Monolithic Bidirectional GaN-Device: Opportunity and Challenges for Highly Efficient Design of Power Electronics Converters

Reza Barzegarkhoo, PhD, Senior Member IEEE
Scientific Research Staff, Kiel University, Germany

**Bodo‘s
Wide Bandgap
Event 2024**

Making WBG Designs Happen

Table of Content

▼ Introduction

- Importance of WBG-based Bidirectional Device
- Emergence of Monolithic Bidirectional Switch (MBS)/Opportunity and Challenges

▼ Applications

- MBS-GaN as an Isolation Switch in Solid State Circuit Breaker (SSCB)
- MBS-GaN in Fault-Tolerant Multi-Winding DC-DC Converters
- MBS-GaN in Reconfigurable Dual Active Bridge (DAB) Converter

▼ Conclusion

INTRODUCTION

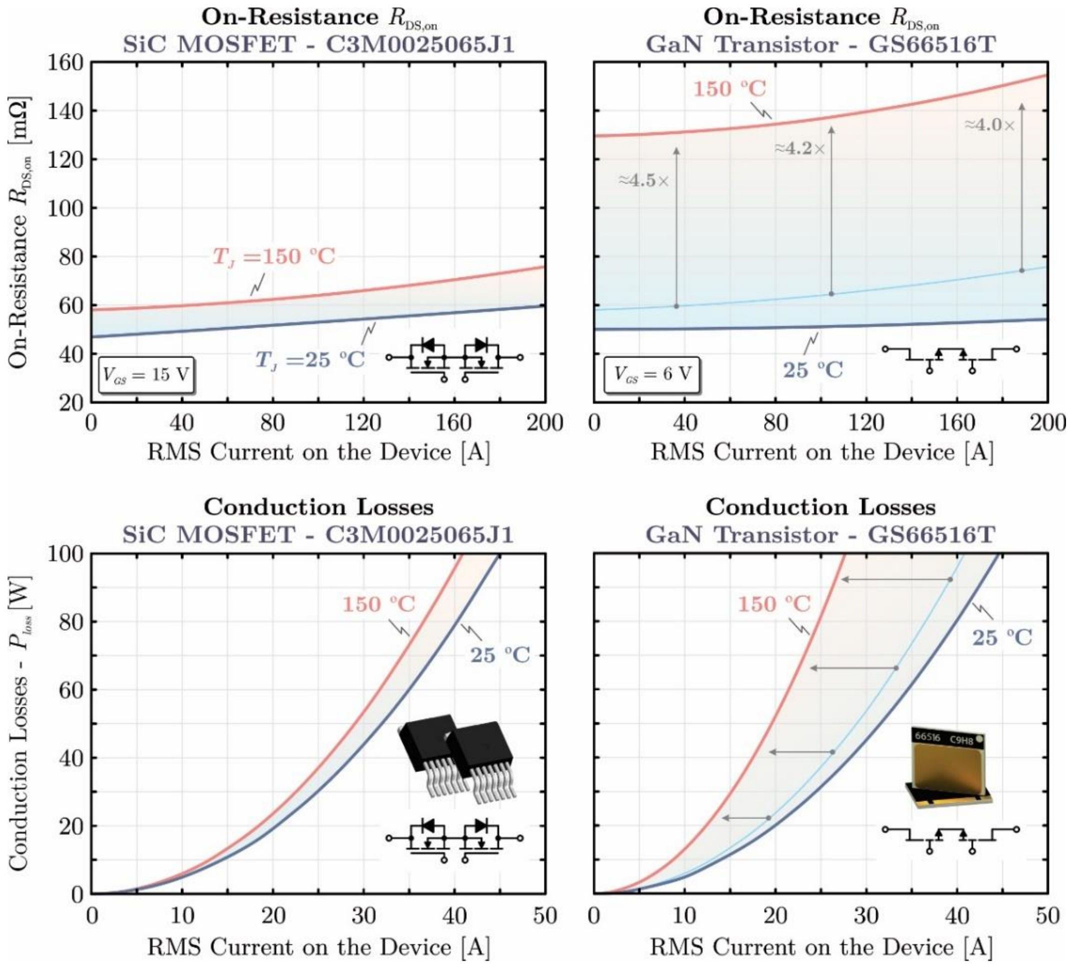
Introduction

Construction of Bi-Directional FETs Using Discrete Wide Band Gap Devices

- **Features: Block** a stress **voltage** in **both** polarities and **conduct** symmetric **current** in **both** directions.
- **Major Applications**: Current-Source Converters, Multilevel Inverters, AC-DC Rectifiers, Resonant/Non-Resonant DC/DC Converters.
- **Typical Configuration:** Common-source/drain configuration with **two or four discrete** devices with **different no of gate drivers**.

Challenges posed by Discrete GaN-HEMTs

- **Higher conduction losses** compared to SiC MOSFETs (4.0 times higher)
- GaN HEMTs are highly sensitive to **Junction Temperature and circuit parasitics.**



▼ Introduction

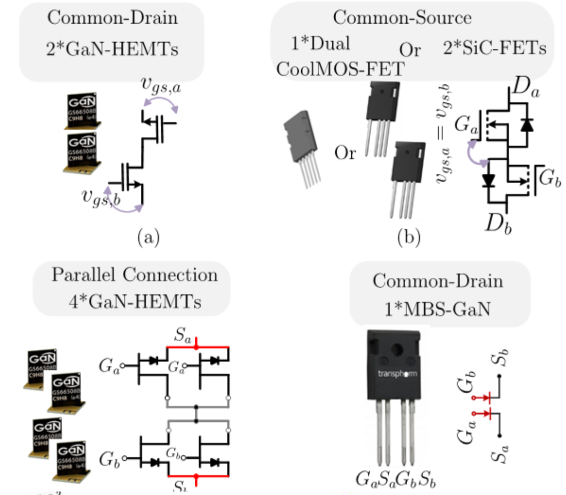
► Monolithic Bidirectional Switch (MBS)-GaN

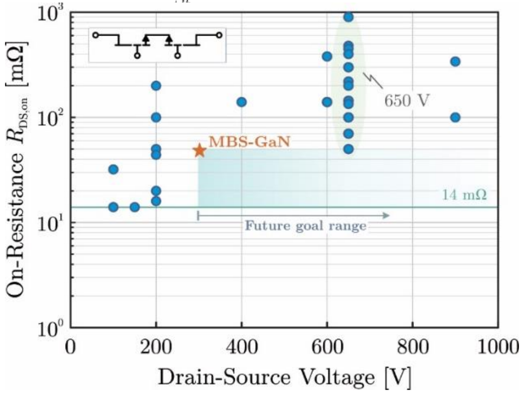
MBS Opportunities:

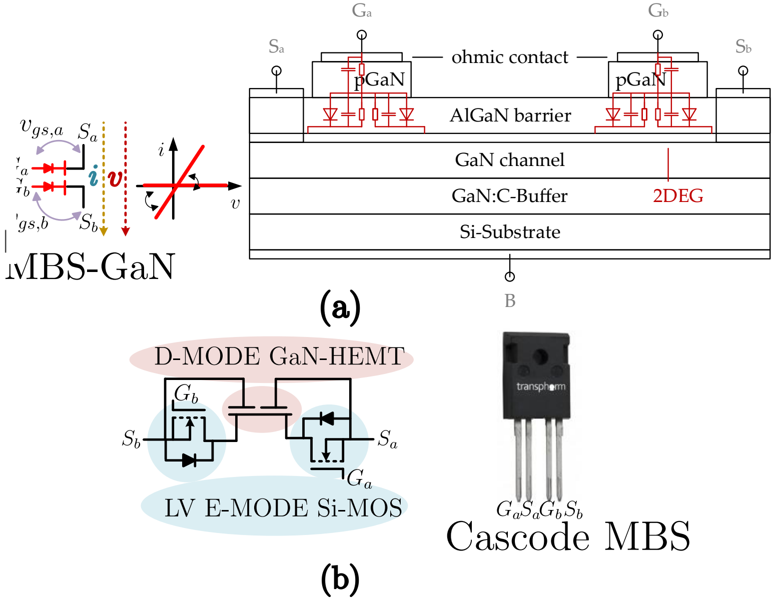
- ✓ Four-Pin **Common-Drain-Based**
- ✓ Lateral **2DEG-based** design (**+-650 V Source-Source Voltage**)
- ✓ **Two controllable gates**
- ✓ **Low ON-state parasitic resistance/capacitors.**
- ✓ Easier implementation for better **power layout.**

MBS Challenges:

- ❖ **Two gate driver/isolated dc supplies.**
- ❖ **Termination process** for **back-gating effect** and **gate** leakage current.
- ❖ **Short-circuit/thermal management behavior.**
- ❖ Large **reverse recovery charge** in **hard switching application (in cascode version).**
- ❖ Lack of **Kelvin-Source** Pins.







MBS alternative of Bi-GaN-HEMT constructed based on (a) a lateral normally-OFF GaN-based fabrication **(Panasonic/Infeneon Device +-650V/140 mili Ohm)**, (b) with a cascode Si/GaN fashion **(Transphorm Device +-650V/70 mili Ohm)**

APPLICATIONS

BIDIRECTIONAL DEVICES
ISOLATION SWITCH

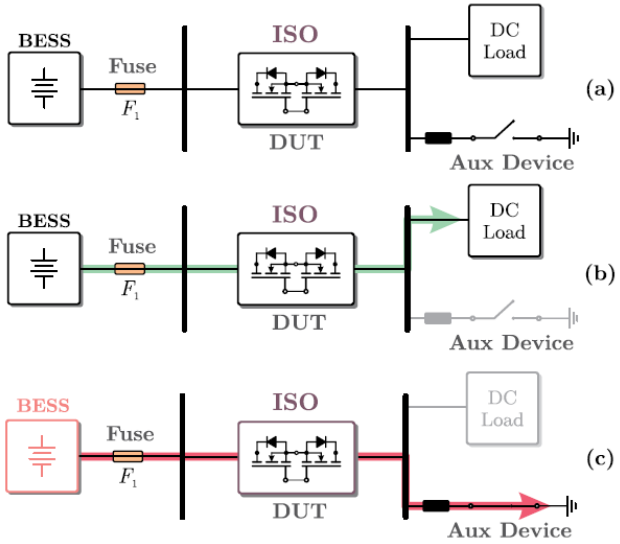
▶ Experimental Verification of the Protection Scheme

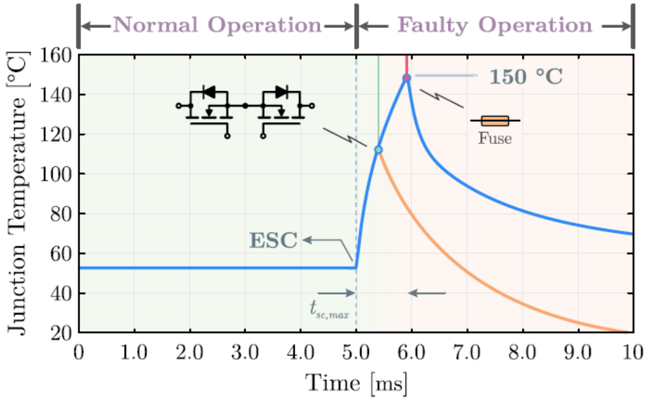
❑ Implemented DC Network to validate the effectiveness of the protection scheme:

a) The main connections and elements are exhibited;

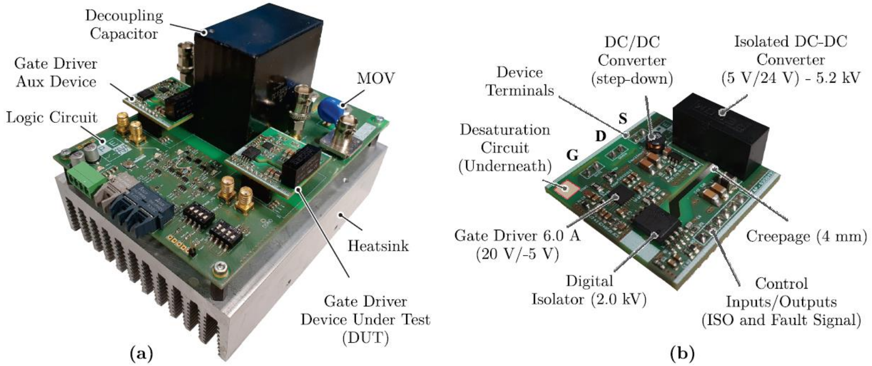
b) Normal operation of the system is highlighted by the power flow from the BESS to the DC load [Green Path]. BESS feeding the DC Load.

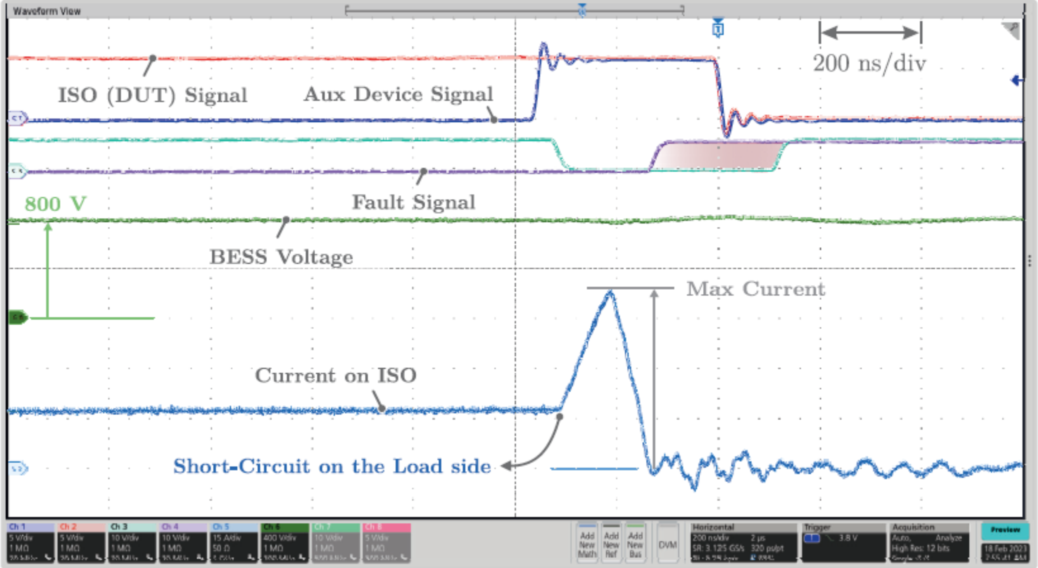
c) True short-circuit is applied to the BESS during the normal operation [FUL].





SSB-protection scheme is configured to trip in the first <u>200 ns</u>, while a slow-blow **fuse** is placed as the latest resource.

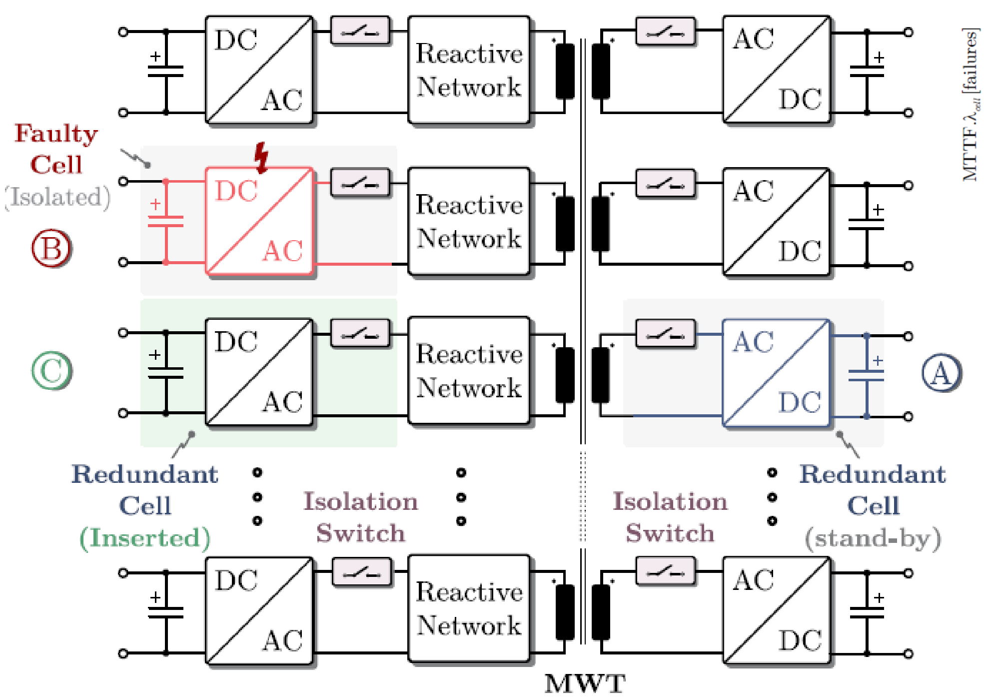


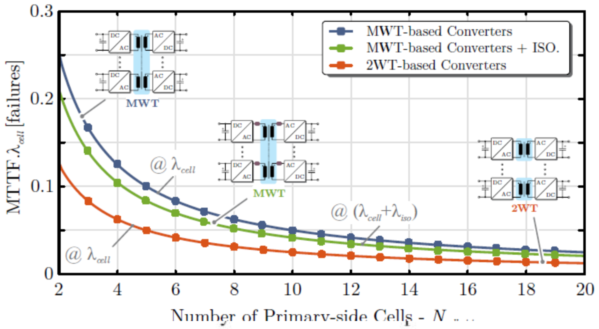


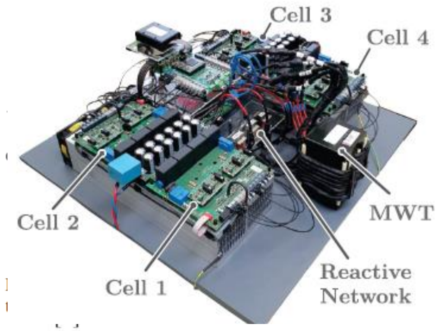
T. Pereira, H. Beiranvand, M. Liserre, **“Advanced Protection Scheme for High-Voltage Li-ion Battery Packs”**, PCIM Europe 2023.

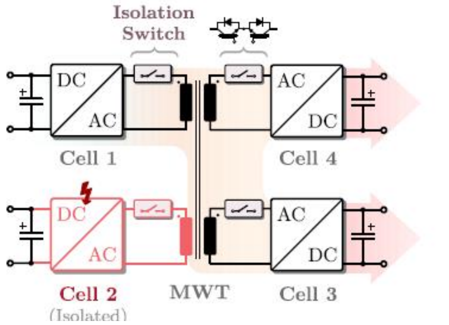
BIDIRECTIONAL DEVICES
ISOLATION SWITCH

▶ Application in Fault-Tolerant MWT DC-DC Converter









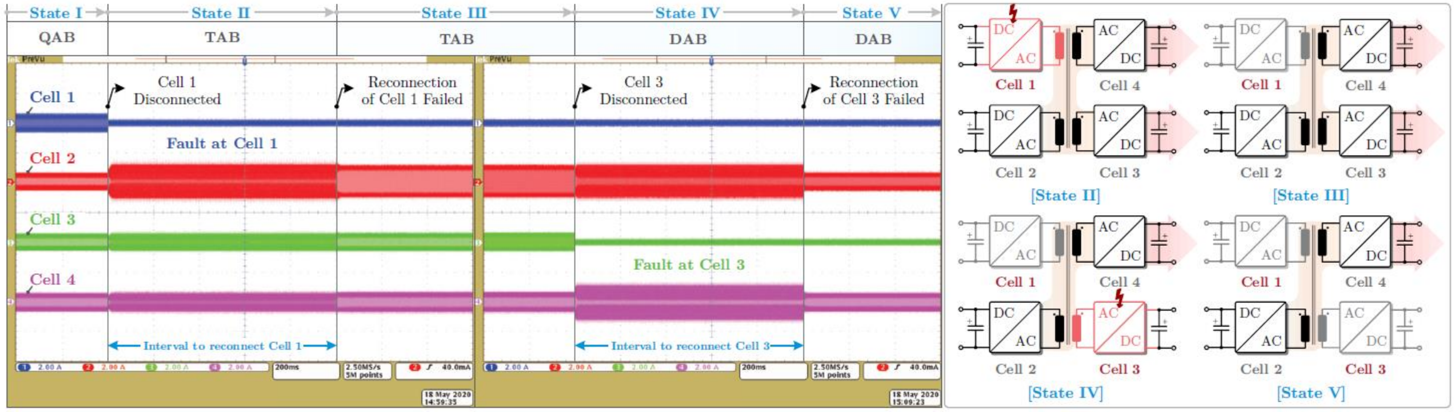


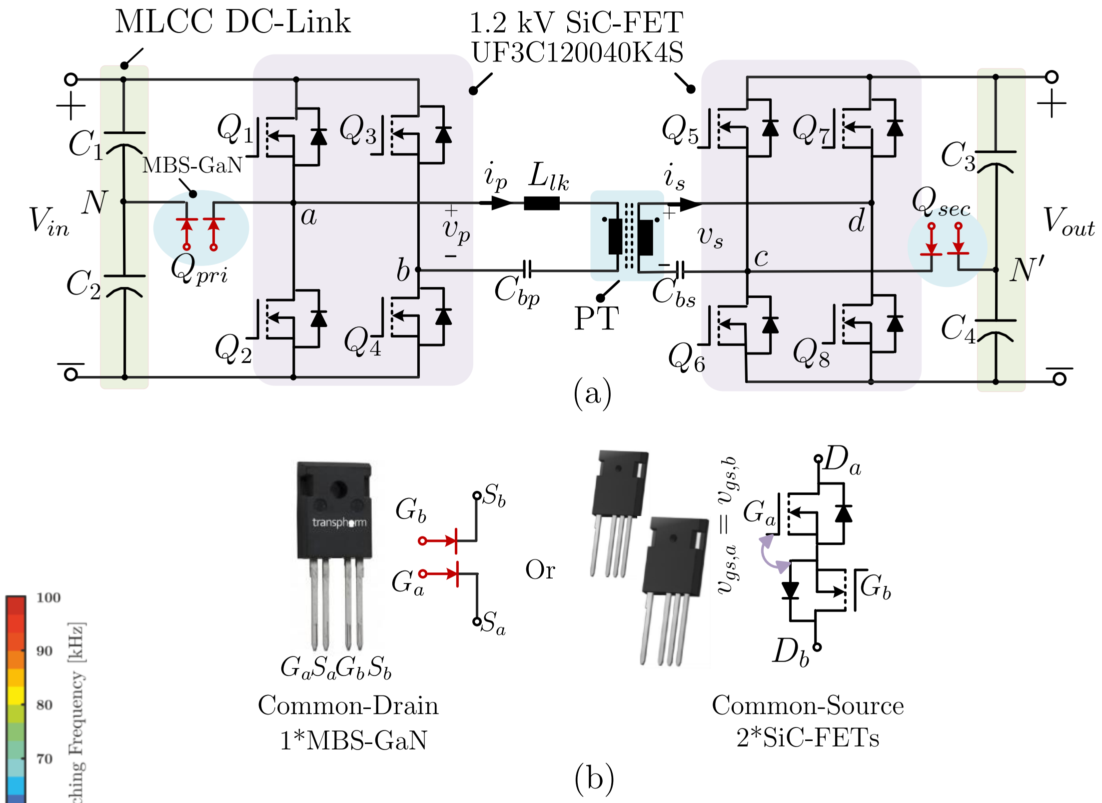
Figure 11. Experimental results of the SQAB under a fault at the cell 1 and cell 3 and the posterior reconfiguration to the resulting DC-DC converter: after the cell 1 be disconnected, the SQAB is reconfigured to a TAB and then when the cell 3 is disconnected the converter is reconfigured to a DAB.

T. Pereira, F. Hoffmann and M. Liserre, **"Performance Evaluation of the Multi-winding Redundancy Approach in MTB DC-DC Converters,"** 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Vancouver, BC, Canada, 2021, pp. 3599-3606.

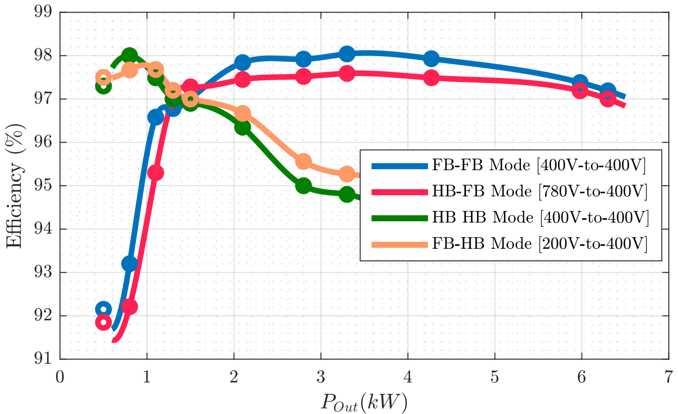
BIDIRECTIONAL DEVICES IN DAB CONVERTER

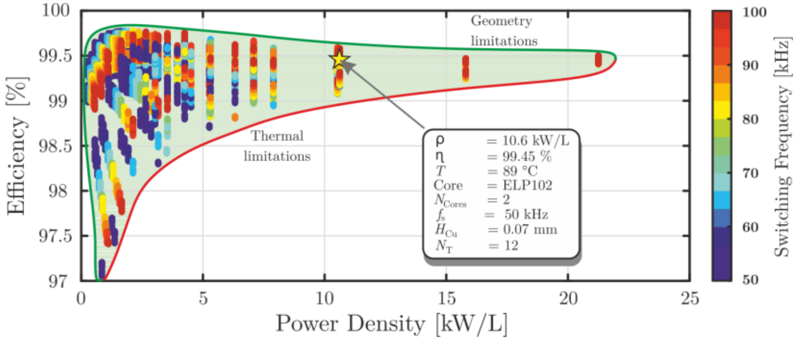
▶ Application in Reconfigurable DAB Converter

- A **Fault Tolerant-Based DAB** converter with MBS-GaN.
- Four different circuit possibilities for a **wide** range of **voltage conversion gain, 200 t0 800 V input and 400 V output**.
- Maintaining the high efficiency of the DAB **(>97%)** even **at low power** with **ZVS** action.
- **Highly Efficient/High power density** design using **MBS-GaN and Planar Transformer**.



(a) The proposed reconfigurable DAB converter, and (b) realization of a four-quarant device using MBS-GaN or SiC-FETs.





R. Barzegarkhoo, F. Groon, A. Sengupta and M. Liserre, " A 6.6 kW Highly Efficient Reconfigurable Dual Active Bridge Converter Designed Using Planar Transformer, SiC-FETs and Monolithic Bidirectional Devices," APEC 2025.

BiDirectional Devices in DAB Converter

▶ Application in Reconfigurable DAB Converter

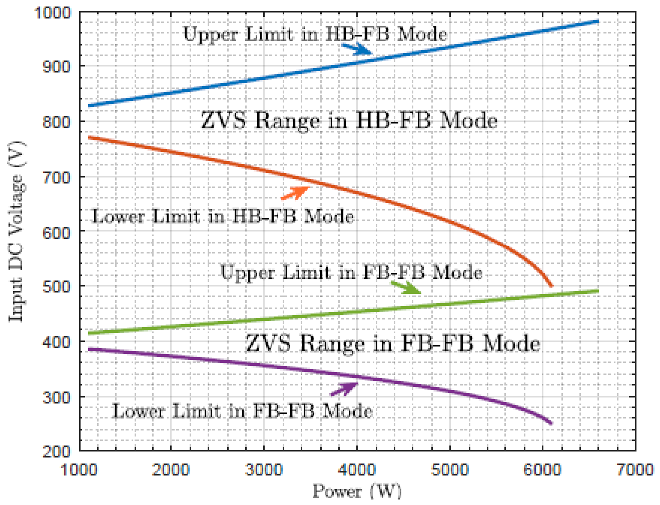
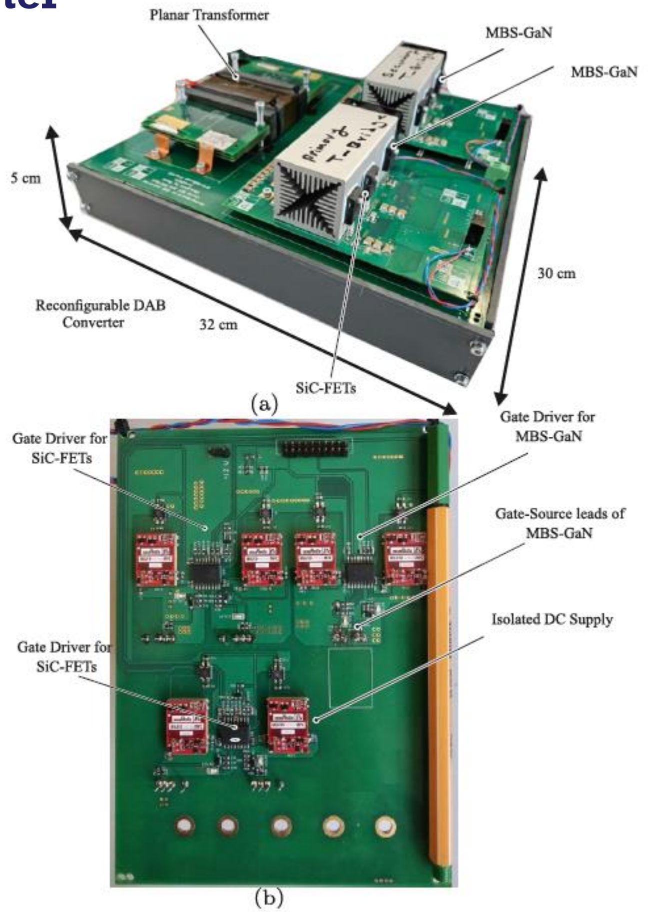
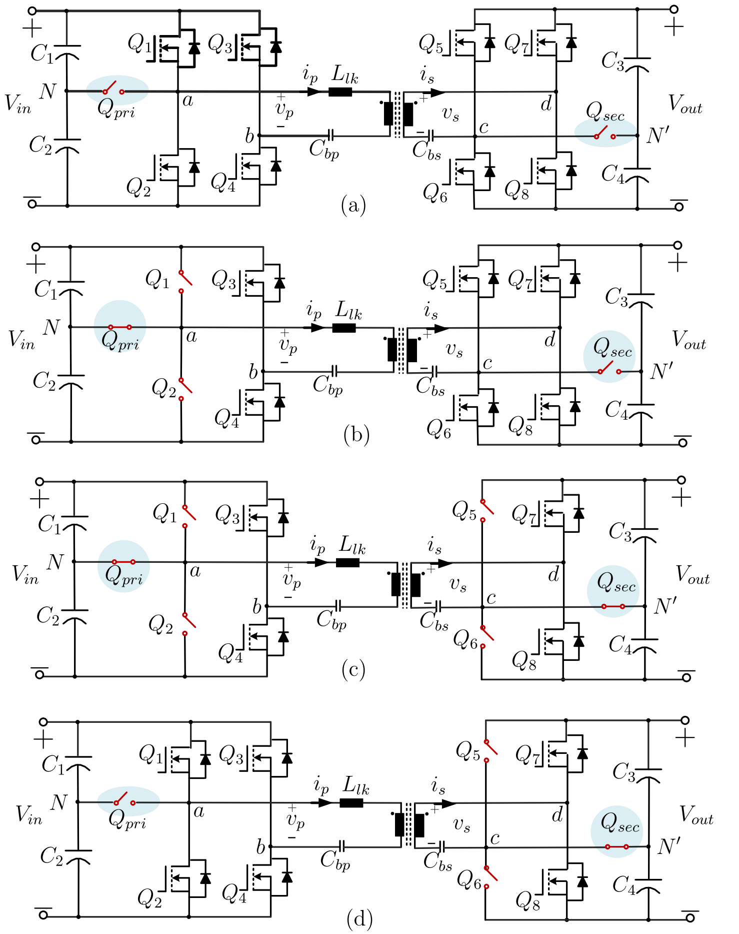


TABLE I: Main parameters used for the experimental prototype

Element	Type and Description
Switching Frequency/Rated Power	50 kHz/ 6.6 kW
SiC-FETs	1.2 kV/UF3C120040K4S
MBS-GaN	±650V/TP65F060WS
MLCCs	10×220nF/GRM55DR7LW224KW1L
V_{in}/V_{out}	200–800V/400V
Microprocessor	DSP-TMS320F28379D
C_{bp}/C_{bs}	8×470nF/2220Y1K00474KXS2
L_{lk}	25uH/E42/21/20 N87
Gate Drivers	UCC21520
Isolated dc/dc ICs	MGJ1D051505MPC
Sensors	AMC3330



6.6 kW fabricated prototype for the proposed reconfigurable DAB converter

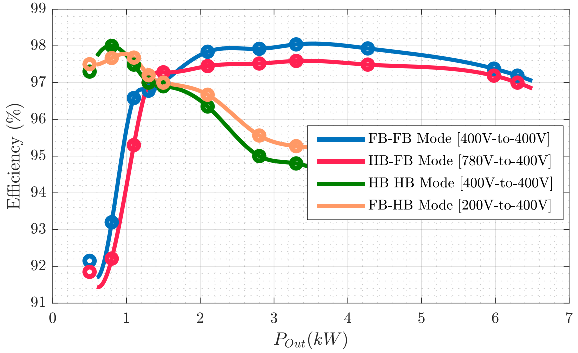


The proposed reconfigurable DAB converter, and its operation mode based on (a) FB-FB, (b) HB-FB, (c) HB-HB, and (d) FB-HB configurations.

BiDirectional Devices in DAB Converter

Christian-Albrechts-Universität zu Kiel

▶ Application in Reconfigurable DAB Converter



Udc1	0.3992	kV
Udc2	0.4044	kV
P1	6.524	kW
P2	6.340	kW
η1	97.190	%
Idc1	16.364	A
Idc2	15.679	A
LOSSES	183.32	W

(b)

Udc1	0.7793	kV
Udc2	0.4005	kV
P1	5.142	kW
P2	5.002	kW
η1	97.282	%
Idc1	6.608	A
Idc2	12.487	A
LOSSES	139.75	W

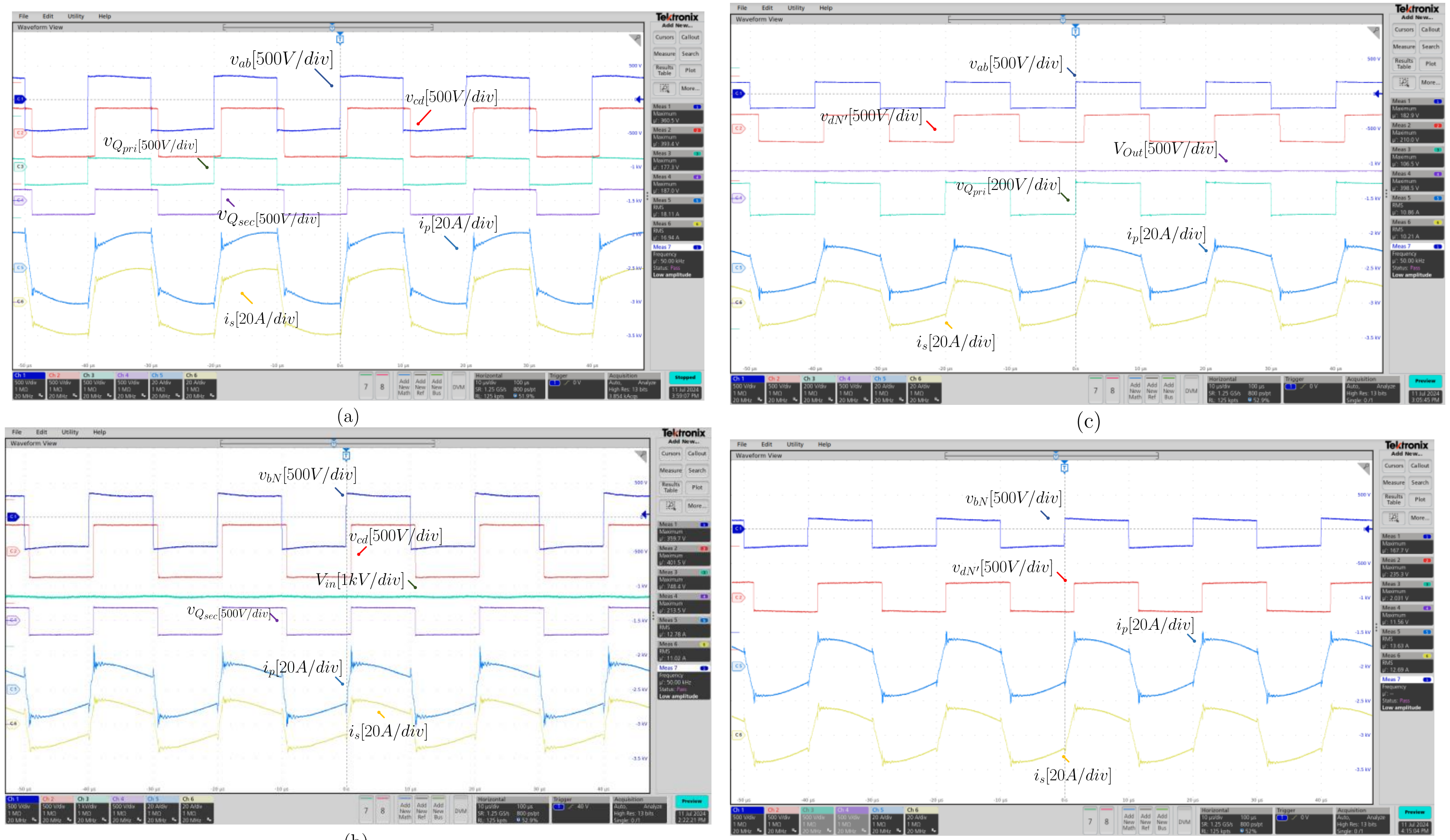
(c)

Udc1	0.1997	kV
Udc2	0.4122	kV
P1	1.187	kW
P2	1.1593	kW
η1	97.679	%
Idc1	5.945	A
Idc2	2.8116	A
LOSSES	27.551	W

(d)

Udc1	0.3896	kV
Udc2	0.4022	kV
P1	1.1303	kW
P2	1.1020	kW
η1	97.492	%
Idc1	2.9016	A
Idc2	2.7396	A
LOSSES	28.351	W

(e)

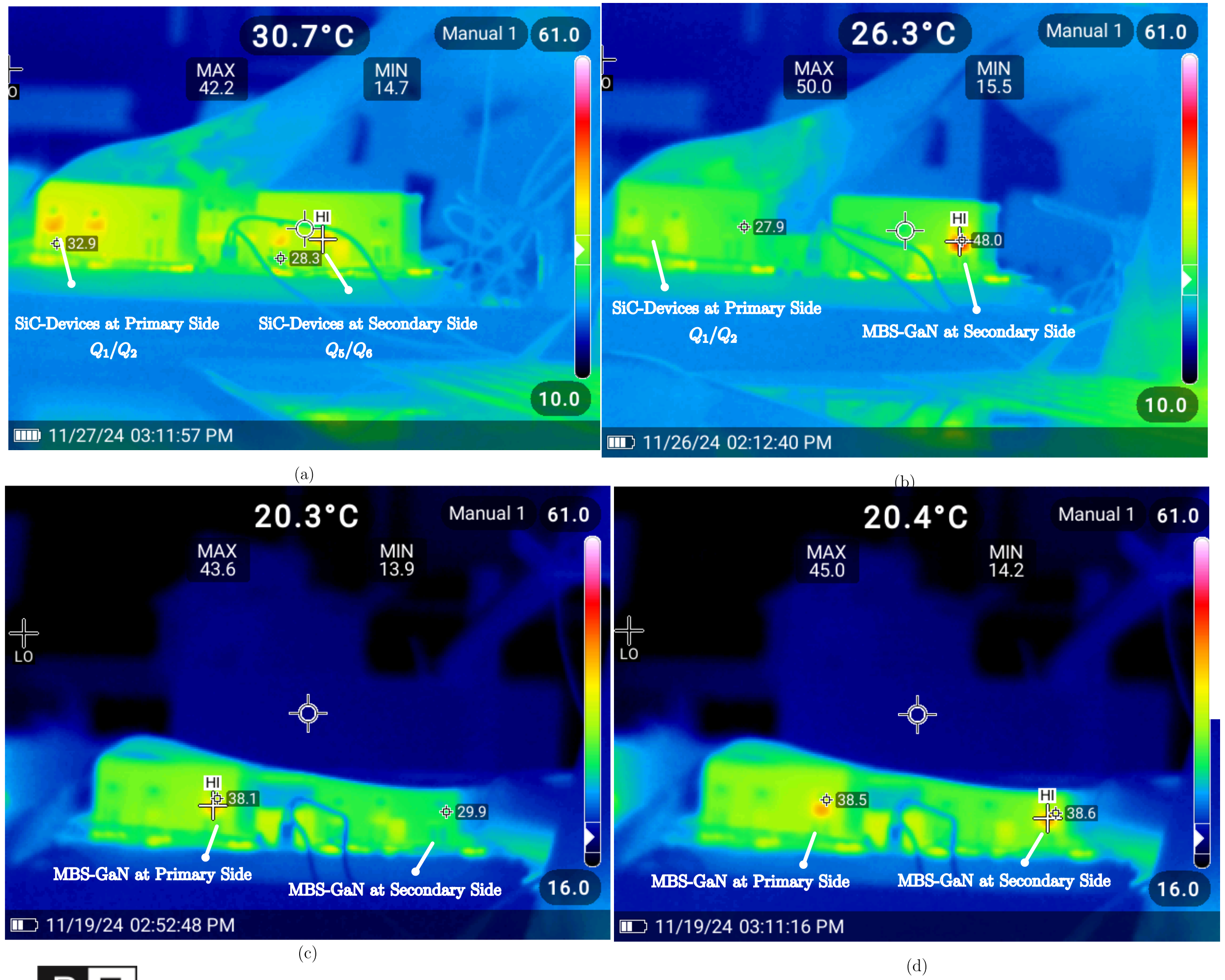


Experimental results of the proposed reconfigurable DAB converter at (a) FB-FB Mode [6.3 kW/400 V to 400 V], (b) HB-FB Mode [4.4 kW/760 V to 400 V], (c) FB-HB Mode [2 kW/200 V to 400 V], and (d) HB-HB Mode [2.5 kW/400 V to 400 V].

BIDIRECTIONAL DEVICES IN DAB CONVERTER

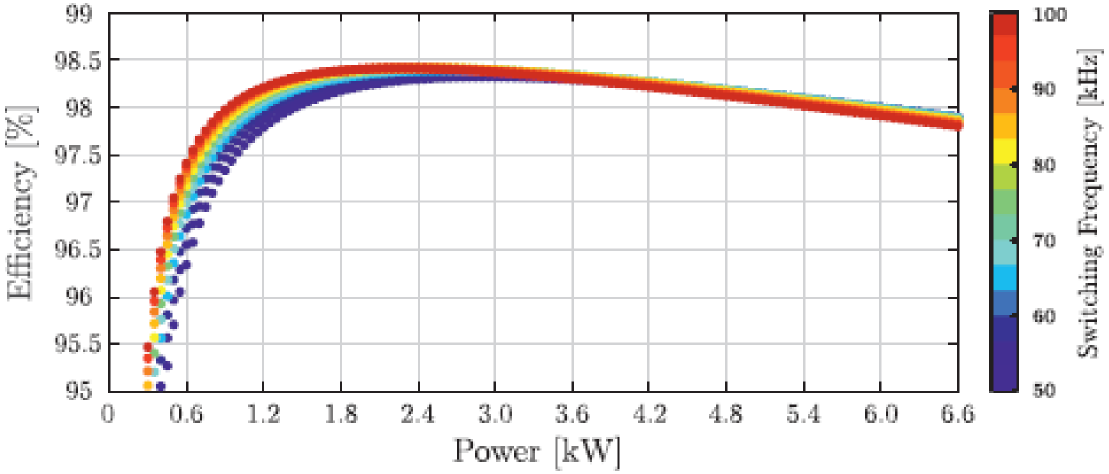
Christian-Albrechts-Universität zu Kiel

▶ Application in Reconfigurable DAB Converter



(a) (b) (c) (d)

MBS-GaN devices temperature in primary and secondary side of the PT after five minutes continuous running at (a) FB-FB Mode [6,6 kW/400 V- to 400 V], (b) FB-HB Mode [2,5 kW/200 V to 400 V], (c) HB-FB mode [3.8 kW/770 V to 400 V], and (d) HB-HB mode [2 kW/400 V to 430 V]



Pareto-Front result for the entire reconfigurable DAB converter at the FB-FB mode considering the switching/conduction losses of the devices as well as the core and winding losses of the designed PT and the leakage inductor.

Conclusion

- ☐ Bidirectional power devices are constructed based on **back-to-back connection of two or four devices in existing topologies to block** a stress voltage in **both polarity** or to conduct a current in **both direction.**
- ☐ Large ON-State resistance/parasitic capacitance, large footprint area and power layout consideration are their main shortcomings (e.g., in comparison to SiC MOSFET, conduction losses increase **4 times** when discrete GaN-HEMT is employed in a bidirectional fashion.)
- ☐ **Monolithic Bidirectional Switch (MBS)** using **Lateral GaN-on Si** design or **Cascode Technique** with a common drain can surpass this shortcoming by offering lower on-state resistance.
- ☐ One of its main applications is its utilization as an isolation switch in SSCBs. Due to lower expected on-state resistance of MBS and fast response of GaN-HEMTs, it is expected to **trip an SSCB within less than 200 ns (the obtained value using SiC-based SSCB).**
- ☐ **MBS-GaN** can also be incorporated into the multiwinding transformer **(MWT)**-based multi-port DAB converters. Based on the analysis done on SSCBs, a fault detection procedure got developed for wide-band-gap device. Hence, the results for **fault tolerant MWT-DAB** with **both discrete GaN-HEMTs and SiC-FETs** got reported in different working scenarios.
- ☐ Thanks to smaller footprint area compared to discrete-based bidirectional device and due to expected lower conduction losses, a reconfigurable DAB converter with **MBS-GaN** got developed. This could help to achieve four-different configurations. Compared to conventional DAB converters, the proposed structure can achieve **>97%** efficiency even **at lower power** and for **wide range of voltage conversion gain.** The power ratio of the designed prototype is **6.6 kW/50 kHz.**
- ☐ Even though such appealing opportunities, the **short circuit ruggedness of MBS-GaN** is expected to be poorer than **discrete GaN-HEMTs (less than 1 uS)**. This needs a careful thermal modeling.
- ☐ MBS-GaN needs **two gate drivers**, while it is expected to see a **reverse recovery loss in its cascode version**. DPT can be performed to distinguish the gate driver dependency to the source-to-source voltage of the device and the switching loss behavior.

Acknowledgment

Christian-Albrechts-Universität zu Kiel

GaNius

Energy Efficient Power Electronics

This work was also supported by the Priority Programme “Energy Efficient Power Electronics ’GaNius’ (DFG SPP 2312)”.

Reza Barzegarkhoo, PhD
Scientific Research Staff/PostDoc Fellow
rbar@tf.uni-kiel.de

THANK YOU!