# Automotive Power Electronics Roadmap

J. W. Kolar, ETH Zurich, Switzerland, M. März, Fraunhofer IISB, Germany, and E. Wolfgang, Germany
Summary authored by S. D. Round, ETH Zurich, Switzerland

Automotive applications for power electronics is increasing rapidly due to the demand for hybrid and future fuel-cell powered vehicles. The power electronic systems are not only required for driving the vehicle (Fig. 1) but are also used to interface energy storage components and to supply high power auxiliary systems such as active suspension, electric valves and air conditioning units. The automotive industry has specific requirements for its power electronic systems such as a compact design, high reliability, long life time and an extremely low cost to power ratio. The systems are further required to operate over a wide ambient temperature range and with liquid cooling temperatures of typically 105°C. In a study from the USA FreedomCAR project, it is projected that the required cost of the power electronic systems has to reduce by a factor of three until the year 2020.

The task of the Automotive Roadmap Committee was to clarify which technologies are needed to achieve the performance and cost targets of the automotive industry. The road mapping effort focused on three systems as circled in Fig. 1:

1. a non-isolated dc-dc converter, in the 40 to 100 kW power range, that can be used as a fuel cell interface,
2. an ac-dc inverter that is integrated into the machine housing of a hybrid drive system (since an integrated solution provides the greatest cost reduction potential), and,
3. an isolated dc-dc converter to provide bi-directional power flow between the high voltage bus and the 14 V accessory power system, where the required power range is 1 to 3 kW.

The main outcomes of the road mapping exercise are that the drive inverter cost target could potentially be meet if the power electronics is integrated, and that the maximum achievable power density of the non-isolated dc-dc converter and the isolated dc-dc converter is 50 kW/liter and 10 kW/liter respectively.

The road mapping process utilized a bottom-up approach. Here, mathematical descriptions for the electrical, thermal, packaging and magnetic components are developed. Using these descriptions a component technology space is formed. By using the specifications, topologies, and operating parameters the component space can be optimally mapped into a system performance space, which gives system performance measures such as efficiency, power density and costs. Exploring the performance space and demanding an improved system performance, and then undertaking a reverse mapping from this new point back into the component space, provides information on how the technologies must be developed to achieve the new desired system performance.

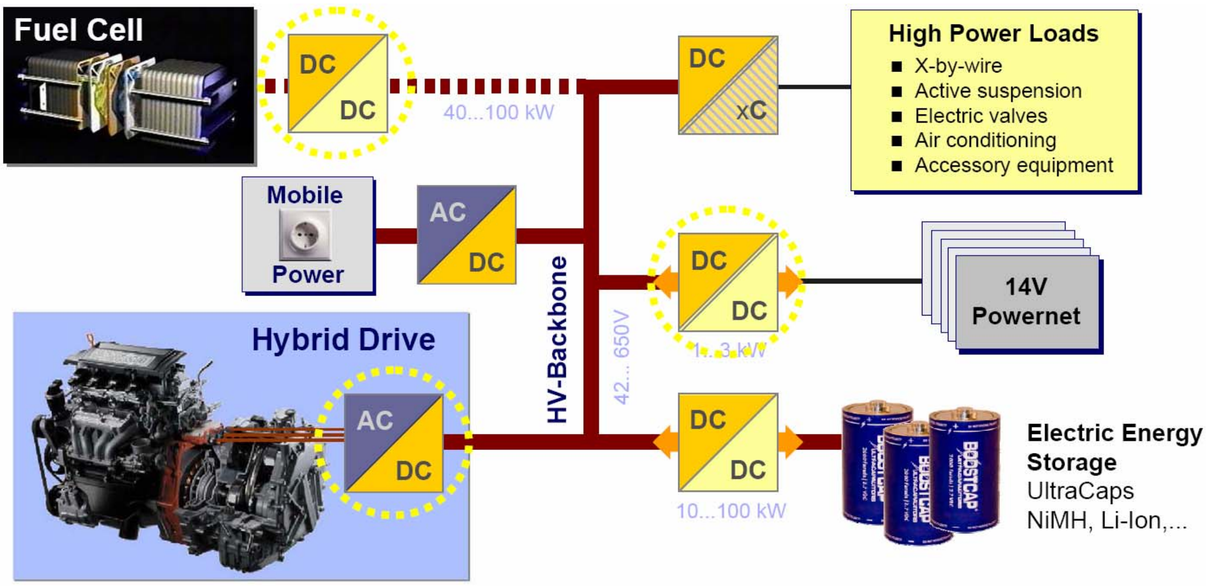



**Fig. 1** Power electronic key systems for the cars of tomorrow. The three considered systems in the automotive power electronics road mapping exercise are encircled in yellow.

Power Electronic Systems Laboratory

Fraunhofer Institut Integrierte Systeme und Bauelementetechnologie

# Automotive Power Electronics Research Roadmap Initiative

**Coordinators**

*Johann W. Kolar*
ETH Zurich

*Martin März*
Fraunhofer IISB

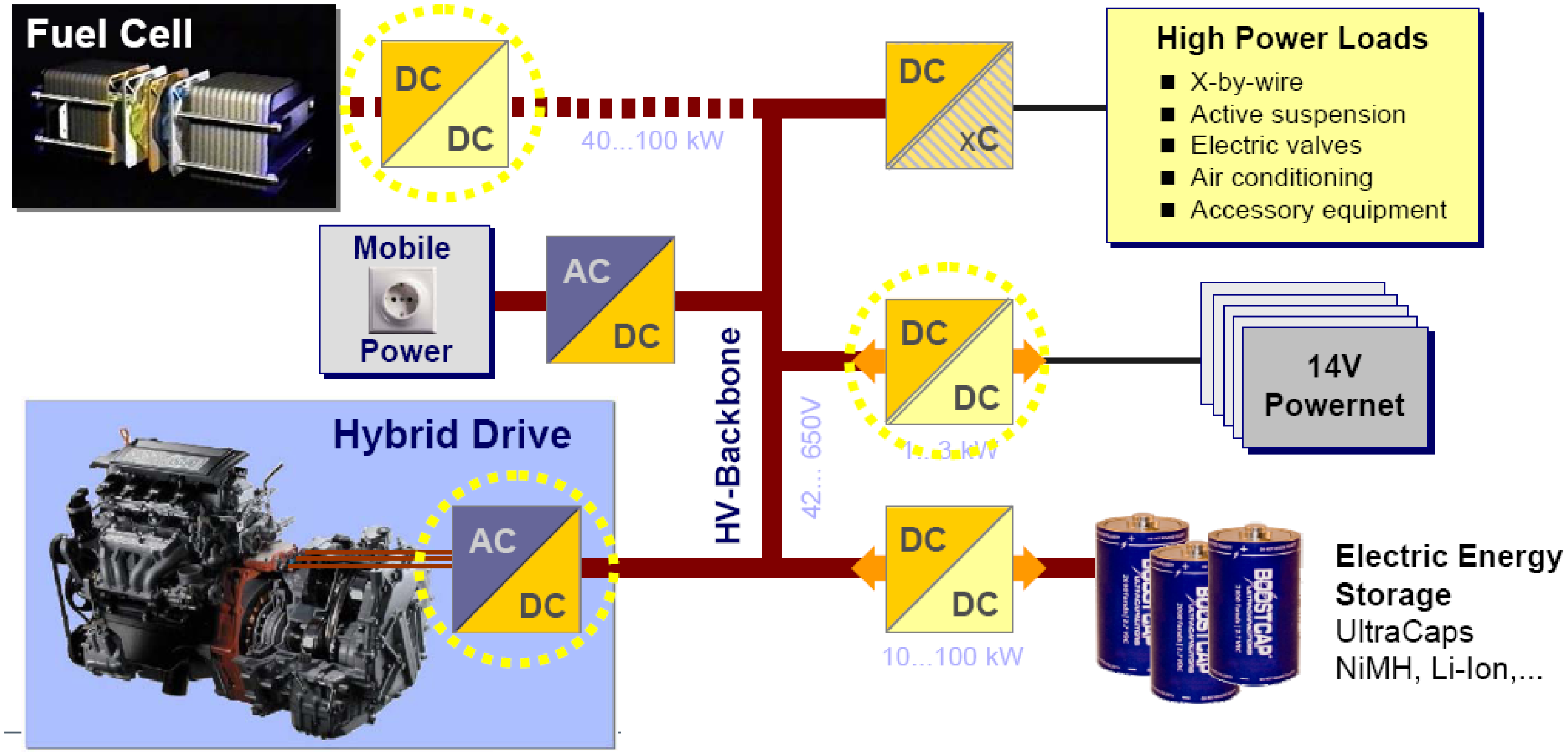
supported by

Eckhard Wolfgang
and *Roadmap Team Automotive*

# Outline

- General Considerations
- Si / SiC Inverter
- Non-Isolated DC/DC Converter
- Isolated DC/DC Converter
- High Temperature Gate Drive
- Optimization

# Power Electronic Key Systems for the Cars of Tomorrow



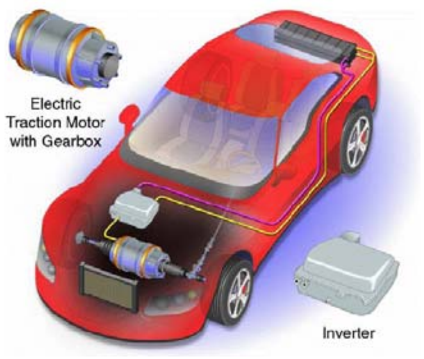
# More Electric Car

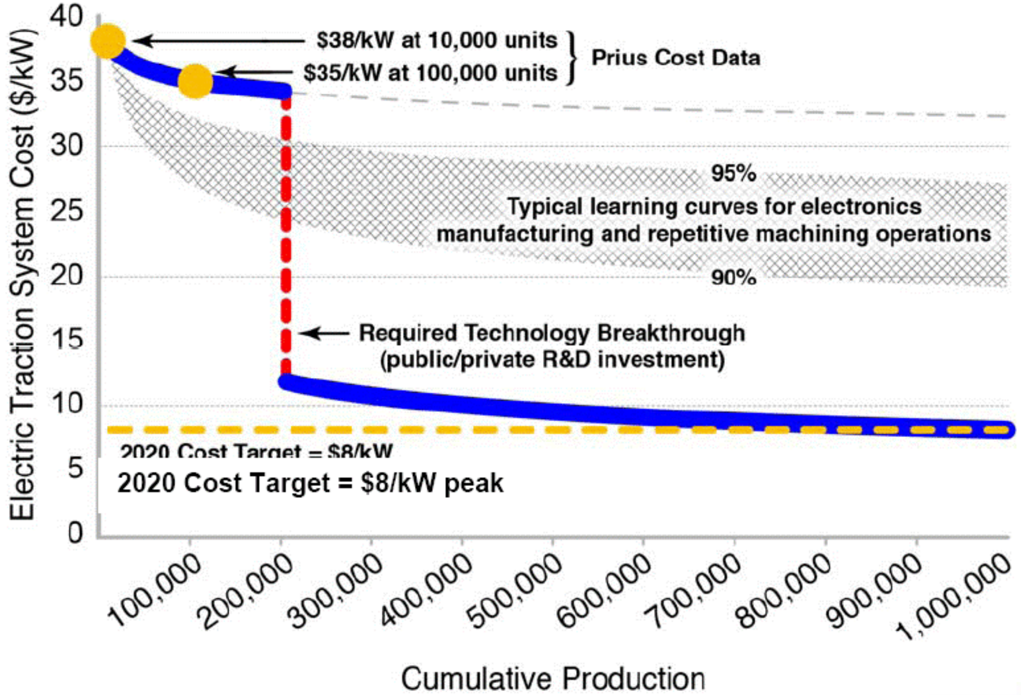
FreedomCAR

## Market Challenges

**2015 Cost Target $12/kW x 55kW = $660**

**Electric Traction Motor**
**Gearbox**
**Inverter**

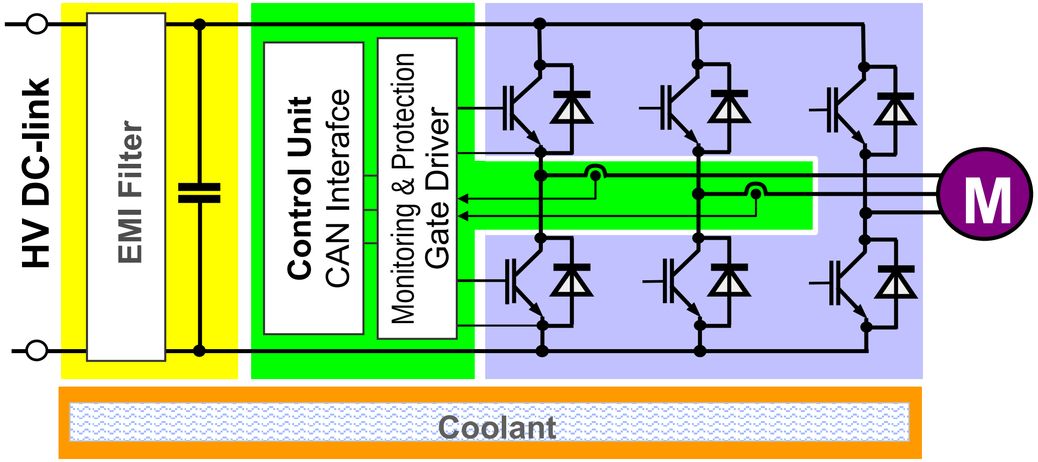


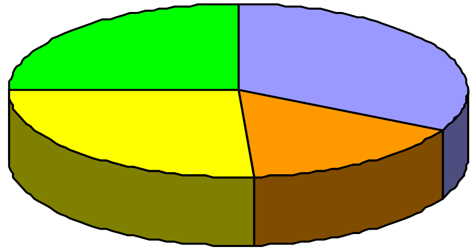
# Inverter

## Topologies
## DOF for Optimization
## Technologies

# Electric Drive for Hybrid Traction



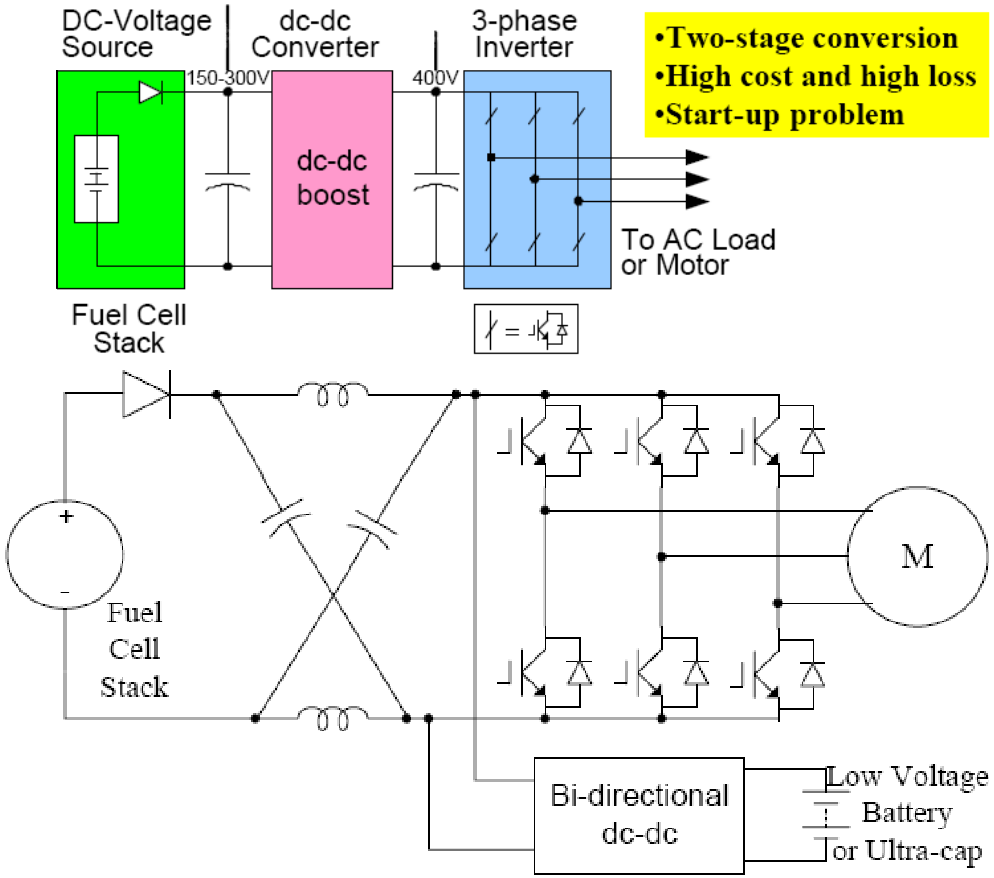

## Typ. Inverter Cost Split




## Alternative Topologies

- Z-Source Inverter
- Current DC Link Inverter
- Matrix Converter

# Z-Source Inverter




- •Two-stage conversion
- •High cost and high loss
- •Start-up problem

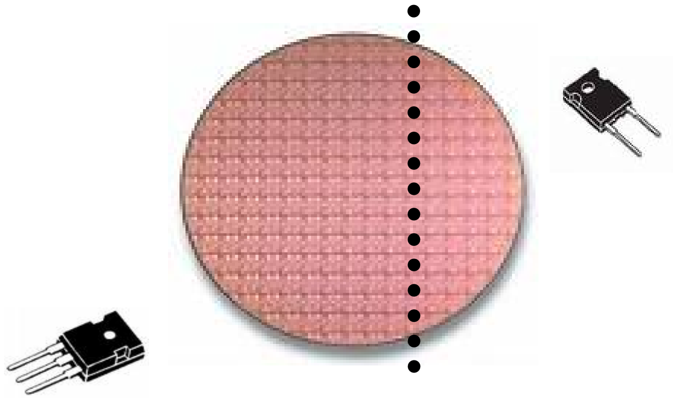
# DOF for Optimization

- Adapted Doping Profile
- Partitioning of Total Si Area
- DC Voltage Level   (P= U * I)
- Modulation Concept
- Output Frequency  (P=M*Ω)
- Switching Frequency

- Semiconductor Technology
- Coolant Temperature
- Cooling Concept
- Temperature Swing
  (Cycles to Failure)

- Gate Drive

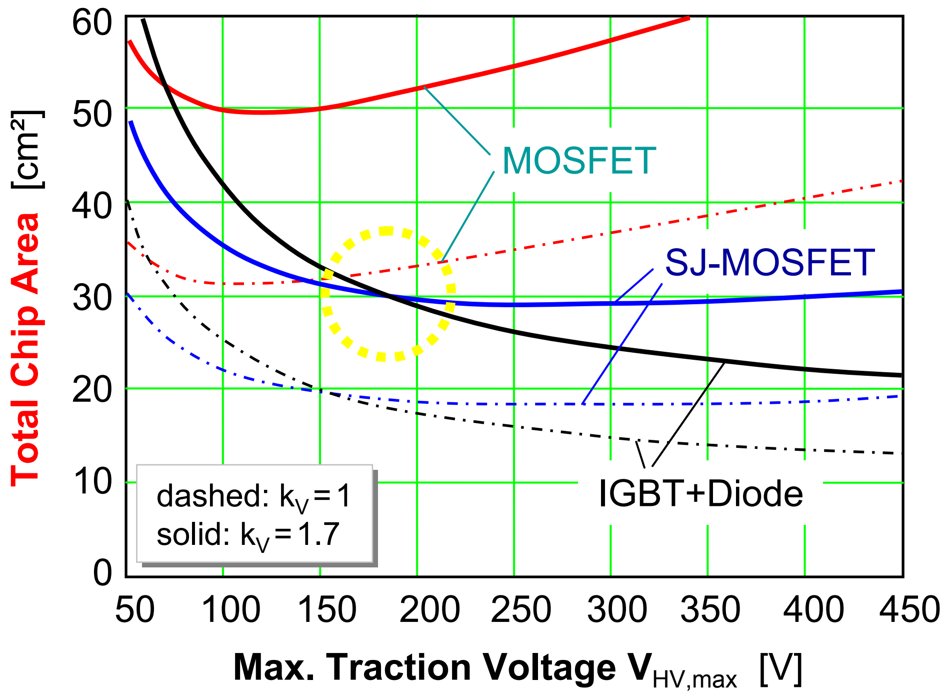
- Packaging / Integration
  (ECPE Demonstrator)



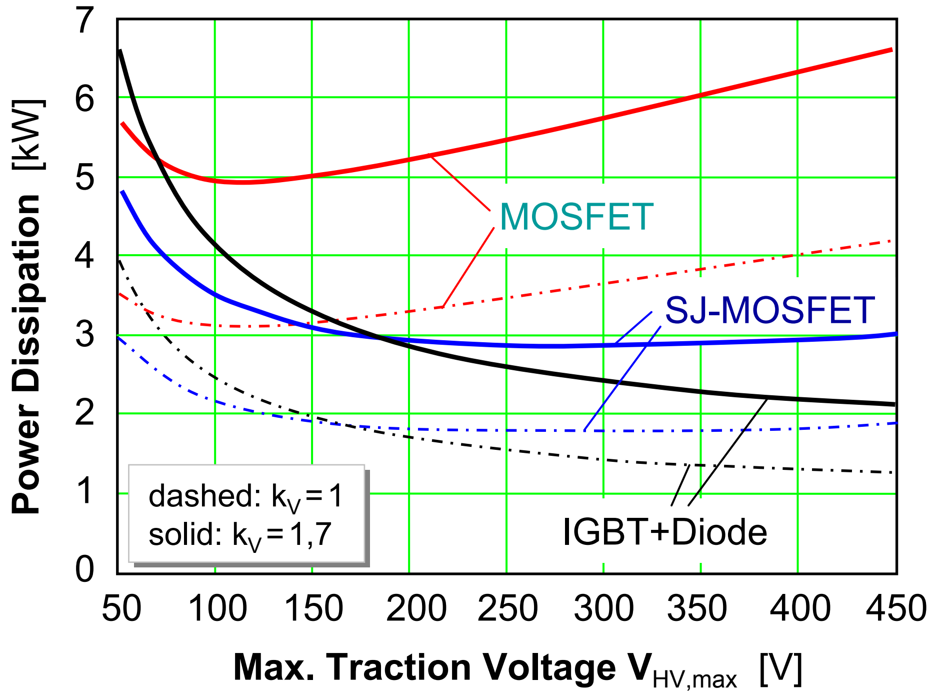
**Optimization  on  System Level**

# Traction Drive Inverter

## Total Power Semiconductor Needs

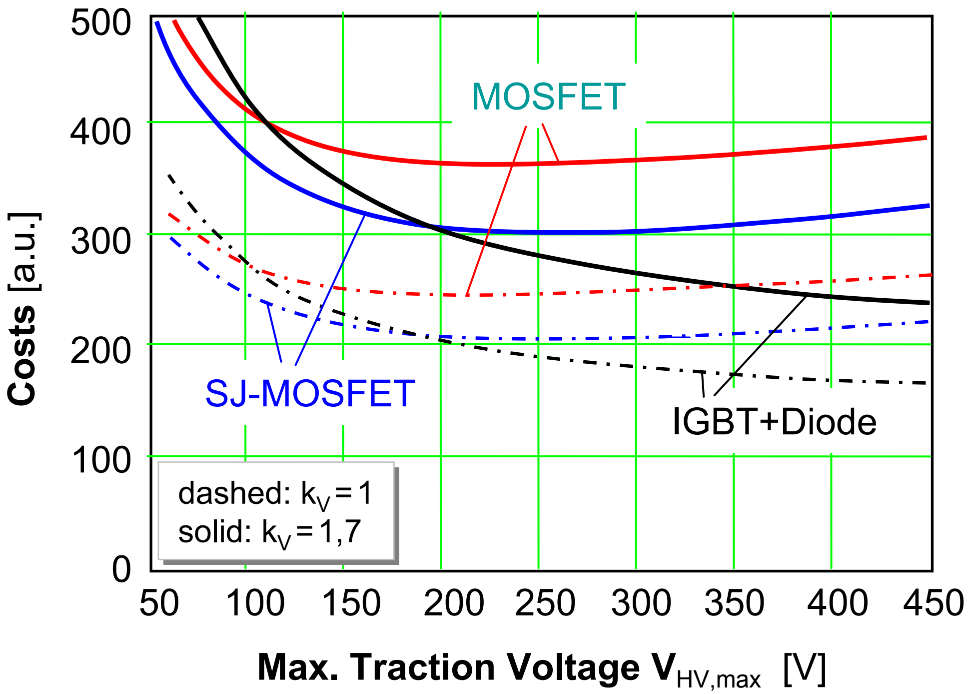



## Total Inverter Losses



# Traction Drive Inverter

## Total Material Costs

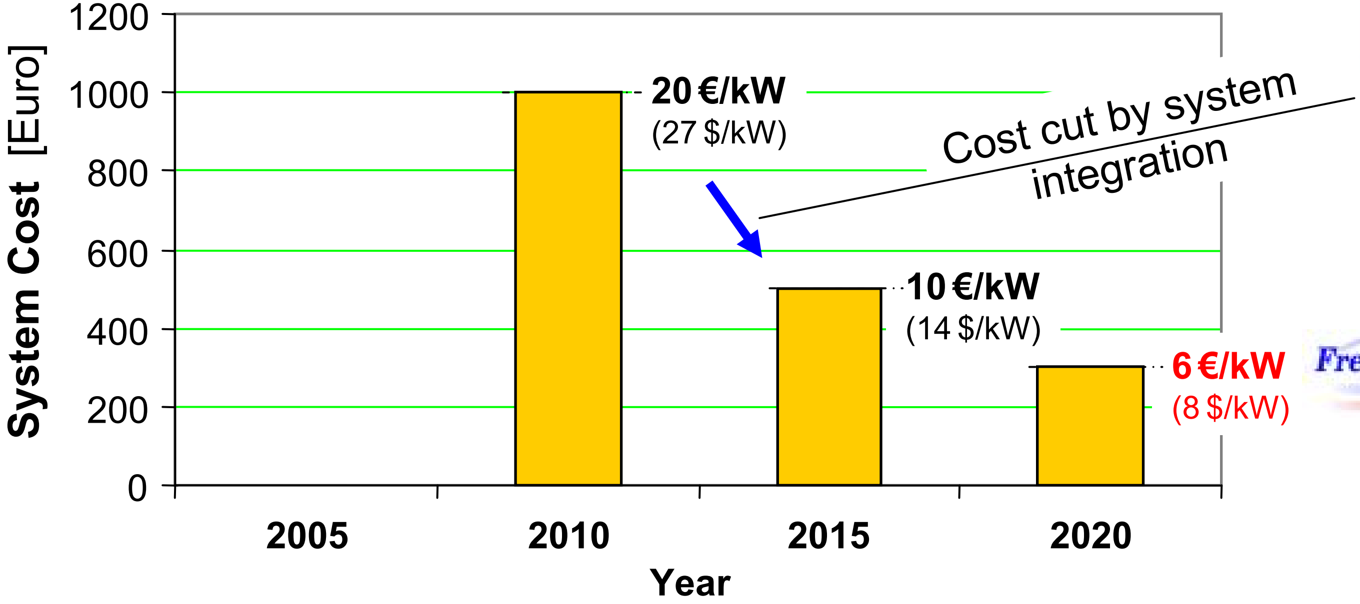



## Results

- **IGBT is the preferred technology for traction voltages above about 150V**
- Total inverter cost, package volume, and losses decrease with increasing traction voltage when using IGBTs
- The inverter becomes considerably less expensive in the case of a constant traction voltage ($k_v$=1)

# Electric Drive for Hybrid Traction

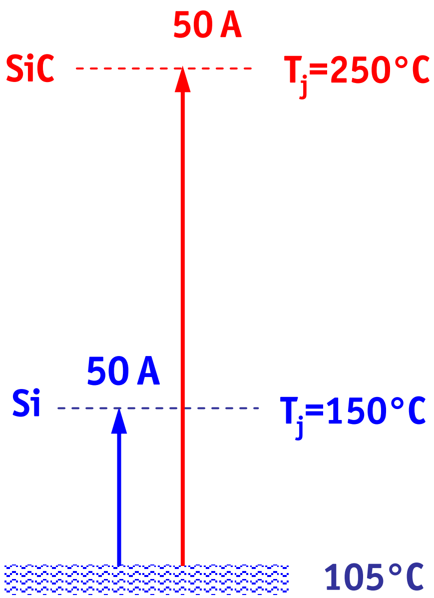
## System Cost Targets

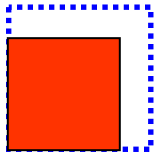



# Comparative Evaluation of SiC for 6-Switch Motor Inverters

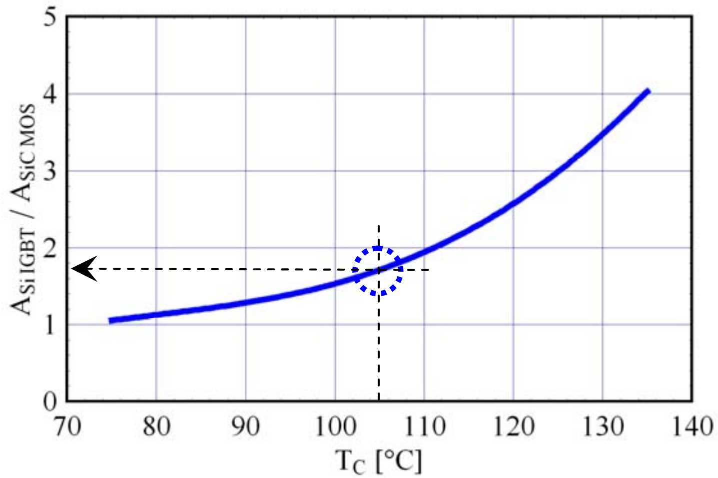
**Trench IGBT 1200V-50A**

**SiC MOSFET 1200V-50A (CREE)**

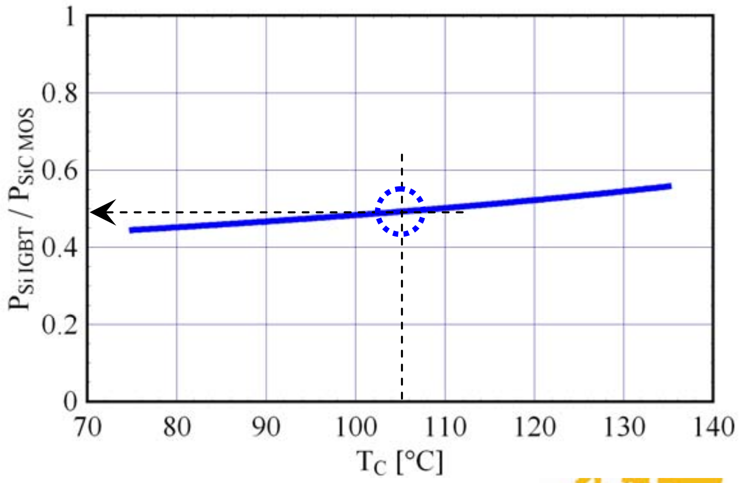


**Chip Area Ratio**

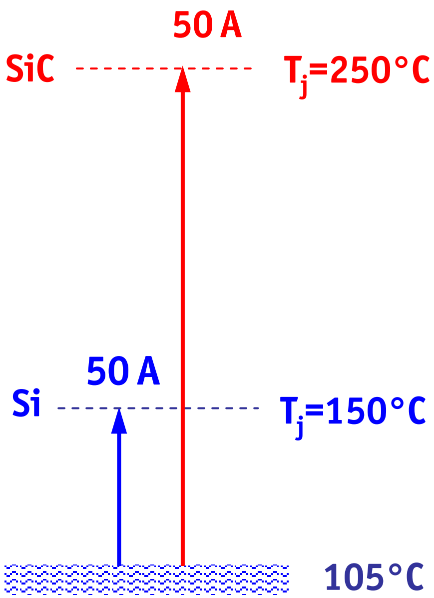


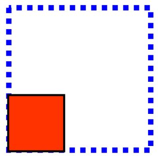

**Ratio of Conduction Losses**



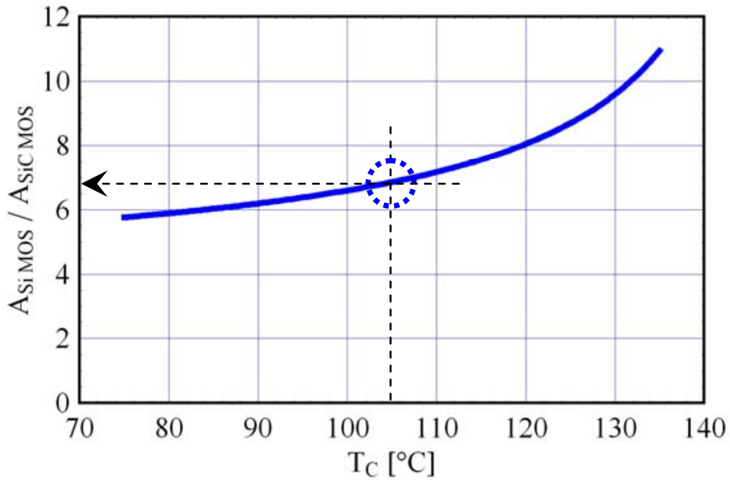
# Comparative Evaluation of SiC for DC/DC Converter

**Si CoolMOS C3 1200V-50A (Extrapolated)**
**SiC MOSFET 1200V-50A (CREE)**

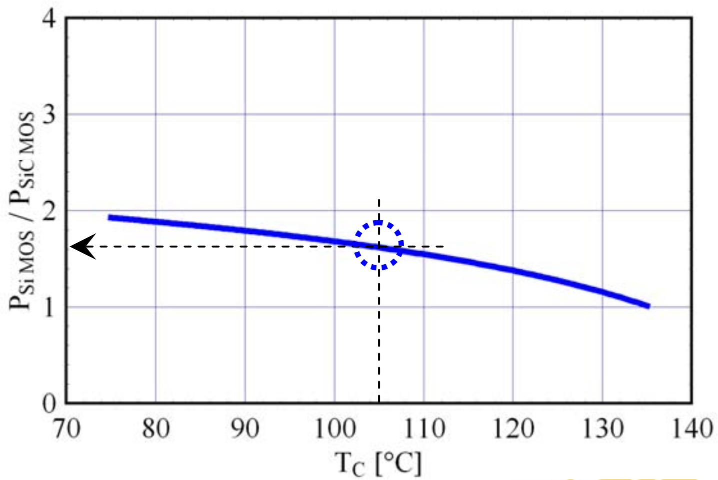


Chip Area Ratio



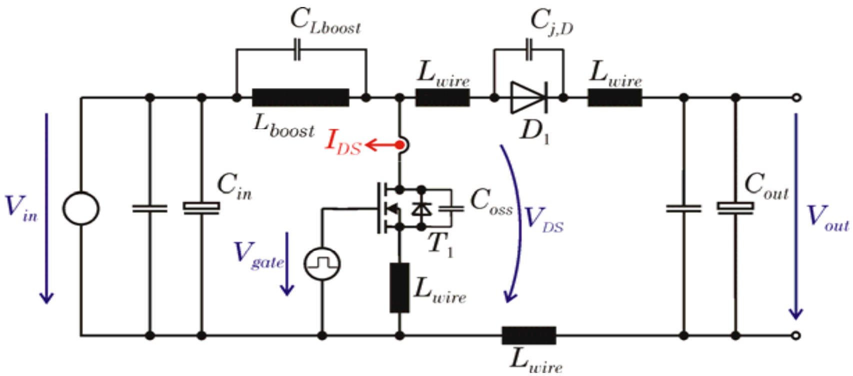

Ratio of Conduction Losses



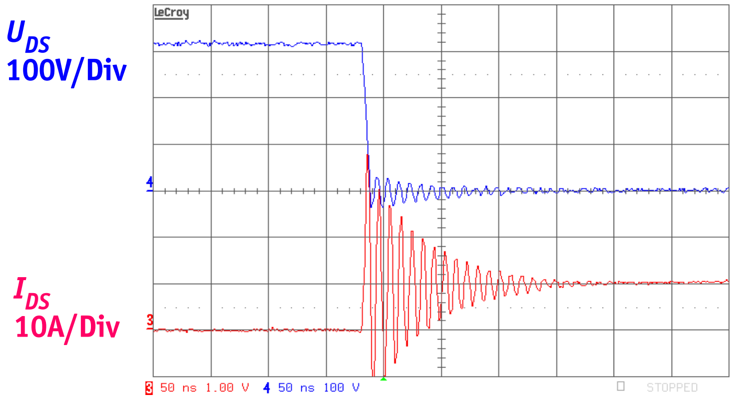
# Switching Transient Shaping

- ▶ Minimization of Parasitics

- ▶ Passive Damping
- ▶ Gate Drive / Active Damping

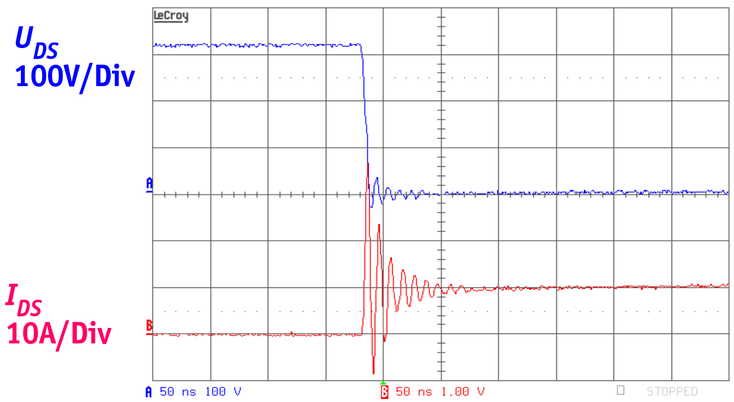



Without Damping Layer




50ns/Div

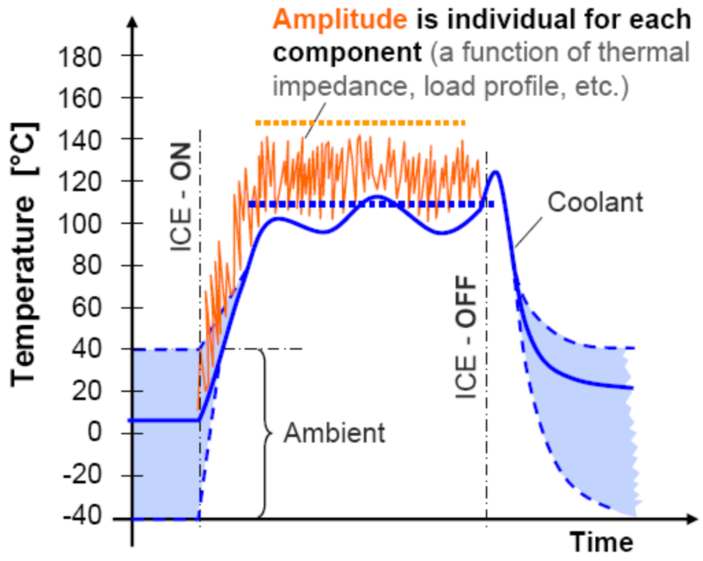
PCB Damping Layer

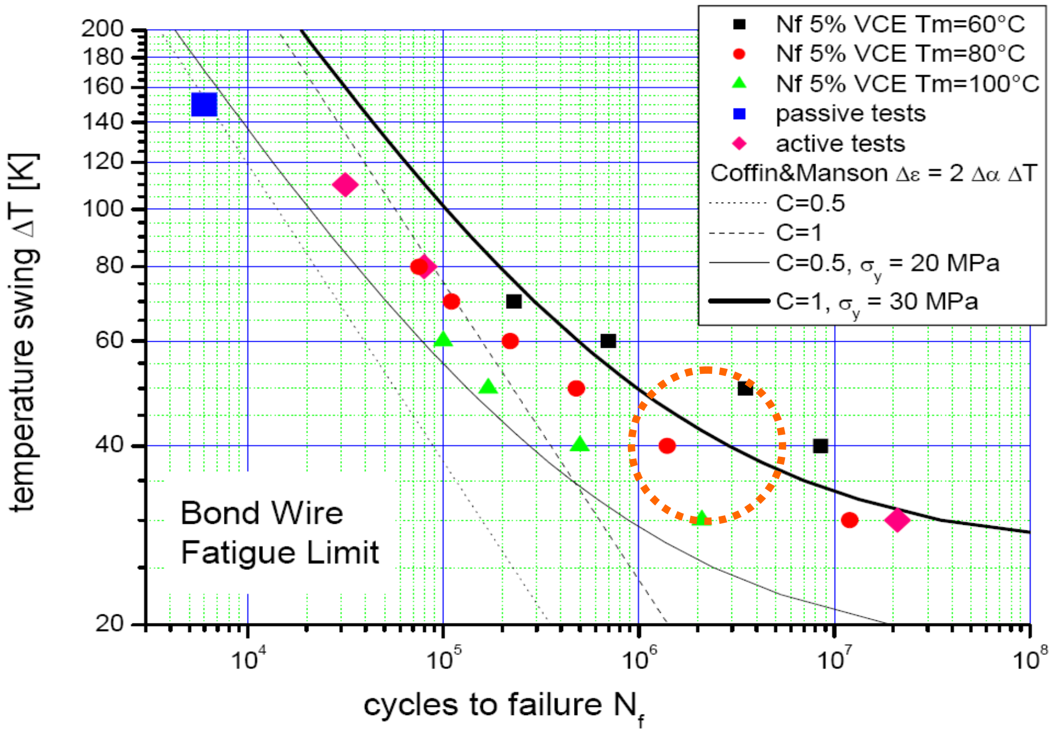


# Thermo-Mechanical Reliability

- ▶ **Passive Cycles** **15'000**
- ▶ **Active Cycles** **> 3'000'000**

**Bond Wire Fatigue Limits**



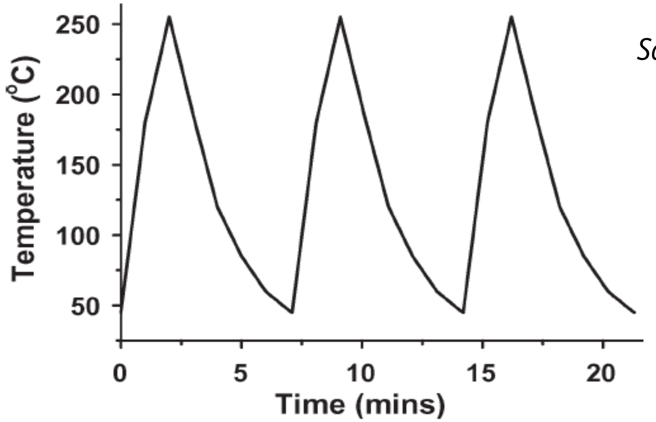



# Thermo-Mechanical Reliability

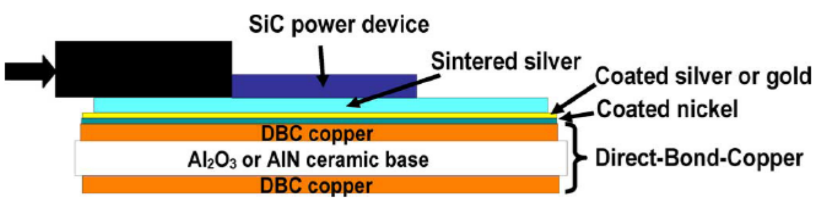
- SiC Power Device Assembly
- Low Temperature Sintered Silver Die Attachment

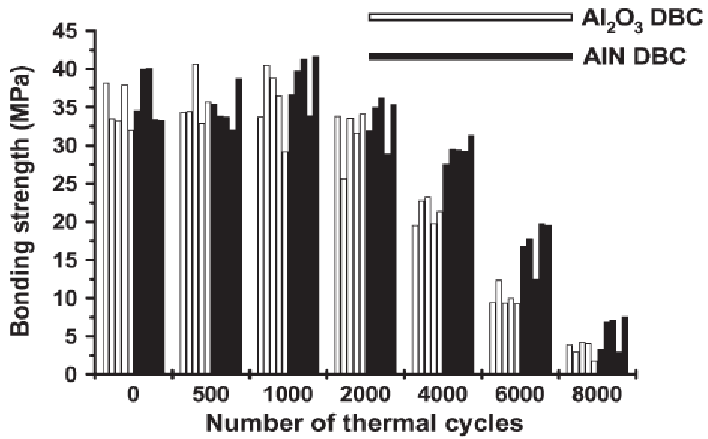
- *Thermal Cycling 50°C .... 250°C*
- *6'000 TC Survived*

*Source: Lu / VPEC*




Die-Shear Test

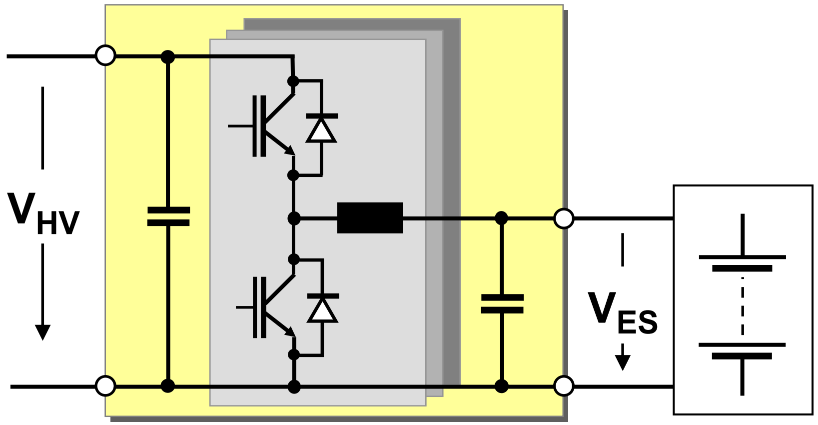


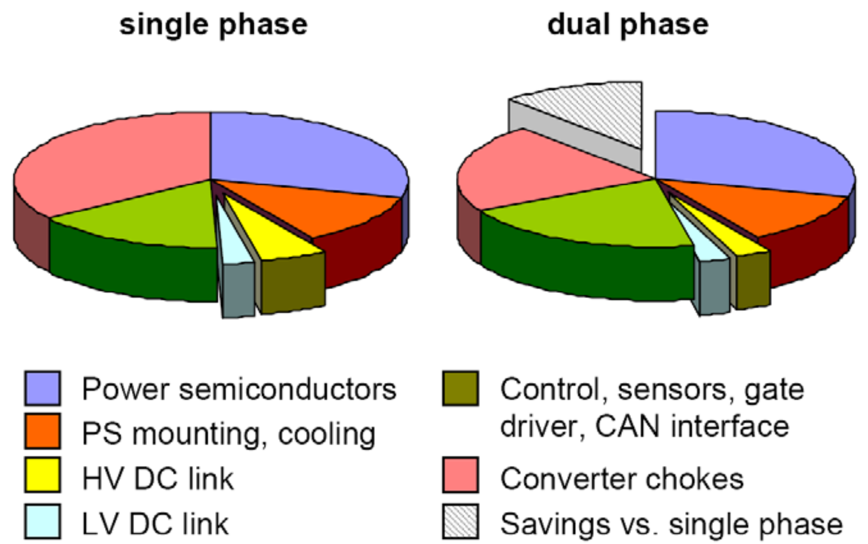
# Non-Isolated DC/DC Converter

## Overlapping Input/Output Voltage Ranges

# Traction Voltage Converter

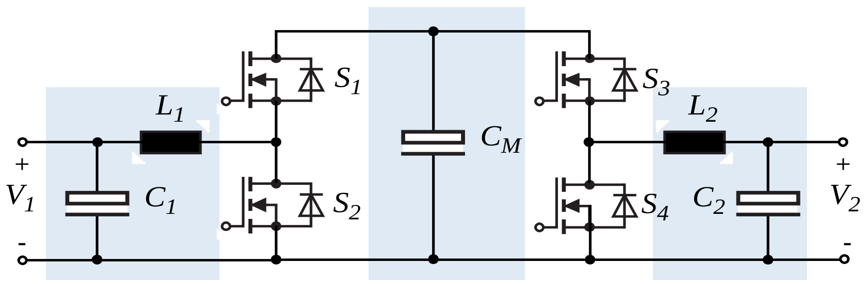



## Typ. Converter Cost Split

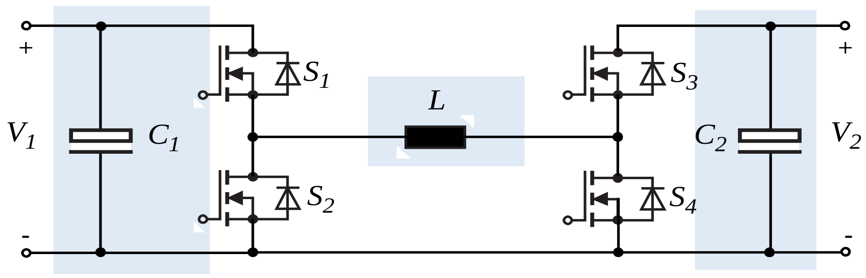


# Bi-Directional DC/DC Converters for Overlapping Voltage Rages

### Cascaded Boost-Buck Converter



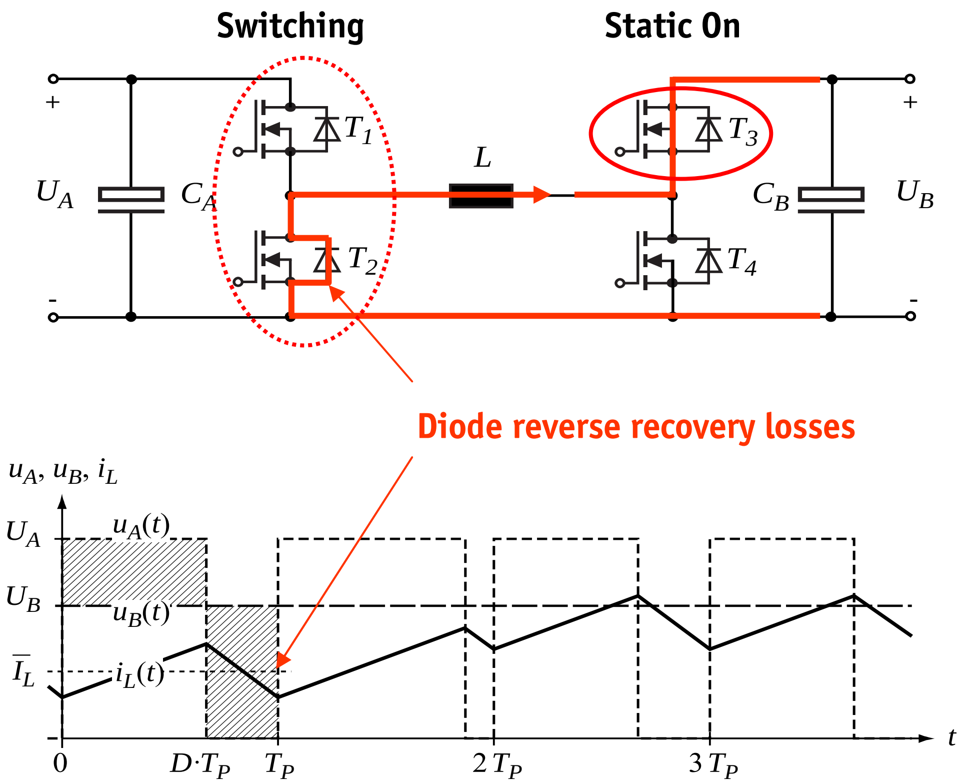

### Cascaded Buck-Boost Converter




**Large Passive Components Count**
- 3 Capacitors
- 2 Inductors

**Minimum Passive Components Count**
- 2 Capacitors
- 1 Inductor

# Cascaded Buck-Boost Converter



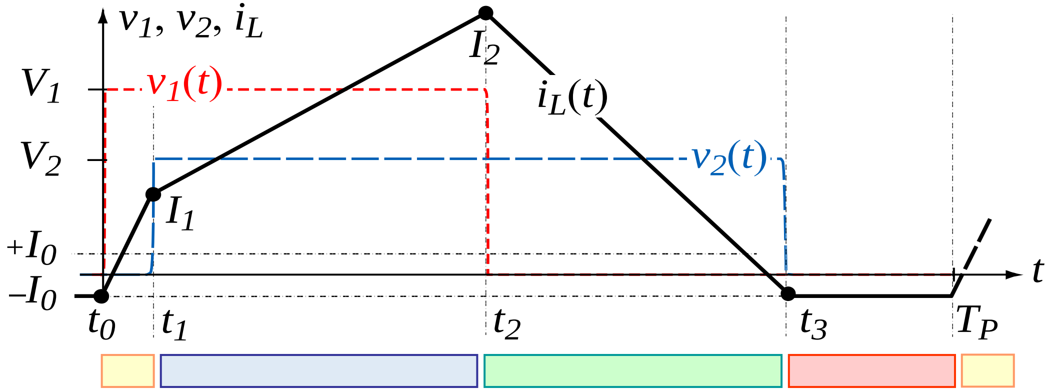

## Methods to Reduce Switching Losses

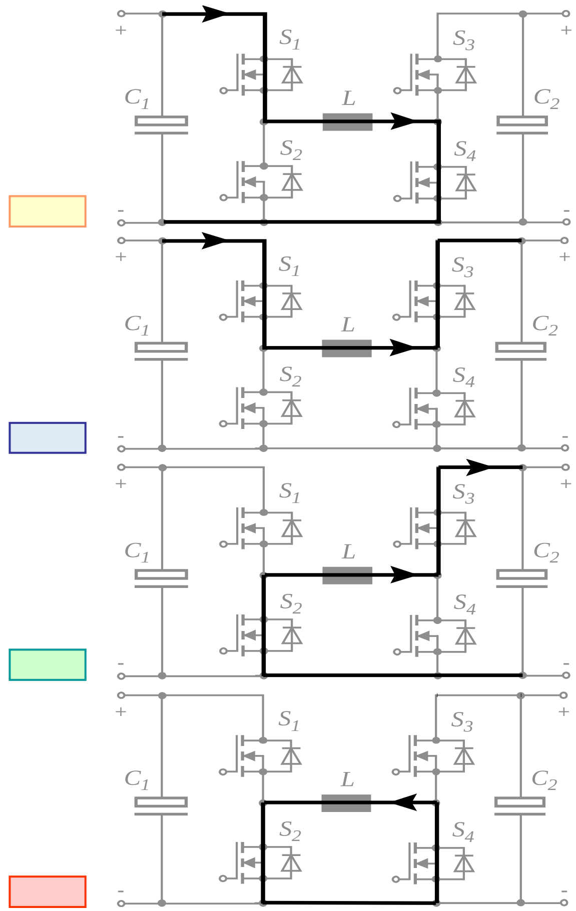
- Silicon Carbide (SiC)
- Soft-Switching - ZVS, ZCS

# Low-Loss Modulation

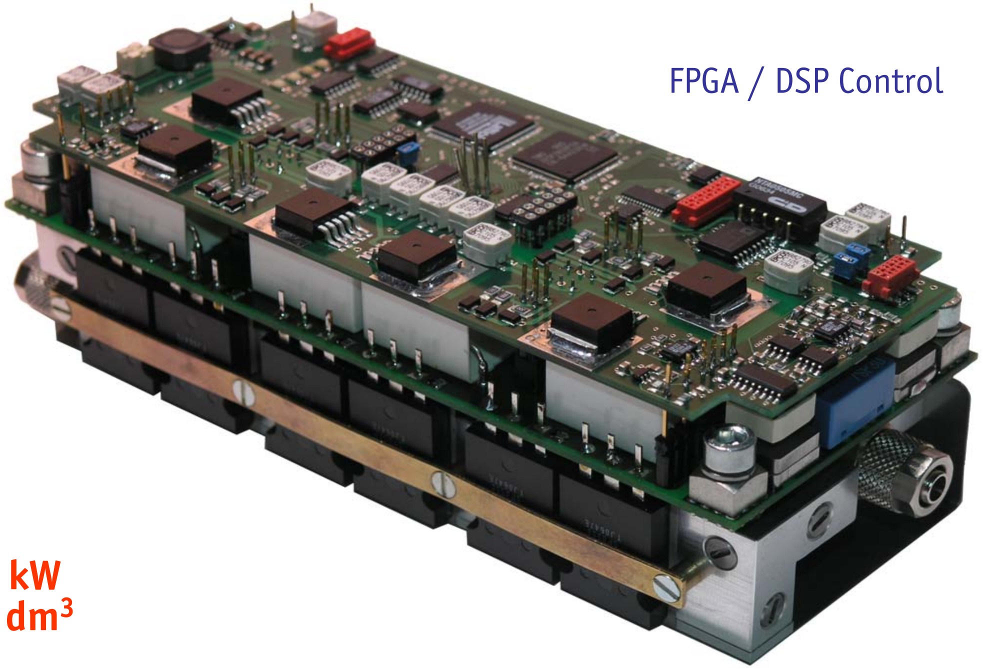
## Operating Modes

Buck operation: $V_2 < V_1$,
Engery Transfer: side 1 → side 2



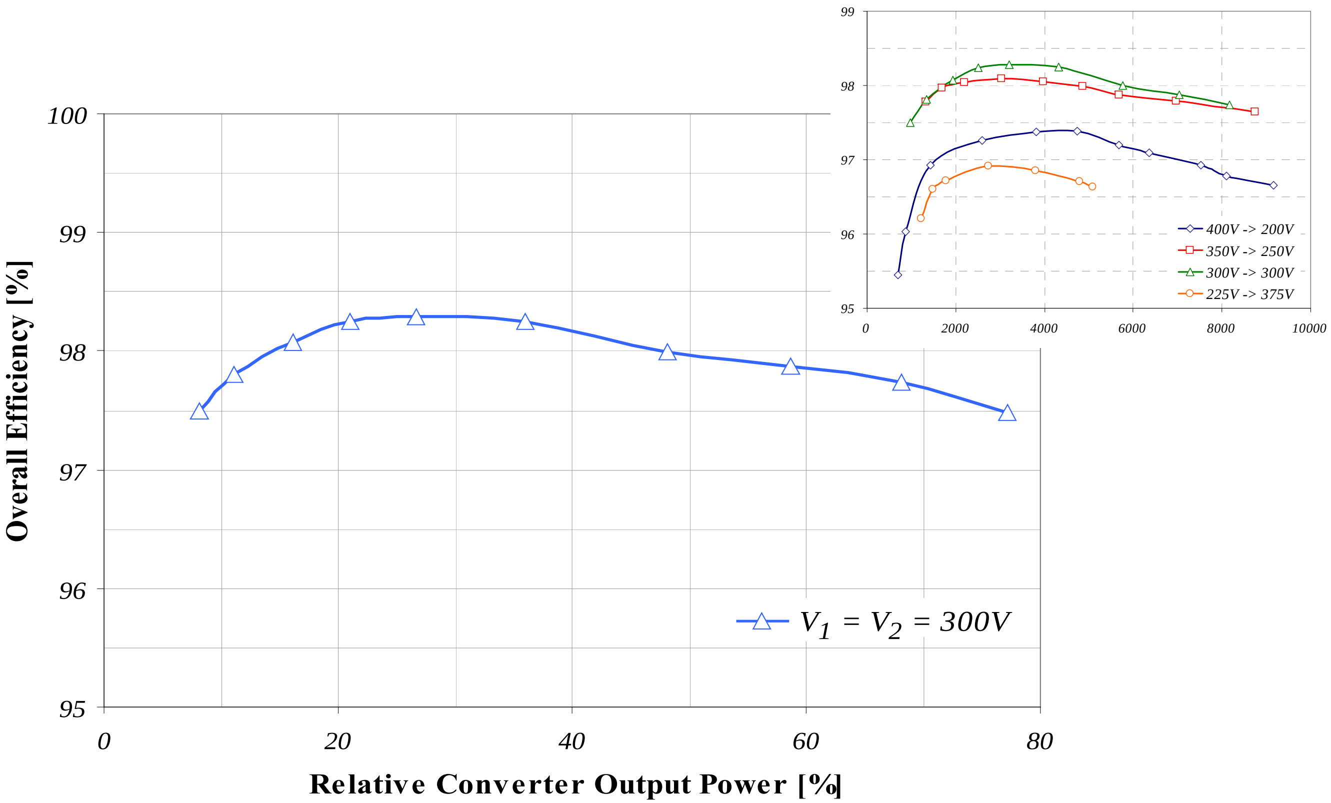
# Converter Module Hardware



FPGA / DSP Control

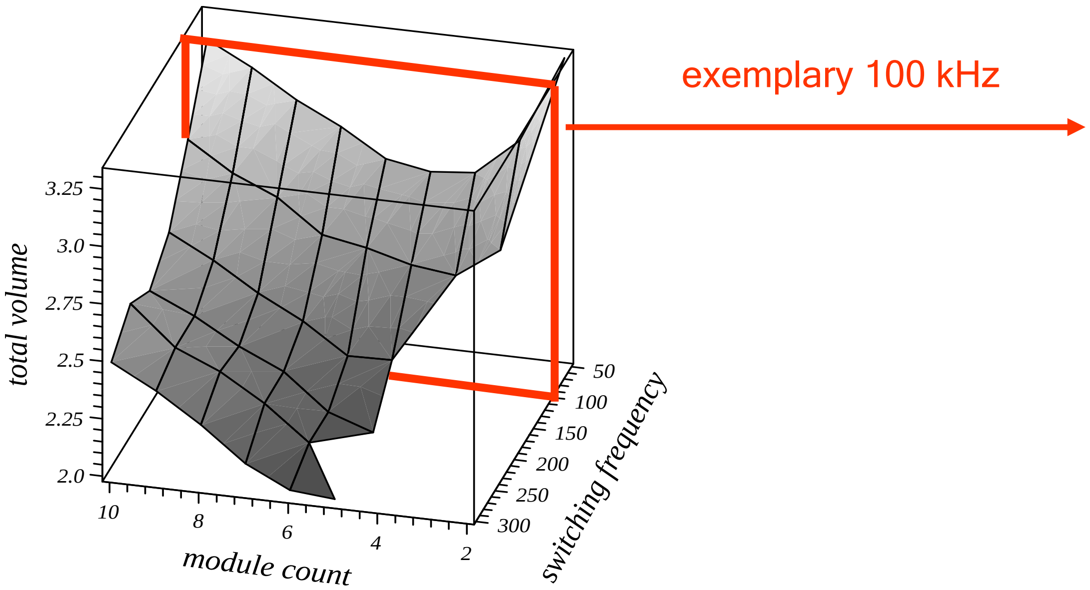
- Peak Power Rating 12 kW
- Power Density 17.5 kW / dm$^3$

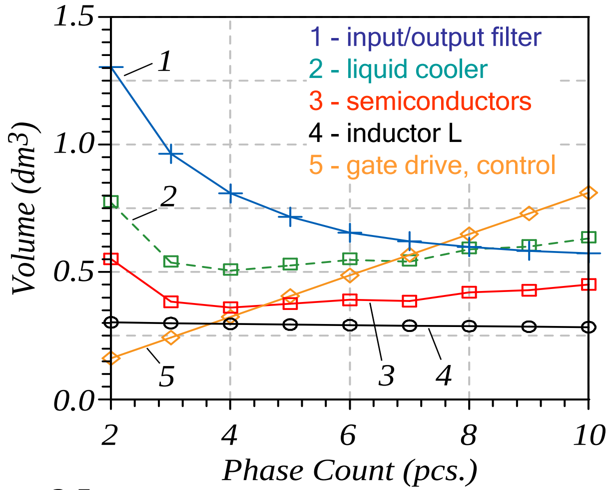
# Overall Efficiency vs. Output Power

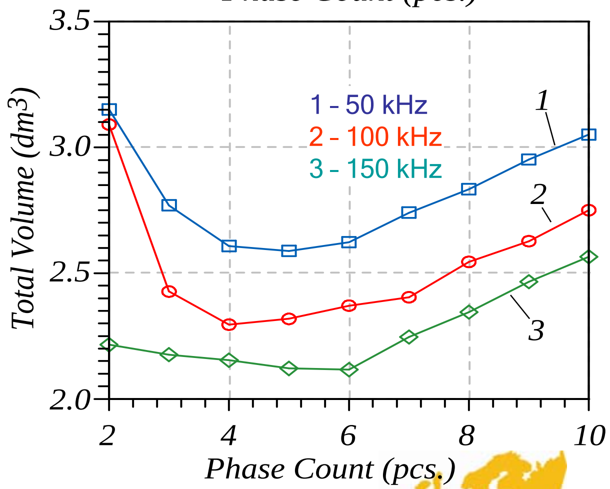


# Converter Volume Optimization

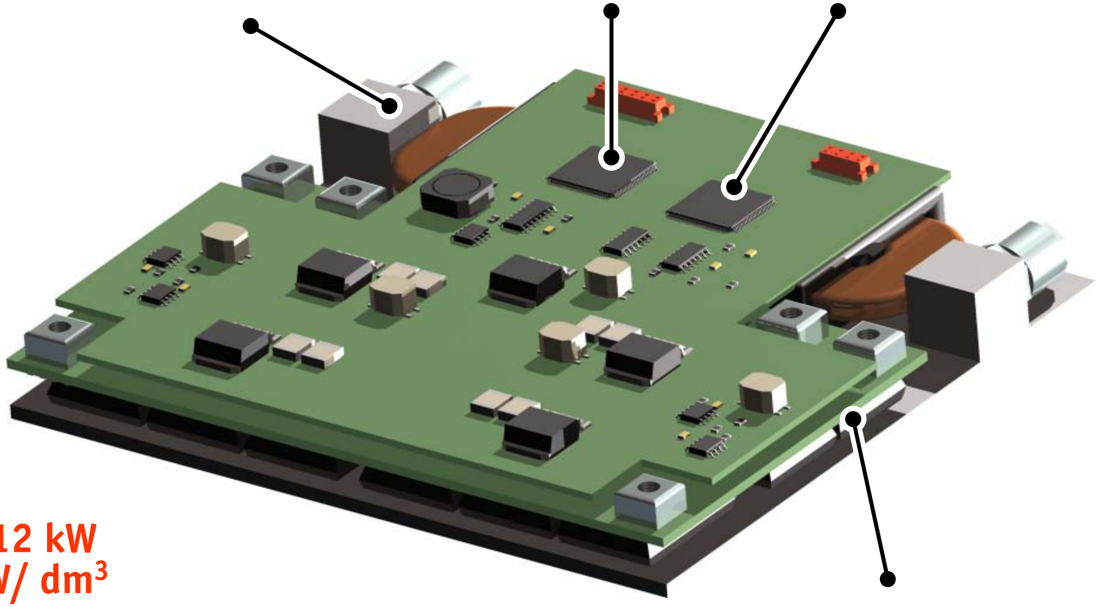
- ▶ **Module Count** 2 .. 10
- ▶ **Switching Frequency** 50 .. 300 kHz



# Ultra-Compact Converter Module




- **Output Power** 12 kW
- **Power Density** 29 kW/ $dm^3$

# Isolated High Temperature SiC J-FET Gate Drive Circuit

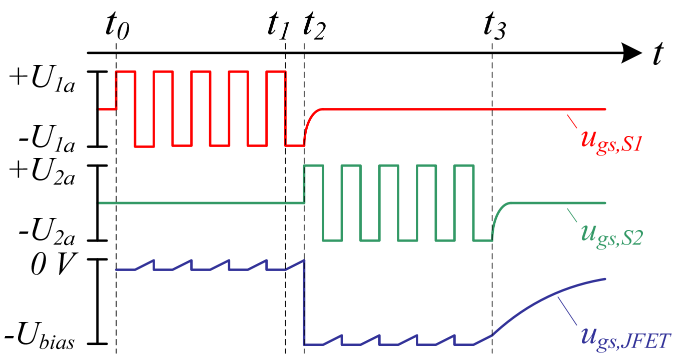
$T_a = 250°C$

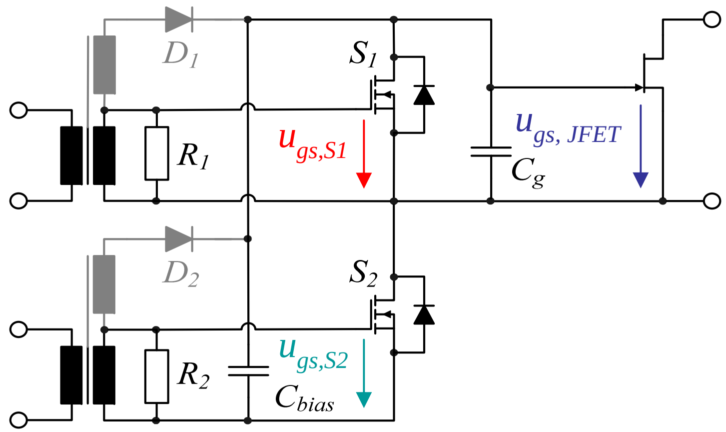
High Density Power Electronics for FC- and ICE-Hybrid Electric Vehicle Powertrains

Fraunhofer Institut Integrierte Systeme und Bauelementetechnologie

# Phase Difference Circuit

*Proposed by D.C. Hopkins, Univ. at Buffalo, USA*



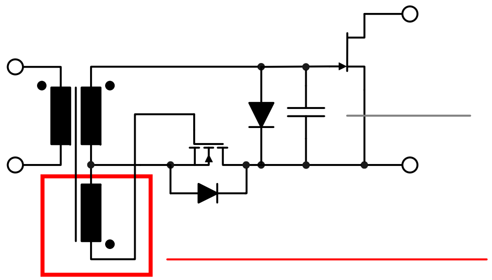




- Vs Product: Bipolar transformer output voltage
- Capacitor $C_g$ to perserve JFET gate voltage during MOSFET $S_1$ or $S_2$ Off-Time

## *Advantages and Drawbacks*

- No Duty-Cycle limitation ( static Turn-Off )
- High switching speeds ( MOSFET half-bridge )
- High complexity
- High costs

# Edge-Triggered Driving Circuits

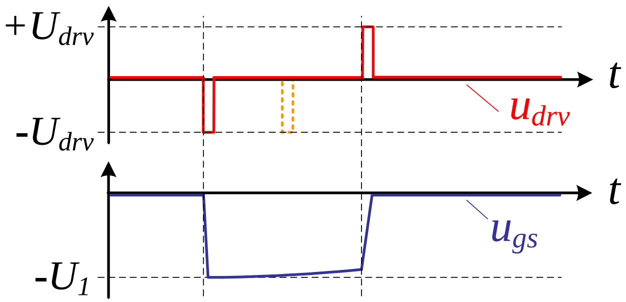


*Size of Capacitor $C_g$*

- *Large capacitances reduce switching speed*
- *Large capacitances cause significant losses*
- *Small capacitances limit Off-Time*

*Second winding due to auxiliary switch $U_{gs}$ limits*

Control Pulses




## *Advantages and Drawbacks*

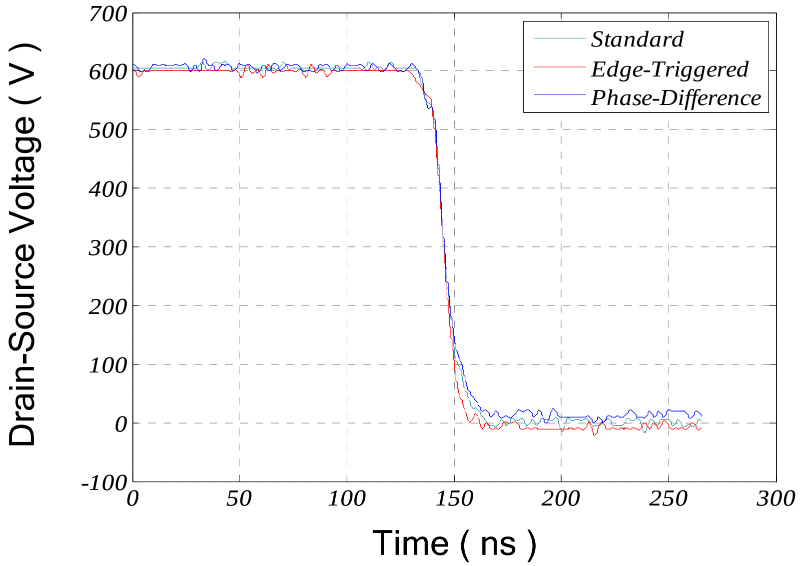
- Moderate Active Component Count
- High Switching Speeds
- Large Duty-Cycle Range ( 1% ... 100% )
- ( Off-Time limited by capacitor size )

► special pulse pattern to provide negative bias useable

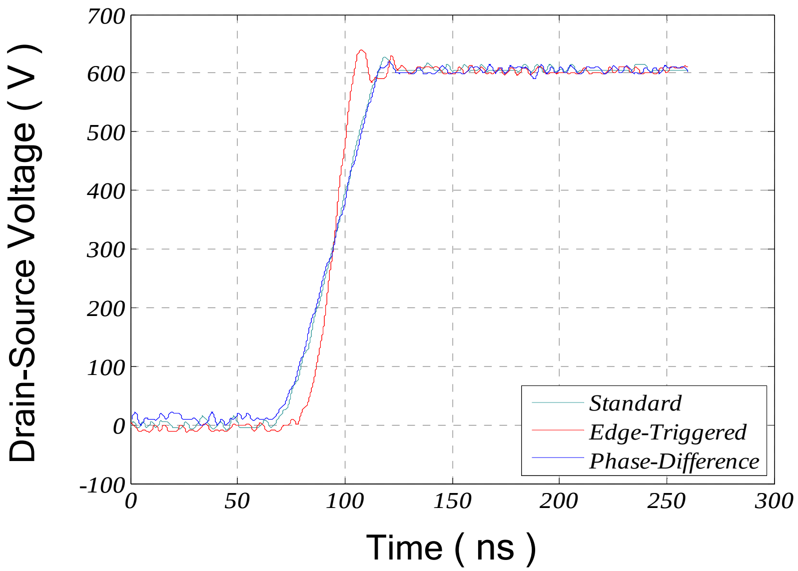
# Experimental Results

## Performance Comparison

**Turn-On** $t_{fall}$ = 13 ns




**Turn-Off** $t_{rise}$ = 18 ns




► Edge-Triggered Circuit shows Excellent Performance

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IISB

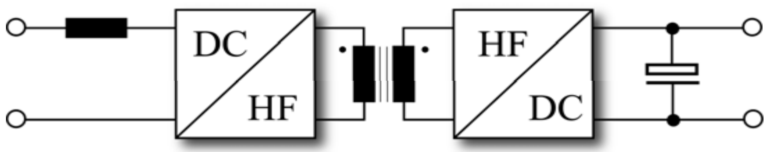
# Isolated DC/DC Converter

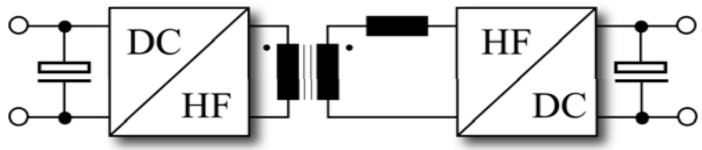
## Dual Active Bridge
## Magnetically Integrated
## Current Doubler

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

# Isolated Bi-Directional DC/DC Converter Topologies

- Single-Stage Topologies
  - *Current-fed Converter Topologies*
  - Voltage-to-Voltage Converters without Choke
    - Series Resonant Converter
    - *Dual Active Bridge*
- Multi-Stage Topologies



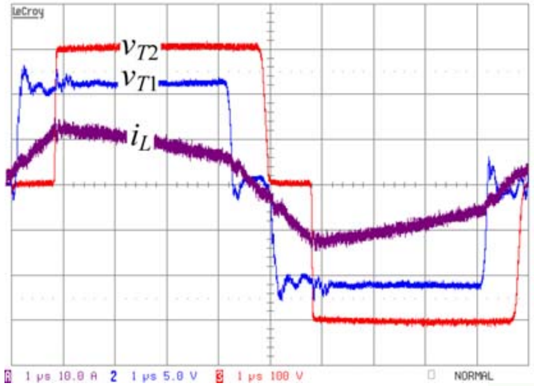

► **No High Current Inductor**

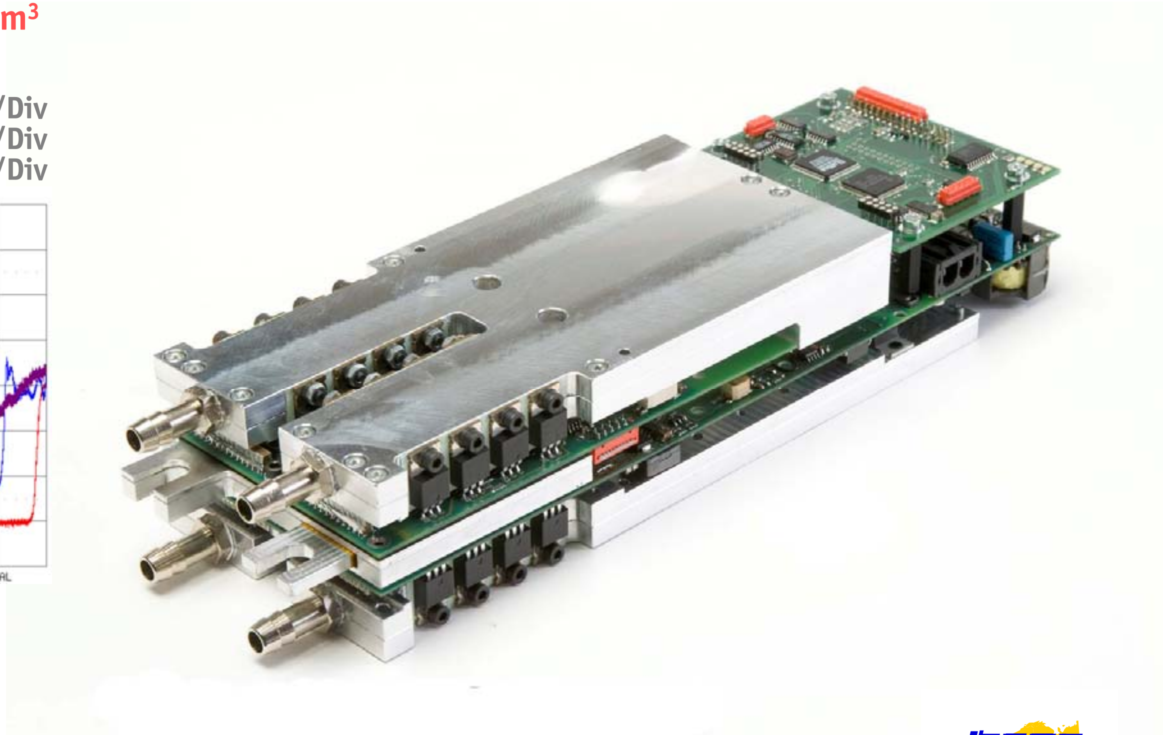
# Prototype of the Dual Active Bridge

2kW
11...16V → 220...450V
η > 90%
100kHz
2 kW/dm³

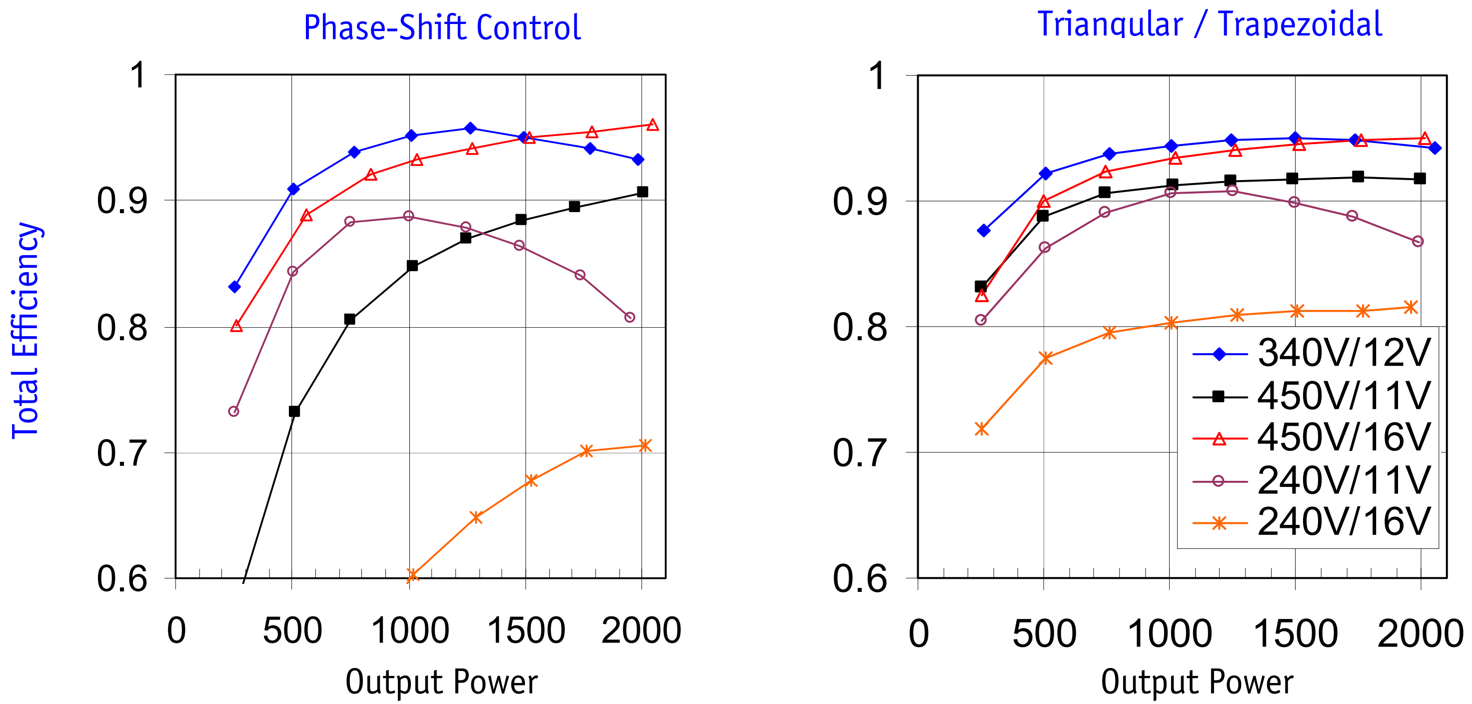
5V/Div
100V/Div
10A/Div

2kW @ 12V → 300V



# Experimental Results

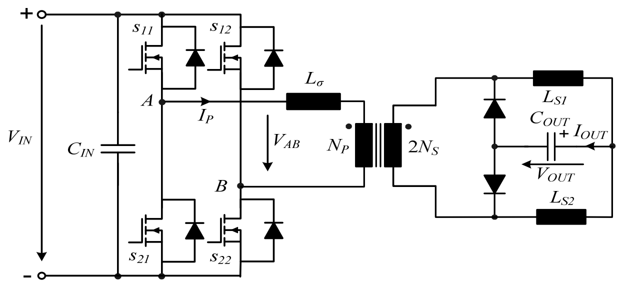


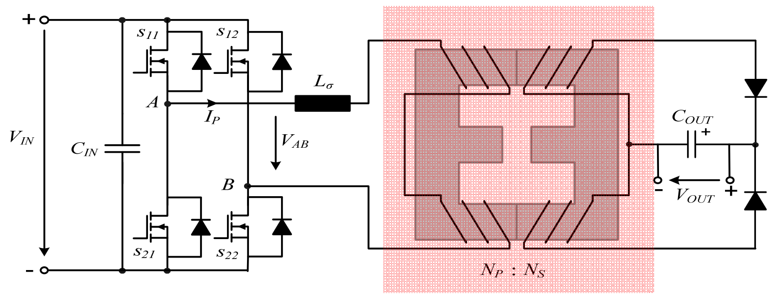

- **Efficiency Increased by 10% at 2kW Output**
- **Significantly Higher Efficiency at Partial Load**

# Isolated DC/DC Converter

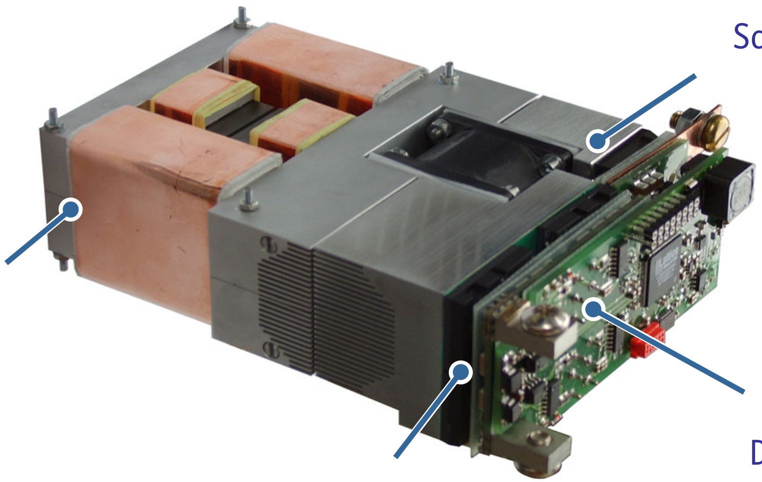
## Magnetically Integrated Current Doubler

# Current Doubler with Integrated Magnetics




**Output Power** 5kW
**Switching Frequency** 200kHz




► **Power Density 8.7 kW/dm$^3$**

# Enabling Technologies Identified in Copenhagen Roadmap Meeting

- Advanced Cooling of Power Semiconductors
- Increased Thermal Cycling Capability / Increased $\Delta T_{j\text{-}c}$
- Advanced Packaging Materials
- Advanced Cooling of Passives
- High Current Low HF Loss Interconnection Technologies
- Local EMI Shielding / Filtering
- Integration of Gate Drives and Sensors etc.
- Reliability / Robustness Test Procedures

- Multi-Domain Design / Optimization Platform

# System Optimization

## Pareto-Optimal Design
## Technology Vectors
## Sensitivities

# *Bottom-Up Roadmap Approach for Power Electronic Systems*

► **How to Identify Future Key Technologies / Required Progress ?**

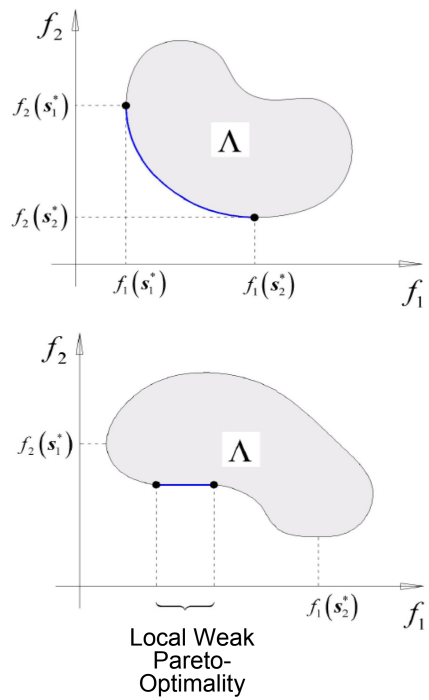
1. **Clarify State of the Art & Mapping of Component Technologies into System Performance**
   **Demonstrator Systems**
2. **Define Goal - as Resulting from *Top-Down Analysis***
3. **Analyze Sensitivities**
4. **Identify Most Influential Technologies**
5. **Derive Required Progress in Specific Technology Metrics / FOM**

# Sensitivities & Technology Vectors

## Conflicting Optimization Goals

- Volume / Weight
- Efficiency
- Costs

## Pareto-Optimal Solutions in a Convex Region




## Technology Space

## Performance Space