ETH zürich

Ultra-High Bandwidth GaN-Based Class-D AC Power Amplifier with 4.8 MHz Switching Frequency

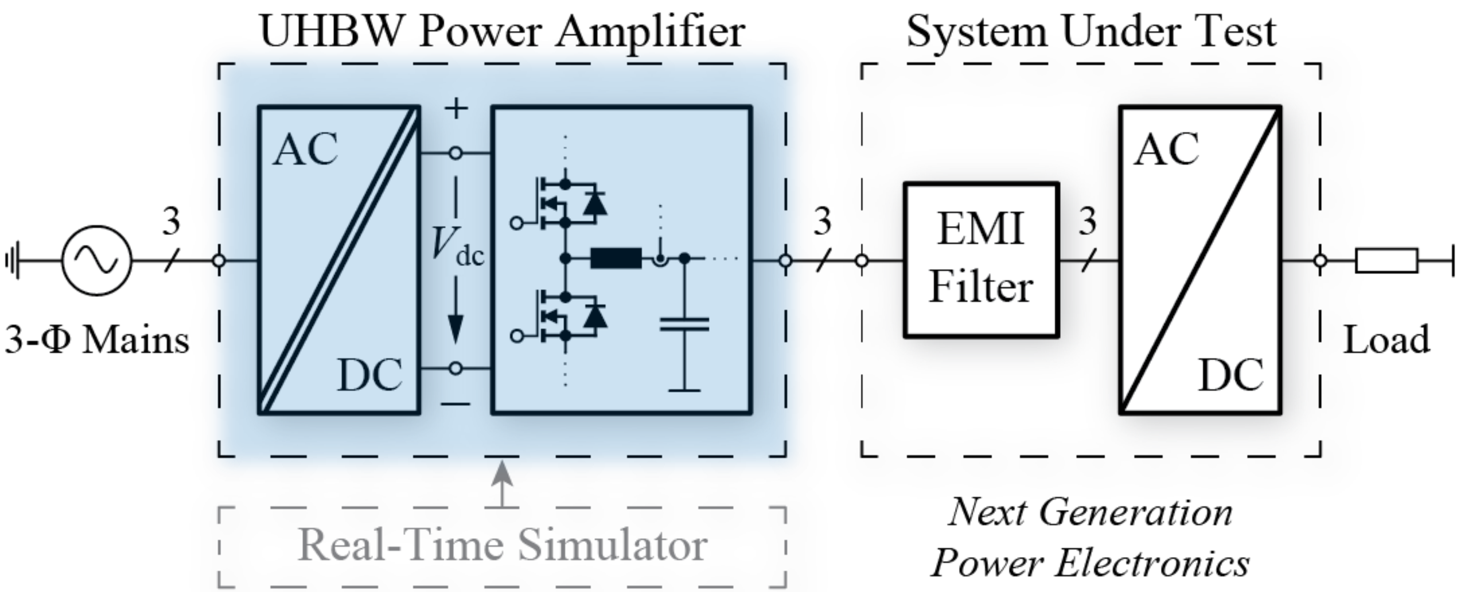
Pascal S. Niklaus, D. Bortis, J. W. Kolar

niklaus@lem.ee.ethz.ch – www.pes.ee.ethz.ch

Real-Time Simulation Workshop 2022

Karlsruher Institut für Technologie

November 24th – 25th 2022

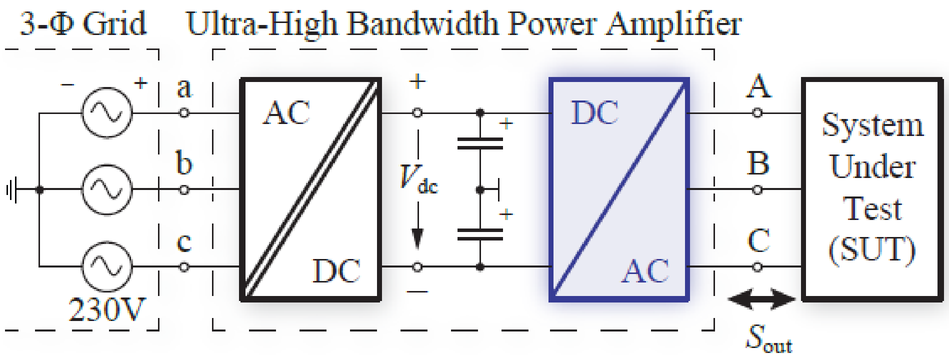


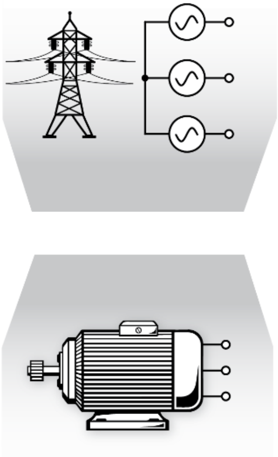
100 kHz Large-Signal Bandwidth
GaN-Based 10 kVA Class-D Power Amplifier

Very High Power Density Converter Systems with Multi-MHz Switching Frequencies

UHBPA: Applications + Specifications

- P-HIL → Three-phase Ultra-High Bandwidth Power Amplifier (UHBPA)
- Focus on single-phase module of DC/AC stage





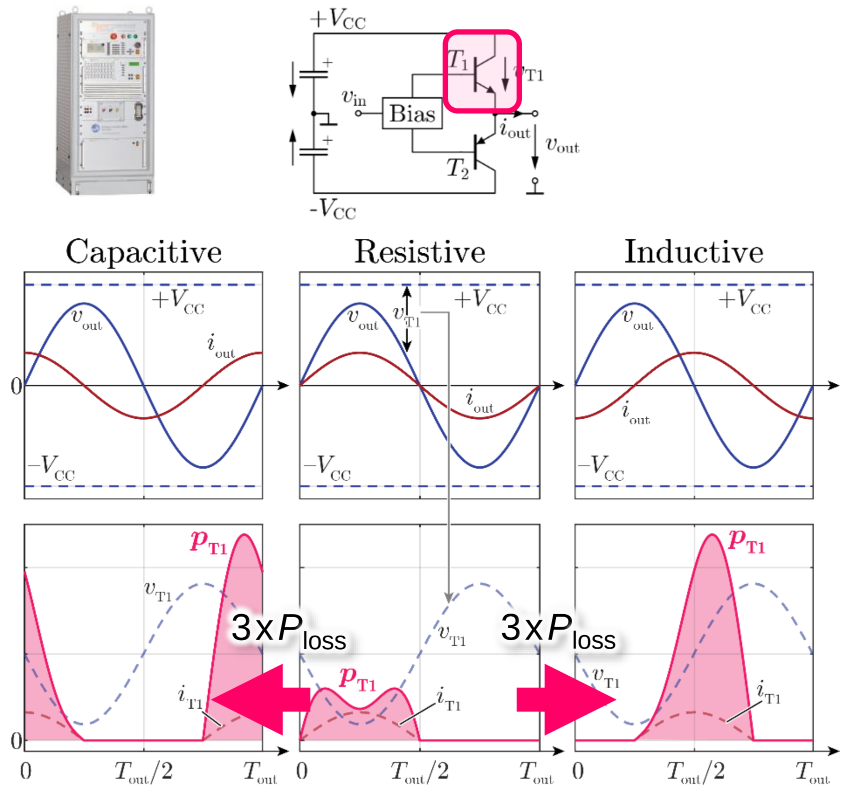
▼ UHBPA Specifications

Parameter		Value
Peak Output Voltage per Phase	$V_{out,pk}$	0 . . . 350 V
Output Frequency	f_{out}	dc. . . 100 kHz
Output Power per Phase	S_{out}	0 . . . 10 kVA
DC Link Voltage	V_{dc}	800 V
Effective Switching Frequency	$f_{sw,eff}$	4.8 MHz
System Efficiency (Nom. Op. Pt.)	η	95 %

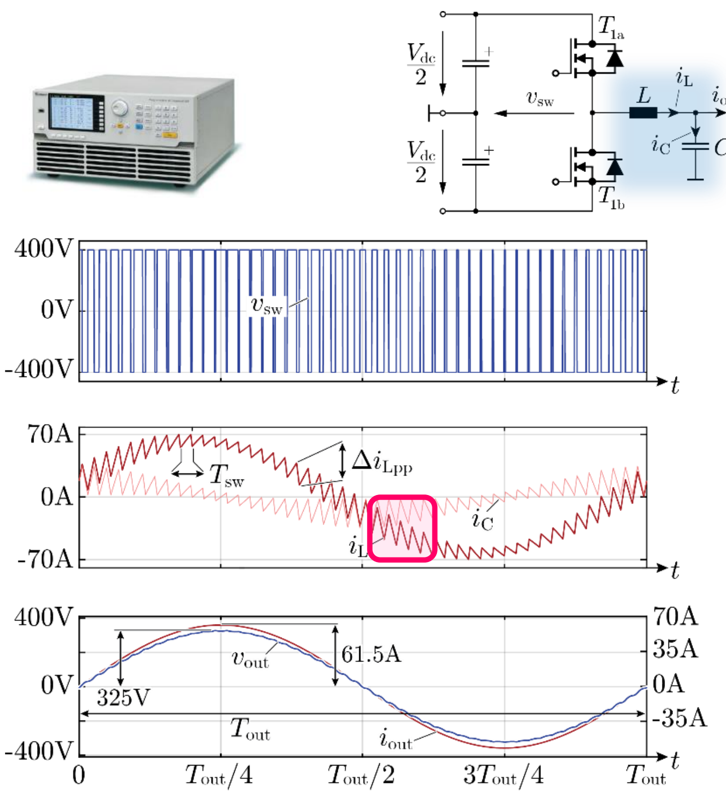
→ Fast dynamics (100 kHz) and high efficiency (95 %) at nominal power of 10 kW per phase

UHBPA: Linear vs. Switch-Mode

▼ Linear UHBPA



▼ Switch-Mode UHBPA

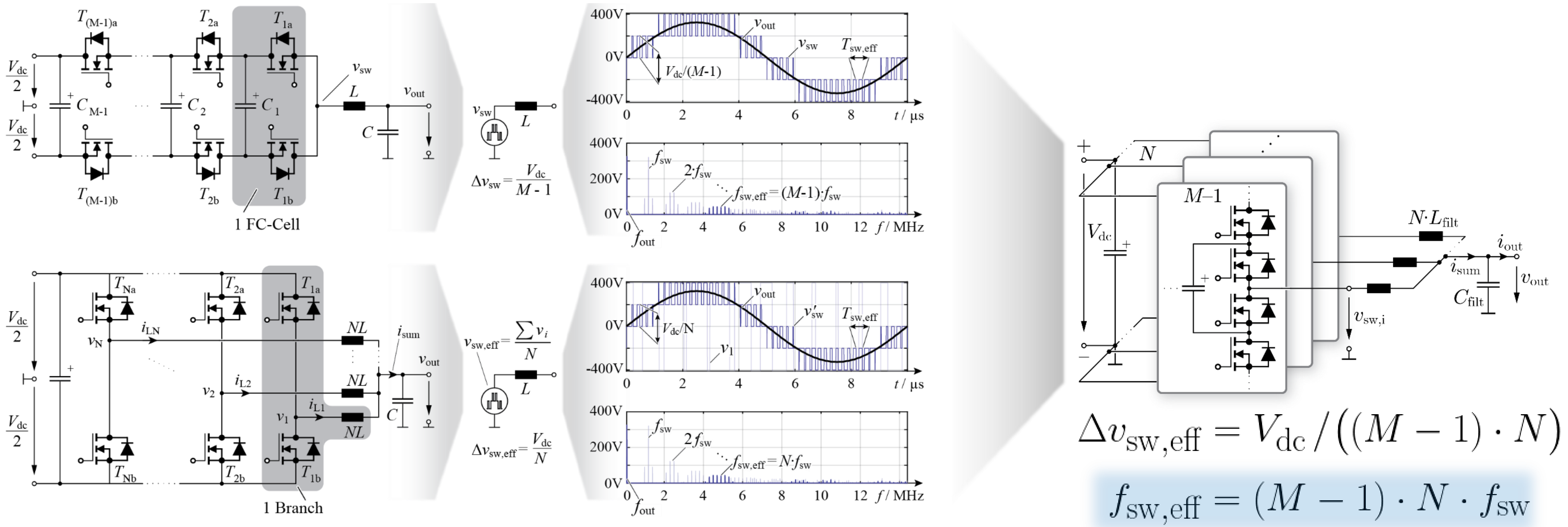


→ Switch-mode for higher efficiency → 100 kHz BW needs ≈5 MHz sw. frequency

→ Advanced topology to increase f_{sw} with minimal losses and to reduce ripple with minimal volume

Advanced Circuit Topology

- Series & Parallel interleaving
- Multi-level switch-node voltage + very high effective switching frequency



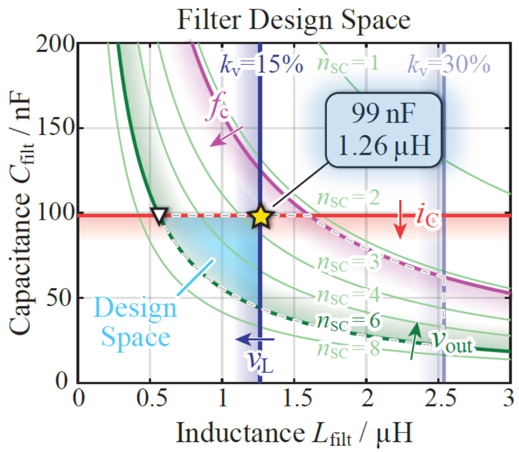
$$\Delta v_{\mathrm{sw,eff}} = V_{\mathrm{dc}} / ((M-1) \cdot N)$$

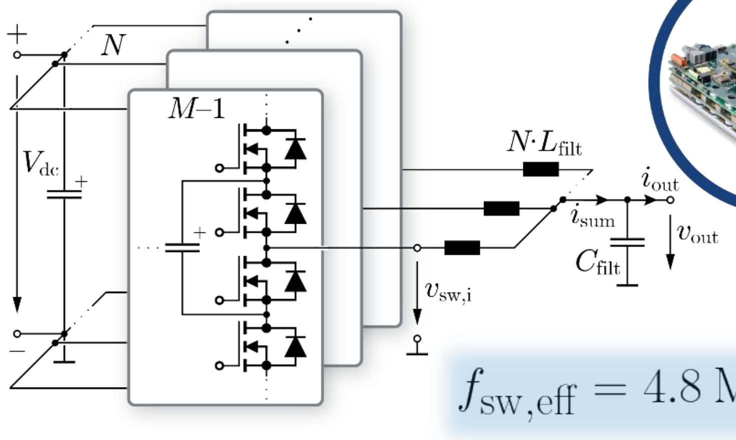
$$f_{\mathrm{sw,eff}} = (M-1) \cdot N \cdot f_{\mathrm{sw}}$$

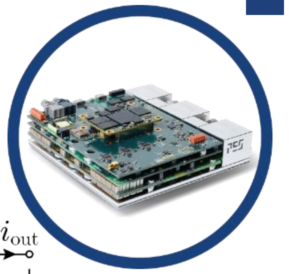
→ Find best combination of series (*M*) and parallel (*N*) interleaving

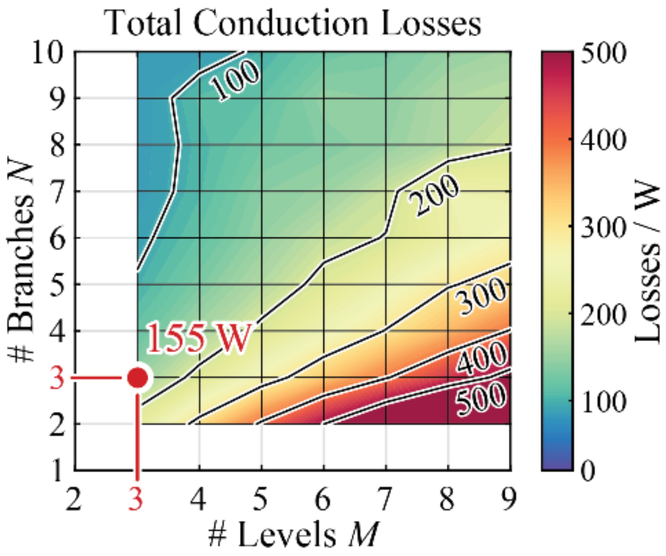
Optimal Design Selection

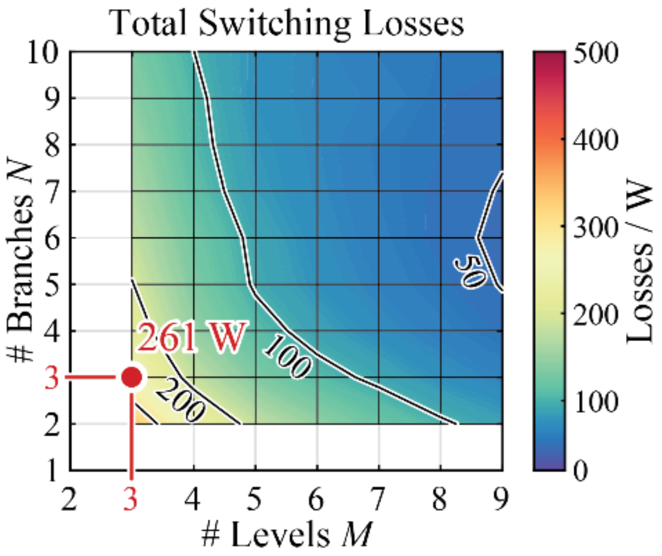
- Filter design space
  - L_{filt} = 1.26 µH, C_{filt} = 99 nF
- Nominal operating point
  - 230 V_{rms}, 10 kW, 100 kHz
- 70 mΩ / 600 V GaN HEMT

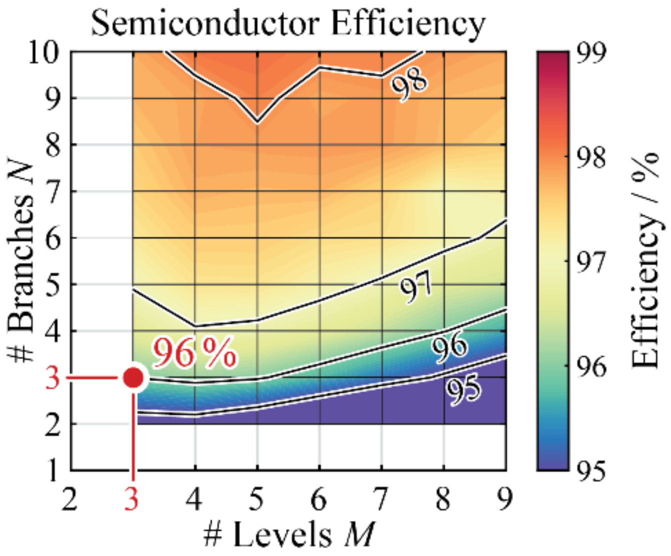








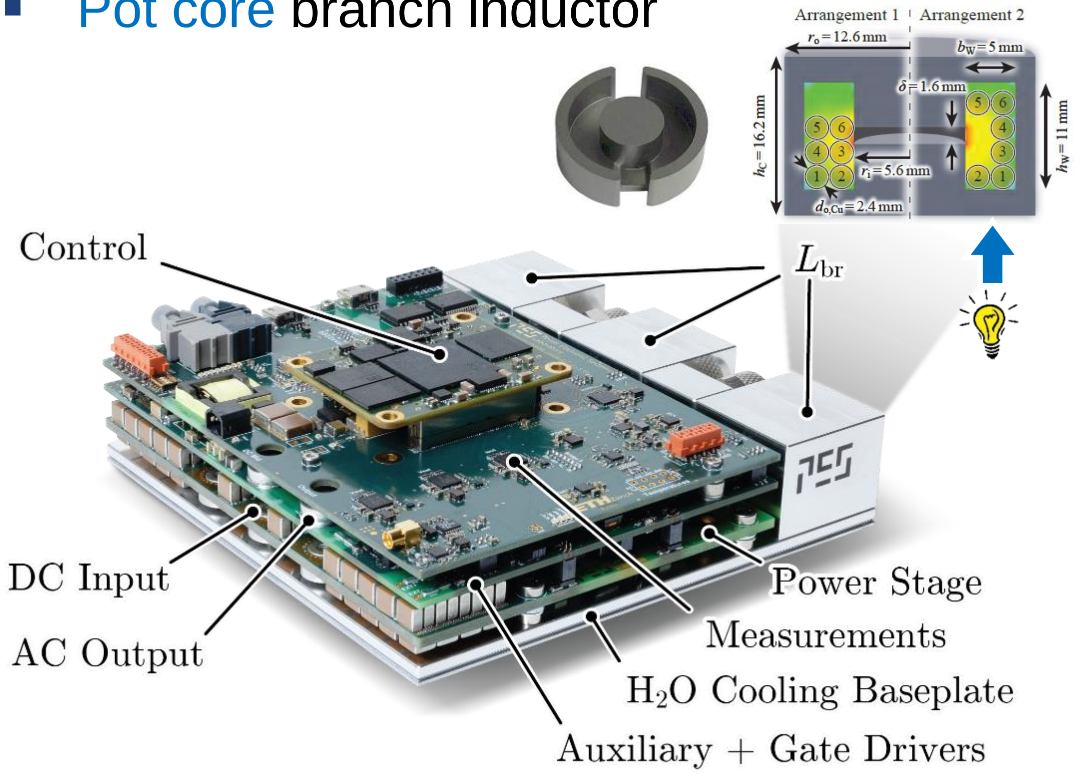


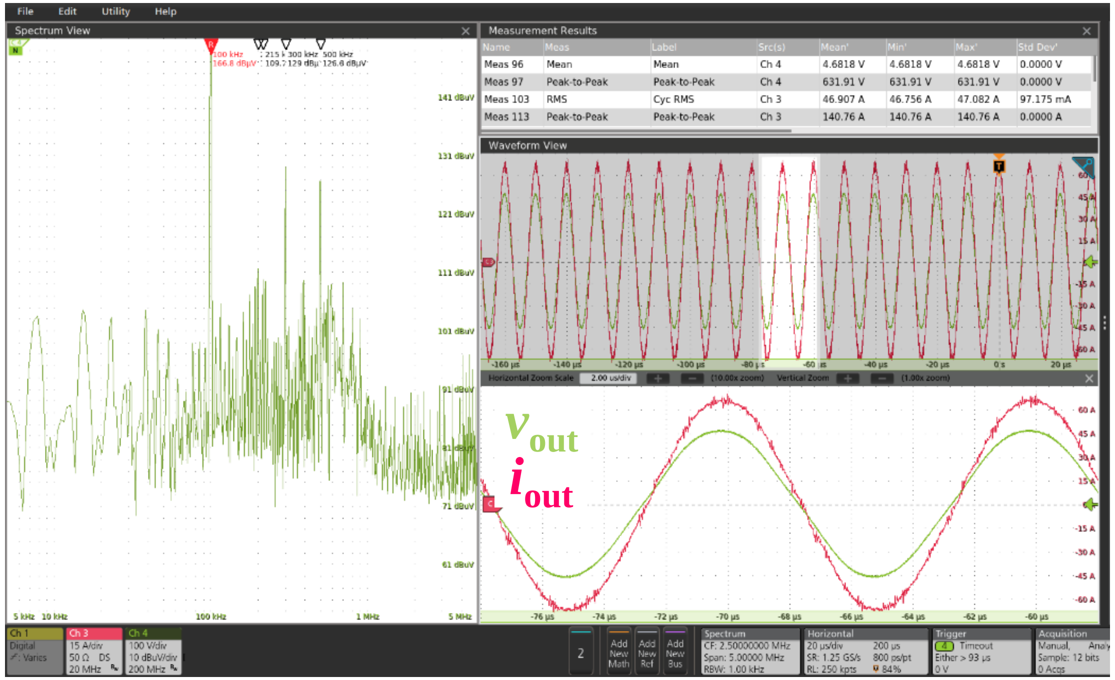


→ Selection of M=3 / N=3 considering efficiency / filter volume / design complexity trade-off

Experimental Verification

- $M=3$ / $N=3$ hardware demonstrator → 25 kW/dm^3 power density, H_2O cooling
- Pot core branch inductor

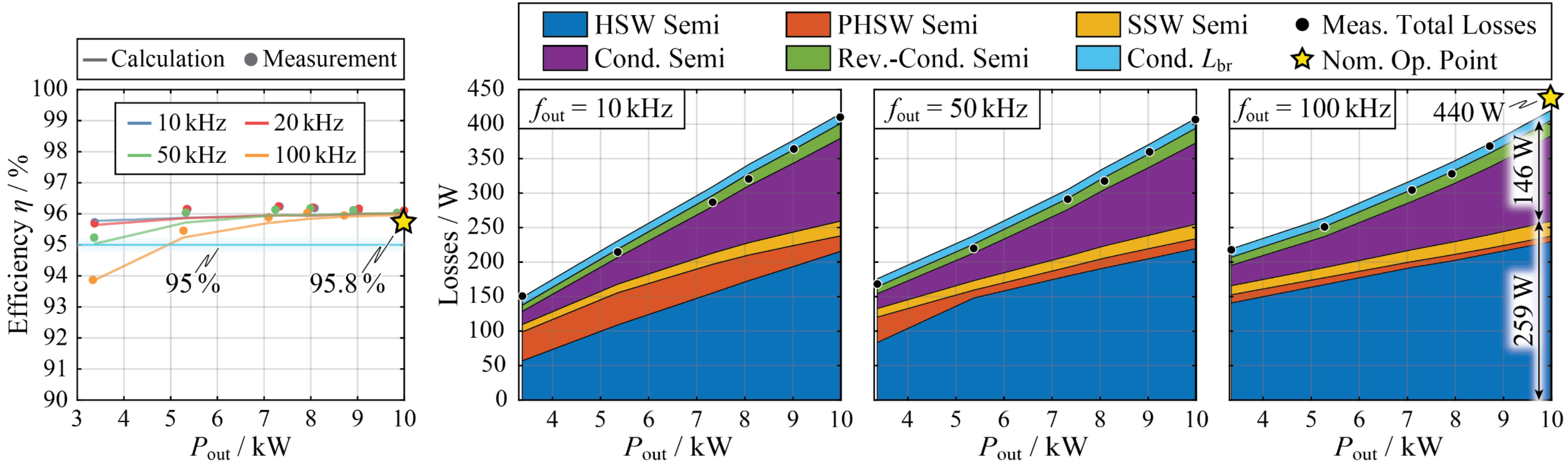




→ 100 kHz sine operation with ≈40 dB attenuation of 3rd and 5th harmonic

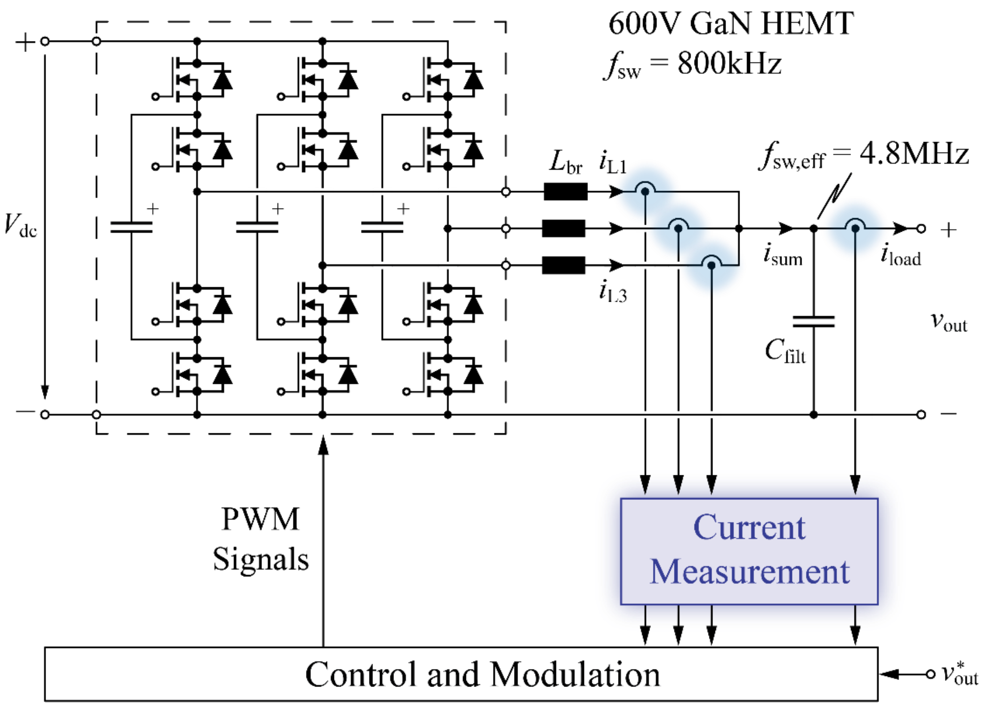
Experimental Verification: Efficiency

- *M*=3 / *N*=3 hardware demonstrator → $f_{\mathrm{sw,eff}}$ = 4.8 MHz
- Open-loop operation with V_{out} = 230 $\mathrm{V_{rms}}$



→ *η* = 95.8 % @ 100 kHz, 10 kW (nom. op. point)

→ Losses dominated by (hard-) switching losses

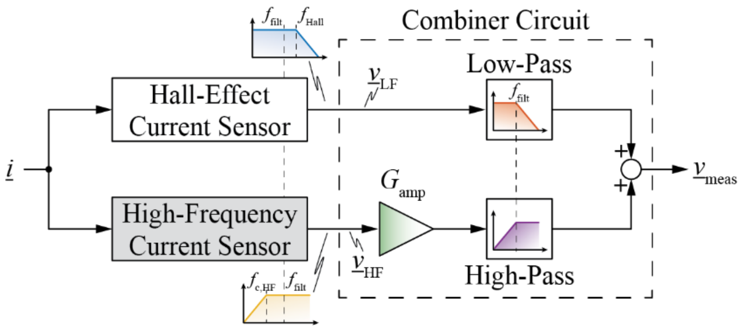


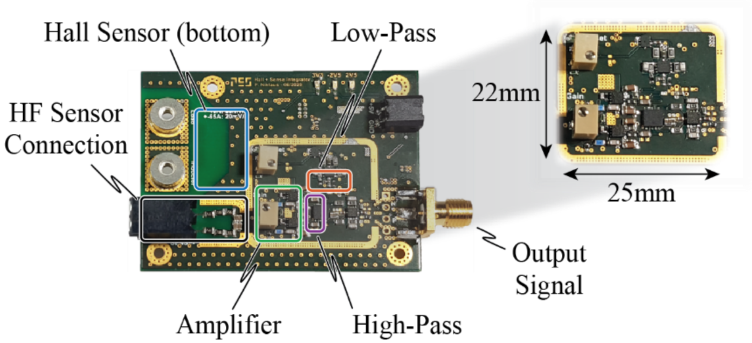
High-Frequency DC-Coupled Current Measurement Sensors

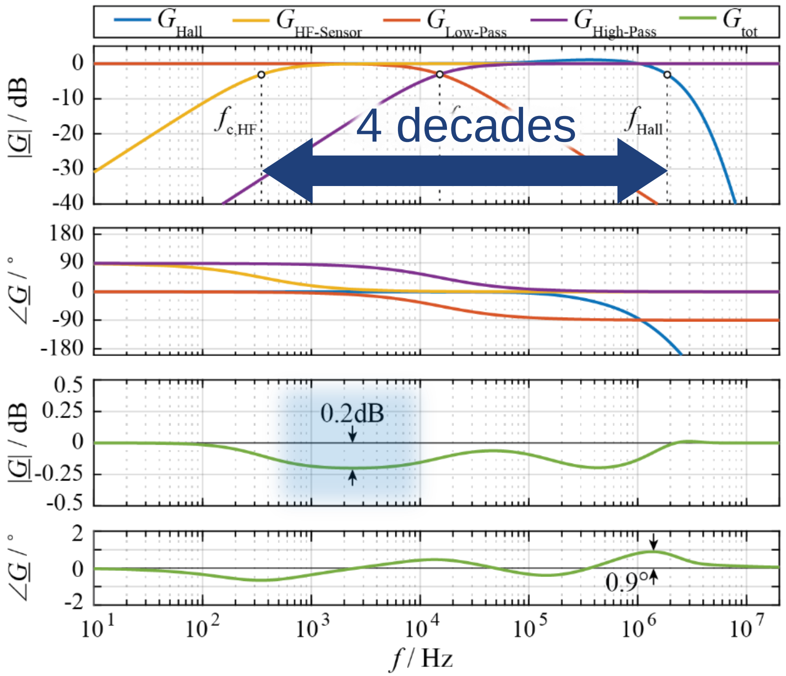
Bandwidth Extension of Commercial Hall-Effect Current Sensors

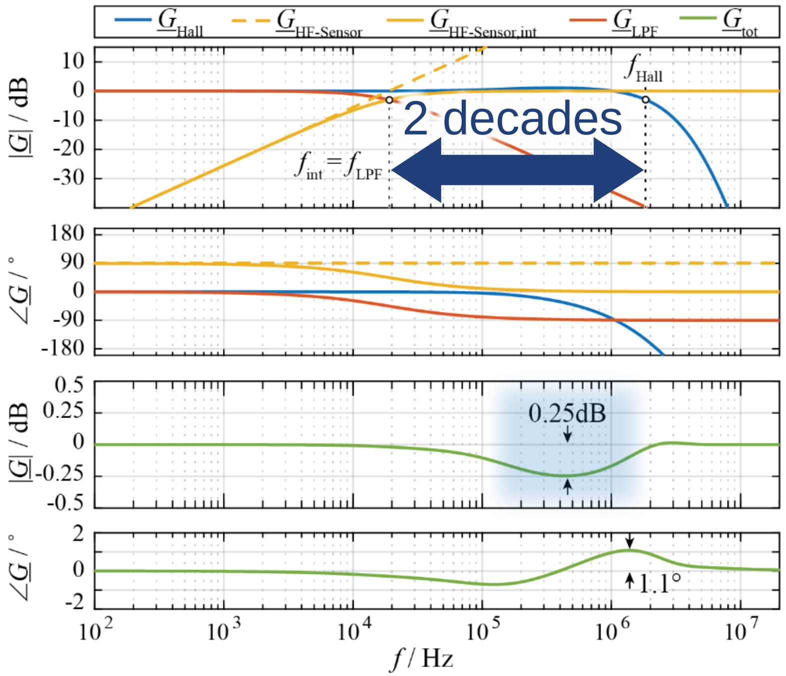
LF + HF Sensor Combination

- Minimal error in the transition / combiner region
- Active combiner circuit







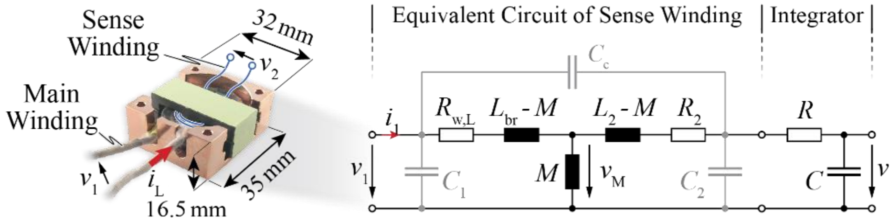


→ Find suitable HF sensors

Investigated HF Sensors

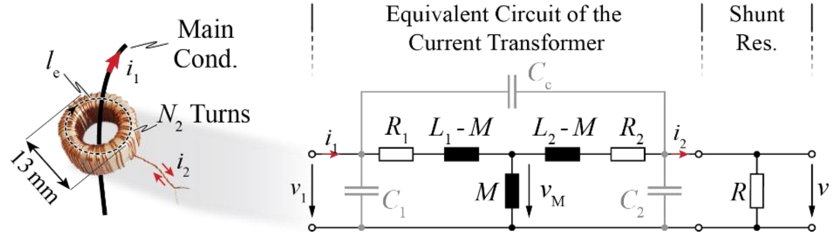
- Max. BW and minimal volume

▼ Isolated Inductive Voltage Sensing

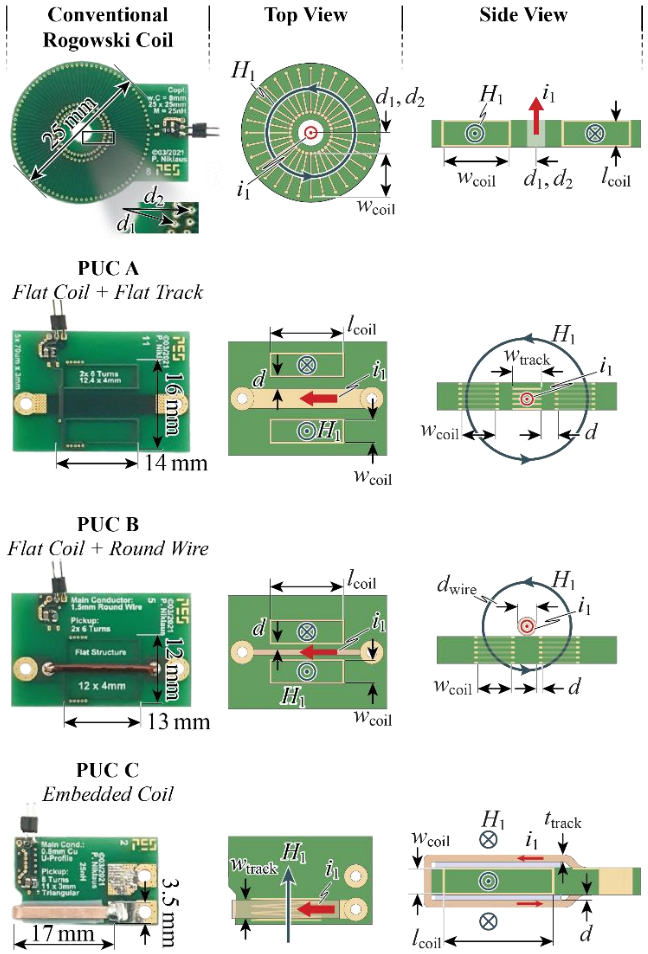


$$v = i_1 \cdot \frac{sM}{1 + sRC}$$

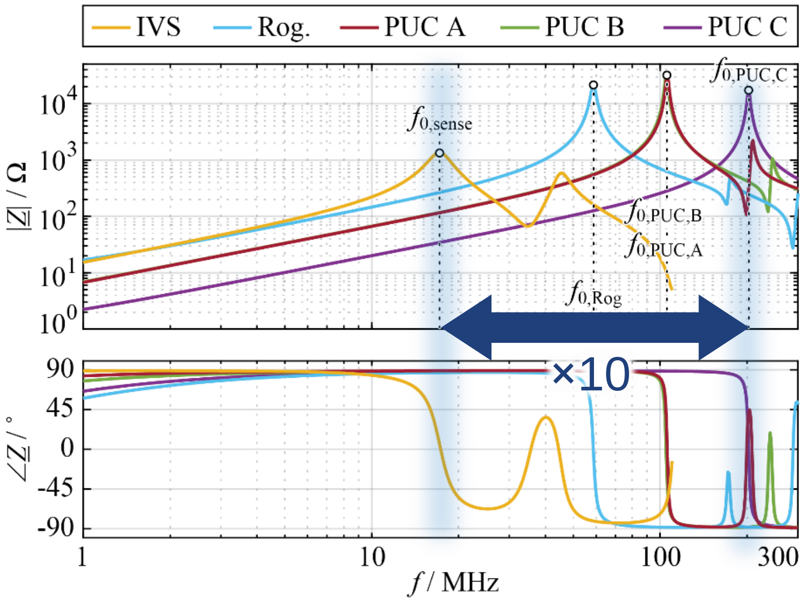
▼ Current Transformer



$$v = i_1 \cdot R \cdot \frac{sM/(R + R_2)}{1 + sL_2/(R + R_2)}$$



◀ Pickup Coils

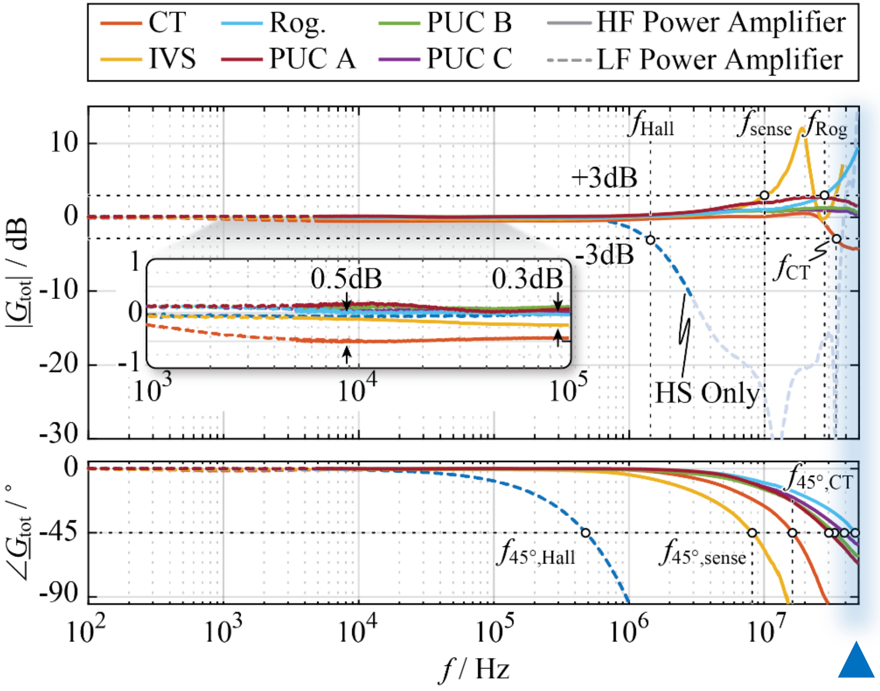


→ Which sensor offers best performance?

Experimental Verification

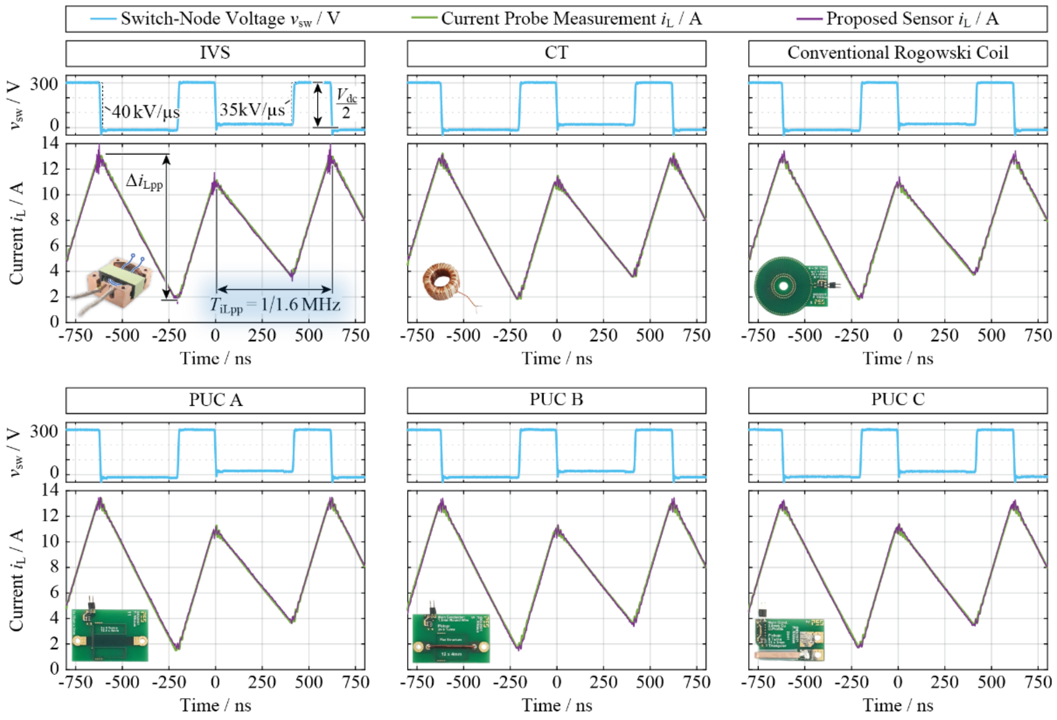
- All sensors tested in-circuit

▼ Frequency Domain



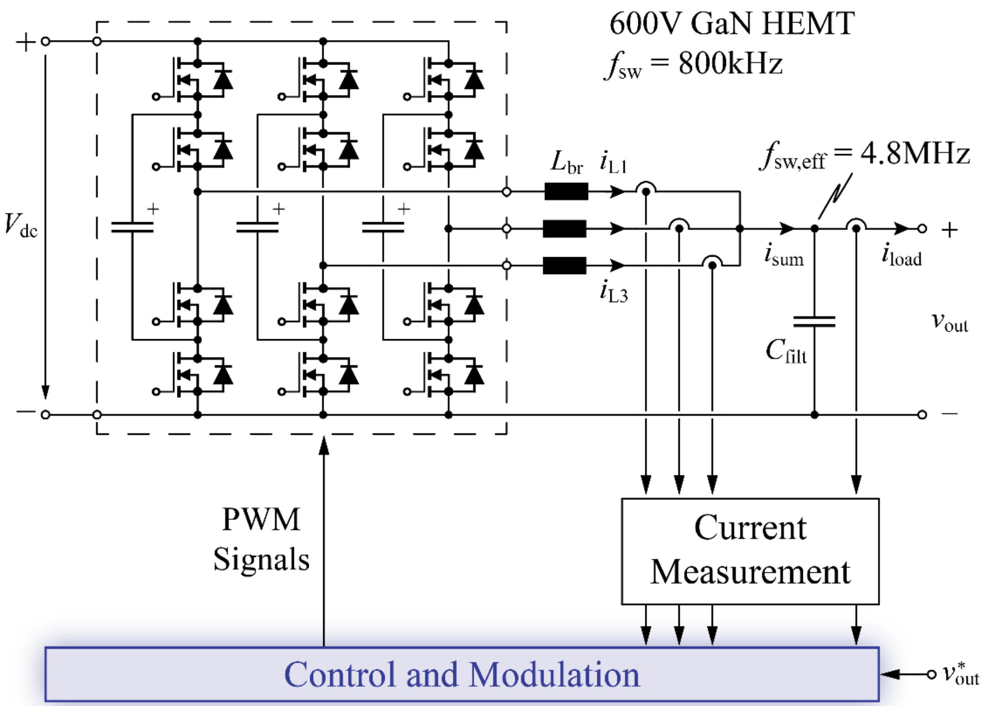
▲ >50 MHz

▼ Time Domain



→ 10 MHz BW fulfilled with all sensors → Accurate tracking of triangular current

→ PUC C with highest BW and smallest form factor

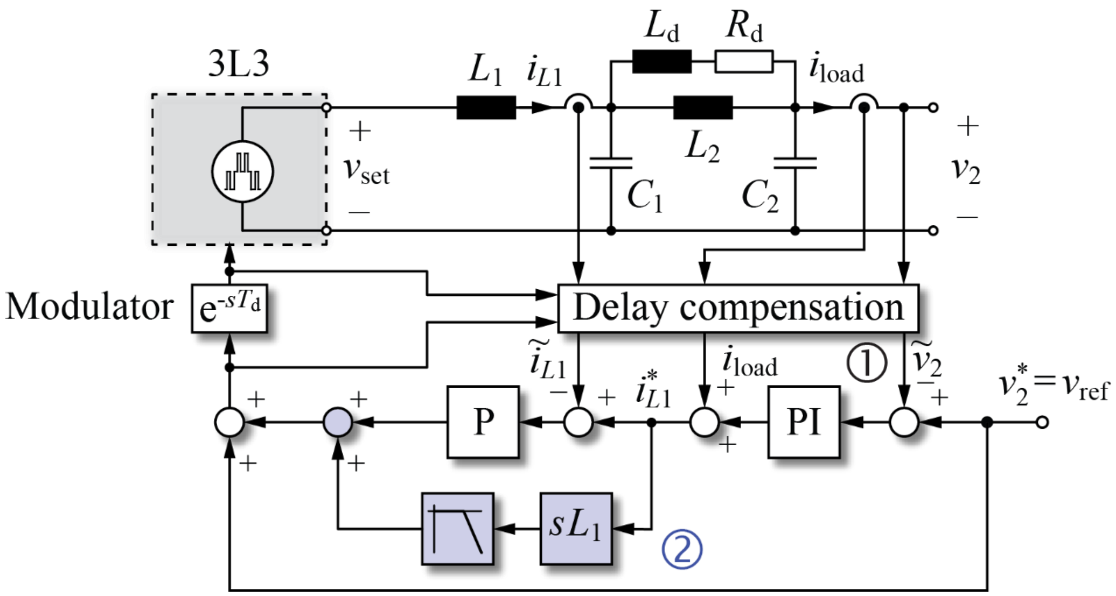


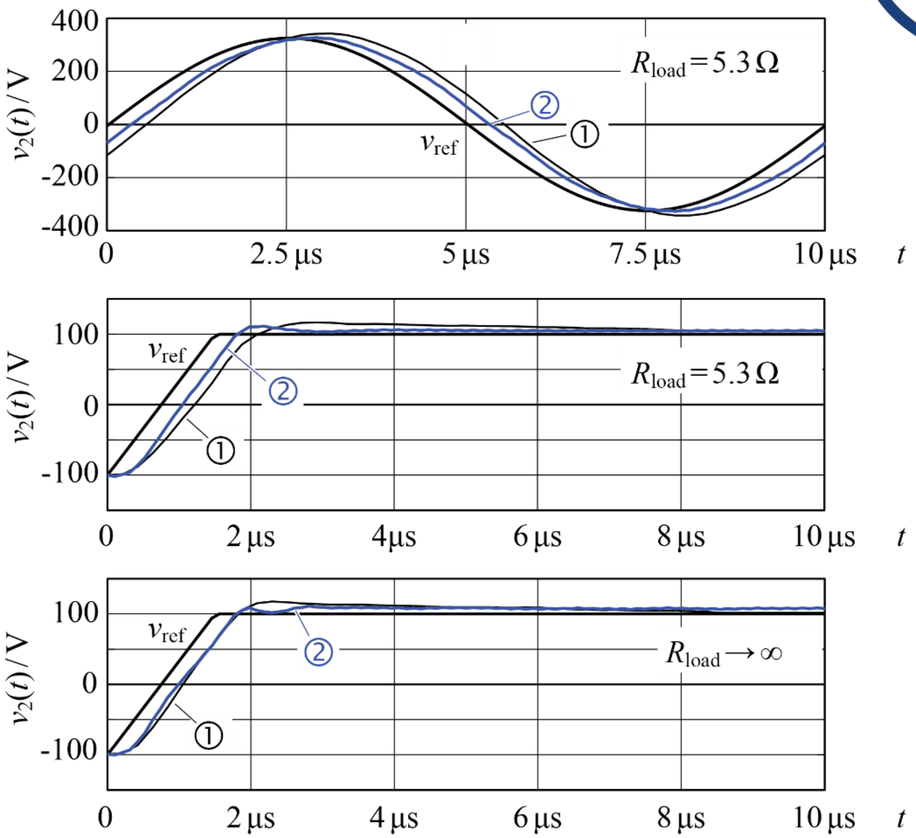
High Bandwidth Closed Loop Control Concepts

Output Voltage and Output Current Control

Closed-Loop Voltage Control Concept

- Cascaded current and voltage control
- v_{ref}, i_{load} and inductor voltage feedforward

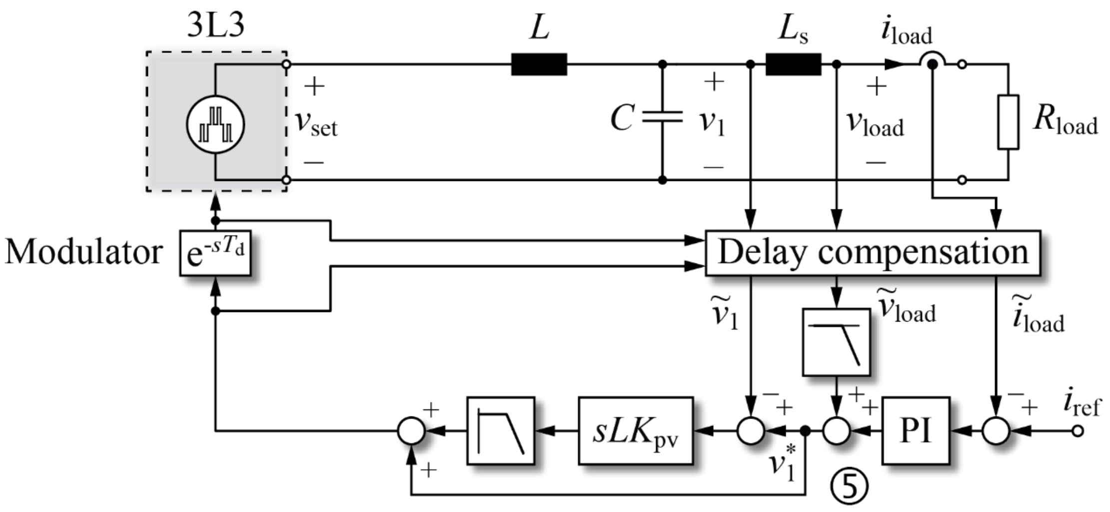


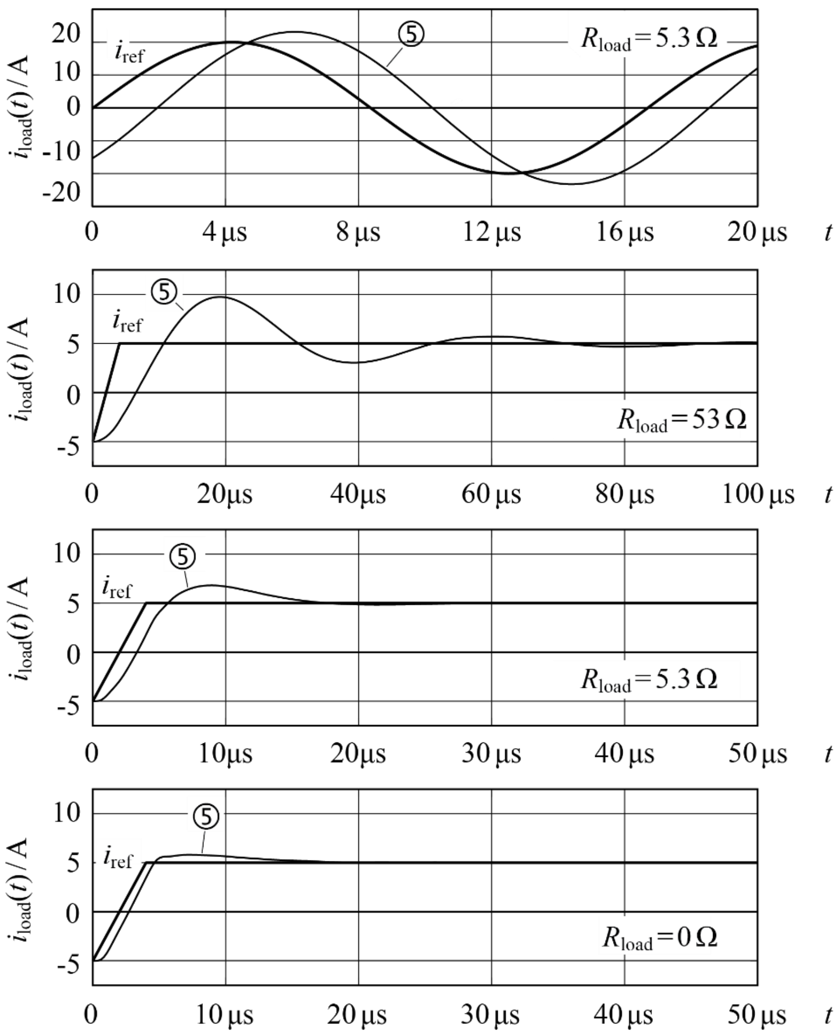


→ Minimal loop delay crucial for ultra-fast control

Closed-Loop Current Control Concept

- Two-loop control structure
- v_L compensation (inner loop)
- v_1 feedforward





→ Minimal loop delay crucial for ultra-fast control

Conclusions / Summary

- Test and verification of Power Electronic Systems

▼ 3L3 UHBPA

- Part of P-HIL test environment
- Topological evaluation
- Hardware demonstrator with 25 kW/dm^3 power density
- 95.8 % efficiency @ 230 V_{rms}, 10 kW, 100 kHz

▼ I-Sensor

- Hall sensor BW extension to > 50 MHz
- Different HF sensors compared
- Superior CMRR
- Compact design

→ Several challenges related to very high switching frequency converters addressed

ETH zürich

Power Electronic Systems Laboratory

Thank you!

Karlsruher Institut für Technologie

► **Slides**

Further Reading:

► P. S. Niklaus, J. W. Kolar, and D. Bortis, “100 kHz Large-Signal Bandwidth GaN-Based 10 kVA Class-D Power Amplifier with 4.8 MHz Switching Frequency,” *IEEE Transactions on Power Electronics*, Vol. 38, No. 2, pp. 2307-2326, February 2023.
DOI: https://doi.org/10.1109/TPEL.2022.3213930

► F. Krismer, V. Behrunani, P. S. Niklaus, and J. W. Kolar, “Optimized Cascaded Controller Design for a 10 kW / 100 kHz Large Signal Bandwidth AC Power Source,” in *Proc. of the IEEE Energy Conversion Congress and Exposition (ECCE USA)*, Detroit, MI, USA, October 11-15, 2020
DOI: https://doi.org/10.1109/ECCE44975.2020.9236149

► P. S. Niklaus, D. Bortis, and J. W. Kolar, “Beyond 50 MHz Bandwidth Extension of Commercial DC-Current Measurement Sensors with Ultra-Compact PCB Integrated Pickup Coils,” *IEEE Transactions on Industry Applications*, Vol. 58, No. 4, pp. 5026-5041, August 2022.
DOI: https://doi.org/10.1109/TIA.2022.3164865