ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Workshop in Memoriam
Prof. Alfio Consoli
28th Jan., 2013

Advanced DC/AC Power Conversion for Automotive Applications

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ECPE Technology Roadmapping

ECPE Research & Technology Roadmaps

8 Teams for the ´Key Applications´ of Power Electronics:	Team Coordinators:
Power grid infrastructure, power generation & distribution	Prof. De Doncker (Aachen) Prof. Herold (Erlangen)
Large drives (large industry and traction drives)	Prof. Bernet (Berlin) Prof. Marquardt (Munich)
High performance motor drives	Prof. Schroedl (Vienna) Prof. Kazmierkowski (Warsaw)
Small drives for home appliances	Prof. Consoli (Catania) Prof. Ferreira (Delft)
High frequency power conversion (> 1kW) (telecom, server, heating, welding, …)	Prof. Petzoldt, Dr. Reimann (Ilmenau)
High frequency power supplies (< 1kW) (stand alone & integr. PS, chargers, lighting, …)	Prof. Cobos (Madrid) Dr. O´Mathuna
Future (renewable) energy sources (wind, PV, fuel cell, …)	Prof. Zacharias (Kassel) Prof. Blaabjerg (Aalborg)
Automotive power electronics (low & high voltage applications)	Prof. Kolar (Zurich) Dr. Maerz (Nuremberg-Erlangen)

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Outline

- 120°C Ambient Power Electronics
- SiC J-FET Optimum Junction Temp.
- High Temp. SiC Inv. Construction
- SiC Normally-Off JFET Gate Drive
- High Temp. Current Sensor
- High Temp. Forced Air Cooling
- Conclusions

High Temperature Motivation

▶ State of the Art

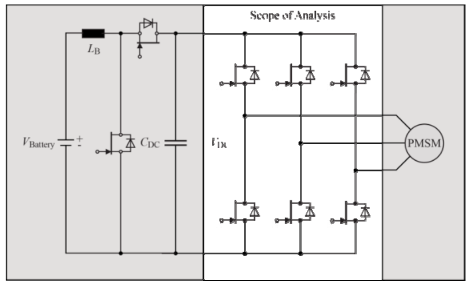
- Ambient Air $T_A \approx 120^\circ C$
- Water-Cooling $T_W = 60^\circ C$
- Switches   Si-IGBTs

Toyota Yaris Hybrid (MY 2011)

⇨

Air-Cooled SiC Inverter with $T_A = 120^\circ C$ and $T_J = 250^\circ C$

- Construction Flexibility &
- Low Complexity Cooling System



▶ Other Fields of Application

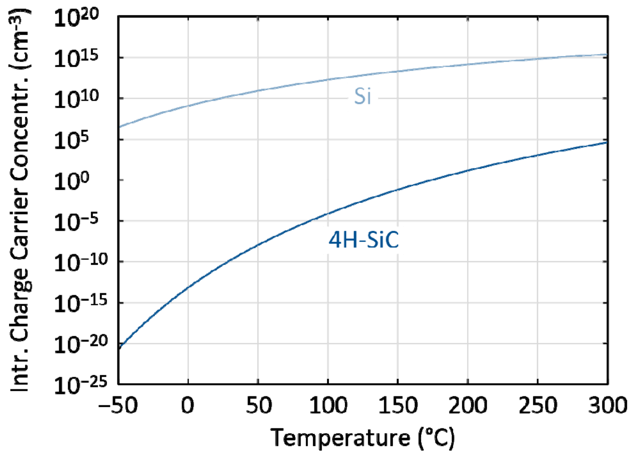
- Aerospace
- Military
- Downhole

SiC vs. Si Power Semiconductors

▶ Low Intrinsic Carrier Concentration

$$n_i = \sqrt{n_n n_p} = \sqrt{N_C N_V} \cdot e^{-\frac{E_G}{2kT}}$$
$$= T^{3/2} \cdot 10^{16}\,\mathrm{cm}^{-3}\mathrm{K}^{2/3} \begin{cases} 3.87 \cdot e^{-\frac{7.02\cdot 10^3\,\mathrm{K}}{T}} & \text{for Si} \\ 1.70 \cdot e^{-\frac{2.08\cdot 10^4\,\mathrm{K}}{T}} & \text{for 4H-SiC} \end{cases}$$

⇒ Higher Operating Temperatures

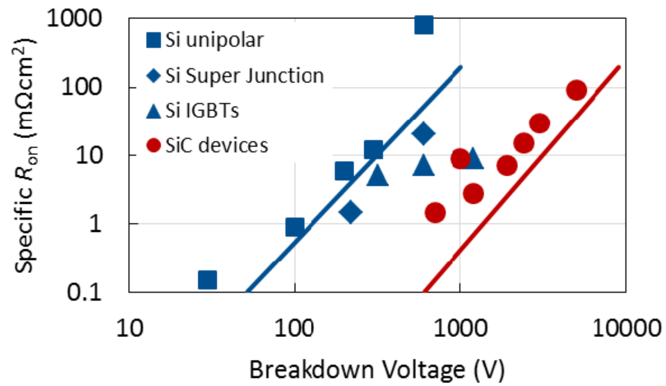


▶ Higher Breakdown Electric Field

- Higher Blocking Voltage
- Lower Specific On-Resistance $R_{\text{on-ideal}} = \frac{4\mathrm{BV}^2}{\varepsilon_S \mu_n E_C^3}$

- Bipolar Si Switches →
- Unipolar SiC Switches for 1.2 kV

⇒ Higher Switching Frequencies



■ Drawbacks Higher Costs & Limited Application Experience

SiC Normally-Off Devices

▶ Normally-On JFET Clamped Cascode

\+ Known Gate Drivers Applicable
\+ Low Gate Drive Power
\+ High Saturation Drain Current

\- Higher $R_{DS,on}$ than VJFETs
\- Schottky Diode requ. at High Temp.
\- LV Si-MOSFET → 175°C Limit

▶ Vertical JFET

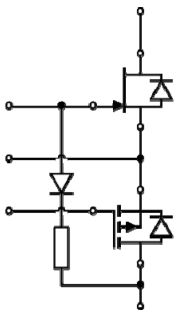
\+ Lowest $R_{DS,on}$
\+ Low Switching Losses
\+ Diode-Free Operation Possible
\+ Full-SiC Solution

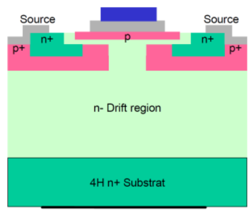
\- No Satisfactory Gate Drive Available

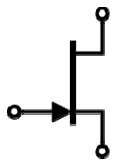
▶ MOSFET

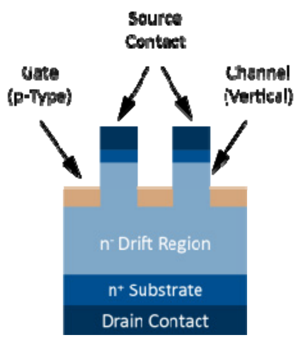
\+ Well Known Gate Drivers Appl.
\+ Low Gate Driving Power
\+ Full-SiC Solution

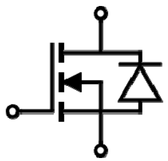
\- Higher $R_{DS,on}$ than VJFETs
\- Gate Interface Issues at > 150°C
\- Gate Oxide Reliability
\- Threshold Voltage Stability

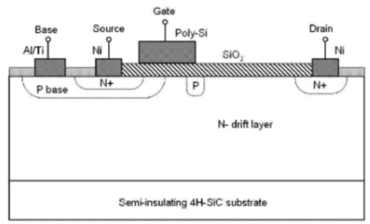








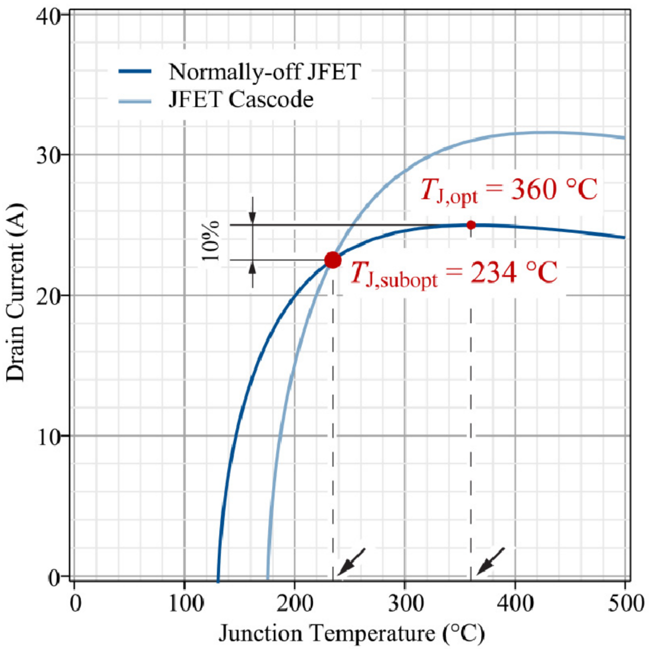




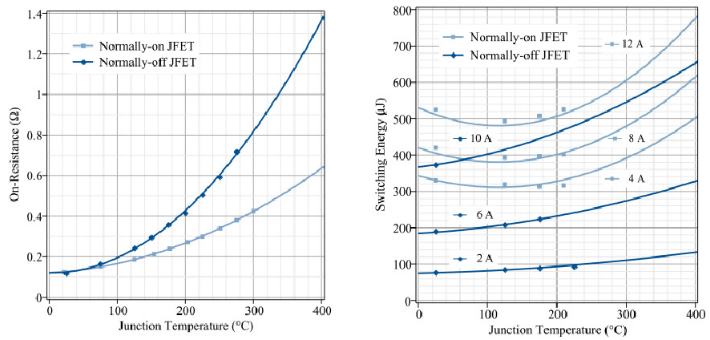
SiC J-FET Optimum Junction Temperature

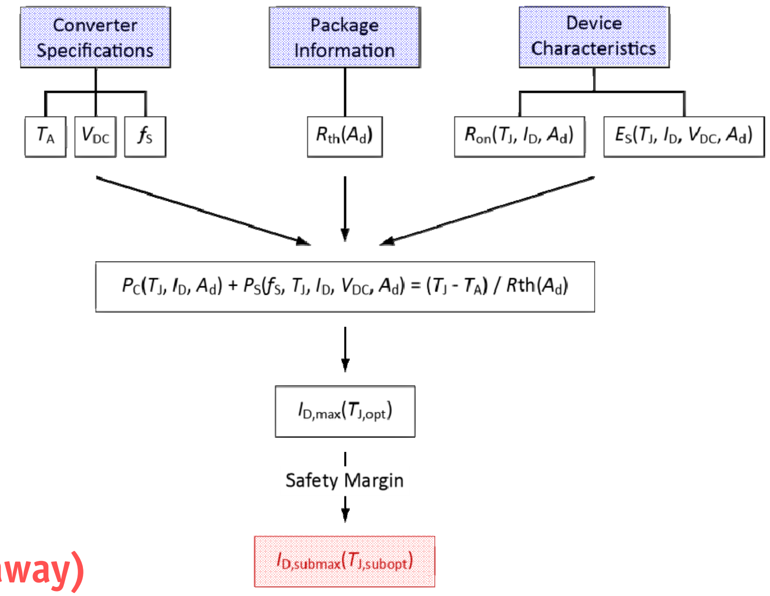
SiC JFET Opt. Junction Temp.

▶ Calculation Procedure



V_{DC} = 700 V
f_S = 50 kHz
A_d = 0.16 cm²





■ **Optimum Junction Temperature (Thermal Runaway)**

HT SiC Inverter Construction

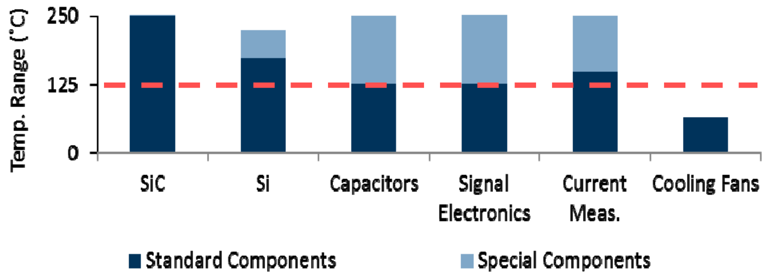
Inverter Construction → Electrical vs. Thermal Constraints

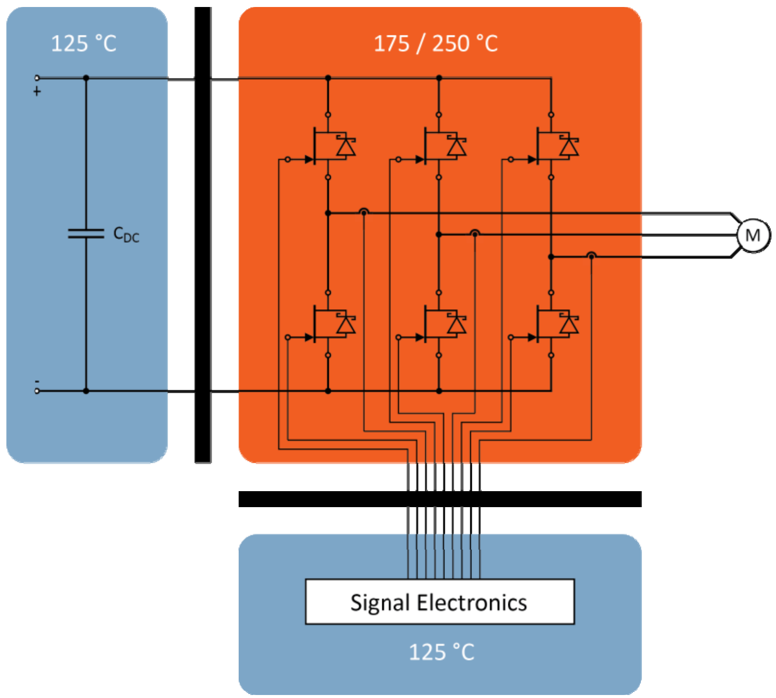
▶ Electrical Constraints

- Low & Symmetrical Gate Ind.
- Low DC-link & Commutation Ind.

▶ Thermal Constraints

- Symm. Switch Thermal Resistance
- Component Temperature Limits





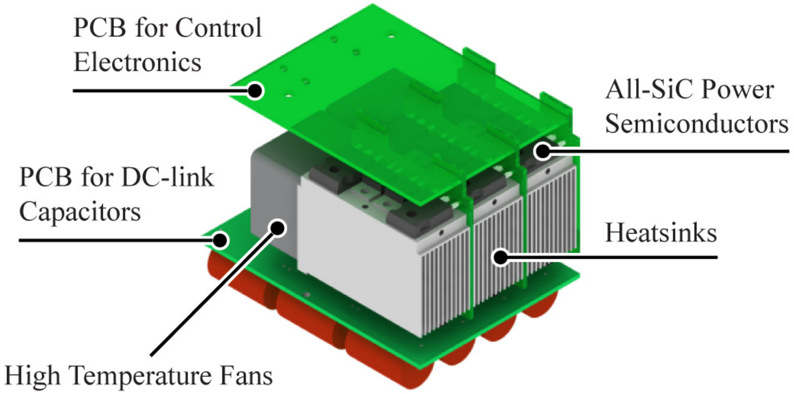
Inverter Construction - Options

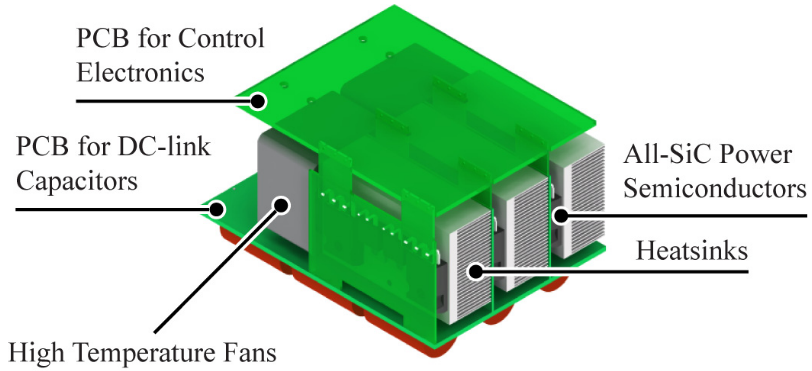
▶ Horizontal Concept

+ Better Utilization of Heat Sink Area & Air Flow
+ No Air Flow Through El. Interconnections
+ Lower Gate Inductance
+ 10% Lower Heatsink R_{th}

▶ Vertical Concept

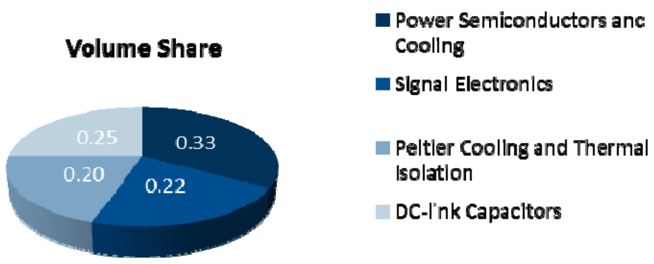
+ Distance between Switches & Signal / DC-Link PCB
+ Less Heat Input in Signal / DC-Link PCBs

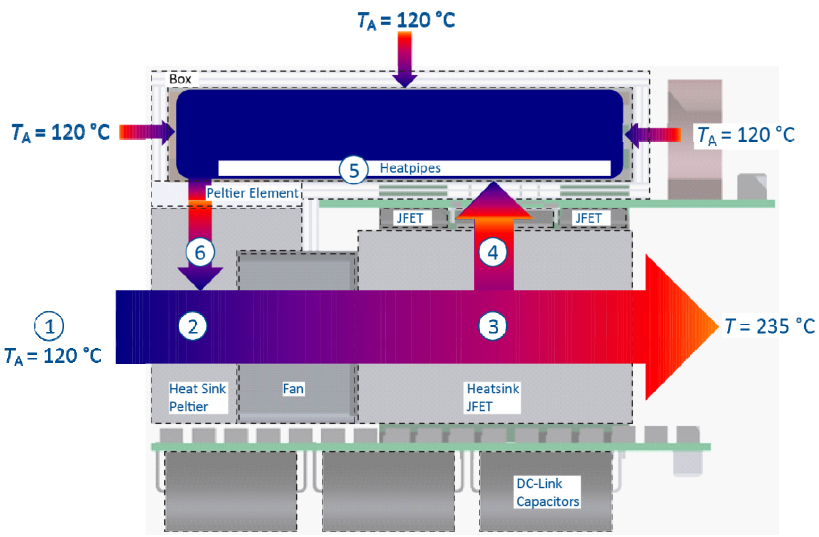


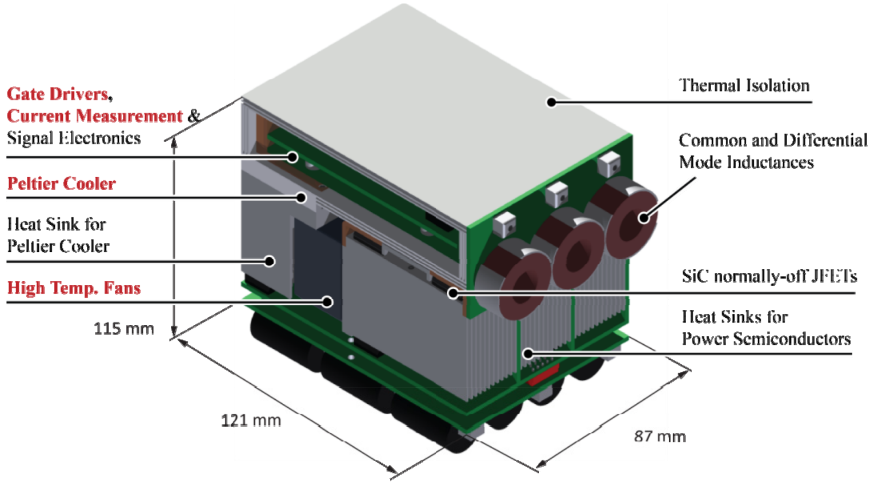


Inverter Thermal Design

1 … Ambient Air Intake
2 … Peltier Cooler Heat Sink
3 … Inverter Heat Sink
4 … Heat Input to Signal PCB
5 … Heat Output of Electronics Box by Peltier Cooler



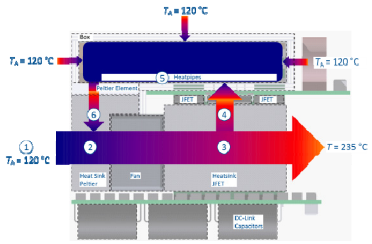


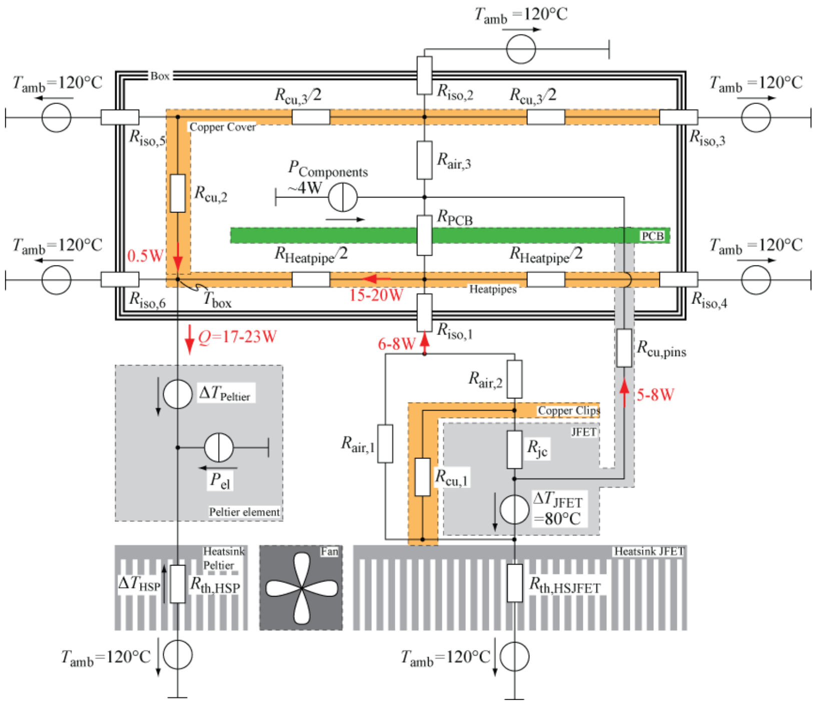


Design of Active Contr. Electr. Cooling

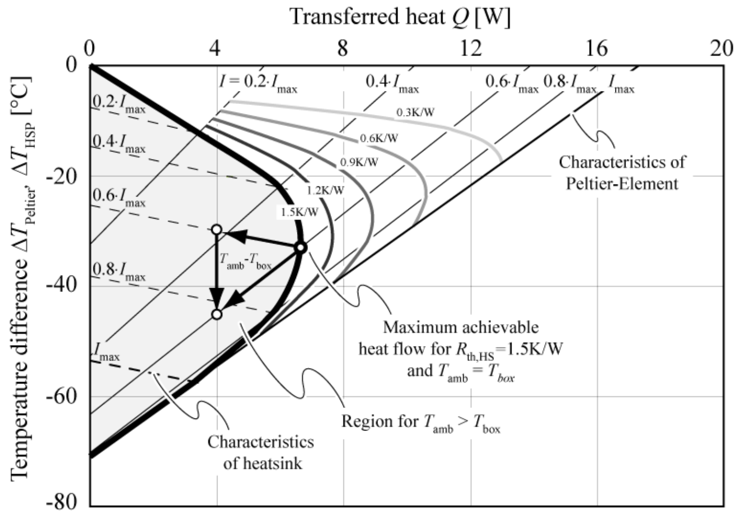
- $R_{th,track}$ = 300 K/W vs.
- $R_{th,TO\text{-}247}$ = 27 K/W
- 20 Tracks in Total

- $Q_{in} = Q_{out}$ = 20 W



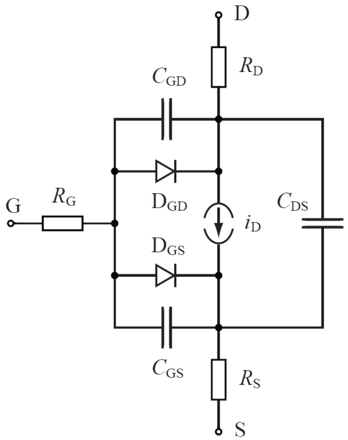


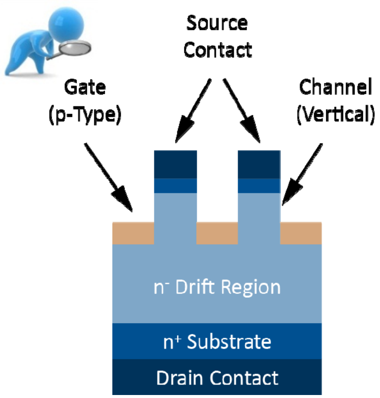
Characteristics of Peltier Cooler (QC-31-1.4-8.5M) 20 mm x 20 mm



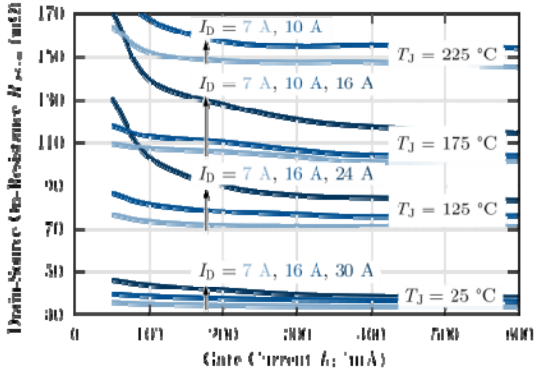
Normally-Off SiC J-FET Gate Drive

SiC Normally-Off JFET Gate Driver Requirements

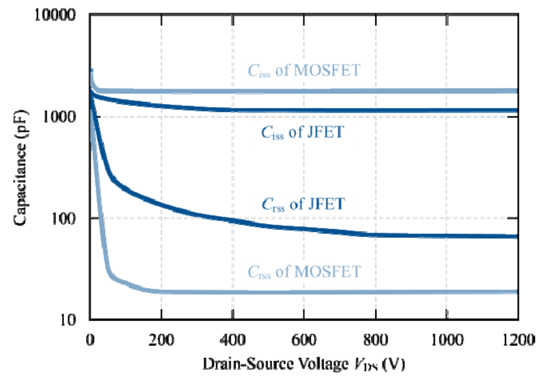




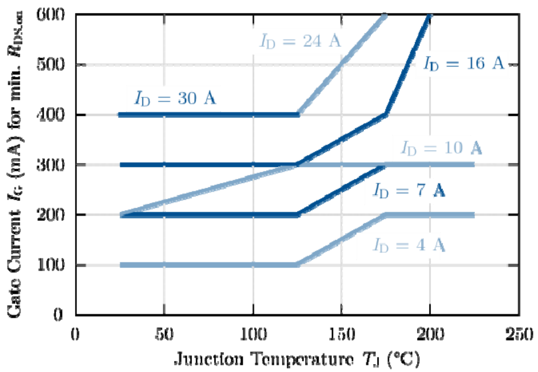
$R_{DS,on} = f\,(T_J, I_G, I_D)$



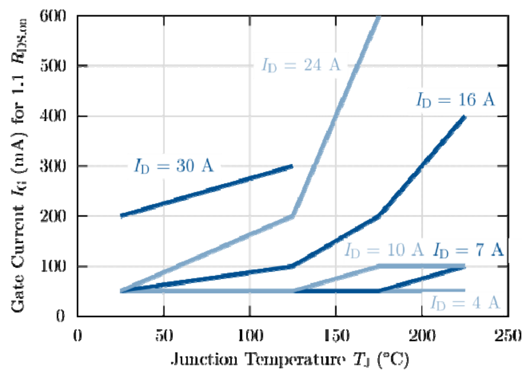
JFET and MOSFET Capacitances



I_G for min. $R_{DS,on}$



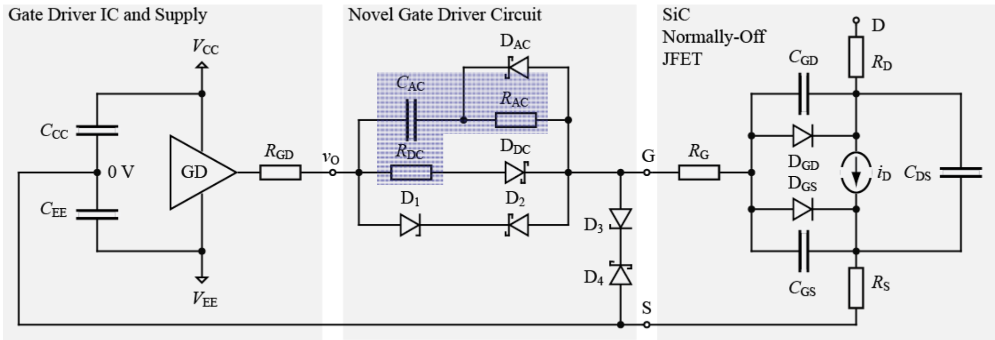
I_G for 1.1 $R_{DS,on}$



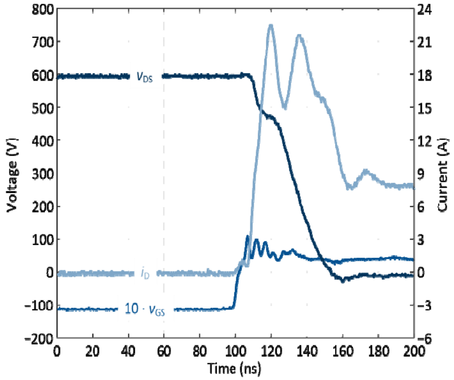
Novel AC Coupled Gate Driver

▶ Eliminate Weaknesses of State-of-the-Art Gate Drives

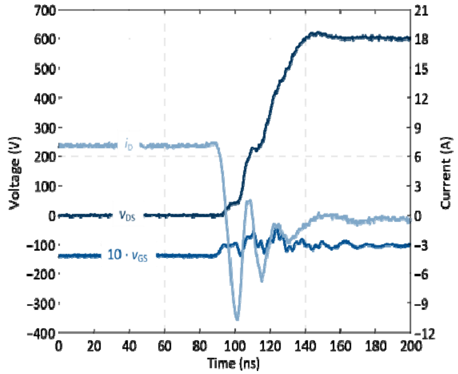
- Significant Power Loss
- Slow Miller Charge Removal
- Duty Cycle Limitations



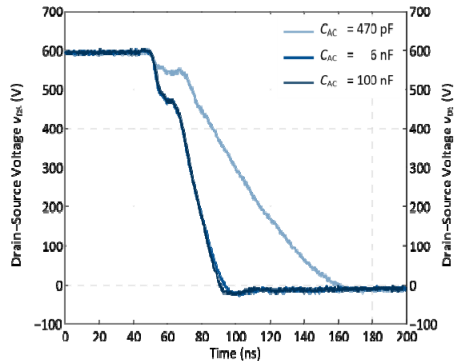
Turn-on: 20V/ns, 0.8 A/ns



Miller Effect Immunity



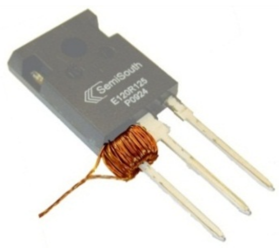
Effect of C_{AC}

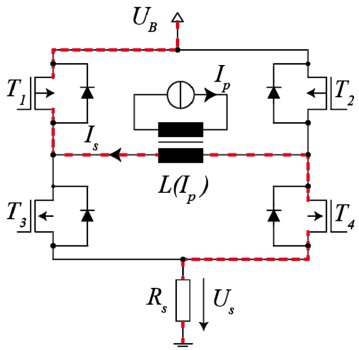


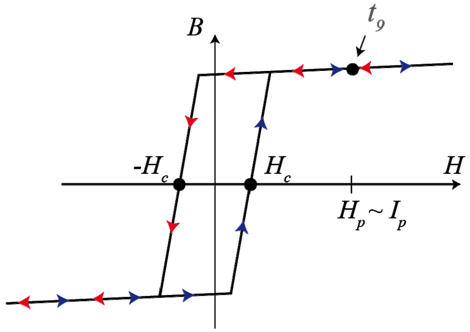
HT Current Measurement

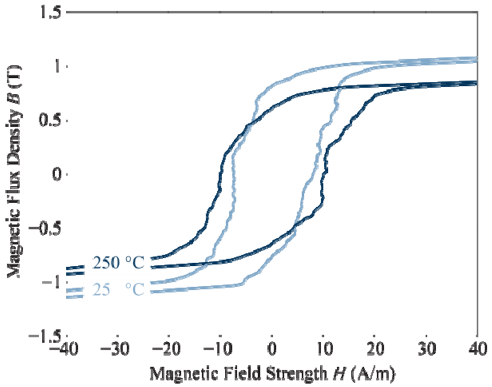
Fast High Temp. Isolated DC & AC Current Sensor

▶ Bidirectionally Saturated Current Transformer

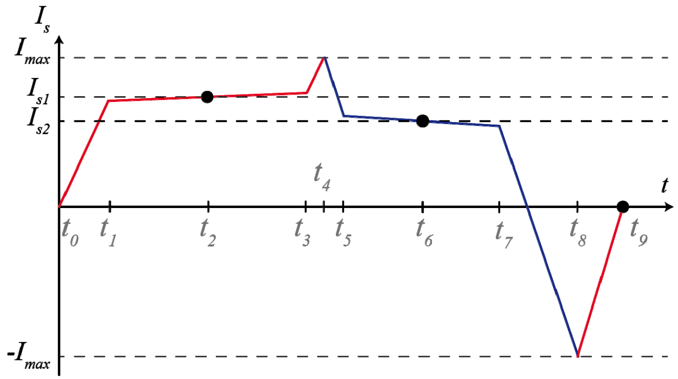








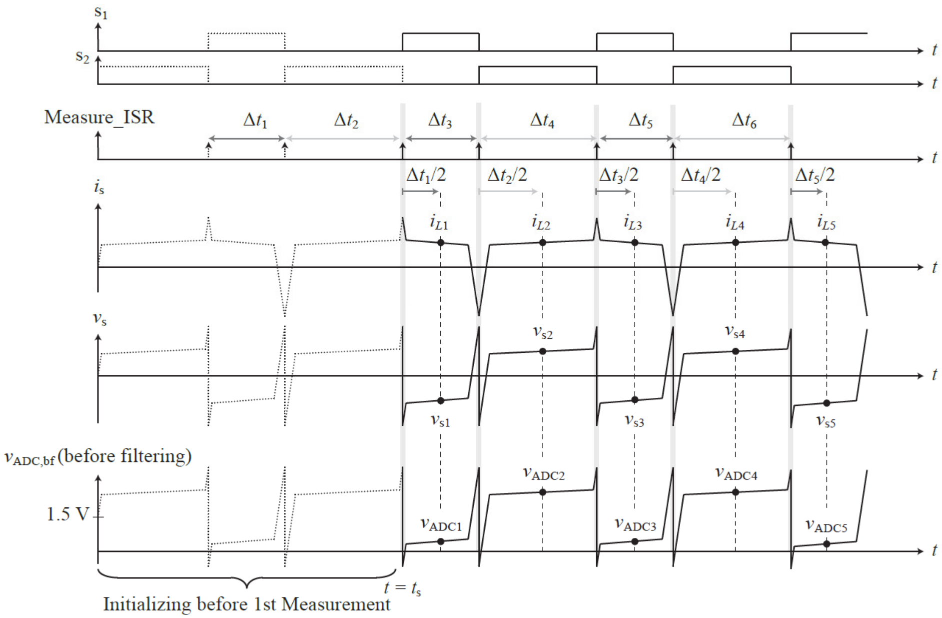
Core Material
(Vitroperm 500F)
Hysteresis



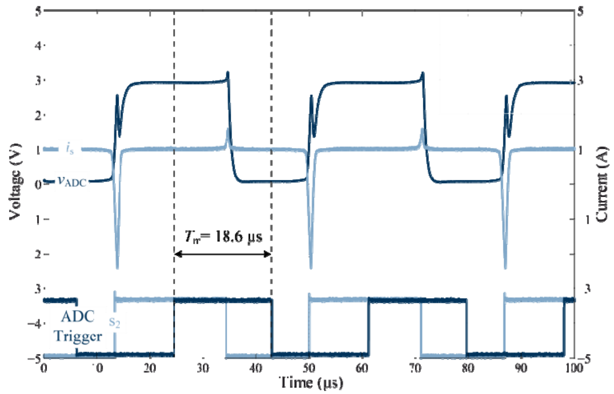
- Low Temperatue Sensitivity due to Temp. Independent Symm. of Hyst. Loop

Fast High Temp. Isolated DC & AC Current Sensor

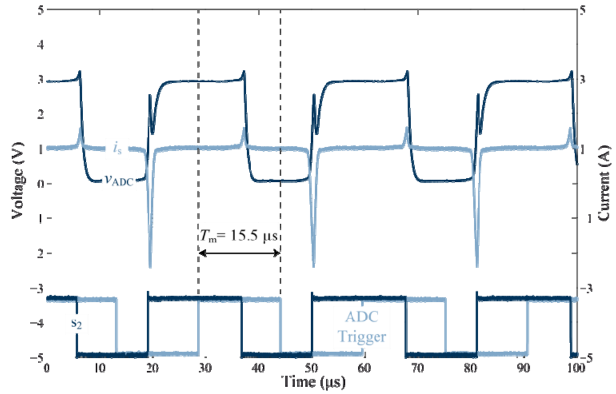
► **Experimental Analysis of Operating Temp. Influence**



I_p = 52 A, T_A = 25°C

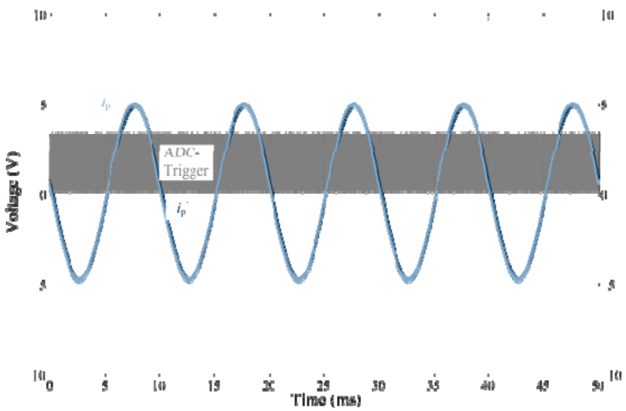


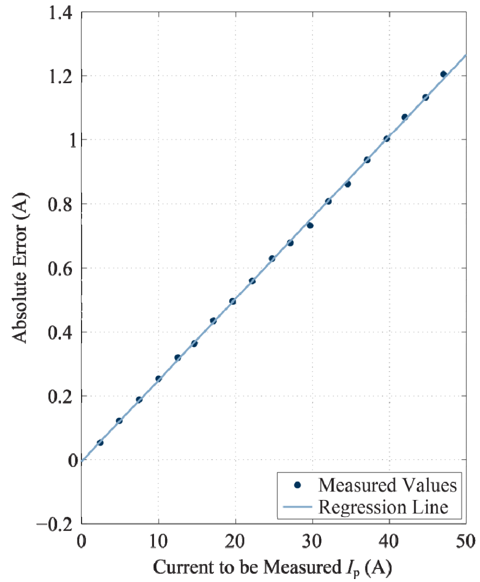
I_p = 52 A, T_A = 250°C

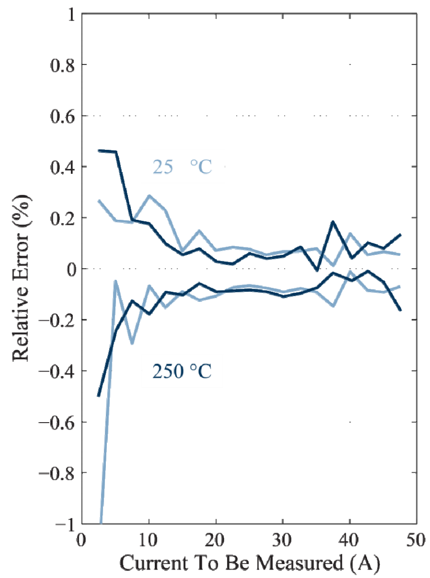


Fast High Temp. Isolated DC & AC Current Sensor

- **Experimental Analysis of Accuracy of Calibr. Sensor**







High Temperature Fan

High Temperature Fan

▶ **Specifications**

- Max. Air Temperature $T_A = 250°C$
- Max. Speed $n_{max} = 19´000 min^{-1}$
- Max. Input Power $P = 15W$
- DC Supply Voltage $U = 12V$

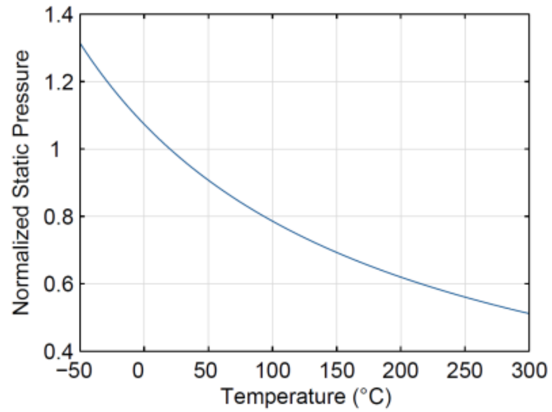
▶ **Fan Issues at High Temperatures**

- Ball Bearings - Lubrication
- CTE Matching for $\Delta T \geq 300$ K
- Winding Insulation
- Mechanical Strength at 250˚C

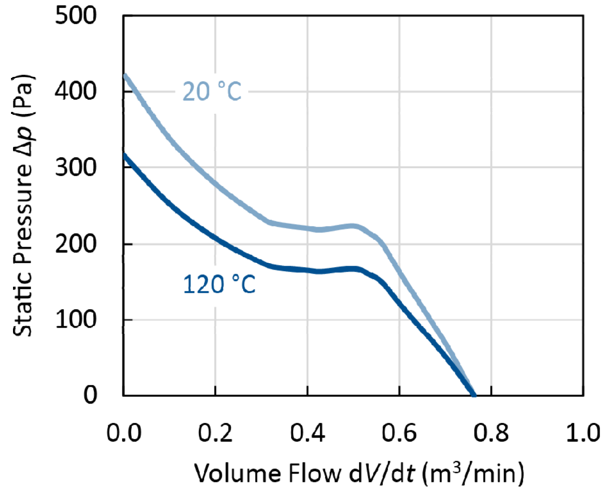
$$P_{S,HTF}(T) = P_{S,RF}(T) \cdot \left(\frac{n_{HTF}}{n_{RF}}\right)^3 = P_{S,RF}(T_{ref}) \cdot \sqrt{\frac{T_{nom}^3}{T_{ref}}} \cdot \frac{1}{T}$$

$$= P_{S,RF}(T_{ref}) \begin{cases} 1.55 & \text{for} \quad T = 20\,°C \\ 1.16 & \text{for} \quad T = 120\,°C \\ 0.87 & \text{for} \quad T = 250\,°C \end{cases}$$

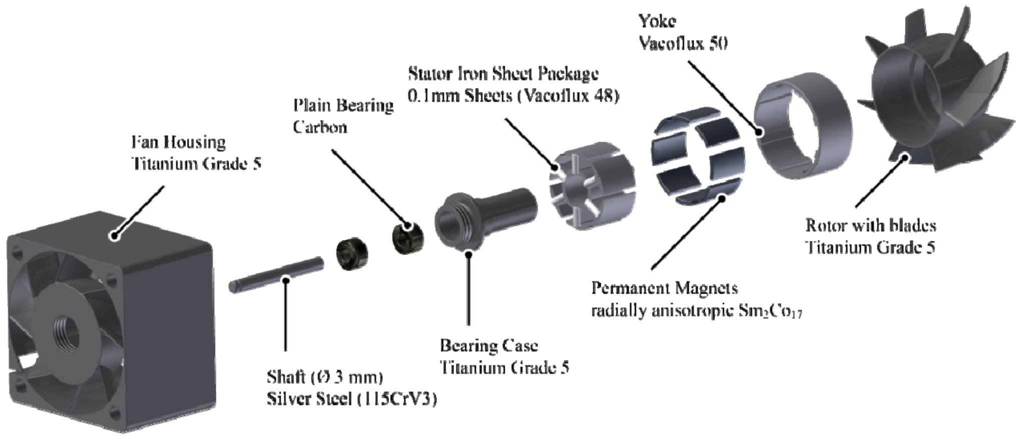
$$n_{HTF} = n_{RF}\sqrt{\frac{\Delta p_{max,HTF}(T_{ref})}{\Delta p_{max,RF}(T_{ref})}} = n_{RF}\sqrt{\frac{T_{nom}}{T_{ref}}}$$



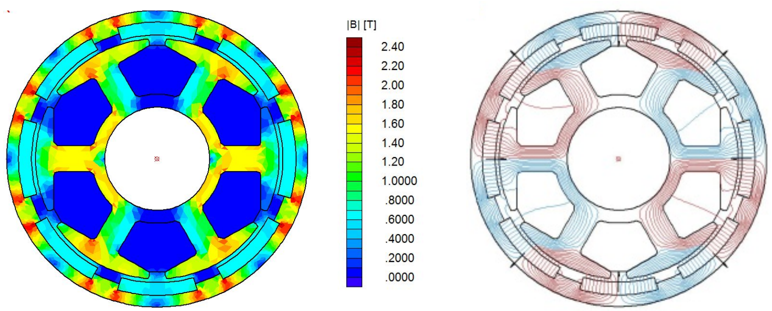
Fan Performance Temp. Dependency



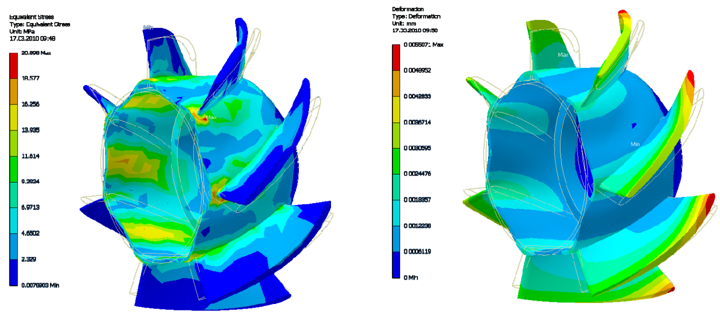
Mechanical Construction



- ▶ **Electrical Machine Design for 300°C**



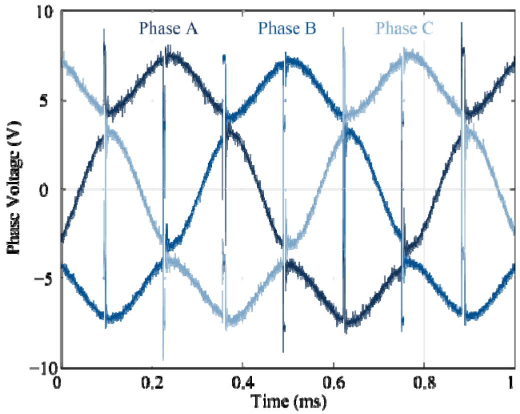
- ▶ **Rotor Mech. Stress Analysis @ 250°C**



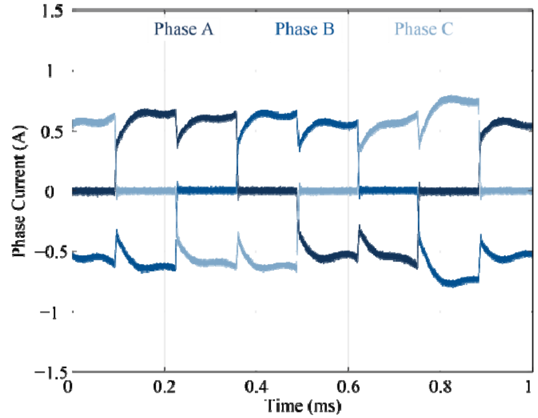
Experimental Analysis

- Electrical
- Fluidic
- Acoustic

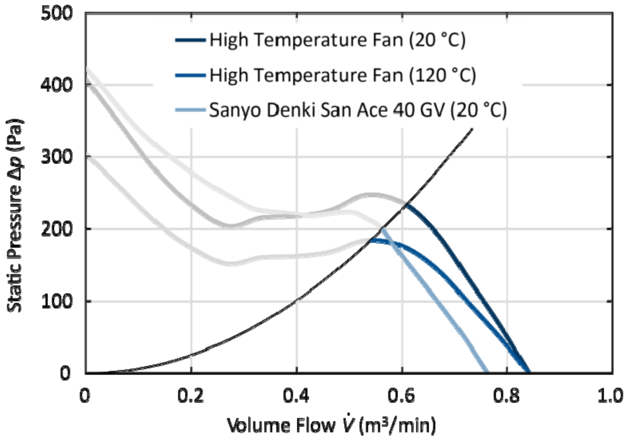
Phase Voltages @ 250°C



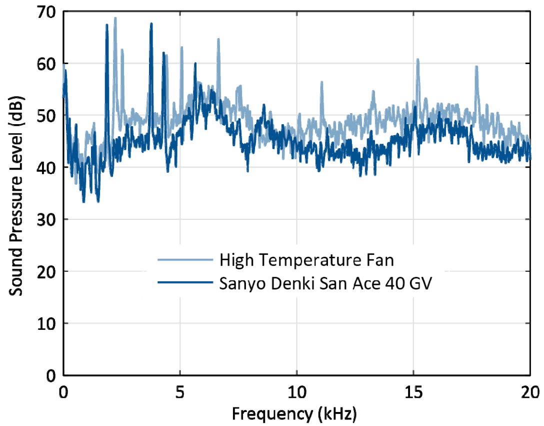
Phase Currents @ 250°C



Fluidic Performance



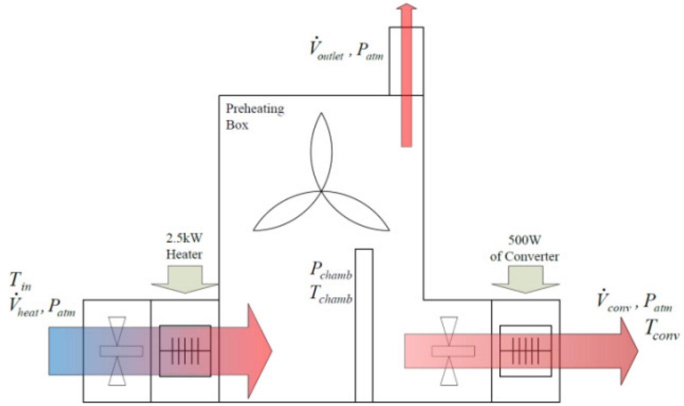
Acoustics



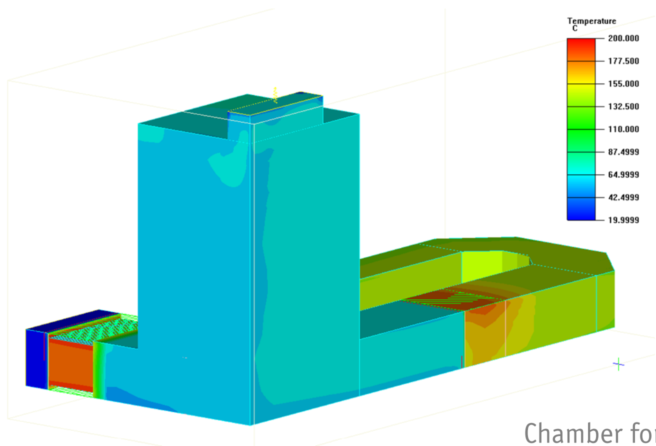
High Temperature Test Setup

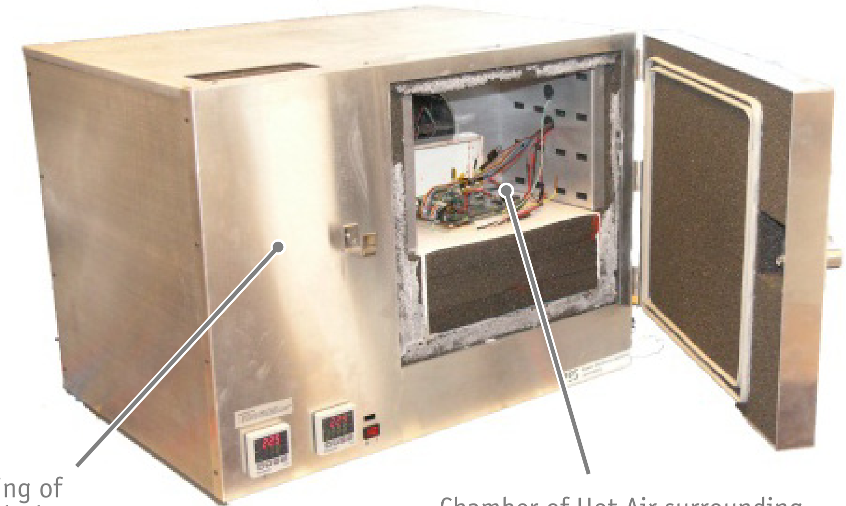
120°C Test Environment

▶ **Individual Controllability of Control Electronics and Power Part Ambient Temperatures**



- **Air Flow Simulation of Power Part Heating**





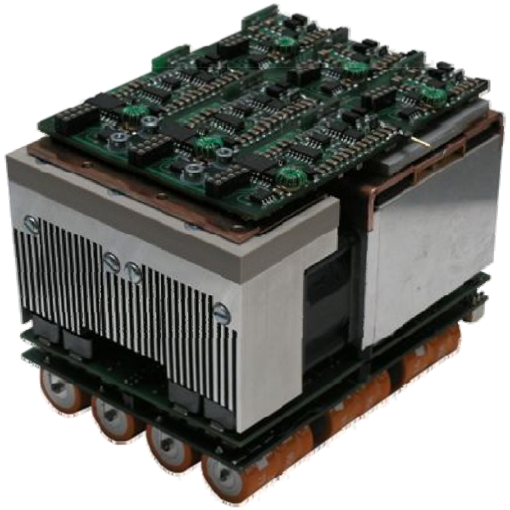
Chamber for Pre-Heating of the Air Flowing through the Heat Sinks and Fans

Chamber of Hot Air surrounding the Control Electronics

Inverter System and Test Bench

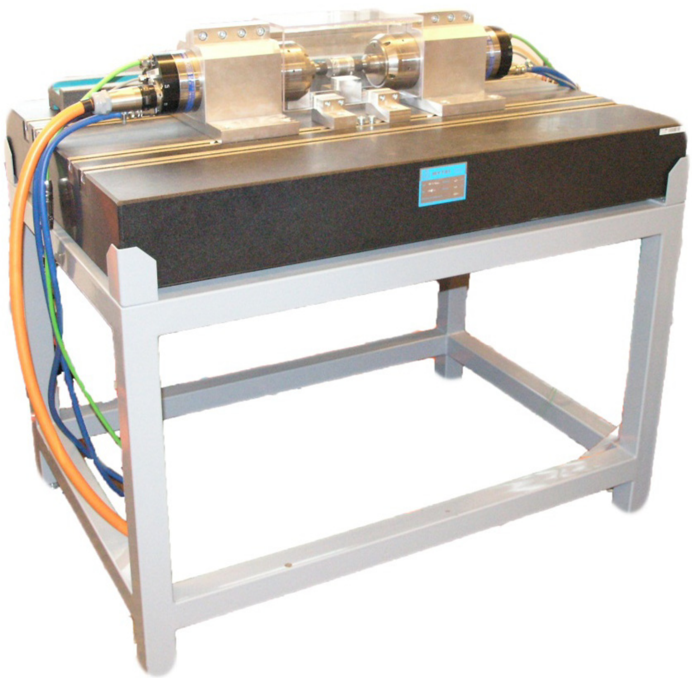
► DC-AC 3-ph Inverter Syst. Specifications

- Ambient Temp. T_A = 120°C
- Switching Frequ. f_{SW} = 50 kHz
- Output Frequency f = 1000 Hz (max.)
- Output Power P = 10 kW
- DC Link Voltage V_{DC} = 700 V



► Test Bench Specifications

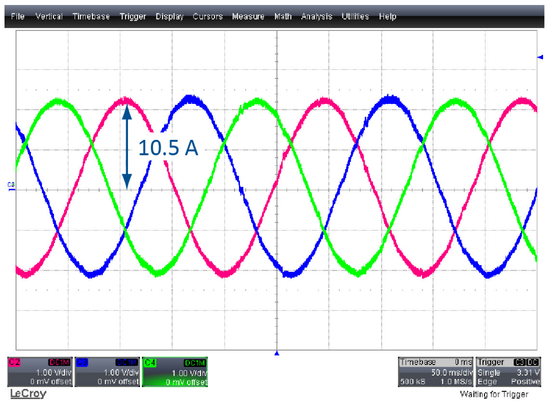
- Power Level P = 10 kW
- Rotational Speed n = 30'000 min^{-1}

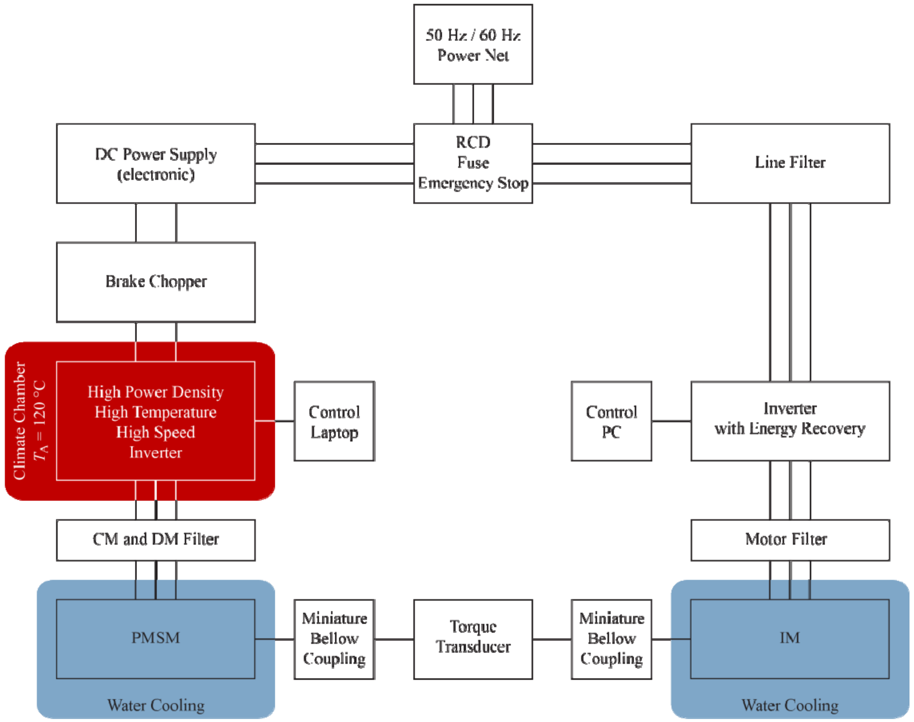


Inverter Test Bench

- Test in Back-to-Back Operation on Mains and Machine Side

PMSM Phase Currents





Conclusion

- ▶ High Temp. / Output Frequency SiC Inverter System
  - Opt. Junction Temp. ≈230°C for SiC JFET and T_A = 120°C
  - Forced Air-Cooled Conv. Design with T_J = 250°C and T_A = 120°C
  - SiC Normally-Off JFET Gate Driver
  - DC and AC Current Measurement for T_A = 250°C
  - High Performance Fan for T_A = 250°C

- ▶ Shifting Operational Temperature Limits is Complex and Costly !
- ▶ Packaging / Thermal Cycling Reliability are Main Challenges !

- ▶ Further Application Areas
  - More Electric Aircraft
  - Downhole Applications
  - Military Applications
  - Exploration of Planets – Venus Lander

Thank You!