Medium-Voltage High-Frequency DC-DC Converter

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Silicon carbide (SiC) semiconductors facilitate a considerably lower specific on-state resistance compared to silicon semiconductors, mainly due to an approximately 10 times higher critical field for avalanche breakdown, E_C. The performance figure of merit $(V_\mathrm{B}^2/R_\mathrm{on})_\mathrm{max} = \mu_\mathrm{N}\varepsilon_\mathrm{S}(2\,E_\mathrm{C}/3)^3$ [V_B: blocking voltage; R_on: theoretically achievable value of the specific on-state resistance of unipolar devices (e.g. Schottky diodes, MOSFETs, JFETs); μ_N and ε_S: electron mobility and semiconductor's dielectric constant, respectively] can be used for the purpose of comparison and results in $\approx 4\ \mathrm{MW/cm^2}$ for Si and $\approx 4000\ \mathrm{MW/cm^2}$ for SiC [1]. On the one hand, the value for the specific on-state resistance R_on achievable with SiC is approximately the 1000$^{\mathrm{th}}$ part compared to that of Si; on the other hand, the blocking voltage achievable with a given chip size and for a given R_on is ≈ 30 times higher for SiC. Thus, SiC facilitates the realization of high voltage / high power unipolar semiconductor devices that cause low switching losses, due to the absence of storage charge.

In spite of these advantages, the very high cost of SiC components confines their use to selected applications, which take particular advantage of the superior device characteristics. One example regards a key component of a smart grid, i.e. the transformer used to transfer power between a Medium Voltage (MV) and a Low Voltage (LV) power network. There, solid-state transformers may economically replace low frequency transformers in the lower power regime and facilitate extended functionality (e.g. reactive power compensation, uninterruptible power supply functionality) [2].

Further fields of applications are niche applications with extreme weight and / or power density requirements. In this context, a light-weight, bidirectional, and isolated DC/DC converter is presented, which provides a MV level DC voltage to the tether of an airborne wind turbine in order to reduce the tether's copper losses [3]. This DC/DC converter transfers power between a LV port (port voltage V_1, 650 V ≤ V_1 ≤ 750 V) and a MV port (port voltage V_2, 6.9 kV ≤ V_2 ≤ 8 kV; the voltage ratio V_1 / V_2 = 750 V / 8 kV ≈ 0.094 remains constant during steady state operation); its rated power is 25 kW (in both directions) and the maximum weight is 6.25 kg [3]. Furthermore, galvanic isolation is required between the LV and MV ports. For this converter the Dual Active Bridge (DAB) topology is selected due to its soft switching properties, which facilitate the use of the high switching frequency, f_S = 100 kHz, needed to achieve a low weight of the converter.

The stringent weight requirements can only be attained with the use of SiC switches. In the presented DAB converter, each switch is composed of the cascode connection of a low voltage MOSFET (IRLB8748PbF, $V_{\mathrm{(BR)DSS}}$ = 30 V) and a 1700 V-SiC JFET. A multi-cell converter setup with 4 cells being connected in series and the use of Neutral Point Clamped (NPC) 3-level converter circuits on the MV side is proposed in order to limit the blocking voltage of a single switch to 1 kV.

The heaviest components of the DAB are the transformer, the inductor, and the 3 heat sinks that are required to cool the different power parts (full bridge on the LV side, NPC converter on the MV side, and transformer / inductor). Dedicated optimization procedures, which are based on the evaluation of respective Pareto fronts, are proposed to optimize these components with respect to minimum weight. For the transformer and the inductor, a combined hardware setup based on E42/21/20 core sets yields a minimum weight of 481 g and the minimum weight of all heat sinks (inclusive fans, and heat pipes) is 419 g. The calculated total weight of one converter cell is 1.41 kg and the calculated minimum efficiency is 96.6 % at rated power. This yields a total weight of 5.7 kg for the final 25 kW DAB converter.

Concluding calculations show that the high switching frequency of 100 kHz is required in order to achieve the specified weight. Furthermore, the targeted weight cannot be achieved with the use of conventional silicon MOSFETs, either due to increased losses or due to increased area requirements (if MOSFETs are operated in parallel), which results in a considerably increased weight of the heat sink and / or the power electronics.

[1] J. A. Cooper, A. Agarwal, "SiC Power-Switching Devices—The Second Electronics Revolution?," Proc. of the IEEE, vol. 90, No. 6, June 2002, pp. 956 – 968.

[2] L. Heinemann, G. Mauthe, "The Universal Power Electronics Based Distribution Transformer, An Unified Approach," 32nd IEEE Power Electronics Specialists Conf. (PESC 2001), Vancouver, Canada, June 17-21, 2001, pp. 504 – 509.

[3] J.W. Kolar, T. Friedli, F. Krismer, A. Looser, M. Schweizer, P. Steimer, and J. Bevirt, "Conceptualization and Multi-Objective Optimization of the Electric System of an Airborne Wind Turbine," 20 th IEEE Intern. Symp. on Ind. Electronics (ISIE 2011), Gdansk, Poland, June 27-30, 2011.

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Outline

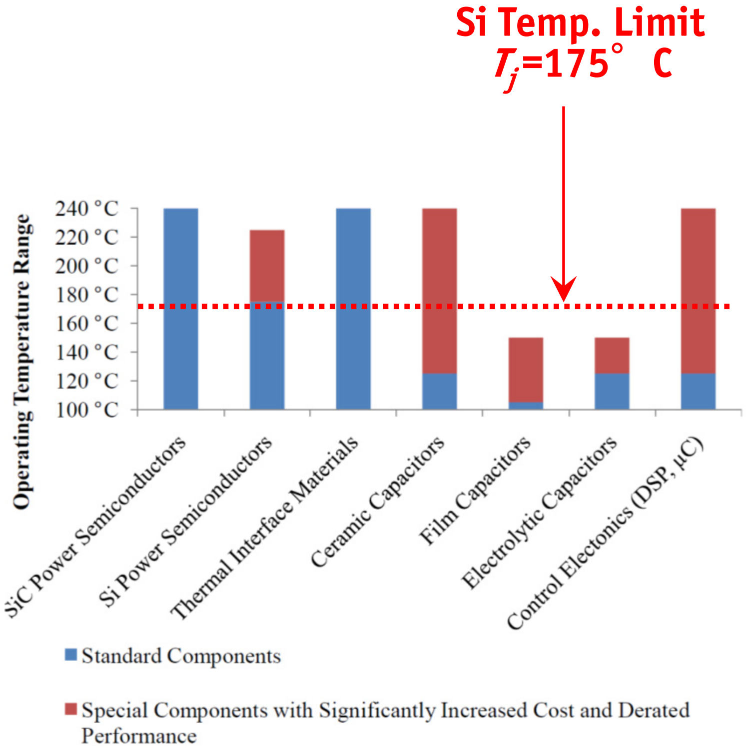
- **Properties of SiC devices**
  - *Higher Operating Temperature*
  - *Faster Switching / Higher Switching Frequency*
  - *Higher Blocking Voltage*
- **Applications of MV and HF Power Converters**
- **Weight optimized MV Dual Active Bridge Converter**
  - *Converter Design*
  - *Comparison: Si vs. SiC*
- **Conclusion**

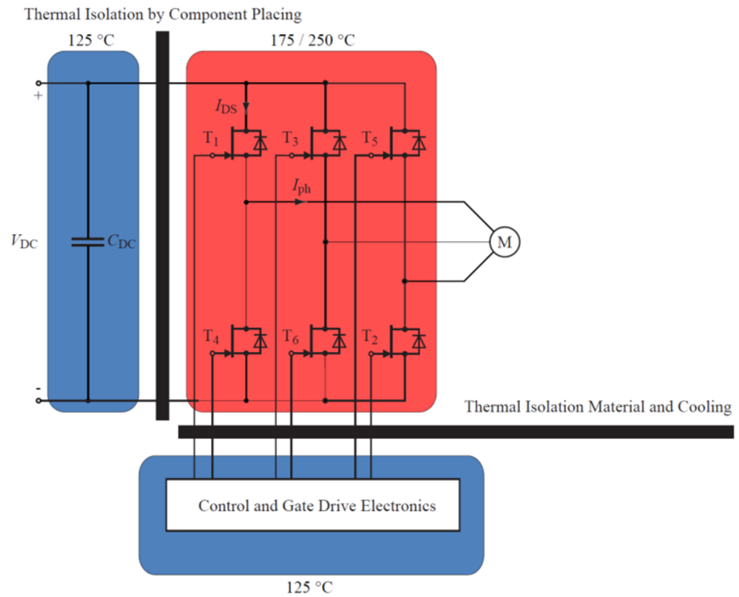
Part I

Properties of SiC Devices

- Higher Operating Temperature
- Faster Switching / Higher Switching Frequency
- Higher Blocking Voltage

Higher Operating Temperature





120° C Ambient Air Cooled Automotive Inverter

- **Missing HT Package (Reliability)**
- **Missing HT Sensors & Control Electronics & Fans etc.**

D. Bortis, B. Wrzecionko, J. W. Kolar, *A 120° C Ambient Temperature Forced Air-Cooled Normally-off SiC JFET Automotive Inverter System, Proceedings of the Applied Power Electronics Conference and Exposition (APEC), Fort Worth, TX, March 6-10, 2011.*

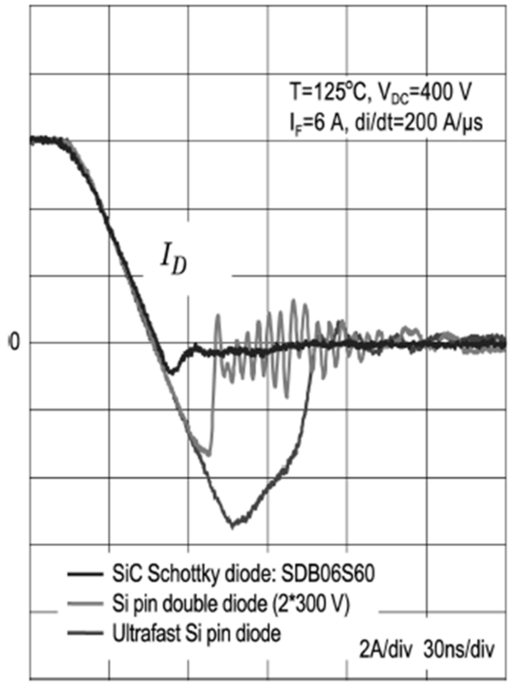
Faster Switching

- Missing HF Package

- Hard Active Turn-off/Turn-on   Often Not Required (ZVS)
- High Switching Frequency   Often Not Required (Passives)

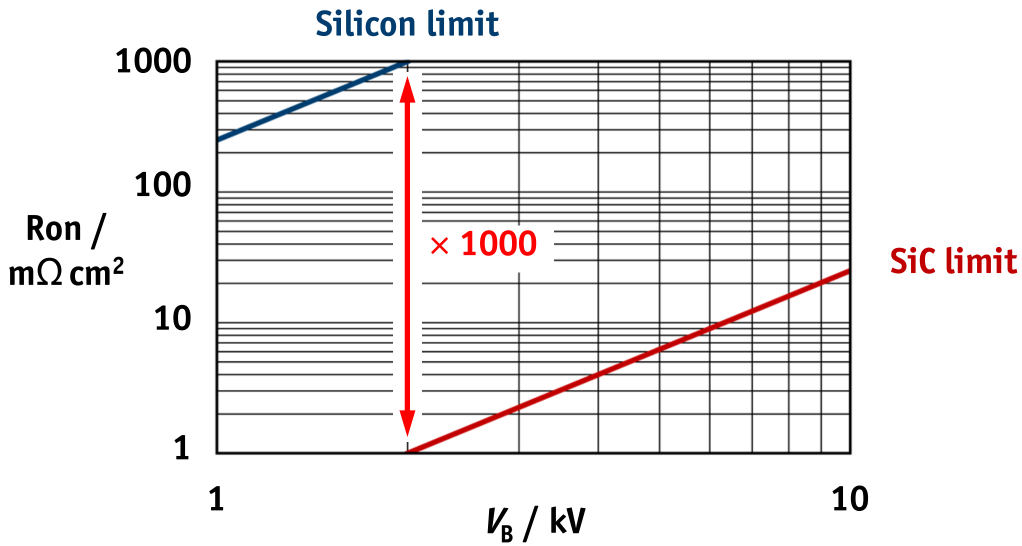
- Zero Recovery Rectifiers
- Zero Tail Current Switches

Unipolar devices



Higher Blocking Voltage (I)

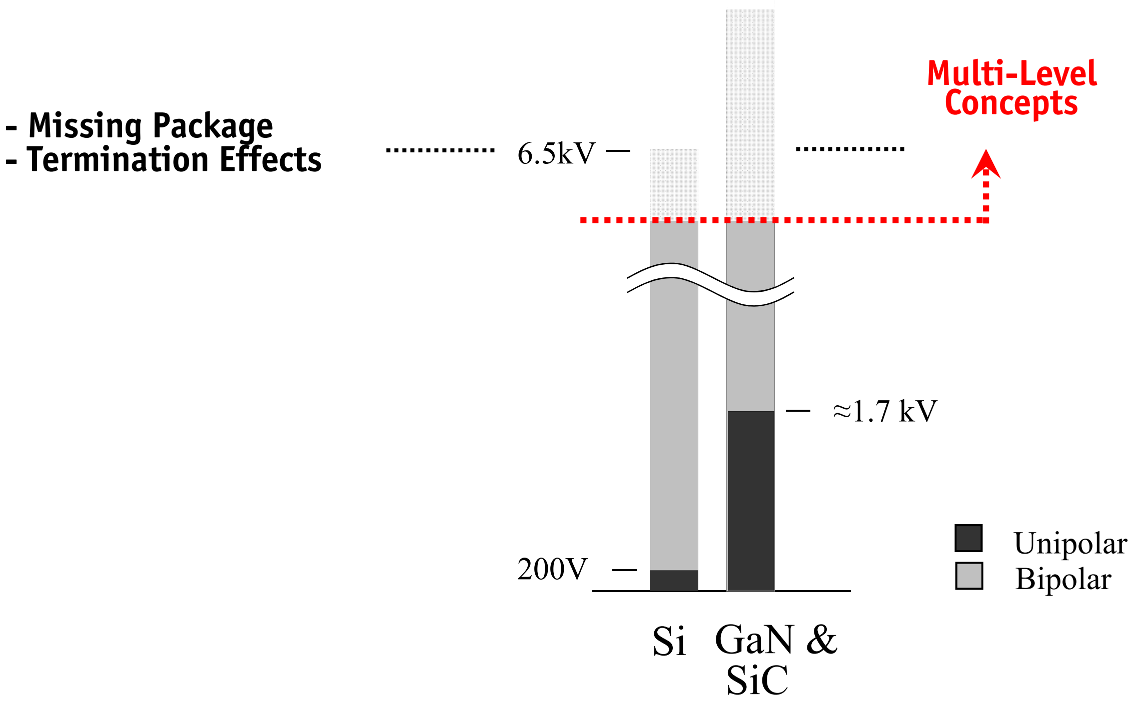
- **Unipolar devices:** $$\left.\frac{V_B}{R_{on}}\right|_{max} = \mu_n \varepsilon \left(\frac{2E_C}{3}\right)^3 = \begin{cases} \approx 4\,\mathrm{MW/cm^2} & \text{for Si} \\ \approx 4000\,\mathrm{MW/cm^2} & \text{for SiC} \end{cases}$$



- **Theoretically achievable specific on-state resistance of SiC ≈ 1/1000 of Silicon**

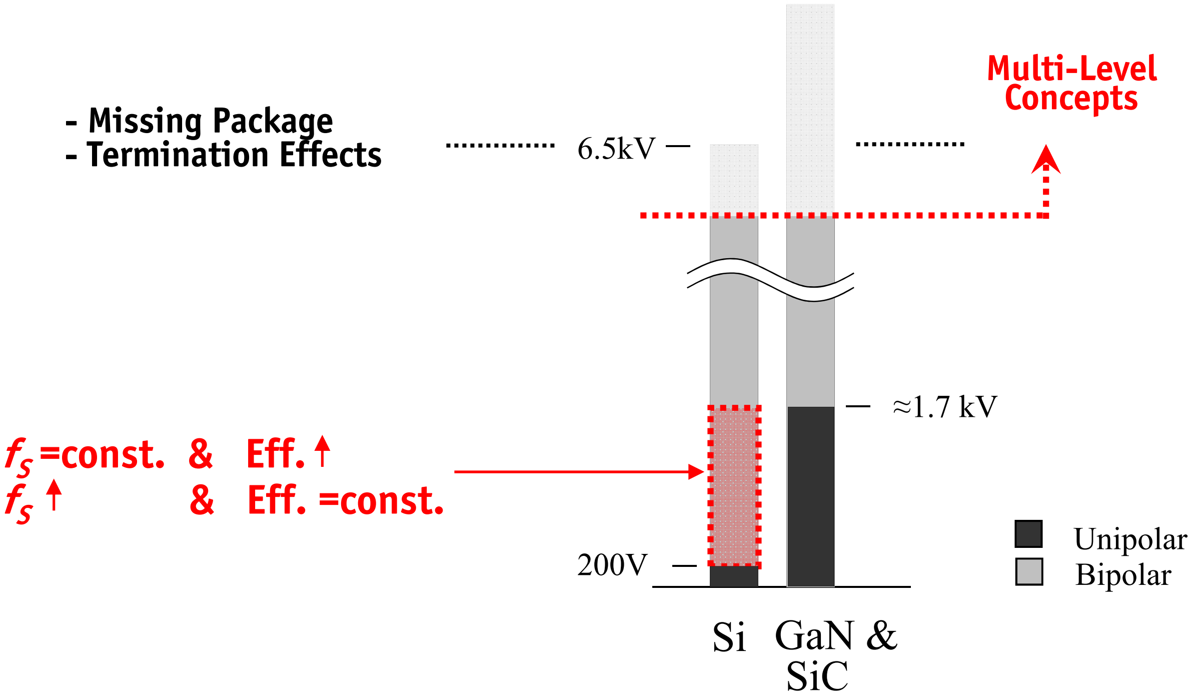
J. A. Cooper, A. Agarwal, *SiC Power-Switching Devices—The Second Electronics Revolution?, Proc. of the IEEE, vol. 90, No. 6, June 2002.*

Higher Blocking Voltage (II)



- Zero Recovery Rectifiers

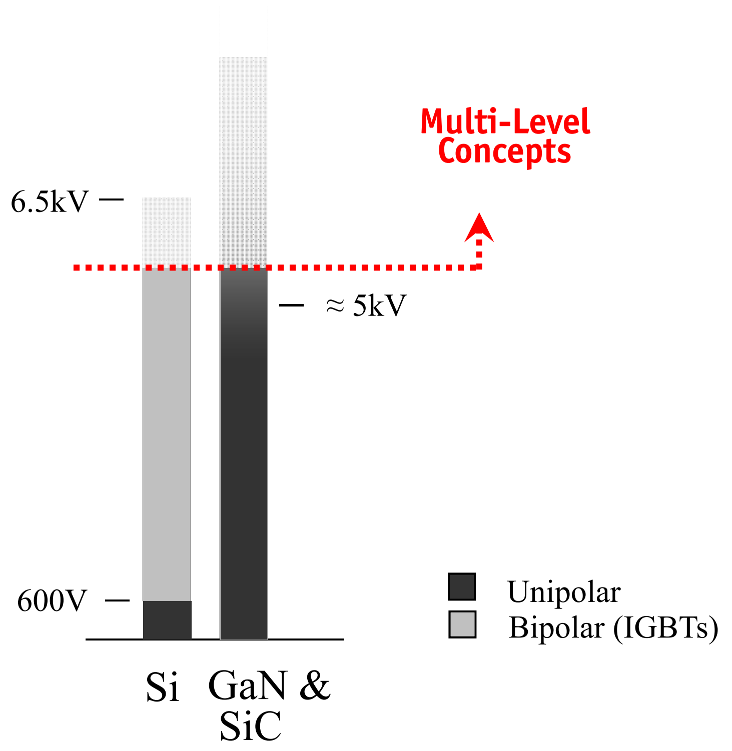
Higher Blocking Voltage (II)



- Zero Recovery Rectifiers - Replace Si Diodes in 0.6 ... ≈ 5kV Range

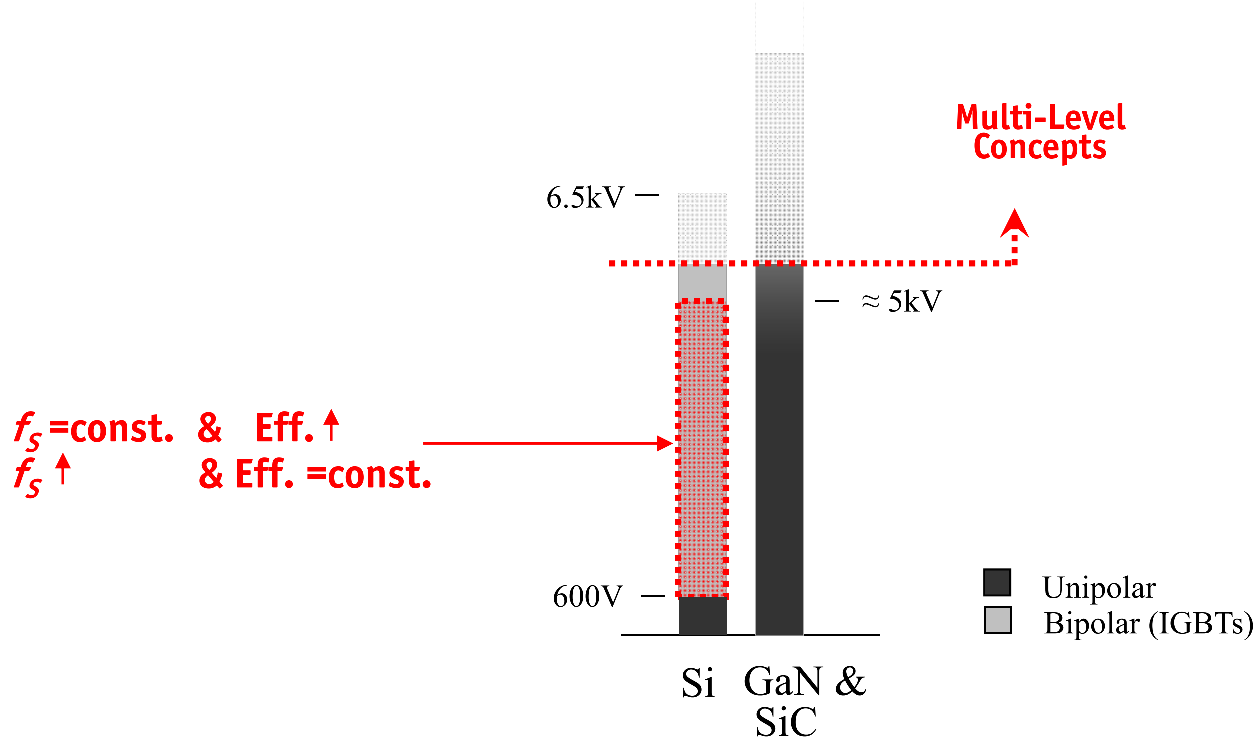
⟶ SiC Diodes: Low/Medium Voltage, High Switching Frequency Applications

Higher Blocking Voltage (III)



- **Zero Tail Current of SiC FETs**
- **Zero $V_{CE,0}$**

Higher Blocking Voltage (III)

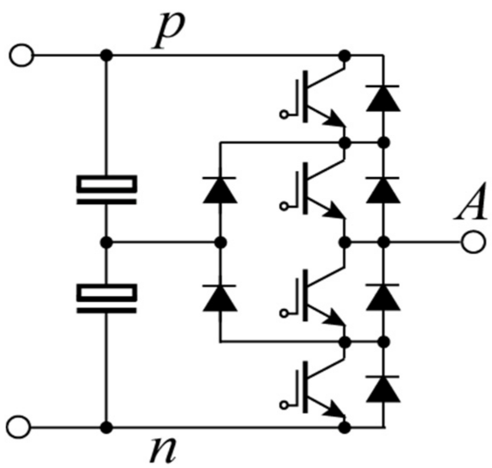


- Zero Tail Current of SiC FETs - Replace Si IGBTs in 1.2 ... ≈ 5kV Range
- Zero $V_{CE,0}$

→ SiC FETs: Medium Voltage, High Switching Frequency Applications

Higher Blocking Voltage (IV)

- **Strong Competitor: Multi-Level Approach**



- **Multiplies Frequency and/or Voltage without Increasing Switching Losses !** → $f_{S,eff} = n \cdot f_S$, $U_{eff} = n \cdot U$, $P_S = P_S(f_S)$

- **Redundancy**
- **Modularity**

- **Complexity** ↑

Part II

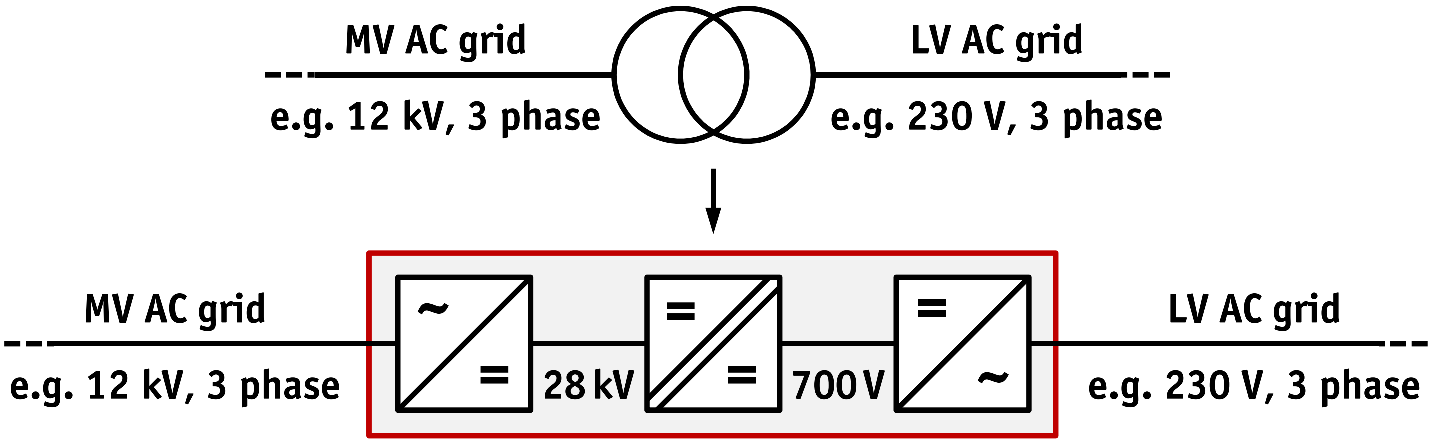
Medium Voltage, High Frequency Power Converters

- Smart Grids: Solid-State Transformer
- DC/DC converter for an airborne wind turbine
  - Design of a weight optimized Dual Active Bridge converter
  - Comparison: Si vs. SiC

Applications of MV and HF Power Converters (I)

■ Smart Grids: Solid-State Transformer

- Economical replacement for low frequency transformers in the lower power range
- Facilitates extended functionality (e.g. reactive power compensation, UPS)



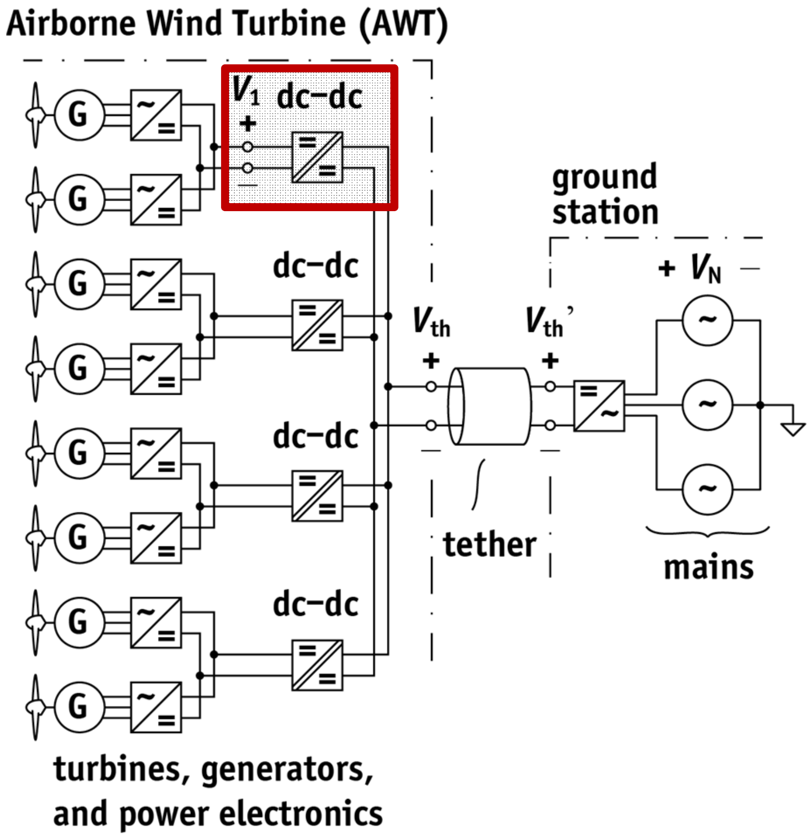
SiC switches facilitate:

- Reduced complexity, increased reliability
- High switching frequency (to reduce audible noise)

L. Heinemann, G. Mauthe, *The Universal Power Electronics Based Distribution Transformer, An Unified Approach, 32nd IEEE Power Electronics Specialists Conf. (PESC 2001), Vancouver, Canada, June 17-21, 2001, pp. 504 – 509.*

Applications of MV and HF Power Converters (II)

- Niche applications with extreme weight and / or power density requirements, e.g. **bidirectional, isolated DC/DC converter** for an airborne wind turbine



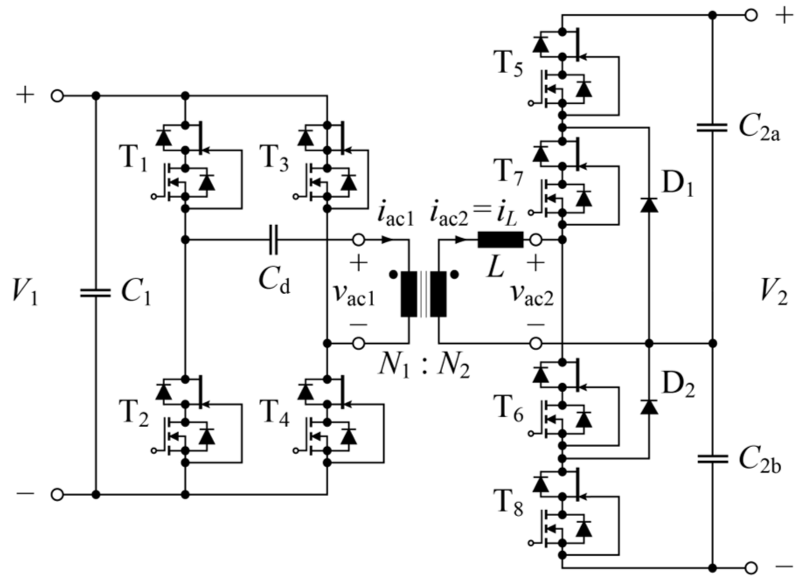
Medium Voltage, High Frequency Dual Active Bridge (DAB)

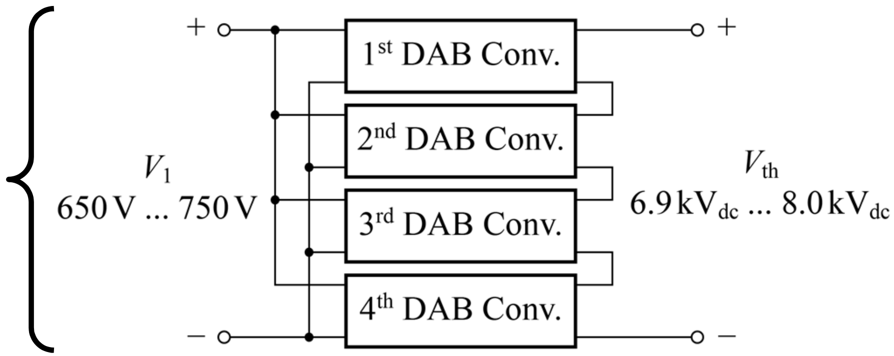
- **High-Frequency Medium Voltage Multi-Cell DC-DC Converter**

  - **Rated total power: 25 kW**
  - **DC bus voltage: 650 V … 750 V**
  - **Tether voltage: 6.9 kV … 8 kV (constant voltage transfer ratio)**
  - **Galvanic isolation**

  - **Maximum weight: 6.25 kg**

  - **Max. blocking voltage of 1000 V / JFET for 4 converter cells (1700 V devices) → Medium Voltage unipolar switch (5 … 6.5 kV) would considerably reduce complexity**





J.W. Kolar, T. Friedli, F. Krismer, A. Looser, M. Schweizer, P. Steimer, J. Bevirt, *Conceptualization and Multi-Objective Optimization of the Electric System of an Airborne Wind Turbine, 20 th IEEE Intern. Symp. on Ind. Electronics (ISIE 2011), Gdansk, Poland, June 27-30, 2011.*

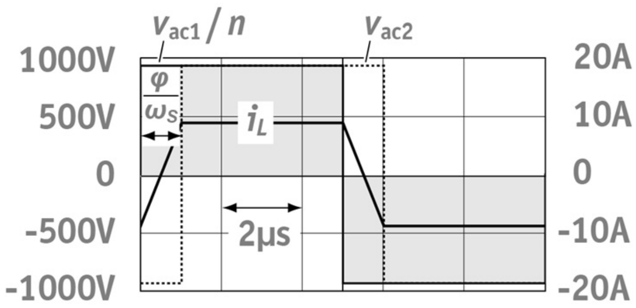
Operating Principle and Design of the DAB

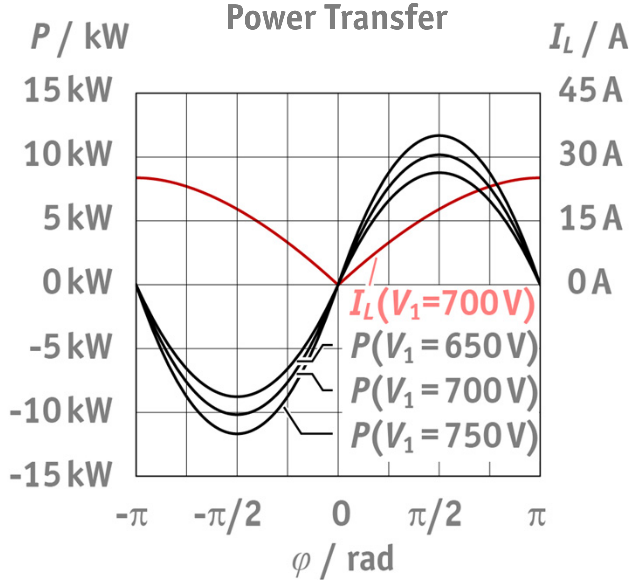
- Rated power, single converter: 6.25 kW
- DC port voltage V_1: 650 V ... 750 V
- DC port voltage V_2: 1.7 kV ... 2 kV
- $V_1 / V_2 \approx 0.38$ = const. → Conventional Modulation
- $n = N_1 / N_2 = \underline{0.75}$
- Selected switching frequency: 100 kHz

$$L = \frac{\min\left(\frac{V_1}{n}\ \frac{V_2}{2}\right)}{2\pi f_S \frac{P_{max}}{\eta_e}} \cdot \varphi_{max} \cdot \left(1 - \frac{\varphi_{max}}{\pi}\right)$$

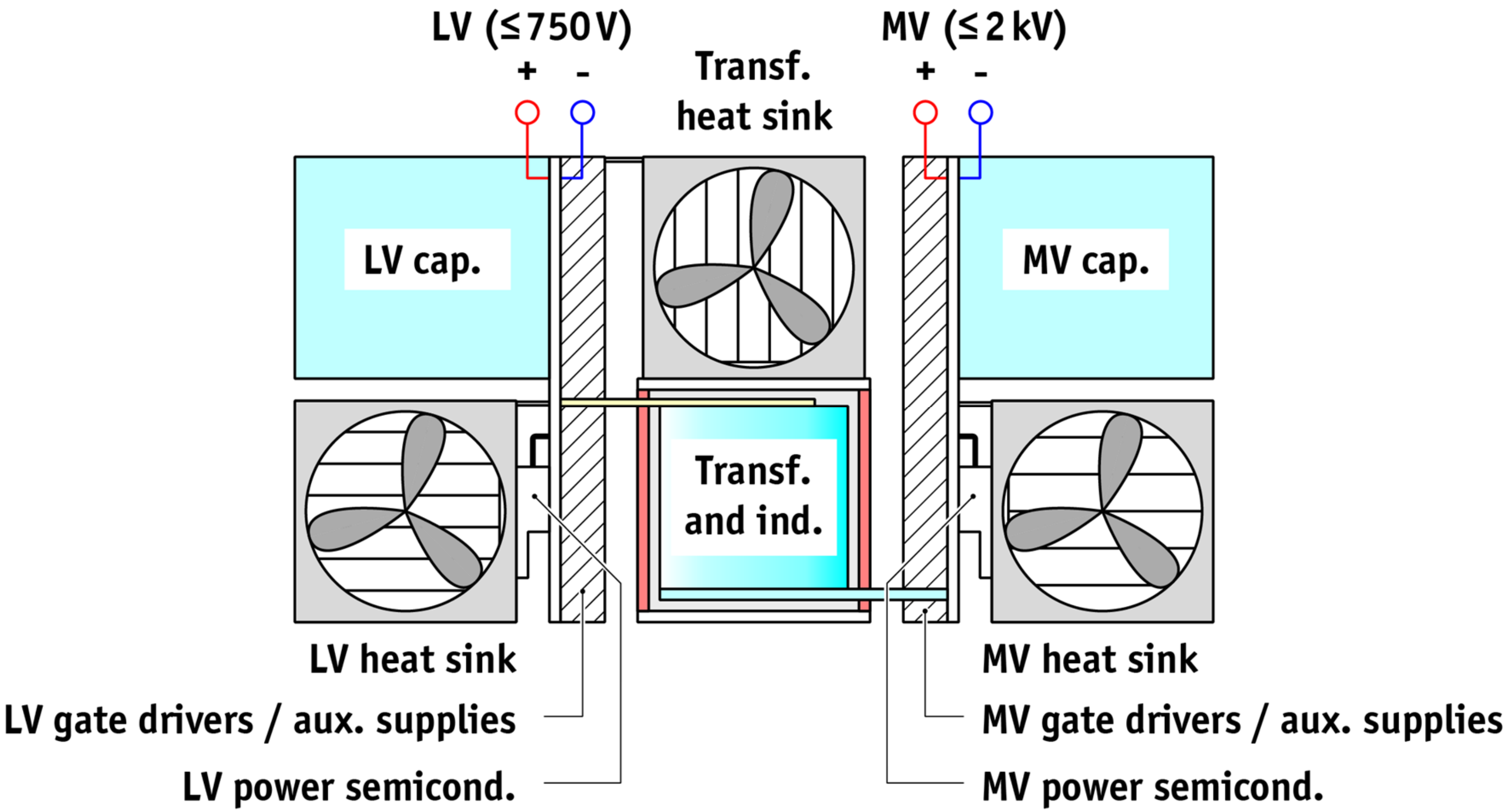
- $\underline{L = 107\ \mu H}$ (for $\varphi_{max} = \pi / 4$ and $\eta_e = 95\%$)

Typical waveforms





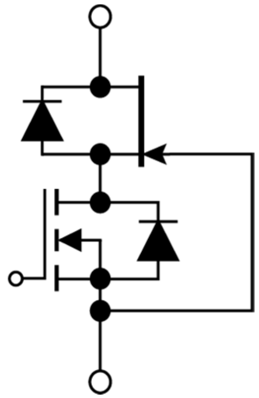
Proposed Converter Setup



- Separate heat sinks for the LV side, the MV side, and the HF transformer / inductor (possible weight savings if LV and MV heat sinks are combined ≈ 30 g for a single DAB)

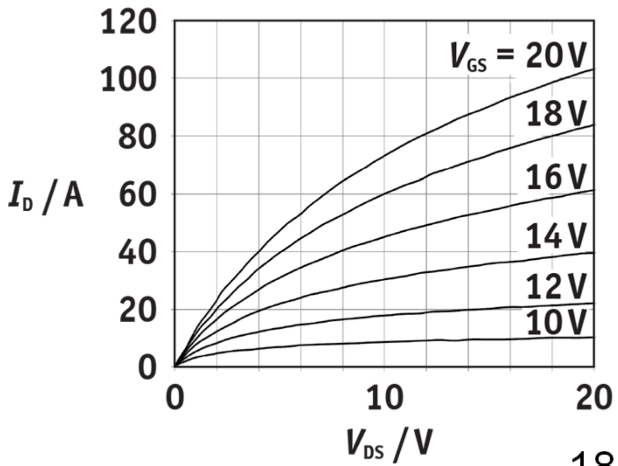
Selected Power Semiconductors (I)

- Normally-on SiC JFETs, Cascode Circuit
  - + Standard gate drive circuit
  - - Low voltage MOSFET required



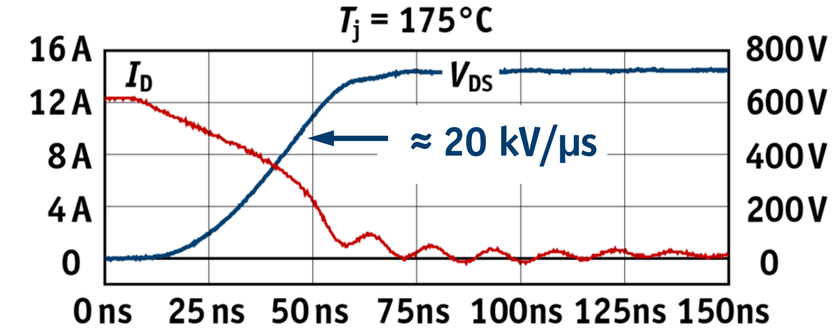
- Normally-off SiC JFETs, e.g. SJEP120R063 (1.2 kV, 63 mΩ)
  - + Normally-off characteristics
  - - Special gate driver; continuous gate current during on-state (e.g. SJEP120R063: $I_G \approx 0.4\,A$ @ $V_{GS} = 3\,V$)

- SiC MOSFETs, e.g. CMF20120D (1.2 kV, 80 mΩ)
  - + Normally-off characteristics
  - - Special gate driver requirements due to low transconductance

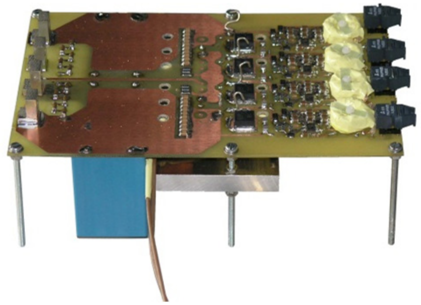


Selected Power Semiconductors (II)

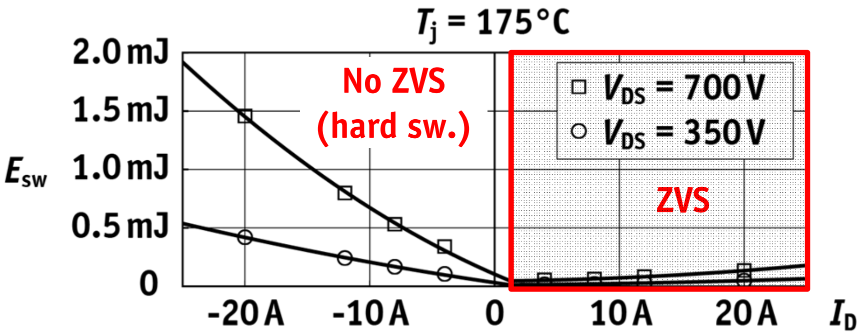
- Measured waveforms during switching

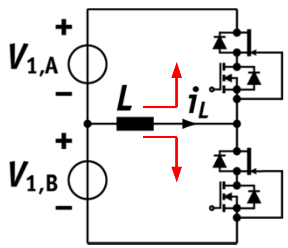


New Measurement Setup: NPC Converter



- Measured switching losses



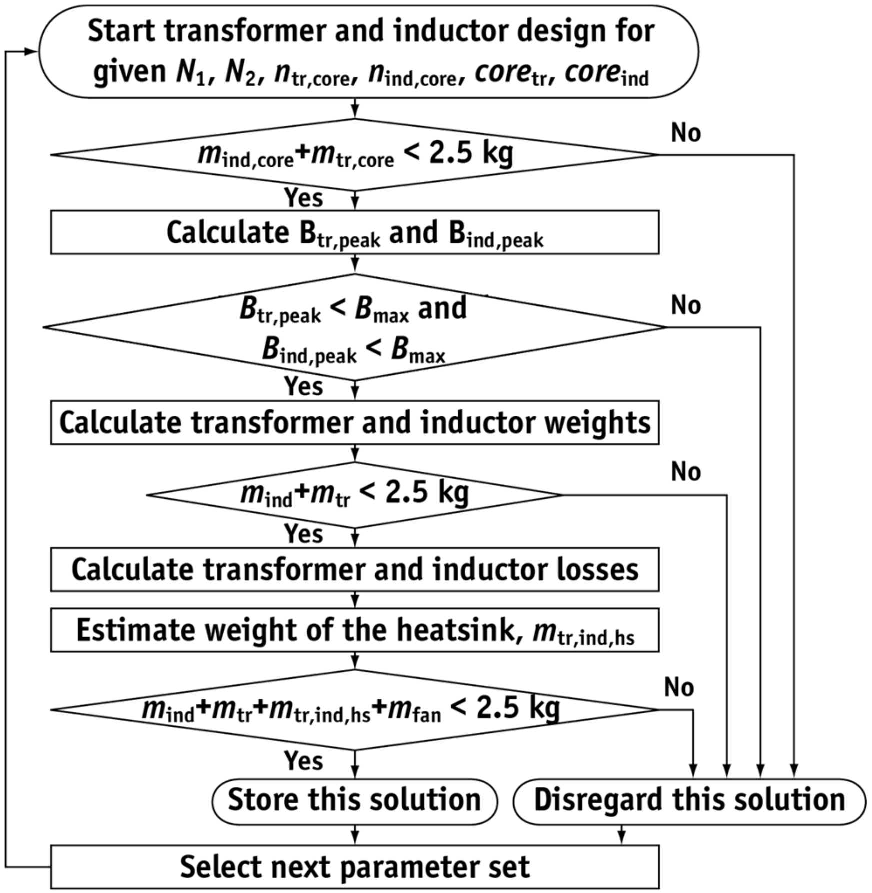


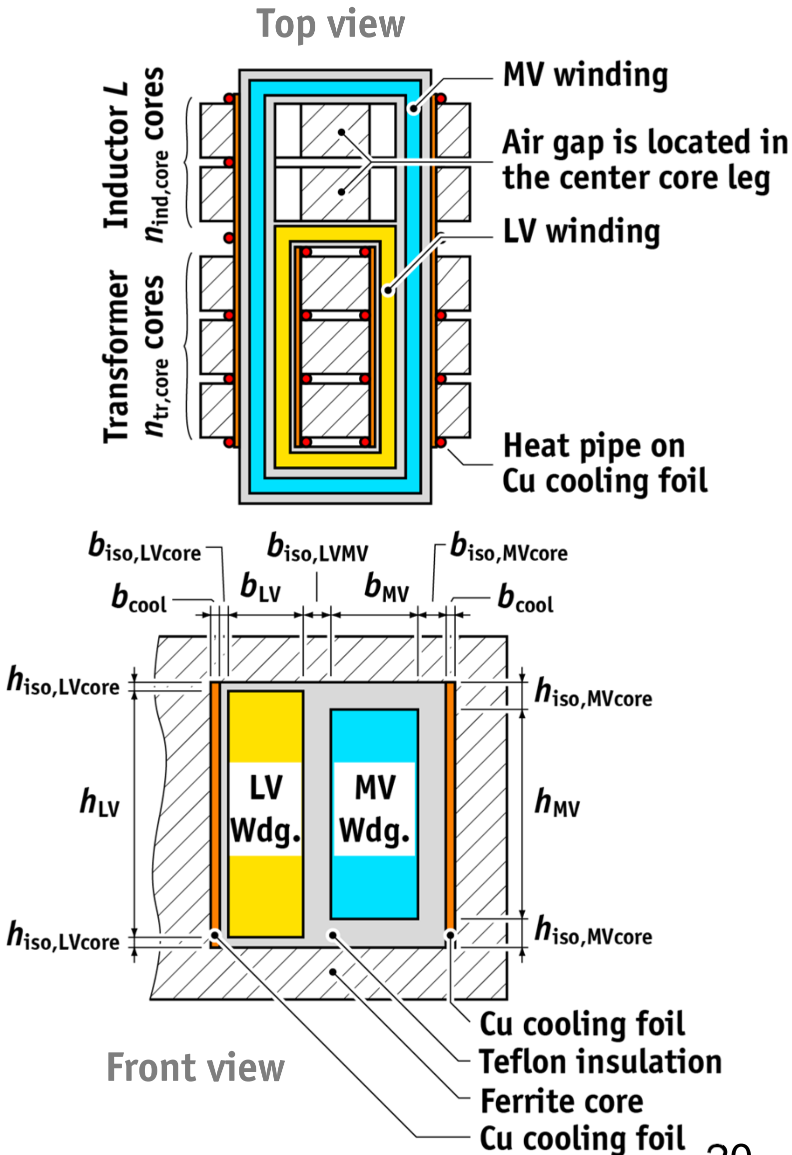
- 1.2 kV devices will be replaced by 1.7 kV devices in the final prototype

→ ZVS: low switching losses; e.g. 74 µJ @ 700 V, 10 A (7.4 W / switch at 100 kHz)

Transformer Optimization (I)

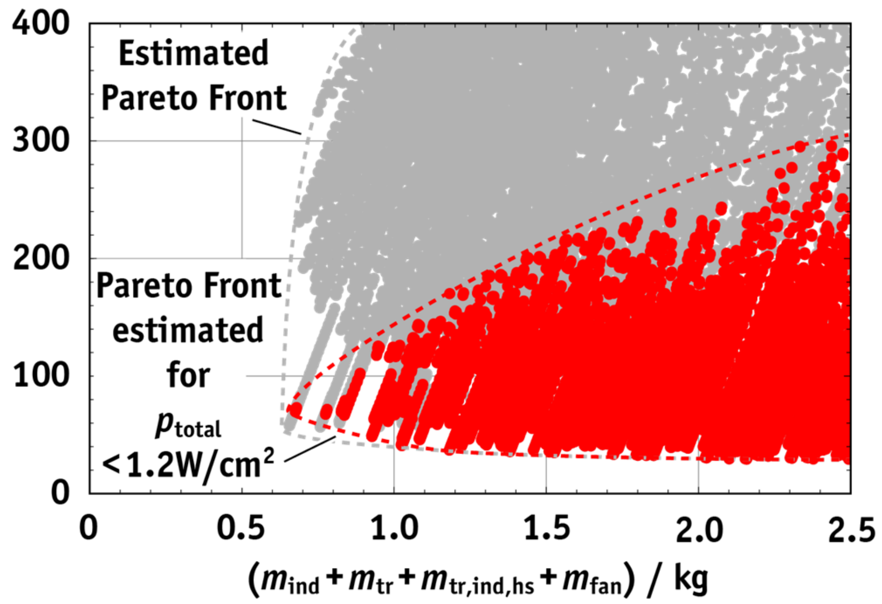
- **Design Procedure**





Transformer Optimization (II)

- **Design Results**



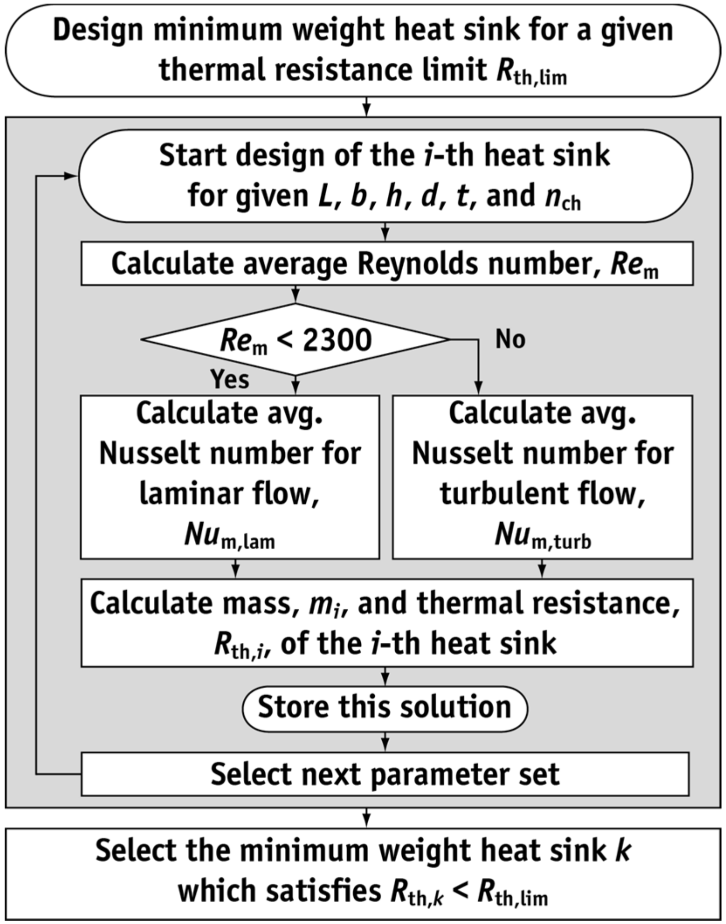
- $N_1 = 21$, $N_2 = 28$, $l_{air} = 2.3$ mm
- Transformer core: 2 × E42/21/20 core sets
- Inductor core: one E42/21/20 core set
- LV litz wire: 151 × 0.071 mm
- MV litz wire: 132 × 0.071 mm

Parameter space considered for $f_S = 100$ kHz

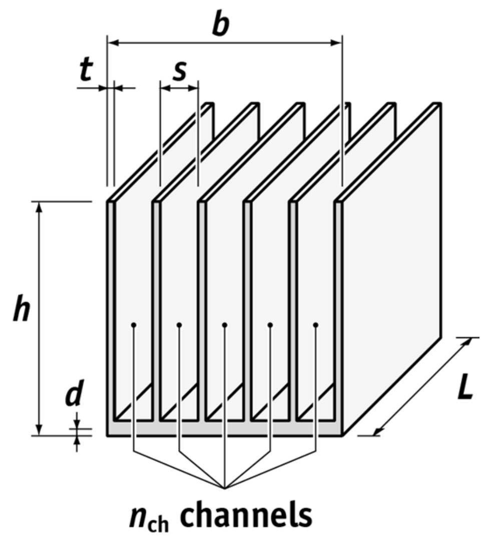
$5 \leq N_1 \leq 40$
$N_2 = \text{round}(N_1 \cdot 1\ \text{kV}/750\ \text{V})$
$n_{tr,core}$ is one out of {1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20}
$n_{ind,core}$ is one out of {1, 2, 3, 4, 5, 7, 10}
$core_{tr}$ is one out of {E30/15/7, E32/16/9, E42/21/20, E55/28/21, E65/32/27, E70/33/32, UI93/76/30, UU93/76/30}
$core_{ind}$ is one out of {E30/15/7, E32/16/9, E42/21/20, E55/28/21, E65/32/27, E70/33/32, UI93/76/30, UU93/76/30}

Heat Sink Optimization

▸ Design Procedure



Front view



▸ Design Results

	L/mm	t/mm	n_{ch}	R_{th}/(K/W)	m/g
LV	47	1.1	7	0.9	61
MV	47	1.1	6	1.0	56
Trf.	79	1.0	7	0.63	97

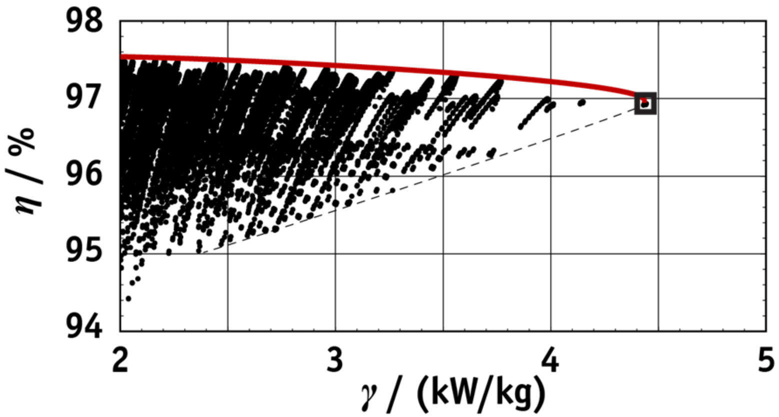
h = 40 mm, b = 40 mm, d = 3 mm, fan: San Ace 40 (50 g)

U. Drofenik, G. Laimer, J. W. Kolar, *Theoretical Converter Power Density Limits for Forced Convection Cooling, PCIM 2005, Nuremberg, Germany, June 07-09, 2005, 12 pp.*

DAB with SiC-JFETs: Design Results

- **Max. converter losses (V_1 = 650 V, P_{in} = 6.25 kW / 0.95 = 6.6 kW)**
  - Semicond. (cond. + sw.), LV: 79 W, MV: 68 W
  - Transformer windings, LV: 17 W, MV: 24 W
  - Core losses, transf.: 29 W, ind.: 8 W
  - Max. losses of transf. + ind.: 70 W
  - Max. converter losses: 217 W
  - **Calculated efficiency: 96.6 %**

γ-η-Pareto front for V_1 = 700 V

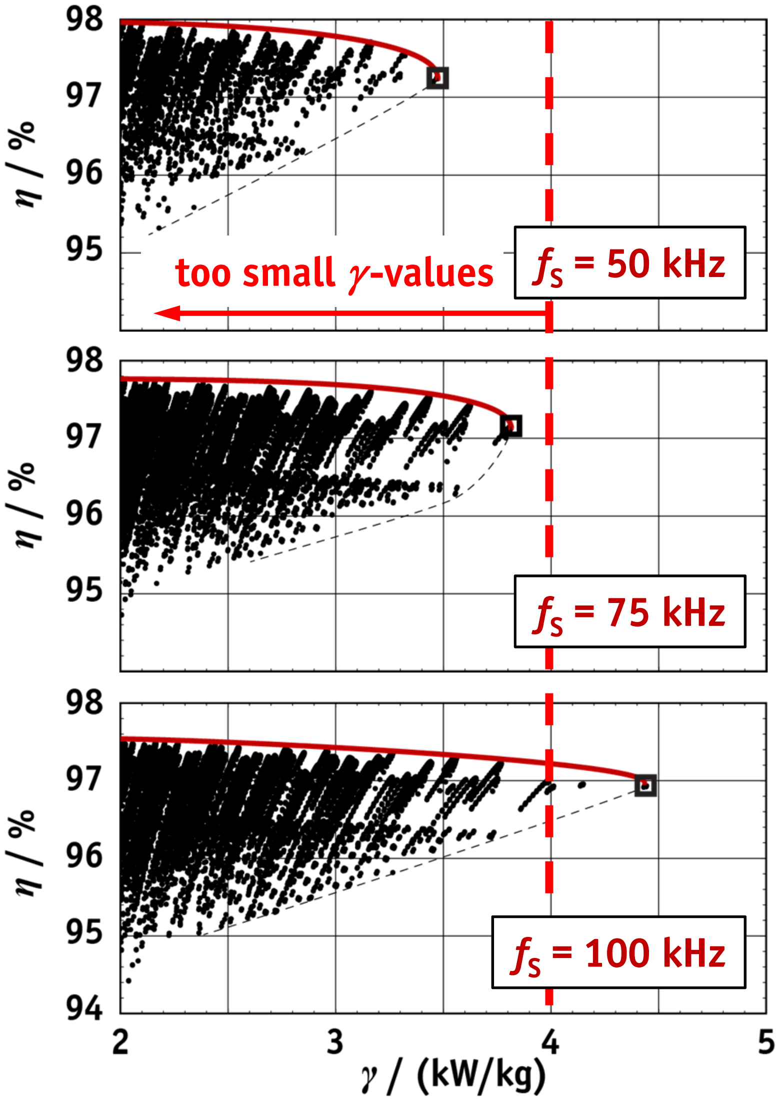


- **Converter Weight:**
  - Semiconductors, LV: 24 g, MV: 30 g
  - Gate drivers (estimated), LV: 80 g, MV: 80 g
  - PCBs (estimated), LV: 40 g, MV: 50 g
  - Capacitors, C_1: 65 g, C_d: 15 g, C_{2a}+C_{2b}: 130 g
  - Transformer + Ind.: 481 g
  - Heat sinks and fans, LV: 111 g, MV: 106 g, Tr.: 202 g (includes bottom plate and heat pipes)
  - **Total weight: 1.41 kg → 5.7 kg for the final 25 kW converter system (4 DABs)**

Justifying the Selected the Switching Frequency

- f_S = 50 kHz
  - η = 97.2 %
  - γ = 3.5 kW/kg
  - m = 7.1 kg > 6.25 kg
- f_S = 75 kHz
  - η = 97.1 %
  - γ = 3.8 kW/kg
  - m = 6.6 kg > 6.25 kg
- f_S = 100 kHz
  - η = 96.9 %
  - γ = 4.4 kW/kg
  - m = 5.7 kg < 6.25 kg

- Even higher switching frequencies feasible?
  - ↳ Will be investigated using a converter prototype



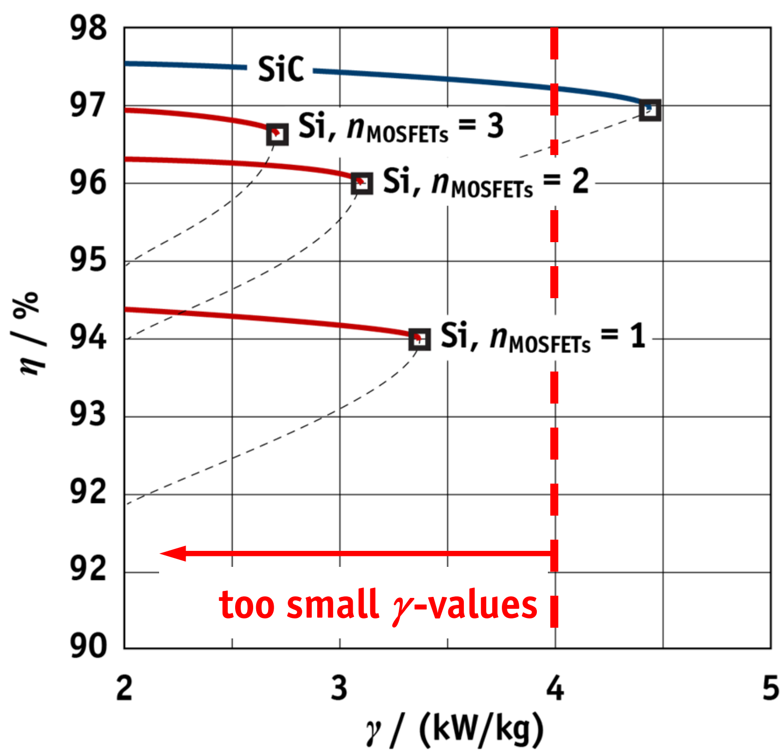
DAB with Si-MOSFETs: Design Results and Comparison

Considered MOSFET: IXFB39N120P

- Max. blocking voltage: 1200 V
- On-state resistance: 350 mΩ
- Package: TO 264
- Weight: 10 g

- 5 stages on the MV side due to reduced max. blocking voltage
- Multiple MOSFETs are connected in parallel ($n_{MOSFETs}$) to achieve a lower on-state resistance

γ-η-Pareto front for V_1 = 700 V and f_S = 100 kHz



→ **With MOSFETs and f_S = 100 kHz the converter weight exceeds the specified limit**

Conclusions

- **SiC Converters**

- Same Topologies	as Si
- Same Modulation (ZVS)	as Si
- Same Passives / Filters	as Si
- Same Sensors	as Si
- Same Digital Control	as Si

- **SiC (Unipolar) Power Semiconductors**

  - Offer a Degree of Design Freedom
  - Offer Extreme Performance @ Higher Costs
  - Costs / Performance Ratio Decides
  - Especially Interesting for MV & HF:
    - Smart grids: solid-state transformer
    - Niche applications with extreme weight and / or power density requirements

Thank You!