Power Electronic Systems Laboratory

ETH zürich

Part 4

Experimental Analysis of 1st Gen. 600 V GaN M-BDSs

Jonas Huber, Johann W. Kolar

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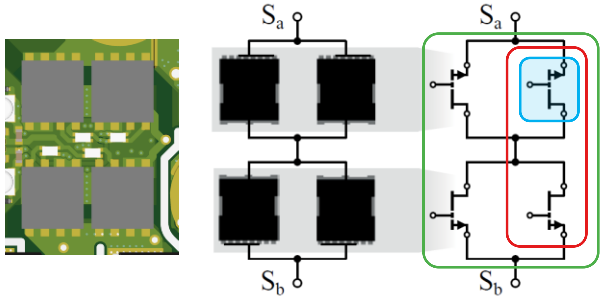
The Switch: 600 V / 140 mΩ GaN M-BDS 1. Gen. Samples Infineon

BDS Realization with Unipolar Devices



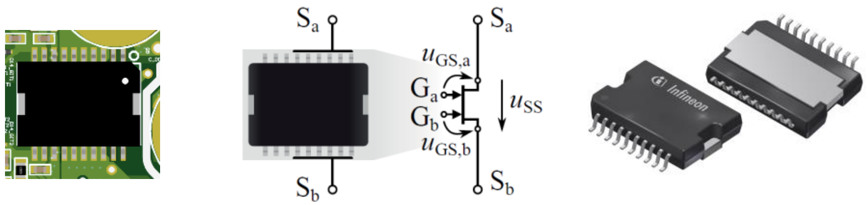
R_{on}

$R_{total} = 2R_{on}$

$R_{total} = R_{on}$

- 4 x Single switch for same R_{on}

Monolithic Bidirectional Realization (M-BDS)

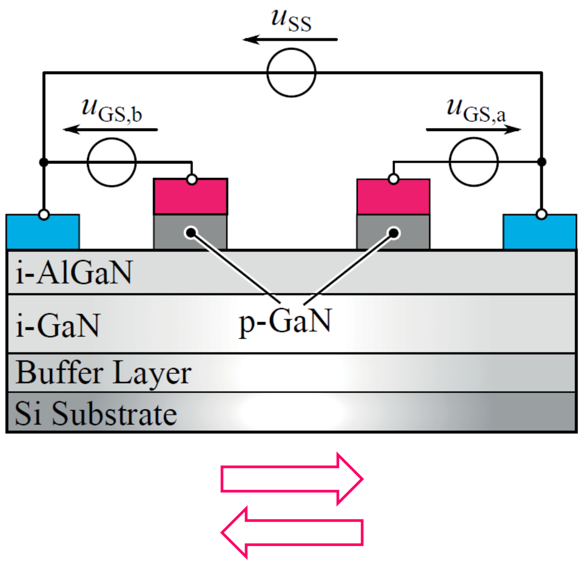


Package Image Source: https://www.infineon.com/cms/en/product/packages/PG-DSO/PG-DSO-20-85/

- ±600 V
- 140 mΩ
- PG-DSO-20-85 Package

GaN M-BDS Internal Structure

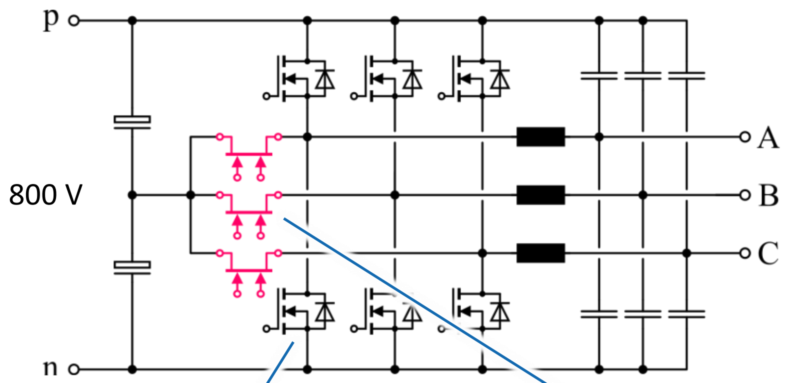
- Infineon 600 V CoolGaN™ Technology Normally-off (Gate Injection Transistor, GIT)
- Two gates (one per blocking direction)
- Internal common-drain configuration



Same chip region used for blocking both voltage polarities!

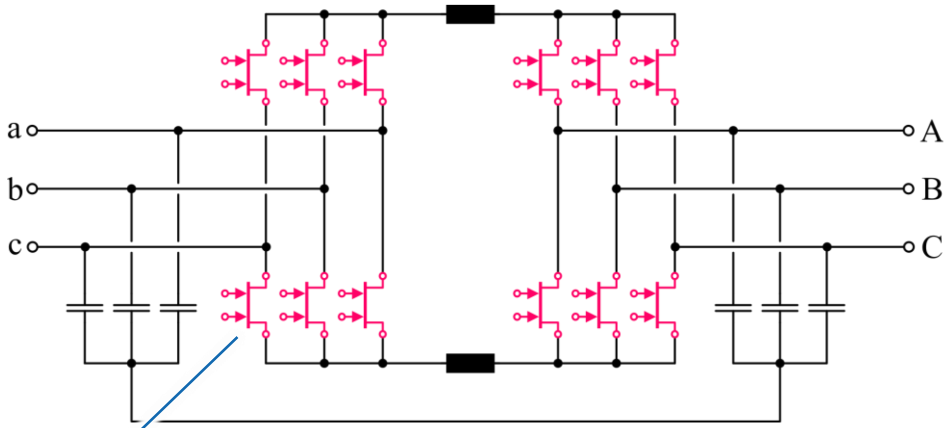
The Topologies

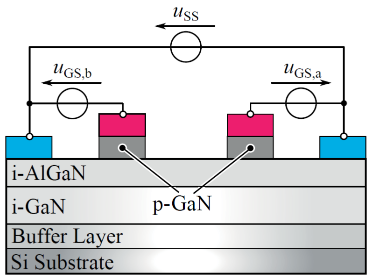
GaN/SiC 3-Level T-Type AC-DC PFC Rectifier / DC-AC Inverter



1200 V / 140 mΩ SiC

All-GaN AC-AC Current-Source Converter



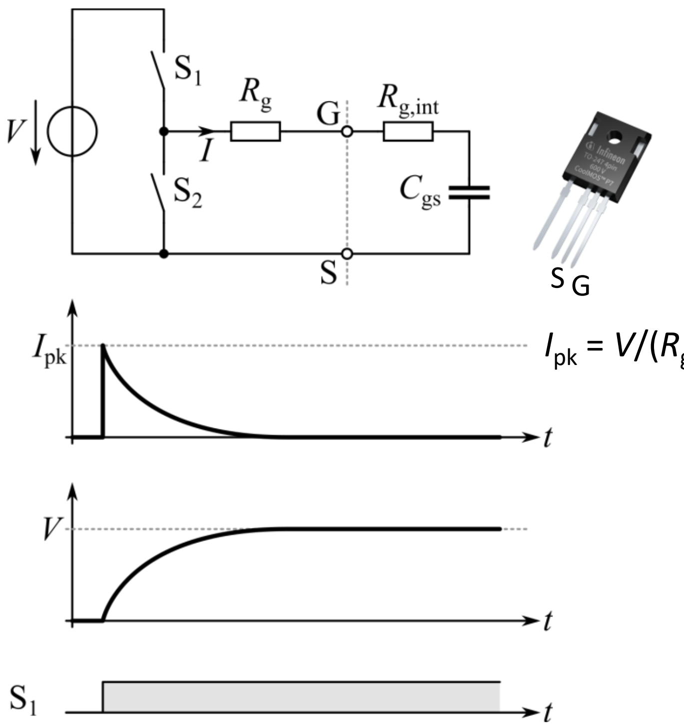


600 V / 140 mΩ
GaN M-BDS

GaN M-BDS Gate Drive Considerations

GaN Gate Injection Transistor (GIT) Gate Behavior

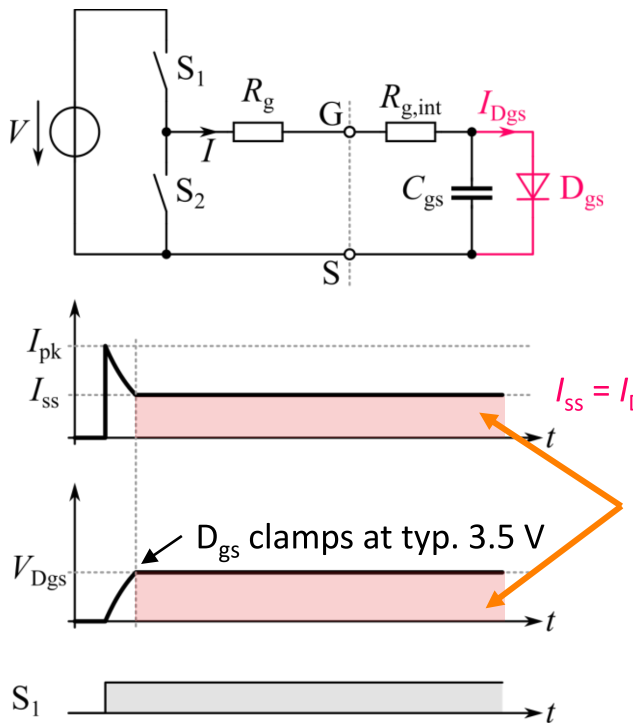
Simplified MOSFET Gate Turn-On



$I_{pk} = V/(R_g+R_{g,int})$

Simplifying assumption: C_{gs} = *const.*

Simplified Gate Injection Transistor (GIT) Gate Turn-On



Ohmic gate contact results in diode-like behavior of GIT

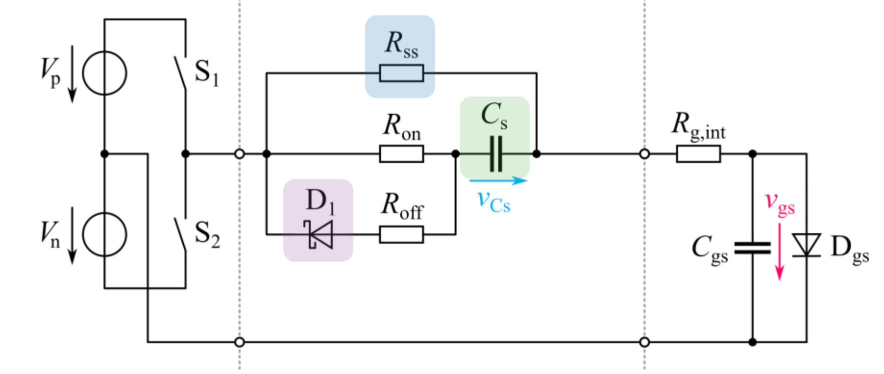
$I_{ss} = I_{Dgs} = (V - V_{Dgs})/(R_g+R_{g,int})$

Further Reading: Infineon Technologies, "Gate drive solutions for CoolGaN 600V HEMTs," White Paper, Dec. 2020.

- Requirements for GIT gate drive
  - **Small R_g** for fast transients (charging/discharging of C_{gs})
  - **Large R_g** during steady-state (small I_{Dgs} of a few 10 mA)

Standard RRC Gate Drive Operating Principle

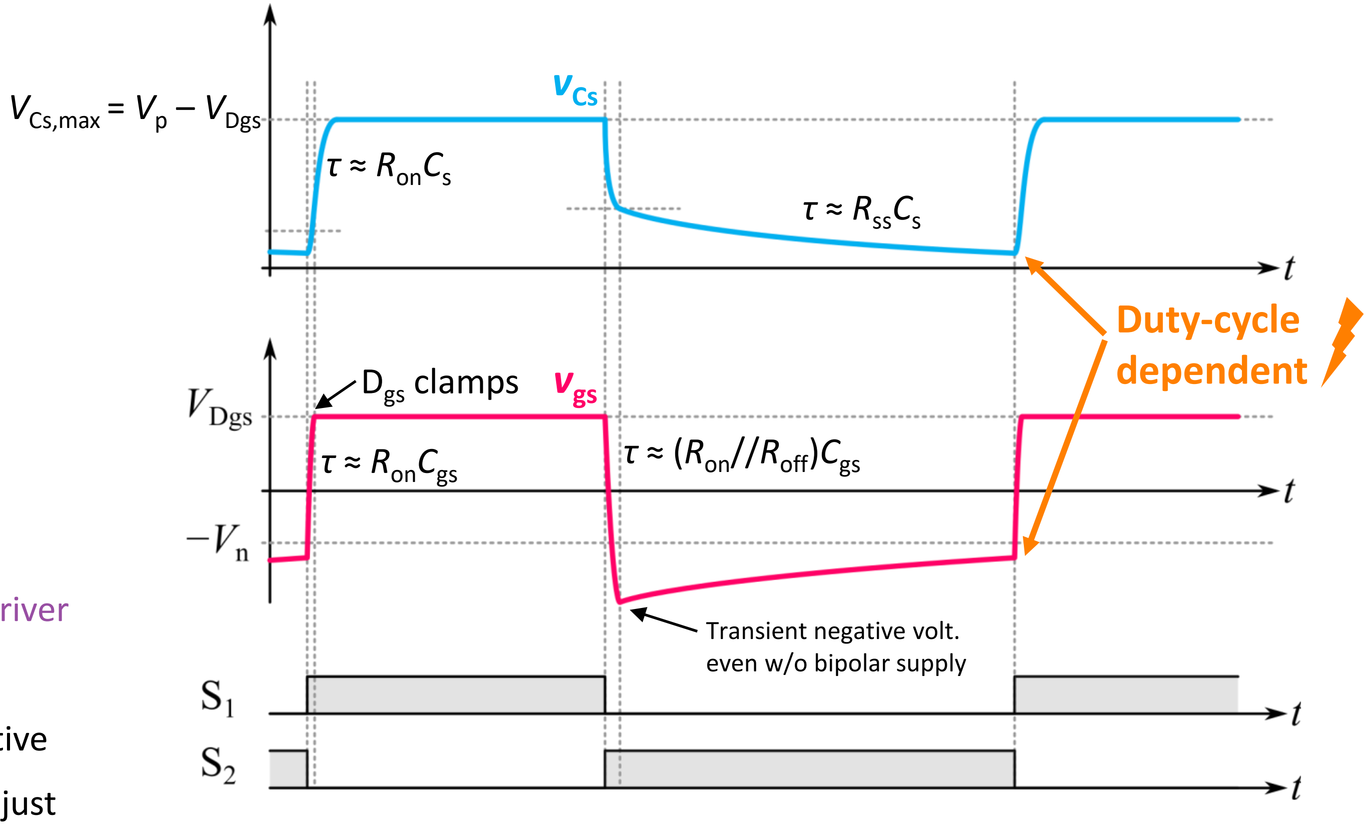
Capacitor to Decouple Transient Low-Impedance Paths



- C_s >> C_{gs} (typ.): Decoupling of High-Current Paths
- R_{ss} >> R_{on}, R_{off}: Steady-state current (milliamperes)
- D_1: Separate turn-on/turn-off gate resistors with HB driver

Note: **Dedicated driver ICs** with multiple outputs as alternative

Note: **Bipolar supply** to ensure negative v_{gs} at all times (not just transiently; relevant for CSI commutation cells)

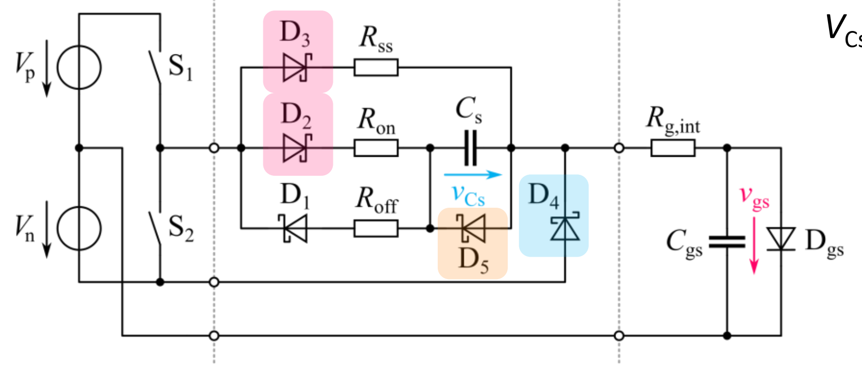


Assumptions: $R_{g,int}$ = 0 Ω, C_s >> C_{gs}, simplified gate model (C_{gs} = *const.*)

Note: unipolar supply possible; bipolar supply for better robustness against parasitic turn-on in current-source converter commutation cells (see later).

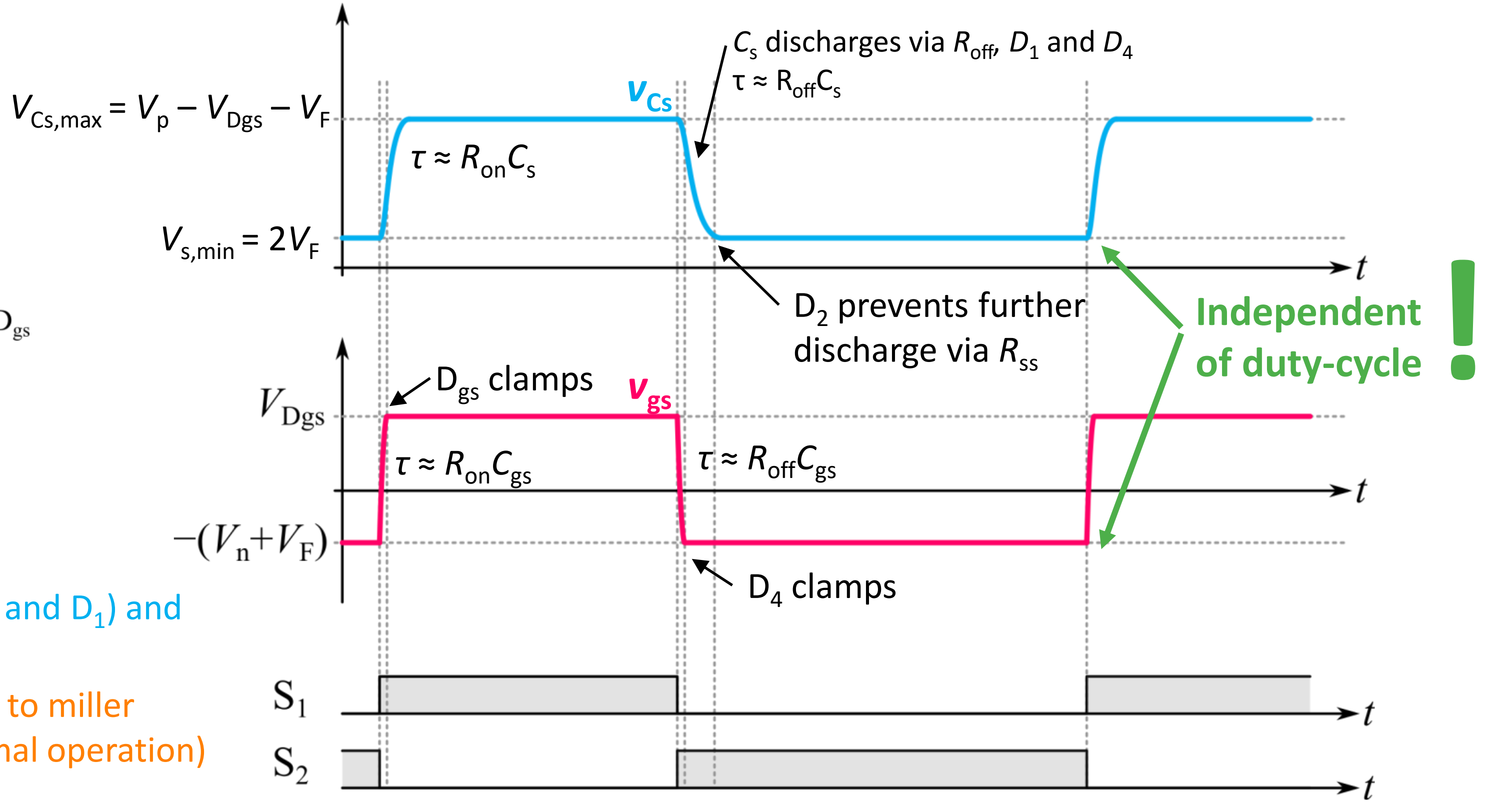
Advanced RRC Gate Drive Operating Principle

Eliminating the Duty-Cycle Dependency of Dynamics



- **D_2:** Prevents full discharge of C_s via R_{ss}
- **D_3:** Decouple R_{ss} during off-state
- **D_4:** Discharge path for C_s during off-state (via R_{off} and D_1) and clamping of gate to negative supply voltage
- **D_5:** Prevents negative voltage across C_s (e.g., due to miller current or other distortions; inactive during normal operation)

► Straightforward option with standard HB driver IC and a few Schottky diodes

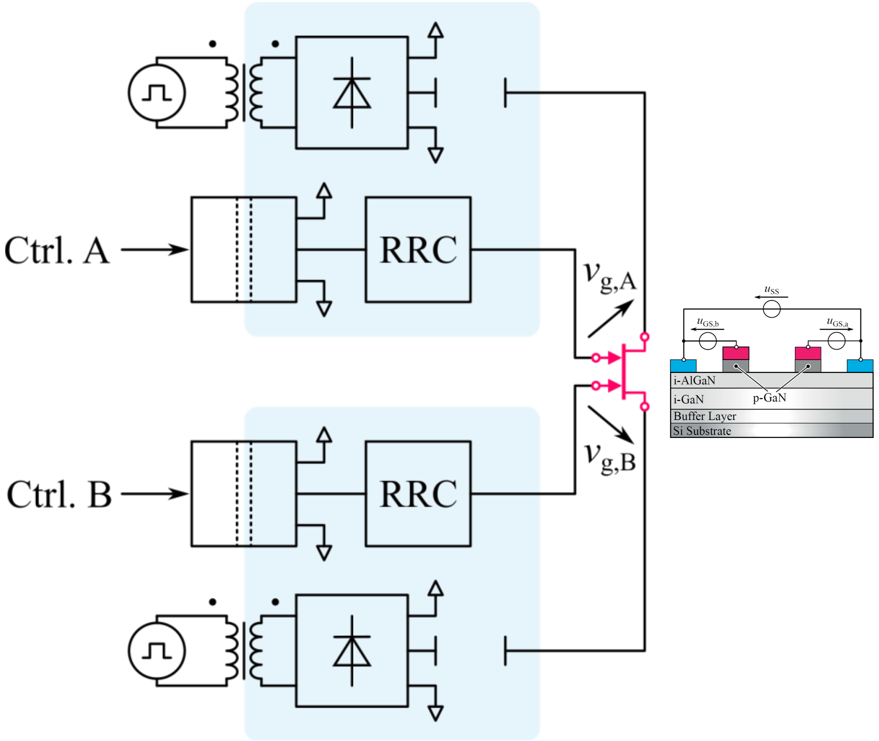


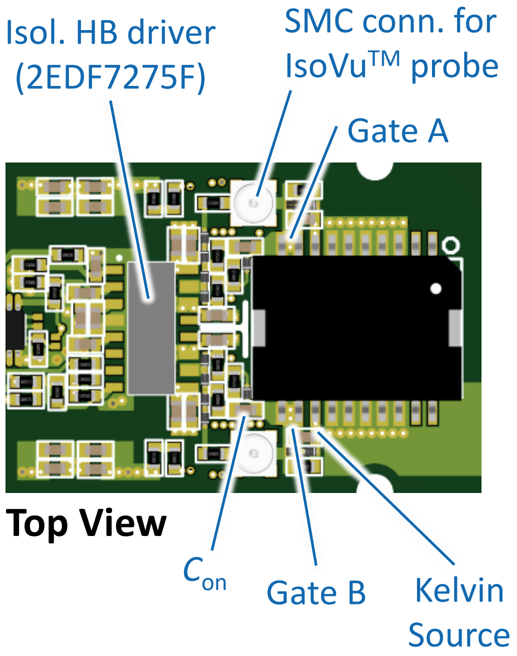
Assumptions: $R_{g,int} = 0\ \Omega$, $C_s >> C_{gs}$, simplified gate model ($C_{gs} = const.$)

Further reading: D. Bortis, O. Knecht, D. Neumayr, and J. W. Kolar, "Comprehensive evaluation of GaN GIT in low- and high-frequency bridge leg applications," in *Proc. 8th IEEE Int. Power Electron. Motion Ctrl. Conf. (IPEMC-ECCE Asia)*, Hefei, China, May 2016, pp. 21–30.

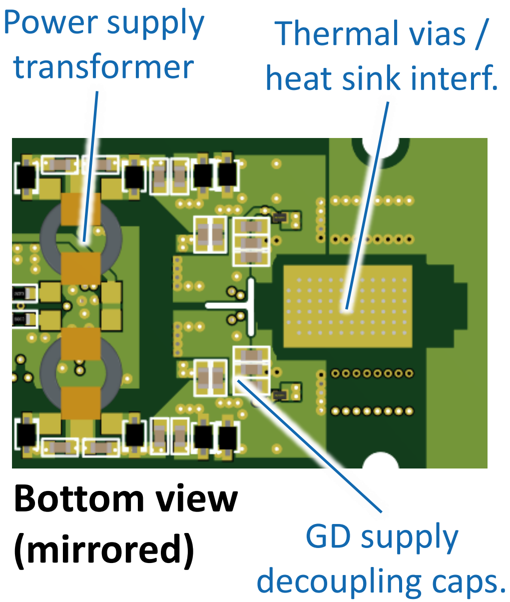
Advanced RRC Gate Drive for M-BDS: Realization

- Two gates per M-BDS / Two isolated power supplies / Two control signals
- Mostly vertical gate loop (ca. 8…10 nH incl. package) / Adv. RRC network on TOP / HB driver supply decoupling on BOT





Top View



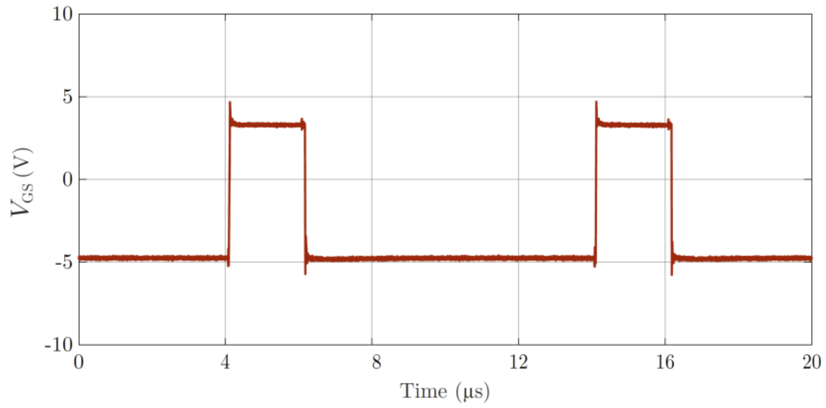
Bottom view (mirrored)

Remark: Integration of gate drive → Significant reduction of PCB area!

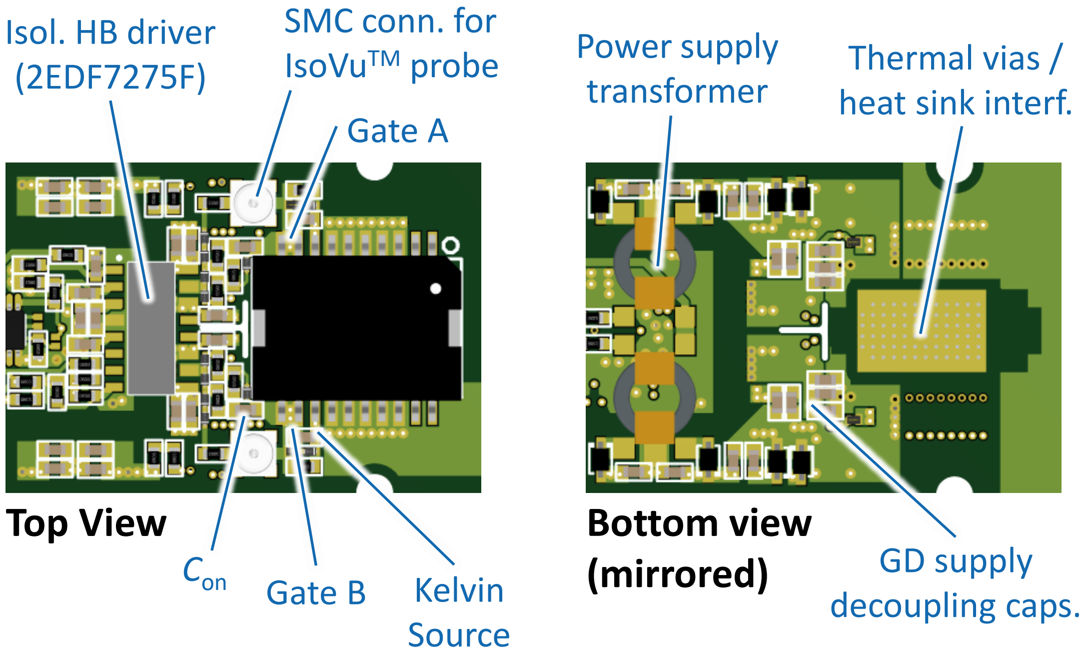
Advanced RRC Gate Drive for M-BDS: Layout / Measurements

- Two gates per M-BDS / Two isolated power supplies / Two control signals
- Mostly vertical gate loop (ca. 8…10 nH incl. package) / Adv. RRC network on TOP / HB driver supply decoupling on BOT

Measured GaN M-BDS v_{gs}



V_p = 8 V, V_n = 5 V
R_{on} = 5 Ω, R_{off} = 4.7 Ω, C_s = 2.2 nF, R_{ss} = 680 Ω



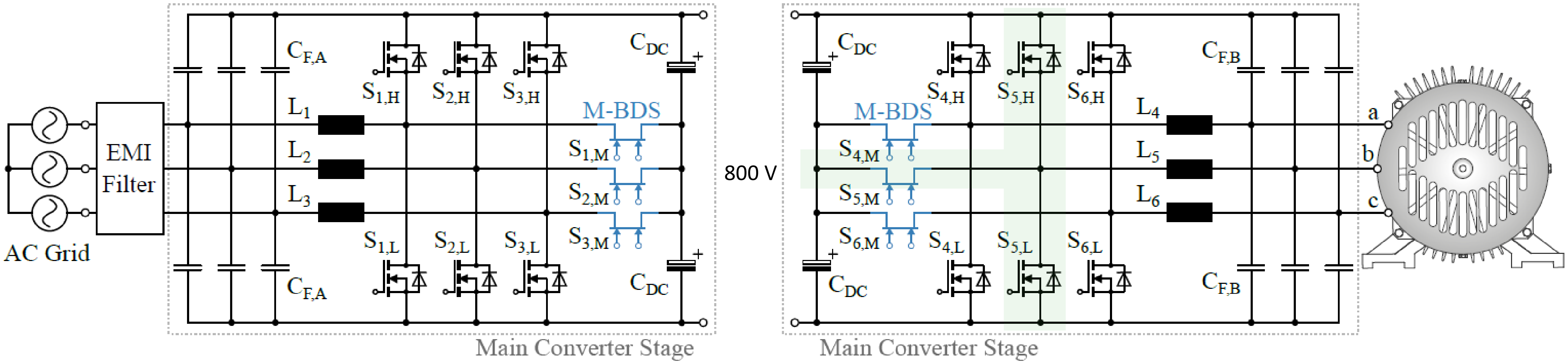
Remark: Integration of gate drive → Significant reduction of PCB area!

3-Level T-Type Inverters/Rectifiers with GaN M-BDSs

Details => Paper @ ECCE USA 2021
F. Vollmaier, N. Nain, J. Huber, J. W. Kolar, K. K. Leong, and B. Pandya, "Performance evaluation of future T-Type PFC rectifier and inverter systems with monolithic bidirectional 600 V GaN switches."

3-Level T-Type (TT) Main Converter Stage

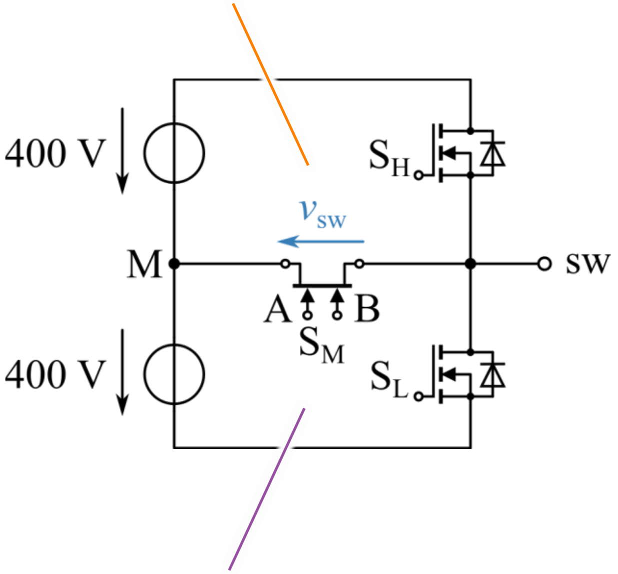
- Bidirectional voltage-source AC-DC or DC-AC conversion / **Basic building block** for PFC rectifiers or motor drive inverters
- Phase-modular DC-link-referenced first LC-filter stage => DM and CM filtering



- **Three-level bridge-leg** via connection to DC-link midpoint: **bidirectional conduction & bipolar blocking => M-BDS**
- 800 V DC / $S_{x,H}$, $S_{x,L}$: 1200 V, 140 mΩ SiC MOSFET / **$S_{x,M}$: 600 V, 140 mΩ GaN M-BDS**

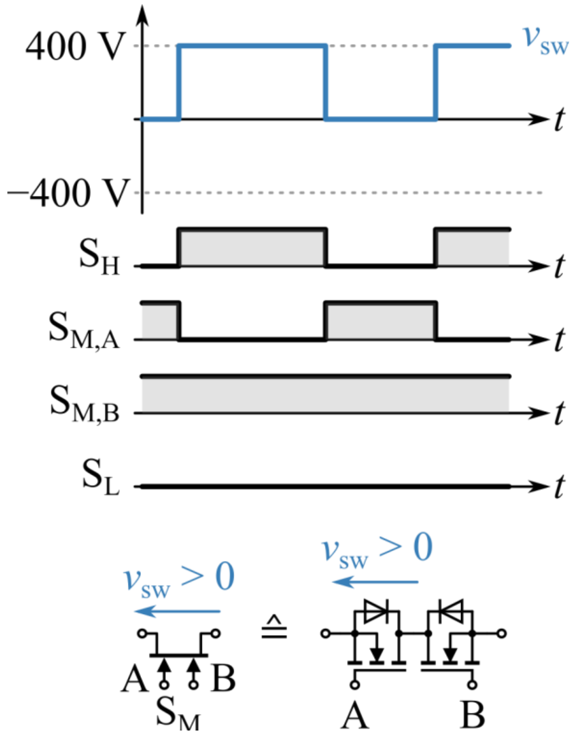
3-Level TT Bridge-Leg Commutation Cells

High-side commutation cell: S_H, $S_{M(A)}$

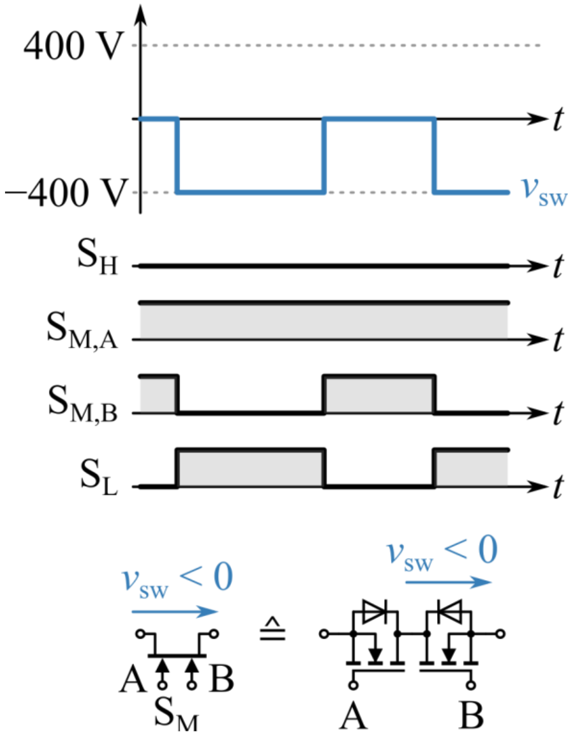


Low-side commutation cell: $S_{M(B)}$, S_L

Positive Output Voltage
→ High-side commutation cell active

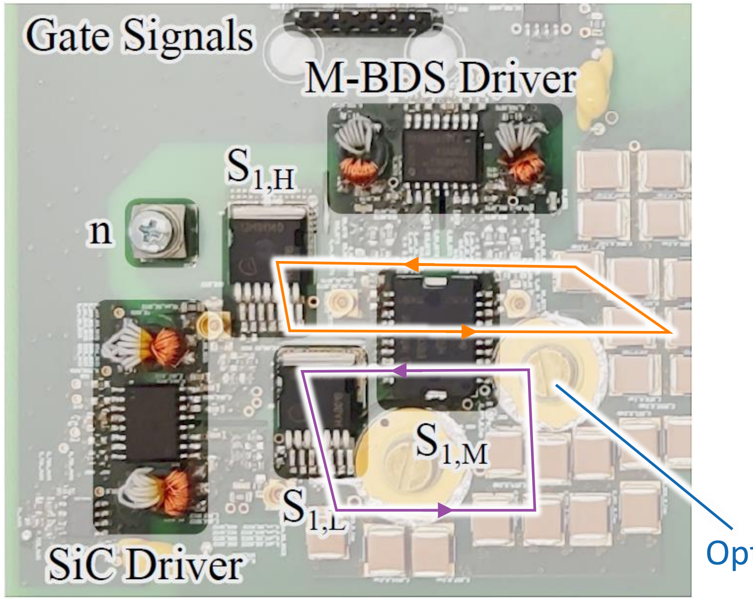


Negative Output Voltage
→ Low-side commutation cell active

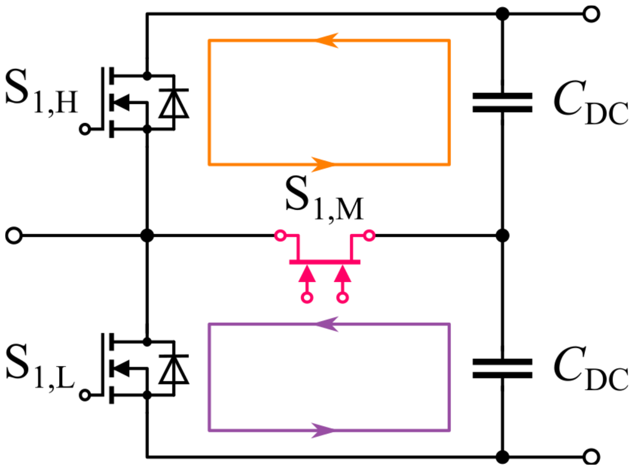


3-Level TT Bridge-Leg Evaluation Board

- 800 V DC / $S_{x,H}$, $S_{x,L}$: 1200 V, 140 mΩ SiC MOSFET (IMBG120R140M1H) / **$S_{x,M}$: 600 V, 140 mΩ GaN M-BDS**
- Two commutation loops: High-side / Low-side / Commutation inductance ca. 15 nH
- Advanced RRC gate drive with HB driver (2EDS8265HXUMA1) for M-BDS

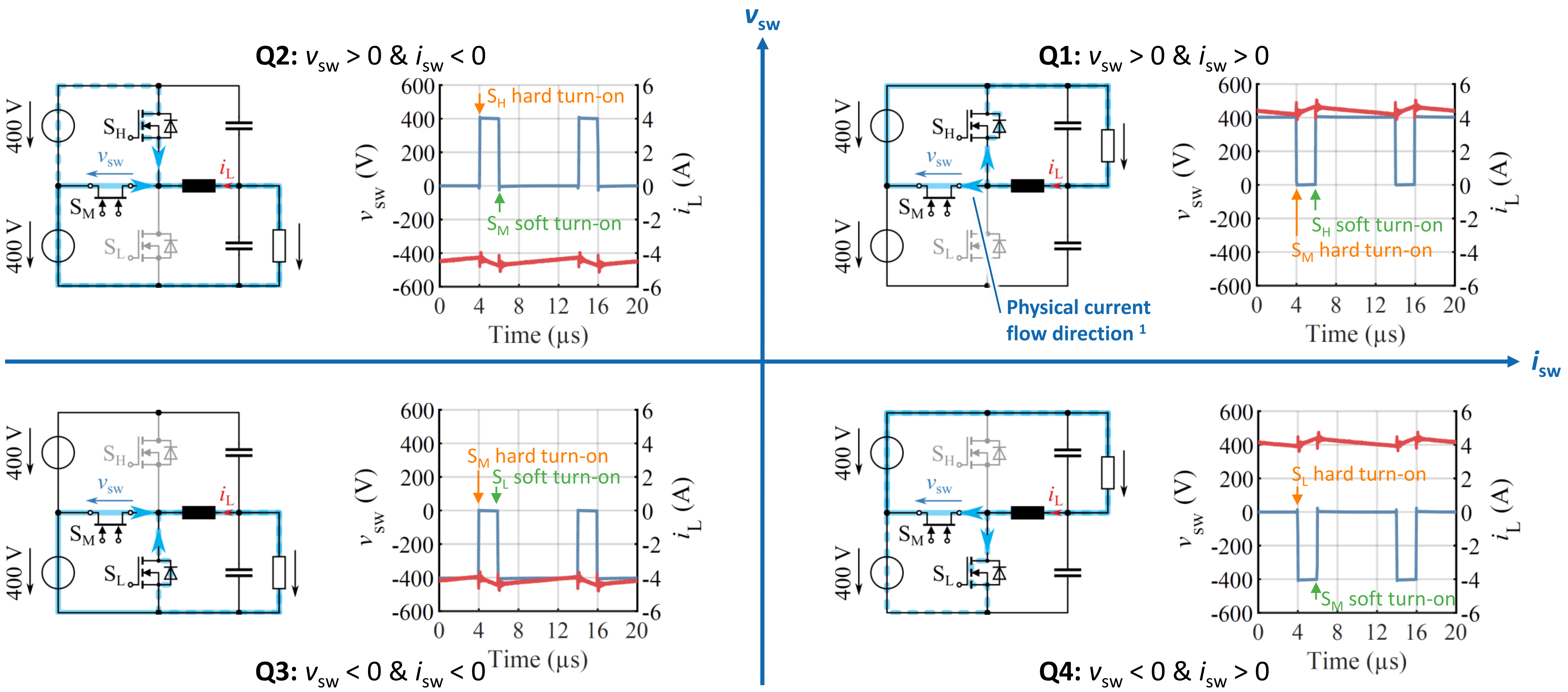


Optional coax. shunt



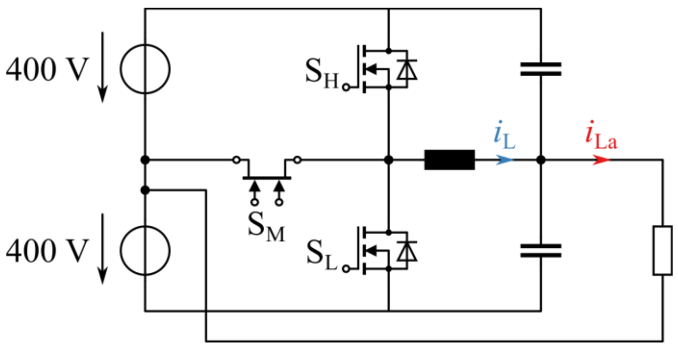
- Cooling through PCB (thermal vias) / **Top-side cooled packages** would facilitate improved layouts

Continuous M-BDS Operation at ± 400 V in CCM



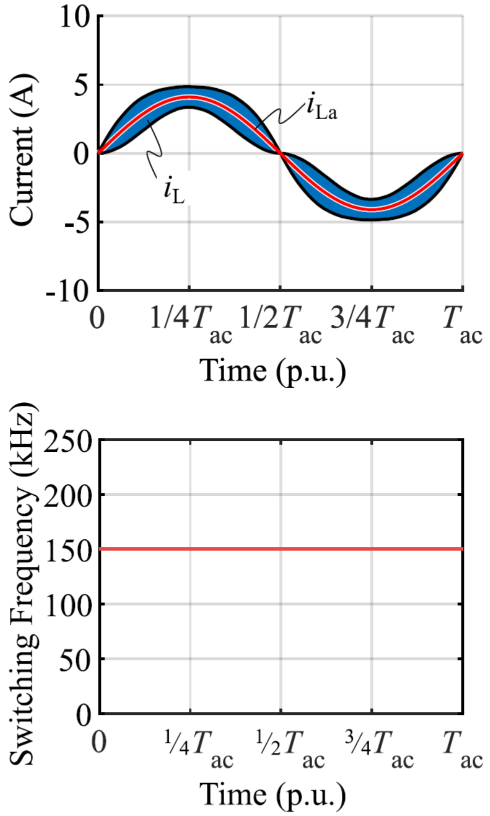
[1] Filter capacitor current not shown for better visibility

Remark: CCM and TCM Operation of TT Bridge-Leg

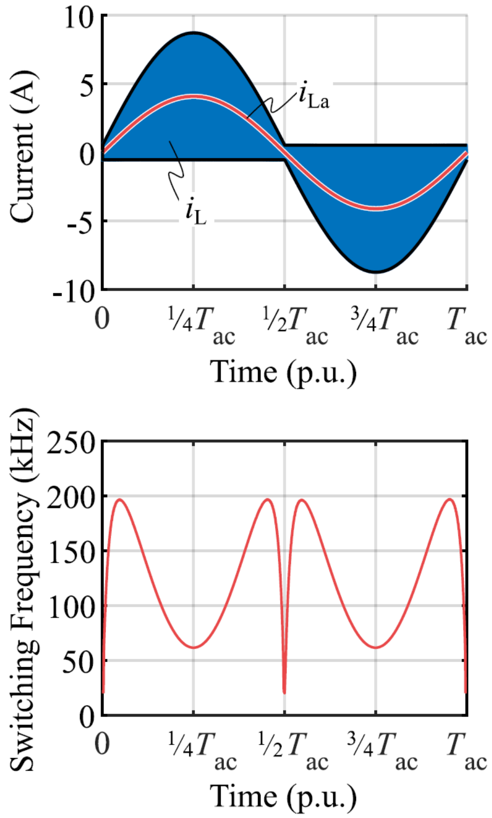


Exemplary simulations for 800 V DC and 2 kW.

CCM: Continuous Conduction Mode



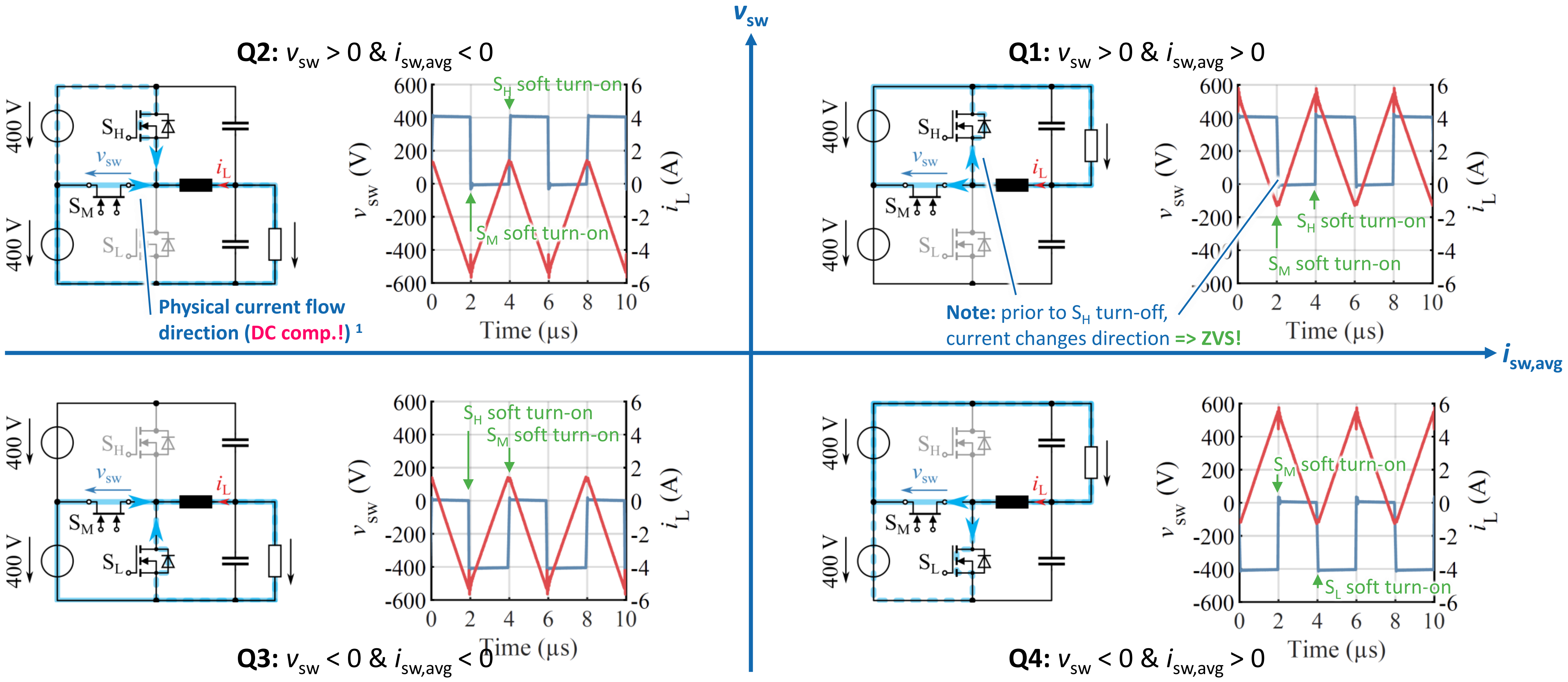
TCM: Triangular Current Modulation



Zero-Voltage Switching (ZVS) for all transitions

Variable sw. frequency

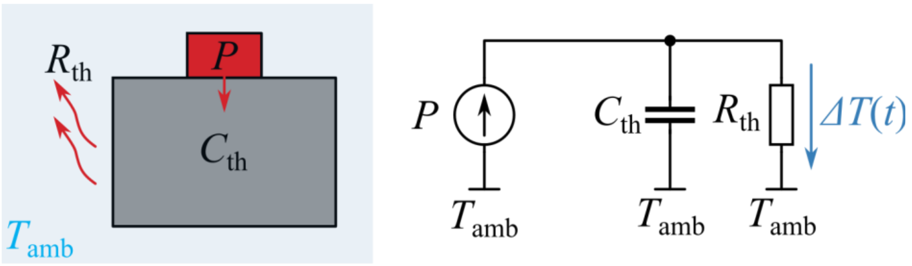
Continuous M-BDS Operation at ± 400 V with TCM (Soft-Switching)

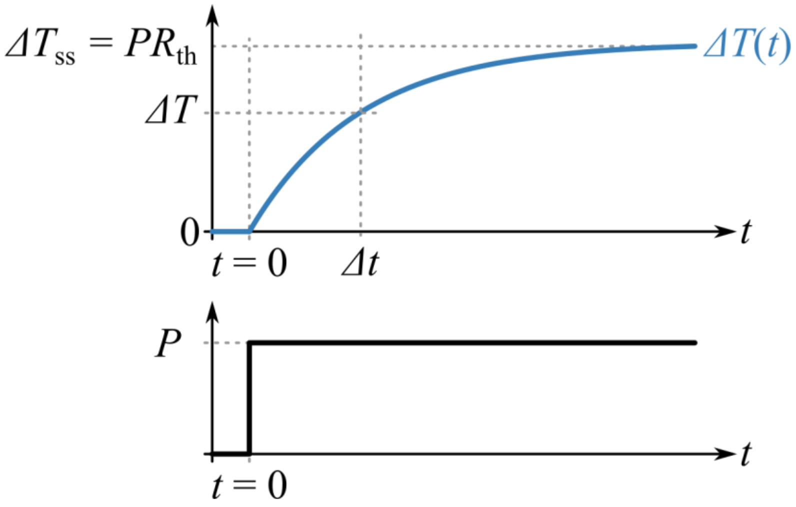


¹ Filter capacitor current not shown for better visibility

Transient Calorimetric Loss Measurement: Principle (1)

- Constant power dissipation into metal block





Step 1: Calibration with Known DC Power → Accurate electrical measurement

- Record $\Delta T(\Delta t)$ for several (at least two) known powers
- Fit model and extract model parameters C_{th} and R_{th}

$$\Delta T(\Delta t) = PR_{th} \cdot \left(1 - e^{-\frac{\Delta t}{R_{th} C_{th}}}\right)$$

Step 2: Measurement of Unknown Power Dissipation

- Measure time Δt to reach temperature difference ΔT
- Use calibrated model to calculate power dissipation

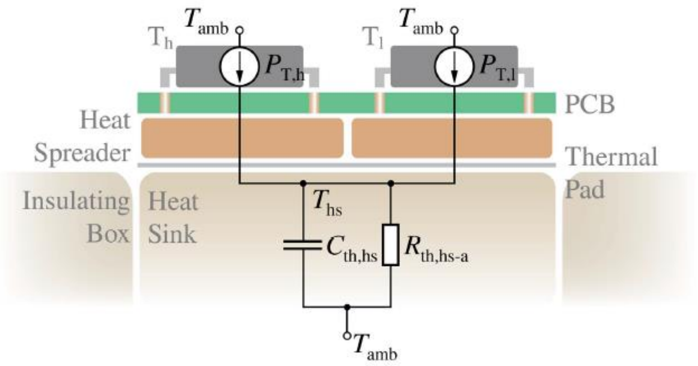
$$\Rightarrow \; P(\Delta T, \Delta t) = \frac{\Delta T}{R_{th} \cdot \left(1 - e^{-\frac{\Delta t}{R_{th} C_{th}}}\right)}$$

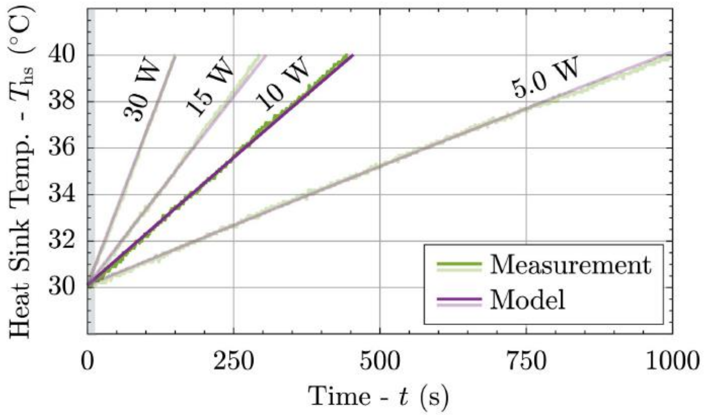
Alternative for Step 2

- Record $\Delta T(\Delta t)$ for unknown power dissipation P'
- Fit model with known R_{th} and C_{th} to identify P'

Transient Calorimetric Loss Measurement: Principle (2)

Half-Bridge with Identical Switches





M. Guacci et al., "Experimental characterization of silicon and gallium nitride 200 V power semiconductors for modular multi-level converters using advanced measurement techniques," IEEE J. Emerg. Sel. Topics Power Electron., vol. 8, no. 3, pp. 2238–2254, Sep. 2020.

Note: Heat sink size (C_{th}) follows from desired temperature rise (resolution), measurement time, and power dissipation

Switching Loss Extraction

- Calorimetric loss meas. gives *total* losses
- Conduction losses can be calculated:

From calibration — Proxy for junction temp.

$$P_{cond} = R_{ds(on)}(P_{total}) \cdot I_{rms}^2$$

- Switching energies follow from switching frequency

$$P_{sw} = P_{total} - P_{cond}$$

$$E_{sw} = E_{on} + E_{off} = \frac{P_{sw}}{f_s} \quad \text{(for CCM)}$$

Half-bridge switching energy dissipation per switching period

Soft-Switching Losses

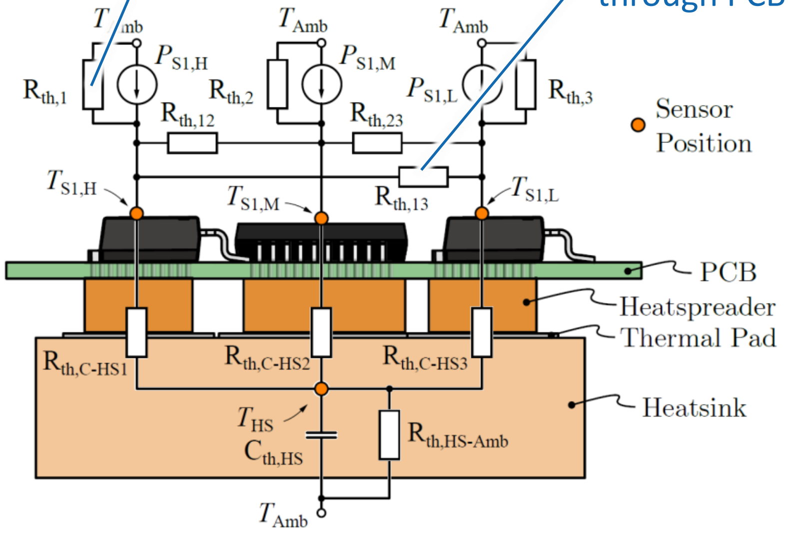
- $E_{sw} = 2E_{off}$ for TCM
- Direct & accurate measurement of residual soft-switching losses!

TT Bridge-Leg Switching Loss Characterization: Method (1)

- Different device types (SiC, M-BDS) require loss separation: **measure individual case temperatures** ($T_{S1,H}$, $T_{S1,M}$, $T_{S1,L}$) and T_{HS}

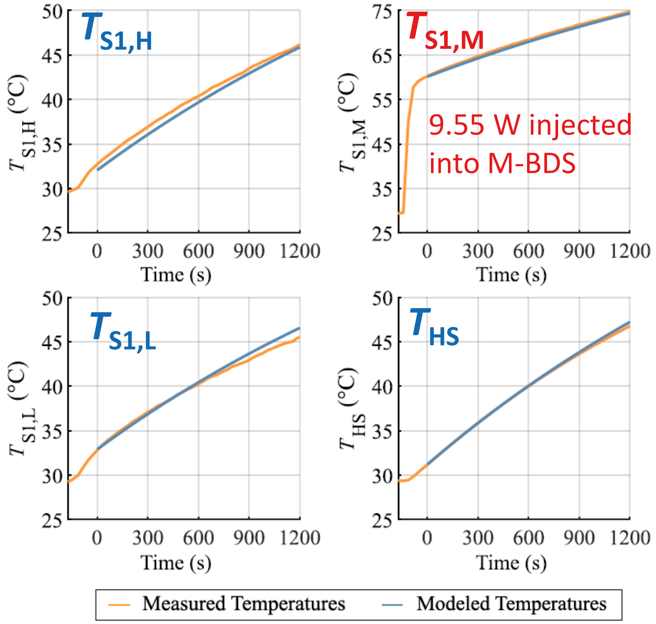
Direct dissipation to ambient ($R_{th,1}$, $R_{th,2}$, $R_{th,3}$)

Thermal cross-couplings through PCB ($R_{th,12}$, $R_{th,23}$, $R_{th,13}$)



- Thermal network with 11 parameters
- Calibration with DC power injection & particle swarm fit (MATLAB)

Calibration Example



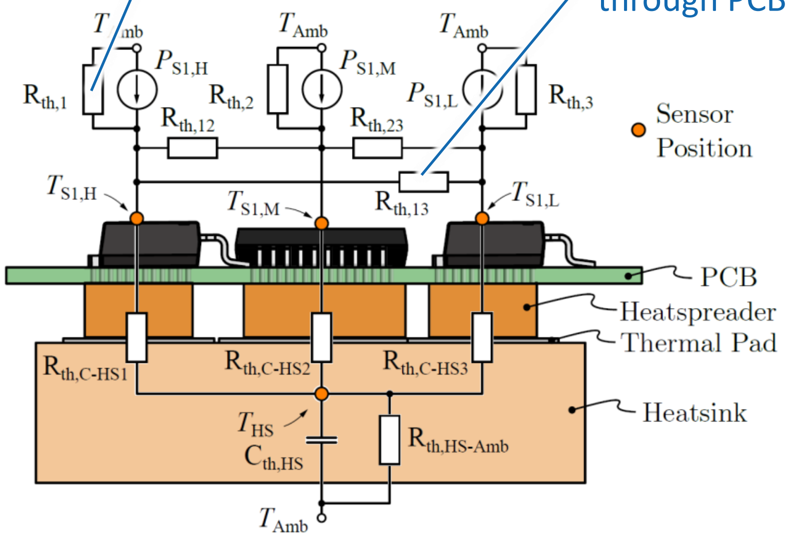
- Note: initial, fast transient ignored (therm. cap. of switches, PCB, heat spreaders, etc.)

TT Bridge-Leg Switching Loss Characterization: Method (2)

- Different device types (SiC, M-BDS) require loss separation: **measure individual case temperatures** ($T_{S1,H}$, $T_{S1,M}$, $T_{S1,L}$) and T_{HS}

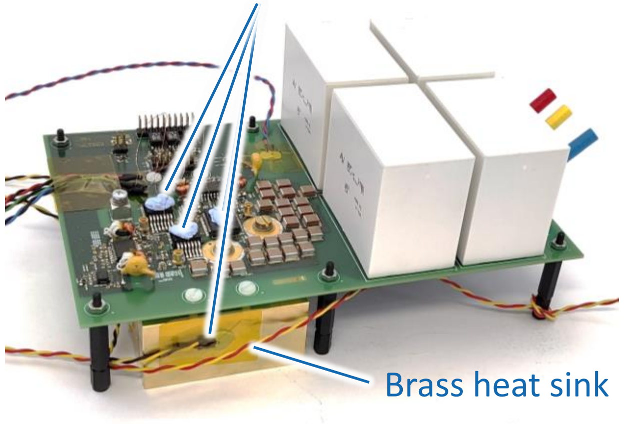
Direct dissipation to ambient ($R_{th,1}$, $R_{th,2}$, $R_{th,3}$)

Thermal cross-couplings through PCB ($R_{th,12}$, $R_{th,23}$, $R_{th,13}$)



- Thermal network with 11 parameters
- Calibration with DC power injection & particle swarm fit (MATLAB)

Precision NTC temp. sensors (PS104J2)



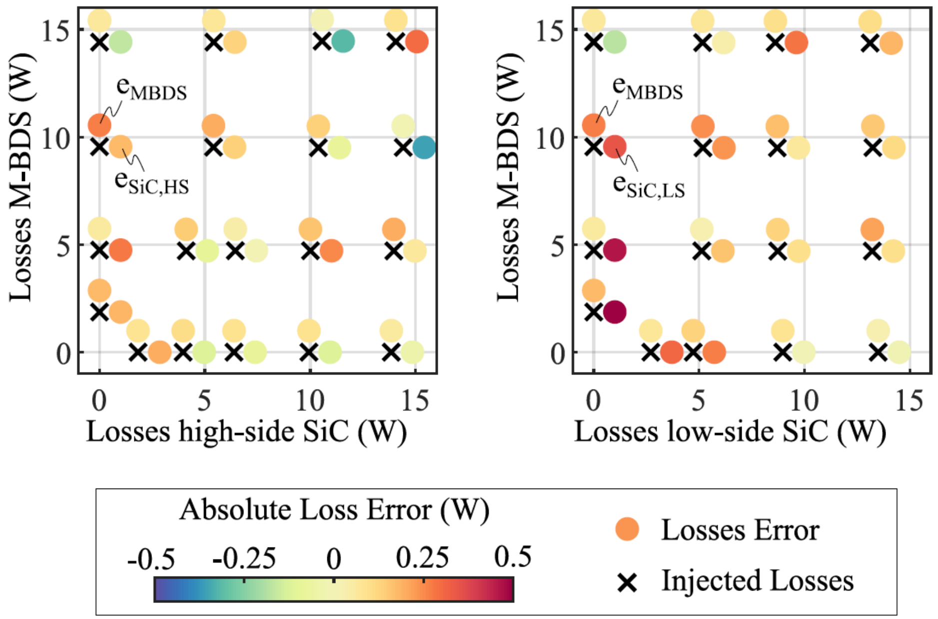
Loss Extraction with Calibrated Model (Example):

$$P_{S1,H} = \underbrace{\frac{T_{S1,H} - T_{Amb}}{R_{th,1}}}_{\text{Direct to ambient}} + \underbrace{\frac{T_{S1,H} - T_{S2,H}}{R_{th,12}} + \frac{T_{S1,H} - T_{S3,H}}{R_{th,13}}}_{\text{Cross couplings}} + \underbrace{\frac{T_{S1,H} - T_{HS}}{R_{th,C-HS1}}}_{\text{To heat sink}}$$

TT Bridge-Leg Switching Loss Characterization: Results

Calibration Data / Accuracy

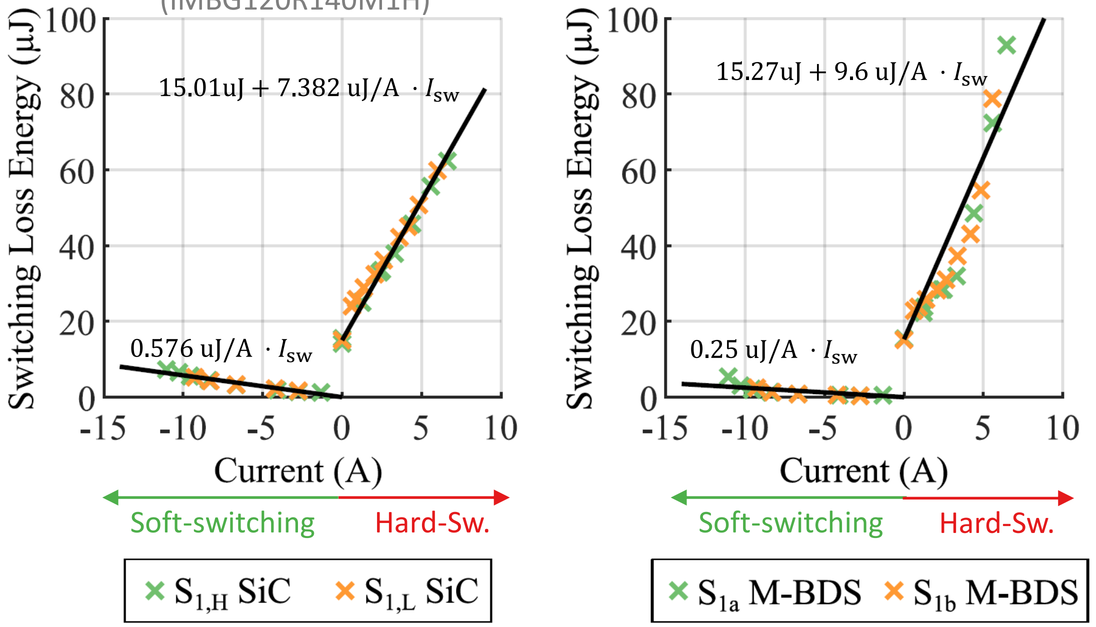
- Injected DC power vs. calorimetric measurement



Measured Hard- and Soft-Switching Losses

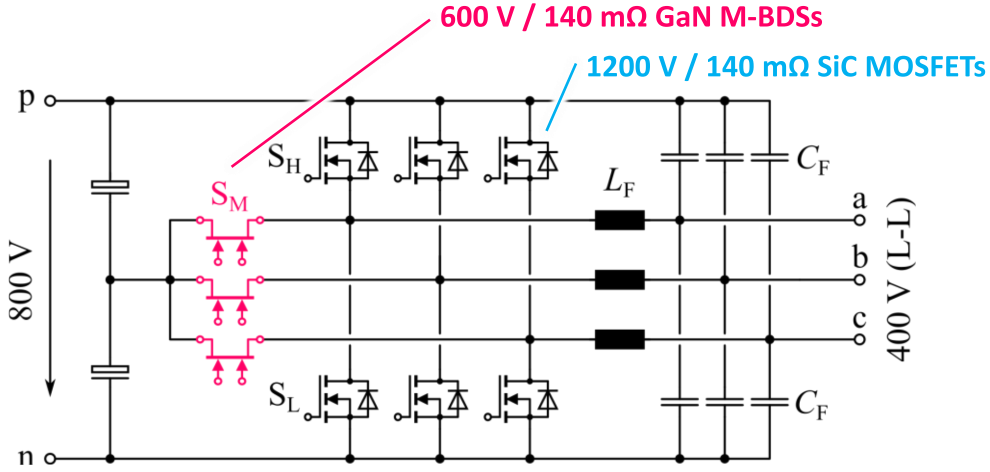
1200 V / 140 mΩ SiC
(IMBG120R140M1H)

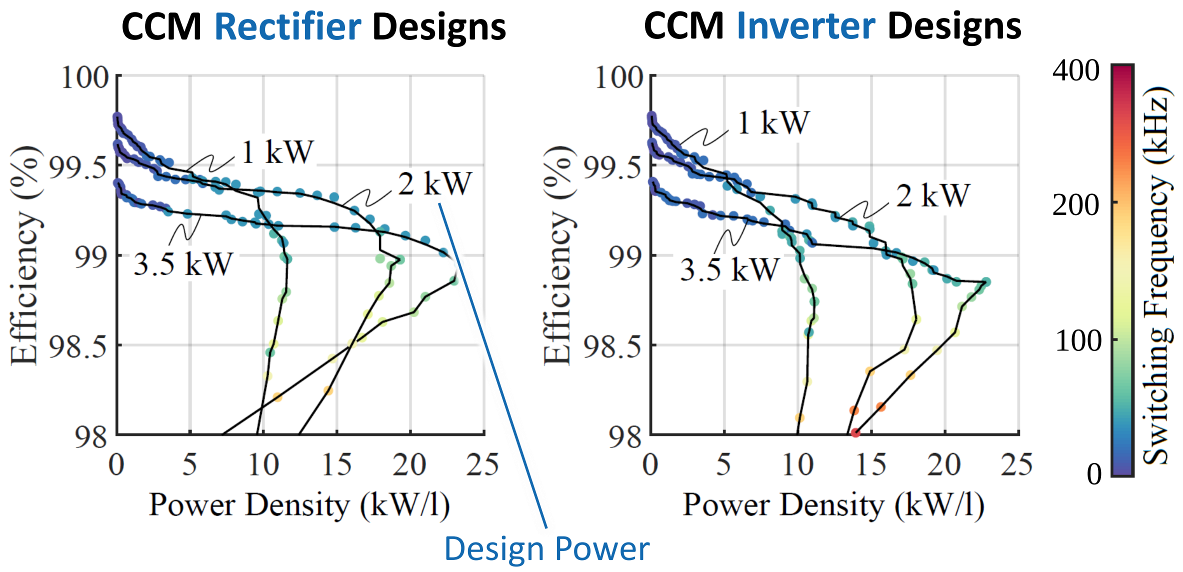
600 V / 140 mΩ GaN M-BDS



Performance Evaluation of TT Main Converter Stage: CCM Designs

TT Main Converter Stage

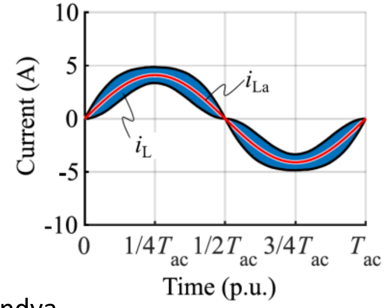




Specifications / Modeling

- T_j = 125 °C, T_{amb} = 45 °C / heat sink volume: CSPI = 15 W/(dm³K)
- $\Delta i_{LF,pp}$ = 30 % (CCM), $\Delta v_{CF,pp}$ = 2 %,
- Pareto-optimal inductor designs (N87 or KoolMu)
- Inverter or rectifier designs with $\cos\phi = \pm 1$

► Sweet spot at 2 kW design power: $\eta > 99$ % at $\rho > 15$ kW/dm³



Further Details => Paper @ ECCE USA 2021

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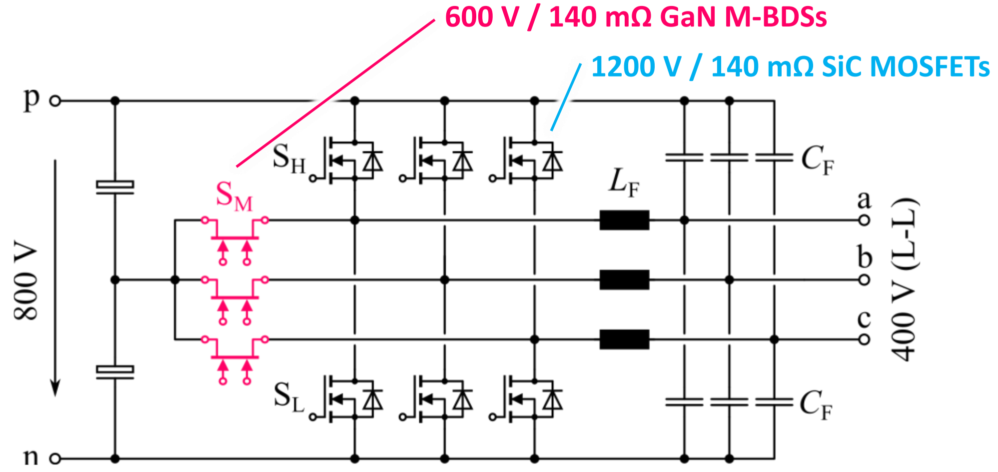
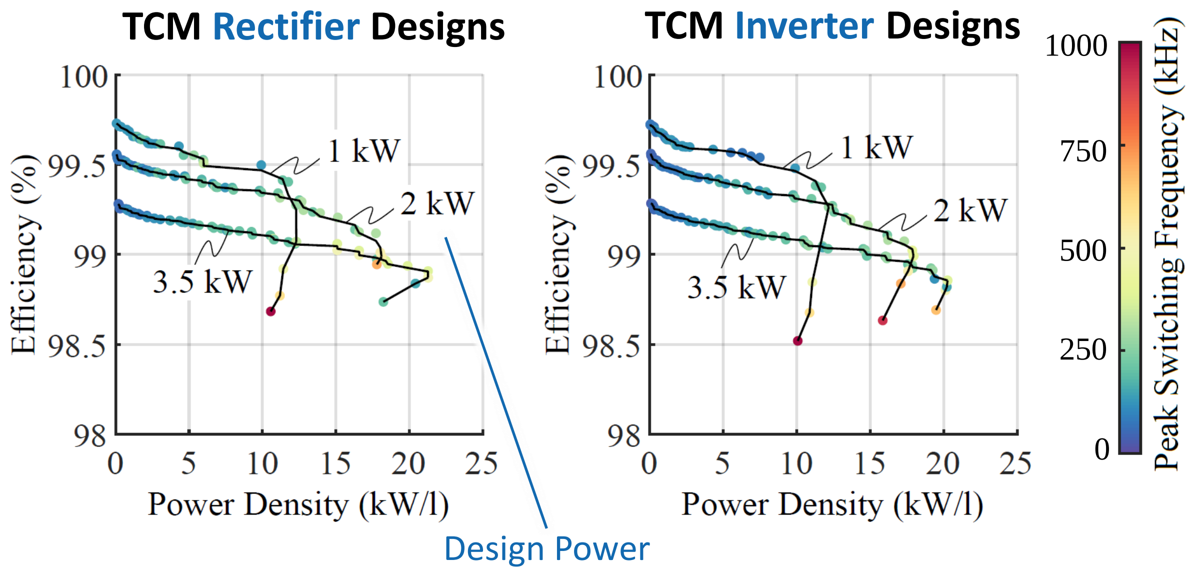
TT Main Converter Stage





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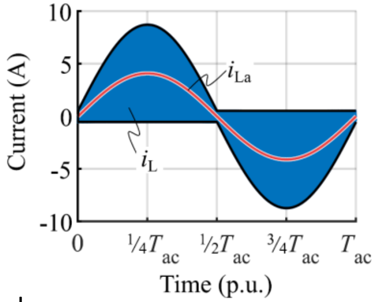
- Inverter or rectifier designs with cosϕ = ± 1

► TCM favorable for lower design powers, e.g., 1 kW



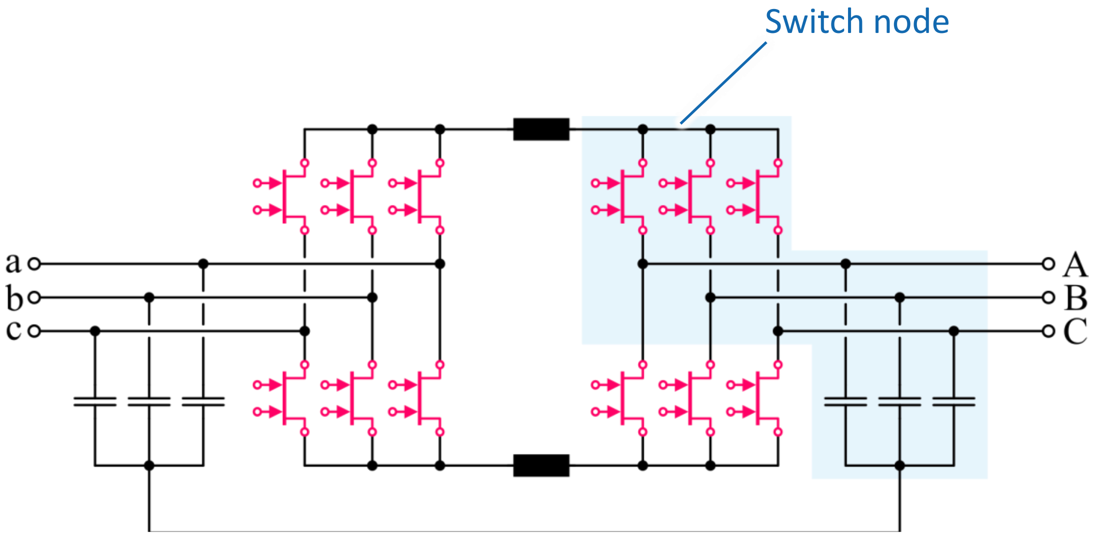
Further Details => Paper @ ECCE USA 2021

F. Vollmaier, N. Nain, J. Huber, J. W. Kolar, K. K. Leong, and B. Pandya, "Performance evaluation of future T-Type PFC rectifier and inverter systems with monolithic bidirectional 600 V GaN switches."

AC/AC Current-Source Converters with M-BDSs

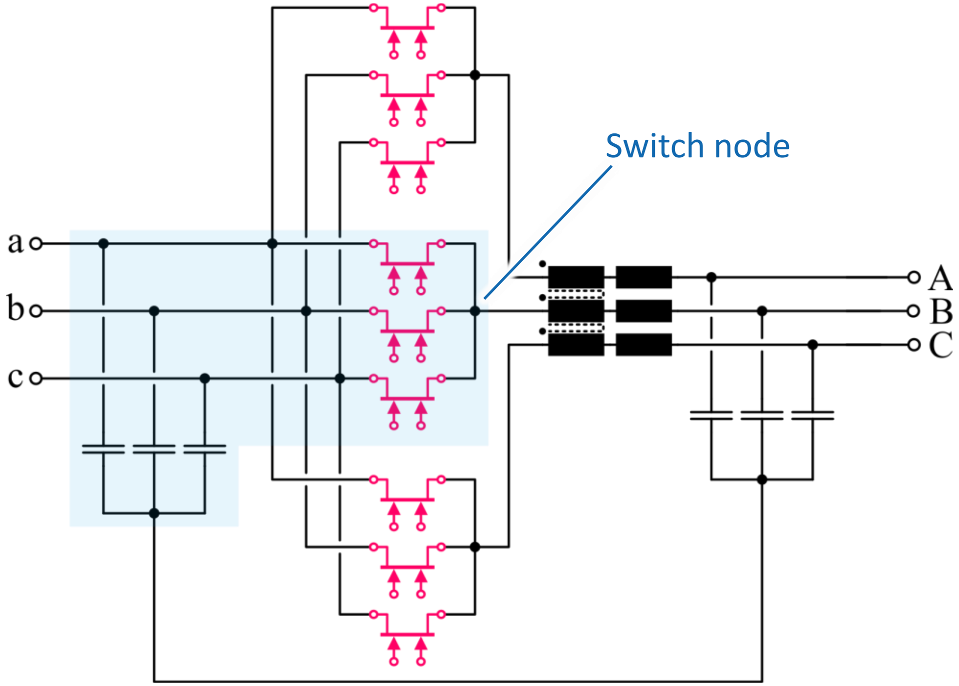
M-BDS Commutation Cell for AC-AC CSC and DMC

AC-AC Current-Source Converter (CSC)



- 4 x Basic Commutation Cell

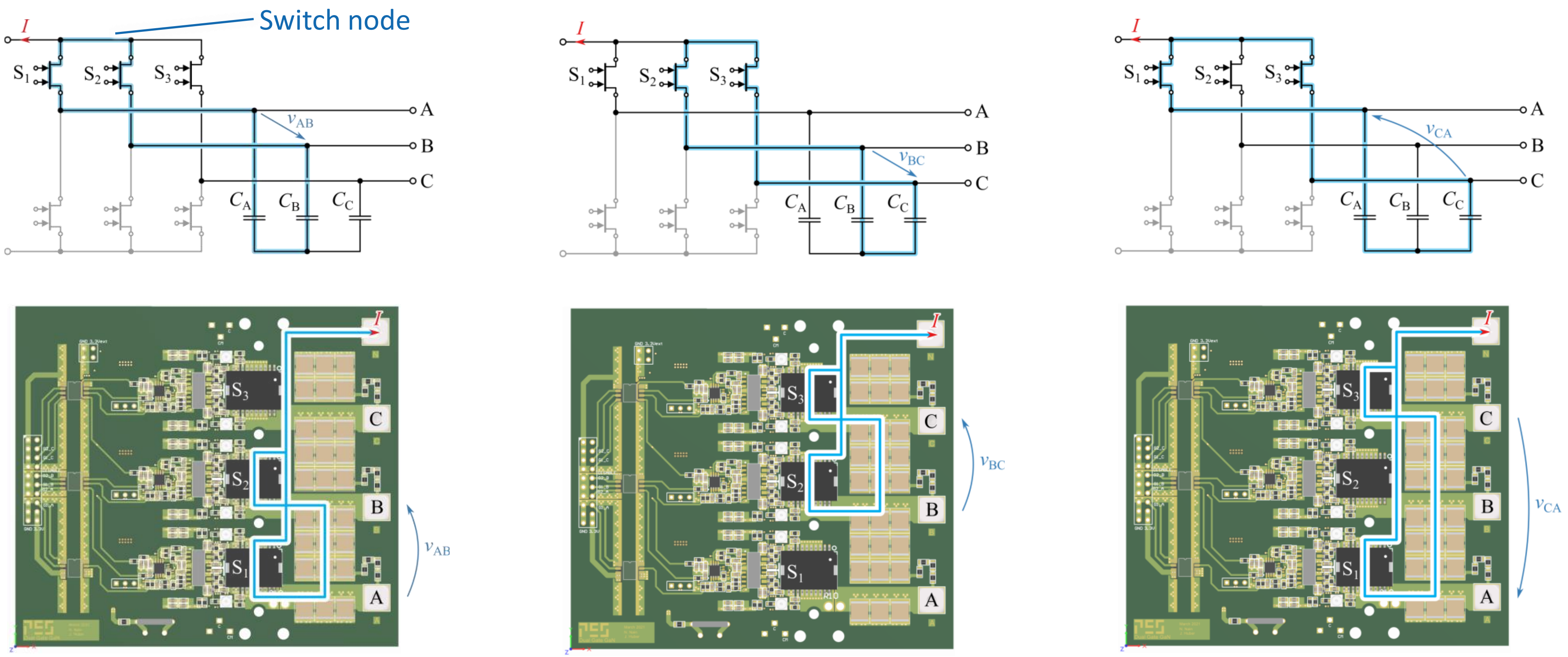
AC-AC Direct Matrix Converter (DMC)



- 3 x Basic Commutation Cell

M-BDS Commutation Cell Test PCB: Commutation Loops

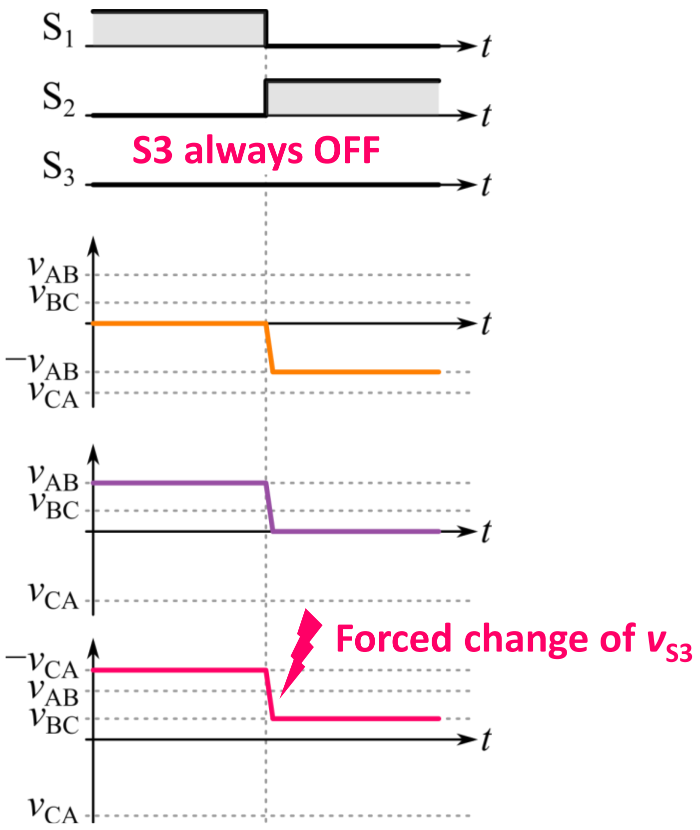
- Commutation voltages: **line-to-line** AC voltages / Commutation capacitors: **two** AC-side filter capacitors

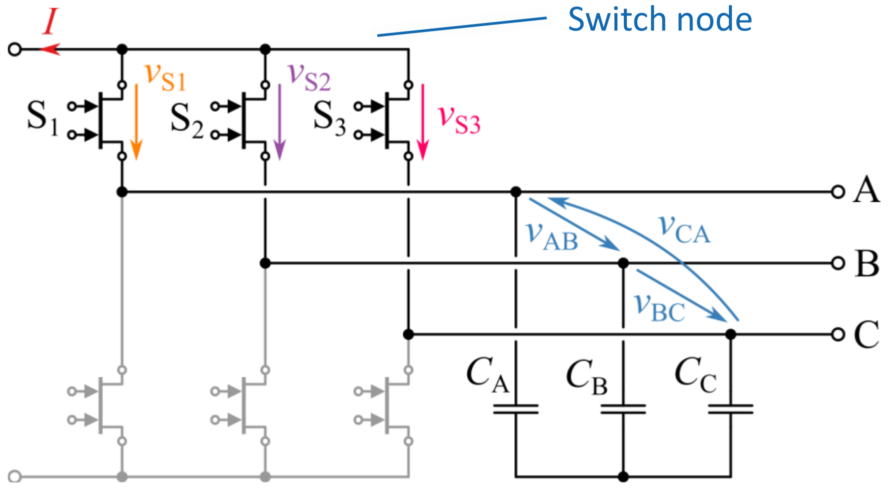


Note: approximate loops only (partly vertical)

Remark: Passive Toggling of Commutation Cell's 3rd Switch

- **Three** switches connected to common switch node / Example: Commutation from S_1 to S_2

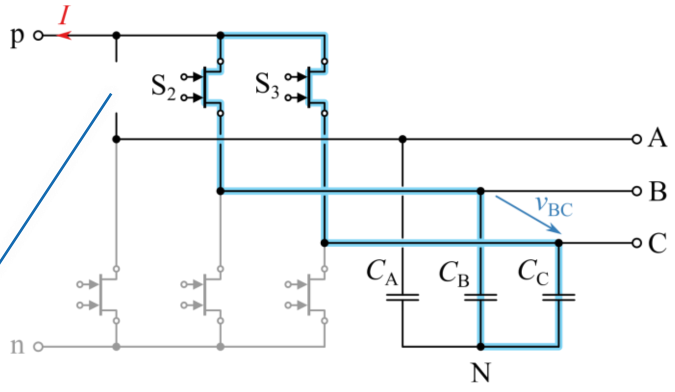




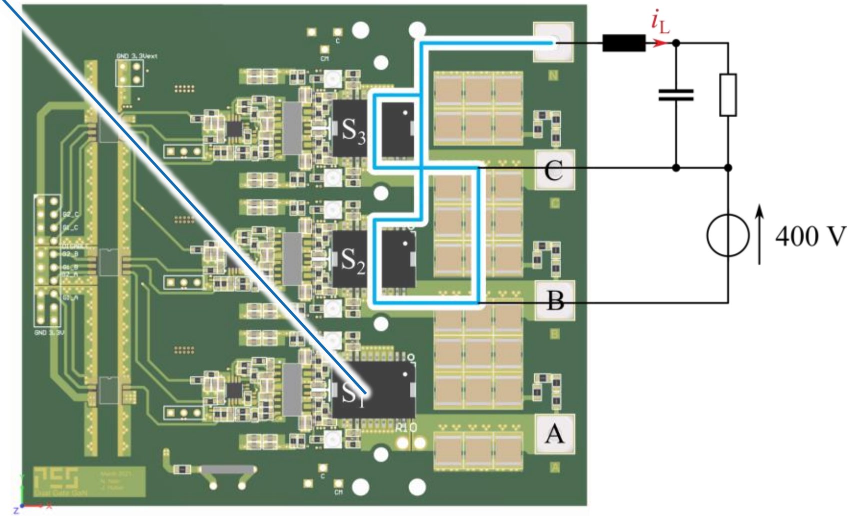
- Charging/discharging of $C_{oss}(S_3)$ creates additional losses[1]
- Risk of parasitic turn-on (dv/dt-induced):
  => Ensure negative gate voltage at all times!

[1] Note: similar effect also observable in TT bridge-legs

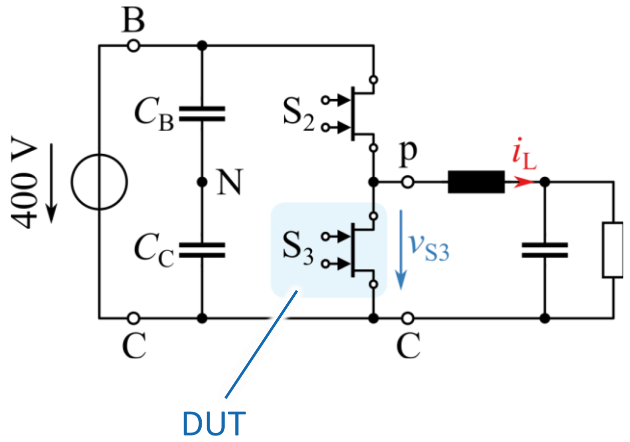
M-BDS Commutation Cell Test PCB: Half-Bridge Configuration



S_1 not placed for initial meas.



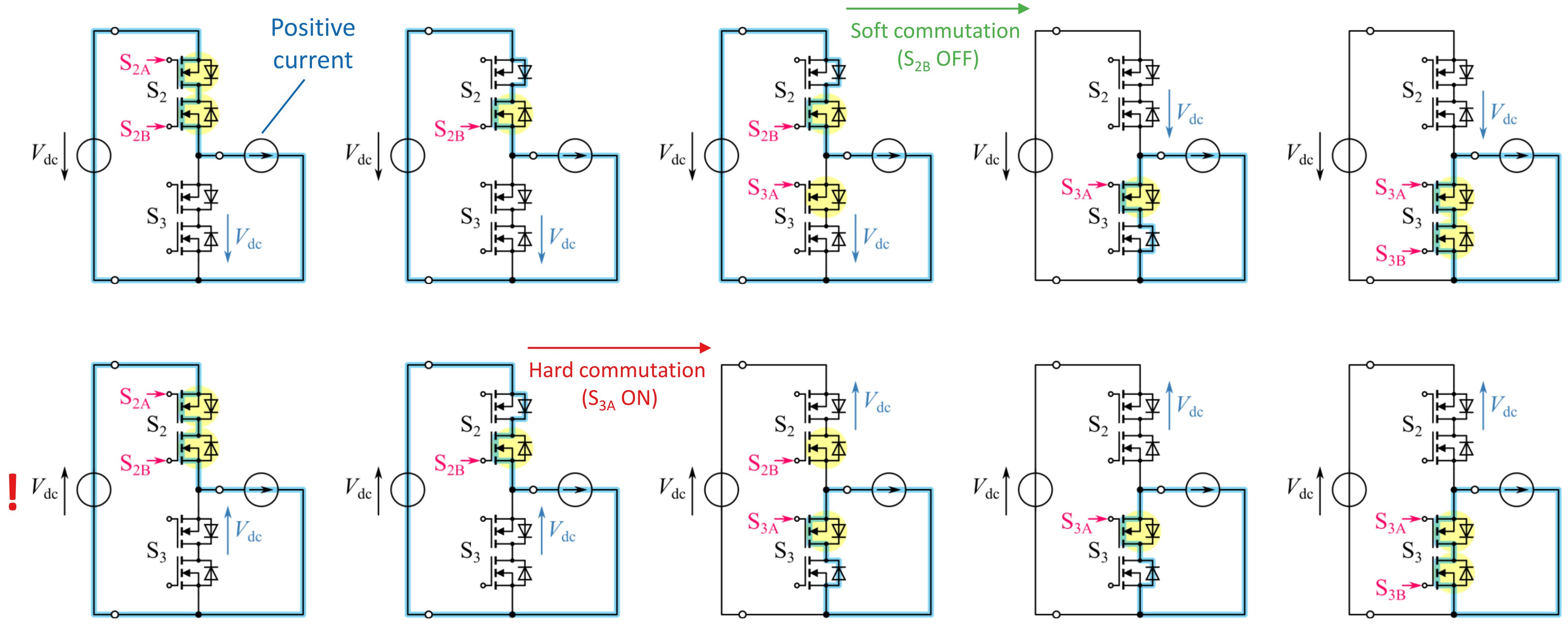
- DUT operation in all **four quadrants** by reconfiguring voltage source / load
  - DC supply between B-C or C-B (± 400 V)
  - Load between p-C or p-B (current direction)



- Impact of S_1 presence to be quantified

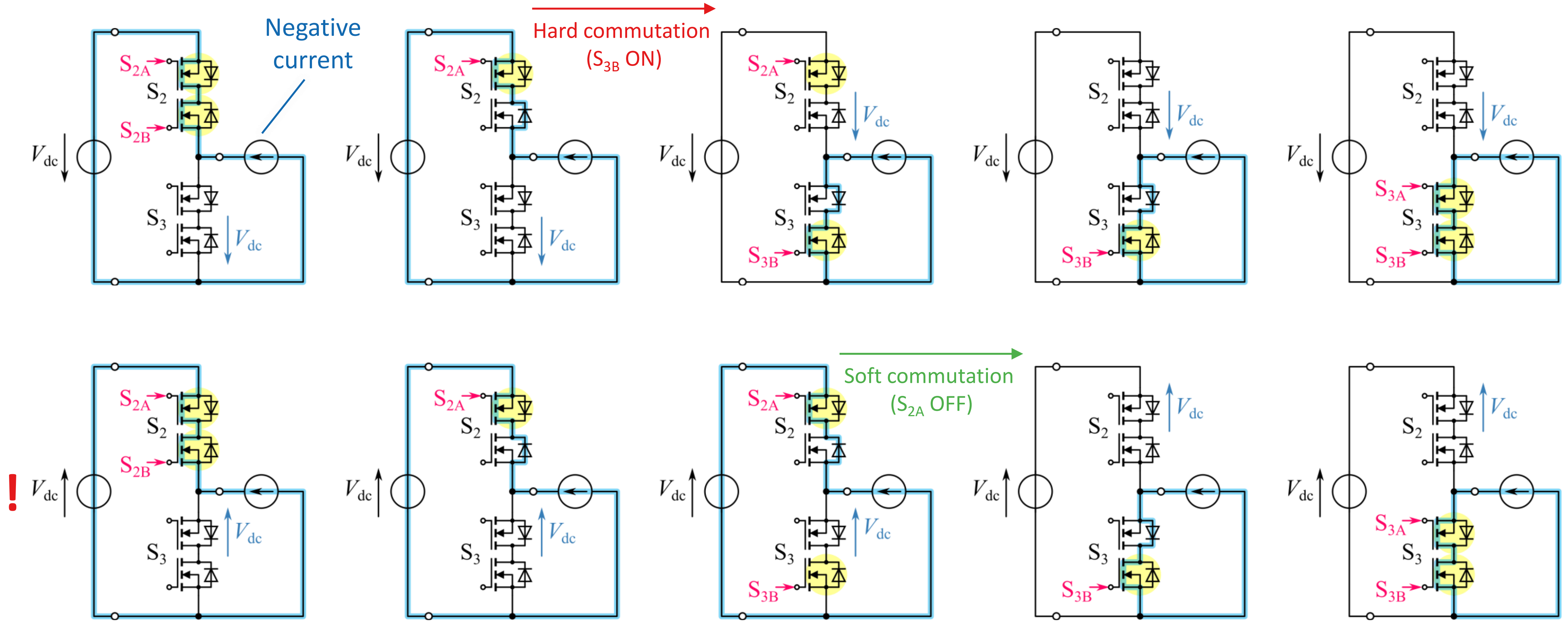
Remark: 4-Step Commutation (Positive Current)

- Ensure current path & avoid DC voltage short-circuit / **Current-direction dependent** gating sequence (pos. current shown)

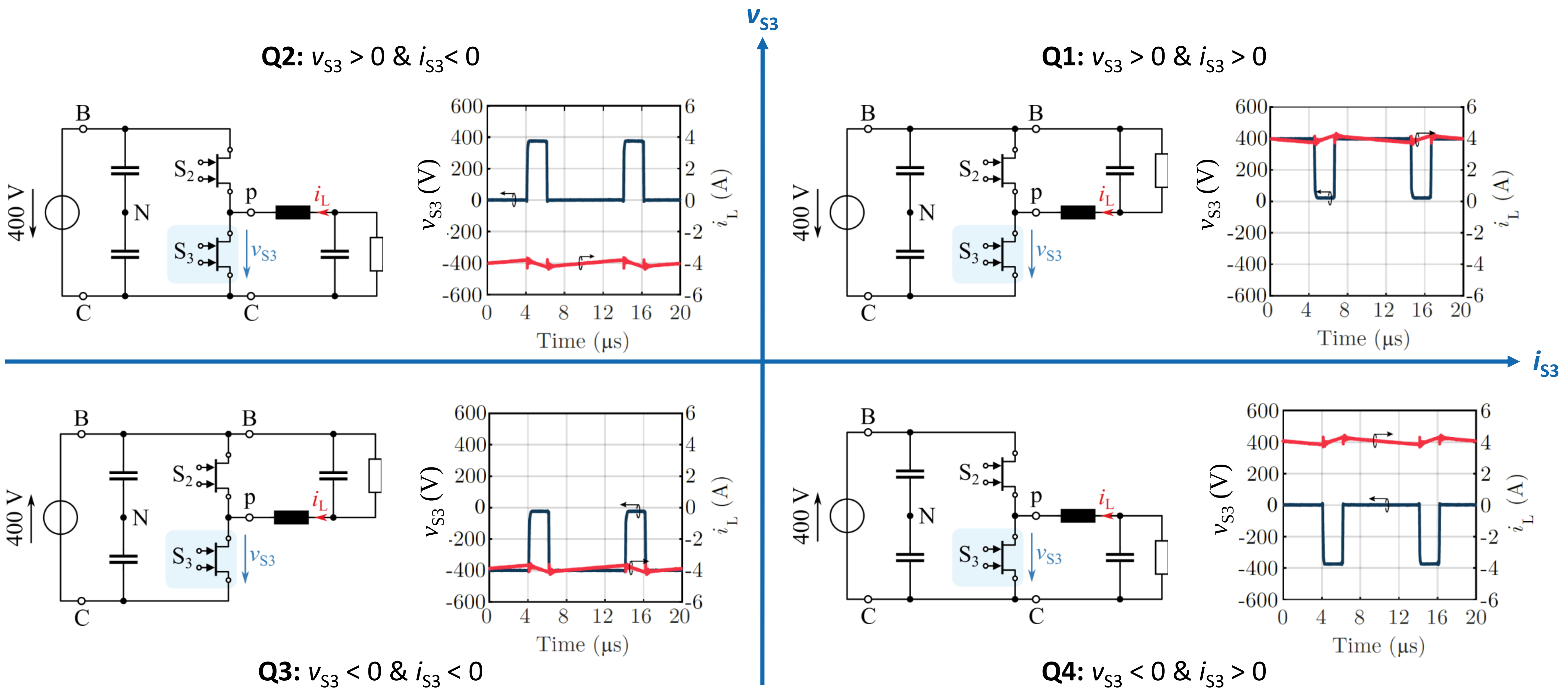


Remark: 4-Step Commutation (Negative Current)

- Ensure current path & avoid DC voltage short-circuit / **Current-direction dependent** gating sequence (neg. current shown)



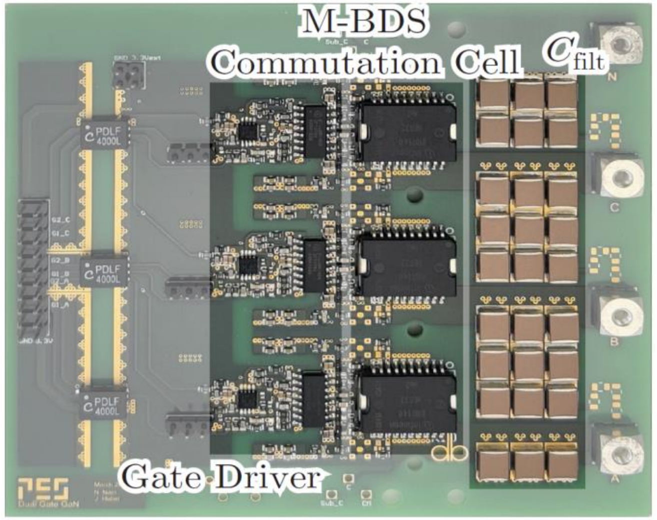
Continuous M-BDS Half-Bridge Operation at ± 400 V



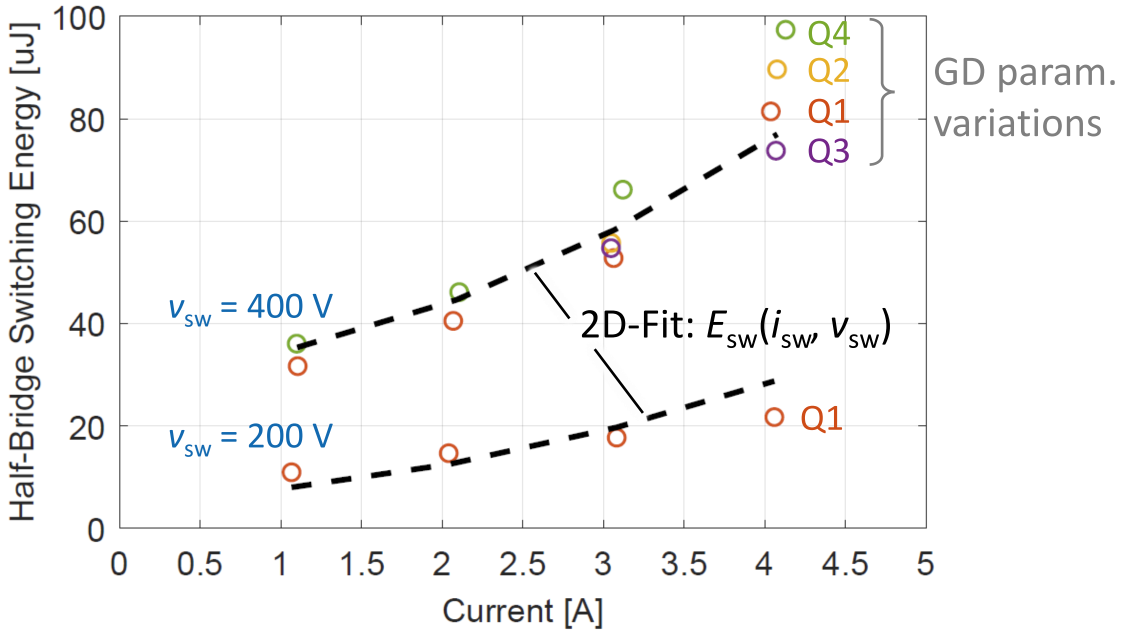
M-BDS Half-Bridge Switching Loss Characterization

- Transient calorimetric method / **4-Step commutation sequence** / All four quadrants / Two voltage levels (CSC)

Test PCB



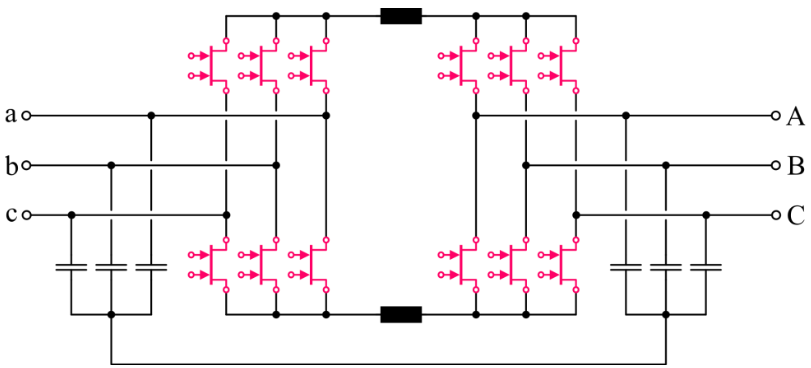
Half-Bridge Hard-Switching Energies (E_{on} + E_{off})



- Note: Preliminary results / Gate setup & timings not yet fully optimized **=> Lower switching losses achievable**

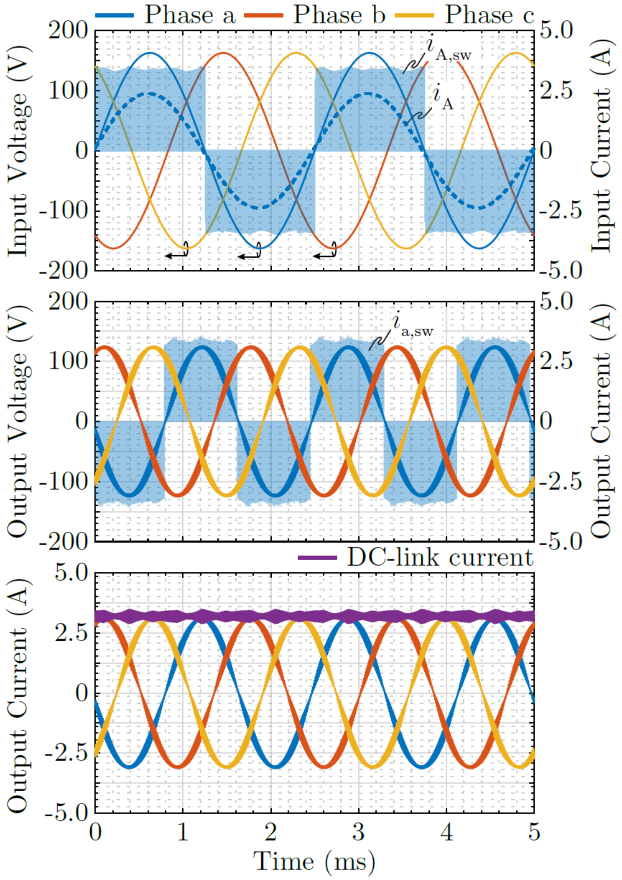
Performance of AC-AC CSC with 600 V / 140 mΩ GaN M-BDSs

- Motor drives for aircraft applications

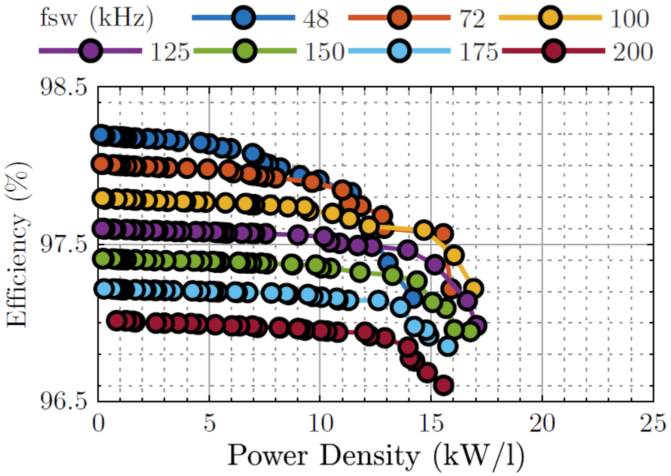


Specifications / Modeling

- 115 V rms, 400 Hz grid
- 92 V rms, 600 Hz, 1 kW output (design point)
- T_j = 100 °C, T_{amb} = 45 °C / heat sink volume: CSPI = 15 W/(dm³K)
- $\Delta i_{Ldc,pp}$ = 10 % (peak-to-peak), ΔQ_{CF} = 5 %
- Pareto-optimal inductor designs (N87 or KoolMu)



- Performance evaluation based on measured M-BDS switching losses



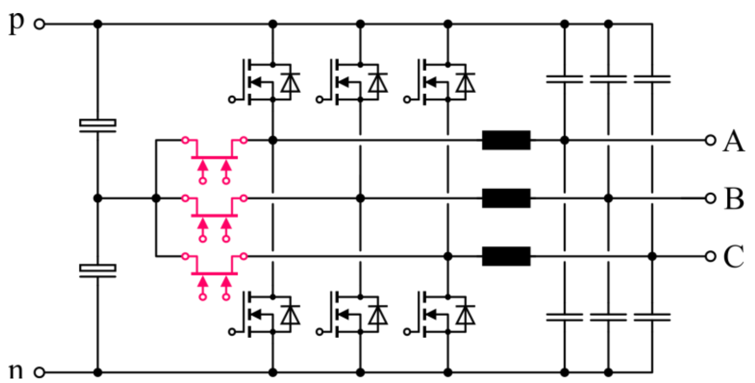
Note: Preliminary results / Work in progress!

Conclusion & Outlook

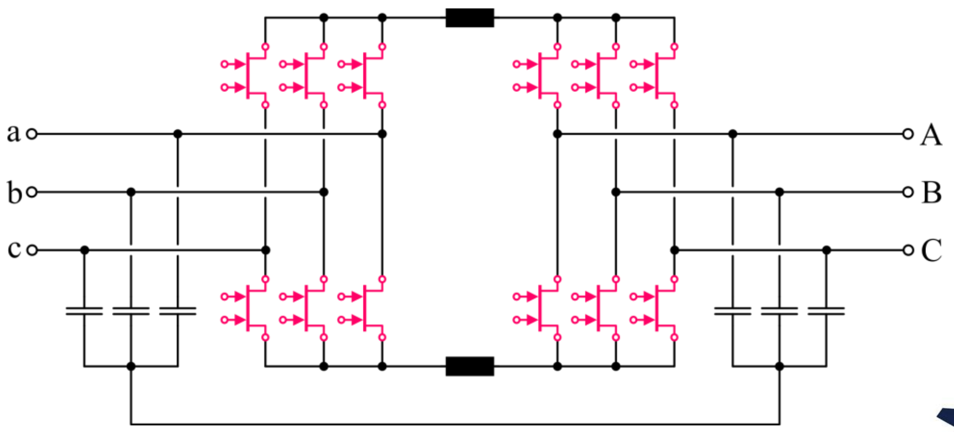
Conclusion & Outlook

- 600 V / 140 mΩ Infineon **GaN M-BDS** continuous operation at ± 400 V
- Calorimetric switching loss characterization of M-BDS in GaN/SiC TT bridge-leg and **all-GaN CSC commutation cell**

TT DC-AC Converter



Current-Source AC-AC Converter



- **Full prototypes** under development / System-level experimental performance verification
- GaN M-BDS technology takes flight and promises **straightforward designs** and **superior performance**

Thank You!