ETH zürich

Acknowledgement
Florian Krismer
Hans-Peter Nee

What are the "Big CHALLENGES" in Power Electronics?

Johann W. Kolar

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

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What are the "Big OPPORTUNITIES" in Power Electronics?

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Power Electronics 2.0

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ETH Zurich
D-ITET / PES

Departments of ETH Zurich

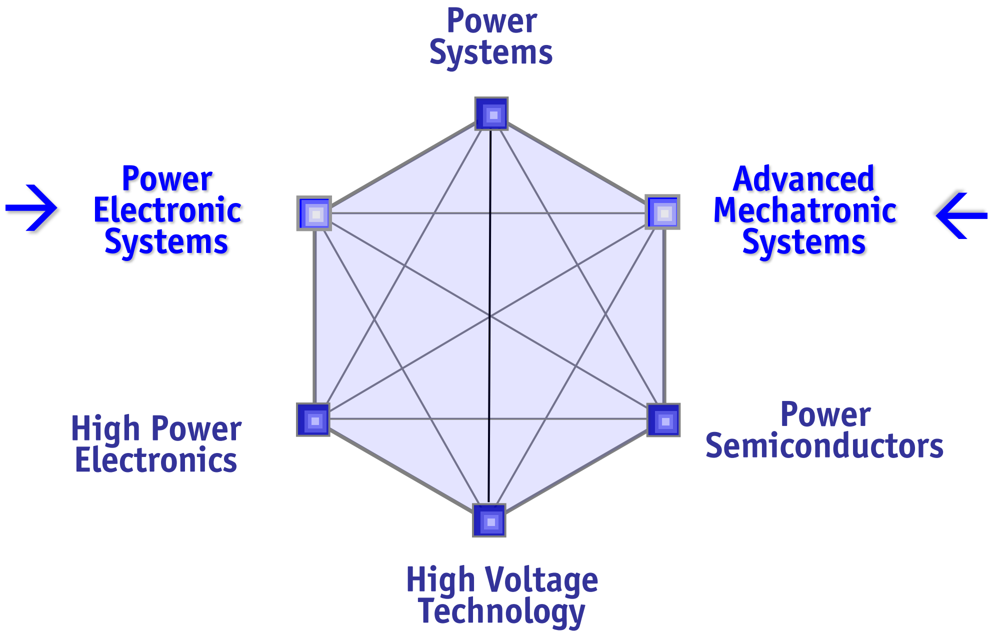
ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	Information Technology and Electrical Eng.
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
90	Nationalities
36	Languages
150th	Anniv. in 2005

Students ETH in total

13’500	B.Sc.+M.Sc.-Students
3’500	Doctoral Students

EEnergy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Power Electronic / Mechatronic Systems

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**			**A. Tüysüz**	**Th. Nussbaumer**
M. Leibl D. Neumayr D. Rothmund L. Schrittwieser	D. Boillat Ch. Gammeter Th. Guillod J. Huber H. Uemura	P. Bezerra M. Kasper	R. Burkart	C. Dittli	R. Bosshard O. Knecht	M. Flankl M. Mauerer M. Kaufmann	Th. Holenstein D. Steinert M. Schuck T. Wellerdieck

Secretariat
M. Kohn / D. Egger

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

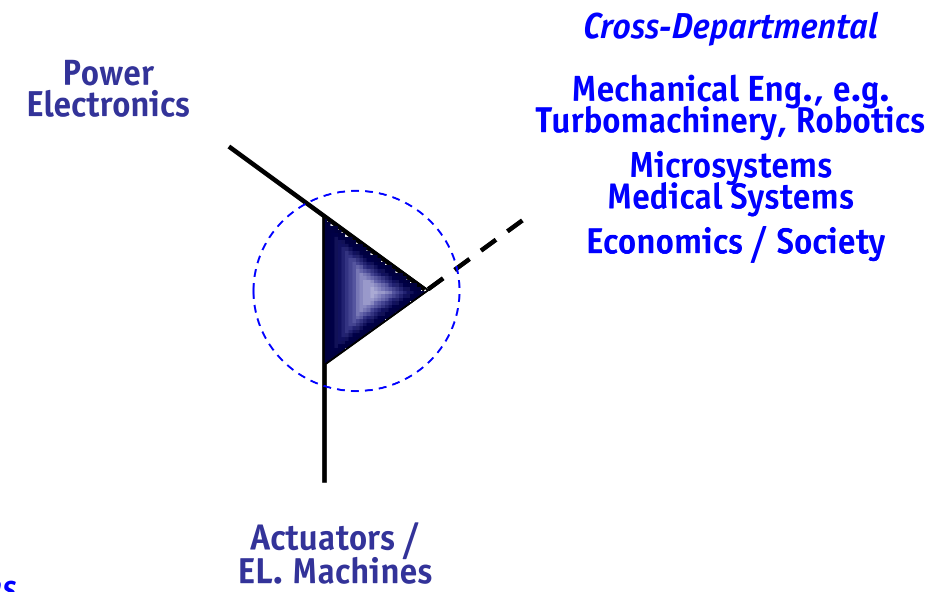
22 Ph.D. Students
3 Post Docs

ECPE Competence Centre

EPSMA

Leading Univ. in Europe

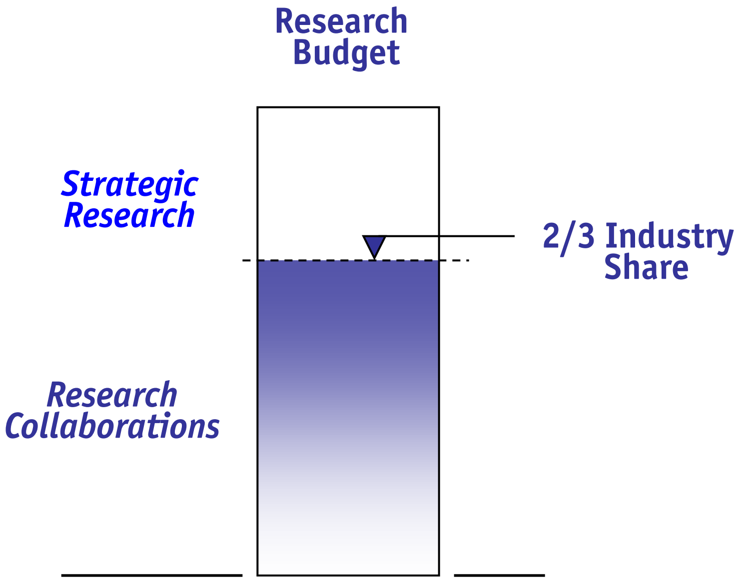
Research Scope



- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Environmental Systems*
- *Pulsed Power*

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 Research Partners*

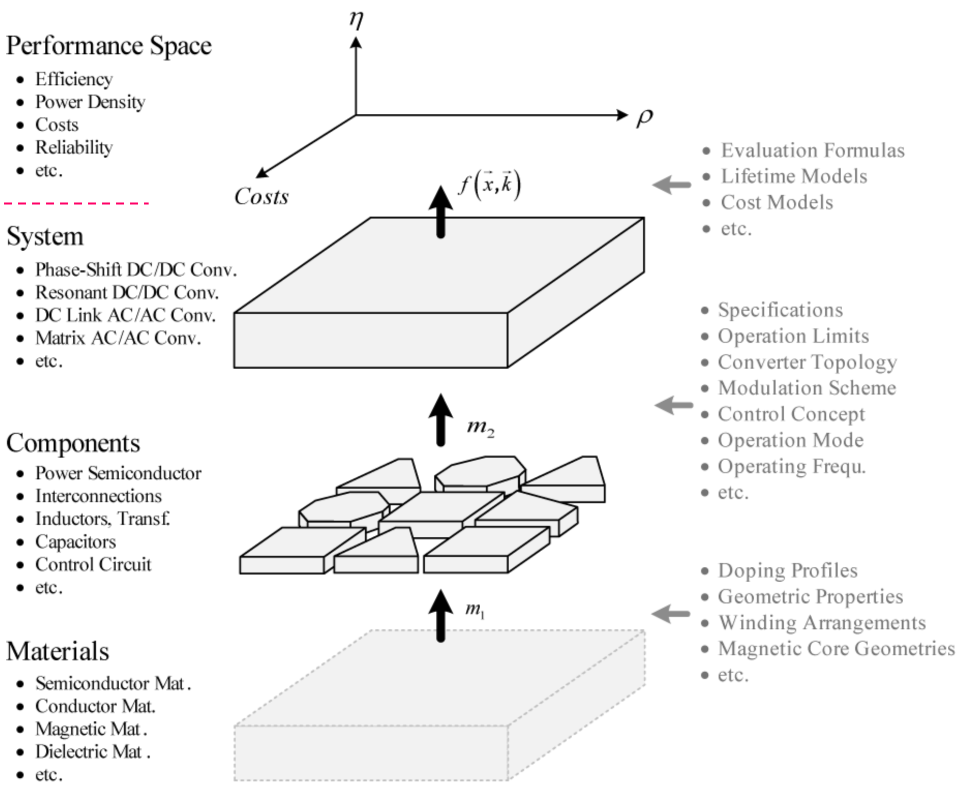


Research Approach

Abstraction of Converter Design

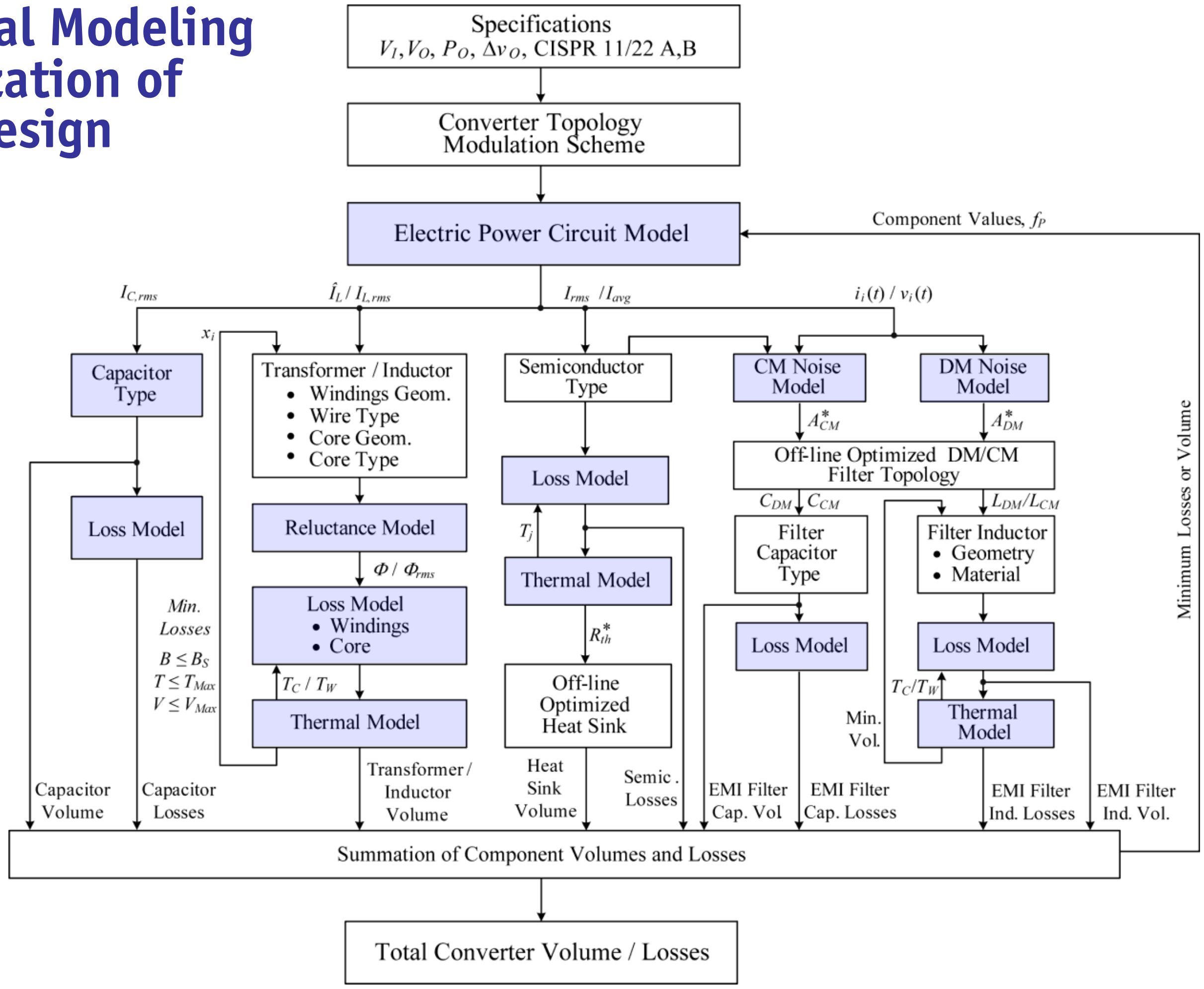
Performance Space

Design Space



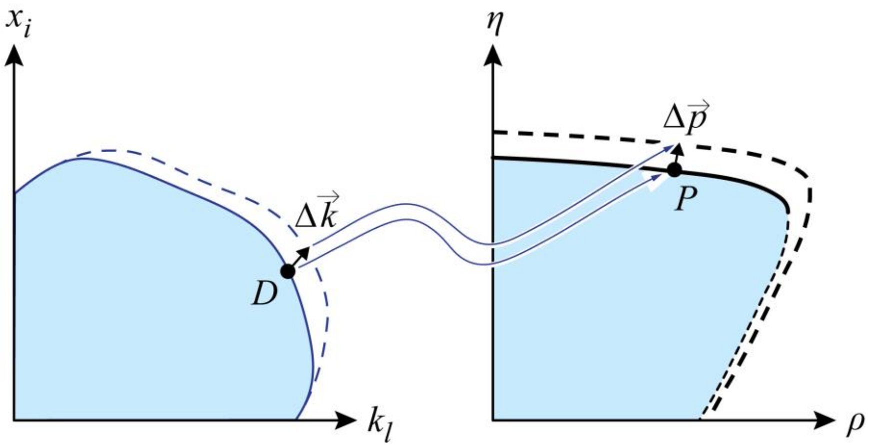
- **Mapping of *Design Space* into System *Performance Space***

Mathematical Modeling and Optimization of Converter Design



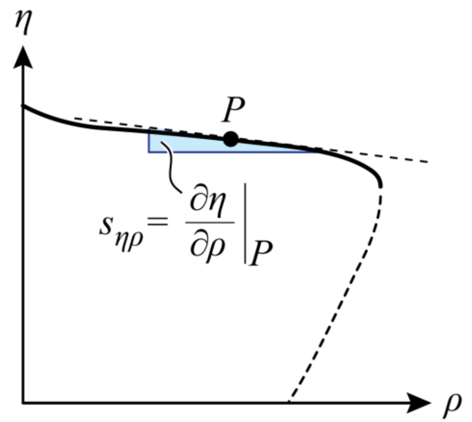
Technology Sensitivity Analysis Based on η-ρ-Pareto Front

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



Design Space

Performance Space



Examples of
Research Results in

Power Electronics

- Ultra-Compact Systems
- Ultra-Efficient Systems

▶ 3-Φ Boost-Type PFC Rectifier

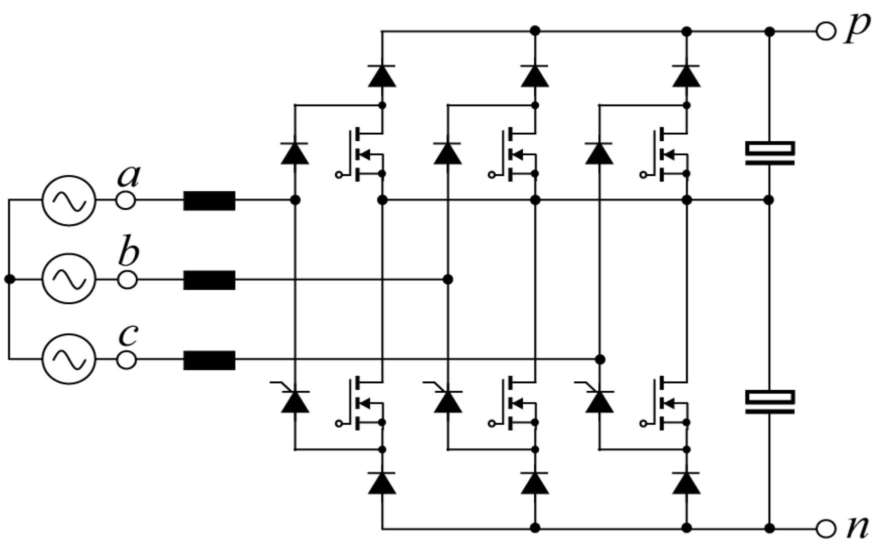
P_0= 10 kW
U_N= 230V_{AC}±10%
f_N= 50Hz or 360…800Hz
U_0= 800V_{DC}

f_P= 250kHz

▶ Si CoolMOS
▶ SiC Diodes

η = 96.2% @ P_0
THD_I= 1.6% @ P_0
γ = 3kW/kg

★ 10kW/dm³ Power Density



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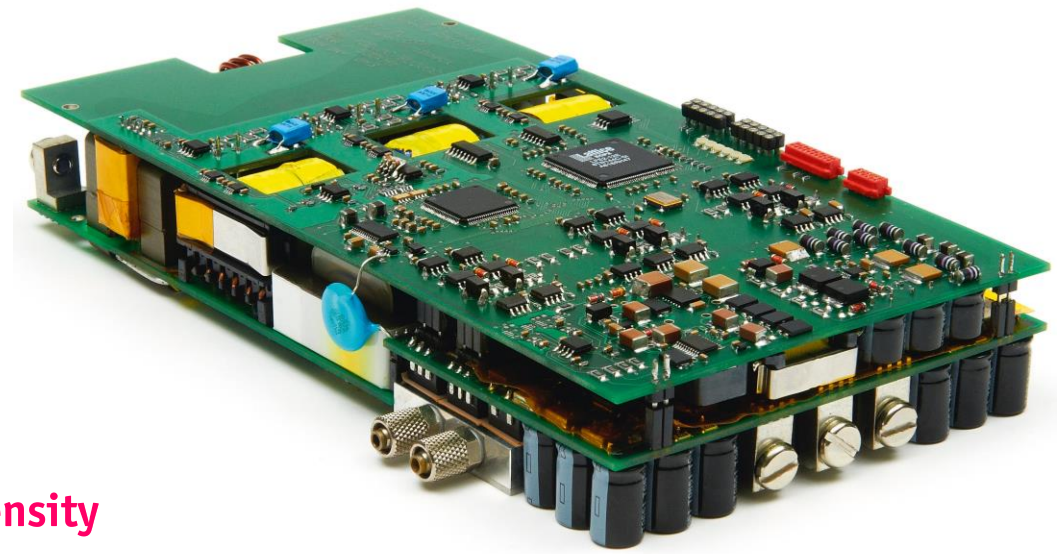
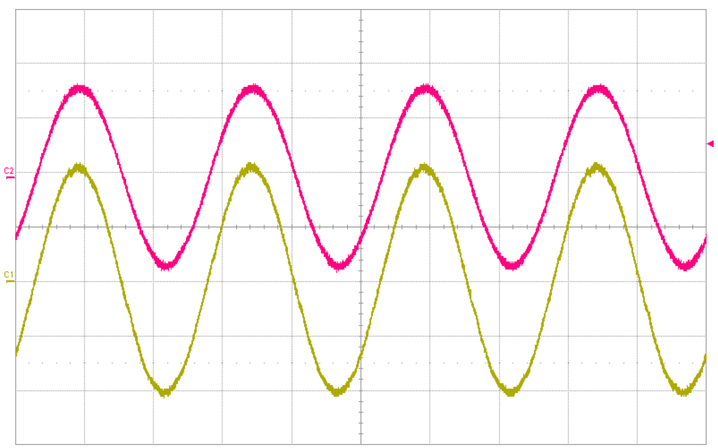


★ 10kW/dm³ Power Density

▶ Mains Behavior @ 400 Hz/800 Hz

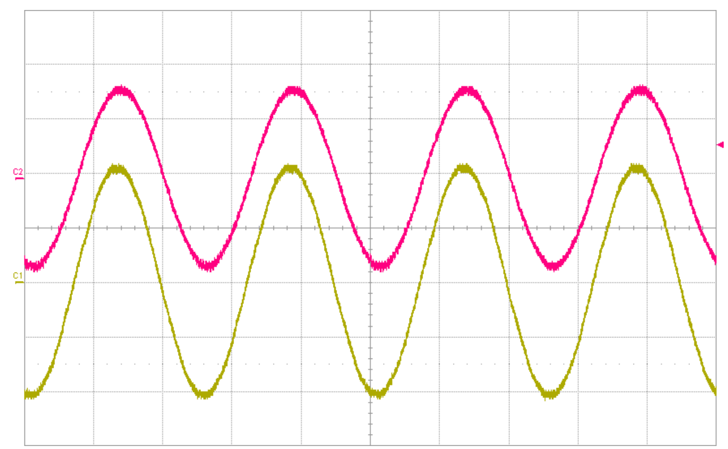
P_O = 10kW
U_N = 230V
f_N = 400Hz
U_O = 800V
THD_i = 1.4%

10A/Div
200V/Div
1ms/Div



P_O = 10kW
U_N = 230V
f_N = 800Hz
U_O = 800V
THD_i = 1.6%

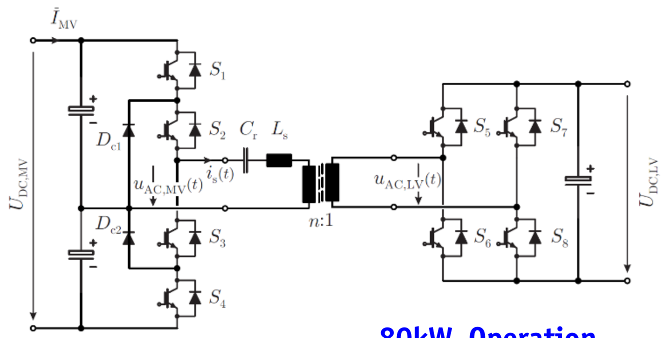
10A/Div
200V/Div
0.5ms/Div



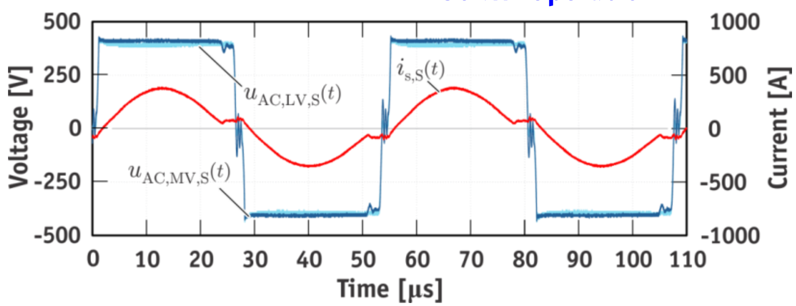
▶ Solid-State Transformer 20kHz DC-DC Converter Cell

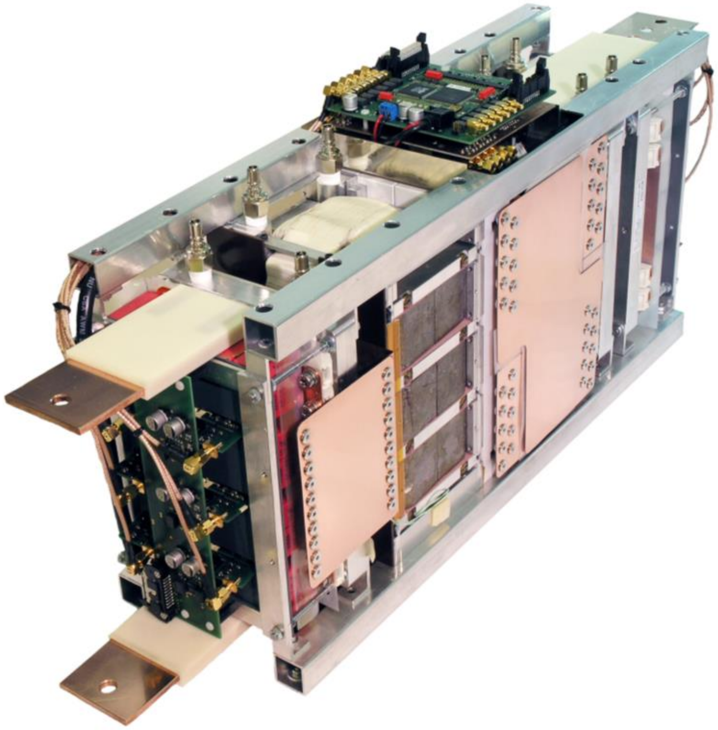
- **Half-Cycle DCM Series Resonant DC-DC Converter**

- **Rated Power** 166kW ←
- **Medium-Voltage Side** 2kV
- **Low-Voltage Side** 400V



80kW Operation

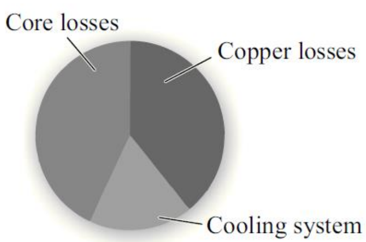


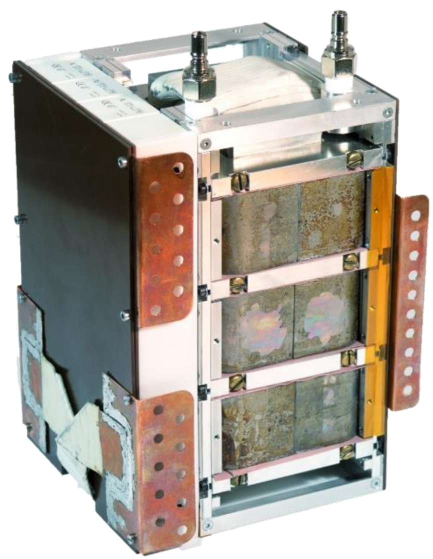


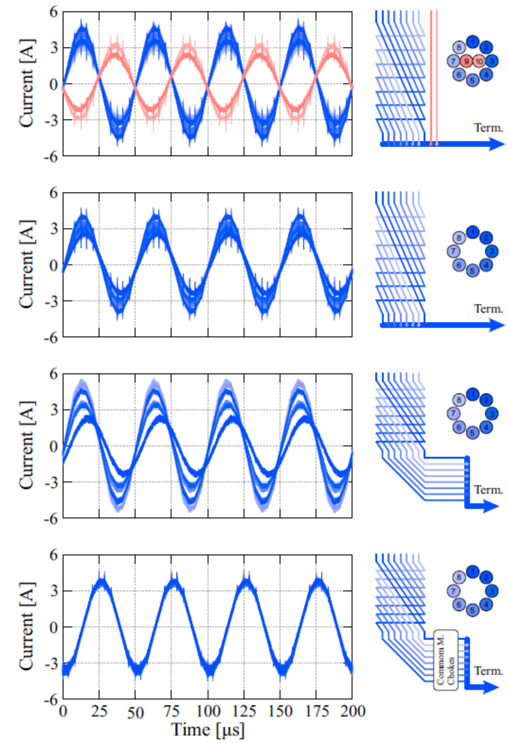
▶ Water-Cooled 20kHz Transformer

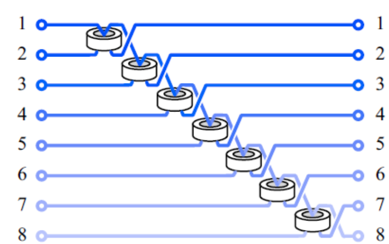
- **Power Rating** 166kW
- **Efficiency** 99.5%
- **Power Density** 32 kW/dm^3

- **Nanocrystalline Cores with 0.1mm Airgaps between Parallel Cores for Equal Flux Partitioning**
- **Litz Wire (10 Bundles) with CM Chokes for Equal Current Partitioning**



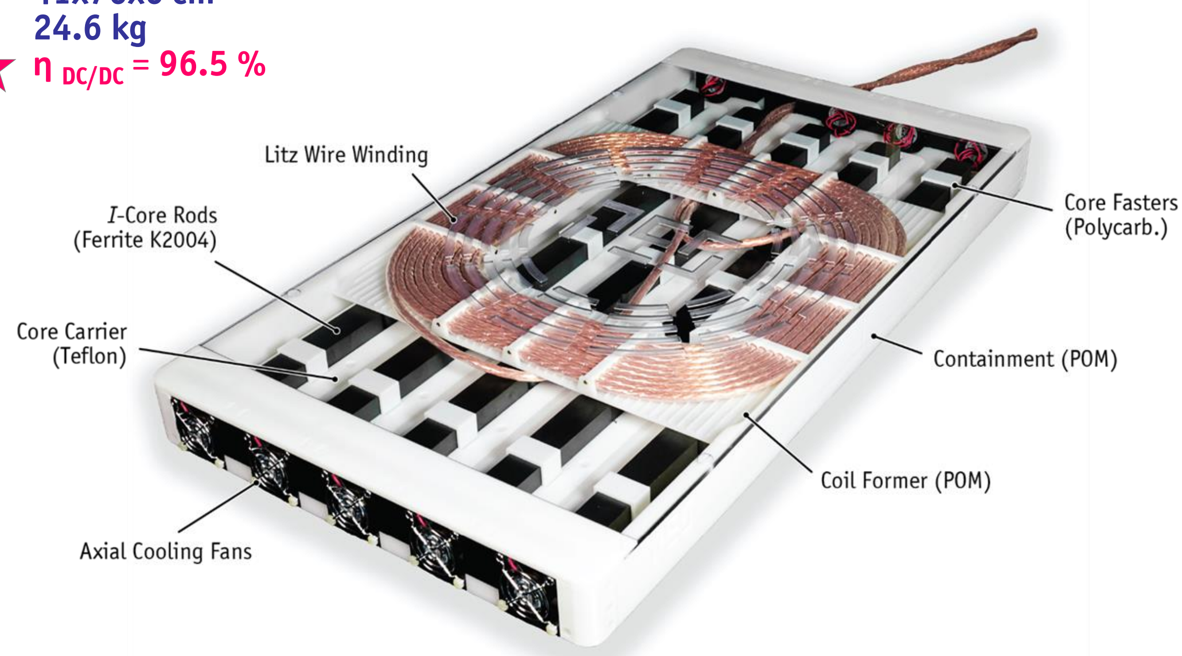






▶ Wireless Power Transfer

- Characteristics
  50kW
  800V / 85kHz
  41x76x6 cm
  24.6 kg
  ★ $\eta_{DC/DC}$ = 96.5 %



- All-SiC Converter System
- Efficiency Optimal Load Matching Control
- Application in Public Transportation / Industrial Environments etc.

Examples of
Research Activities in

Mechatronics

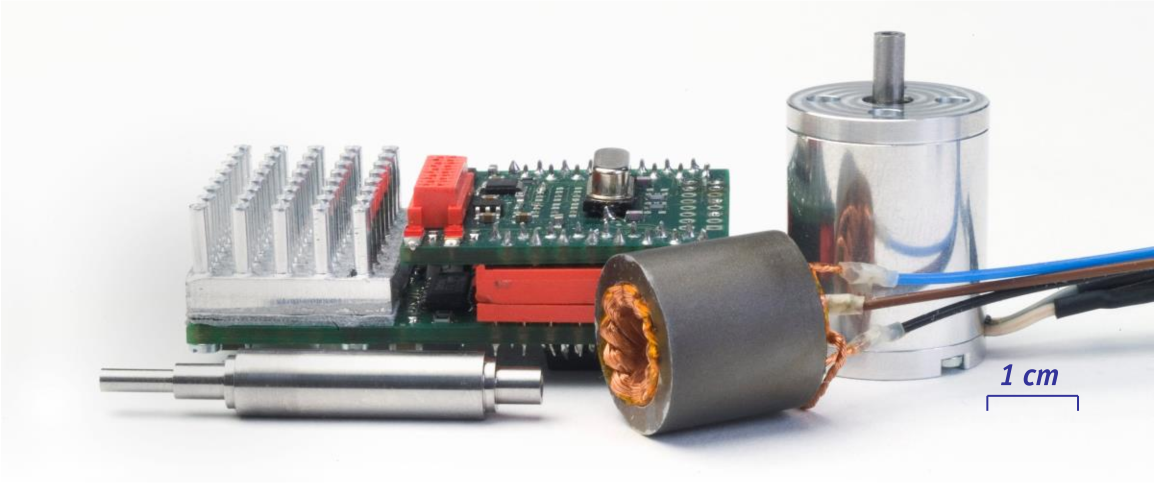
- Ultra High Speed Drives
- Bearingless Machines

► Ultra High Speed Drive Systems

World Record !

100W @ 1‘000‘000 rpm

- ► µm-Scale PCB Drilling
- ► Dental Technology
- ► Laser Measurement Technology
- ► Turbo-Compressor Systems
- ► Air-to-Power
- ► Artificial Muscles
- ► Mega Gravity Science

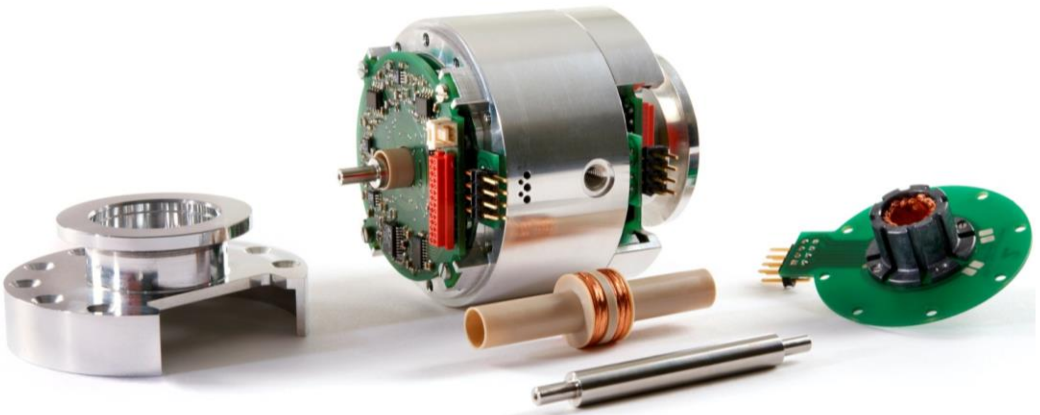


► Ultra High Speed Magnetically Levitated Drive Systems

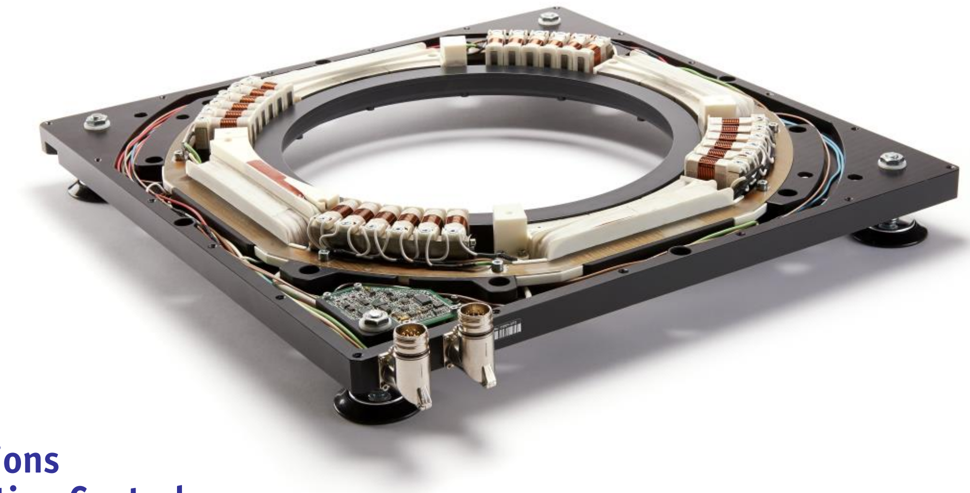
World Record !

500‘000 rpm

- ► Laser Measurement Technology
- ► Active Damping of Air Bearings
- ► Satellite Attitude Control



► Bearingless Motors



- Maximum Speed 2000rpm
- High Acceleration Capability (3.8s from 0 → 2000rpm)
- 7mm Air Gap
- Two Phase Winding Configurations
- Adaptive Unbalance Compensation Control

Outline

- Application Areas & Performance Trends
- Component Technologies → Challenges
- Topologies & Modulation/ Control → Challenges
- Design & Testing Procedure → Challenges
- Future CHALLENGES → Opportunities (!)
- Future Univ. Research & Education
- Conclusions

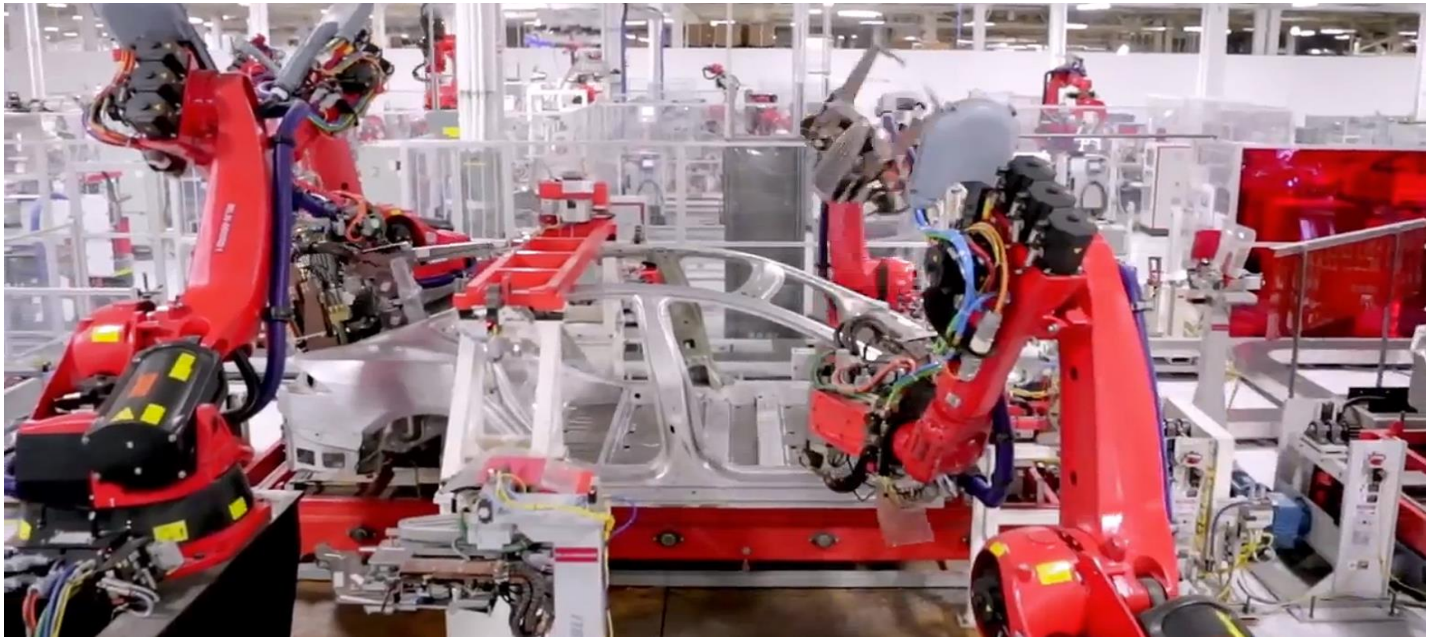
Application Areas
Performance Trends

Application Areas

- Industry Automation / Processes
- Communication & Information
- Transportation
- Lighting
- etc., etc.

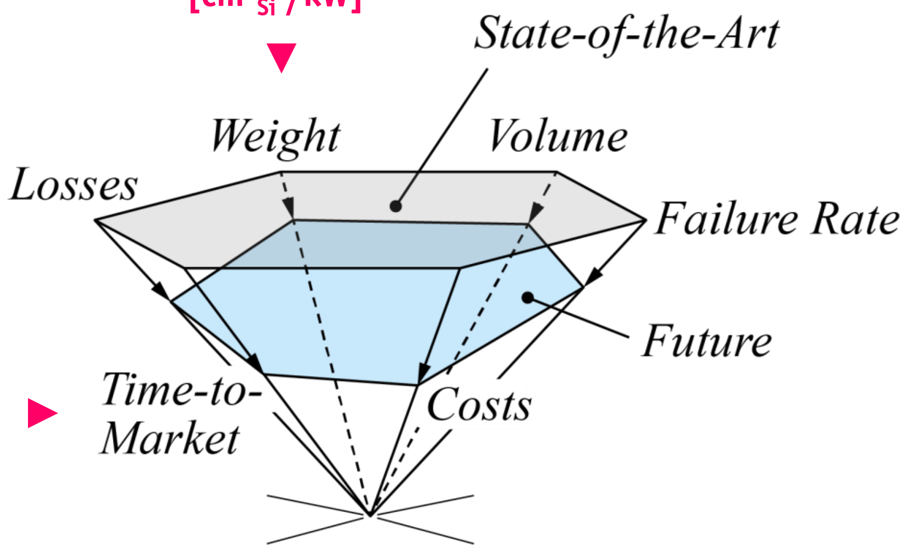
.... Everywhere !

Source: TESLA MOTORS



Power Electronics Converters Performance Trends

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



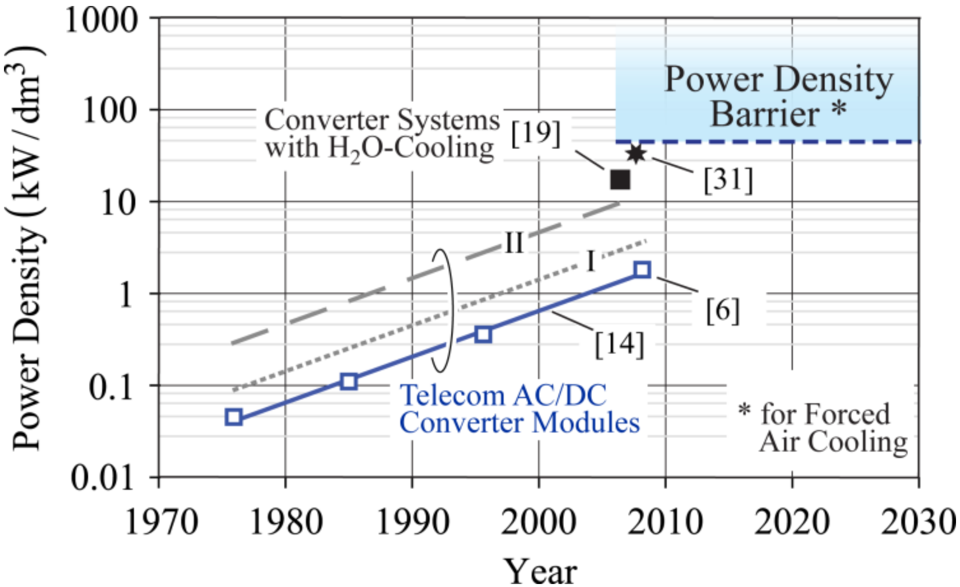
Performance Indices

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

▶ Performance Improvements (1)

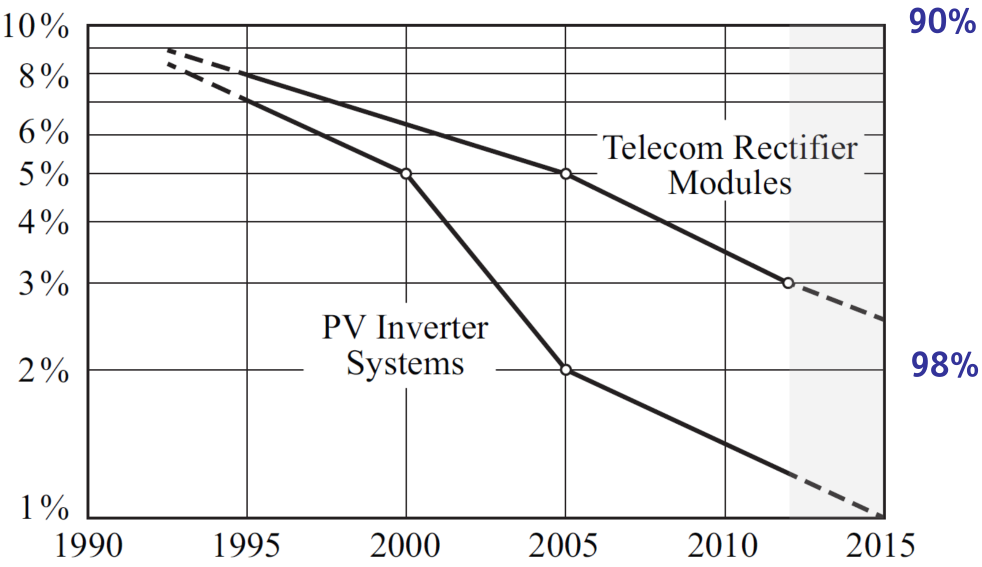
■ **Power Density**

— **Telecom Power Supply Modules: Typ. Factor 2 over 10 Years**



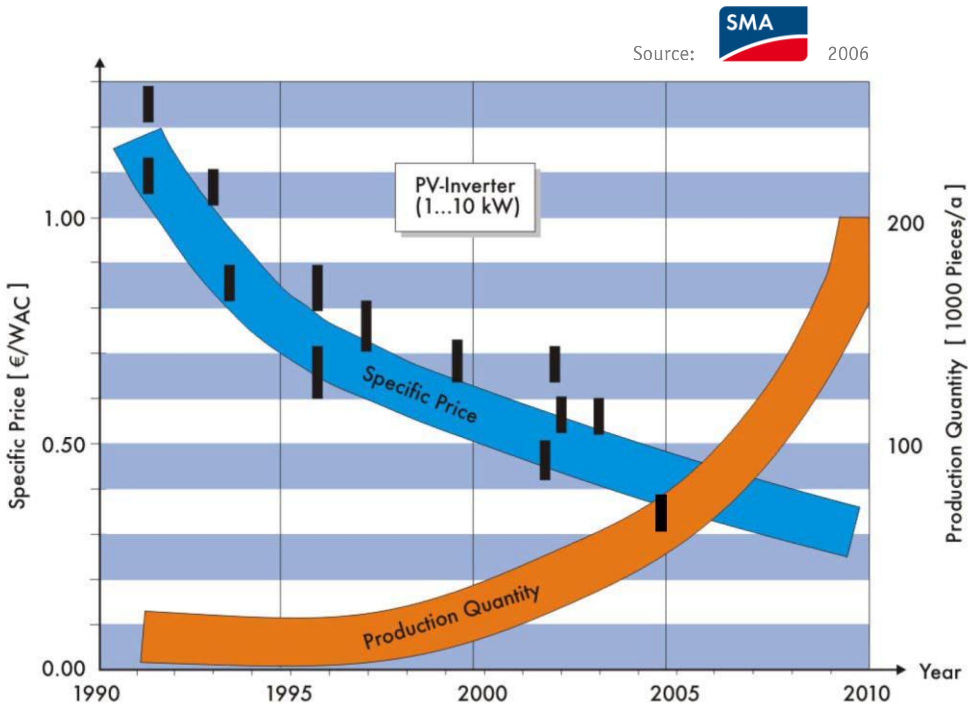
▶ Performance Improvements (2)

Inefficiency (Losses)... $1-\eta$



- **Efficiency**
  - PV Inverters: Typ. Loss Reduction of Factor 2 over 5 (10) Years

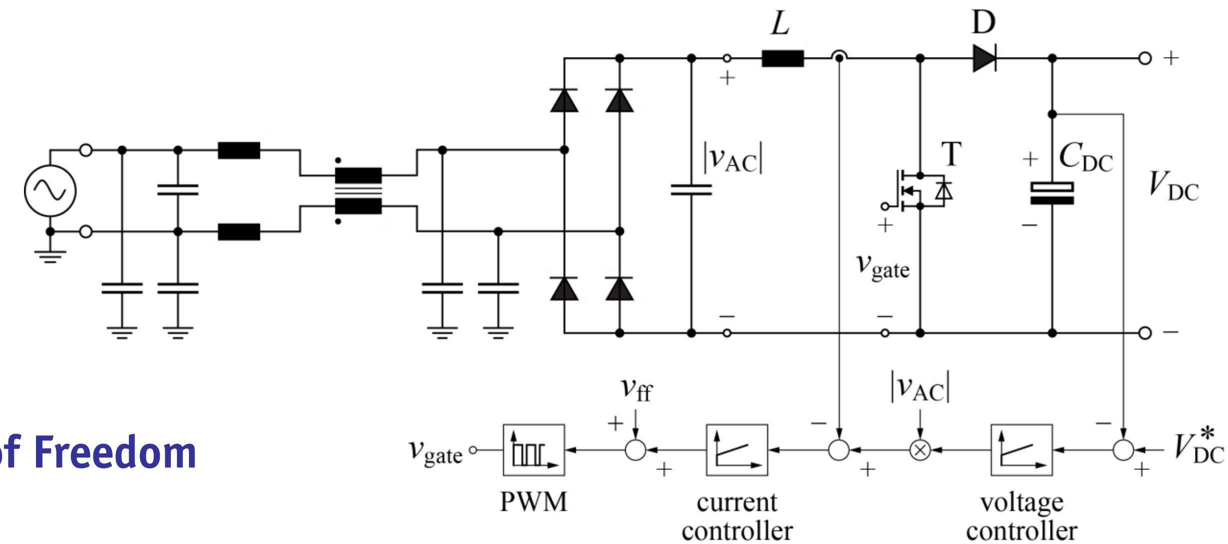
▶ Performance Improvements (3)



- **Costs**
  - Importance of Economy of Scale

▶ Challenge

■ How to Continue the Dynamic Performance Improvement (?)



■ Degrees of Freedom

- Components
- Topologies
- Modulation & Control
- Design Procedure
- Modularization / Standardization / Economy of Scale
- Manufacturing
- New Applications

Components

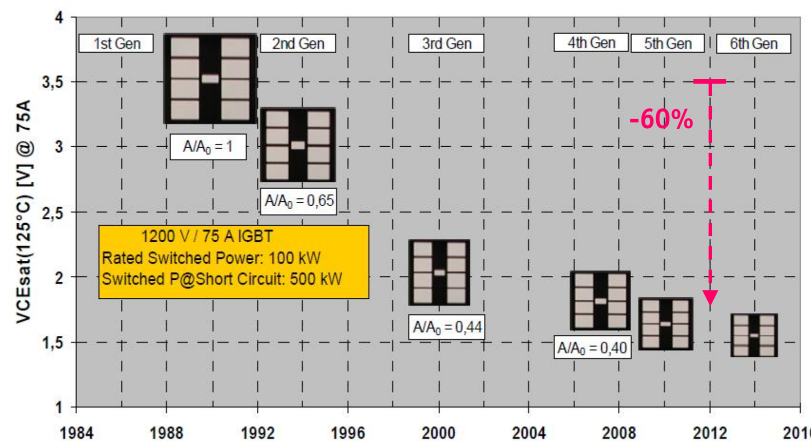
Potentials & Limits

Power Semiconductors

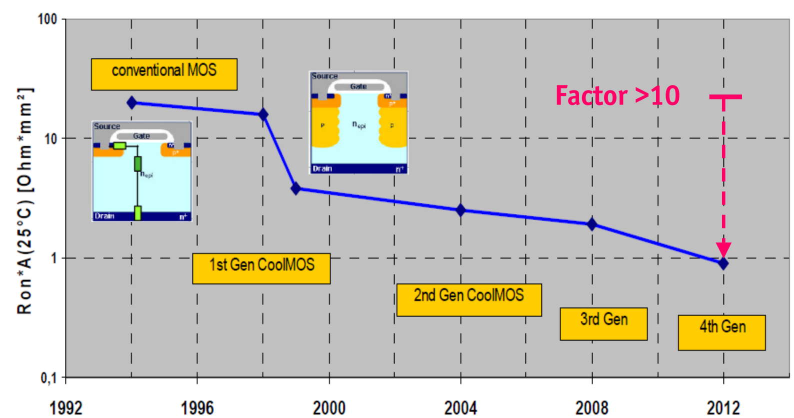
→ Si / SiC / GaN

▶ Si Power Semiconductors

Source: Dr. Miller / Infineon / CIPS 2010



600V Devices

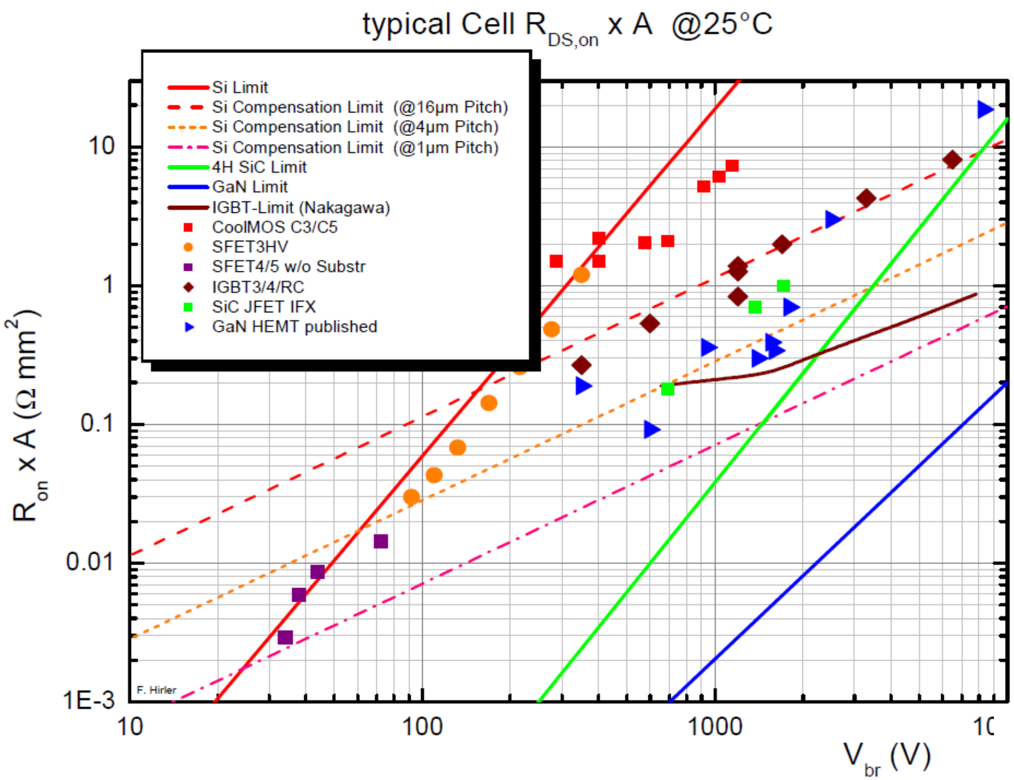


■ **Past Disruptive Changes**

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

▶ WBG Power Semiconductors

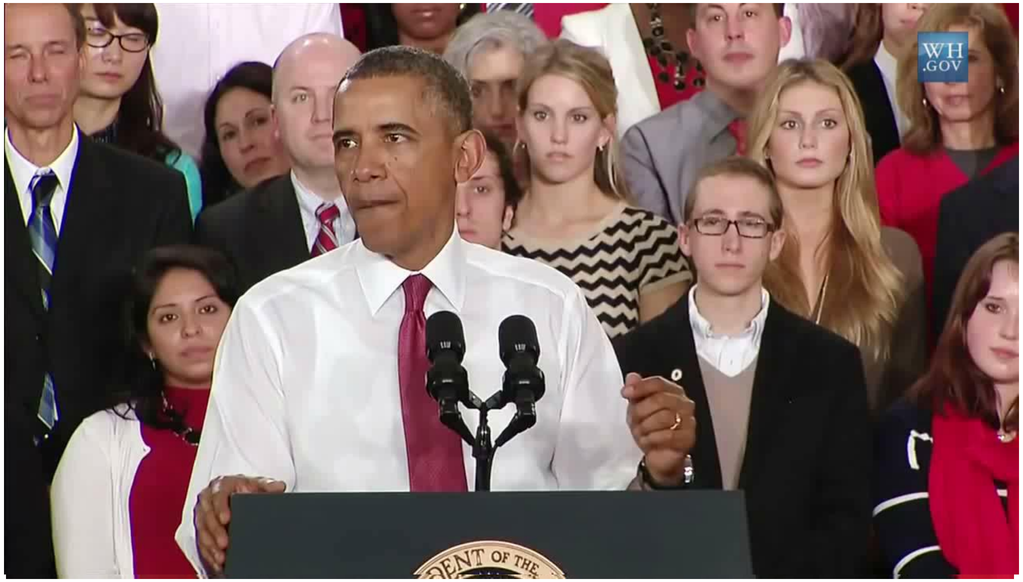
Source: Dr. Miller Infineon CIPS 2010



- **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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— Extremely Low $R_{DS(on)}$
— Very High $T_{j,max}$
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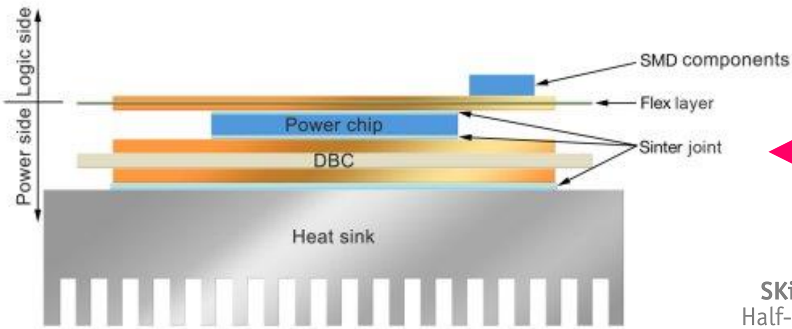
- Utilization of Excellent Properties → Main Challenges in Packaging (!)

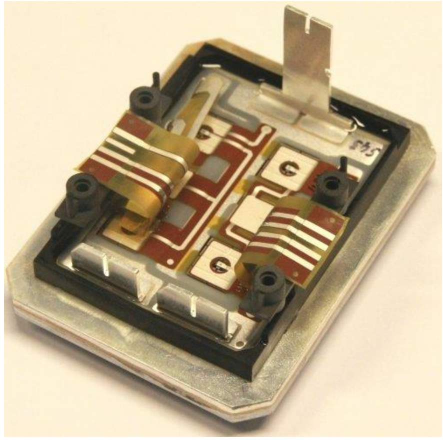
SKiN Technology

- No Bond Wires, No Solder, No Thermal Paste
- Ag Sinter Joints for all Interconnections of a Power Module (incl. Heatsink)
- Extremely Low Inductance & Excellent Thermal Cycling Reliability

Source: SEMIKRON innovation+service Dr. Scheuermann Dr. Beckedahl CIPS 2008



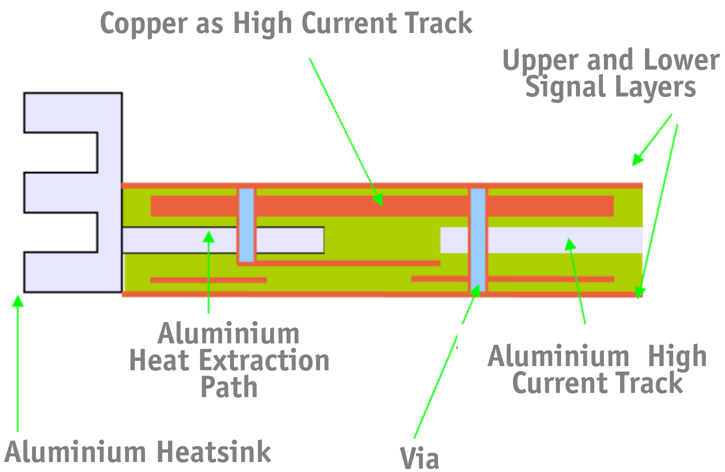
SKiN 600V/400 A
Half-Bridge Module

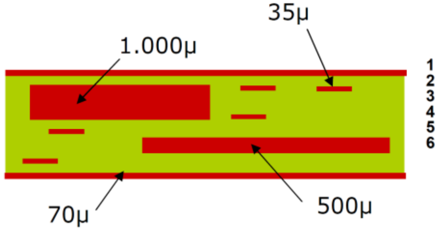


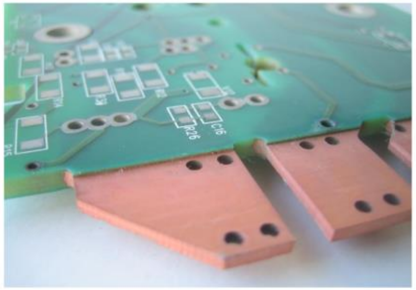
- Allows Extension to 2-Side Cooling (Two-Layer Flex-Foil)
- Allows Integration of Passive & Active Comp. (Gate Drive, Curr. & Temp. Measurem.)
- Disruptive Improvement (!)

▶ Multi-Functional PCB

- Multiple Signal and High Current Layers
- Integrated Thermal Management







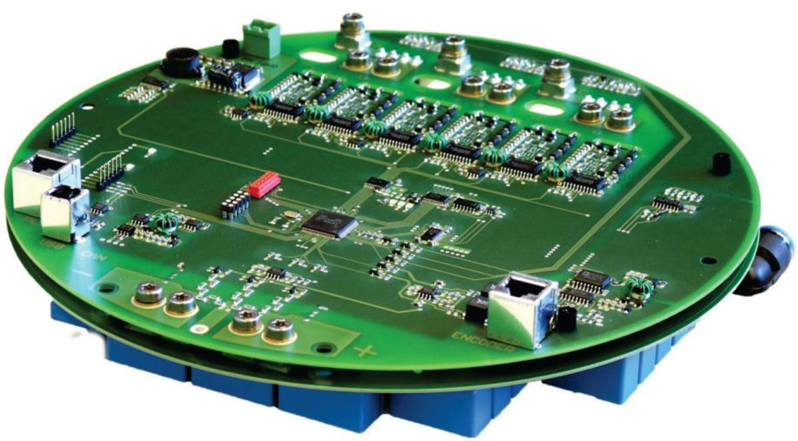
- Substantial Change of Manufact. Process → "Fab-Less" Power Electronics
- Advanced Simul. Tools of Main Importance (Coupling with Measurem.)
- Testing is Challenging (Only Voltage Measurement)
- Once Fully Utilized – Disruptive Change (!)

► 3ph. Inverter in p²pack-Technology

- Rated Power 32kVA

- Input Voltage $700V_{DC}$
- Output Frequency 0 ... 800Hz
- Switching Frequency 20kHz

Source: SCHWEIZER ELECTRONIC, enertronics



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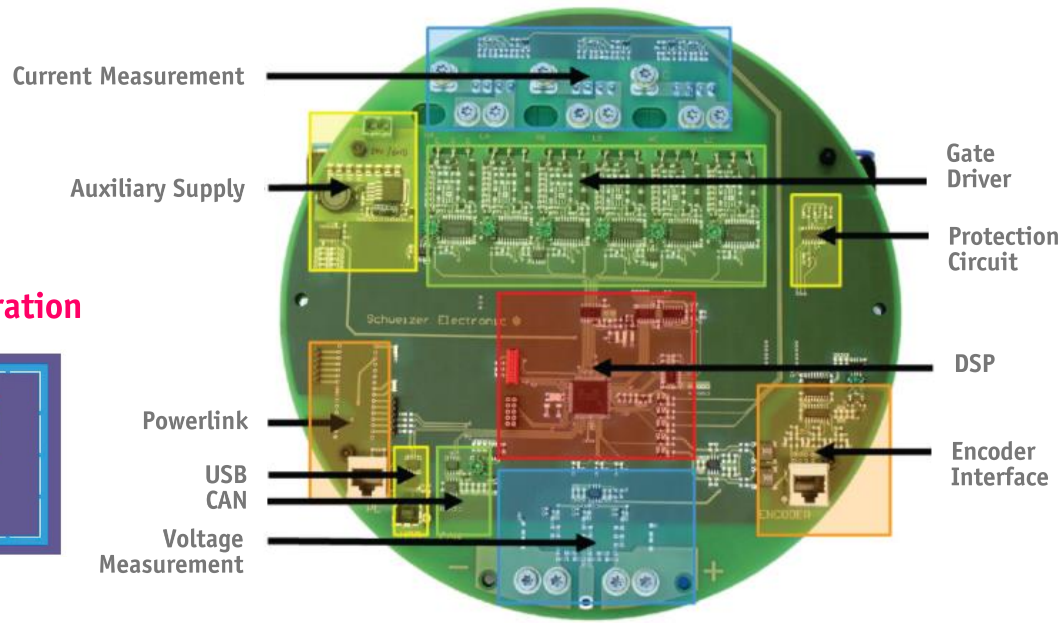
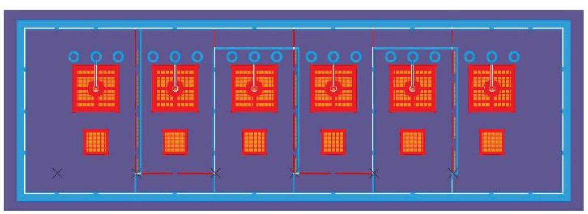
Source: SCHWEIZER ELECTRONIC, enertronics



– Power Semiconductor PCB Integration

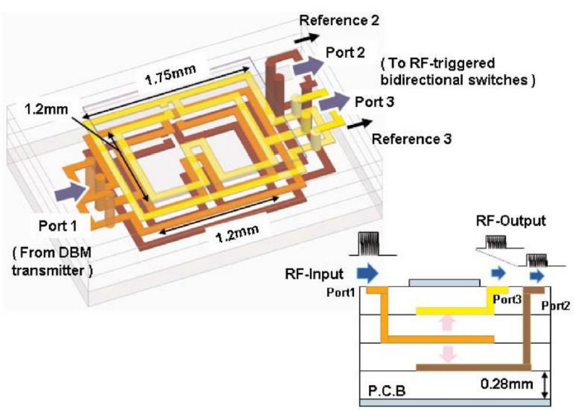


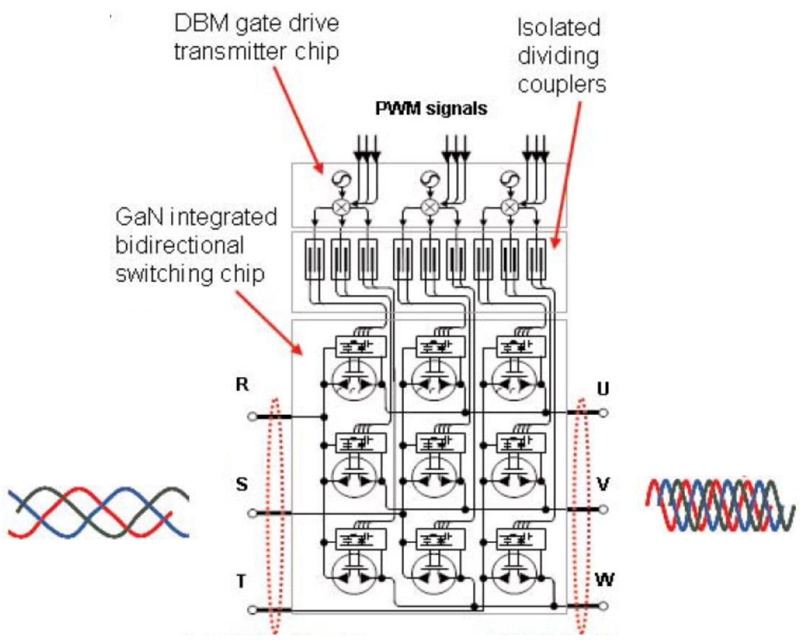
▶ Latest Systems Using WBG Devices → GaN

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 mm² (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler





Σ

Power Semiconductors
Gate Drive
Packaging

- Disruptive Changes Happened – WBG, LTJT
- Cont. Further Improvements – Packaging, Reliability (!)

→ Main Challenges to Manufacturers
→ Main Challenges to General Users

Passive Components

→ Capacitors / Magnetics / Cooling

Capacitors

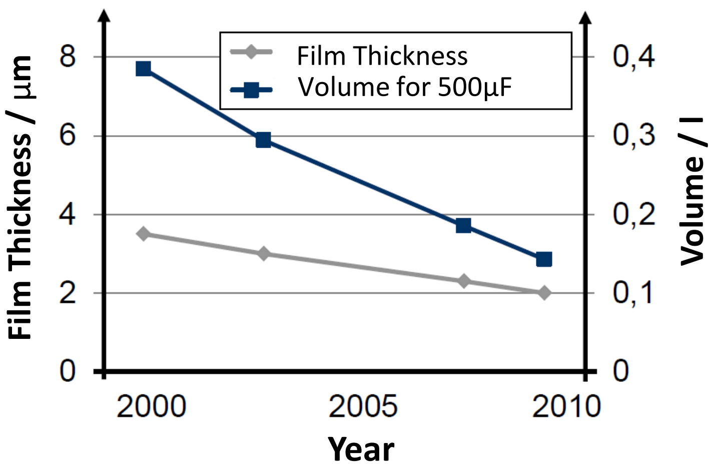
- Relatively (Slow) Technology Progress
- Recently Significant Improvement (incl. Packaging) – e.g. CeraLink

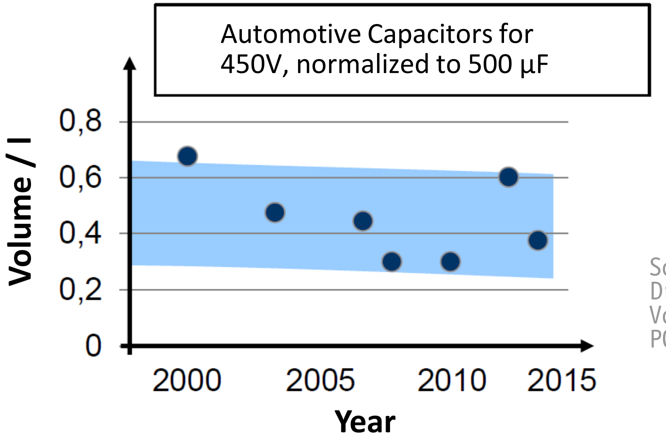
– Foil Capacitors

OPP = Oriented Polypropylene
PHD = Advanced OPP
COC = Cycloolefine Copolymers

Source: EPCOS

	2000	2005	2010	2015
Energy Density	100%	100%	110%	120%
Film Material	OPP	PHD	COC	?
Max. Temperature	105 °C	115 °C	150 °C	160 °C
Self Inductance	60 nH	30 nH	15 nH	10 nH

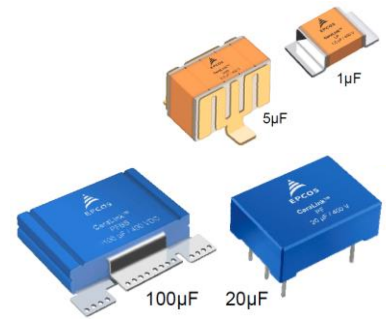




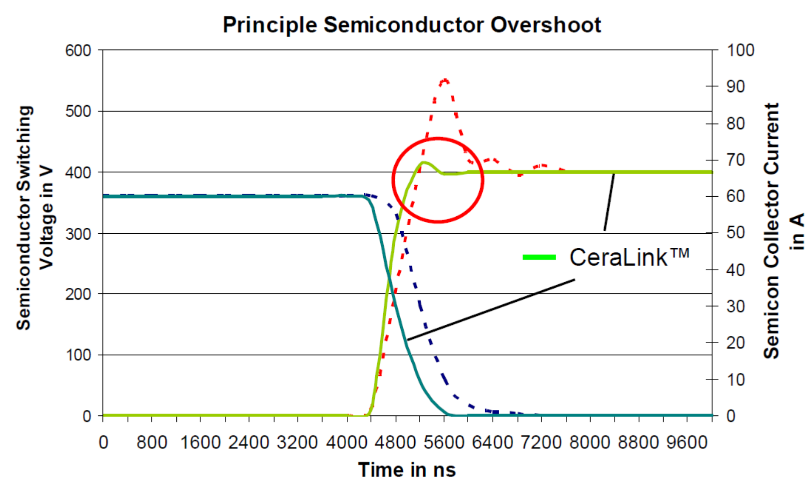
Source:
Dr. Plikat et al.
Volkswagen AG
PCIM 2013

▶ Power Chip Capacitors

- Targeting Automotive Applications up to 90kW
- High Voltage Ratings / High Current Densities (>2A/µF)
- Low Volume / High Volume Utilization Factor
- Low Ind. Busbar Connection / Low Switching Overshoot



Source: EPCOS TDK



► Magnetics

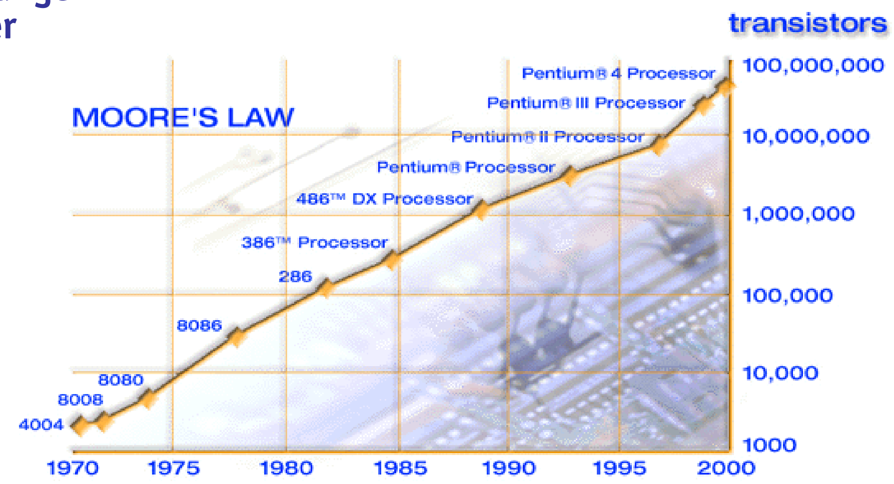
→ **There is No "Moore's Law" in Power Electronics !**

■ **Example: Scaling Law of Transformers**

$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

↑

$\hat{B}_{max}$ ... Relatively Slow Technology Progress
J_{rms} ... Limited by Conductivity – No Change
f ... Limited by HF Losses & Converter
& General Thermal Limit



■ **No Fundamentally New Concepts**

→ **We have to Hope for Progress in Material Science**

Magnetics

→ **There is No "Moore's Law" in Power Electronics !**

- **Example: Scaling Law of Transformers**

$$A_{Core} A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

↑

- **No Fundamentally New Concepts**

→ **We have to Hope for Progress in Material Science (Magnetic, Thermal – Could take > 10Years)**

▶ Operation Frequency Limit

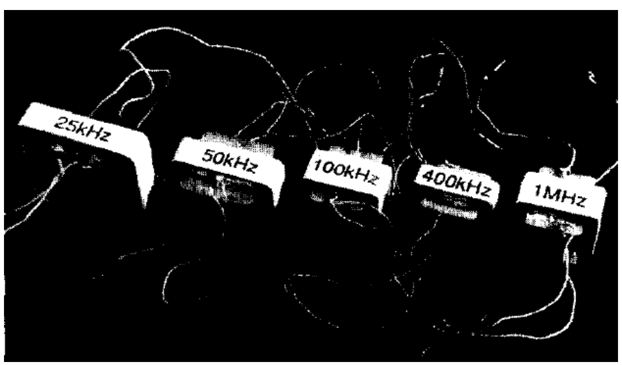
■ **Relationship of Volume and Weight vs. Frequency**

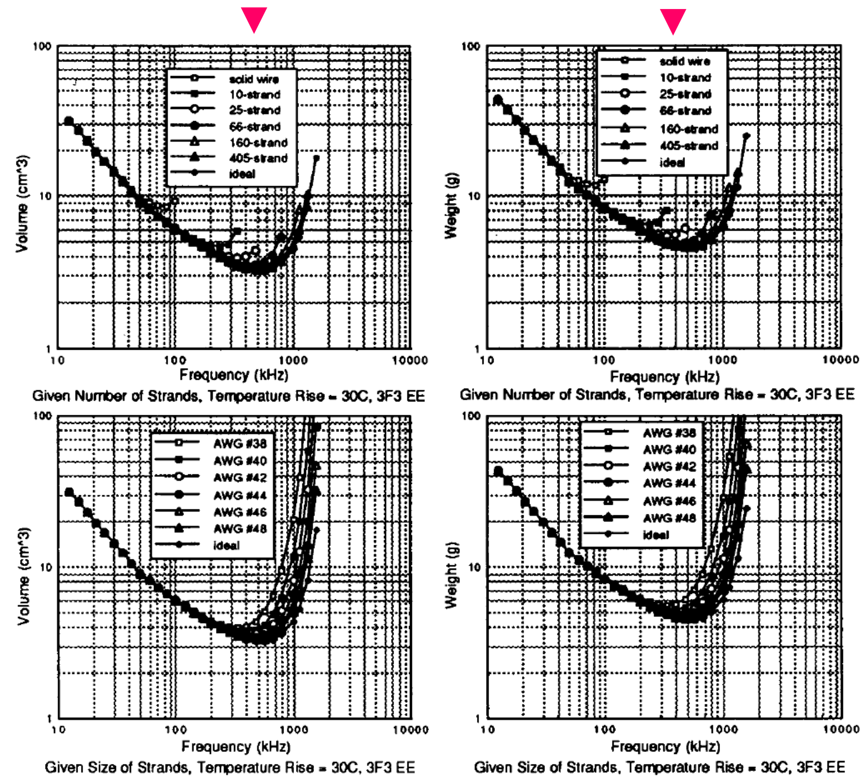
— Higher Frequency Results in Smaller Transformer Size only Up to Certain Limit

— Opt. Frequencies for Min. Weight and Min. Volume (!)

Source: Philips

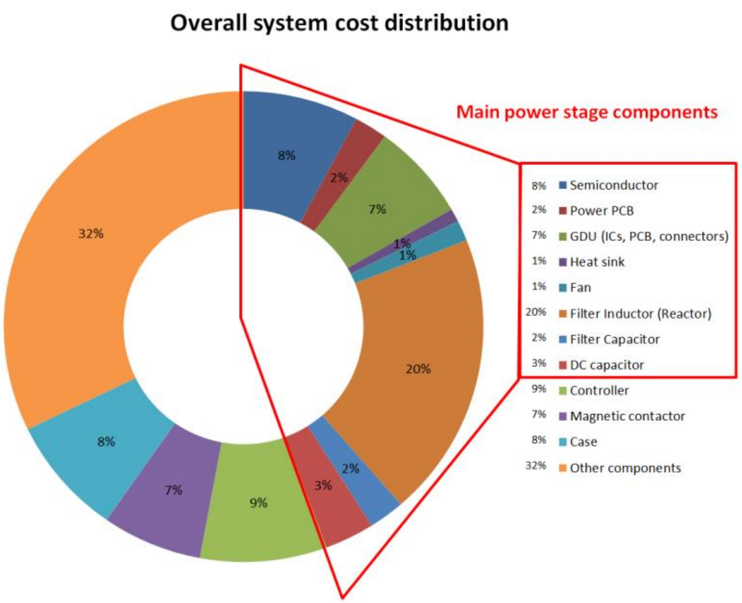
■ 100Vx1A 1.1 Transformers, 3F3, 30°C Temp. Rise





▶ Influence of Magnetics on System Costs

- Example of 20kVA UPS System (Single-Stage Output Filter)



- 44% of Main Power Stage Costs (!)

Σ Magnetics Capacitors

- Large Volume Share / Cost Factor
- Only Gradual Improvements

→ Magnetics
- Careful Design Absolutely Mandatory (!)
- Hope for Adv. Power Transformer/ Inductor Materials
- Improved Heat Management

→ Capacitors
- High Frequ. Operation for Minim. Vol. (e.g. DC Link)
- Replace Storage Capacitors by Active Circuits
- Hope for Adv. Dielectrics

Converter Topologies

History and Development of the Electronic Power Converter

E. F. W. ALEXANDERSON
FELLOW AIEE

E. L. PHILLIPI
NONMEMBER AIEE

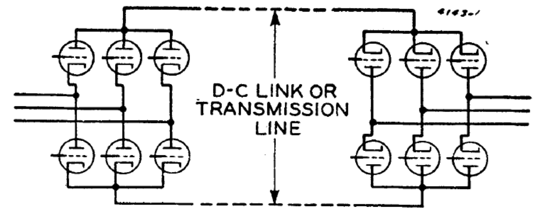


Figure 1. Electronic converter, dual-conversion type

THE TERM "electronic power converter" needs some definition. The object may be to convert power from direct current to alternating current for d-c power transmission, or to convert power from one frequency into another, or to serve as a commutator for operating an a-c motor at variable speed, or for transforming high-voltage direct current into low-voltage direct current. Other objectives may be mentioned. It is thus evidently not the objective but the means which characterizes the electronic power converter. Other names have been used tentatively but have not been accepted. The emphasis is on electronic means and the term is limited to conversion of power as distinguished from electric energy for purposes of communication. Thus the name is a definition.

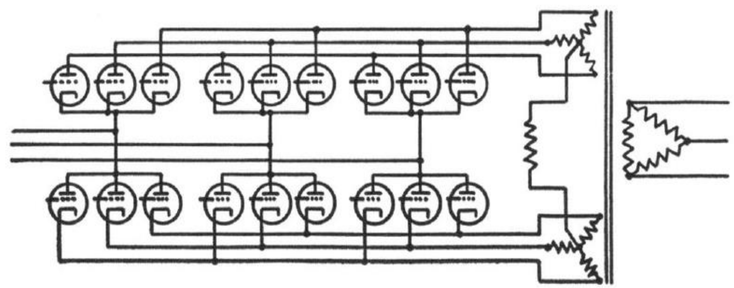
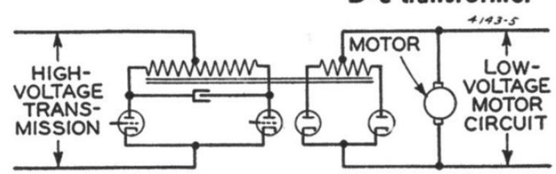


Figure 4 (left). Single-conversion-type frequency changer

Figure 5 (below). D-c transformer



Paper 44-143, recommended by the AIEE committee on electronics for presentation at the AIEE summer technical meeting, St. Louis, Mo., June 26–30, 1944. Manuscript submitted April 25, 1944; made available for printing May 18, 1944.

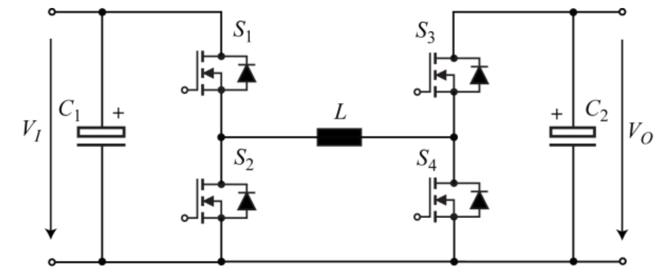
E. F. W. Alexanderson and E. L. Phillipi are with the General Electric Company, Schenectady, N. Y.

1944 !

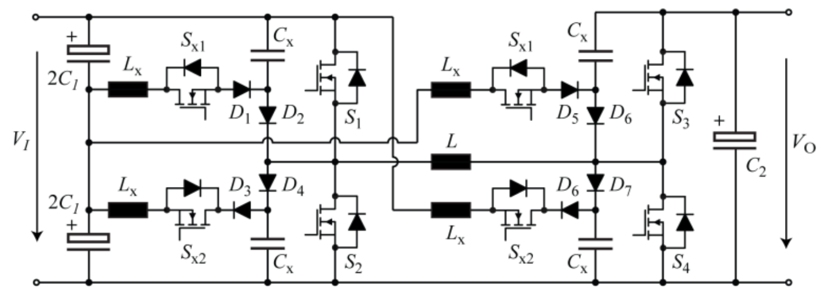
▶ Auxiliary Circuits

— **Example: Non-Isolated Buck+Boost DC-DC Converter for Automotive Applications**

98% Efficiency
$29kW/dm^3$



a)



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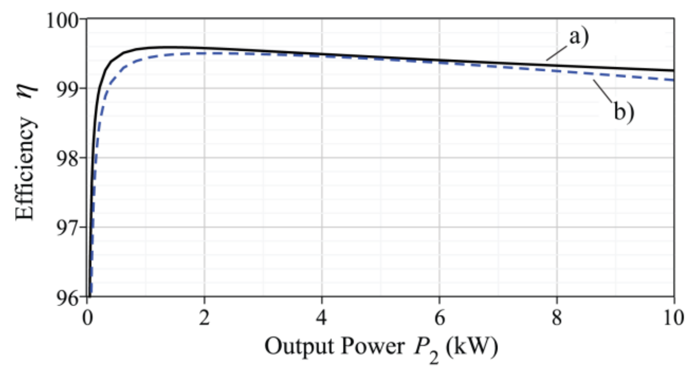
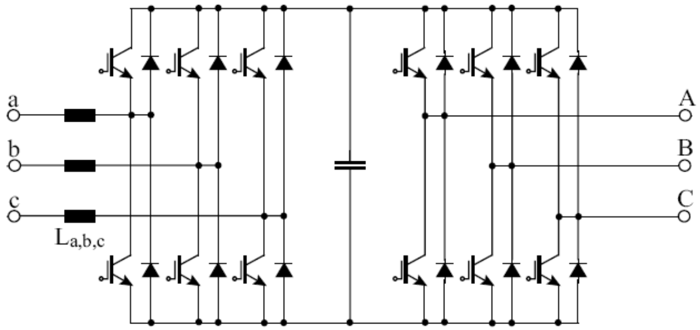
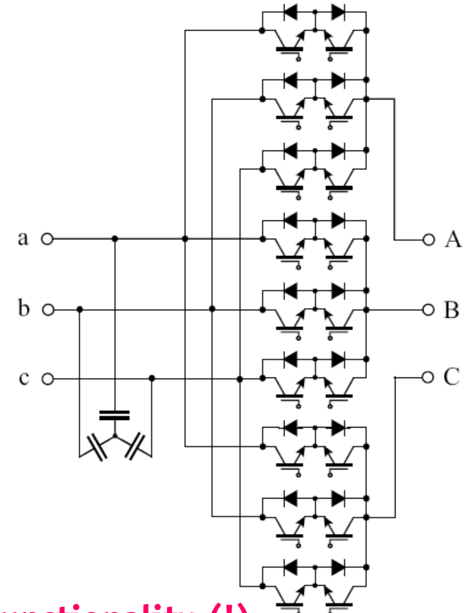


- **Instead of Adding Aux. Circuits**
  Change Operation of BASIC (!) Structures -
  "Natural" Performance Limit

▶ Integration of Functions

— **Examples:**
* Single-Stage Approaches / Matrix Converters
* Multi-Functional Utilization (Machine as Inductor of DC/DC Conv.)
* etc.

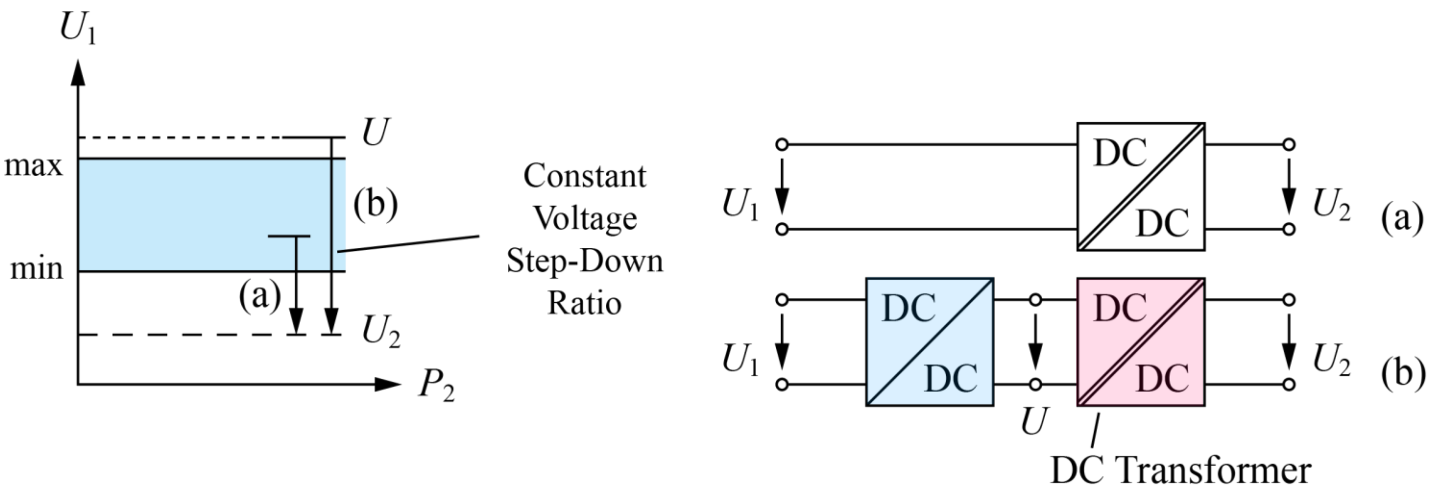




- Integration typ. Restricts Controllability / Overall Functionality (!)
- Typ. Lower Performance / Higher Control Compl. of Integr. Solution
- Basic Physical Properties remain Unchanged (e.g. Filtering Effort)

▶ Extreme Restriction of Functionality

- Highly Optimized Specific Functionality → High Performance for Specific Task
- Restriction of Functionality → Lower Costs



- Example of Wide Input Voltage Range Isolated DC/DC Converter

Σ New Topologies

→ **Some Exceptions**

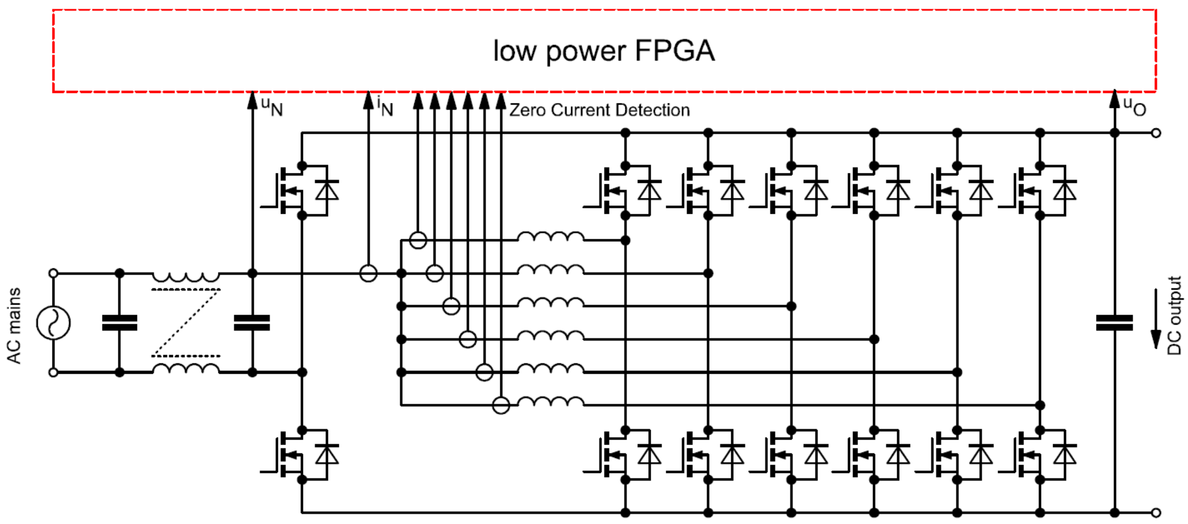
- Multi-Cell Converters
- 3-ph. AC/DC Buck Converter
- etc.

Multi-Cell Converters

→ Ultra-Efficient 1ph. PFC
→ 1ph. Telecom PFC Rectifier

▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

★ 99.36% @ 1.2kW/dm³

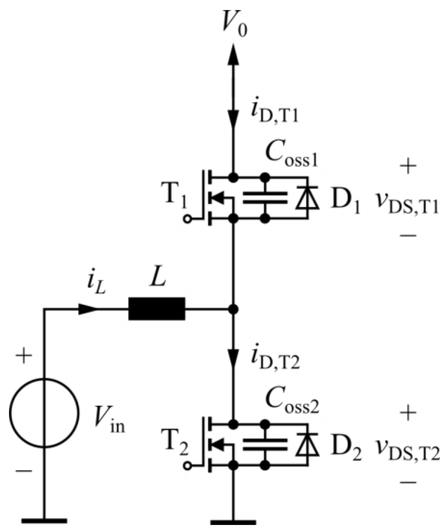


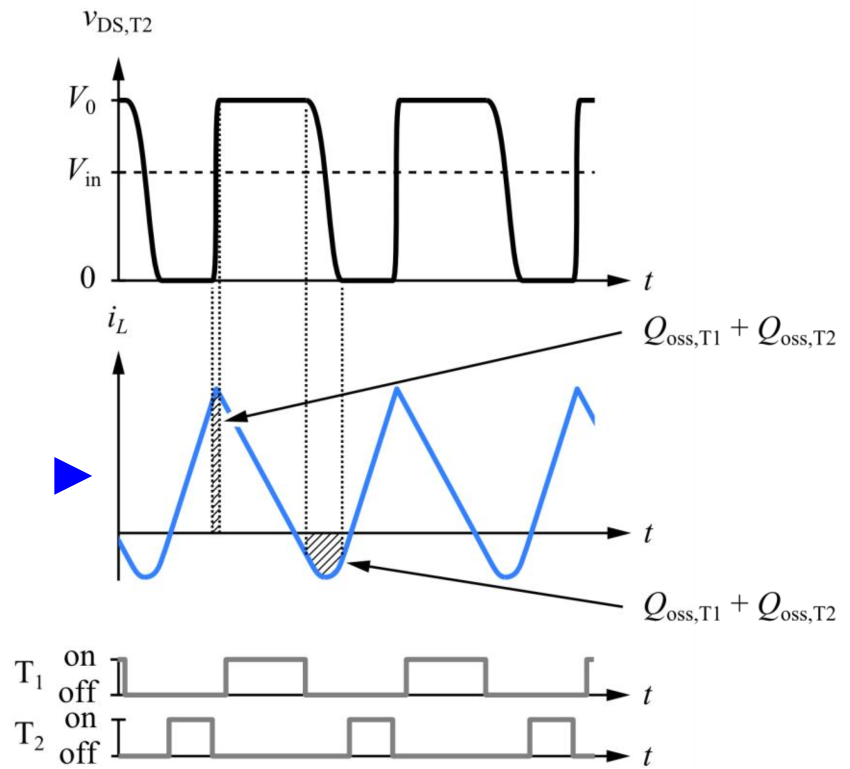
- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only

Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

- Zero Voltage Switching – Triangular Current Mode

- Synchronous Rectification
- Negative Current Ensures ZVS





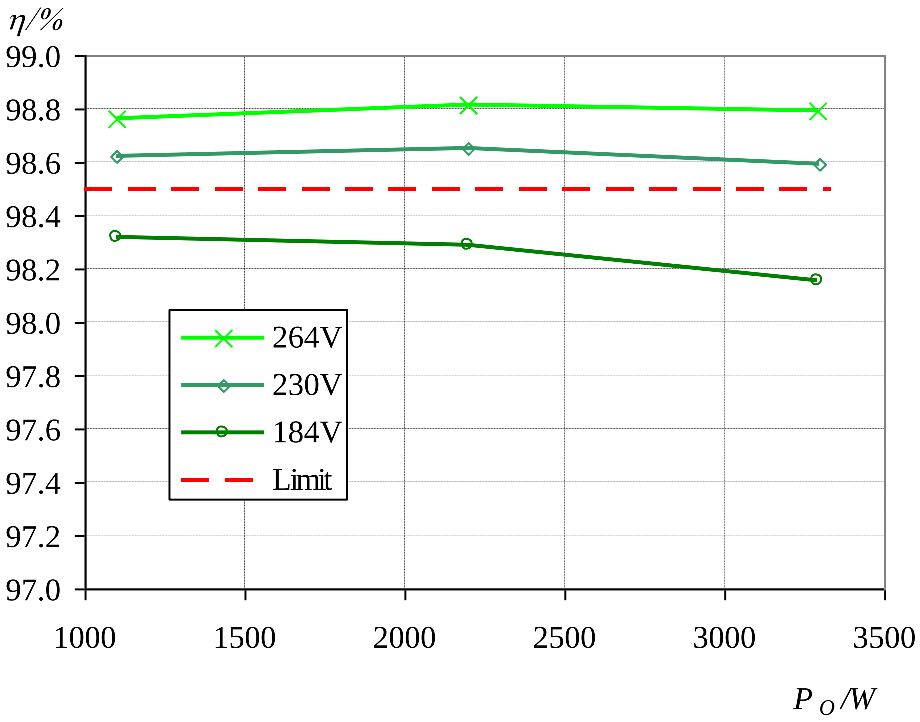
▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

★ 99.36% @ 1.2kW/dm³

- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only

▶ 1-Φ Telecom Boost-Type TCM PFC Rectifier

- **Input Voltage** 1-ph. 184...264V_{AC}
- **Output Voltage** 420V_{DC}
- **Rated Power** 3.3kW

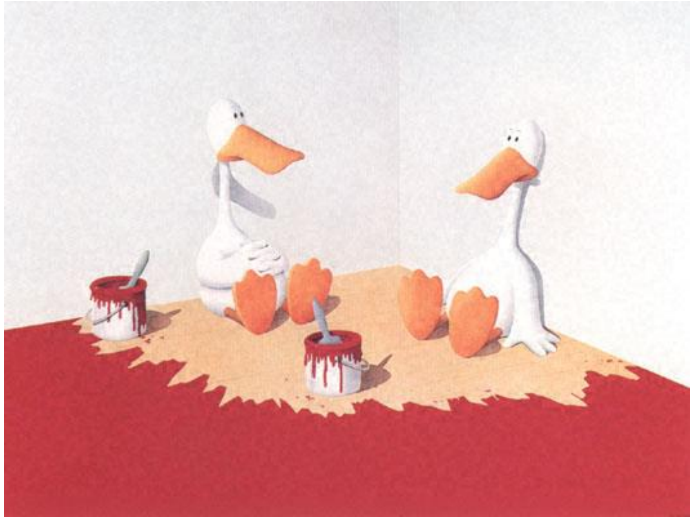


★ **98.6% @ 4.5kW/dm³**

▶ Observation

- **Very Limited Room for Further Performance Improvement !**

Efficiency



Power Density

Σ Topologies
Modulation Schemes
Control Schemes

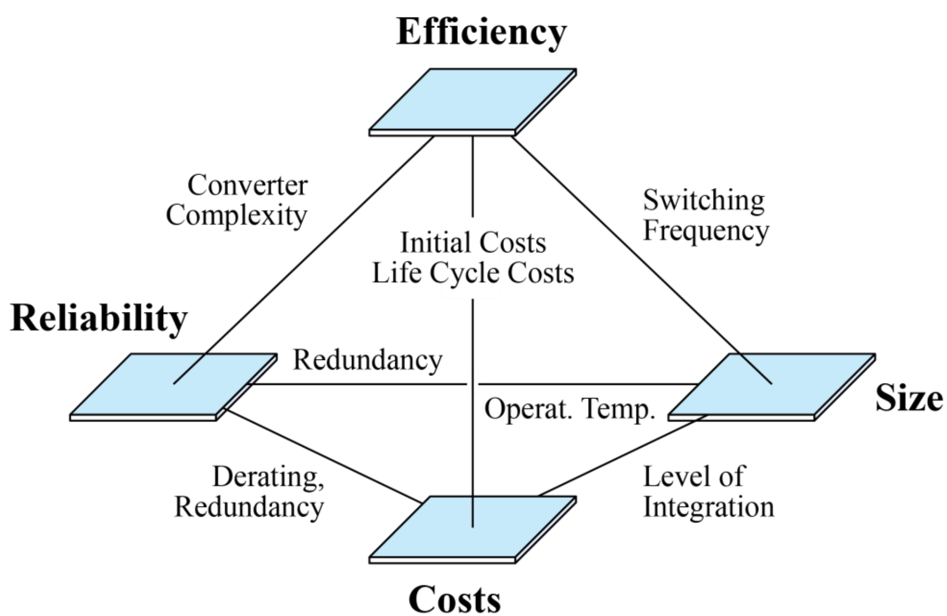
→ **Topologies**
- Basic Concepts Extremely Well Known - Mature
- Comprehensive Comparative Evaluations Missing (!)
- Promising Multi-Cell Concepts (!)

→ **Modulation / Control Schemes**
- Basic Concepts Extremely Well Known - Mature
- Modified Concepts for Basic Converter Structures (!)
- Digital Power – All Diff. Kinds of Functions (!)

**Advanced
Design**

▶ Design Challenge

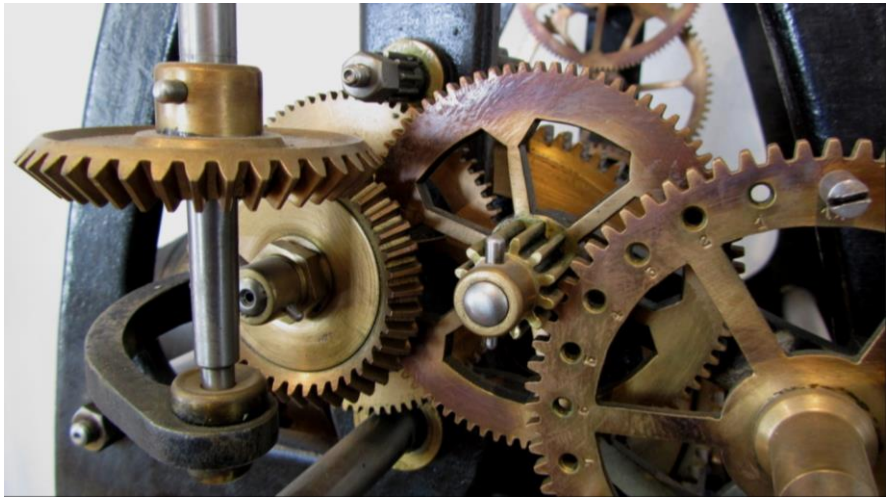
- **Mutual Couplings of Performance Indices → Trade-Offs**



— **For Optimized System Several Performance Indices Cannot be Improved Simultaneously**

▶ Design Challenge

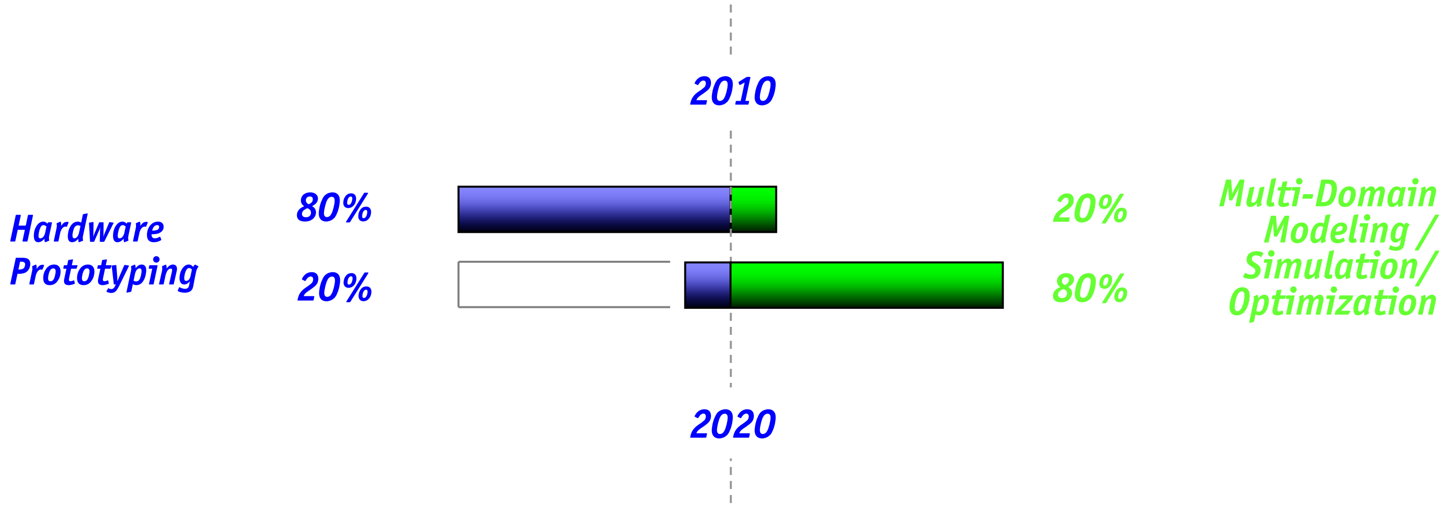
- Mutual Couplings of Performance Indices → Trade-Offs



— For Optimized System Several Performance Indices Cannot be Improved Simultaneously

▶ Future Design Process

■ Challenge: Virtual Prototyping



- Reduces Time-to-Market
- More Application Specific Solutions (PCB, Power Module, and even Chips)
- Only Way to Understand Mutual Dependencies of Performances / Sensitivities (!)
- Simulate What Cannot Any More be Measured (High Integration Level)

Σ Virtual Prototyping

→ **Remaining Challenges**

- Comprehensive Modeling (e.g. EMI, Reliability)
- Model Order Reduction

... will Take a "Few" More Years

"Power Electronics 1.0"

Maturing → Reduce Costs, Ensure Reliability (!)

"New Challenges"

▶ Consider Converters like "Integrated Circuits"

- If Only Incremental Improvements of Converters Can Be Expected → Shift to New Paradigm !

$$p(t) \rightarrow \int_0^t p(t)\,\mathrm{d}t$$

- "Converter" → "Systems" (Microgrid) or "Hybrid Systems" (Autom. / Aircraft)
- "Time" → "Integral over Time"
- "Power" → "Energy"

▶ Consider Converters like "Integrated Circuits"

- If Only Incremental Improvements of Converters Can Be Expected ... → Shift to New Paradigm !

$$p(t) \rightarrow \int_0^t p(t)\,\mathrm{d}t$$

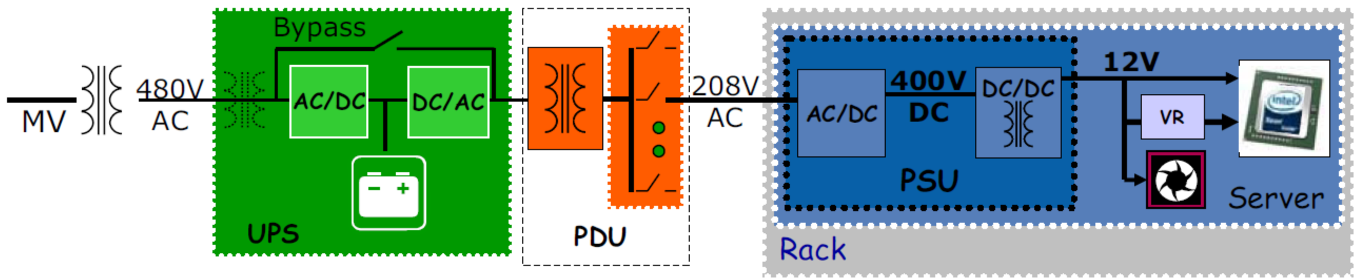
- Power Conversion → Energy Management / Distribution
- Converter Analysis → System Analysis (incl. Interactions Conv. / Conv. or Load or Mains)
- Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)
- Cap. Filtering → Energy Storage & Demand Side Management
- Costs / Efficiency → Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency
- etc.

AC vs. Facility-Level DC Systems for Datacenters

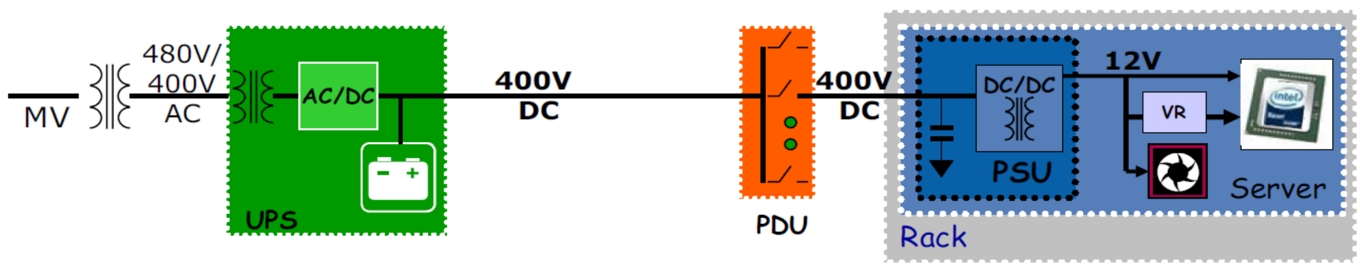
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US $480V_{AC}$ Distribution

Source: intel 2007



— Facility-Level 400 V_{DC} Distribution



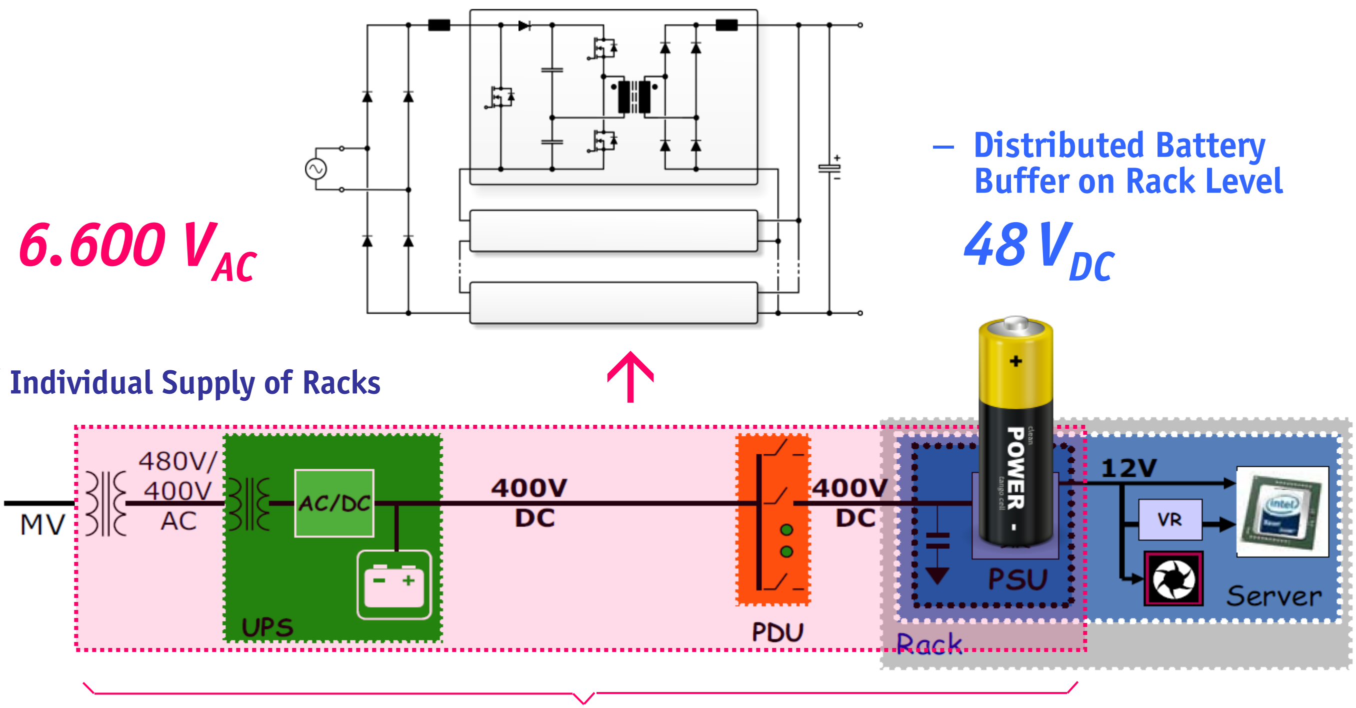
- Proposal for Public $+380V_{DC}$/$-380V_{DC}$ Systems by Philips, EMerge ALLIANCE, etc.

▶ SST-Based Rack-Level 48V DC Power Supply System

- **Reduces Costs** (Losses / Material Effort / Footprint)
- **High Reliability** (Maximum Modularity / Redundancy)

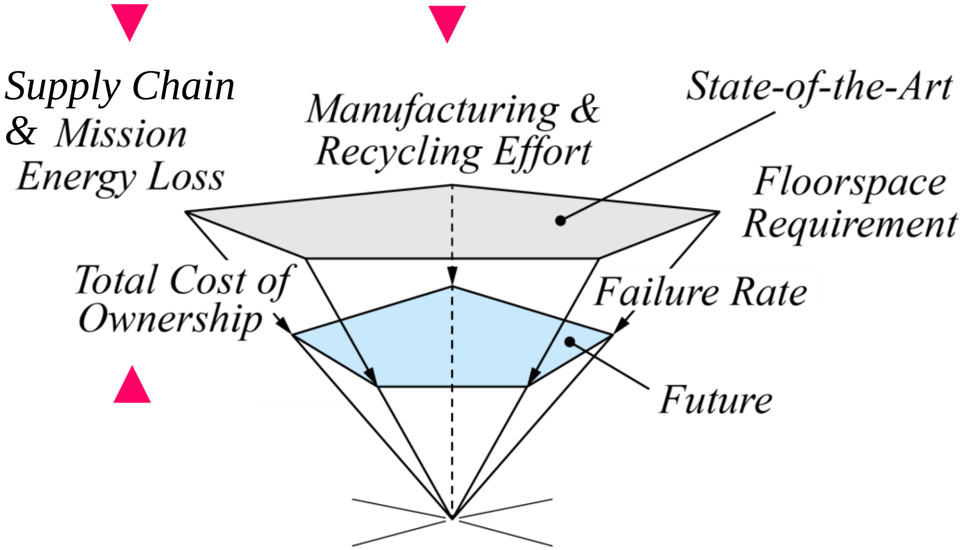
– Distributed Battery Buffer on Rack Level

– Direct / Individual Supply of Racks



- Future Concept: Direct **6.6kV AC → 48 V DC** Conversion / Unidirectional SST w. Integr. Storage

▶ Power Electronics Systems Performance Figures/Trends



■ Complete Set of New Performance Indices

- — Power Density [kW/m²]
- — Environm. Impact [kWs/kW]
- — TCO [$/kW]
- — Mission Efficiency [%]
- — Failure Rate [h^{-1}]

Σ System-Oriented Analysis

→ **Main Challenges**

- Get to Know the Details of Power Systems
- Theory of Stability of Converter Clusters
- Autonomous Control

Remarks on University Research

▶ University Research Orientation

■ **General Observations**

— Gap between Univ. Research and Industry Needs
— In Some Areas Industry Is Leading the Field

▶ University Research Orientation

- Gap between Univ. Research and Industry Needs

— Industry Priorities

1. Costs
2. Costs
3. Costs

- Multiple Objectives ...
- Low Complexity
- Modularity / Scalability
- Robustness
- Ease of Integration into System

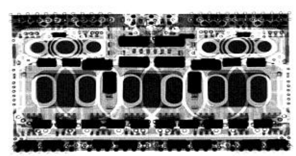
→

— **Basic Discrepancy !**

Most Important Industry Variable, but Unknown Quantity to Universities

▶ University Research Orientation

■ In Some Areas **Industry Is Leading the Field !**



— Industry Low-Power Power Electronics (below 1kW) Heavily Integrated –
PCB Based Demonstrators Do Not Provide Too Much Information (!)
Future: "Fab-Less" Research

— Same Situation above 100kW (Costs, Mech. Efforts, Safety Issues with Testing etc.)
— Talk AND Build Megawatt Converters (!)

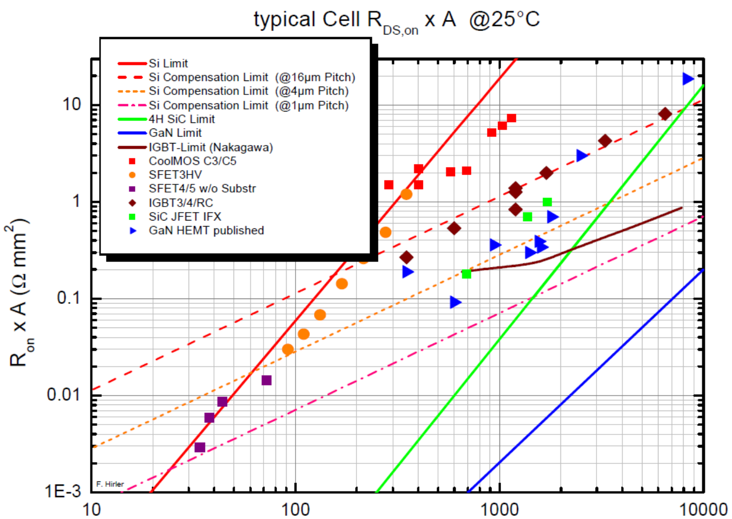
Finally, ...

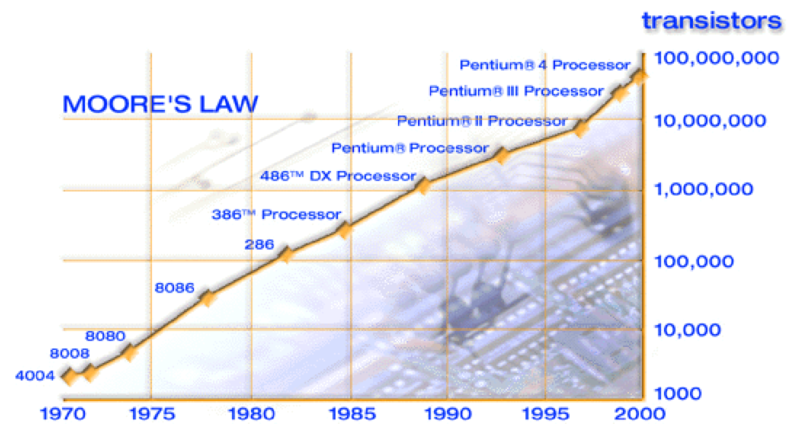
Power Electronics 2.0

▶ Enablers (1)

... besides CO_2 Reduction / Ren. Energy Integration etc.

- **WBG Semiconductor Technology → Higher Efficiency, Lower Complexity**
- **Microelectronics → More Computing Power**





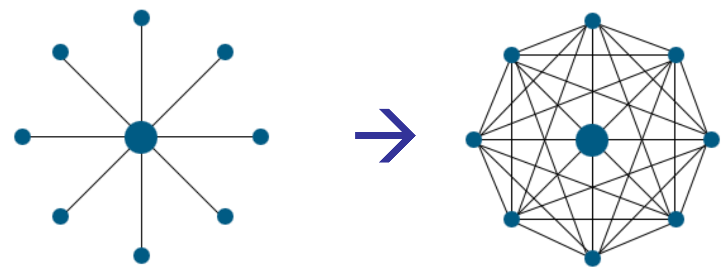
→ + Advanced Packaging (!)

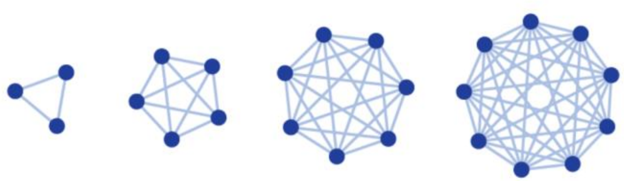
→ Moore's Law

▶ Enablers (2)

■ Metcalfe's Law

– Moving form Hub-Based Concept to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))





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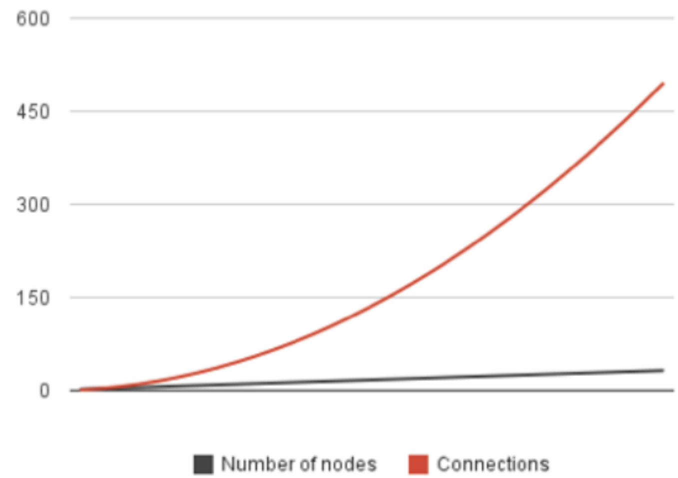


Power Electronics Technology S-Curve

...after Switches and Topologies

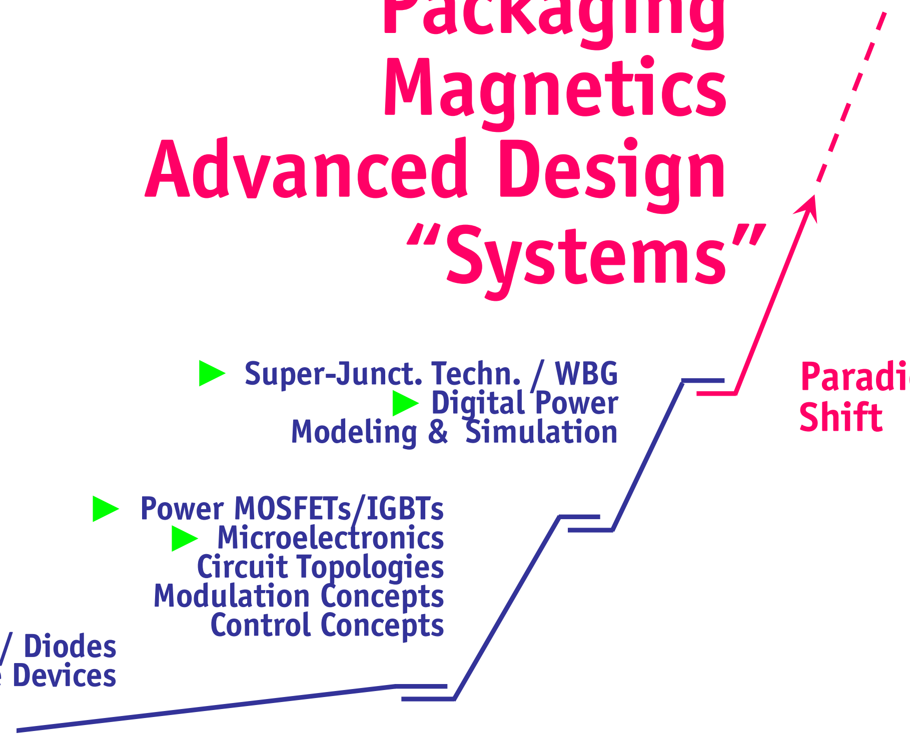
Packaging
Magnetics
Advanced Design
“Systems”

Super-Junct. Techn. / WBG
Digital Power
Modeling & Simulation

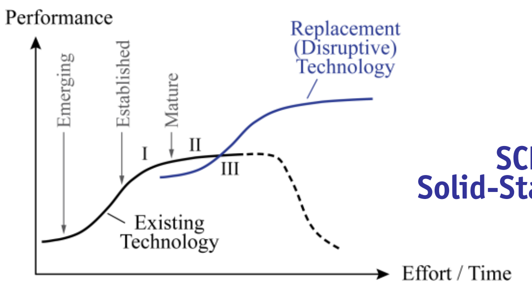
Paradigm Shift

Power MOSFETs/IGBTs
Microelectronics
Circuit Topologies
Modulation Concepts
Control Concepts

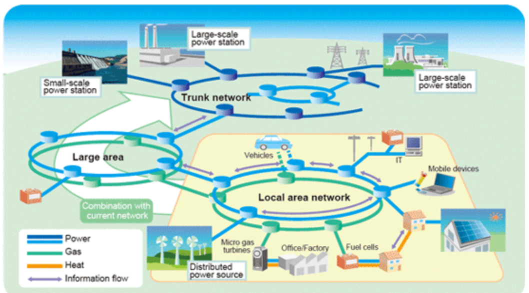
SCRs / Diodes
Solid-State Devices



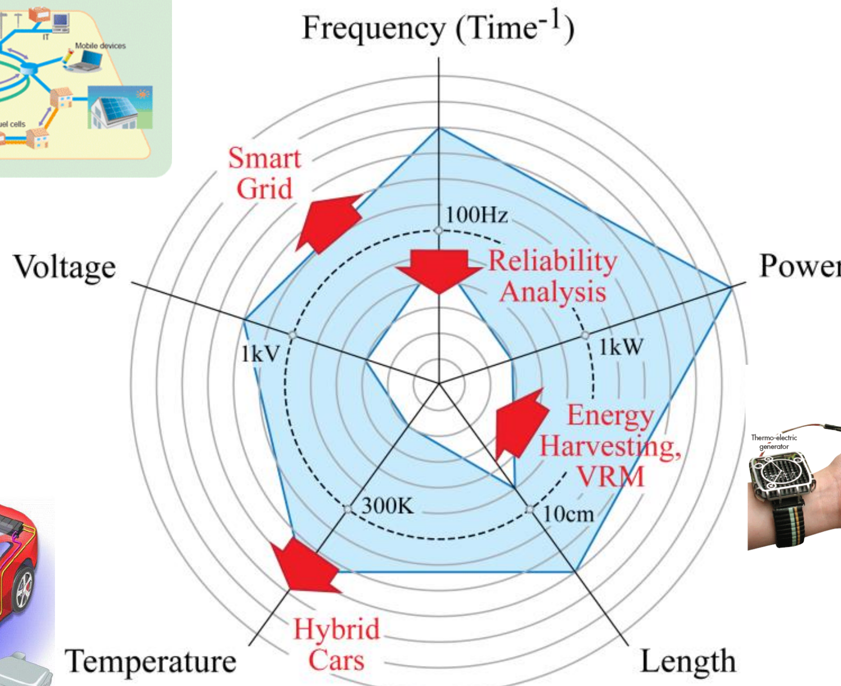
2010
2025

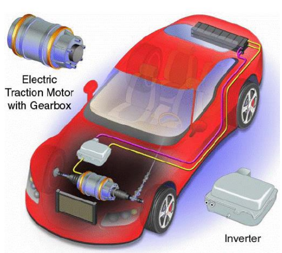


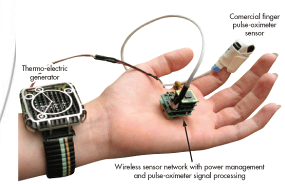
▶ Future Extensions of Power Electronics Applications



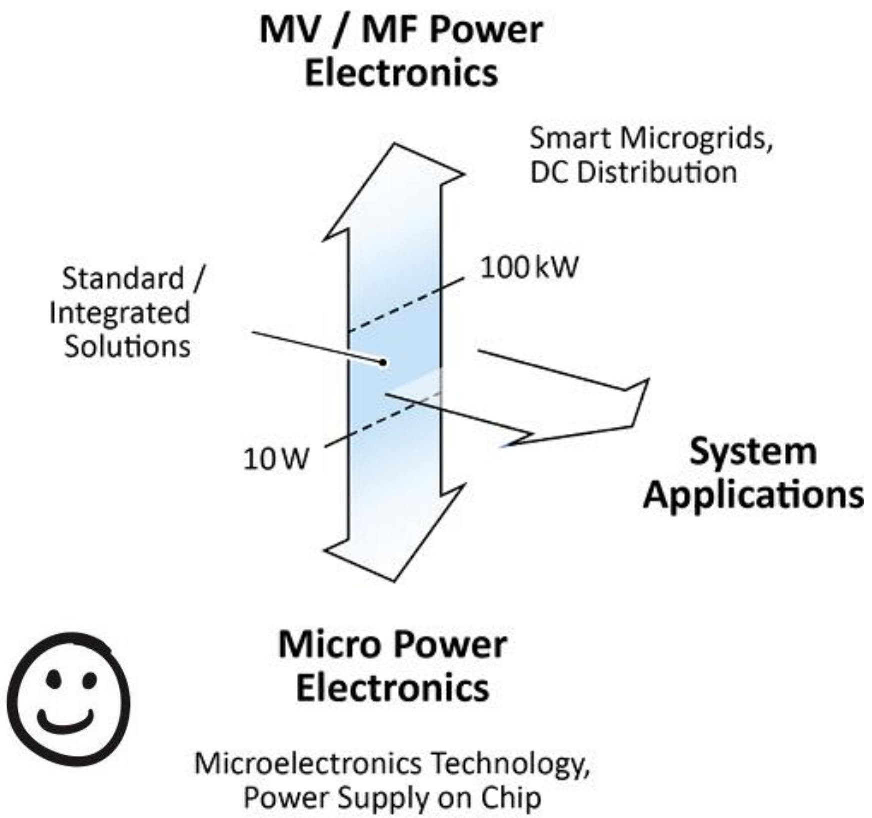
Source: AIST







▶ Future Extensions of Power Electronics Applications



Power Electronics 2.0

New Application Areas

- Smart XXX (Integration of Energy/Power & ICT)
- Micro-Power Electronics (VHF, Link to Microelectronics)
- MEGA-Power Electronics (MV, MF)

Paradigm Shift

- From "Converters" to "Systems"
- From "Inner Function" to "Interaction" Analysis
- From "Power" to "Energy" (incl. Economical Aspects)

Enablers / Topics

- New (WBG) Power Semiconductors (and Drivers)
- Adv. Digital Signal Processing (on all Levels – Switch to System)
- PEBBs / Cells & Automated (+ Application Specific) Manufaturing
- Multi-Cell Power Conversion
- Multi-Domain Modeling / Multi-Objective Optim. / CAD
- Cybersecurity Strategies

Thank You !

Questions ?