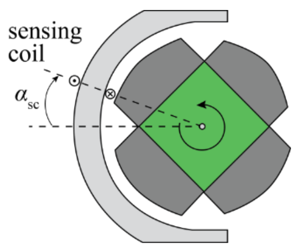
■ Optimization of Machine Design for Application Specific Requirements

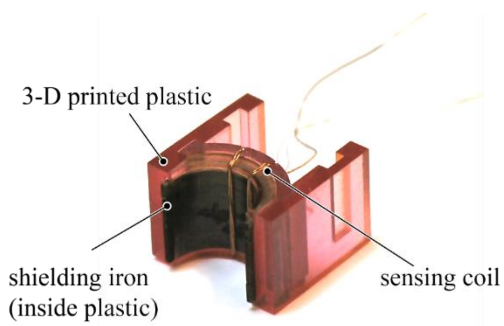
■ Lateral-Stator Machine Concept
- Novel Actuator Topology
- Direct Drive
- 3 x Higher Local Torque Density

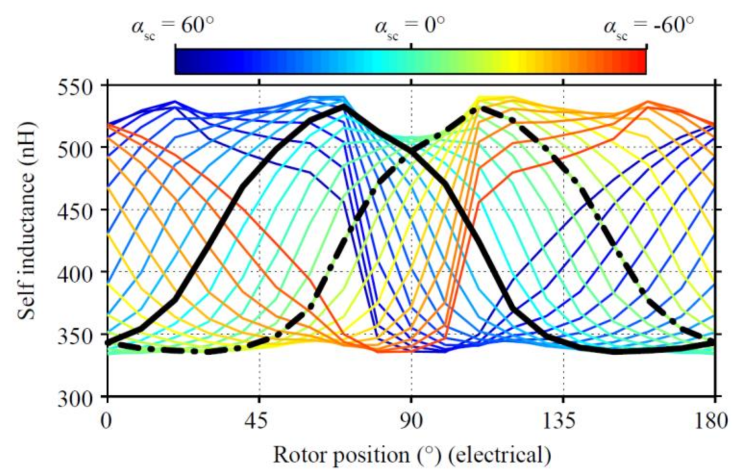




■ Topology-Specific Integrated Position Sensor
- Compact Realization
- Load Independent







Tüysüz, Kolar, New Position-Sensing Concept for Miniature Lateral-Stator Machines, IEEE Trans. on Ind. Electr., 2016

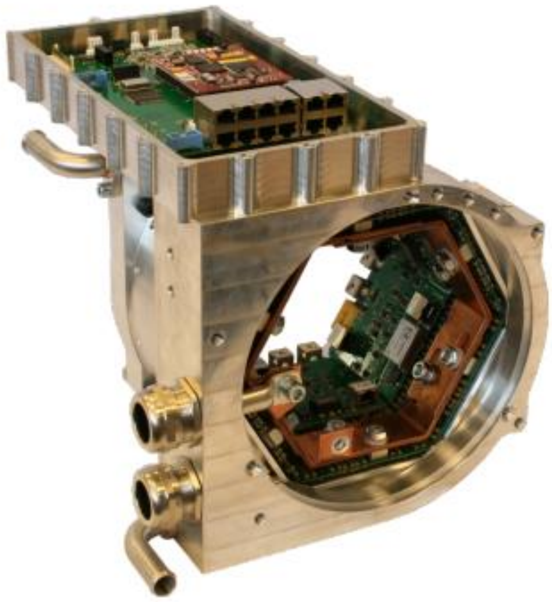
Electrical Drives: Performance Trends

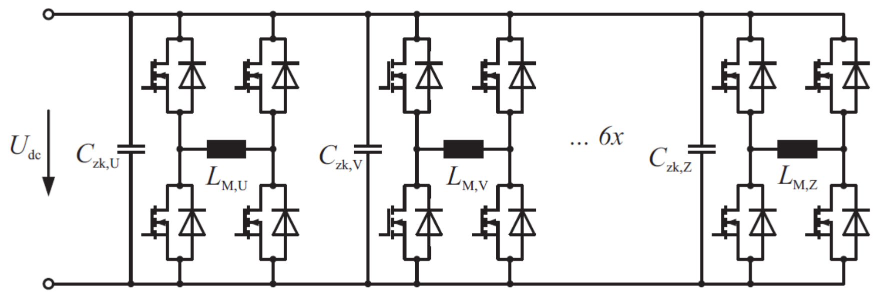
Compact & Lightweight Drives
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

▶ 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





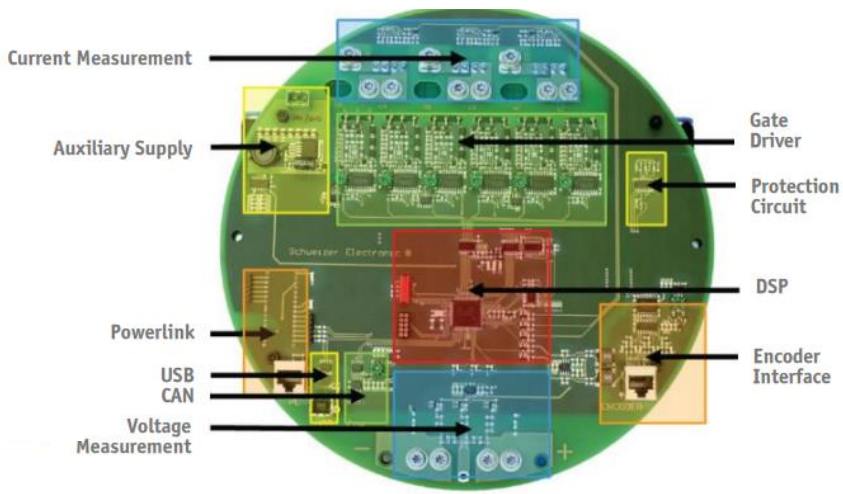
\+ Fault Tolerant Design
\- Number of Power Switches

Source: Engelmann et. al. A Highly Integrated Drive Inverter using DirectFETs and Ceramic DC-Link Capacitors for Open-End Winding Machines in Electric Vehicles, APEC 2015

▶ Integration of Power Electronics & Electrical Machine (2)

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

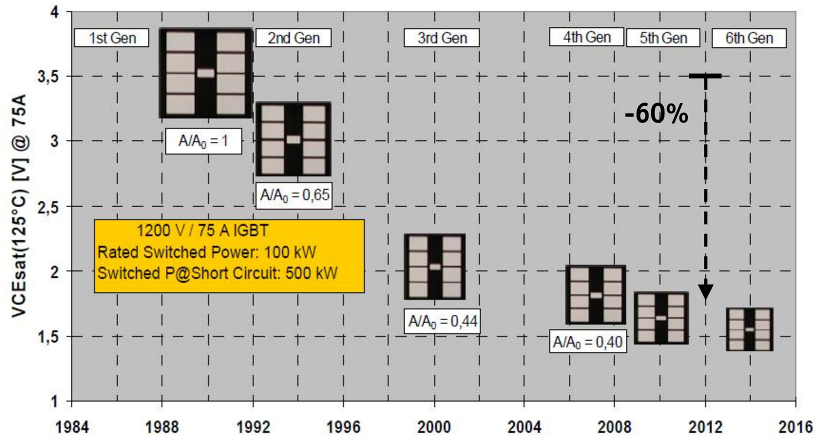
- **3-Phase Si-IGBT Inverter in p²pack-Technology**
  - S_{nom} 32 kVA
  - V_{in} 700 V
  - f_{out} 0 - 800 Hz
  - f_{sw} 20 kHz



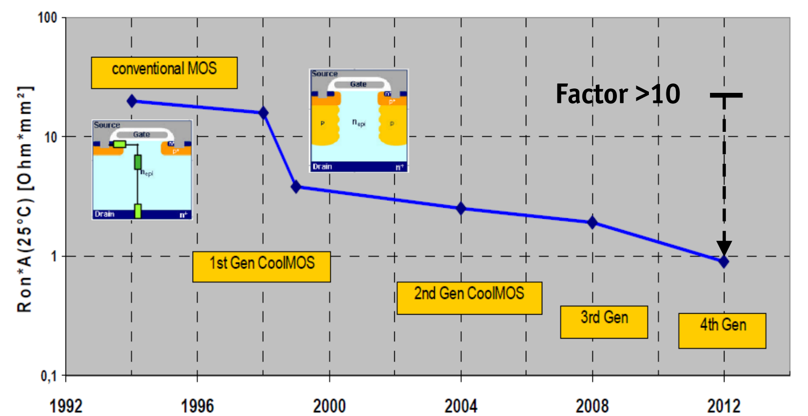
SCHWEIZER ELECTRONIC
enertronics

▶ Si Power Semiconductors

Source: Miller Infineon CIPS 2010



600V Devices

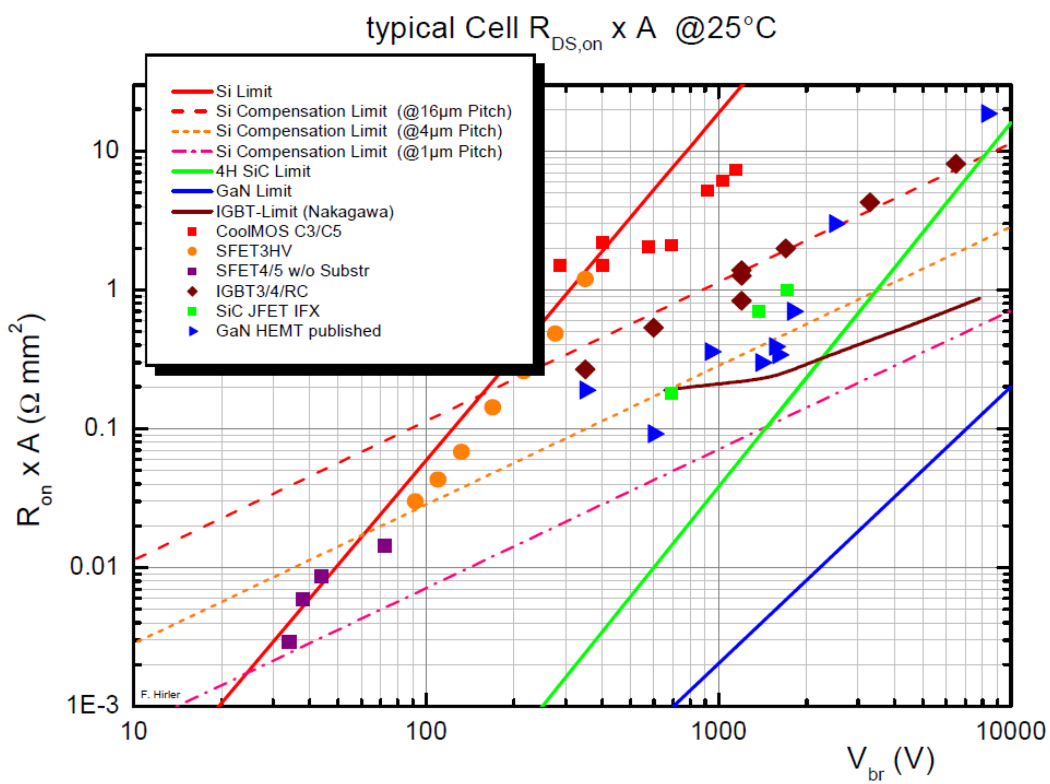


- **Past Disruptive Changes**

  — IGBT Trench & Field-Stop
  — MOSFET Superjunction Technology

▶ WBG Power Semiconductors

Source: Miller Infineon CIPS 2010



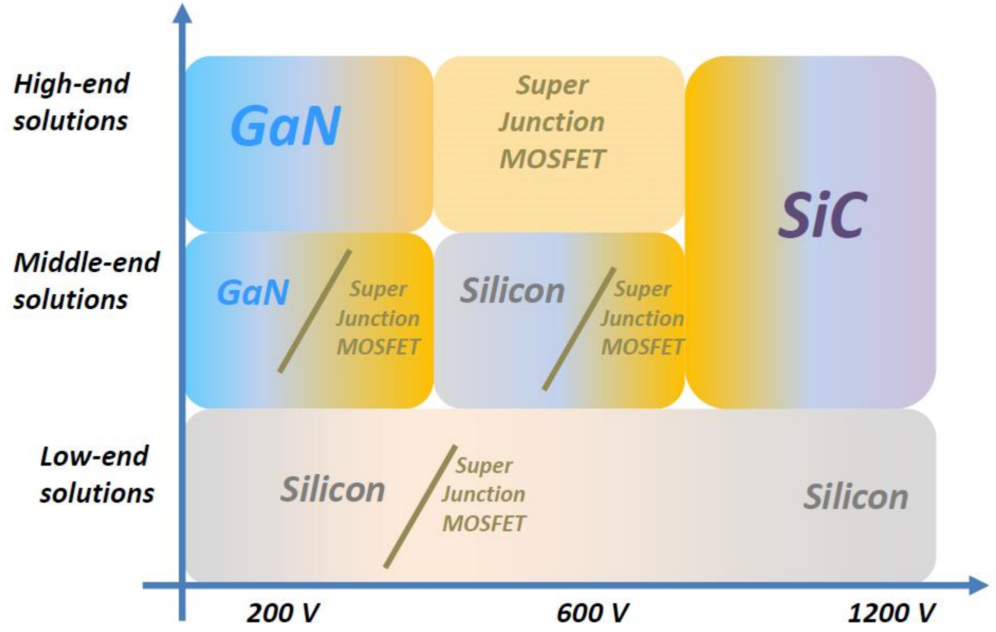
- **Disruptive Change**

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

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

▶ WBG Power Semiconductors

■ Application Perspectives



Source: Honea PEDG 2013

transphorm

What Yole Developement showed in 2011 as future view

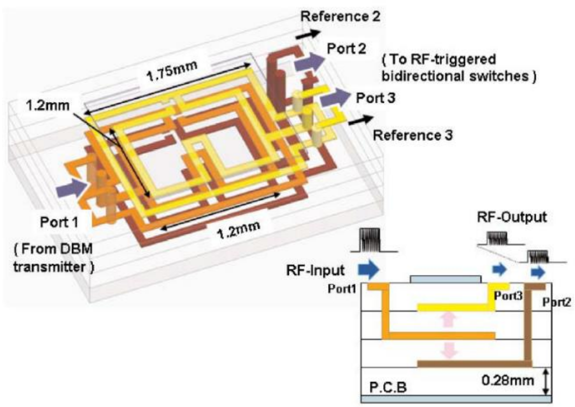
▶ Latest Systems Using WBG Devices → GaN

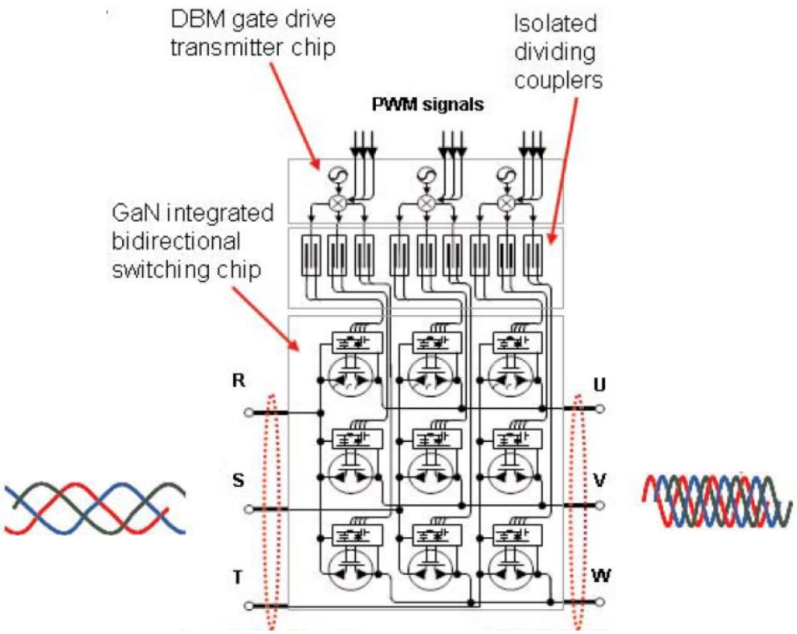
Source: Panasonic ISSCC 2014

■ 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

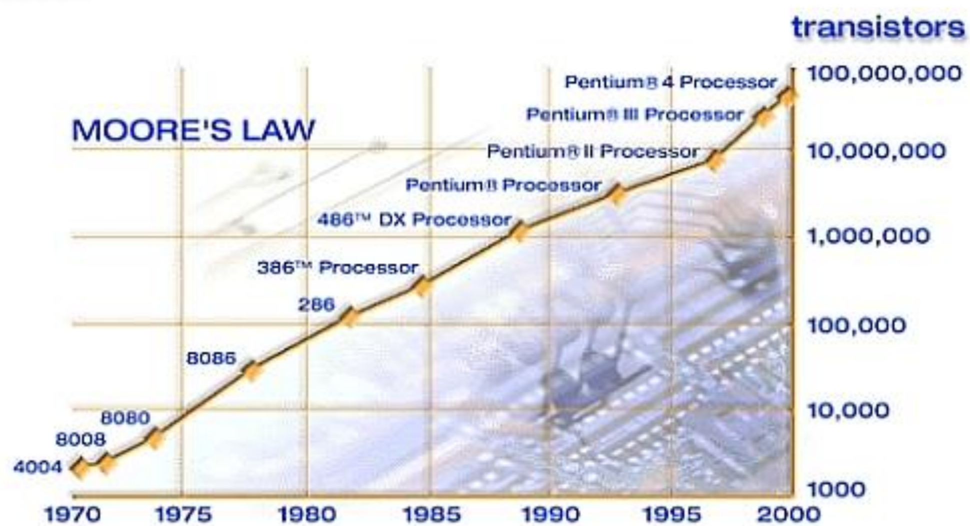




► Moore's Law: Key Enabler for Advanced Mechatronics

- **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



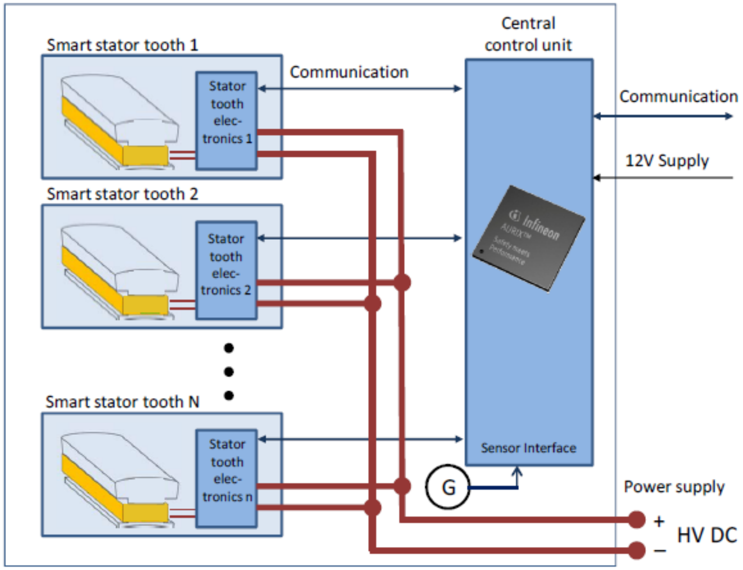
Electrical Drives: Performance Trends

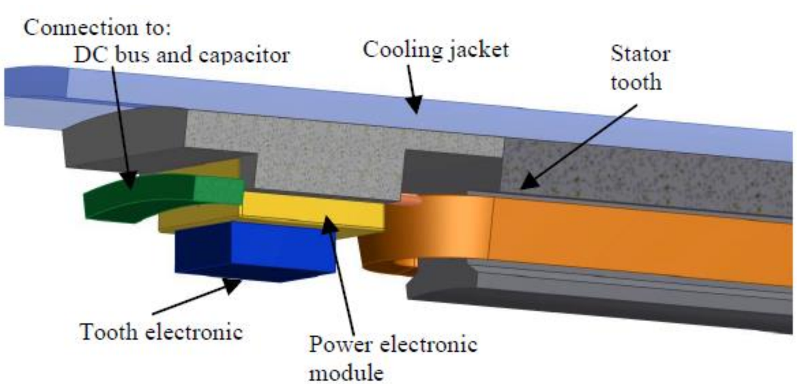
Compact & Lightweight Drives
Power Electronics & Integration
Fault Tolerant Systems
Minimum Energy/Cost in Manufacturing
High Accuracy & Dynamics
Extreme Ambient Conditions

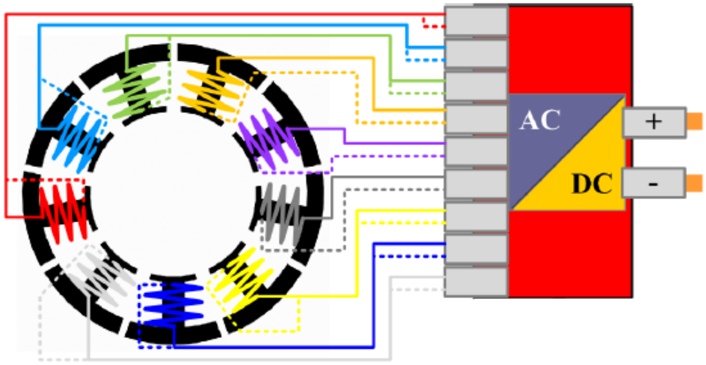
▶ Smart Tooth Concept for Fault Tolerant Machines

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

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



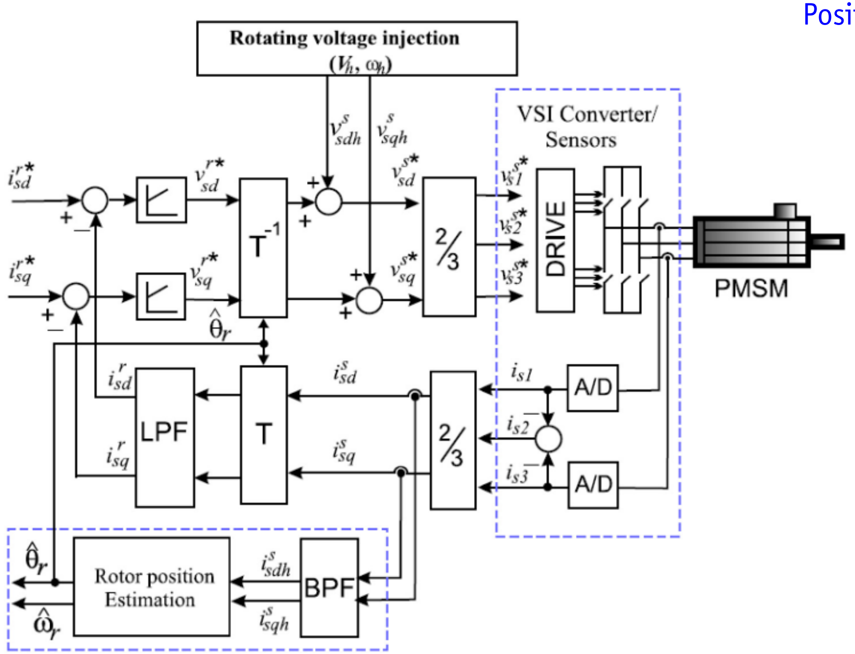




Source: Brockerhoff et. al.
Highly Integrated Drivetrain Solution:
Integration of Motor, Inverter and Gearing, EDPC 2014

► Self-Sensing High-Reliability Drive Systems

- **Elimination of the Position Sensor**
  - Increased Reliability
  - Compact & Cost Effective
  - Additional Signal Processing
  - Challenging for Certain Machine Types



Source: galilmc.com

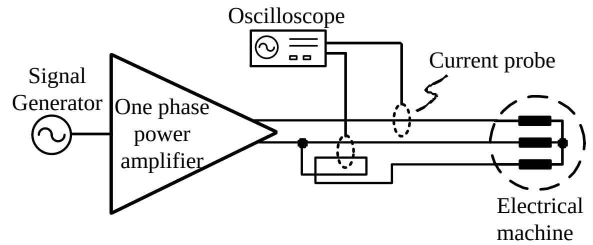
▶ Optimum Control of High-Speed Electrical Drives

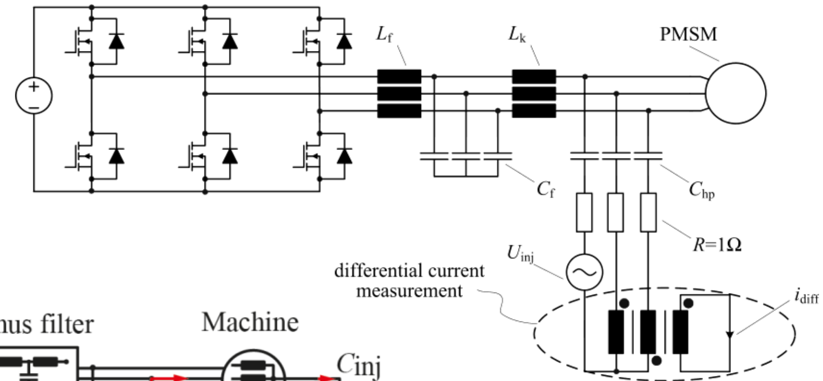
■ Sensorless Position Sensing

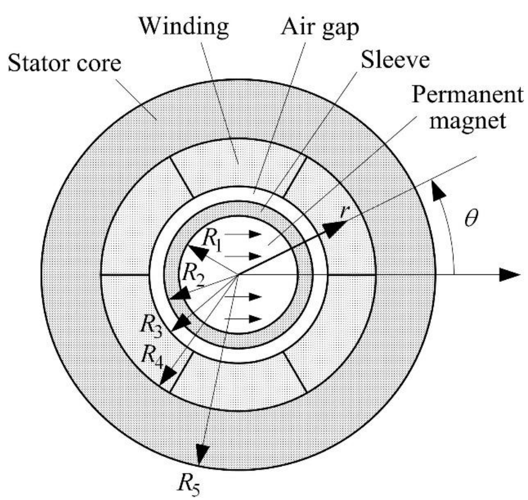
- Symmetrical Construction
- Very Low Saliency

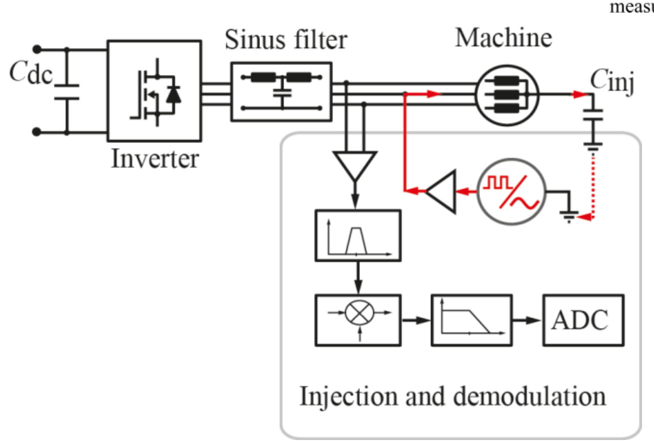
- High-Frequency Signal Injection
- Differential Measurements

- Integration with Drive Inverter









Source: Tüysüz et. al., Novel Signal Injection Methods for High Speed Self-Sensing Electrical Drives, ECCE 2012

Electrical Drives: Performance Trends

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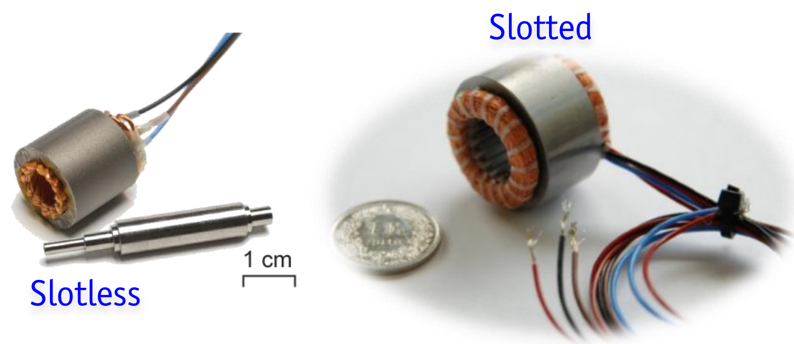
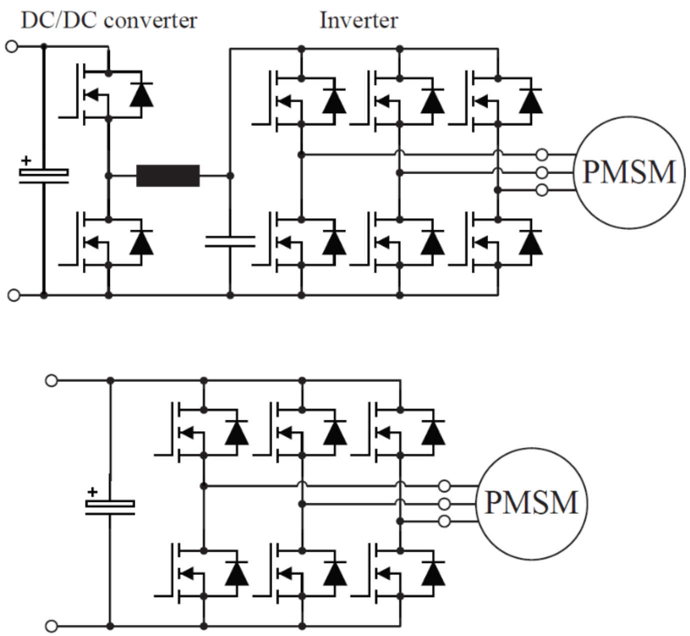
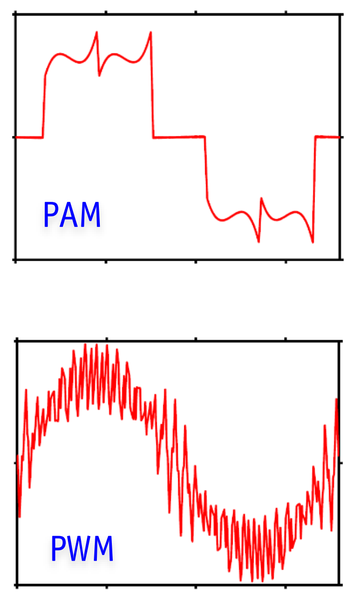
▶ Optimized Modulation Scheme for High Efficiency

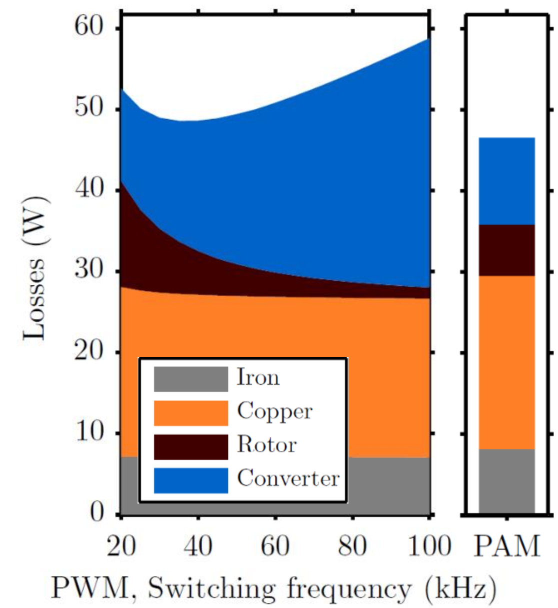
■ Modulation Scheme as a Degree-of-Freedom

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









Source: Schwager et. al., Modeling and Comparison of Machine and Converter Losses for PWM and PAM in High-Speed Drives, IEEE Trans. on Ind. Appl., 2014

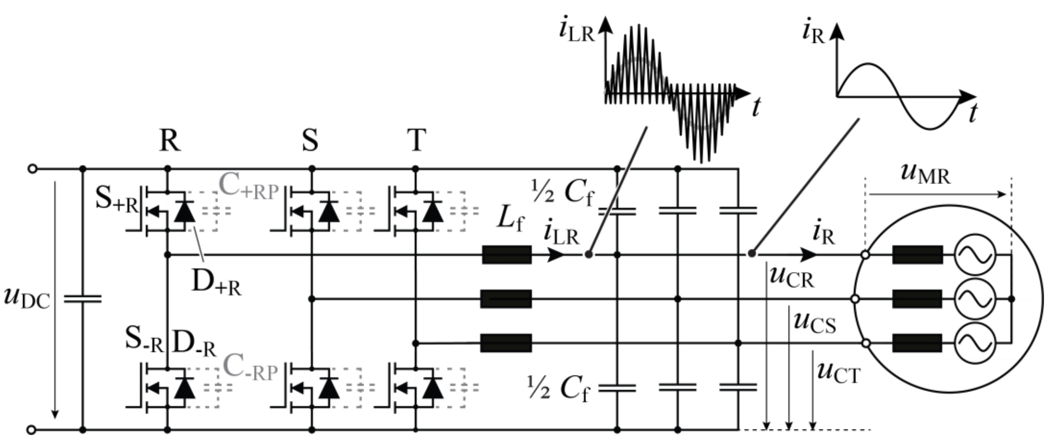
▶ Optimized Modulation Scheme for High Efficiency

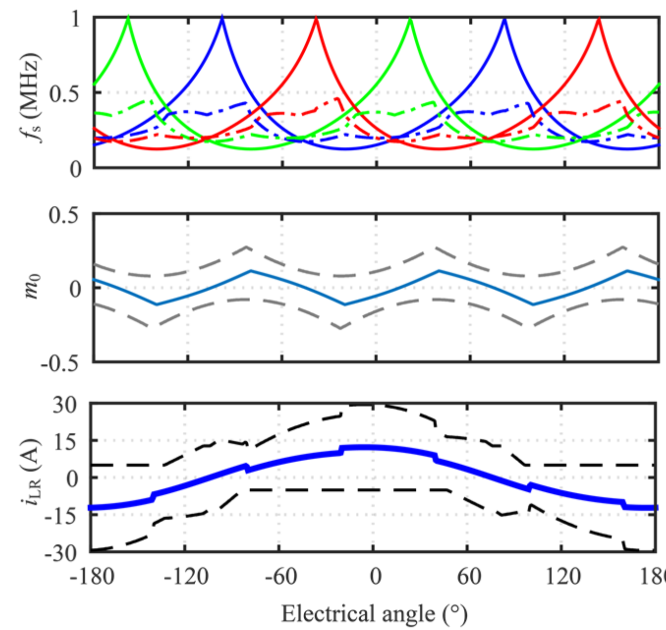
■ Soft-Switching Drives with Sinusoidal Output

- Compact Filter
- Electromagnetically Quiet Switching
- Low Switching Losses

- Variable Switching Frequency
- HF Flux in Inductor

- Zero-Sequence Voltage
- Current Envelope





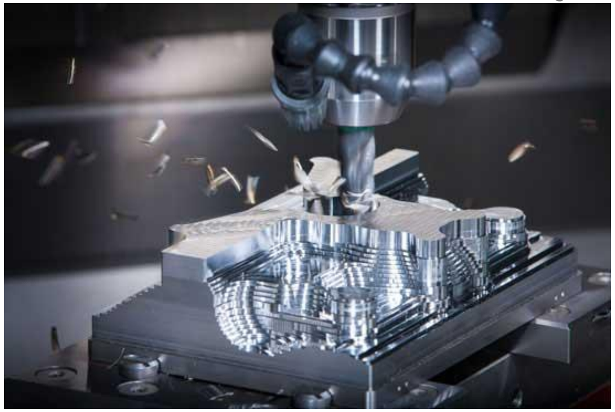
Source: Kaufmann et. al., New Optimum Modulation of Three-Phase ZVS Triangular Current Mode GaN Inverter Ensuring Limited Switching Frequency Variation, PEMD 2016

▶ Increased Productivity in Manufacturing

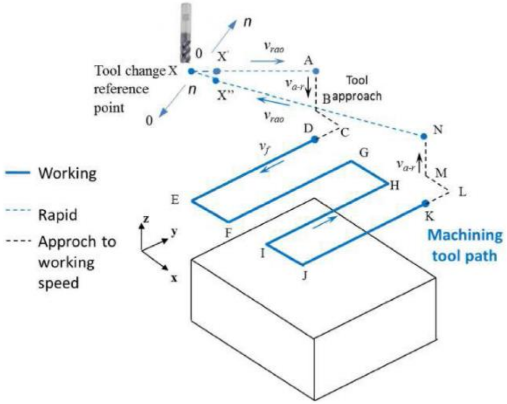
- **Industry Consumes 43% of the Electricity Production Globally**
  - In Germany as much as 47%
  - Machining is a Major Energy Consumer
  - Metal Cutting has Largest Share in Automotive Industry

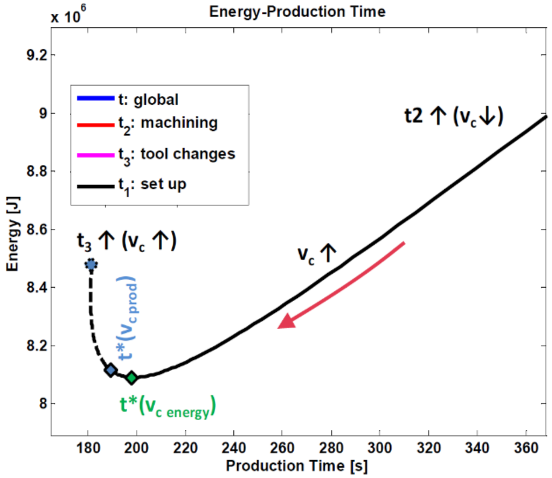
- **High Motivation for Sustainable Manufacturing**
  - Legislative Initiatives: 2009/125/EC and 2012/27/EU
  - Cost Savings from Reduced Energy Consumption

Source: ut-machining.com



- **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, CIRP 2013

Electrical Drives:
Performance Trends

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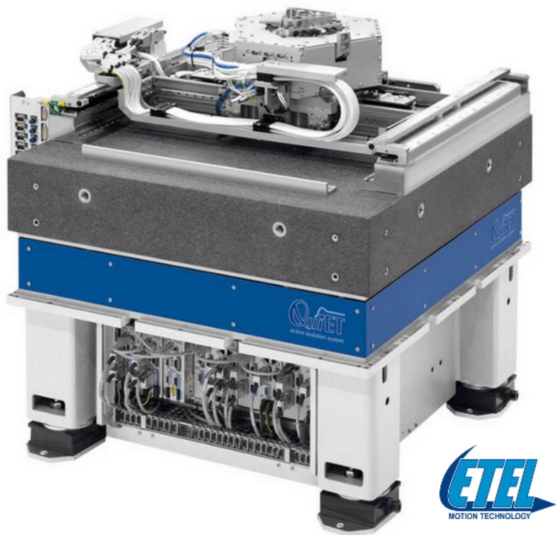
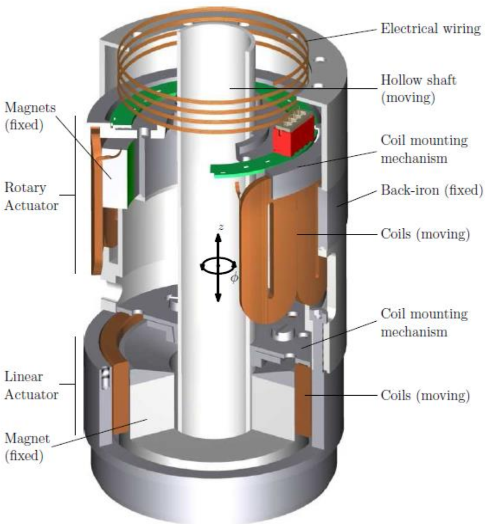
Extreme Ambient Conditions

▶ Motion Control with Extreme Accuracy & Dynamics





■ 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

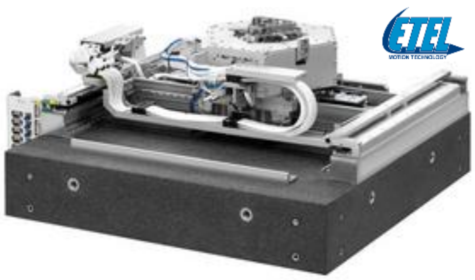
- S_ϕ 1 turn
- S_Z 10 mm
- a_Z 15 g
- a_ϕ 73 500 rpm/s

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

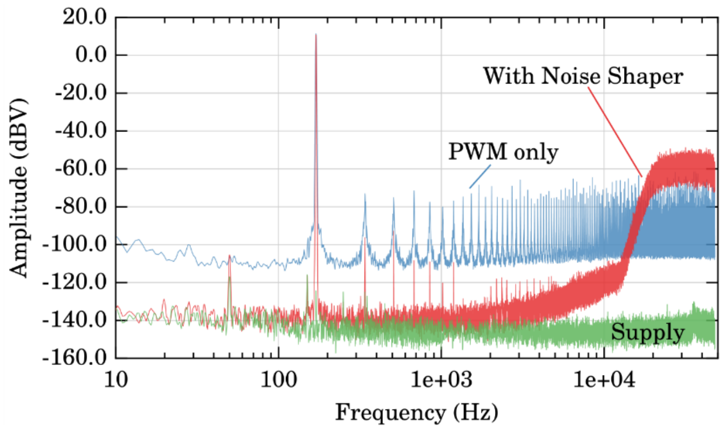
Source: Overboom et. al., Design and Optimization of a Rotary Actuator for a Two Degree-of-Freedom z-ϕ Module, IEEE Trans. on Ind. Appl. 2010

▶ High-Precision Amplifiers for Mechatronic Applications

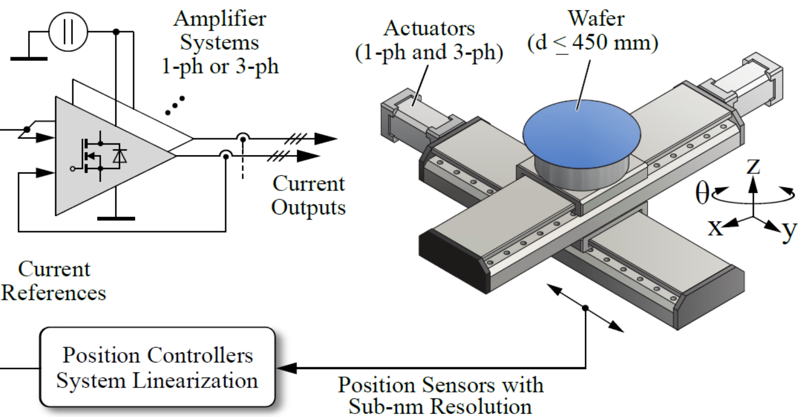
- **1 or 3-Phase nm-Precision Positioning System**
  - Linear/Rotational Permanent Magnet Machine
  - Magnetic Bearing System to Avoid Friction
  - Ultra-Low Noise/Distortion of Output Current
    → SNR & THD > 100 dB Required



- **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)**



Source: Mauerer et. al., Gate Signal Jitter Elimination and Noise Shaping Modulation for High-SNR Class-D Power Amplifiers, APEC 2015



Source: Mauerer et. al., Distortion Analysis of Low-THD/High-Bandwidth GaN/SiC Class-D Amplifier Power Stages, ECCE 2015

Electrical Drives: Performance Trends

Compact & Lightweight Drives
Power Electronics & Integration
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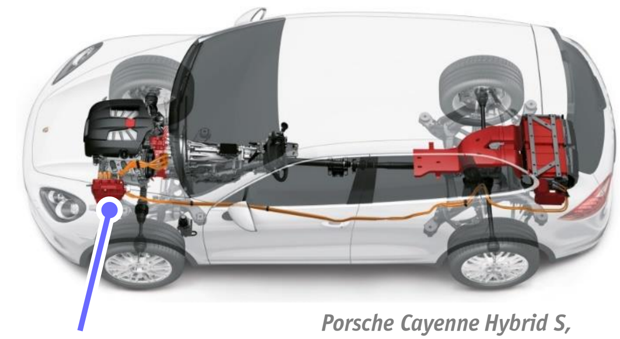
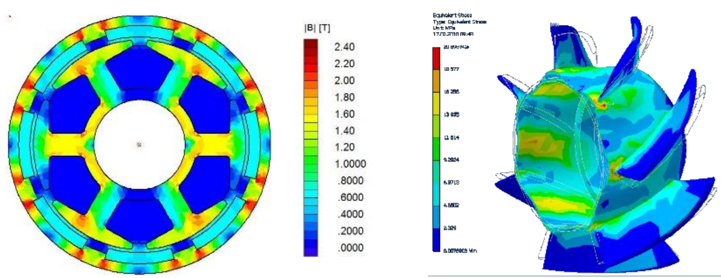
Extreme Ambient Conditions

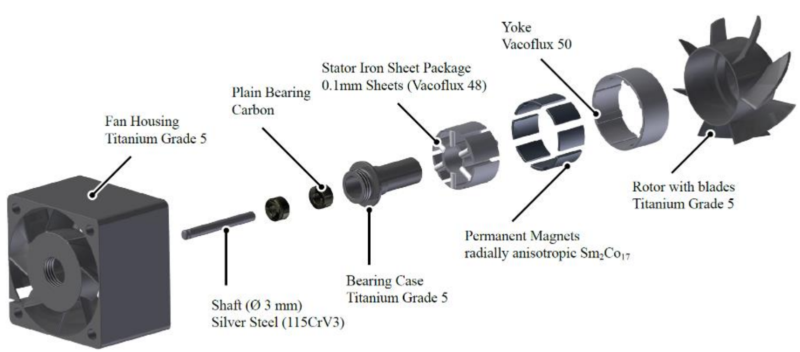
► Extreme Temperature Drive System

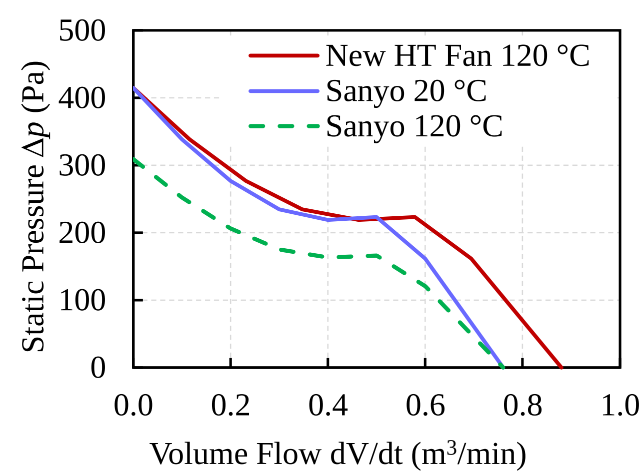
- **Extreme Ambient Temperatures Common in Automotive Applications (e.g. Hybrid EV)**
  - Cooling of Power Electronics Critical
  - High Complexity of Liquid Cooling System
  - Dedicated High Temp. Fan Required for Forced-Air Cooling



Porsche Cayenne Hybrid S,
www.porsche.de





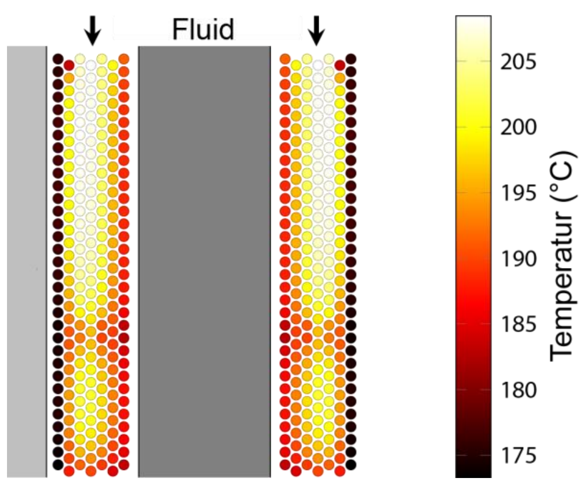


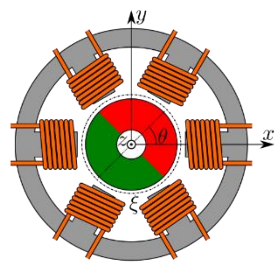
Source: Wrzecionko et. al., High-temperature (250°C / 500°F) 19'000 rpm BLDC fan for forced air-cooling of advanced automotive power electronics, IECON 2011

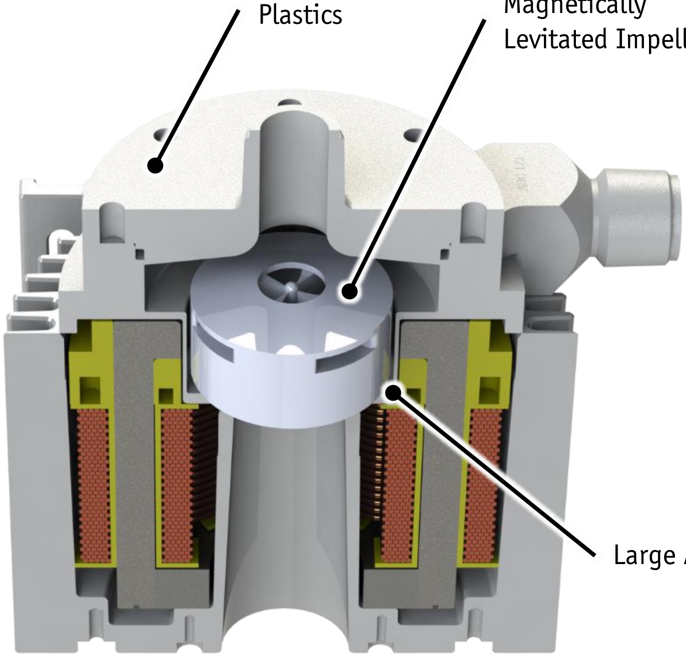
High-Temperature Pump for Acidic Environment

- **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



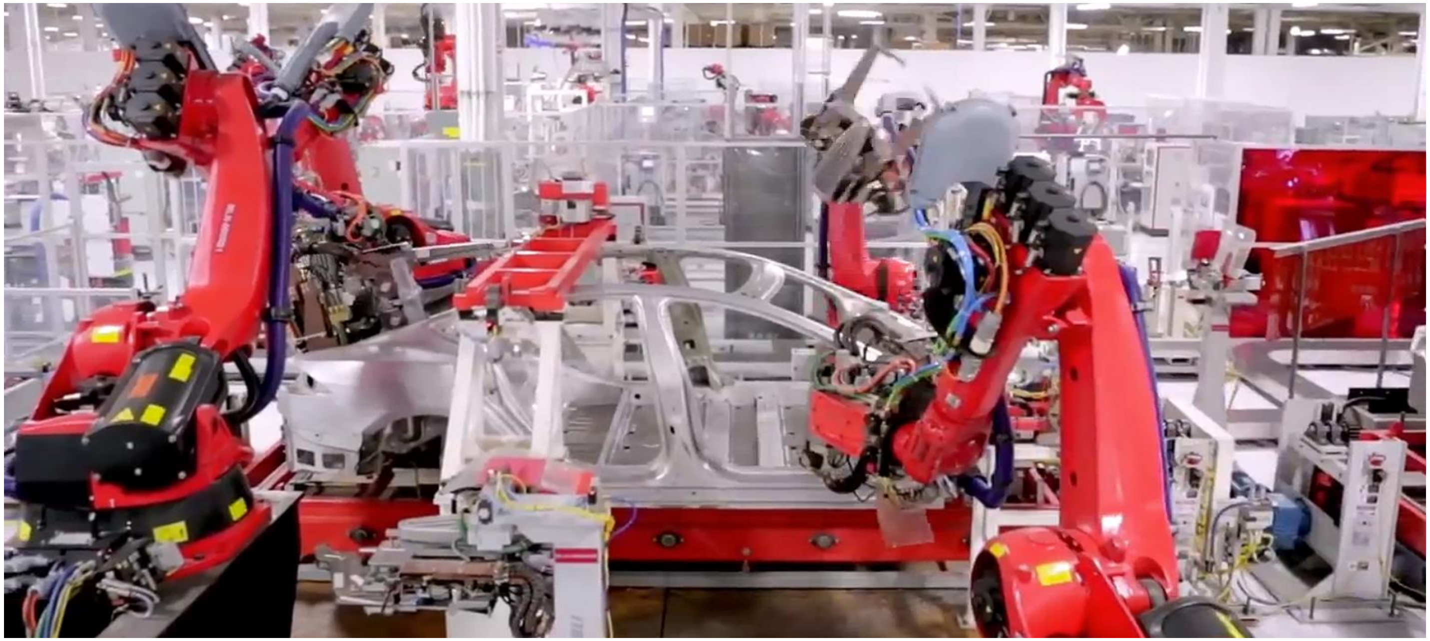




Source: Wellerdieck et. al., Contributions to an ultra-high temperature (250 °C/500 °F) bearingless pump, ICEMS 2015

► 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

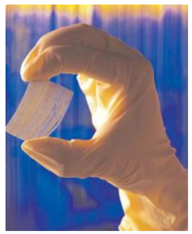
Selected Applications in Future Mechatronics

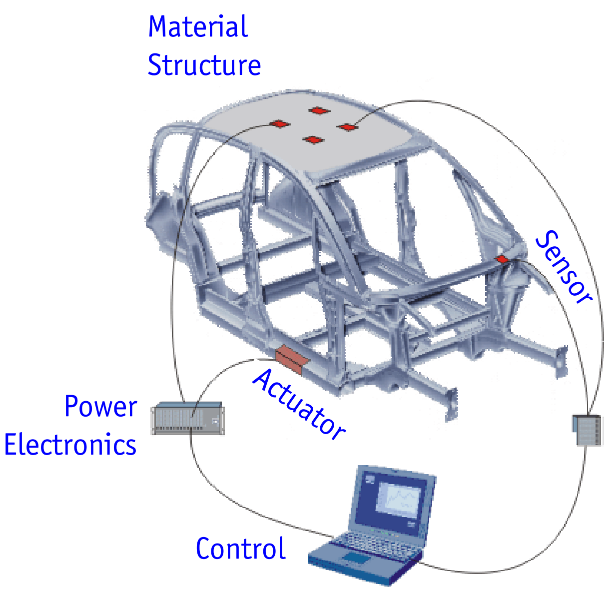
Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

Adaptronics: Adaptive Mechanical Structures

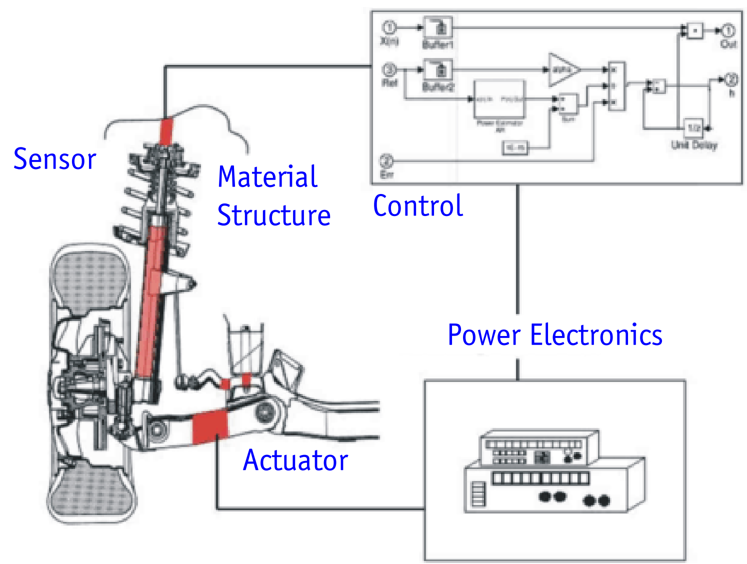
Lightweight Mechanical Structures with Active Piezoelectric Vibration Damping

Flexible Piezoelectric Fibers Incorporated in Material Layers



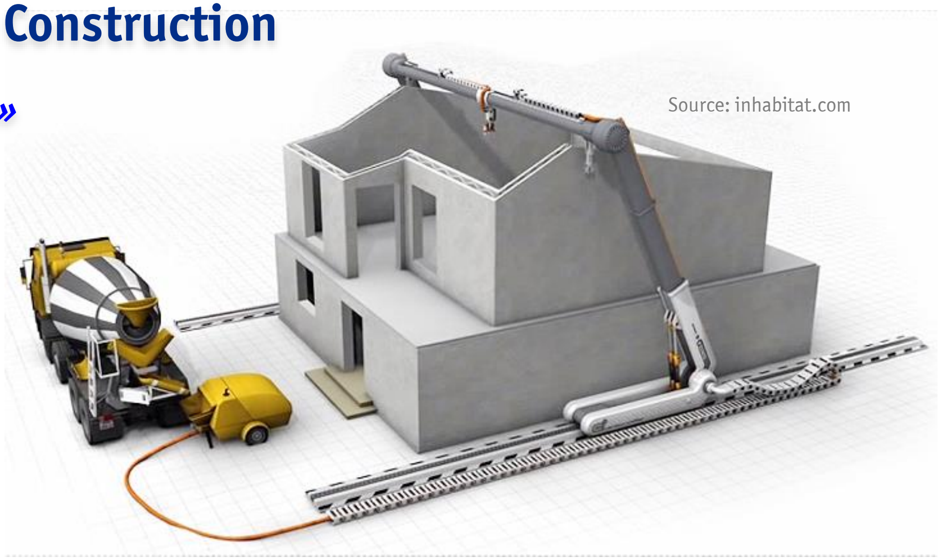


Fraunhofer ADAPTRONIK



▶ Robots for Autonomous Construction

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



Source: inhabitat.com

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

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

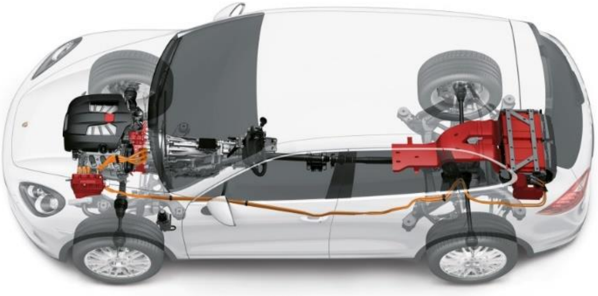
Selected Applications in Future Mechatronics

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

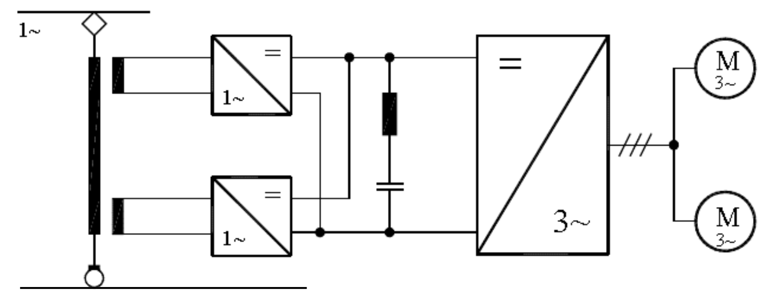
UNIST,
www.unist.ac.kr

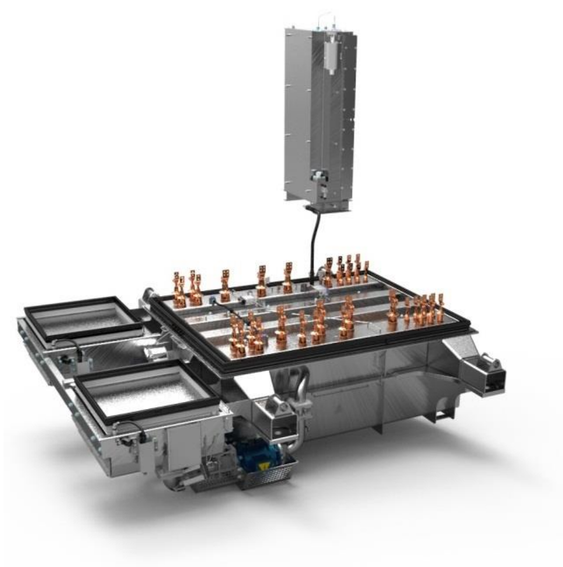
BRUSA 22kW Charger,
www.brusa.biz

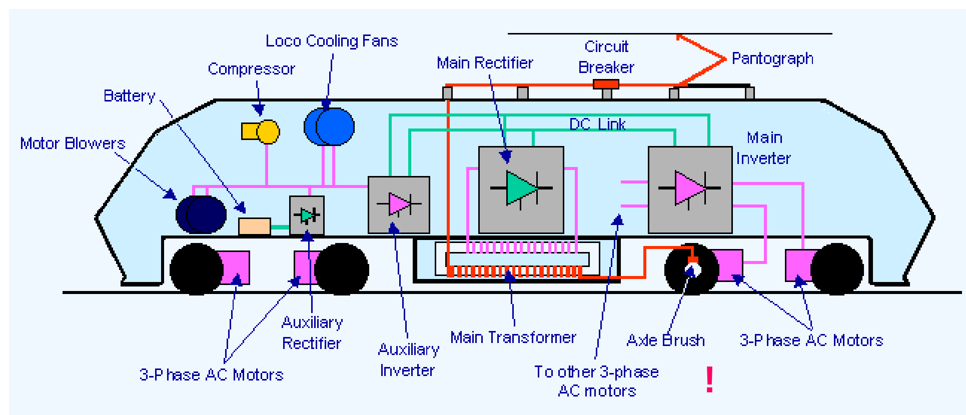
Honda Accord Hybrid,
www.honda.com

▶ 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

ABB

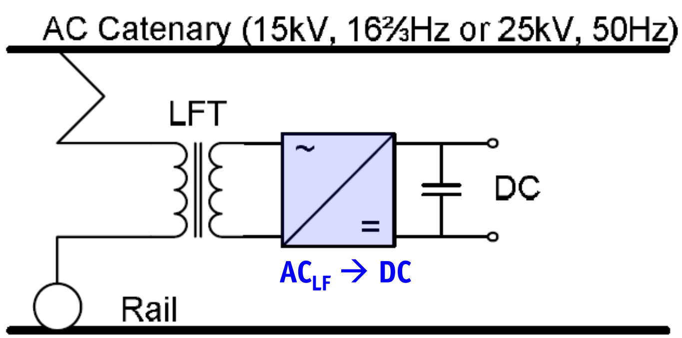


Fig. 1. *Conventional AC-DC conversion with a line frequency transformer (LFT).*

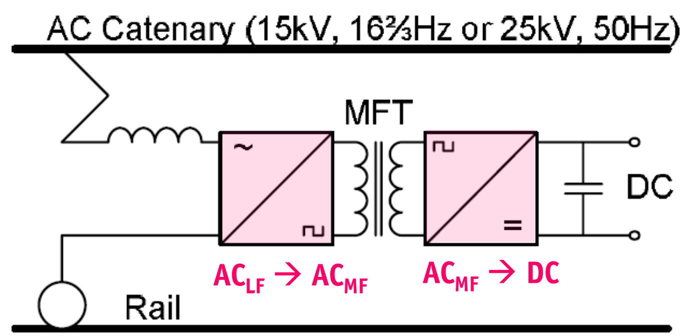


Fig. 2. *AC-DC conversion with medium frequency transformer (MFT).*

- 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

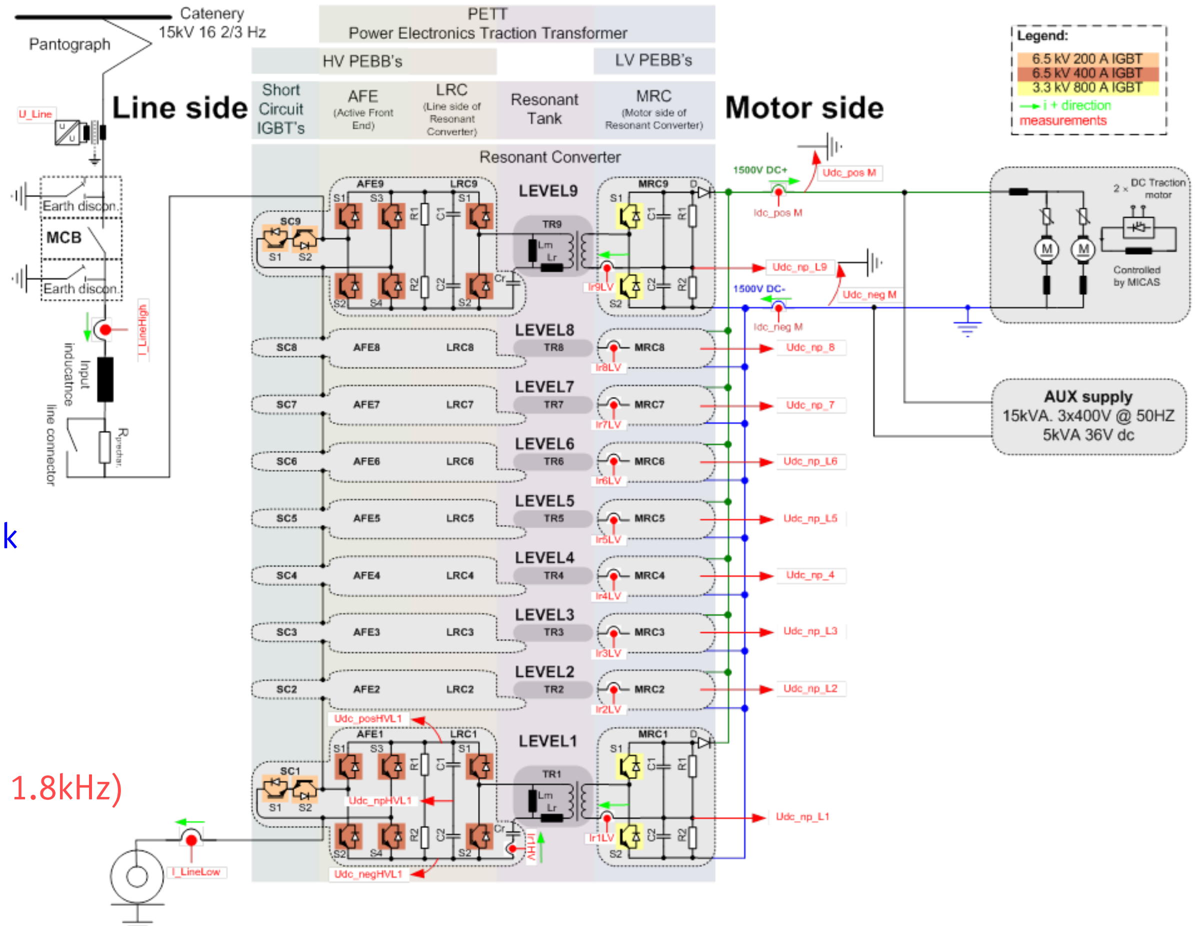
ABB
- Dujic et al. (2011)

- 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)

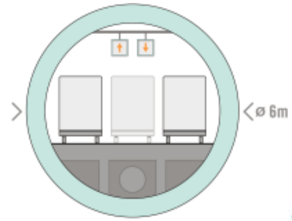
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

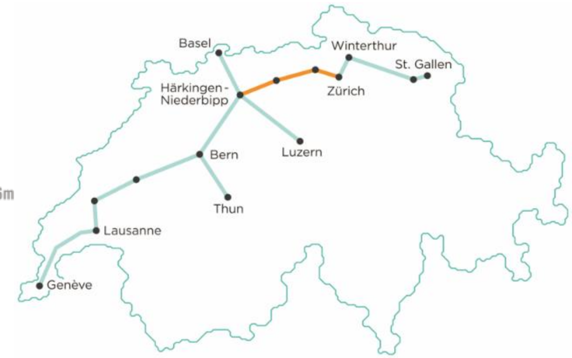


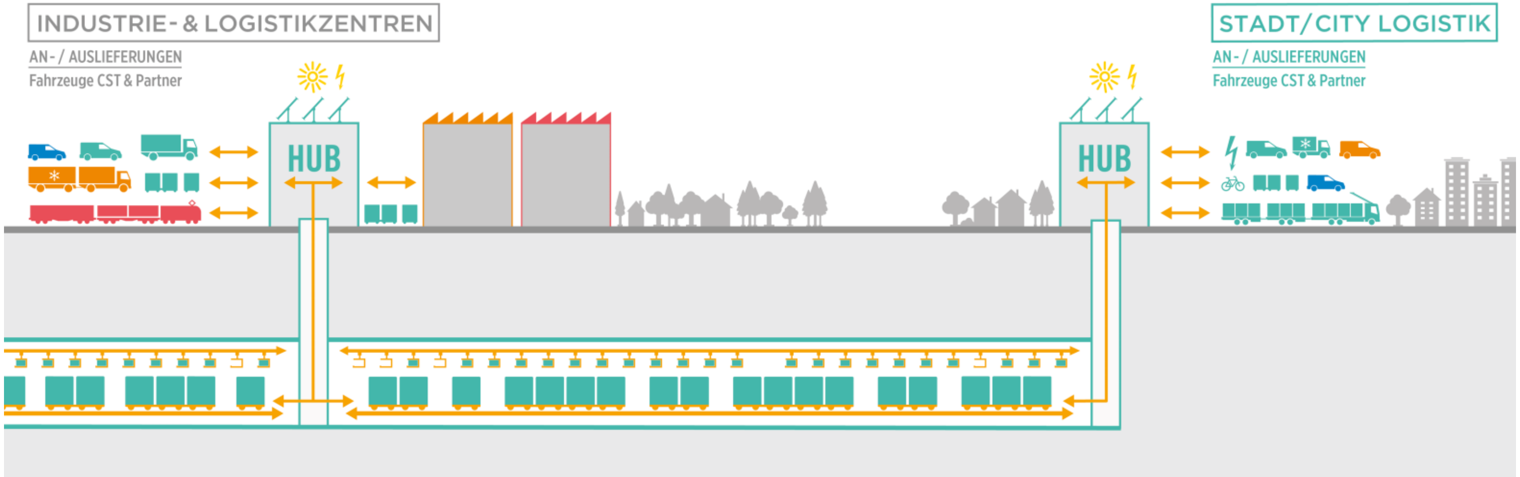
▶ Cargo Sous Terrain in Switzerland

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

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

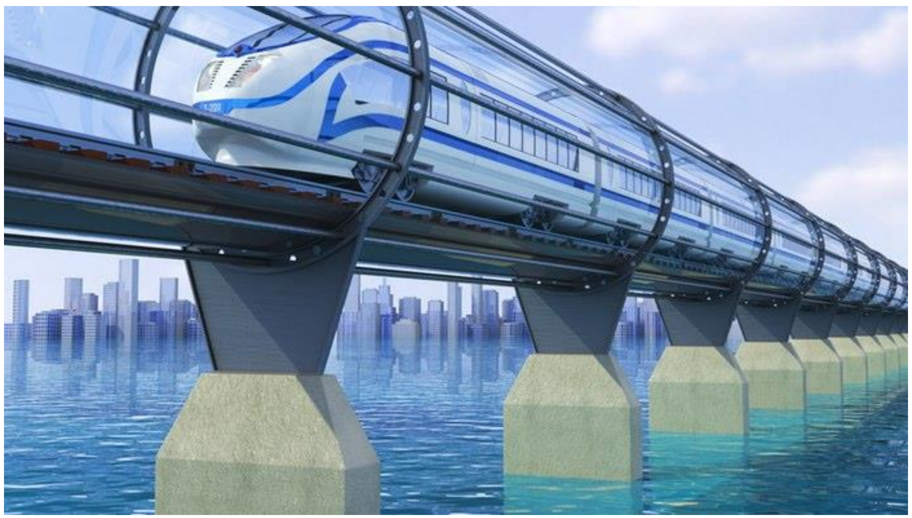




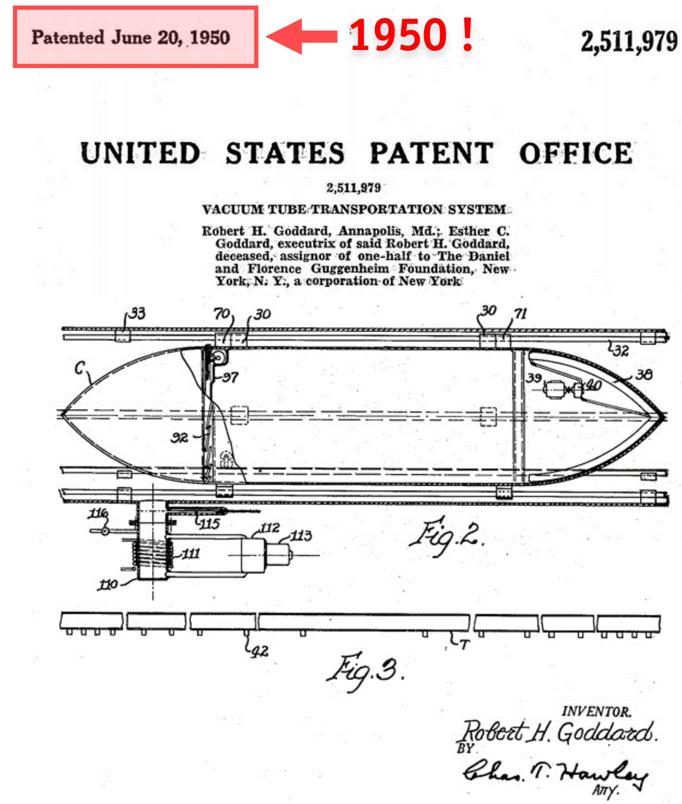


Source: cargosousterrain.ch

▶ Futuristic (!) Transportation: Hyperloop



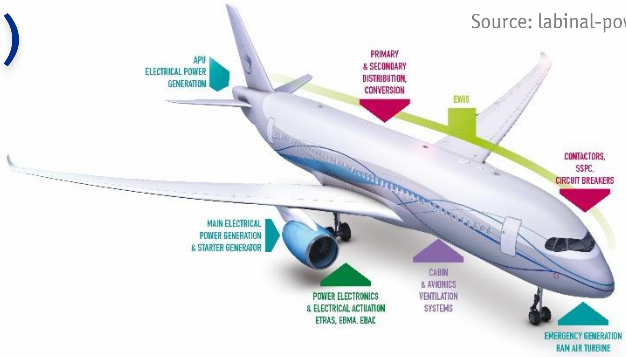
Source: gizmag.com



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

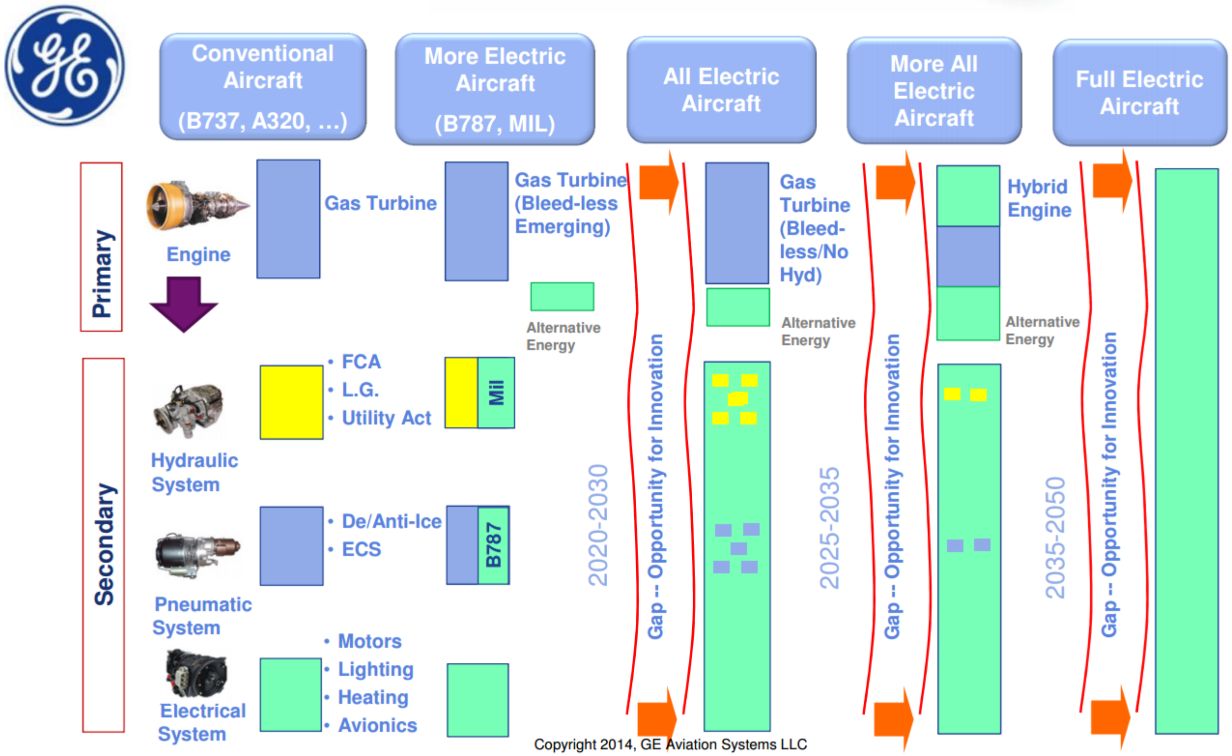
▶ Towards the Full Electric Aircraft (1)

Source: labinal-power.com



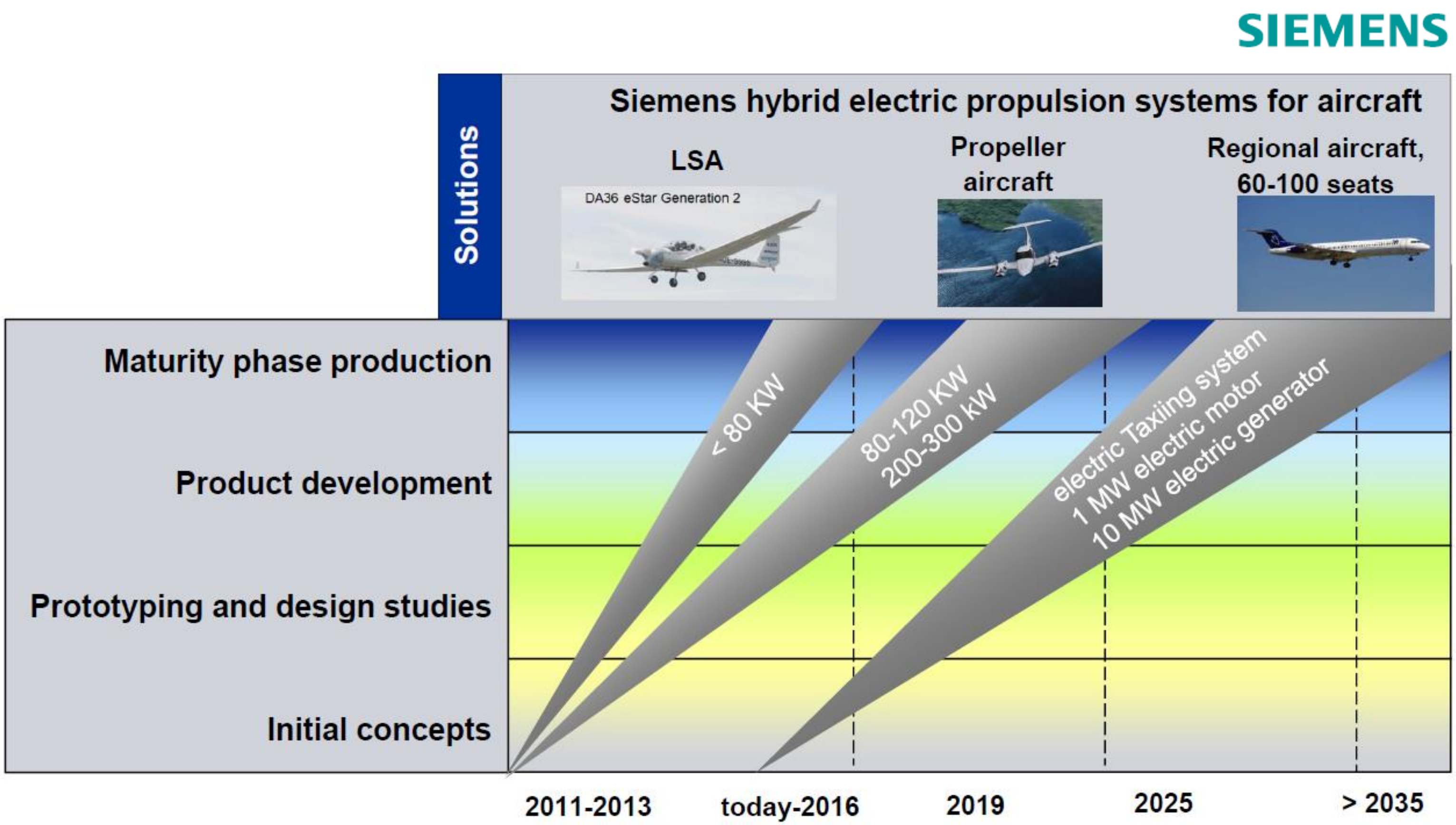
- Reduction of Fuel Consumption and CO_2-Footprint
  - Lower Noise Emissions and Environmental Impact

- Multi-Disciplinary Innovation Opportunities!



▶ Towards the Full Electric Aircraft (2)

- **Today:** Full electric 2-seater planes for pilot training
- **Near Future:** Electric propulsion for regional transportation



Source: Anton, Electric Propulsion for Aircraft, AERO Friedrichshafen 2015

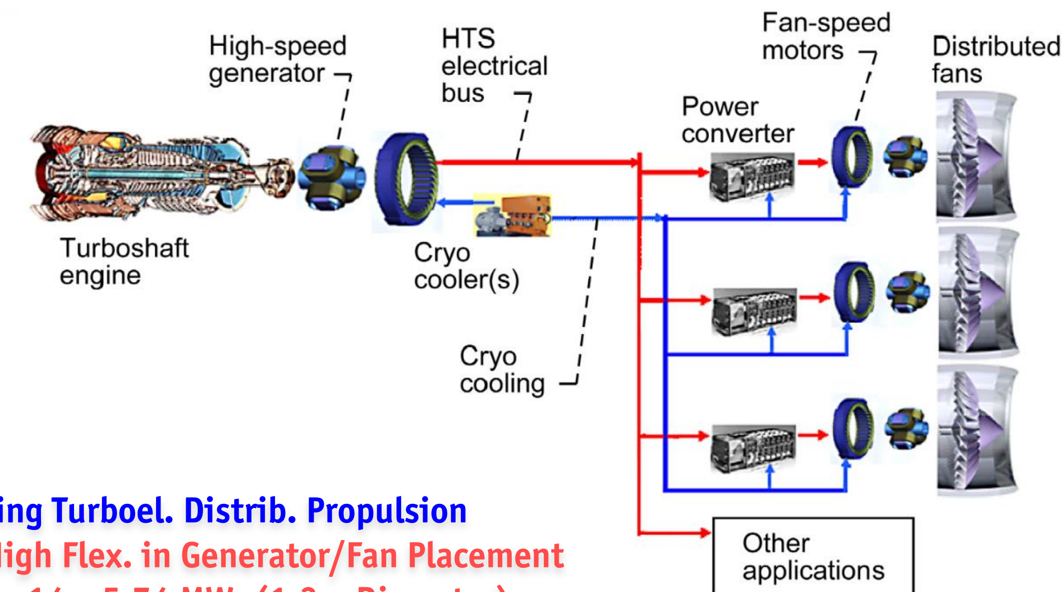
▶ Future Hybrid or All-Electric Aircraft

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



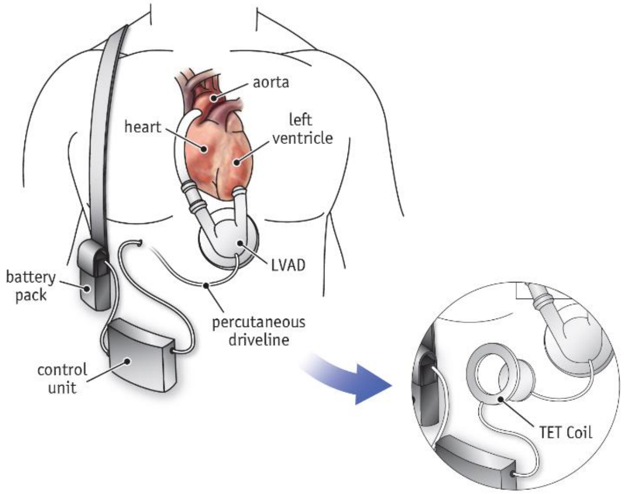
- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

Selected Applications in Future Mechatronics

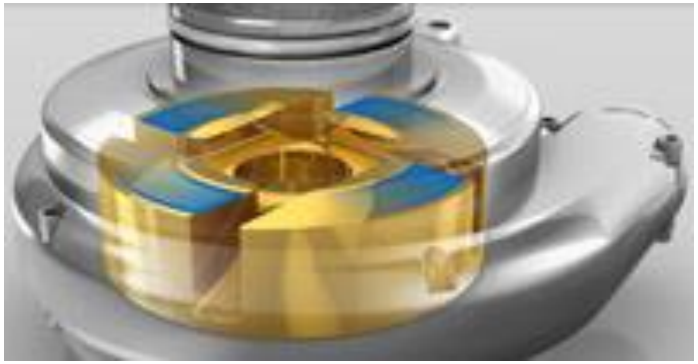
Advanced Manufacturing
Future Mobility
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

► 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

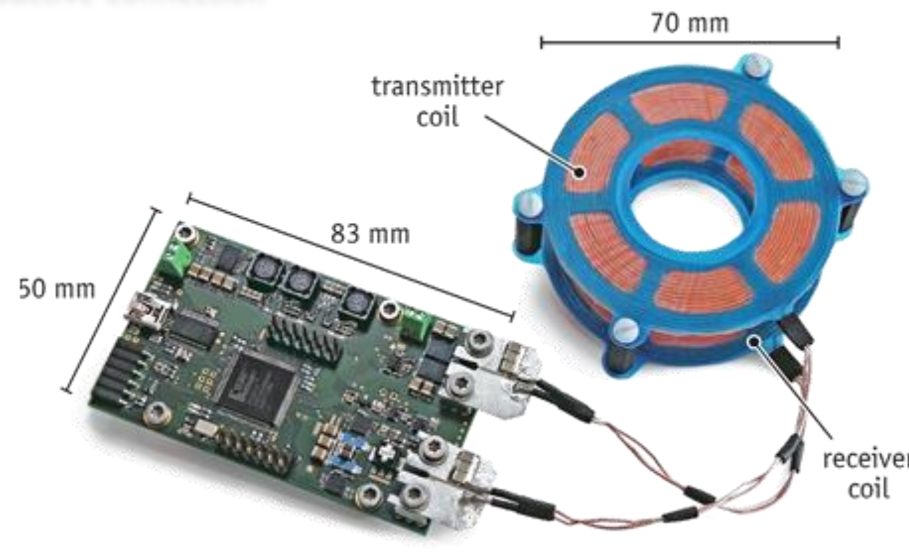


Source: heartware.com

► 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



Source: Knecht et. al., Optimization of Transcutaneous Energy Transfer Coils for High Power Medical Applications, COMPEL 2014

► Zurich Heart Project:

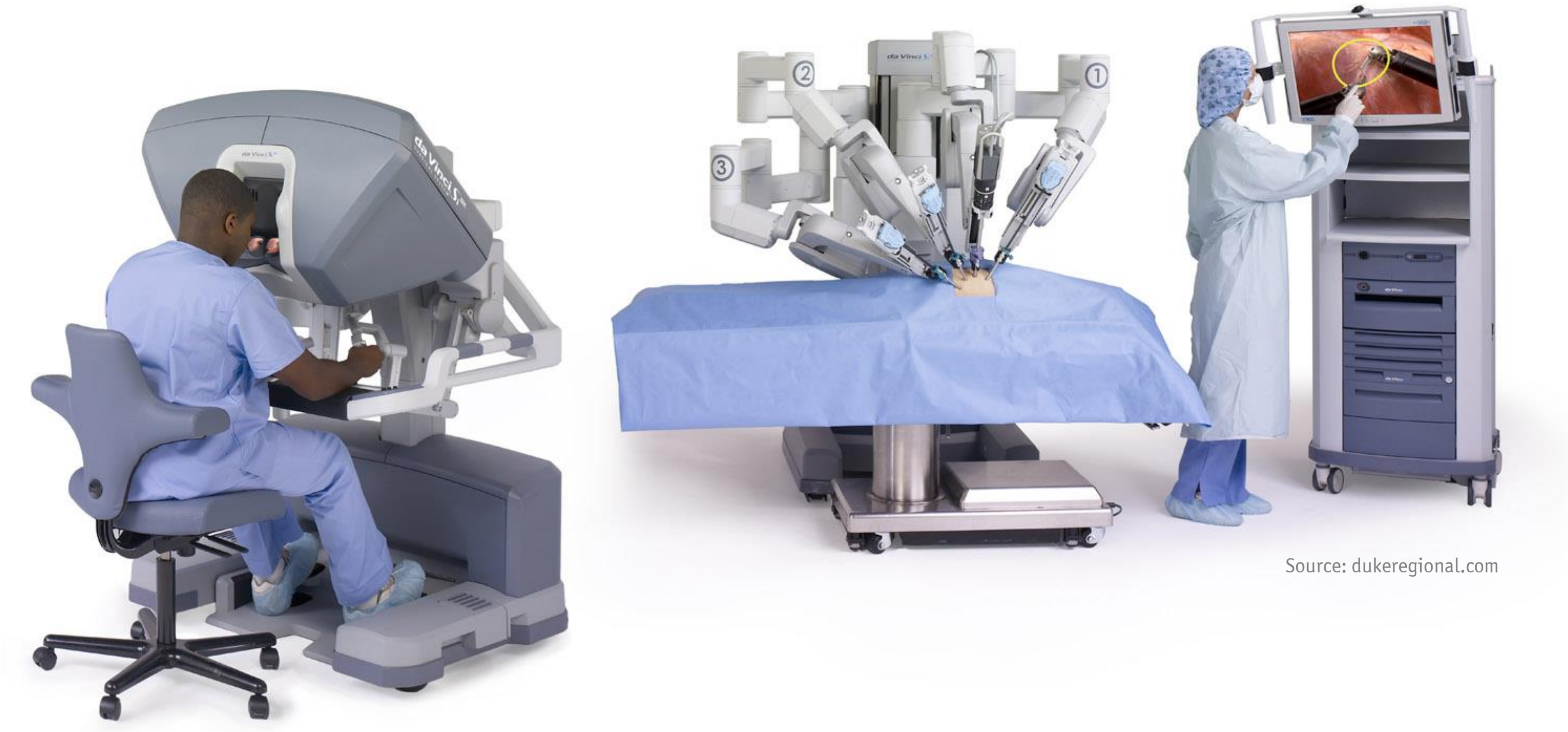
ETH zürich

University of Zurich[UZH]

UniversityHospital Zurich

Source: heartware.com

► Robotically Assisted Surgical Systems



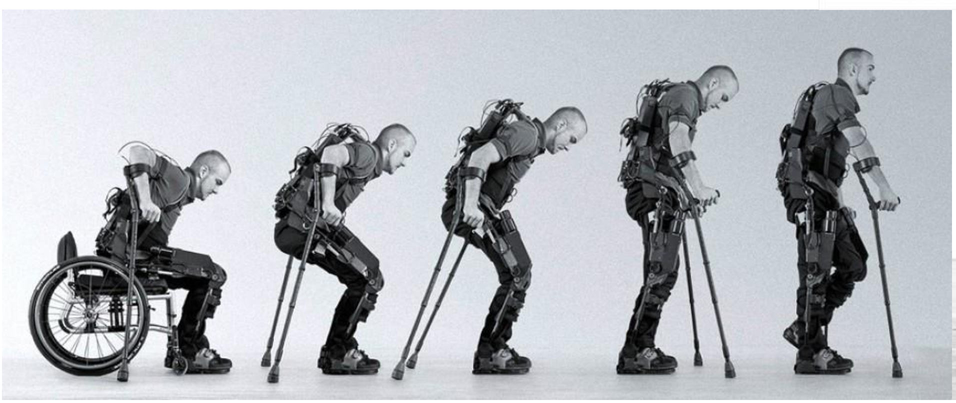
Source: dukeregional.com

- 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

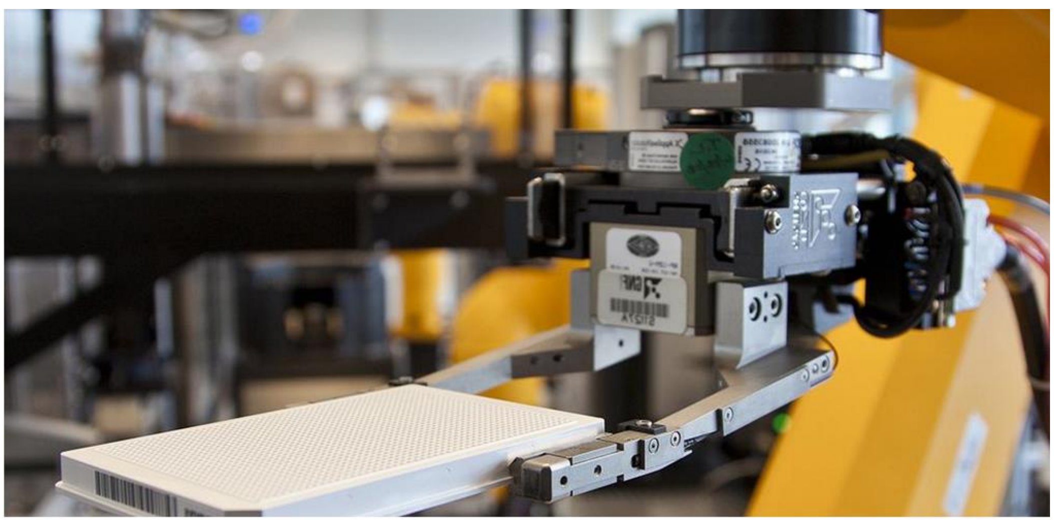


► High-Throughput Screening in Pharmaceutical Industry

- **Automatic and Consistent Screening of Millions of Compounds for Different Diseases**
- **40 Samples per Day by Hand → Hundreds of Thousands of Samples per Day Using Robots**

NOVARTIS

Source: ddw-online.com



▶ Challenging Environments and Disaster Response

- Inspection of Oil-Gas Sites
- Human-Robot Teaming for Robot-Assisted Disaster Response

RSL Robotic Systems Lab

Source: tradr-project.eu

Selected Applications in Future Mechatronics

Advanced Manufacturing
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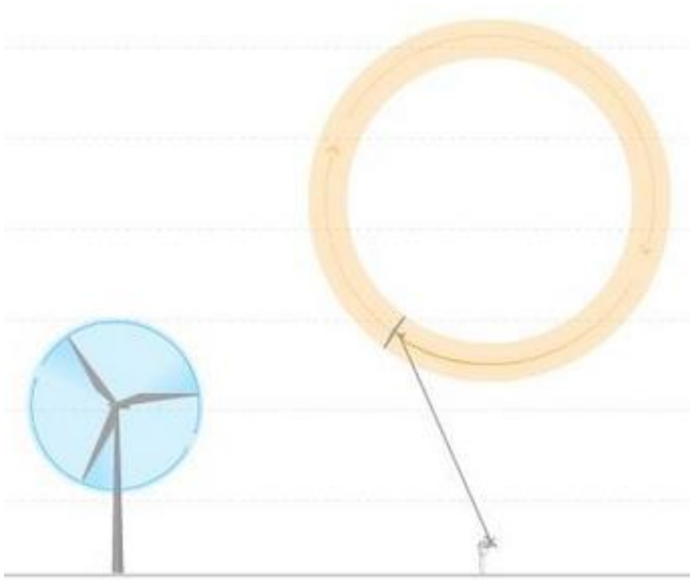
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

▶ Airborne Wind Turbines

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



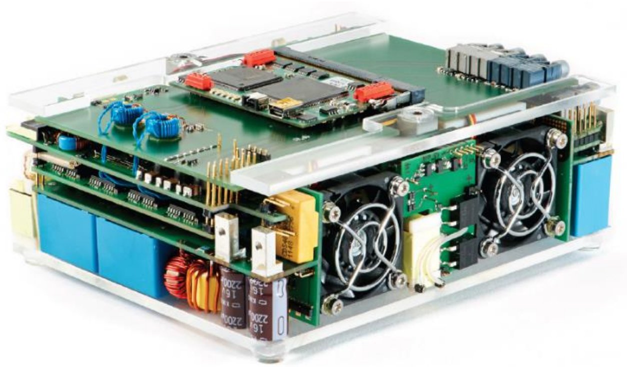
MAKANI POWER

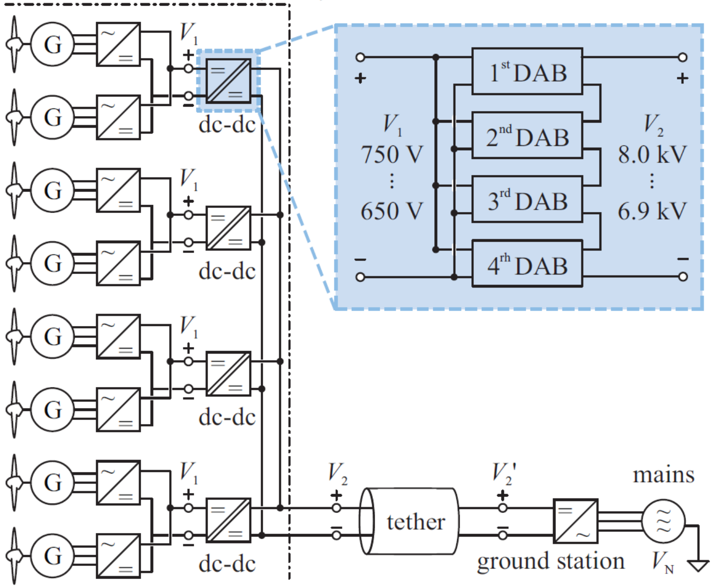
Google X

▶ 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



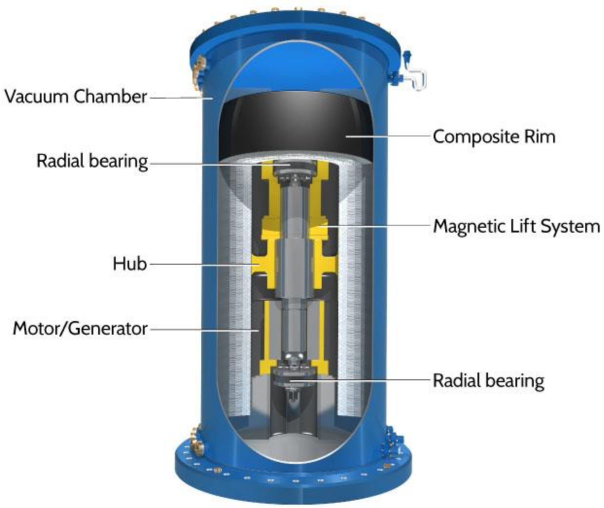


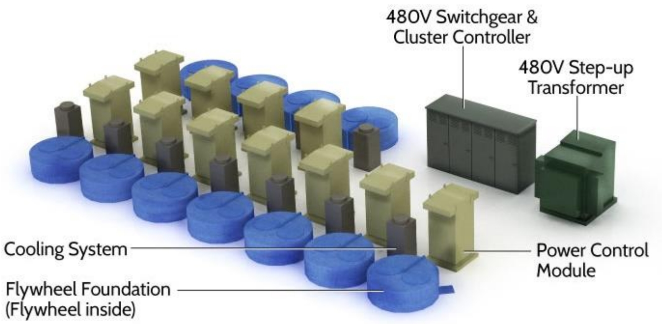
Source: Gammeter et. al., Comprehensive Conceptualization, Design, and Experimental Verification of a Weight-Optimized All-SiC 2kV/700V DAB for an Airborne Wind Turbine, IEEE Jour. on Emer. and Sel. Top. in Pow. Electr., 2015

▶ 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

Source: beaconpower.com

Selected Applications in Future Mechatronics

Advanced Manufacturing
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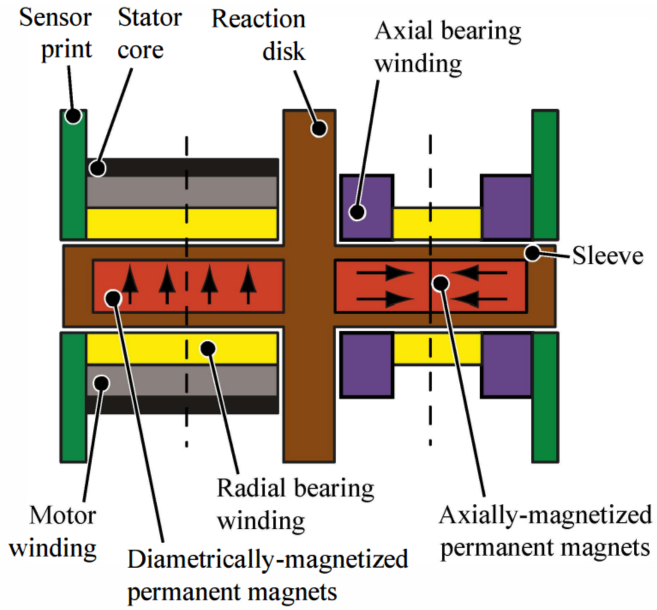
Healthcare & Medical
Renewable Energy
Space Applications
Developing World

▶ 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

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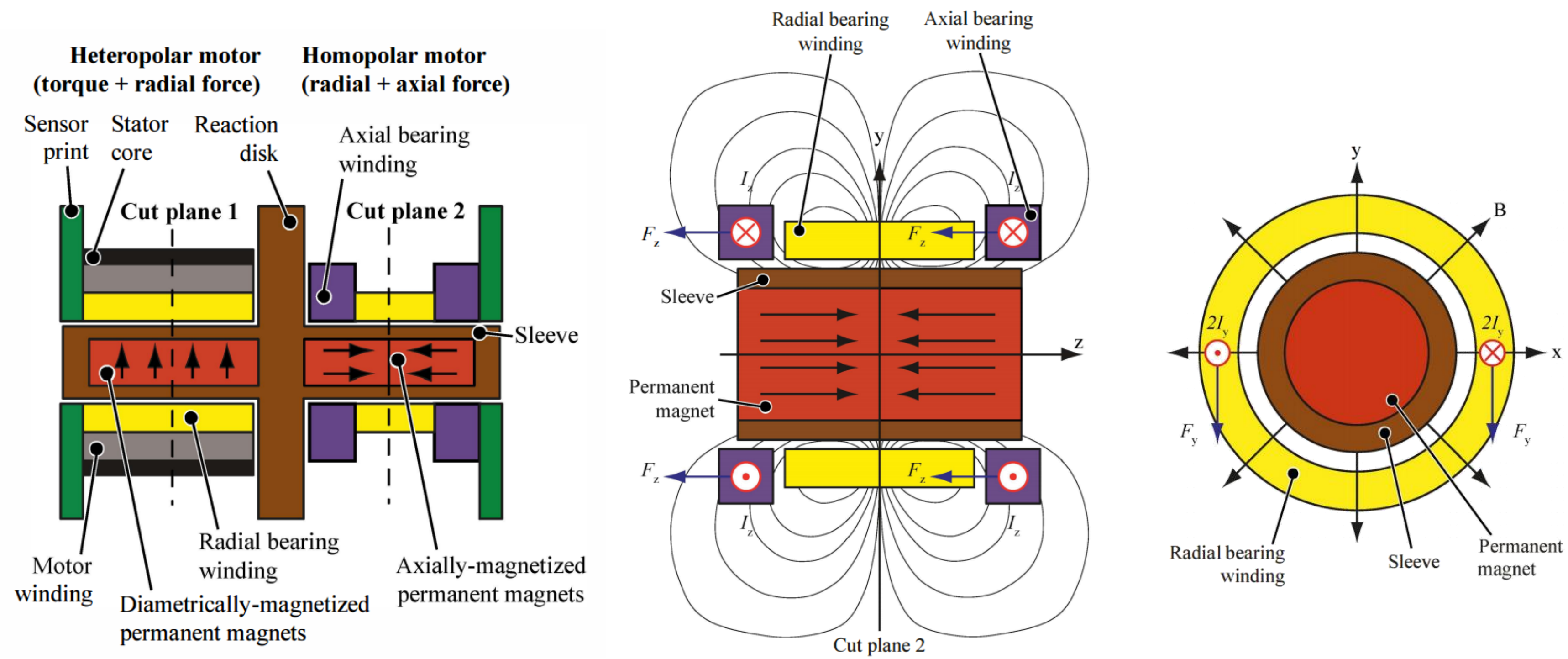

Source: Zwyssig et. al., High-Speed Magnetically Levitated Reaction Wheel Demonstrator, IPEC 2014

Selected Applications in Future Mechatronics

Advanced Manufacturing
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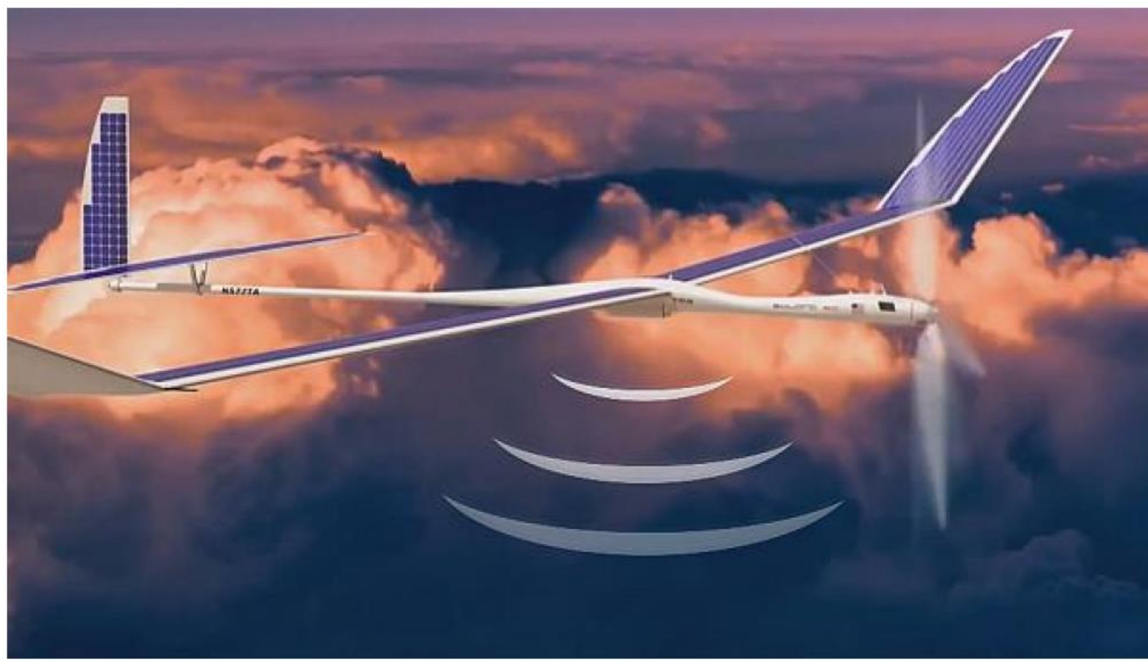
Space Applications
Developing World

▶ High-Altitude Drones

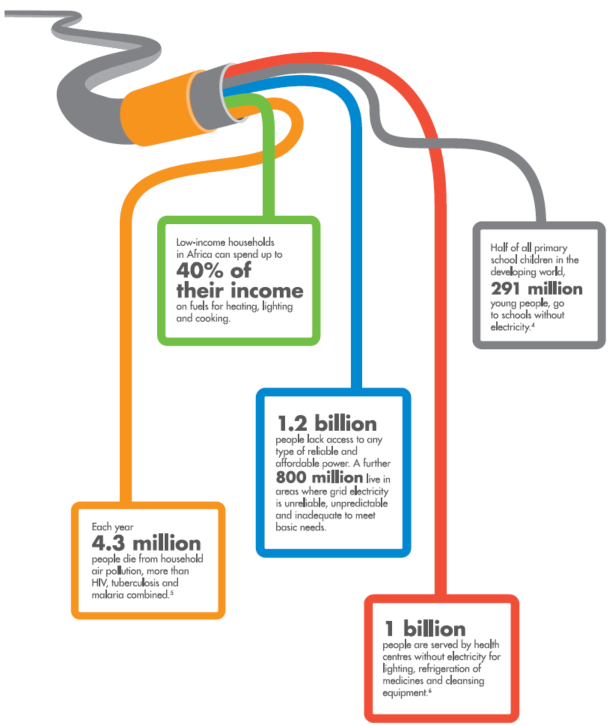
- **Provide Internet Access to Large Underdeveloped Areas**
- **Facebook Drone Research**
  - Solar Powered Drones
  - Stratospheric Flight
  - Can Stay Aloft for 90 days
  - High-Speed Laser Communication Between Drones

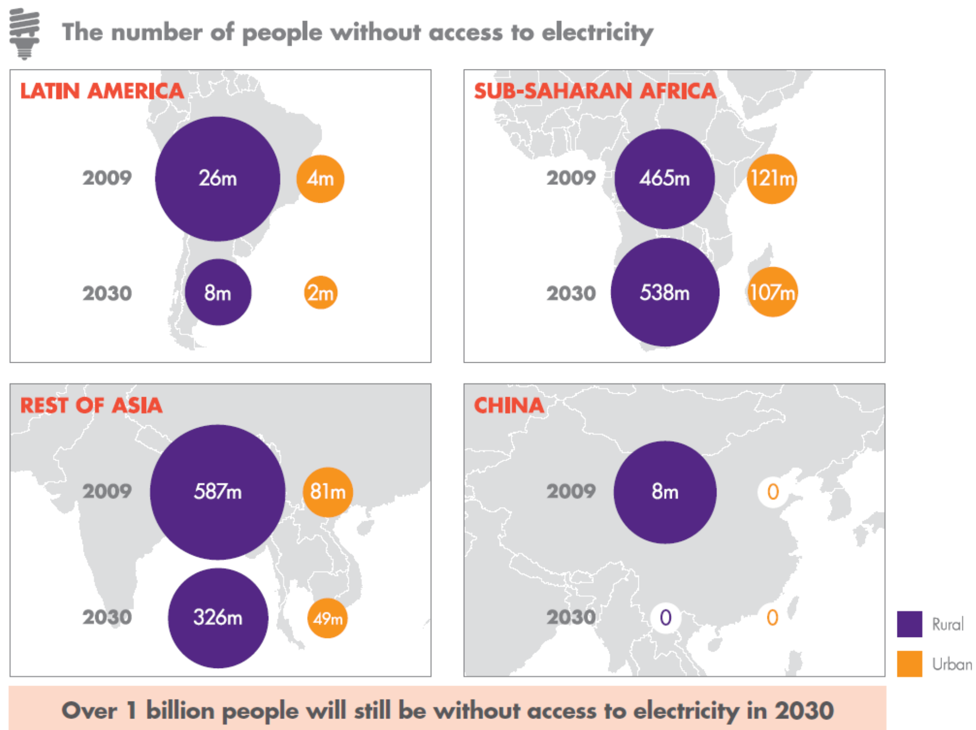


Source: guardianlv.com

▶ Rural Power Generation

- 1.2 Billion "Bottom-of-the-Pyramid People" Lack Access to Clean Energy
- 17% of the Global Population





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.

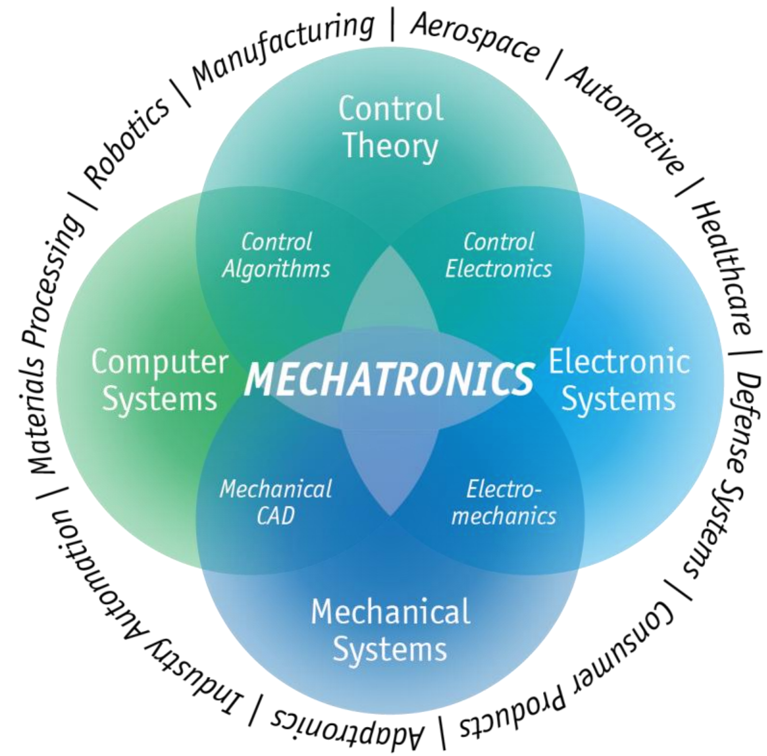
► Mechatronic Systems

■ **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***

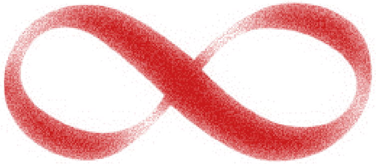


► Endless Product Innovation Possible by Combination of Core Elements

Bounded only by

- **Laws of Physics**
- **Material Properties**
- **Imagination / Vision**

«Multiplication by Infinity»



Thank You!

Questions?