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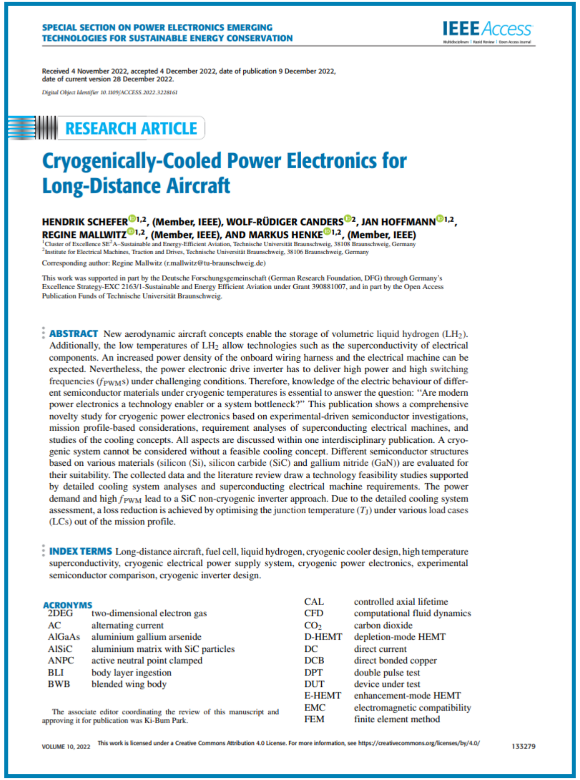
Kryogen gekühlte Leistungselektronik für Langstreckenflugzeuge

Hendrik Schefer

Cryogenically-Cooled Power Electronics for Long-Distance Aircraft, IEEE Access



SPECIAL SECTION ON POWER ELECTRONICS EMERGING TECHNOLOGIES FOR SUSTAINABLE ENERGY CONSERVATION

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RESEARCH ARTICLE

Cryogenically-Cooled Power Electronics for Long-Distance Aircraft

HENDRIK SCHEFER[1,2], (Member, IEEE), WOLF-RÜDIGER CANDERS[2], JAN HOFFMANN[1,2], REGINE MALLWITZ[1,2], (Member, IEEE), AND MARKUS HENKE[1,2], (Member, IEEE)

[1]Cluster of Excellence SE[2]A–Sustainable and Energy-Efficient Aviation, Technische Universität Braunschweig, 38108 Braunschweig, Germany
[2]Institute for Electrical Machines, Traction and Drives, Technische Universität Braunschweig, 38106 Braunschweig, Germany

Corresponding author: Regine Mallwitz (r.mallwitz@tu-braunschweig.de)

This work was supported in part by the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) through Germany's Excellence Strategy-EXC 2163/1-Sustainable and Energy Efficient Aviation under Grant 390881007, and in part by the Open Access Publication Funds of Technische Universität Braunschweig.

ABSTRACT New aerodynamic aircraft concepts enable the storage of volumetric liquid hydrogen (LH_2). Additionally, the low temperatures of LH_2 allow technologies such as the superconductivity of electrical components. An increased power density of the onboard wiring harness and the electrical machine can be expected. Nevertheless, the power electronic drive inverter has to deliver high power and high switching frequencies (f_{PWM}s) under challenging conditions. Therefore, knowledge of the electric behaviour of different semiconductor materials under cryogenic temperatures is essential to answer the question: "Are modern power electronics a technology enabler or a system bottleneck?" This publication shows a comprehensive novelty study for cryogenic power electronics based on experimental-driven semiconductor investigations, mission profile-based considerations, requirement analyses of superconducting electrical machines, and studies of the cooling concepts. All aspects are discussed within one interdisciplinary publication. A cryogenic system cannot be considered without a feasible cooling concept. Different semiconductor structures based on various materials (silicon (Si), silicon carbide (SiC) and gallium nitride (GaN)) are evaluated for their suitability. The collected data and the literature review draw a technology feasibility studies supported by detailed cooling system analyses and superconducting electrical machine requirements. The power demand and high f_{PWM} lead to a SiC non-cryogenic inverter approach. Due to the detailed cooling system assessment, a loss reduction is achieved by optimising the junction temperature (T_J) under various load cases (LCs) out of the mission profile.

INDEX TERMS Long-distance aircraft, fuel cell, liquid hydrogen, cryogenic cooler design, high temperature superconductivity, cryogenic electrical power supply system, cryogenic power electronics, experimental semiconductor comparison, cryogenic inverter design.

ACRONYMS

2DEG	two-dimensional electron gas
AC	alternating current
AlGaAs	aluminium gallium arsenide
AlSiC	aluminium matrix with SiC particles
ANPC	active neutral point clamped
BLI	body layer ingestion
BWB	blended wing body
CAL	controlled axial lifetime
CFD	computational fluid dynamics
CO_2	carbon dioxide
D-HEMT	depletion-mode HEMT
DC	direct current
DCB	direct bonded copper
DPT	double pulse test
DUT	device under test
E-HEMT	enhancement-mode HEMT
EMC	electromagnetic compatibility
FEM	finite element method

The associate editor coordinating the review of this manuscript and approving it for publication was Ki-Bum Park.

Hendrik Schefer, Wolf-Rüdiger Canders, Jan Hoffmann, Regine Mallwitz und Markus Henke

Dezember 2022 veröffentlicht

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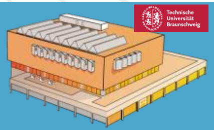

DFG Deutsche Forschungsgemeinschaft

Open-Access-Publikationsfonds

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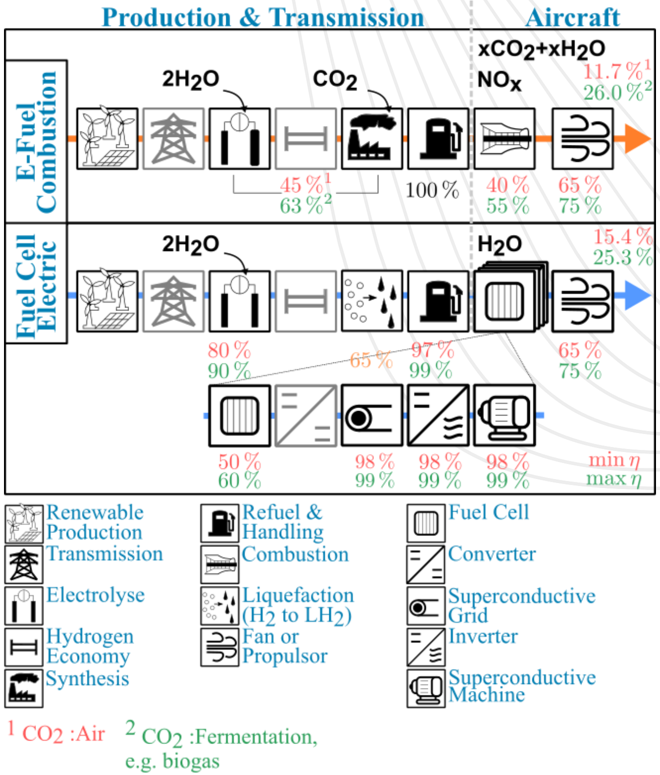
Agenda

Motivation

- Einleitung
- Analyse
- Halbleiter
- DC/AC WR
- Fazit



Motivation

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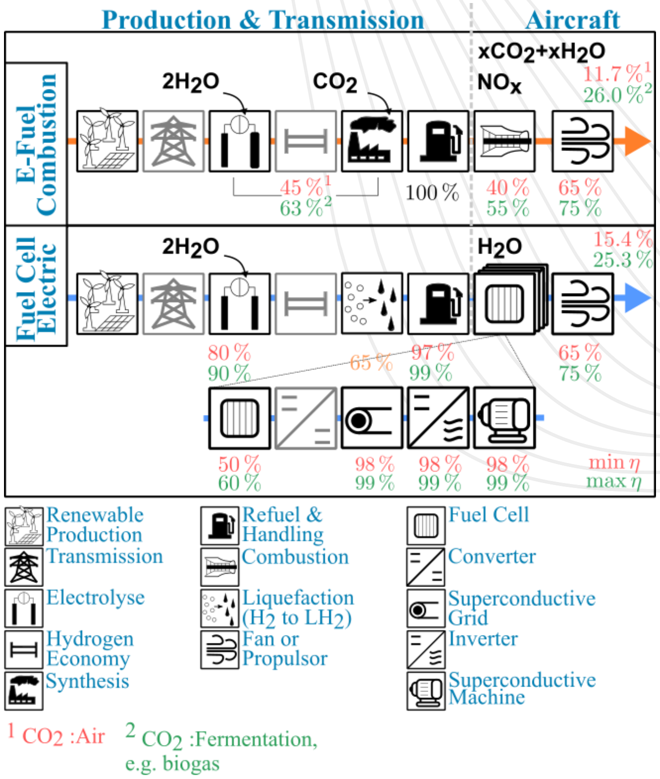
- **Fazit**

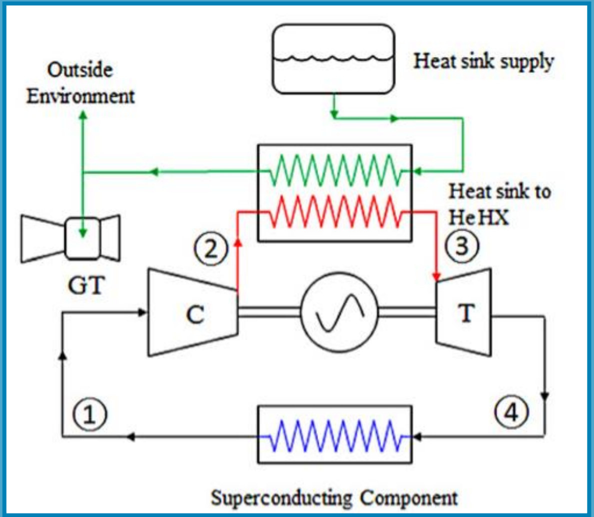


Herausforderungen:

- Produktion von grünem H_2 und Transport
- Leichte und sichere Speicherung des H_2
- Leistungsdichte der Brennstoffzelle (10 kW/kg)
- Effizienzsteigerung und Kühlung der Brennstoffzellen
- **Umrichtergespeiste supraleitende Maschine**
- **Kryogener oder nicht-kryogener Umrichter**

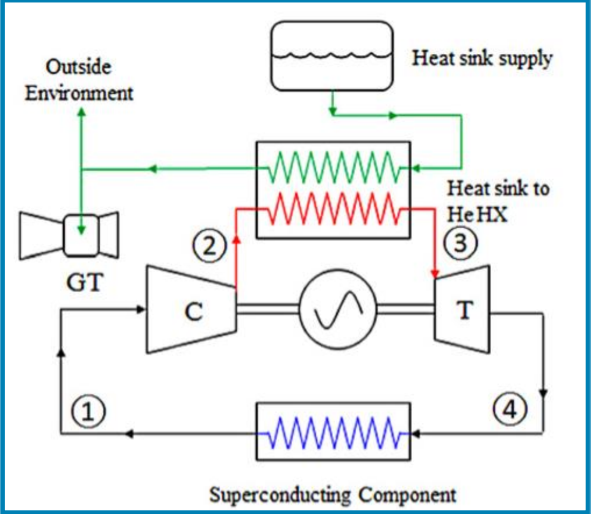
Stand der Technik

- **Einleitung**
- **Analyse**
- **Halbleiter**
- **DC/AC WR**
- **Fazit**



[1] Modelling of cryogenic cooling system design concepts for superconducting aircraft propulsion

Stand der Technik



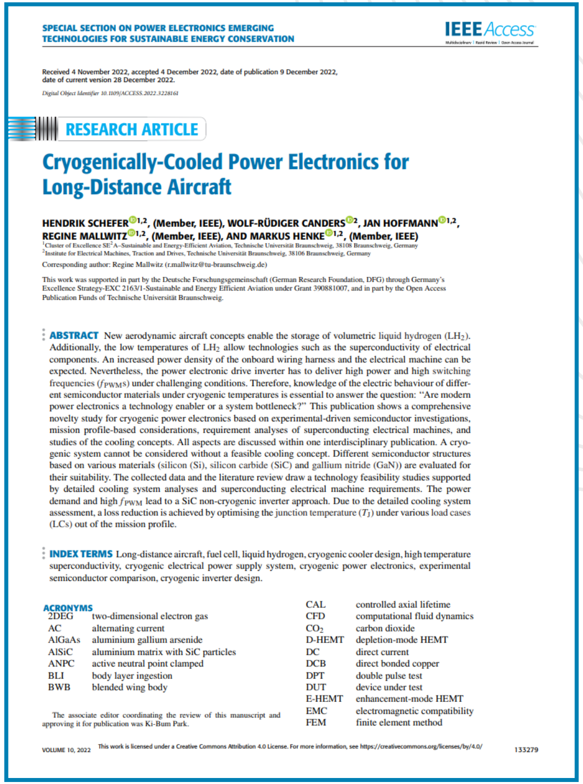
[1] Modelling of cryogenic cooling system design concepts for superconducting aircraft propulsion

[2] Development of High-Power High Switching Frequency Cryogenically Cooled Inverter for Aircraft Applications

[3] MW-Class Cryogenically-Cooled Inverter for Electric-Aircraft Applications

Wissenschaftlicher Beitrag

- **Einleitung**
- **Analyse**
- **Halbleiter**
- **DC/AC WR**
- **Fazit**



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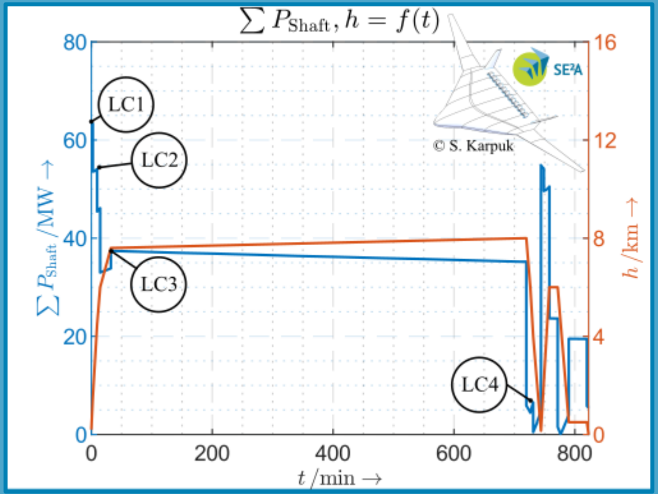
Forschungsfragen:

- Sind Halbleiter der Flaschenhals eines supraleitenden elektrischen Antriebsstrangs?
- Welcher Halbleiter ist geeignet?
- Welche Anforderungen bestehen an die Leistungselektronik?

- Teillastbetrieb
- He-Kühlung und H_2-Kühlung
- Anforderungen der E-Maschine
- Halbleiteruntersuchungen
- Umrichterdesign

Elektrisches System

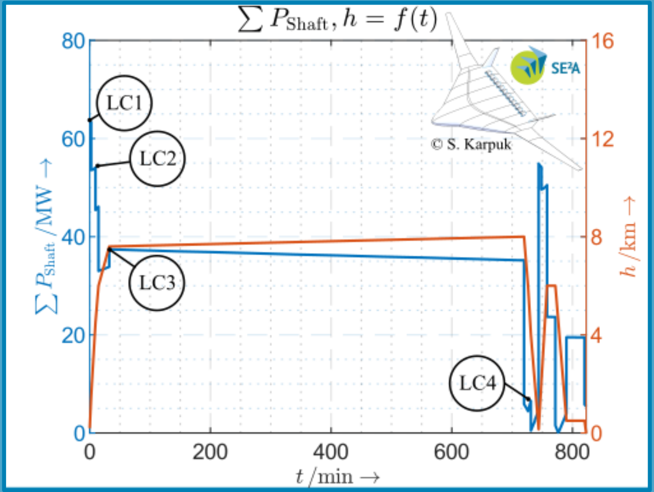
- Einleitung
- **Analyse**
- Halbleiter
- DC/AC WR
- Fazit



- Hohe Leistungsanforderung
- Teillastbereiche

Elektrisches System

- Einleitung
- **Analyse**
- Halbleiter
- DC/AC WR
- Fazit



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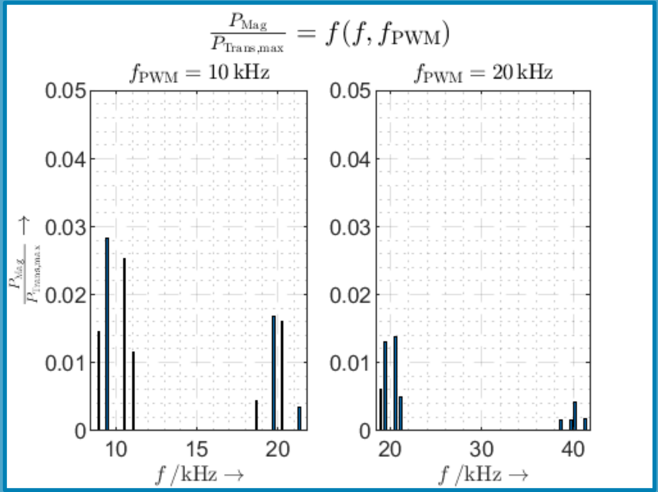
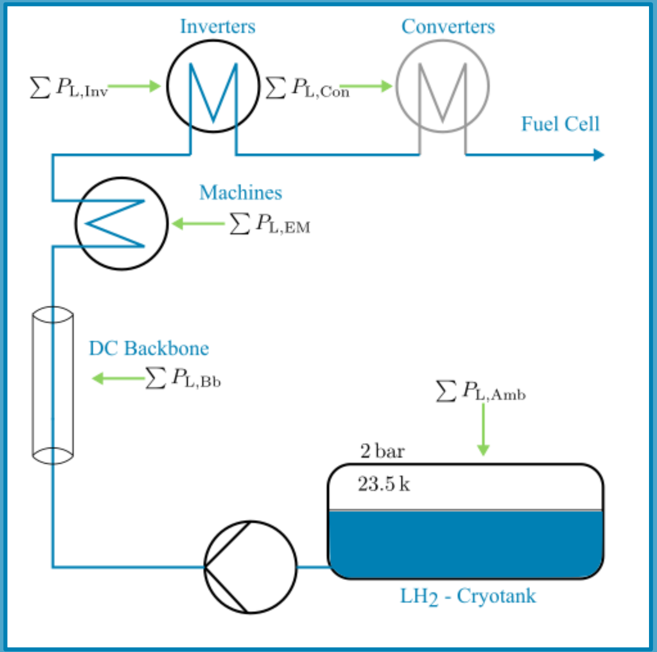


- Magnetisierungs- und Transportverluste sind von dem THD_i abhängig

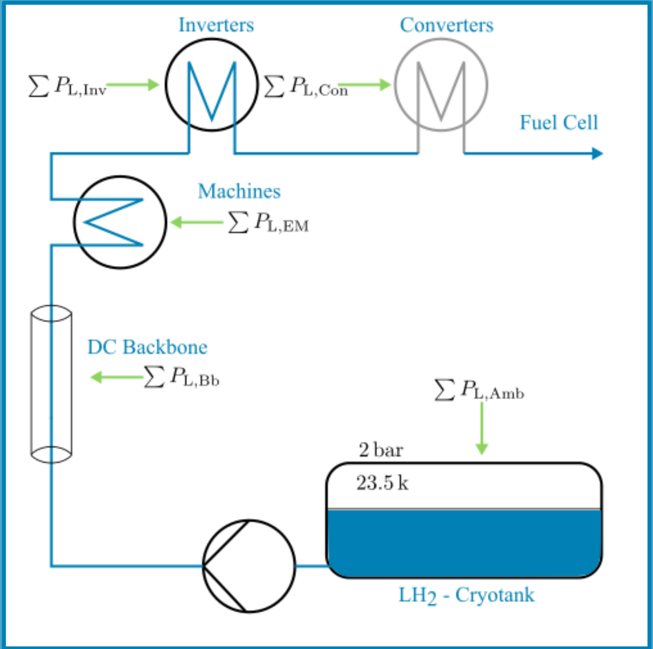
Thermisches System

- Einleitung
- **Analyse**
- Halbleiter
- DC/AC WR
- Fazit



H_2-Kühlung

Thermisches System



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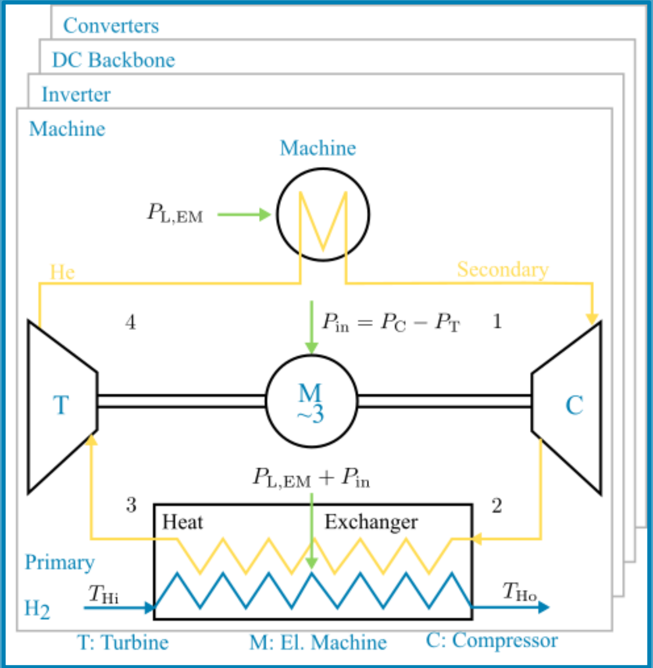


He-Kühlung

Zusammenfassung der Analyse

Einleitung

Analyse

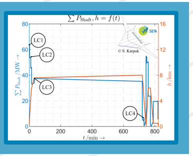
Halbleiter

DC/AC WR

Fazit

Elektrische Leistung (MW)

- Verhältnis Strom (Supraleiter) : Spannung (Halbleiter)



Zusammenfassung der Analyse

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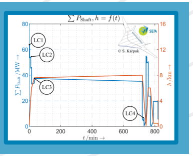
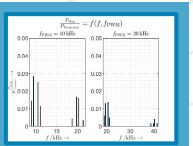


Oberschwingungsgesamtverzerrung (THD_i)

- Relativ hohe Schaltfrequenzen im MW-Bereich
- Leistungsdichte der Filter vs. kein Filter



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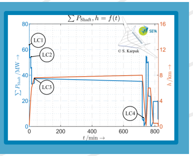

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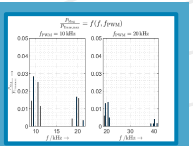
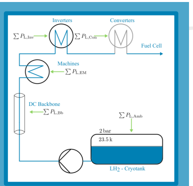


Kühlleistung ist vom Betriebspunkt abhängig

- H_2: Kühlung
- He: Kühlung



Stand der Technik

- Einleitung
- Analyse
- **Halbleiter**
- DC/AC WR
- Fazit

Device	Spannung	Quellen
Si-Diode		[4][5][6]
SiC-Diode		[4][5][6]
Si-MOSFET	< 650 V	[6][7][8][9][10]
Si-IGBT	< 650 V	[5][11][12][13]
Si-IGBT	> 1200 V	[5] [13][14][15]
SiC-MOSFET	1200 V	[14][16][17][18][19]
GaN-HEMT GaN-Cascode	< 650 V	[19][20][21][22][23][24][25][26][27]

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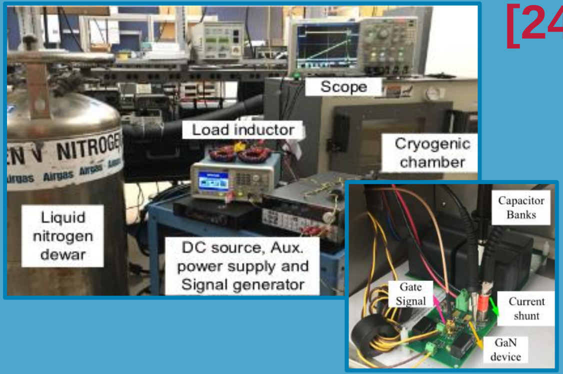

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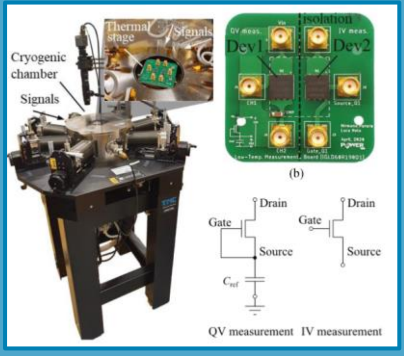

[27]

Untersuchungsmethodik

- Einleitung
- Analyse
- **Halbleiter**
- DC/AC WR
- Fazit

- Halbleitermaterialvergleich
- Vergleichbare Leistungsebene
- Untersuchungstemperatur
- Applizierbare Halbleiter: TO 247-3
- Halbleiterparameter:
  - Widerstand im leitenden Zustand
  - Sperrspannung
  - Ansprechspannung
  - Schaltverlustenergien

Untersuchungsmethodik

- Einleitung
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  - Schaltverlustenergien

Device	U_{Device}	I_{Device}	Herst.
Si-MOSFET	650 V	47 A	A
SiC-MOSFET	650 V	38 A	A
Si-IGBT	650 V	96 A	B
GaN-Cascode	650 V	35 A	C

Prüfstand und Ergebnisse

- TO 247-3
- Dynamische und statische Charakterisierung
- -200 °C (flüssigem Stickstoff)

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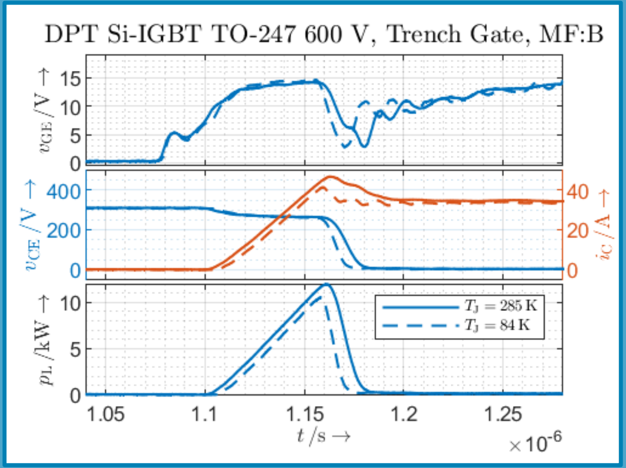
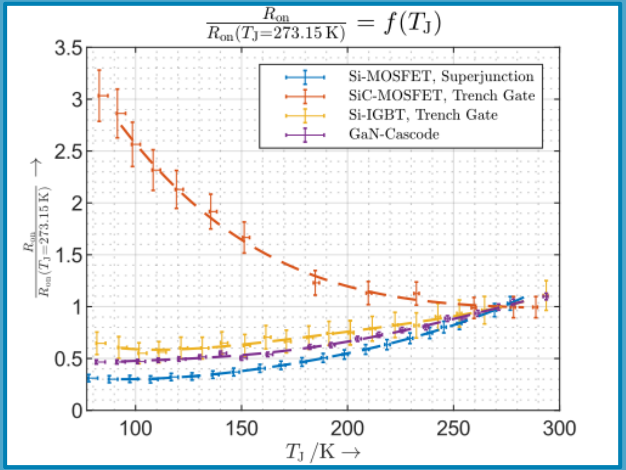


- Reduzierung der Einschalt- und Ausschaltverluste im IGBT

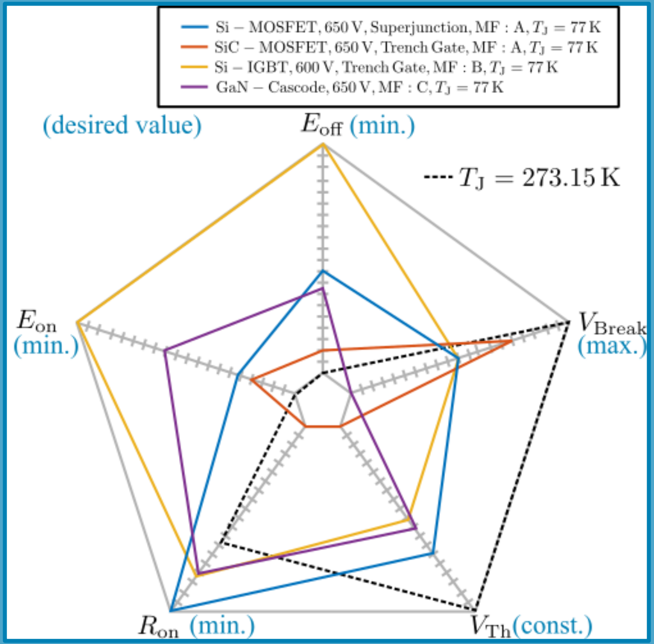
Prüfstand und Ergebnisse

- TO 247-3
- Dynamische und statische Charakterisierung
- -200 °C (flüssigem Stickstoff)



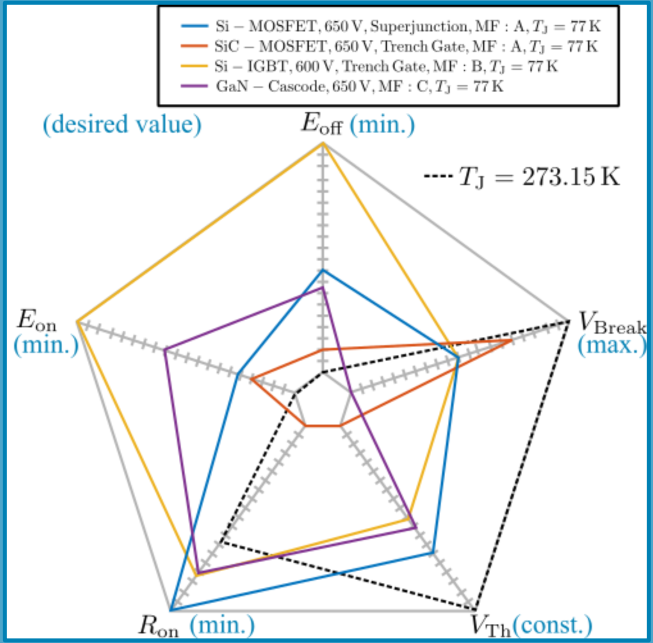
- SiC: früheinsetzender Carrier Freezeout
- Optimierung von Si- und GaN-Bauteilen

Zusammenfassung Halbleiter



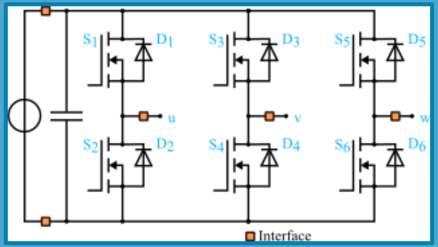
Zusammenfassung Halbleiter

- Einleitung
- Analyse
- **Halbleiter**
- DC/AC WR
- Fazit



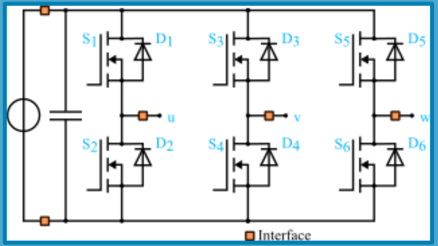
Device	Kryo.	Leist.	Kühl.
Si-MOSFET	✓	mittlerer	Indirekt 77 K <
SiC-MOSFET	×	hoher	Indirekt 200 K <
Si-IGBT	✓	hoher	Indirekt 77 K <
GaN. Cascode	✓	mittlerer	Indirekt 77 K<
GaN-HEMT	✓	mittlerer	Direkt

Elektrisches Design Inverter



- 9 Phasen
- 2 Level-Topologie
- 3 kV DC / 6,5 kV Bare Die
- 20 kHz
- Thermische Schnittstelle

Elektrisches Design Inverter



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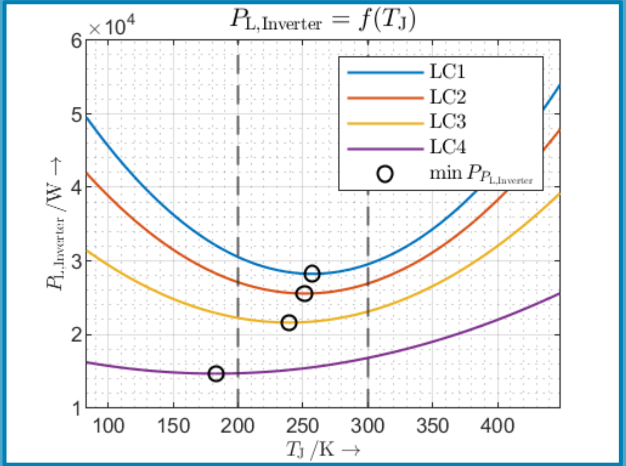
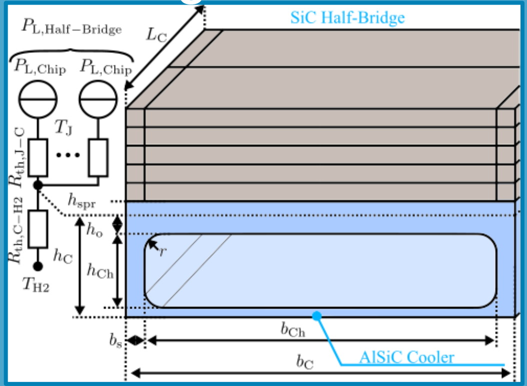


Thermisches Design Inverter

H_2-Kühlung:



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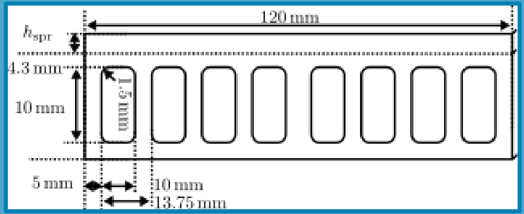

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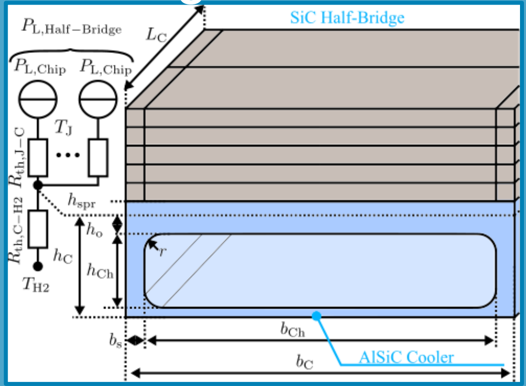

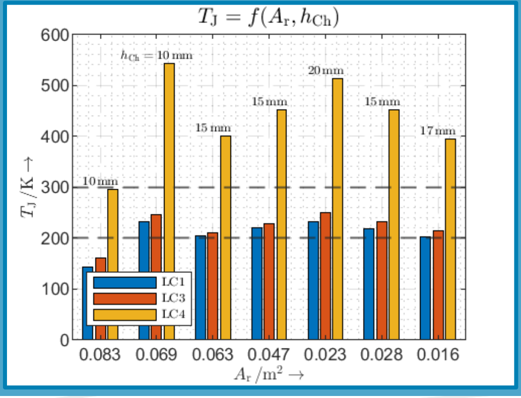

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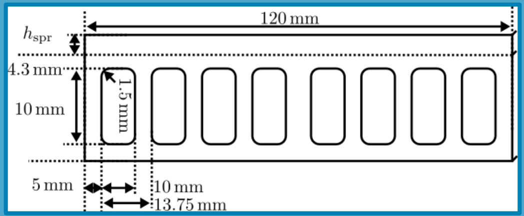


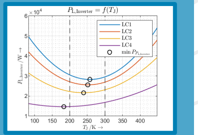
Load Case	Sperrschichttemperatur
LC1	250 K
LC2	247 K
LC3	236 K
LC4	332 K

Zusammenfassung DC/AC WR

- Einleitung
- Analyse
- Halbleiter
- **DC/AC WR**
- Fazit

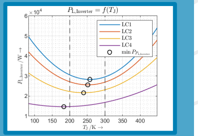
Elektrisches Design Inverter:

- 6,5 kV Bare Die Data / 3 kV DC
- 9 Phasen: Fehlertoleranz
- 20 kHz (low THD_i)



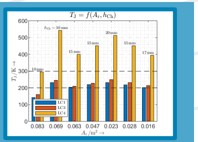
Zusammenfassung DC/AC WR

Elektrisches Design Inverter:



- 6,5 kV Bare Die Data / 3 kV DC
- 9 Phasen: Fehlertoleranz
- 20 kHz (low THD_i)

Thermisches Design Inverter:

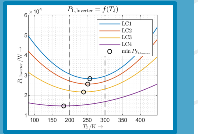


- Teillastbereich
- Hohe Temperaturänderung

Zusammenfassung DC/AC WR

- Einleitung
- Analyse
- Halbleiter
- **DC/AC WR**
- Fazit

Elektrisches Design Inverter:



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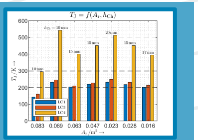

- Teillastbereich
- Hohe Temperaturänderung

Leistungsdichte:

- H_2-Kühlung: $42{,}9\,\frac{\mathrm{kW}}{\mathrm{kg}}$
- He-Kühlung: $40{,}4\,\frac{\mathrm{kW}}{\mathrm{kg}}$

Zusammenfassung

- Einleitung
- Analyse
- Halbleiter
- DC/AC WR
- **Fazit**

Systemanforderung

- Hohe Systemleistungen (Strom und Spannung)
- Geringer THDi → Filteraufwand vs. Kein Filter
- H_2: Kühlung vs. He: Kühlung

Zusammenfassung

- Einleitung
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Halbleiteruntersuchung

- Leitwiderstand und die Verluste der Halbleiter können teilweise durch die niedrigen Temperaturen verbessert werden
- Der Leitwert erreicht nicht die Werte eines Supraleiters

Zusammenfassung

- Einleitung
- Analyse
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Systemanforderung
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Halbleiteruntersuchung
- Leitwiderstand und die Verluste der Halbleiter können teilweise durch die niedrigen Temperaturen verbessert werden
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Wechselrichterdesign:
- SiC :Systemleistungen u. Schaltfrequenzen (THD_i) abdecken
- Beide Kühlungsansätze erreichen relativ hohe abgeschätzte gravimetrische Leistungsdichten

Ausblick

Einleitung

Analyse

Halbleiter

DC/AC WR

Fazit

Elektrisches System

- Ganzheitlicher Optimierungsansatz → Ströme, Spannungen, Verluste, Fehlertoleranz und Zuverlässigkeit

Ausblick

- Einleitung
- Analyse
- Halbleiter
- DC/AC WR
- **Fazit**

Elektrisches System

- Ganzheitlicher Optimierungsansatz → Ströme, Spannungen, Verluste, Fehlertoleranz und Zuverlässigkeit

Halbleiteruntersuchungen:

- Vertikale GaN-Strukturen für höhere Spannungen
- GaN: Aufbau- u. Verbindungstechnik (integrierte Lösung)

Ausblick

- Einleitung
- Analyse
- Halbleiter
- DC/AC WR
- **Fazit**

Elektrisches System
- Ganzheitlicher Optimierungsansatz → Ströme, Spannungen, Verluste, Fehlertoleranz und Zuverlässigkeit

Halbleiteruntersuchungen:
- Vertikale GaN-Strukturen für höhere Spannungen
- GaN: Aufbau- u. Verbindungstechnik (integrierte Lösung)

Wechselrichterdesign:
- Thermischen Schnittstellen

Ausblick

- Einleitung
- Analyse
- Halbleiter
- DC/AC WR
- **Fazit**

Elektrisches System

- Ganzheitlicher Optimierungsansatz → Ströme, Spannungen, Verluste, Fehlertoleranz und Zuverlässigkeit

Halbleiteruntersuchungen:

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Wechselrichterdesign:

- Thermischen Schnittstellen

Wie geht es weiter am IMAB?

- Bewilligter Antrag LuFo VI und SE²A

Vielen Dank für Ihre Aufmerksamkeit

Hendrik Schefer
Raum 205, 2.OG
Hans-Sommer-Str. 66
38106 Braunschweig
Telefon: +49 531 / 391 - 3960
Telefax: +49 531 / 391 - 5767
Mail: mailto:h.schefer@tu-braunschweig.de

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