ETH zürich

ECCE 2023 Nashville, TN | OCT.29-Nov.2

Ultra-Compact GaN-BDS-Based Single-Stage Isolated 1-Φ/3-Φ-Operable Bidirectional OBCs

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Special Session

Bidirectional Switches are Coming! Are You Ready?

Nov. 1, 2023

ETH zürich

ECCE 2023 Nashville, TN | OCT.29-Nov.2

Ultra-Compact GaN-BDS-Based Single-Stage Isolated 1-Φ/3-Φ-Operable Bidirectional OBCs

J. W. Kolar, J. E. Huber, D. Menzi, D. Zhang, J. Schäfer, S. Weihe

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Special Session

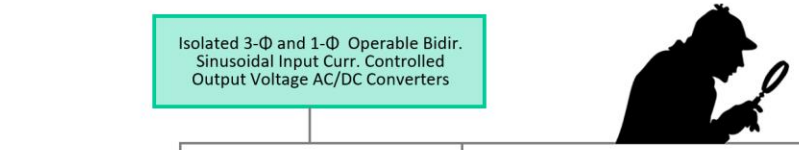
Bidirectional Switches are Coming! Are You Ready?

Nov. 1, 2023

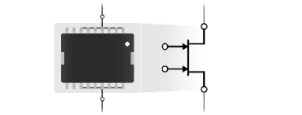
Outline

- *Introduction*
- *Non-Modular DAB-Type Matrix Converter*
- *Partly-Modular DAB-Type Converter*
- *Partly-Modular Series Res. Converter*
- *Exp. Analysis of BDS Samples*
- *Conclusions*

Classification of AC/DC-Converter Topologies



- Isolated 3-Φ and 1-Φ Operable Bidir. Sinusoidal Input Curr. Controlled Output Voltage AC/DC Converters
  - Two-Stage AC/DC–DC/DC Unipol.-Sw.-Based Converter Concepts
  - Single-Stage AC/DC Unipol.-Sw.-Based Converter Concepts ★
  - Single-Stage AC/DC Bidir.-Sw.-Based Converter Concepts
    - Non--Mod. Inp. Stage / Non-Mod. Output Stage
    - Phase-Mod. Inp. Stage / Non-Mod. Output Stage
      - Dual-Active-Bridge-Type Converter
        - Single 3-Φ Transformer
          - 3-Φ Input Voltage Sec.-Side Space Vect. Mod ☆
          - 1-Φ Input Voltage Sec.-Side Space Vect. Mod.
        - Three 1-Φ Transformers
      - Series-Resonant-Type Converter
        - Single 3-Φ Transformer
          - 3-Φ Input Voltage Sec.-Side Space Vect. Mod. ☆
          - 1-Φ Input Voltage Sec.-Side Space Vect. Mod. ☆
        - Three 1-Φ Transformers
    - Phase-Mod. Inp. Stage / Phase-Mod. Output Stage
    - Non-Mod. Inp. Stage / Phase-Mod. Output Stage



Source: ST Engineering / www.idirect.net

3-Φ Input Voltage Sec.-Side Synchr. Rect.

DC-Transformer-(DCX)-Type / Uncontrolled Output Voltage

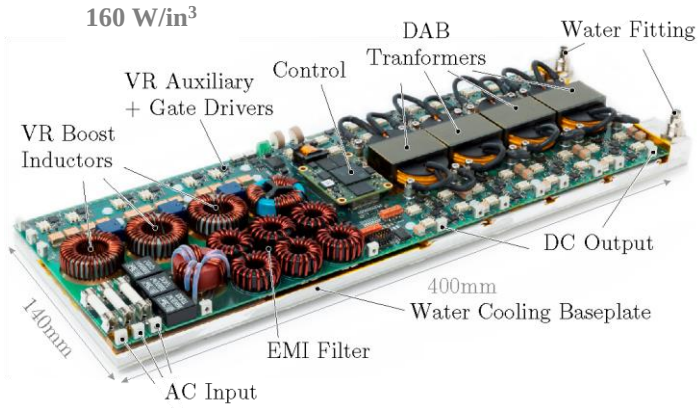
- *Numerous New BDS-Based Single-Stage Conv. Concepts & Related Mod. Schemes (!)*

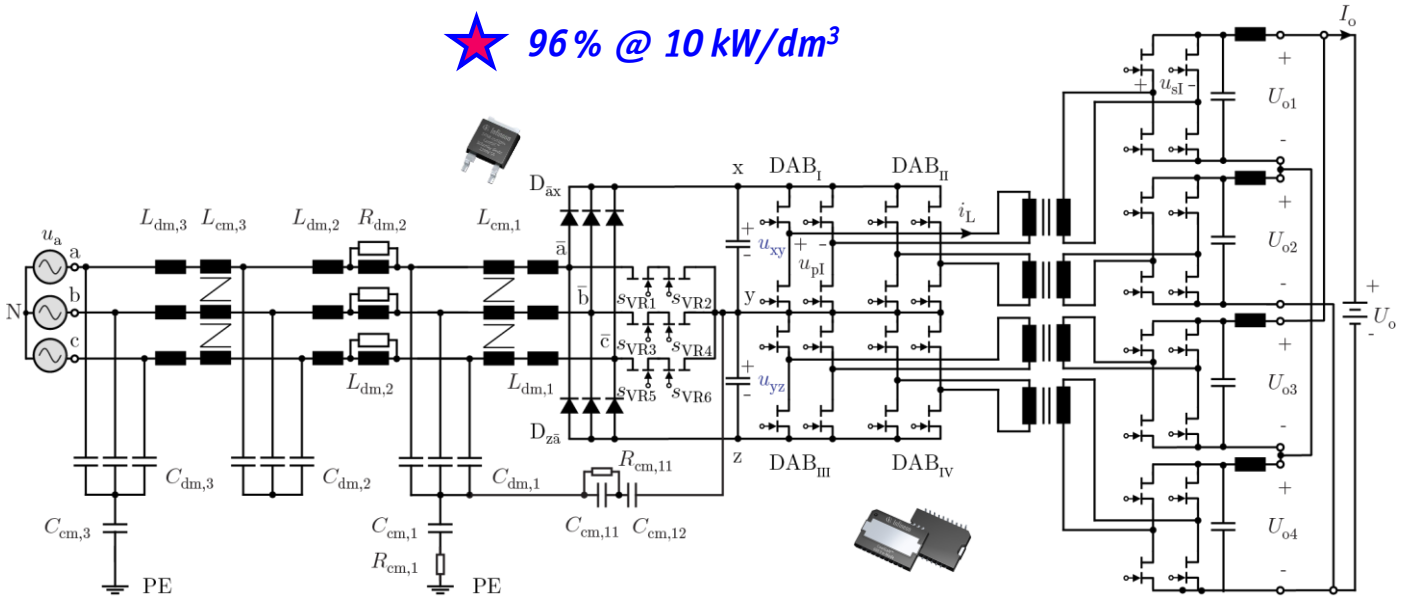
Isolated Two-Stage 3-Φ AC/DC Converter

- *3-Φ AC/DC Converter Front-End — Vienna Rectifier / Split DC-Link | f_{sw}=560 kHz*
- *2x 2 Dual Active Bridge DC/DC Converter Isolation Stages | f_{sw} = 180…330 kHz*

— *P = 10kW*
— *U_{in} = 400 V_{AC} line-to-line*
— *U_{out} = 250 … 800 V_{DC}*
— *CISPR 11/ Class A*

★ *96 % @ 10 kW/dm³*

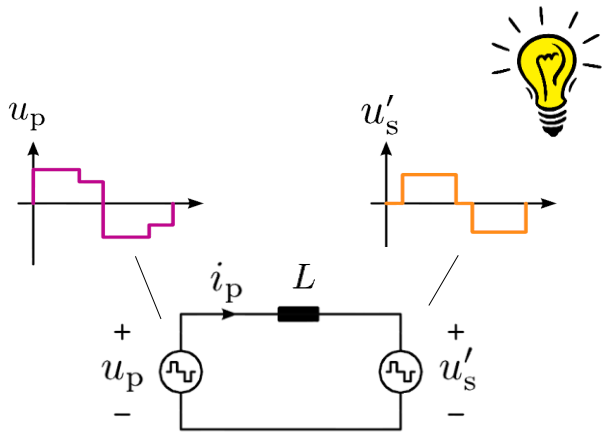




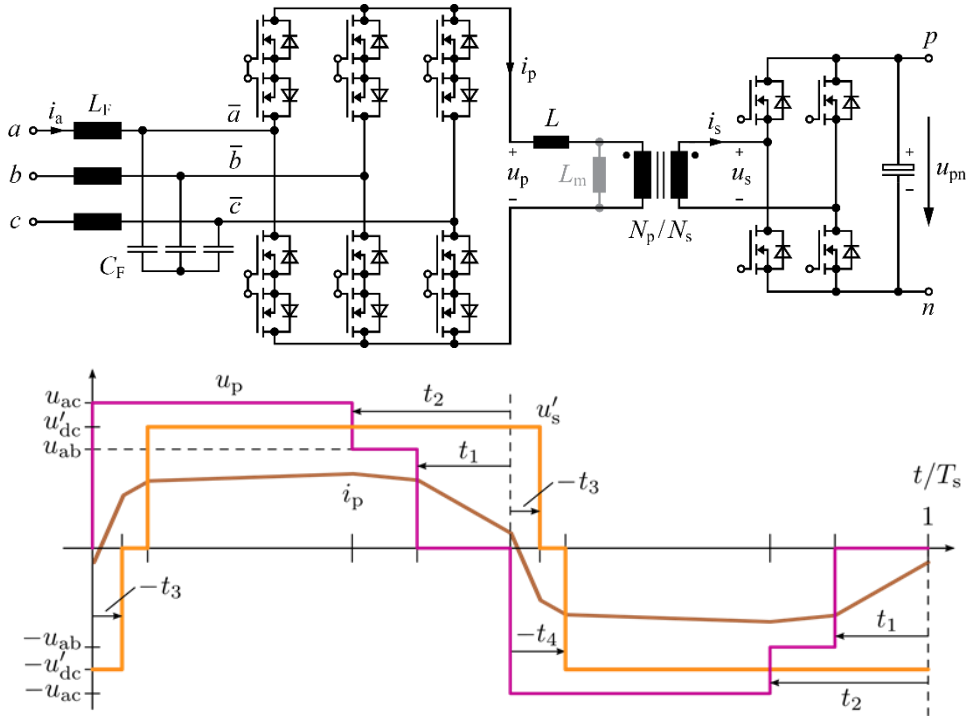
- *600V CoolGaN GIT HEMTs/ 1200V CoolSiC Schottky Diodes*
- *Low Sw. Loss Synergetic Control of Input & Output Stage — Six-Pulse-Shaped DC-Link Voltage*

Isolated Single-Stage 3-Φ AC/DC Converter

- *Low-Frequ. 3-Φ AC / High-Frequ. 1-Φ AC Matrix Converter Input Stage*
- *Converter Operation Based on the Dual Active Bridge (DAB) Concept*
- *Bidirectional Buck-Boost Operation*



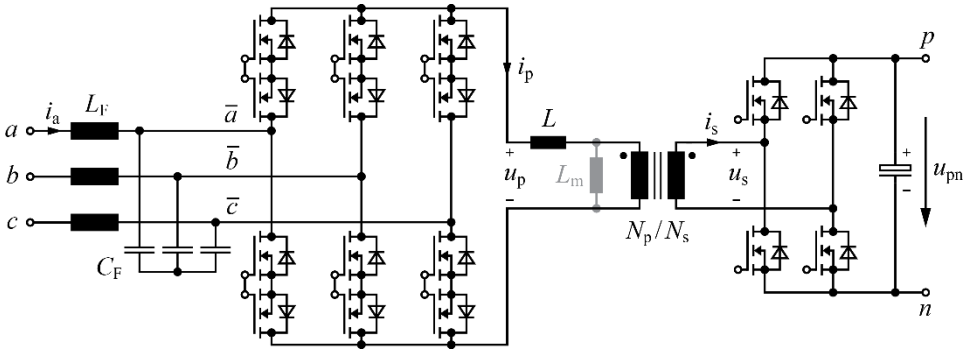
- *Equivalent Circuit*

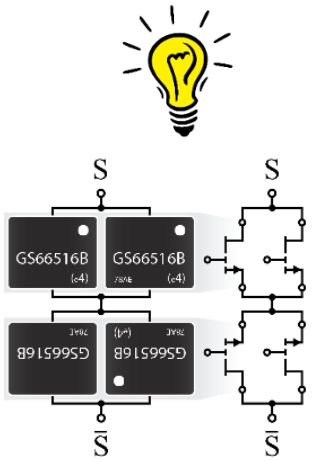


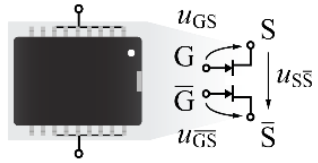
- *Transformer Voltages / Currents*

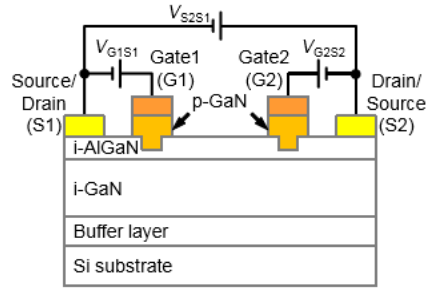
Isolated Single-Stage 3-Φ AC/DC Converter

- *Low-Frequ. 3-Φ AC / High-Frequ. 1-Φ AC Matrix Converter Input Stage*
- *Converter Operation Based on the Dual Active Bridge (DAB) Concept*
- *Bidirectional Buck-Boost Operation*







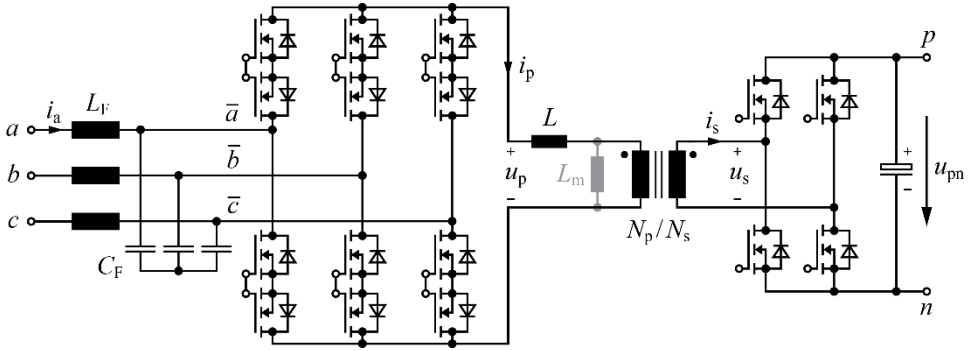


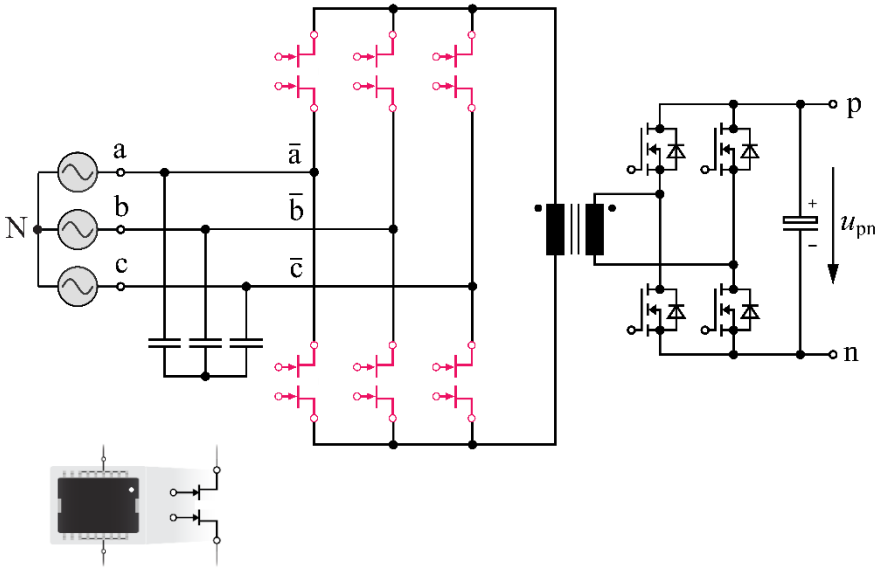
Source: Panasonic ideas for life

- *Monolithic Bidirectional / Bipolar Switches (M-BDS) for Replacing Inverse-Series Conn. MOSFETs*
- *Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Isolated Single-Stage 3-Φ AC/DC Converter

- *Monolithic Bidirectional / Bipolar Switches (M-BDS) for Replacing Inverse-Series Conn. MOSFETs*
- *Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*



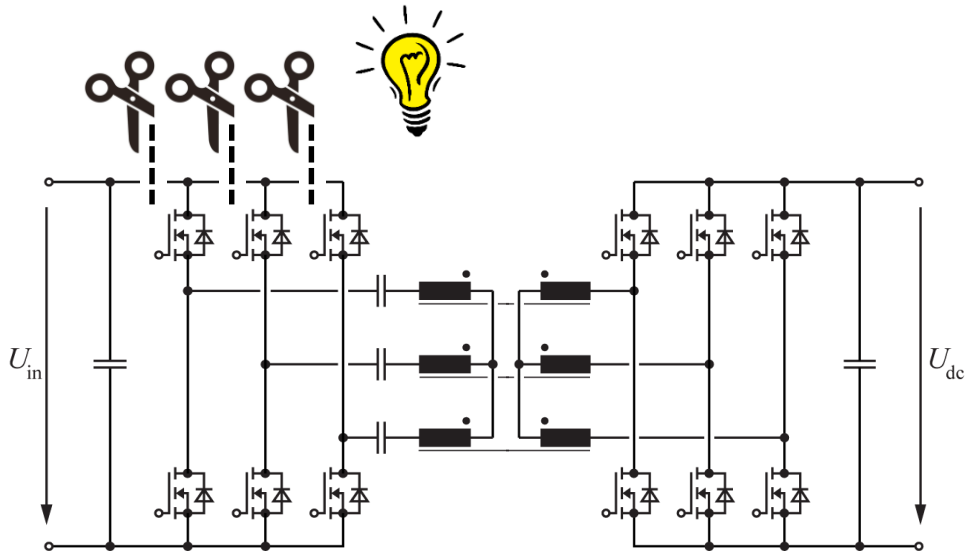


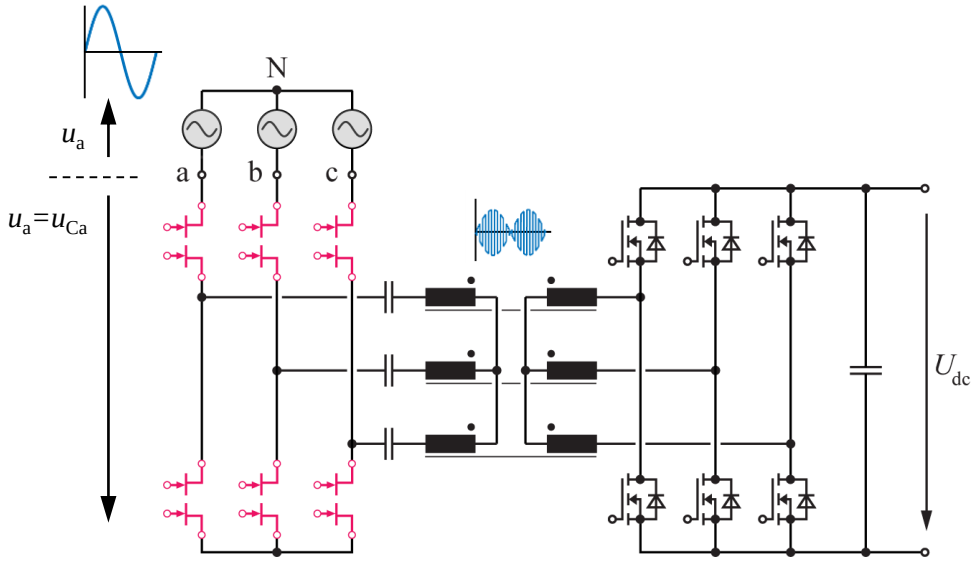
- *Rated 3-Φ Output Power NOT Available in 1-Φ Line-to-Line Operation*
- *Rated Power Operation for 3-Φ AND 1-Φ Grid Connection → Requires Phase-Modular Input Stage*

Primary-Side Phase-Modular Converter Topology

3-Φ Input DAB-Type AC/DC Converter (1)

- *Modification of 3-Φ Xfrm DAB → Prim.-Side Phase-Modular AC/DC Converter Topology*
- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle*



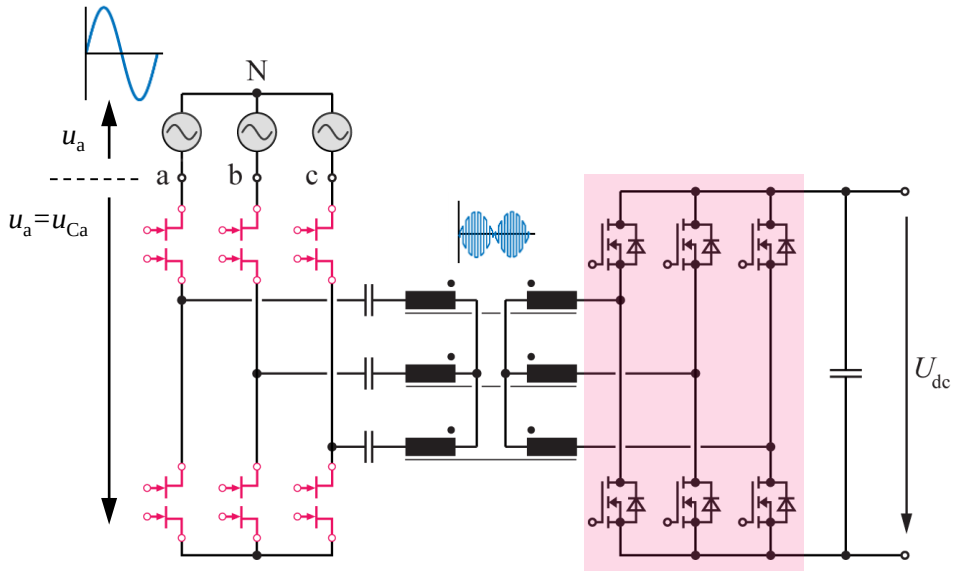


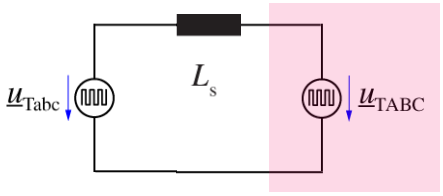
- *Voltage Stress on Prim.-Side AC Switches Determined by Peak Value of Grid PHASE Voltage (!)*
- *Bidirectional Power Flow*

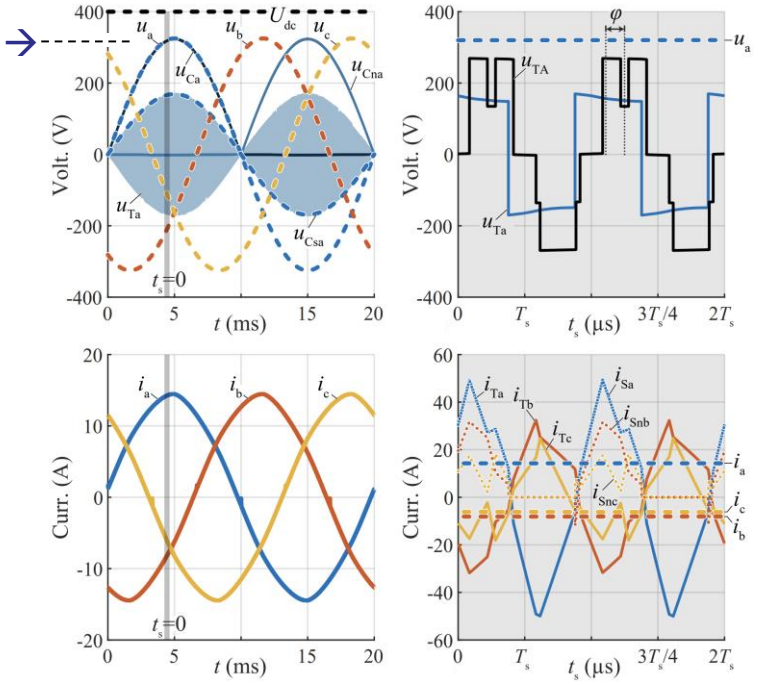
3-Φ Input DAB-Type AC/DC Converter (2)

P704 | New 600V GaN Single-Stage Isolated Bidirectional 400V Input Three-Phase PFC Rectifier [#1675]
David Menzi, Johann W. Kolar, Hector Sarnago, Oscar Lucia and Jonas E. Huber
ETH Zurich, Switzerland; University of Zaragoza, Spain

- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle*
- *Dual-Active-Bridge-(DAB)-Type Operation | Low-Frequ. Blocking Series Capacitors*
- *Sec.-Side Modulation Ensures Sinusoidal Input Currents & Defines Power Flow*





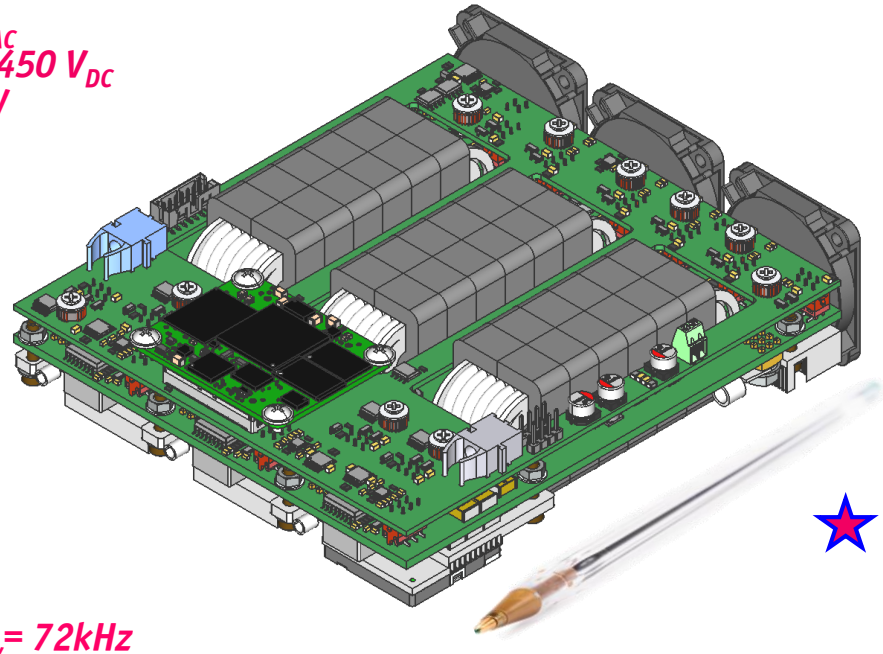


- *Allows Bidirectional Buck-Boost Operation*
- *Full Rated Power Operation @ 3-Φ AND 1-Φ Grid Input (!)*

3-Φ Input DAB-Type AC/DC Converter (3)

- *Voltage Stress on AC-Side Power Transistors Determined by PHASE Voltage Amplitude (!)*
- *600V GaN MBDS for 400V RMS Line-to-Line Grid ($U_{L\text{-}L,pk}$ = 560V)*
- *Unity Power Factor / Bidirectional*

- *Line-to-Line Input* *400 V_{AC}*
- *DC Output* *250...450 V_{DC}*
- *Rated Output Power* *6.6 kW*



★ *98% (typ.) @ 8kW/dm³*

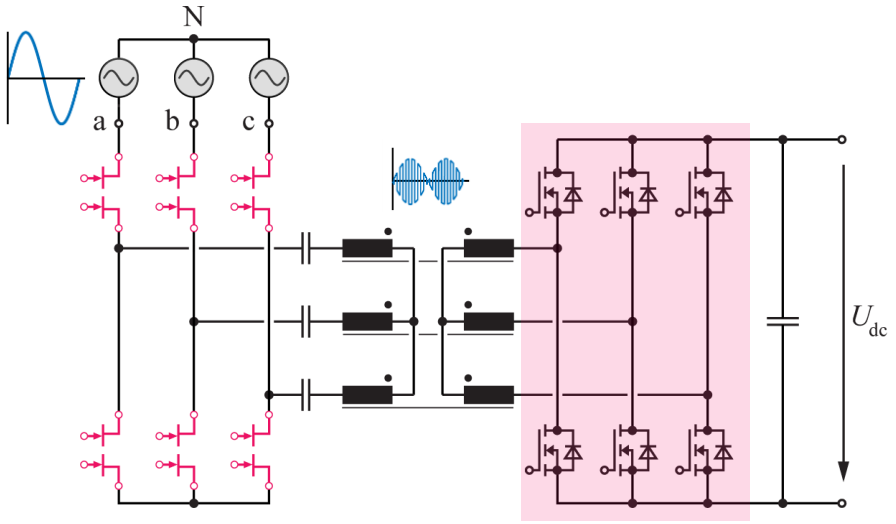
- *Prim.-Side Sw. Frequency f_{sw} = 72kHz*
- *14.5x13.1x3.7 cm³ / 5.7x5.2x1.5 in³*
- *Power Density w/ EMI-Filter ≈ 6kW/dm³ (98W/in³)*

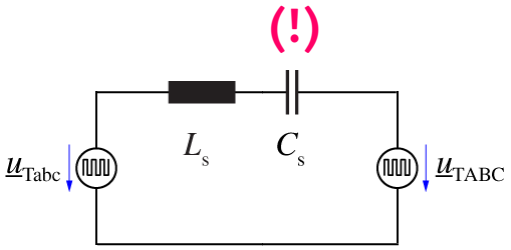
New 3-Φ OR 1-Φ Operable Resonant AC/DC Converter

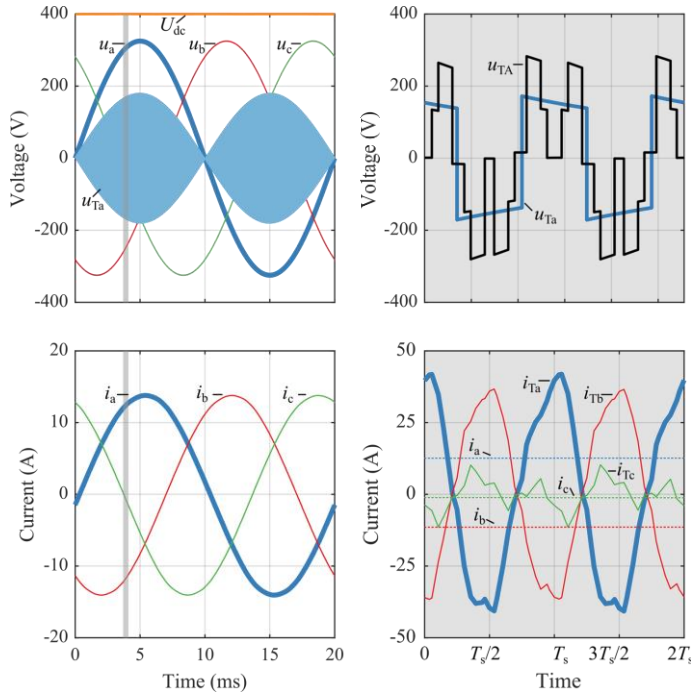
3-Φ Input Resonant AC/DC Converter

- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle | Series Res. Circuit L_{stray}, C_{res} Tuned to f_{sw}*
- *Sec.-Side Modulation Replicates Prim.-Side Phase Voltage Local Avg. Values / Operates @ 2 x f_{sw}*

N_1:N_2 = 1:1



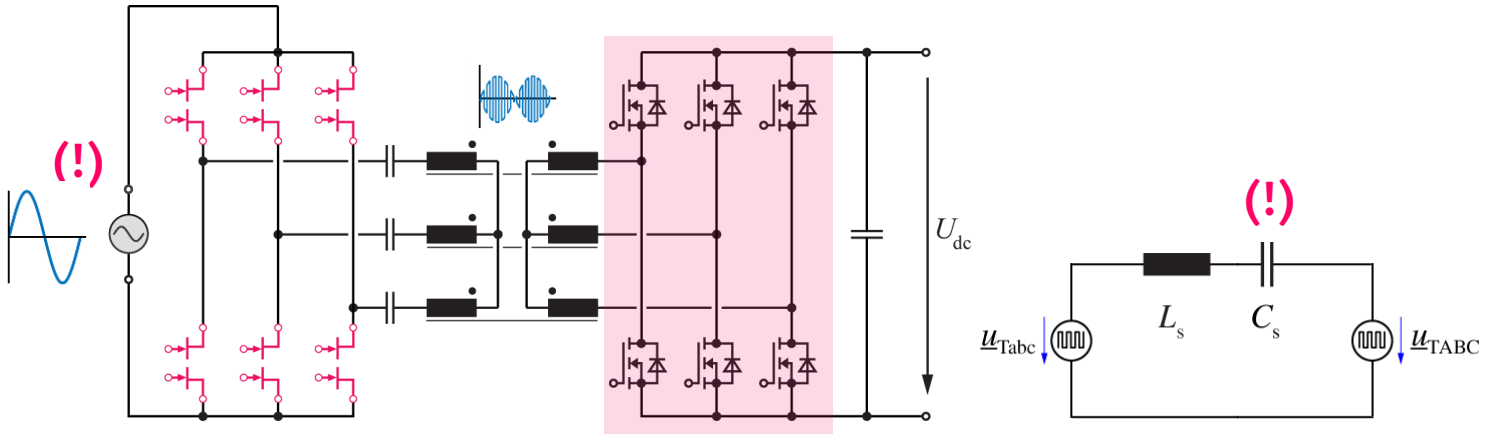




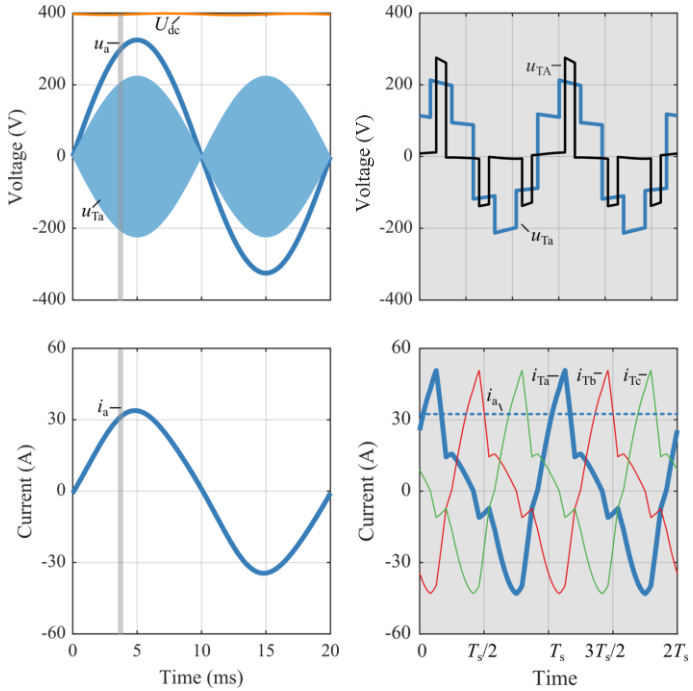
- *Boost Operation w/ Sec.-Side Zero Volt. Intervals | Buck Operation w/ Prim.-Side Zero Volt. Intervals*
- *Sinusoidal Grid Currents / Bidirectional Power Flow*

1-Φ Input Resonant AC/DC Converter

- *All Prim.-Side Phase Modules Operated in Parallel*
- *120° Phase-Shifted Sw. @ 50% Duty Cycle & Res. Frequency*
- *3-Φ Sw. Frequ. Six-Step Voltage Syst. Applied to Xfrm Primary*
- *Sec.-Side Mod. Replicates Prim.-Side Phase Voltage Local Avg. Values*



$N_1:N_2$ = 3:1

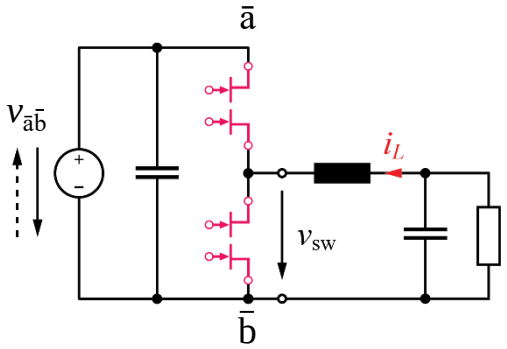


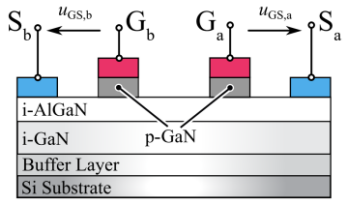
- *Boost Operation w/ Sec.-Side Zero Volt. Intervals | Buck Operation w/ Prim.-Side Zero Volt. Intervals*
- *Sinusoidal Grid Currents / Bidirectional Power Flow*

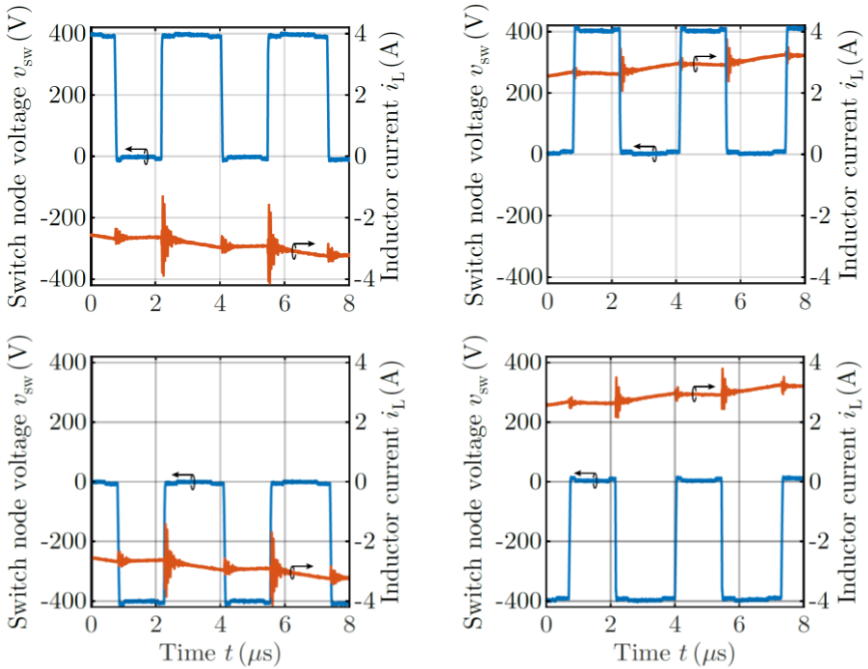
Experimental Analysis of 600V GaN BDS-Samples

Exp. Analysis of 1st Gen. 600V GaN M-BDS

- PowerAmerica *Program — Based on Infineon's CoolGaN™ HEMT Technology*
- *Dual-Gate Device / Controllability of Currents in Both Directions*
- *Bipolar Voltage Blocking Capability | Normally-On or Normally-Off*



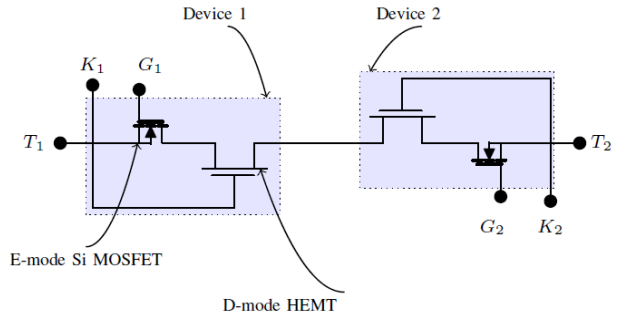


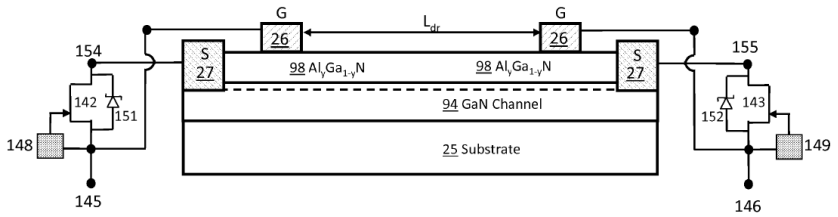


- *Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ | 600V Sample @ ± 400V*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

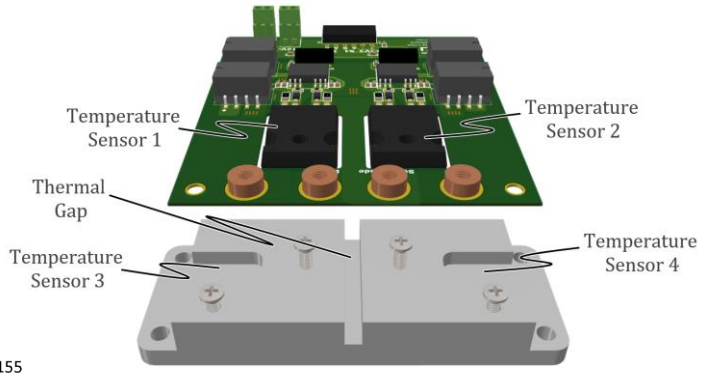
Four-Quadrant Cascode GaN Switch (FQS)

- *Common-Drain Arrangement of Two Cascode Switches (600V GaN D-Mode HEMT + LV Si E-Mode MOSFET)*
- *Up to 1200V Samples for Demonstration Purposes*



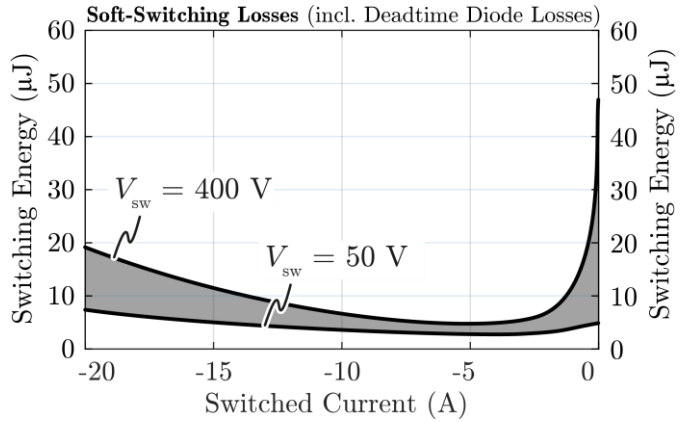


Honea et al., 2008



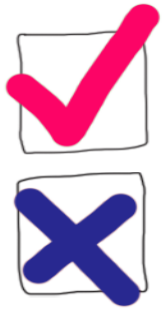
transphorm

$R_{(on)}$ = 70 mΩ
T_{dead} = 250 ns
1 nF C0G Parallel Caps @ 20 A



- *4Q — Current Conduction Only in Quadrants I & III*
- *Shared Drift Region for Blocking Pos. & Neg. Voltage & Separate Cascode MOSFETs*

Bi-Directional Switches are Coming !



- Samples Tested
- New Topologies Invented ?
- Patents Filed ?
- Demonstrators Built ?