Future Challenges in Power Electronics

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Future Opportunities in Power Electronics

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Acknowledgement
Florian Krismer
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Power Electronics 2.0

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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
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Computer Systems
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Electronics Laboratory
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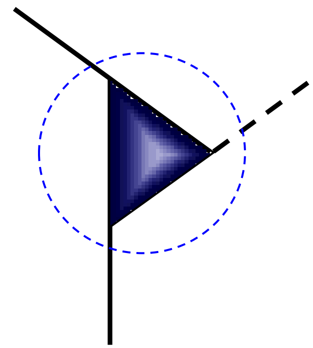
22 Ph.D. Students
3 Post Docs

Competence Centre

Leading Univ. in Europe

Research Scope



Cross-Departmental

Mechanical Eng., e.g. Turbomachinery, Robotics

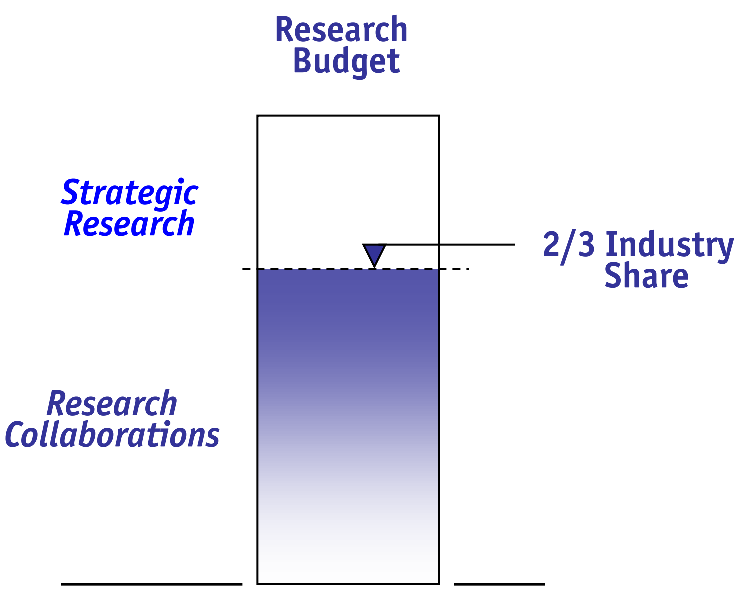
Microsystems
Medical Systems

Economics / Society

- *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*



Outline

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

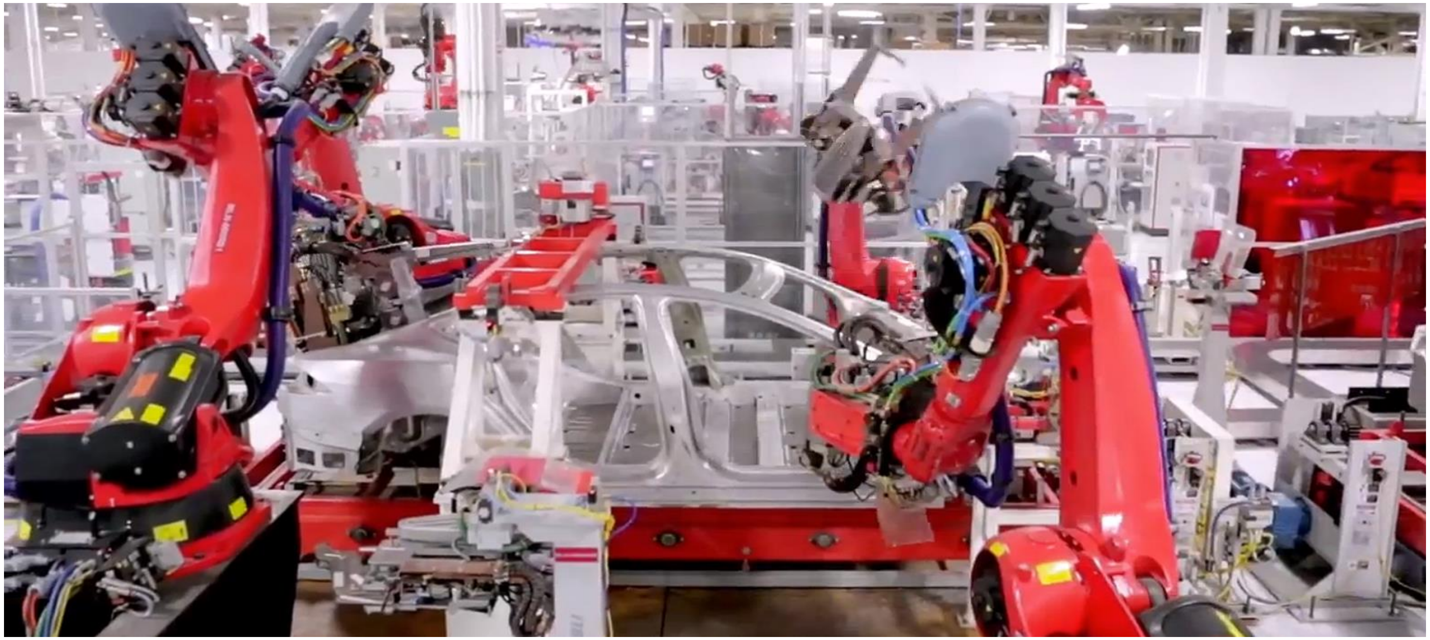
Application Areas
Performance Trends

▶ Application Areas

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

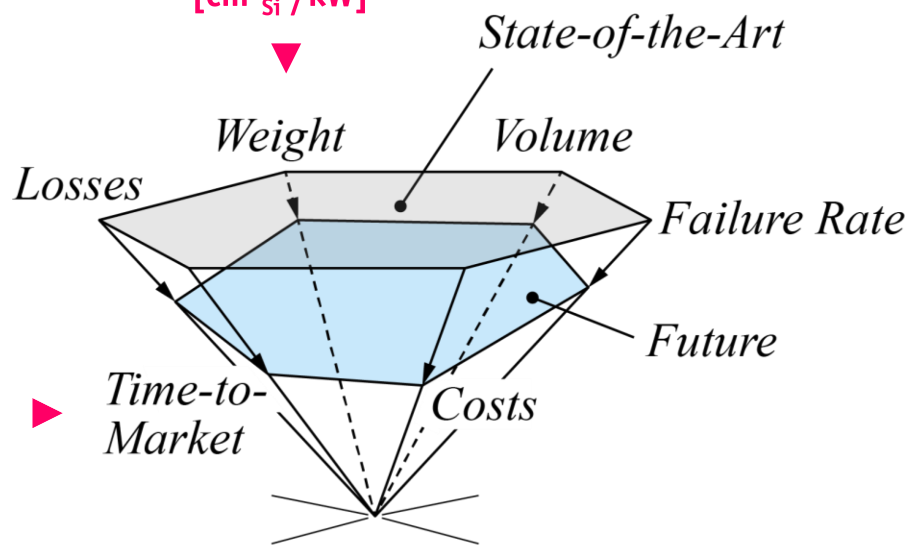
.... Everywhere !

Source: TESLA MOTORS



▶ Power Electronics Converters Performance Trends

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

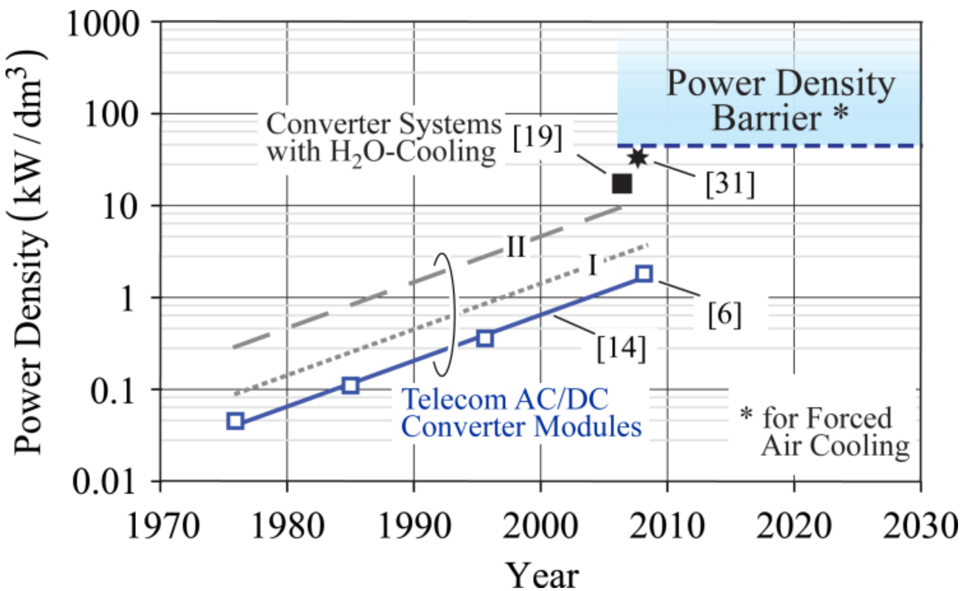


■ Performance Indices

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

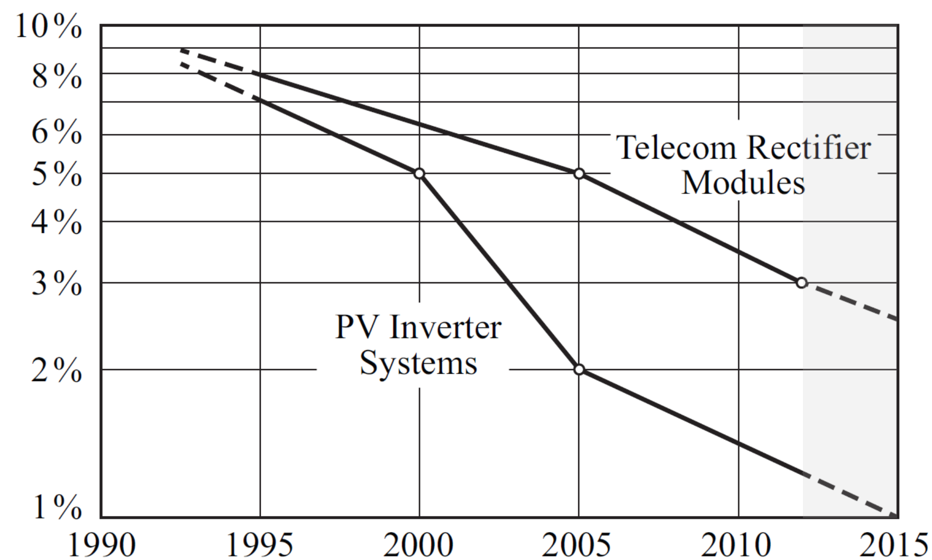
Performance Improvements (1)

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



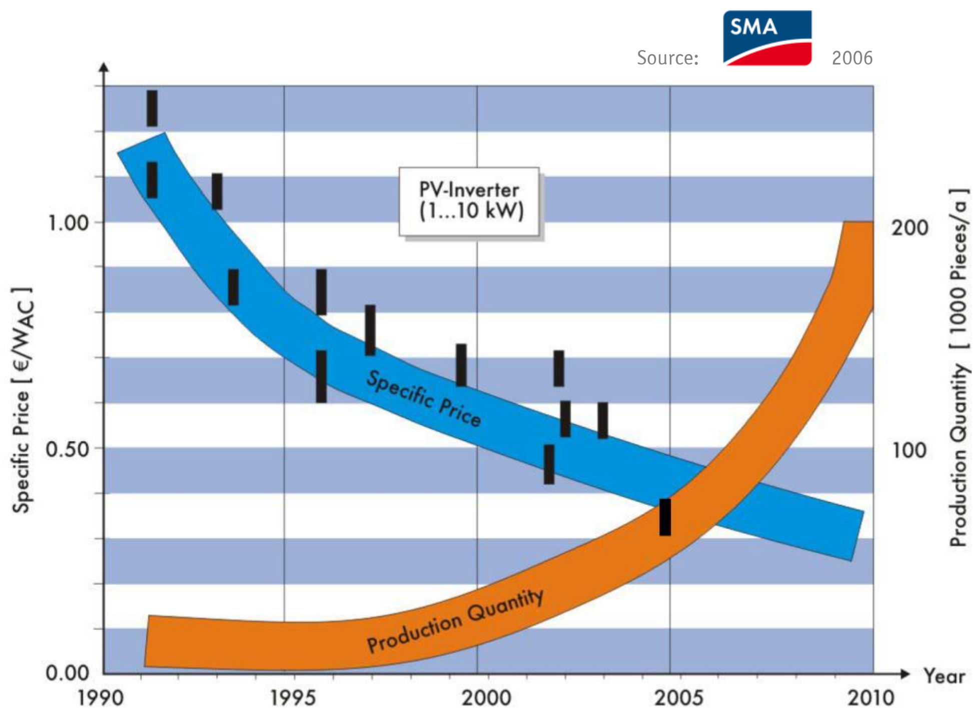
▶ Performance Improvements (2)

Inefficiency (Losses)… $1\text{-}\eta$



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

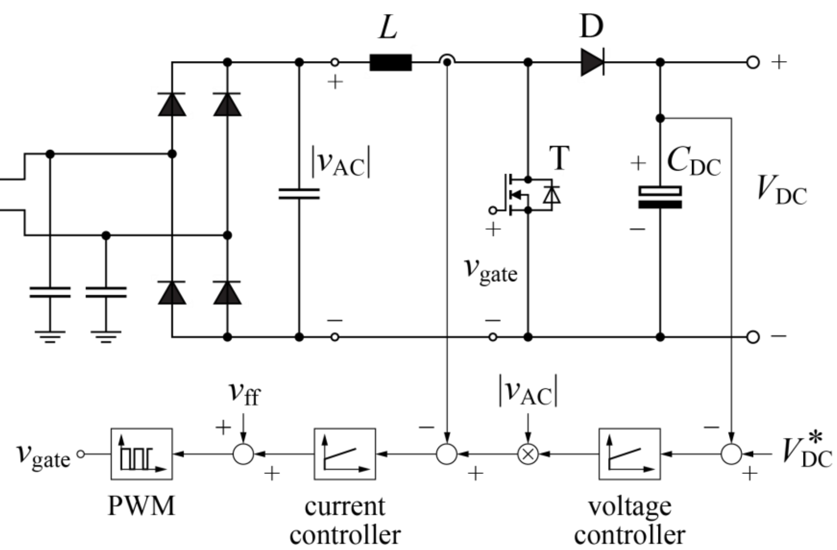
▶ Performance Improvements (3)



- **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

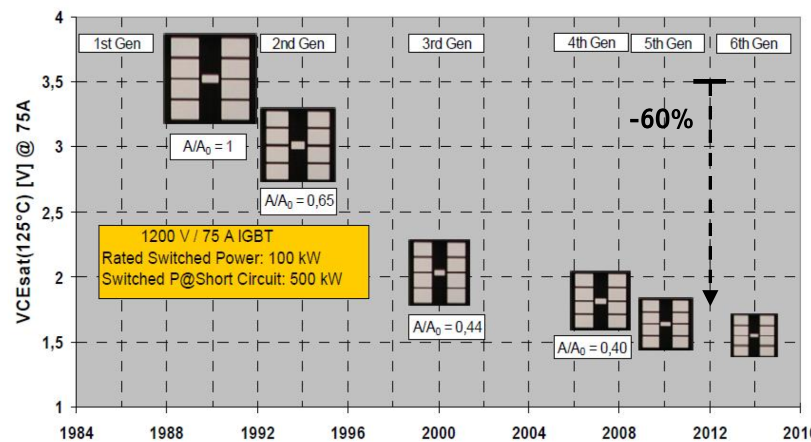
Potentials & Limits

Power Semiconductors

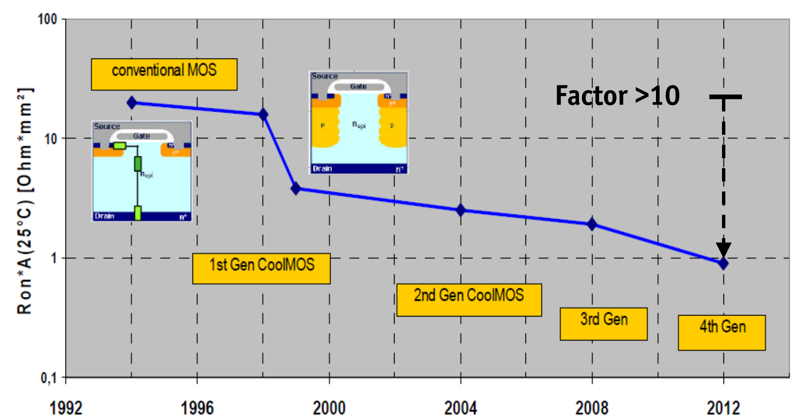
→ Si / SiC / GaN

▶ Si Power Semiconductors

Source: Dr. Miller / Infineon / CIPS 2010



600V Devices

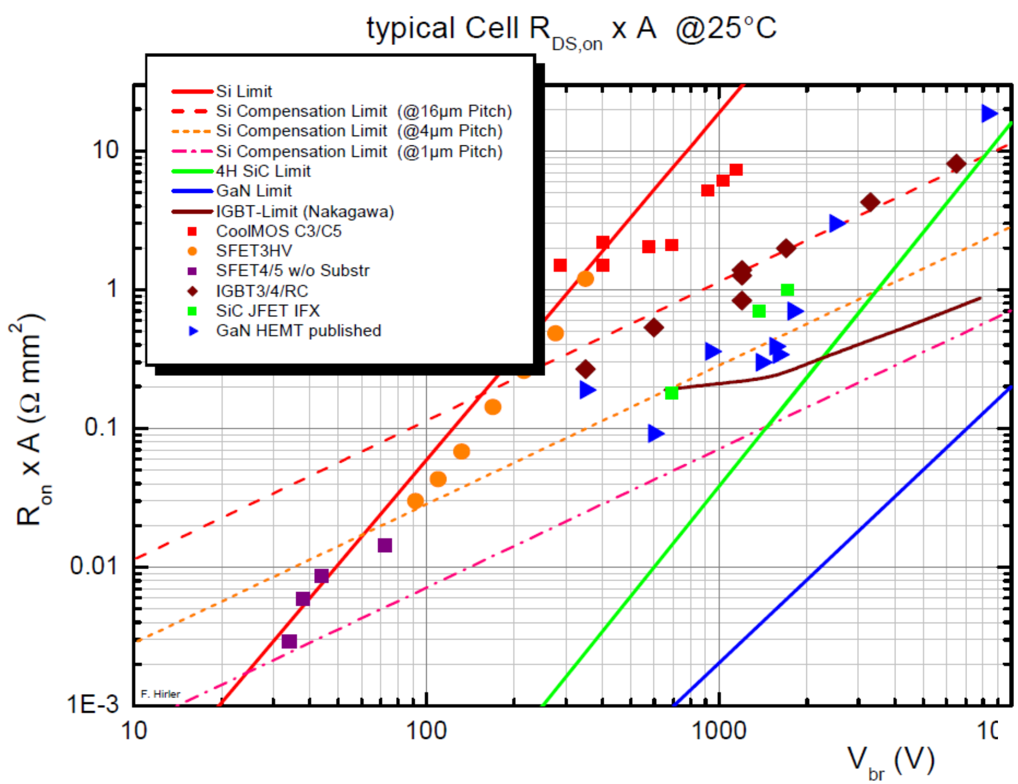


- **Past Disruptive Changes**

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

WBG Power Semiconductors

Source: Dr. Miller Infineon CIPS 2010

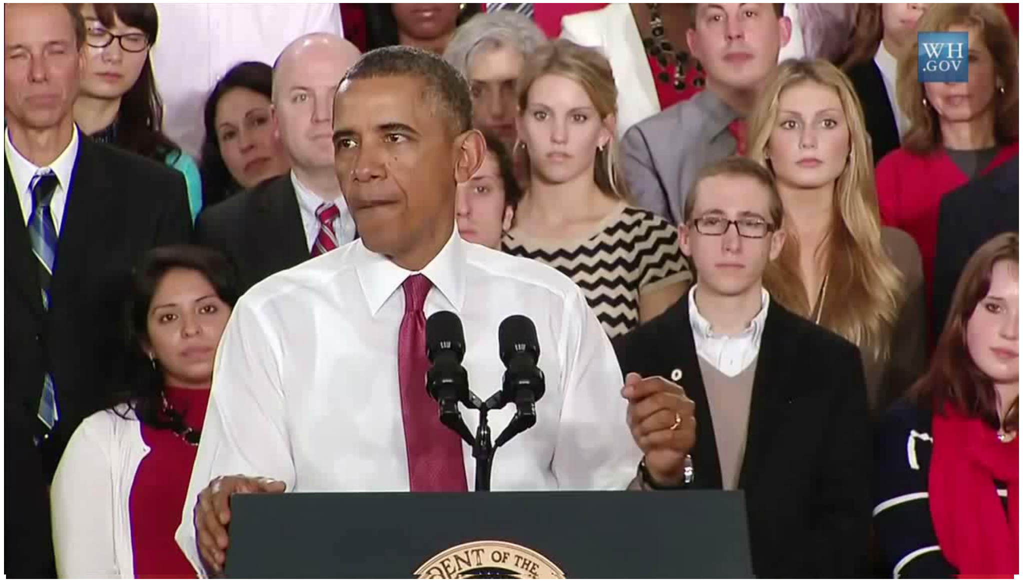


- **Disruptive Change**

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

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

WBG Power Semiconductors



- **Disruptive Change**

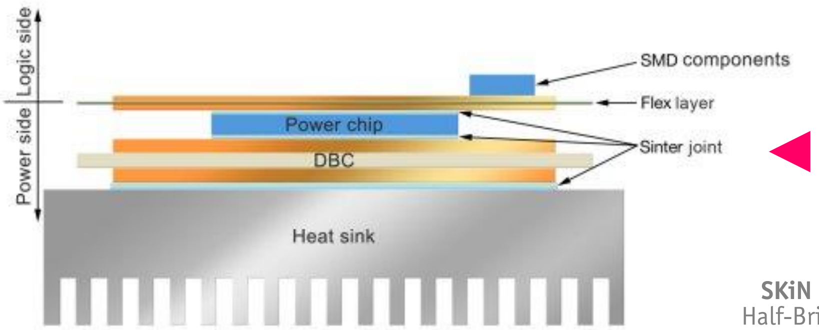
— Extremely Low $R_{DS(on)}$
— Very High $T_{j,max}$
— Extreme Sw. Speed

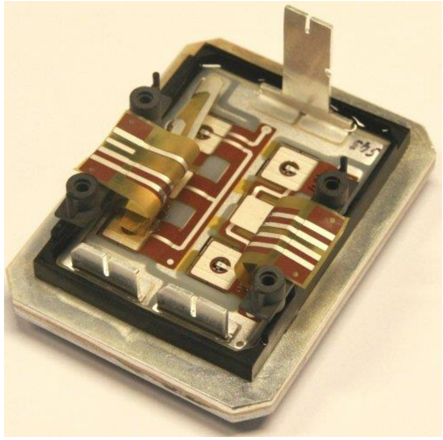
- **Utilization of Excellent Properties → Main Challenges in Packaging (!)**

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



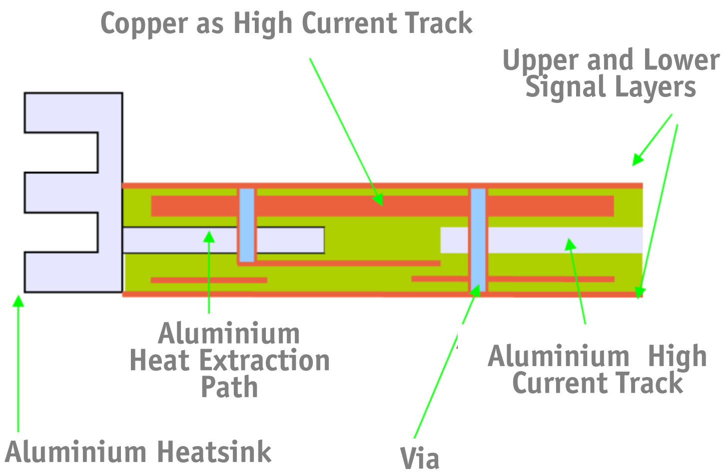


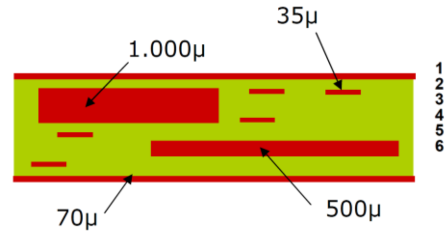
SKiN 600V/400 A
Half-Bridge Module

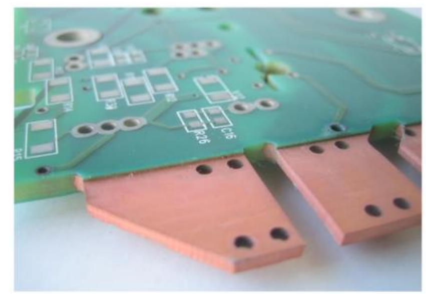
- Allows Extension to 2-Side Cooling (Two-Layer Flex-Foil)
- Allows Integration of Passive & Active Comp. (Gate Drive, Curr. & Temp. Measurem.)
- Disruptive Improvement (!)

▶ Multi-Functional PCB

- Multiple Signal and High Current Layers
- Integrated Thermal Management







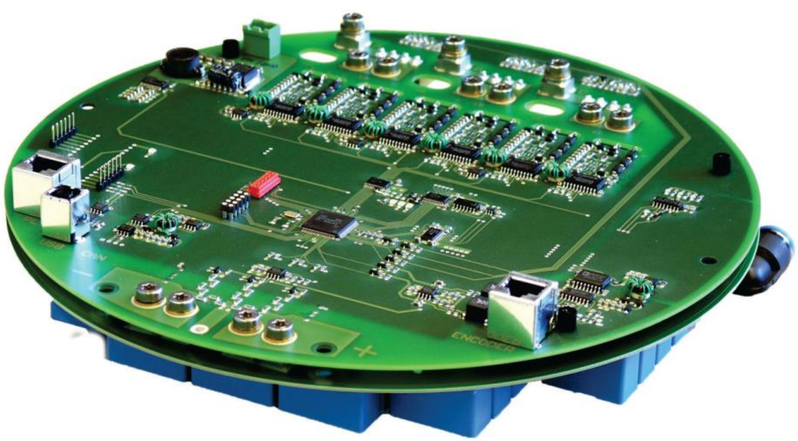
- Substantial Change of Manufact. Process → "Fab-Less" Power Electronics
- Advanced Simul. Tools of Main Importance (Coupling with Measurem.)
- Testing is Challenging (Only Voltage Measurement)
- Once Fully Utilized – Disruptive Change (!)

▶ 3ph. Inverter in p²pack-Technology

- Rated Power 32kVA

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

Source: SCHWEIZER ELECTRONIC enertronics



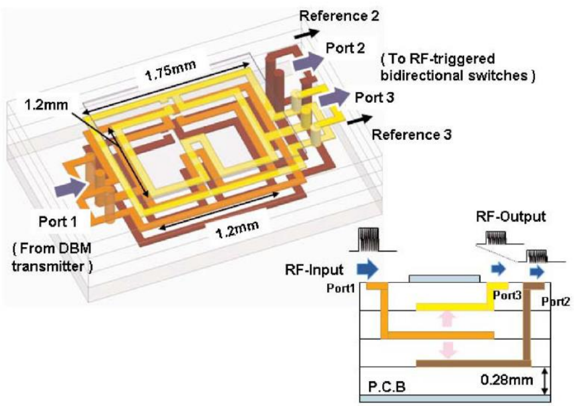
▶ Latest Systems Using WBG Devices → GaN

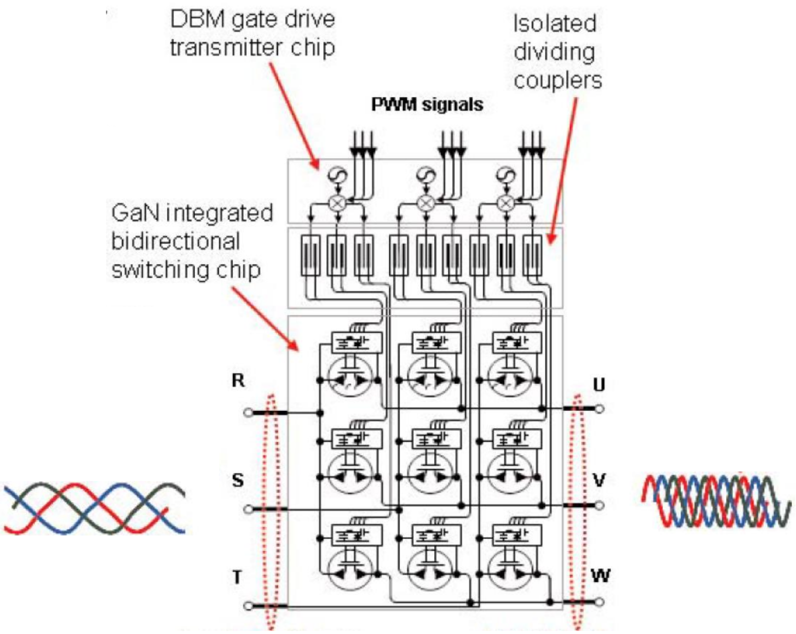
Source: Panasonic ISSCC 2014

■ 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

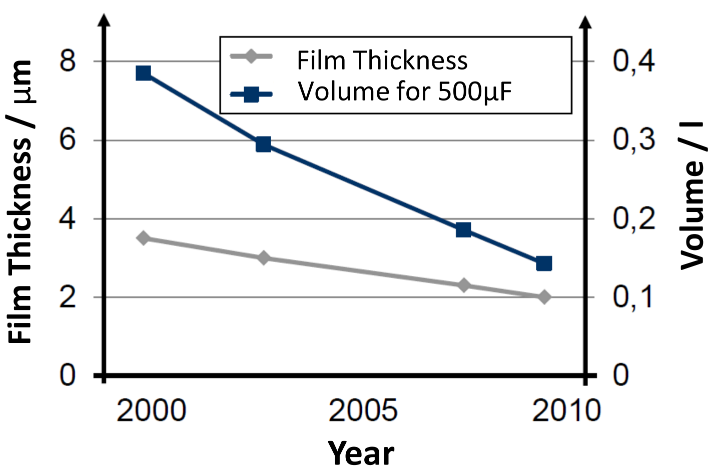
- Relatively (Slow) Technology Progress
- Recently Significant Improvement (Packaging) – e.g. CeraLink

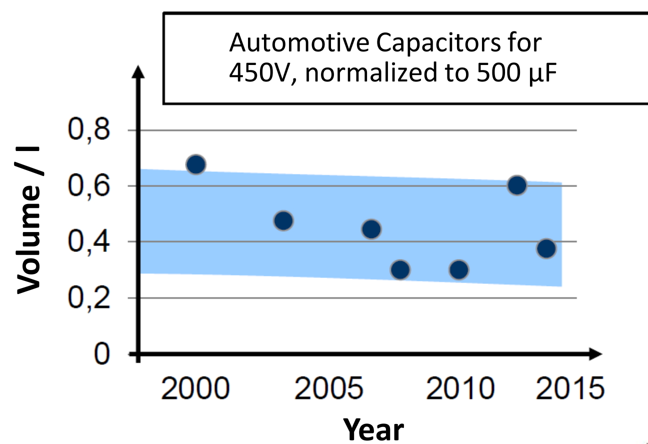
Source: EPCOS

— Foil Capacitors

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

	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

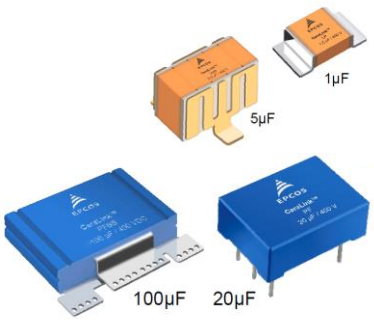




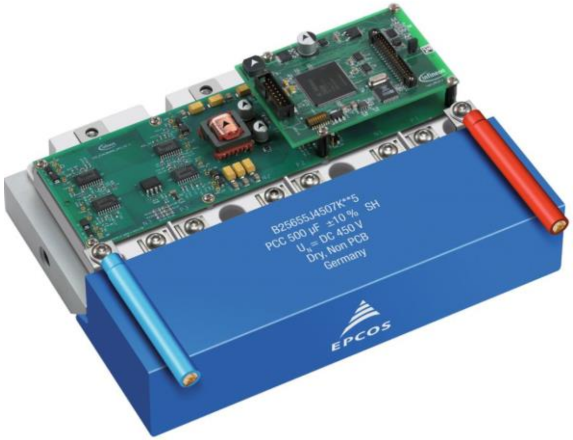
Source:
Dr. Plikat et al.
Volkswagen AG
PCIM 2013

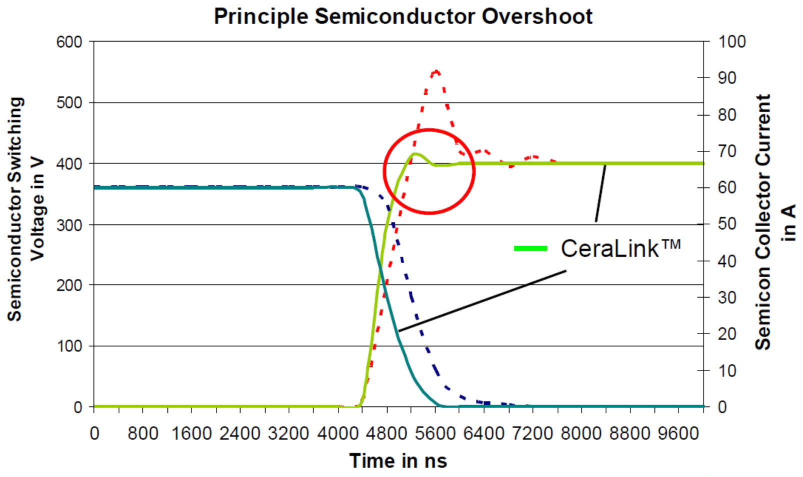
▶ Power Chip Capacitors

- 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

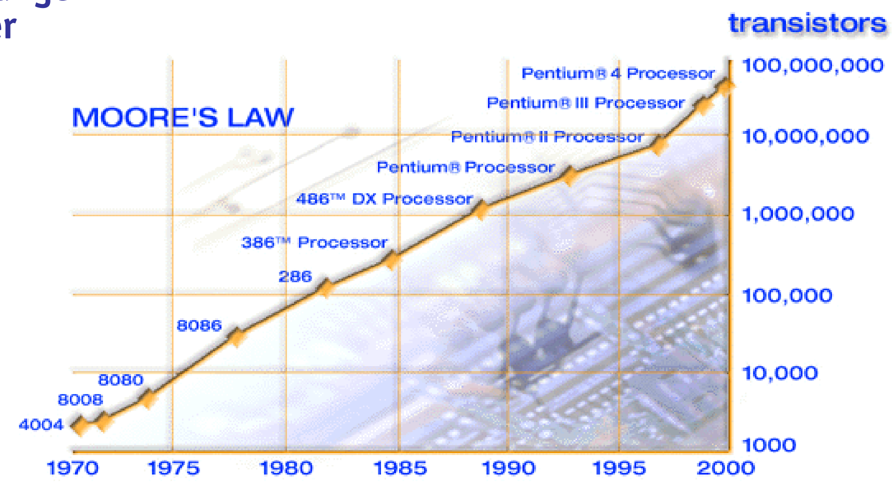
→ **There is No "Moore's Law" in Power Electronics !**

■ **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 of

→ 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 of**

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

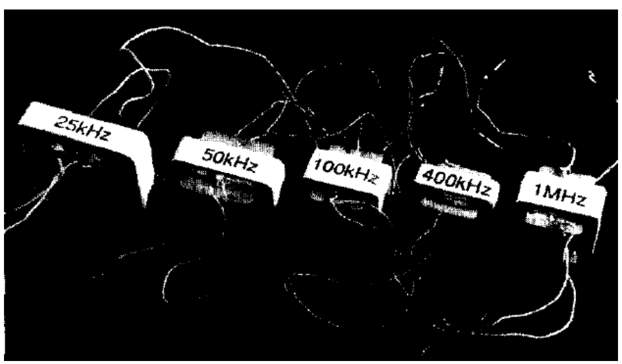
Operation Frequency Limit

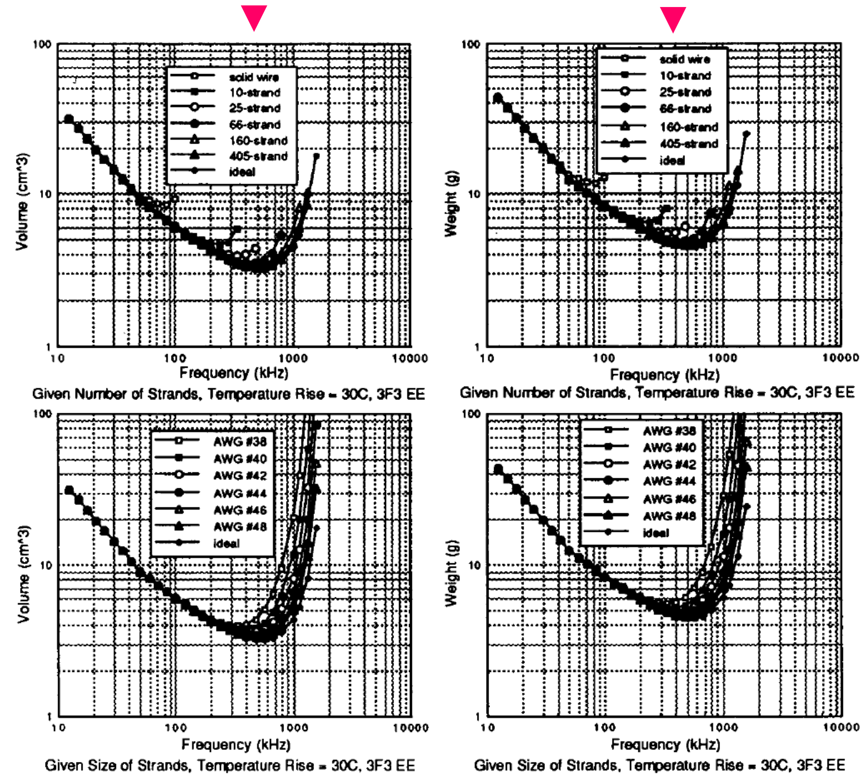
- **Relationship of Volume and Weight vs. Frequency**

— **Higher Frequency Results in Smaller Transformer Size only Up to Certain Limit**
— **Opt. Frequencies for Min. Weight and Min. Volume (!)**

Source: Philips

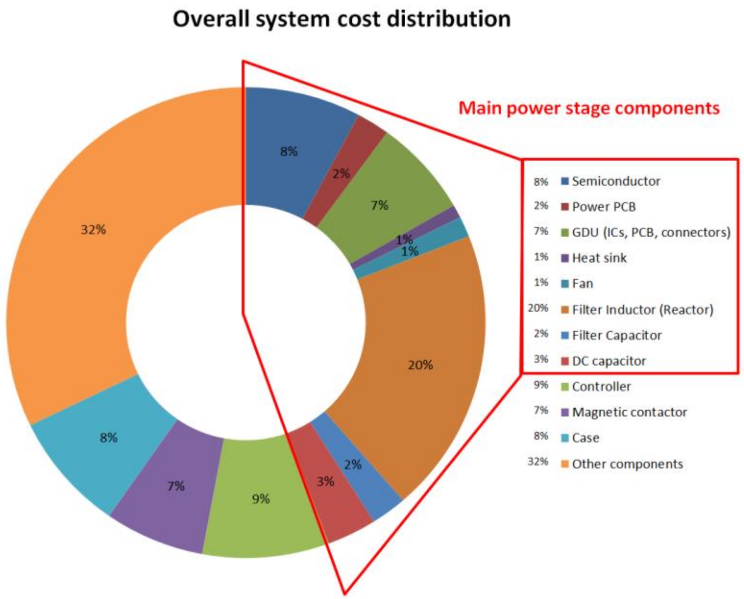
- 100Vx1A 1.1 Transformers, 3F3, 30°C Temp. Rise





▶ 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 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

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.

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 !

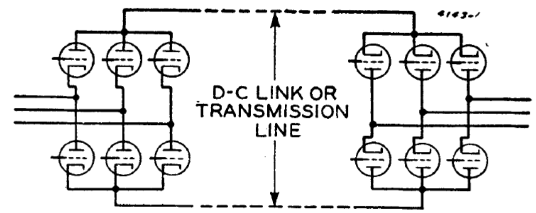


Figure 1. Electronic converter, dual-conversion type

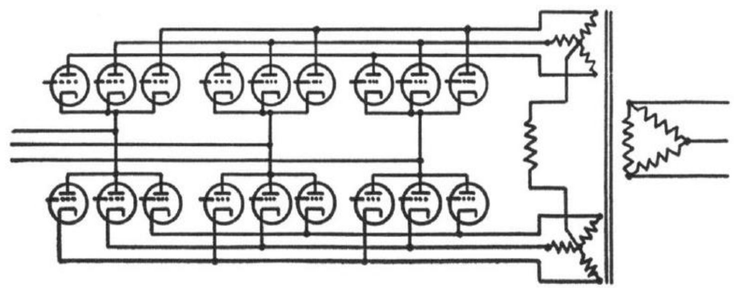
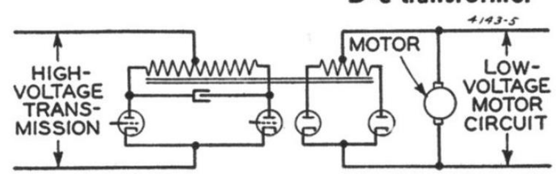


Figure 4 (left). Single-conversion-type frequency changer

Figure 5 (below). D-c transformer



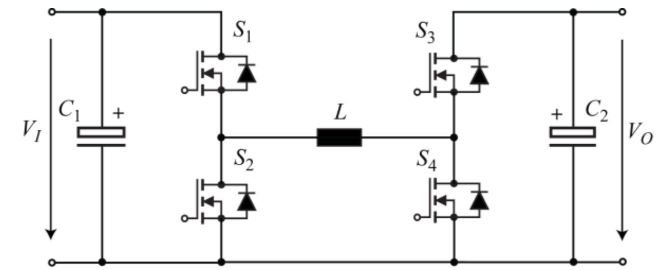
ETH zürich

Queen's University

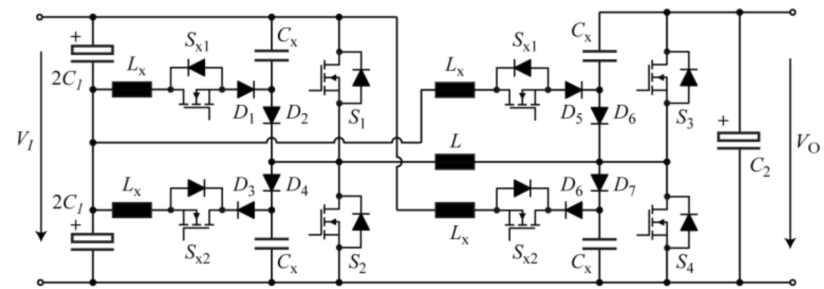
► Auxiliary Circuits

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

98% Efficiency
29kW/dm³



a)



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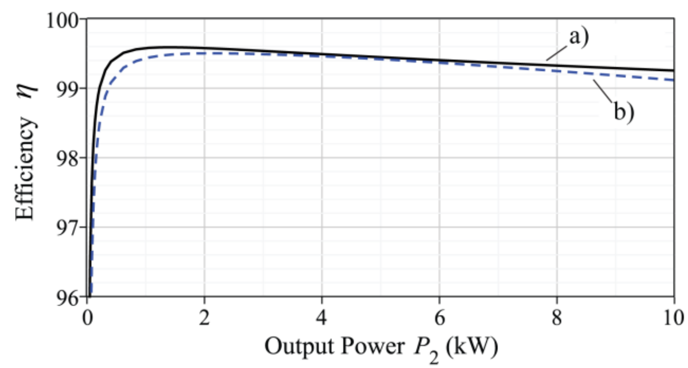
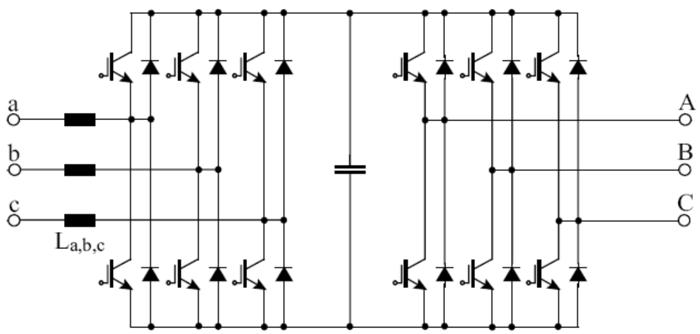
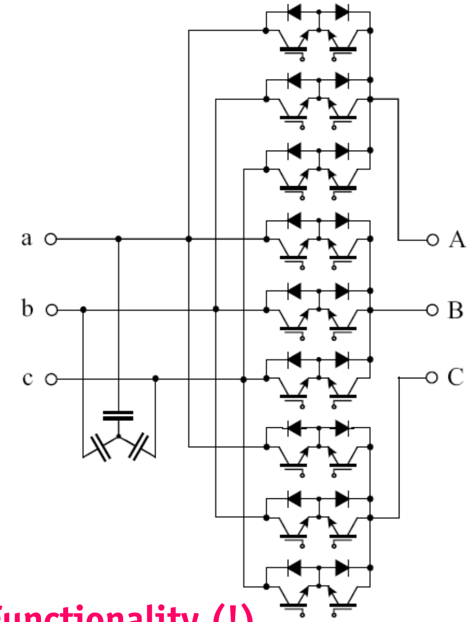


- Instead of Adding Aux. Circuits
  Change Operation of BASIC (!) Structures - "Natural" Performance Limit

▶ Integration of Functions

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

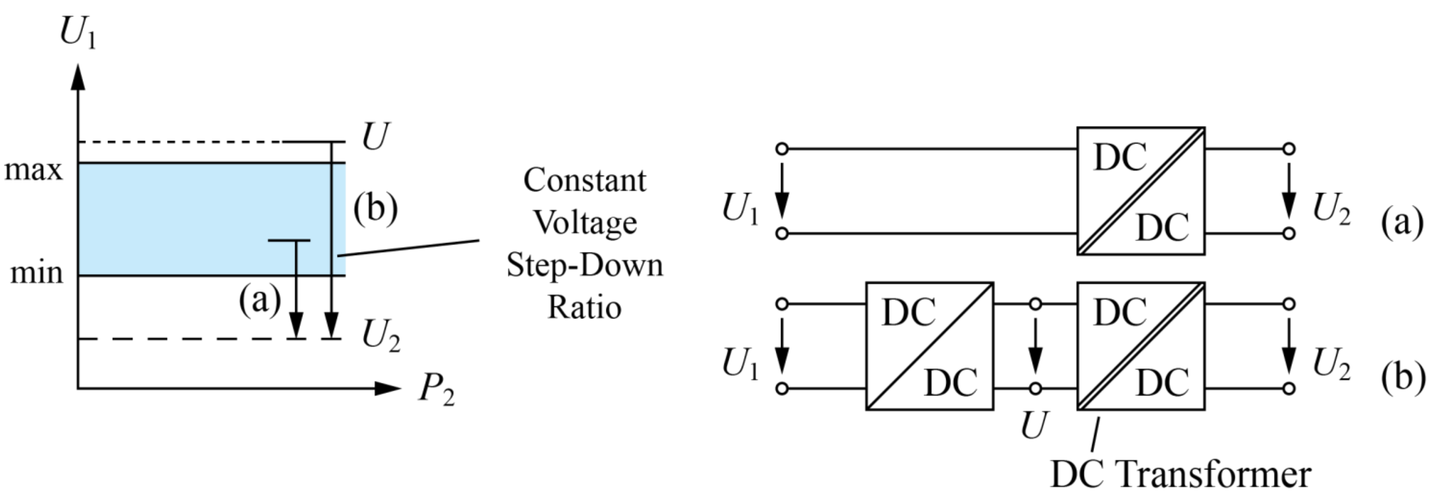




- Integration typ. Restricts Controllability / Overall Functionality (!)
- Typ. Lower Performance / Higher Control Compl. of Integr. Solution
- Basic Physical Properties remain Unchanged (e.g. Filtering Effort)

▶ 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**

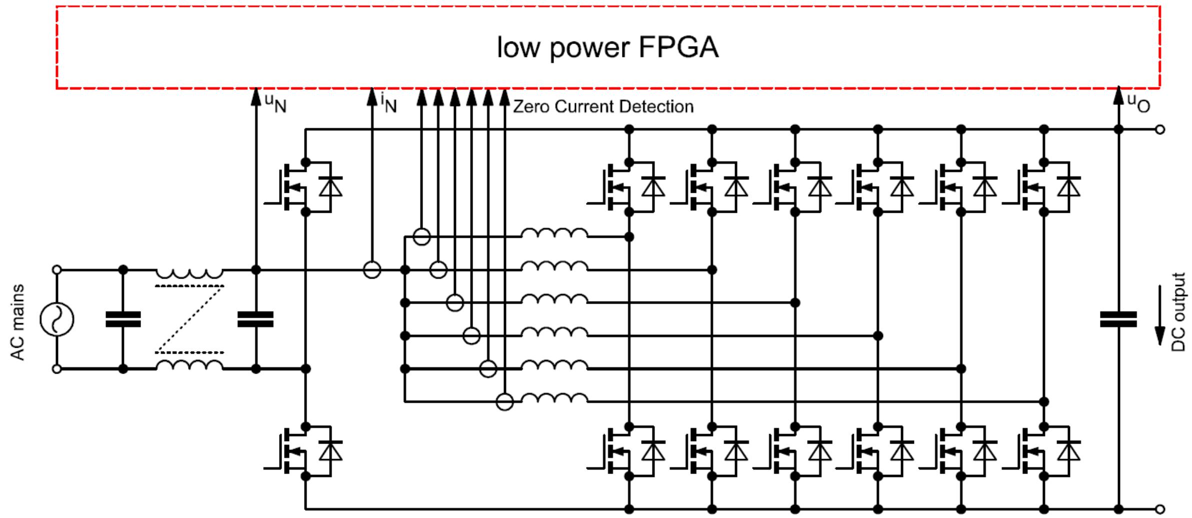
- Multi-Cell Converters
- 3-ph. AC/DC Buck Converter
- etc.

Multi-Cell Converters

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

▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

★ 99.36% @ 1.2kW/dm³

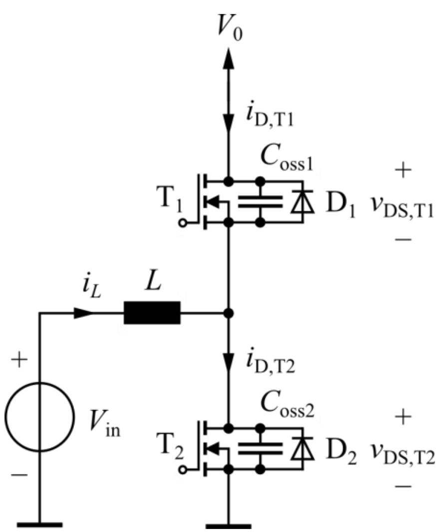


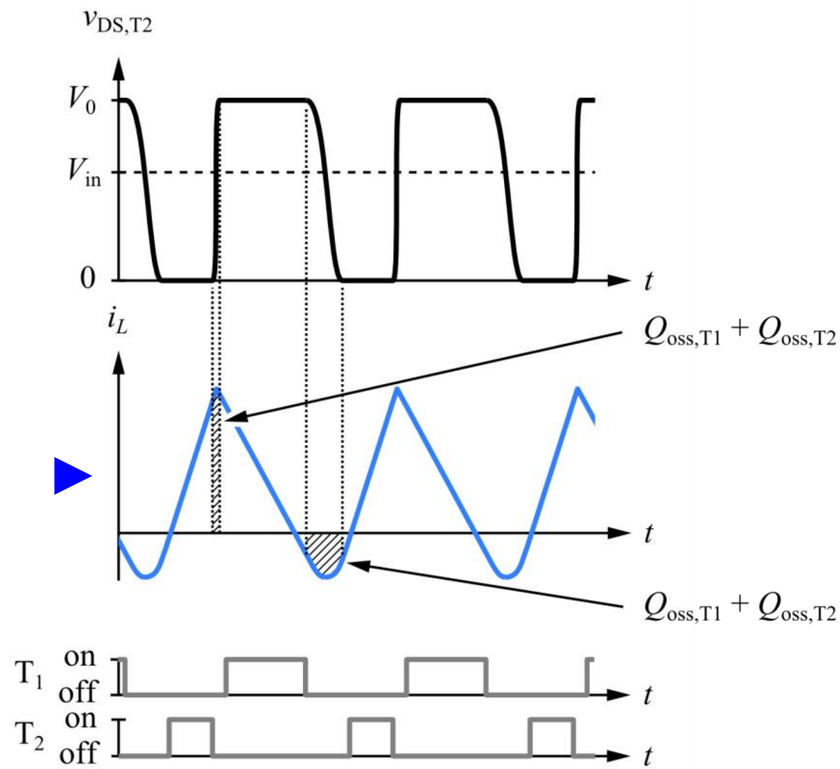
- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only

▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

- Zero Voltage Switching – Triangular Current Mode

- Synchronous Rectification
- Negative Current Ensures ZVS





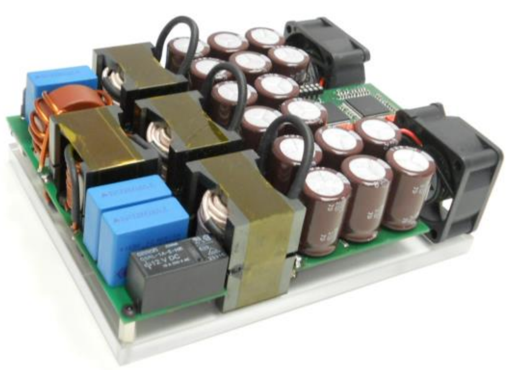
▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

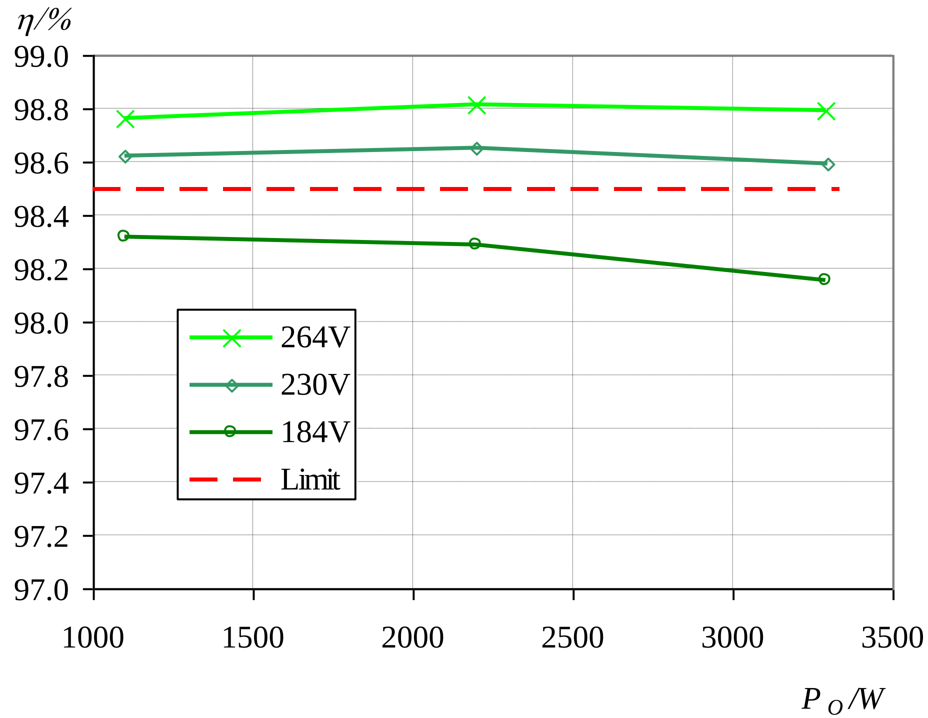
★ 99.36% @ 1.2kW/dm³

- 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



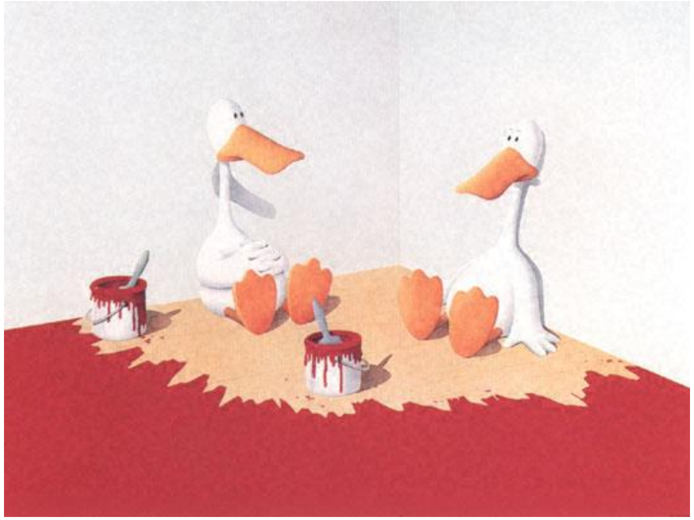


★ 98.6% @ 4.5kW/dm³

► 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 (!)

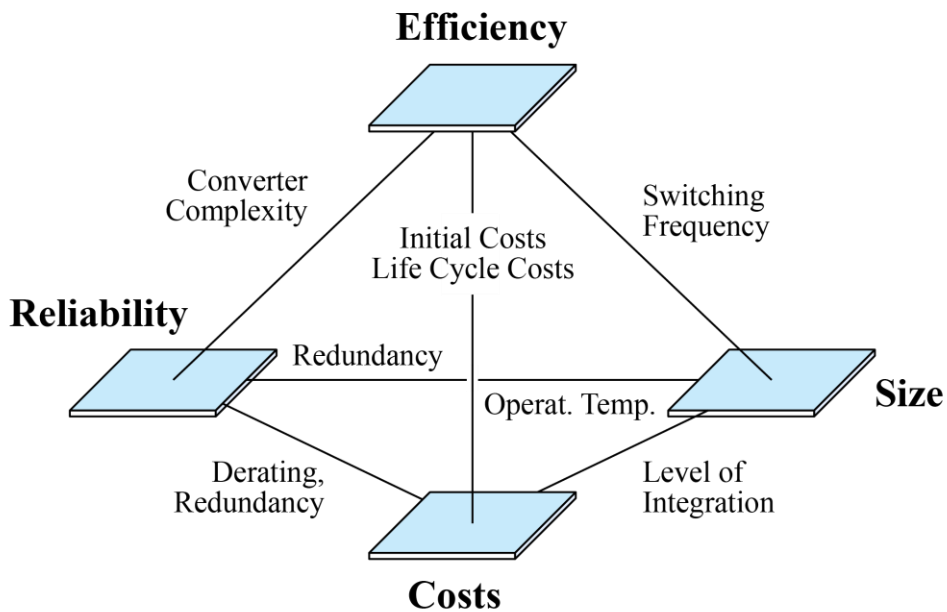
→ **Modulations / Control Schemes**

- Basic Concepts Extremely Well Known - Mature
- Modified Concepts for Basic Converter Structures (!)
- Digital Power – All Diff. Kinds of Functions

Advanced Design

▶ Design Challenge

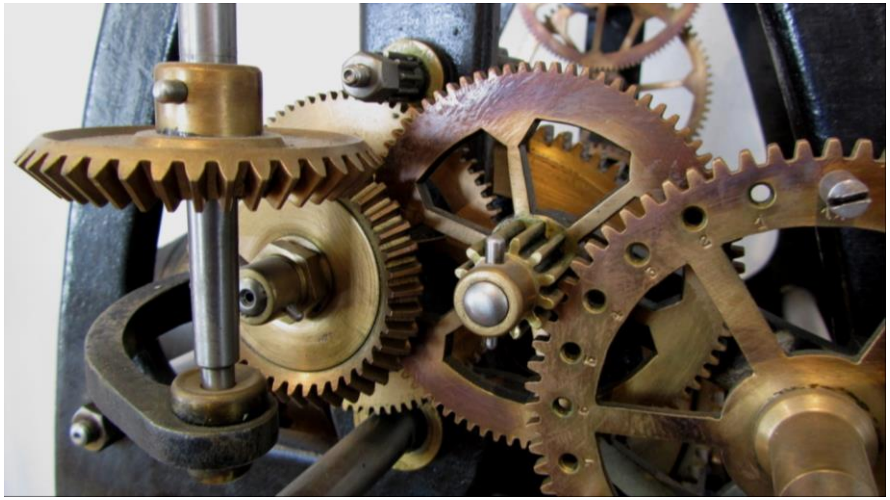
- Mutual Couplings of Performance Indices → Trade-Offs



— For Optimized System Several Performance Indices Cannot be Improved Simultaneously

▶ Design Challenge

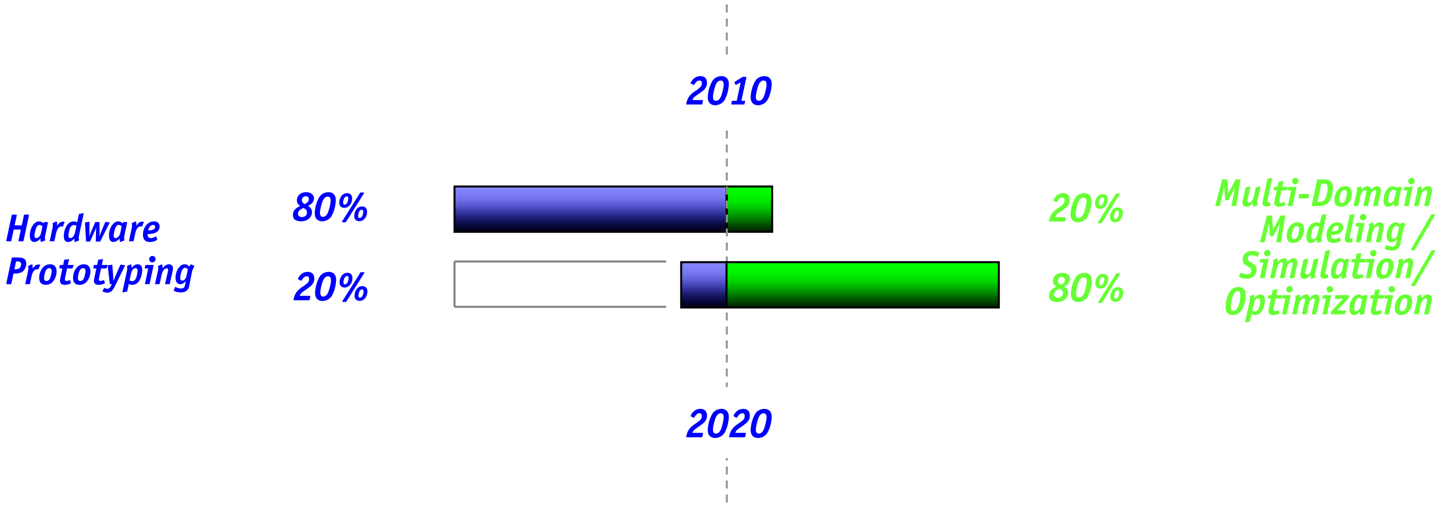
■ **Mutual Couplings of Performance Indices → Trade-Offs**



— **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 "ICs"

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

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

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

► Consider Converters like "ICs"

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

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

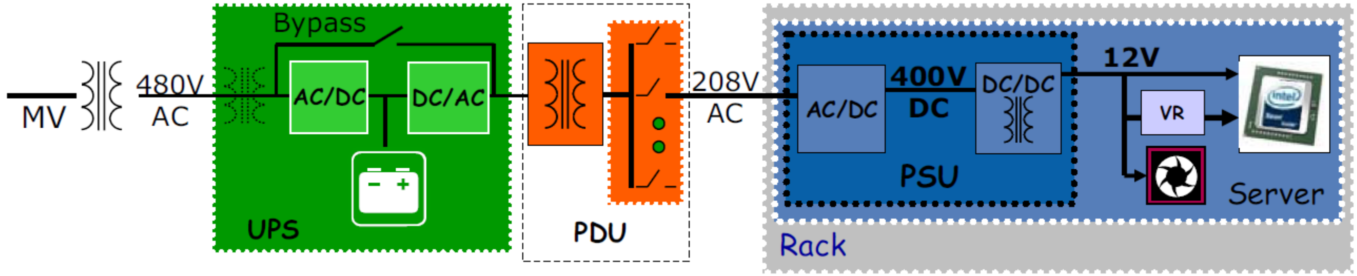
- Power Conversion → Energy Management / Distribution
- Converter Analysis → System Analysis (incl. Interactions Conv. / Conv. or Load or Mains)
- Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)
- Cap. Filtering → Energy Storage & Demand Side Management
- Costs / Efficiency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

▶ AC vs. Facility-Level DC Systems for Datacenters

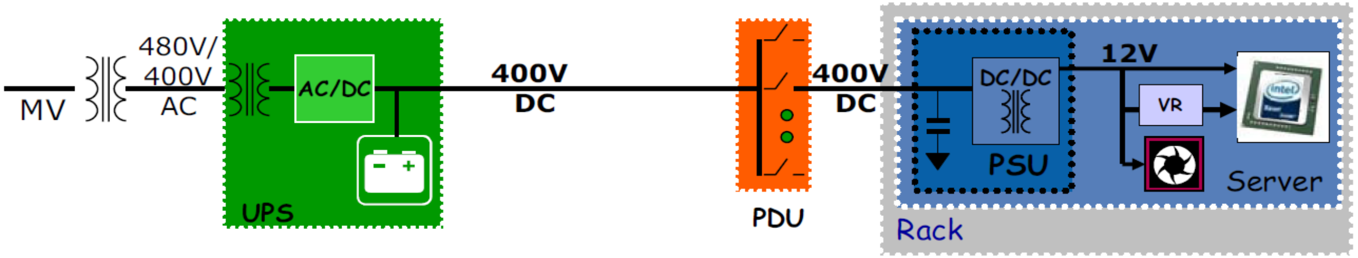
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US 480V_{AC} Distribution

Source: intel 2007



— Facility-Level 400 V_{DC} Distribution

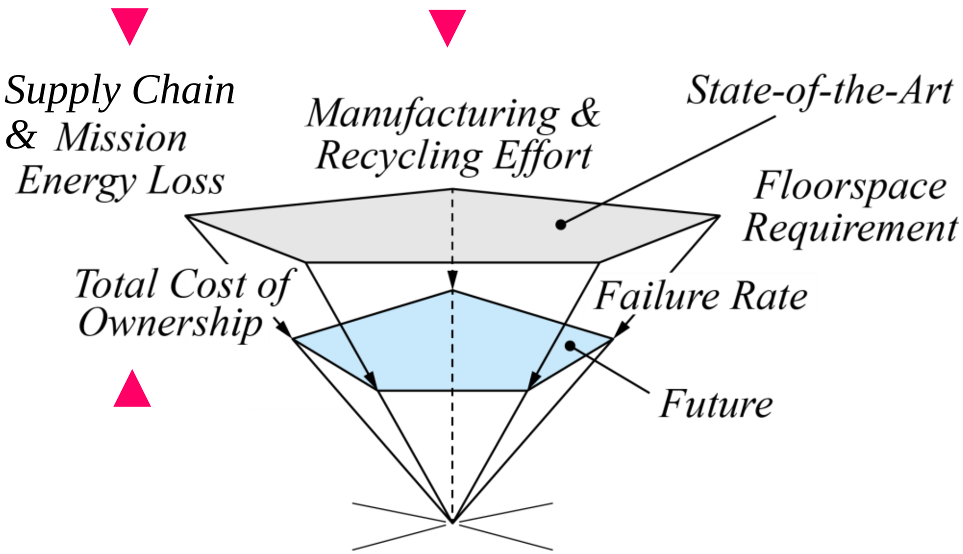


- Proposal for Public +380V_{DC}/-380V_{DC} Systems by Philips, EMerge ALLIANCE, etc.

► 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

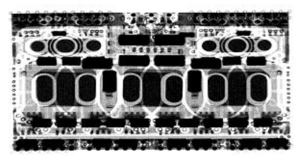
→

— **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

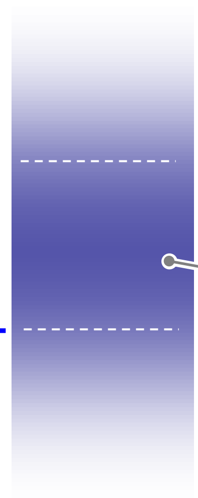
— Same Situation above 100kW (Costs, Mech. Efforts, Safety Issues with Testing etc.)
— Talk AND Build Megawatt Converters (!)

► University Research Orientation

MEGA Power Electronics

(Medium Voltage, Medium Frequency)

1 MW



"Largely" Standard Solutions

Micro Power Electronics

10W

(Microelectronics Technology Based, Power Supply on Chip)

+ System Applications

- Bridge to Power Systems
- Establish (Closer) University / Industry (Technology) Partnerships
- Establish Cost Models, Consider Reliability as Performance

Finally, ...

Power Electronics 2.0

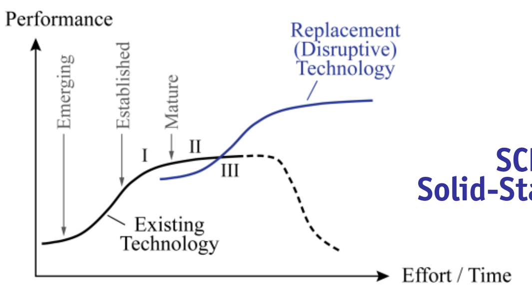
▶ Converter Technology S-Curve

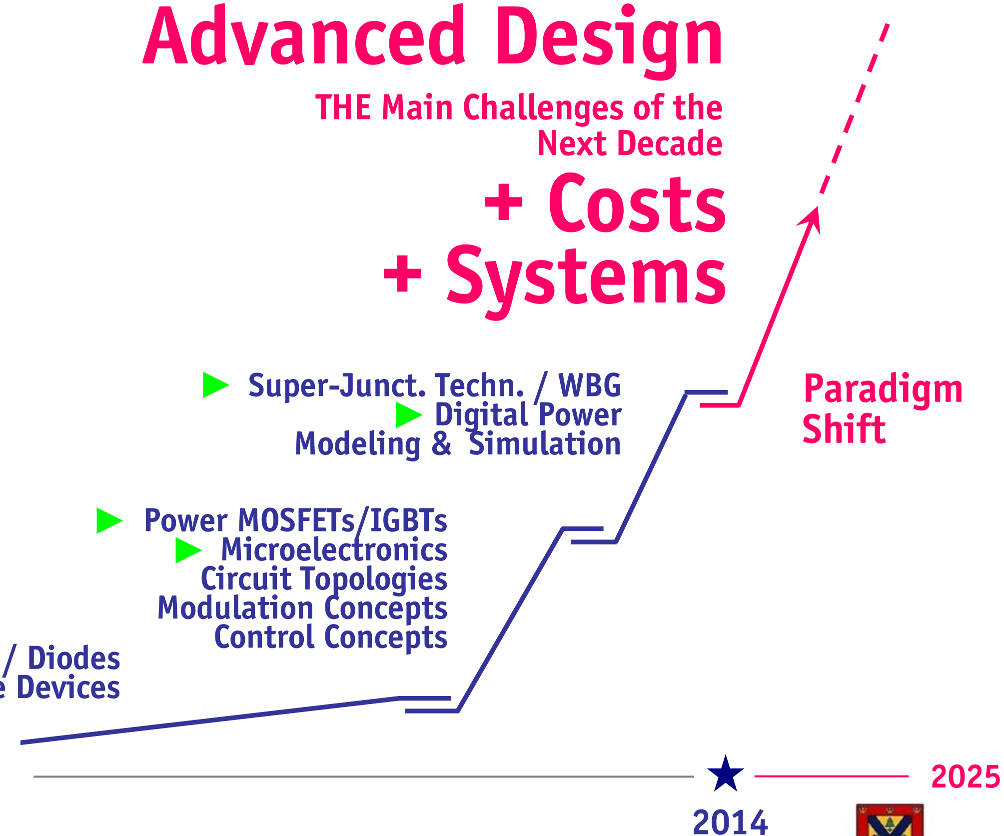
...after Switches and Topologies

"Passives" & Advanced Design

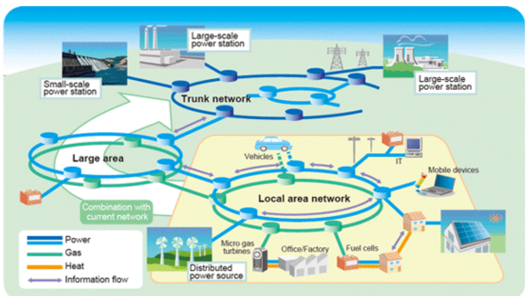
THE Main Challenges of the Next Decade

+ Costs
+ Systems

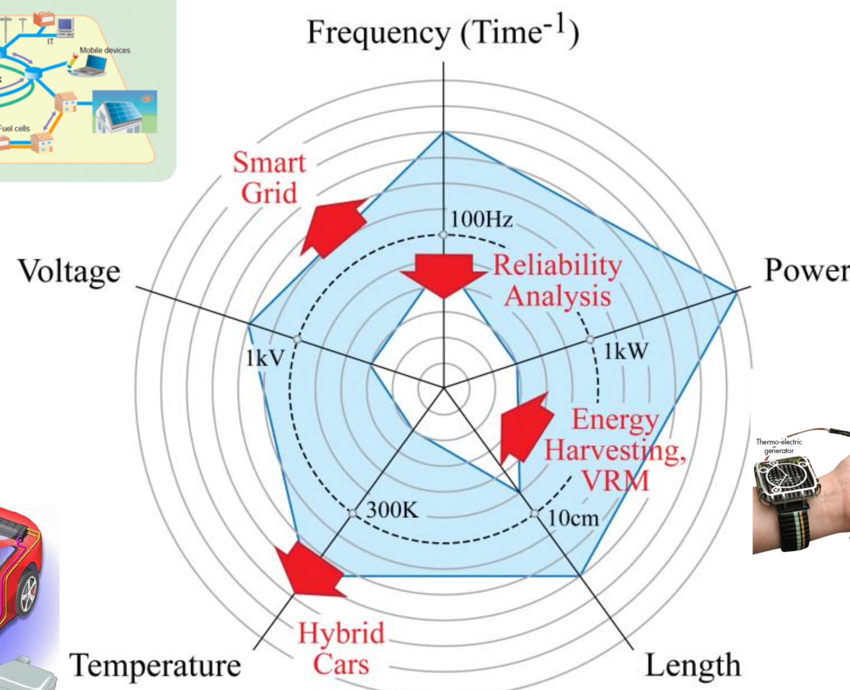


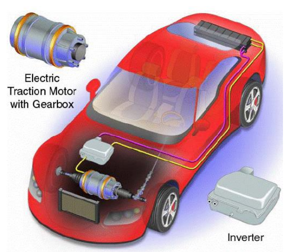


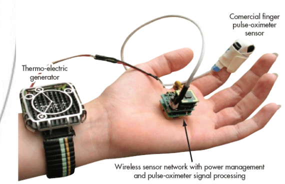
▶ Future Extensions of Power Electronics Applications



Source: AIST







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 ?