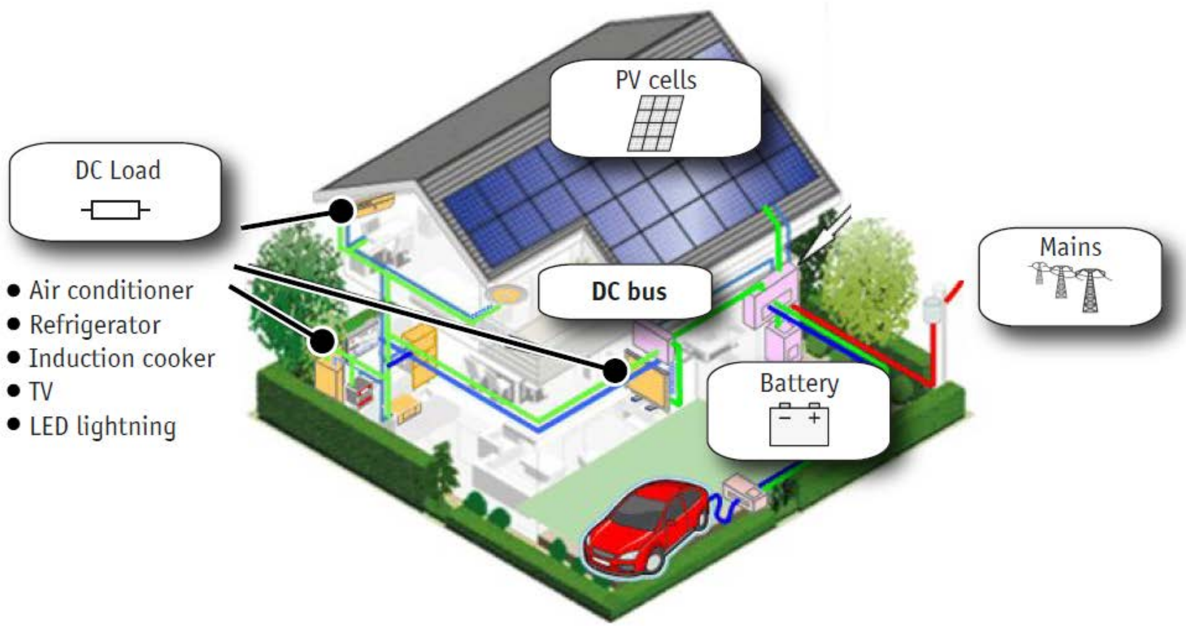
Case Study

Bidirectional Isolated DC/DC Converter with Wide Input Voltage Range for Residential Energy Management Applications

Ralph M. Burkart and J. W. Kolar
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

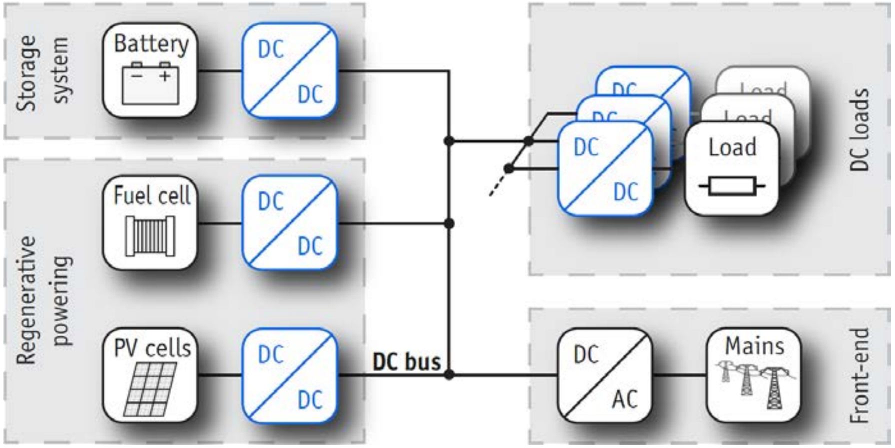
Motivation

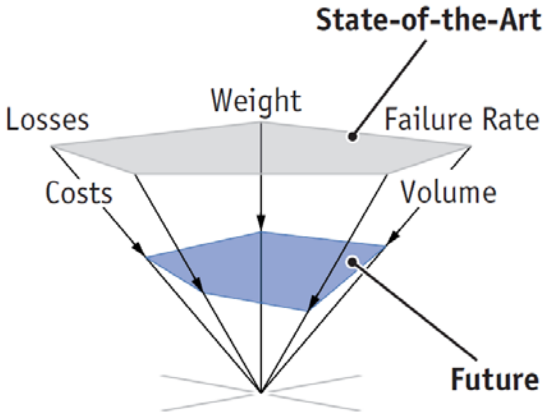


Next generation residential energy management systems

- Renewable energy sources, local storage systems and intelligent load management
- DC distribution bus and single connection point to AC utility grid
- Possible element of a future smart grid system

▶ Challenges





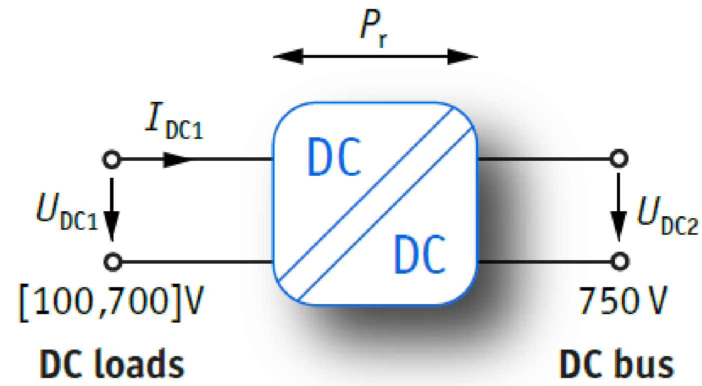
Requirements for DC/DC converters

- **High functionality**
  - **Bidirectional power flow**
  - **Galvanic isolation**
  - **Wide voltage range**
- **High conversion efficiency at low volume and costs**

▶ Bidirectional Isolated DC/DC Converter with Wide Input Voltage Range

Universal DC/DC converter

- Meets all requirements at once
  - Bidirectional power flow
  - Galvanic isolation
  - Wide voltage range
  - High efficiency & power density
- Universal building block at low costs
  - Reduced system complexity
  - Development costs only once
  - Economies of scale



Converter specifications

Rated power	P_r	5 kW
Input voltage range	$[U_{DC1,min}, U_{DC1,max}]$	[100,700] V
Output voltage	U_{DC2}	750 V
Maximum input current	$I_{DC1,max}$	22 A
Maximum efficiency	η_{max}	> 98 %

▶ Design Steps

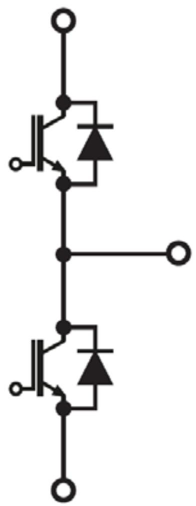
i. Selection of semiconductors & topology

ii. Selection of modulation scheme

iii. Multi-objective modeling and optimization

iv. Experimental verification

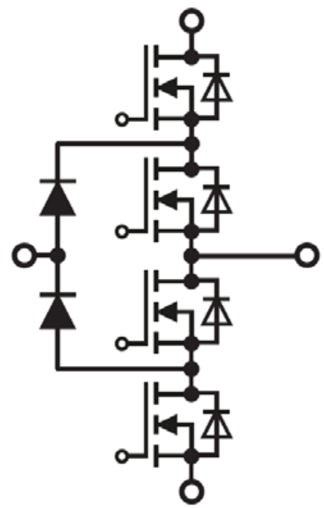
▶ Selection of Semiconductor Type



Si IGBT

- Cheap
- 1200 V rated available

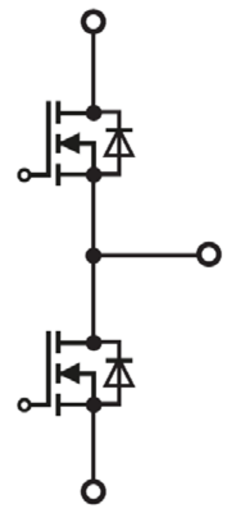
- Conduction losses not scalable
- No ZVS possible
  - ▶ Only ZCS
  - ▶ Topological restrictions



Si super junction MOSFET

- Conduction losses scalable
- ZVS possible

- Non-zero ZVS losses (due SJ)
- Large specific C_{oss}
- Only 650 V rated available
  - ▶ NPC half-bridge necessary
  - ▶ Increased part count

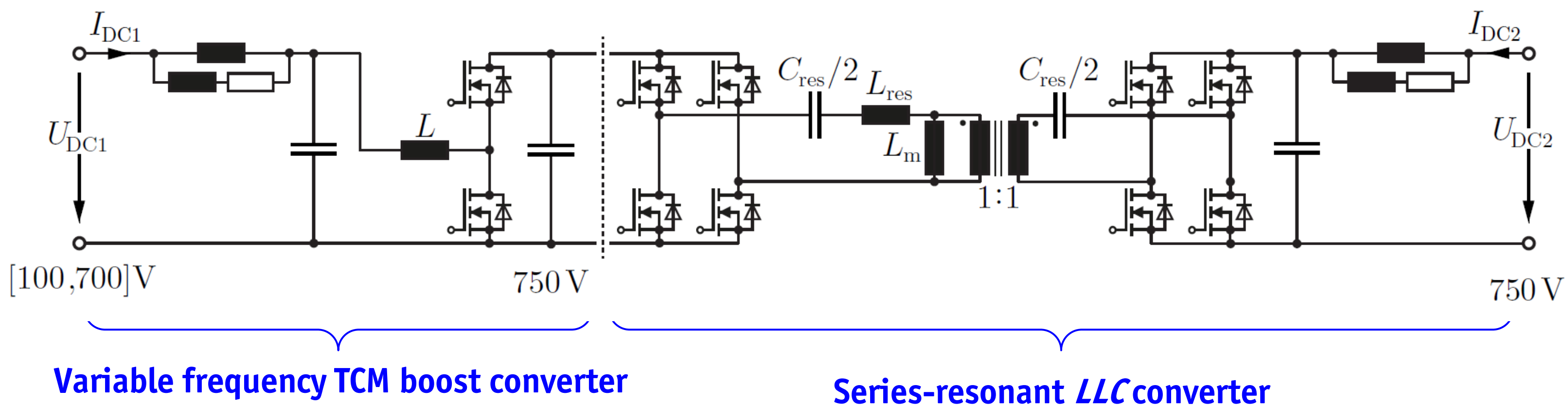


SiC vertical D-MOSFET

- Conduction losses scalable
- Very low ZVS losses
- 1200 V rated available
- Low specific C_{oss}

- Costs

▶ Selection of Topology: Two-Stage Converter



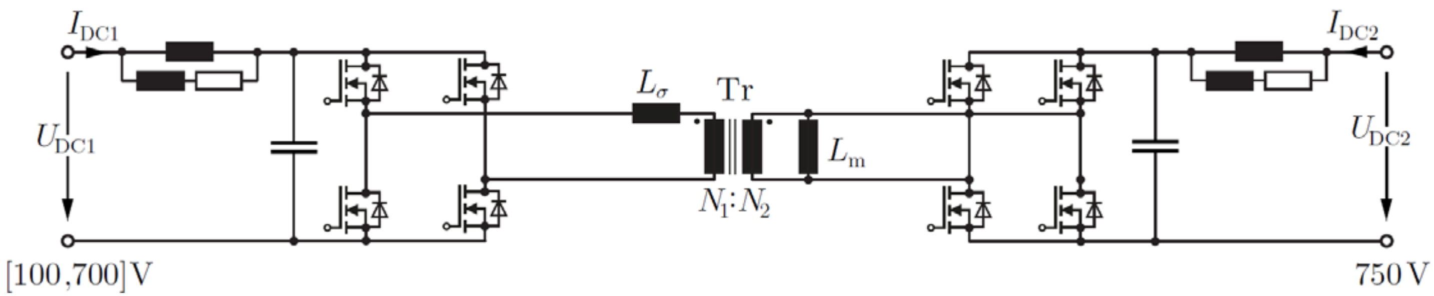
Two-stage approach

- Boost converter to adapt the voltage
- Resonant converter for galvanic isolation
- ZVS possible in both stages

Pros/cons

- Optimized/tailored converter topology for each task
- Simple control
- High part count
  - ▶ Reliability
  - ▶ Costs
- High efficiency questionable as many components in series

▶ Selection of Topology: Single-Stage DAB Converter



Single-stage approach

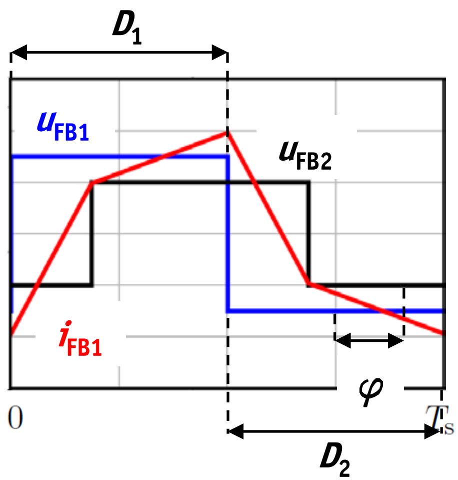
- Integrated voltage adaption and galvanic isolation
- ZVS possible

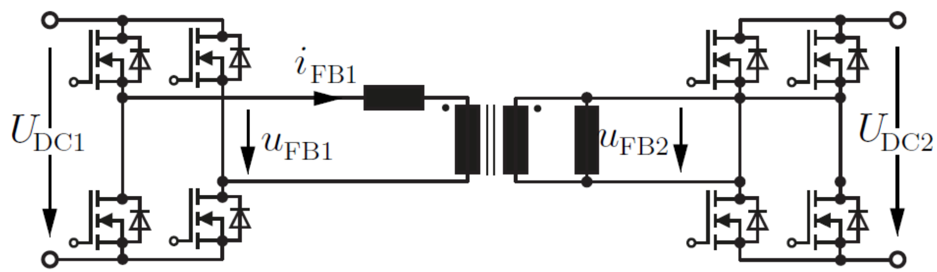
Pros/cons

- Low part count
- Operation at fixed frequency

- Optimization more challenging
- Advanced modulation scheme necessary

▶ Modulation Scheme (I)



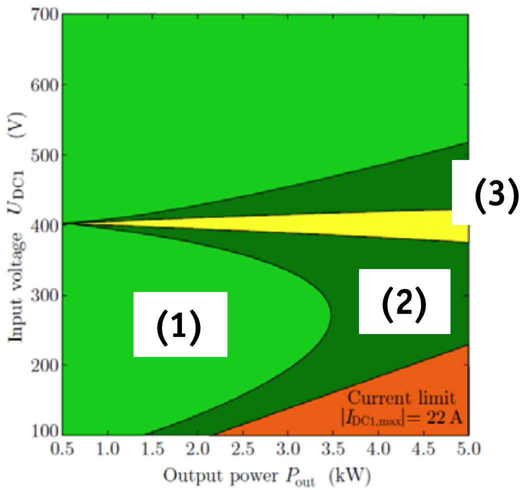


Objectives

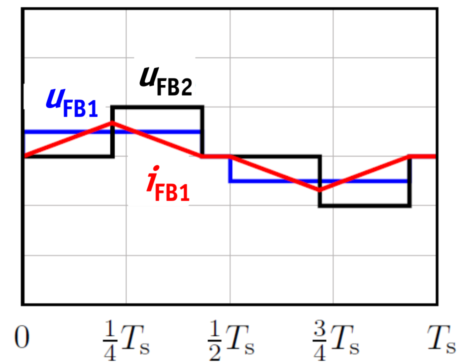
- Choose control parameters (D_1, D_2, φ) so as to minimize RMS currents
  - Minimizes the conduction losses
  - Assumption of low switching losses (ZVS)
- Optimization problem must be solved for all operating points (U_{DC1}, U_{DC2}, P_{out})
- Closed form solutions in:

F. Krismer and J.W. Kolar, *"Closed Form Solution for Minimum Conduction Loss Modulation of DAB Converters"*, IEEE Transactions on Power Electronics, Vol. 27, No. 1, January 2012

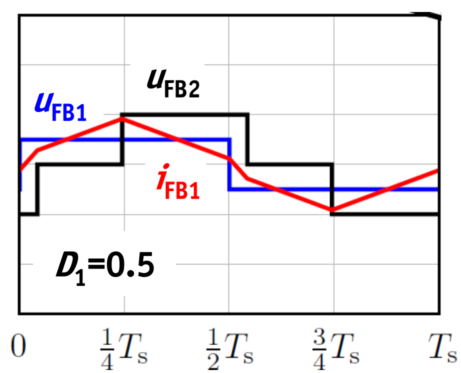
▶ Modulation Scheme (II)



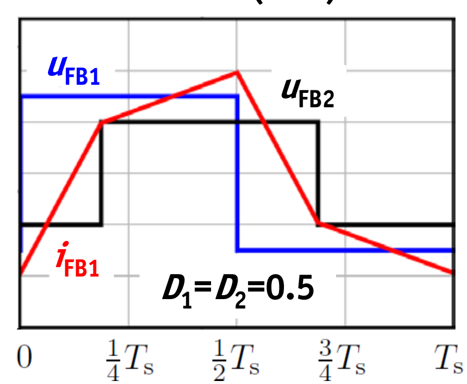
(1) Triangular Current Mode (TCM)



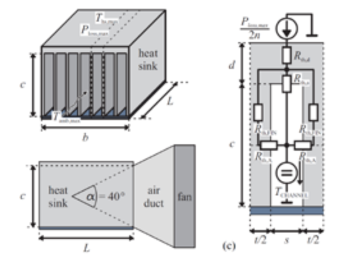
(2) Optimal Transition Mode (OTM)



(3) Conventional Phase-Shift Modulation (CPM)



▶ Multi-Physics Modeling and Optimization Framework



Heat sink and semiconductors

- Experimentally verified heat sink models
- Conduction loss model based on data sheet information

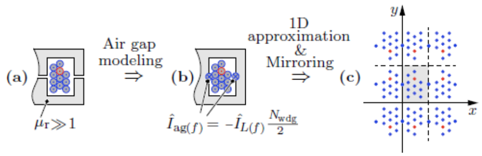
$$P_{\mathrm{cond,MOSFET}} = \frac{1}{T}\int_0^T R_{\mathrm{DS,on}}(i_{\mathrm{DS}}(t),\, T_{\mathrm{j}})\, i_{\mathrm{DS}}^2(t)\mathrm{d}t$$

- Switching loss model based on switching loss measurements

$$P_{\mathrm{sw,on/off}} = f_{\mathrm{sw}} E_{\mathrm{on/off}}(I_{\mathrm{sw,on/off}}, U_{\mathrm{sw}}, T_{\mathrm{j}})$$

Magnetics

- Core losses based on iGSE and core loss measurements
- HF winding losses based on mirroring method
- Advanced reluctance and thermal models

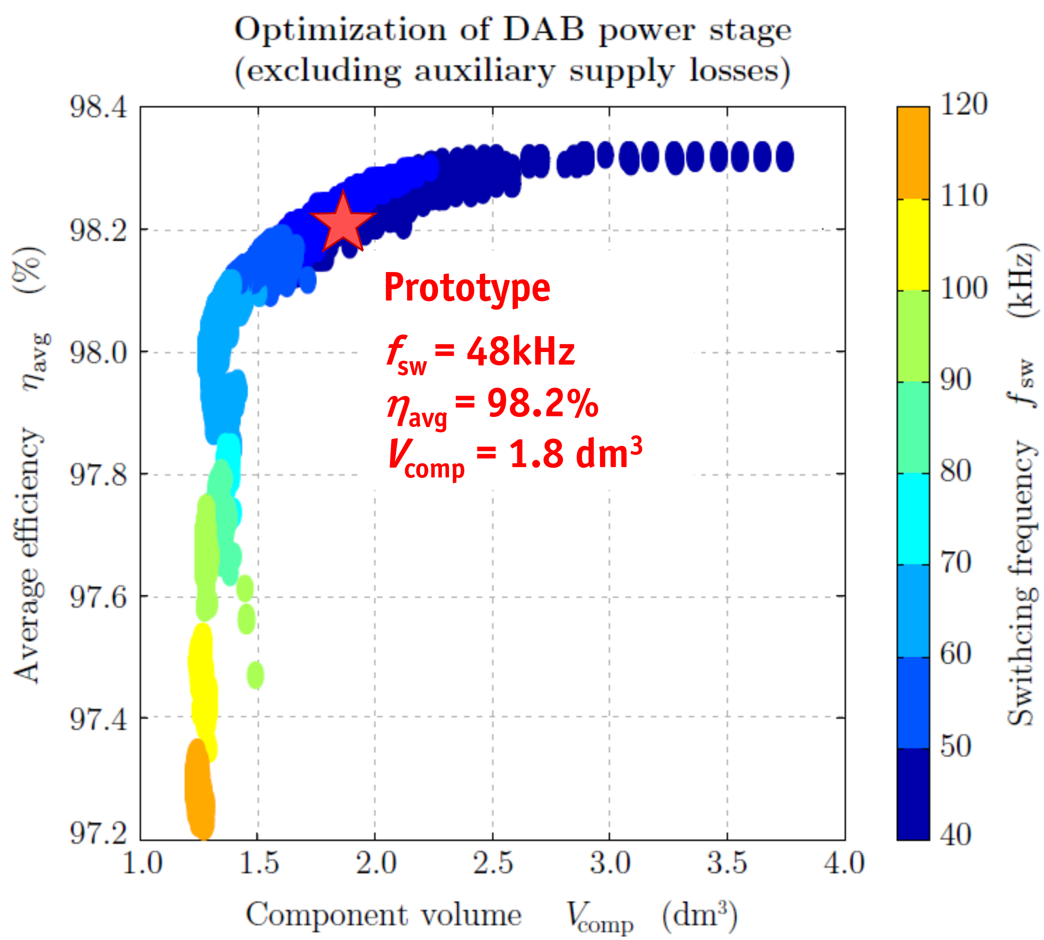


Capacitors

- Data sheet information

▶ Optimization Results

Loss of ZVS!



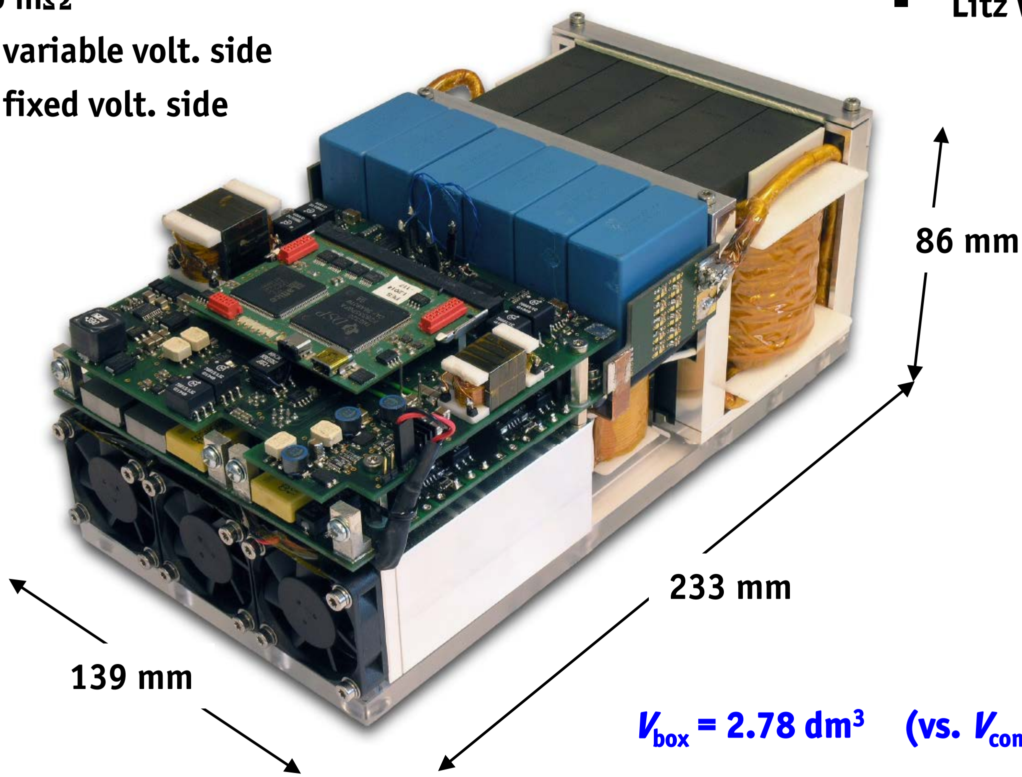
► Experimental Verification: Hardware Prototype

Semiconductors

- CREE SiC MOSFET C2M0080120D
  1200 V 80 mΩ
- 2 x par. on variable volt. side
- 1 x par. on fixed volt. side

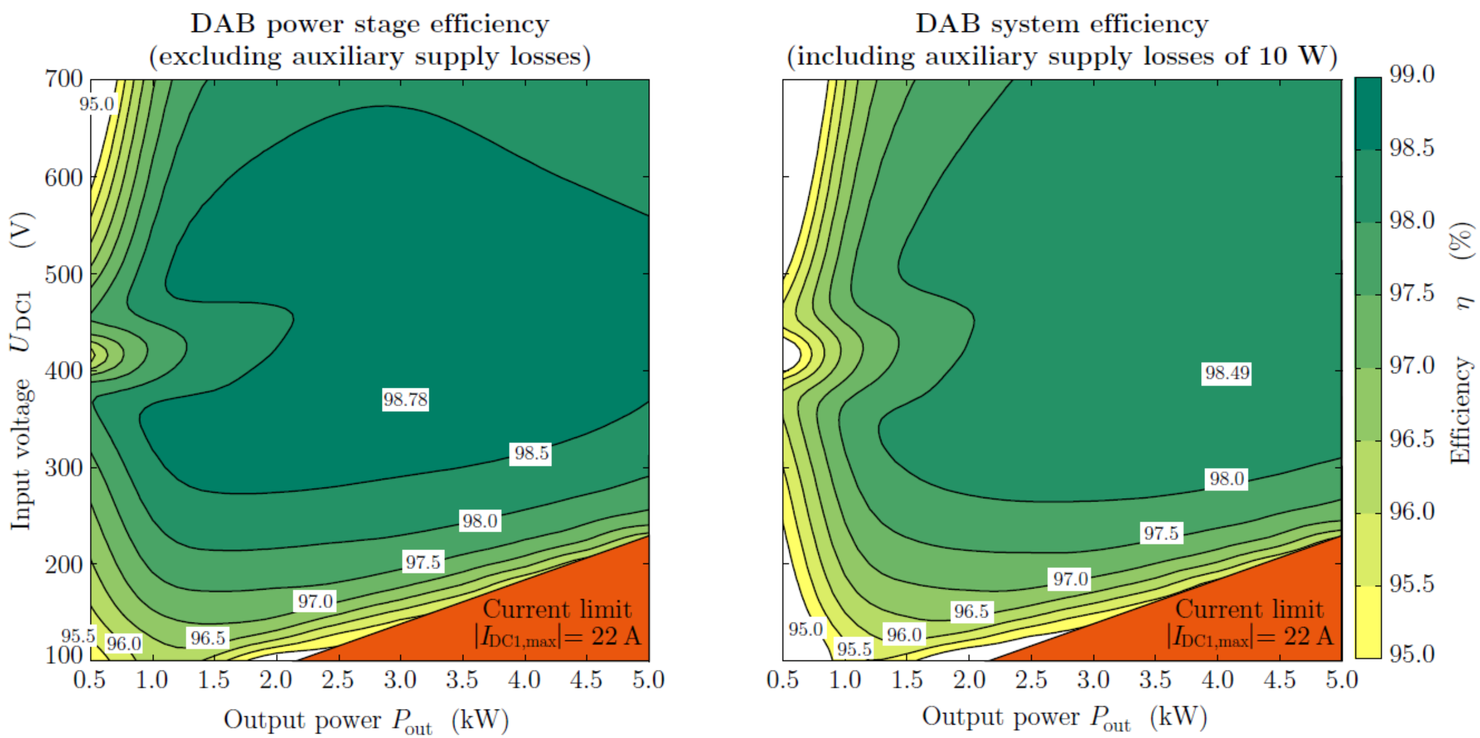
Magnetics

- FerroxCube 3C91
- Litz wire 71 µm



V_{box} = 2.78 dm^3 (vs. V_{comp} = 1.8 dm^3)

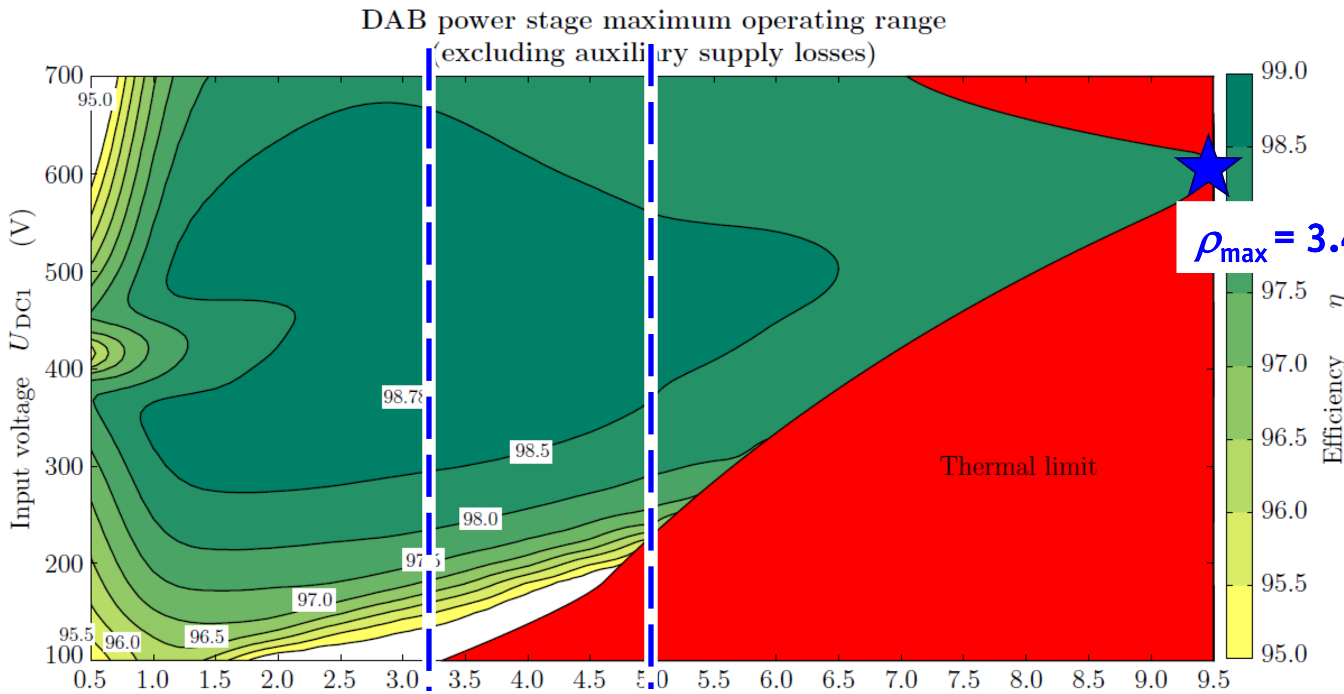
▶ Experimental Verification: Efficiency



Exceptional performance despite high functionality

- **Peak efficiencies of 98.8% (without auxiliary) and 98.5% (incl. 10 W auxiliary power)**
- **High efficiency over extremely wide parameter range (η_{avg} = 98.2%)**
- **ZVS in most operating points**

▶ Experimental Verification: Power Density



$\rho_{[100,700]V}$ = 1.2 kW/dm³ ρ_r = 1.8 kW/dm³

Definition of power density

- **Power density only meaningful in combination with specification of**

  $[U_{DC1,min}, U_{DC1,max}]$ / $[U_{DC2,min}, U_{DC2,max}]$ / η_{avg} / costs

- **DAB specifically designed for narrow input voltage range: $\rho_{estimated}$ > 5 − 10 kW/dm³**

► Summary & Conclusion

Bidirectional isolated DC/DC converter with wide input voltage range

- High functionality for universal application in residential energy management systems
- Experimentally verified performance

  (η_{avg} = 98.2% / ρ_r = 1.8 kW/dm^3 / U_{DC1} = [220,700] V)

- Possible cost savings due to lower system complexity, development costs and due to economies of scale
- **Performance not achievable without optimized modulation scheme and SiC**

▶ Thank you for your attention!

Updated slides on: http://www.pes.ee.ethz.ch