Converter Architectures

UK Centre for Power Electronics Annual Conference

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Overview of the Converter Architecture Project

- Project duration: 1st November 2017 to 31st October 2021.

- WP1 Converter Topology Investigation
- WP2 Passive Components
- WP3 Advanced Control
- WP4 Design Optimisation
- WP5 Demonstrator

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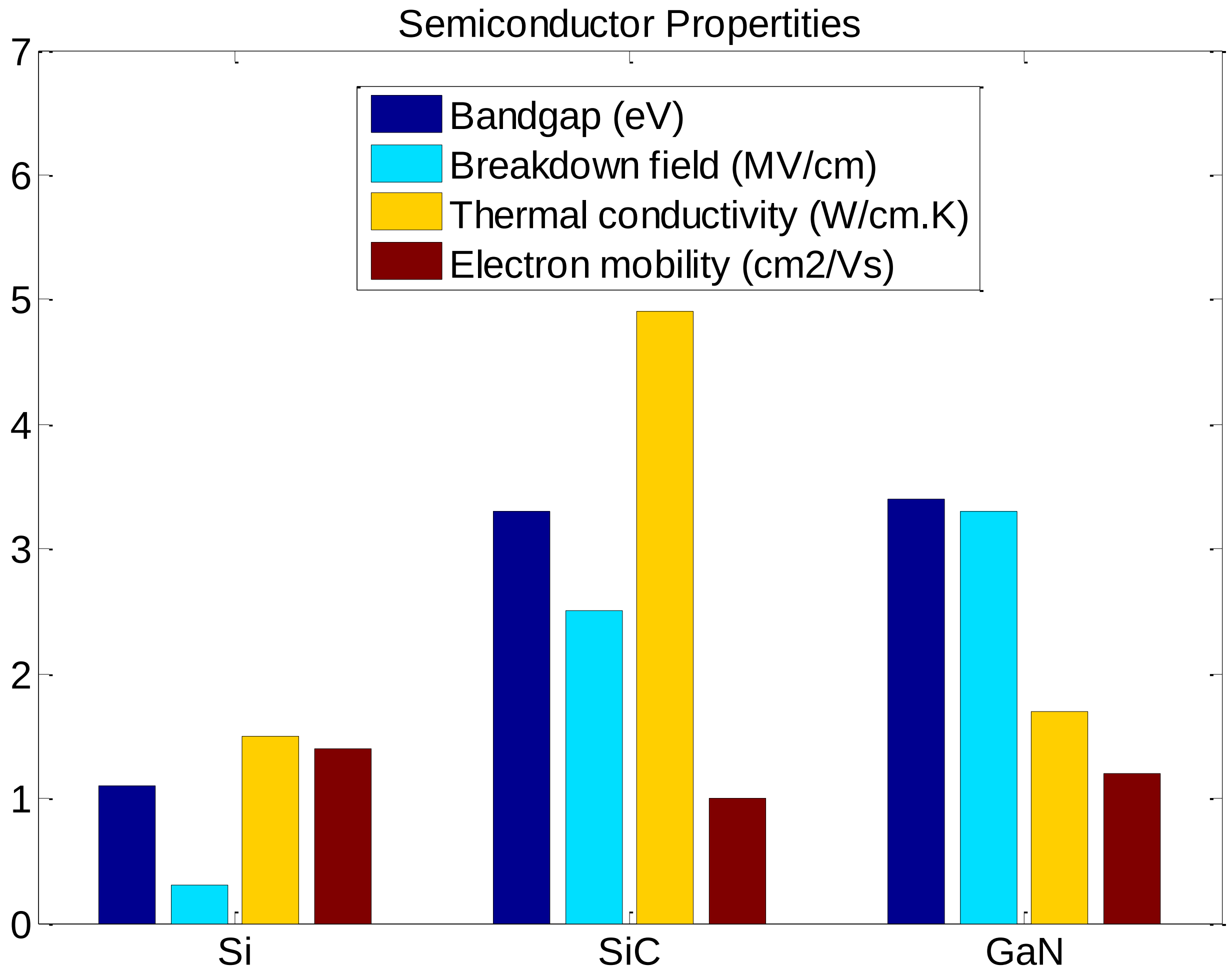
Opportunities: Wide-bandgap Material Properties



Higher

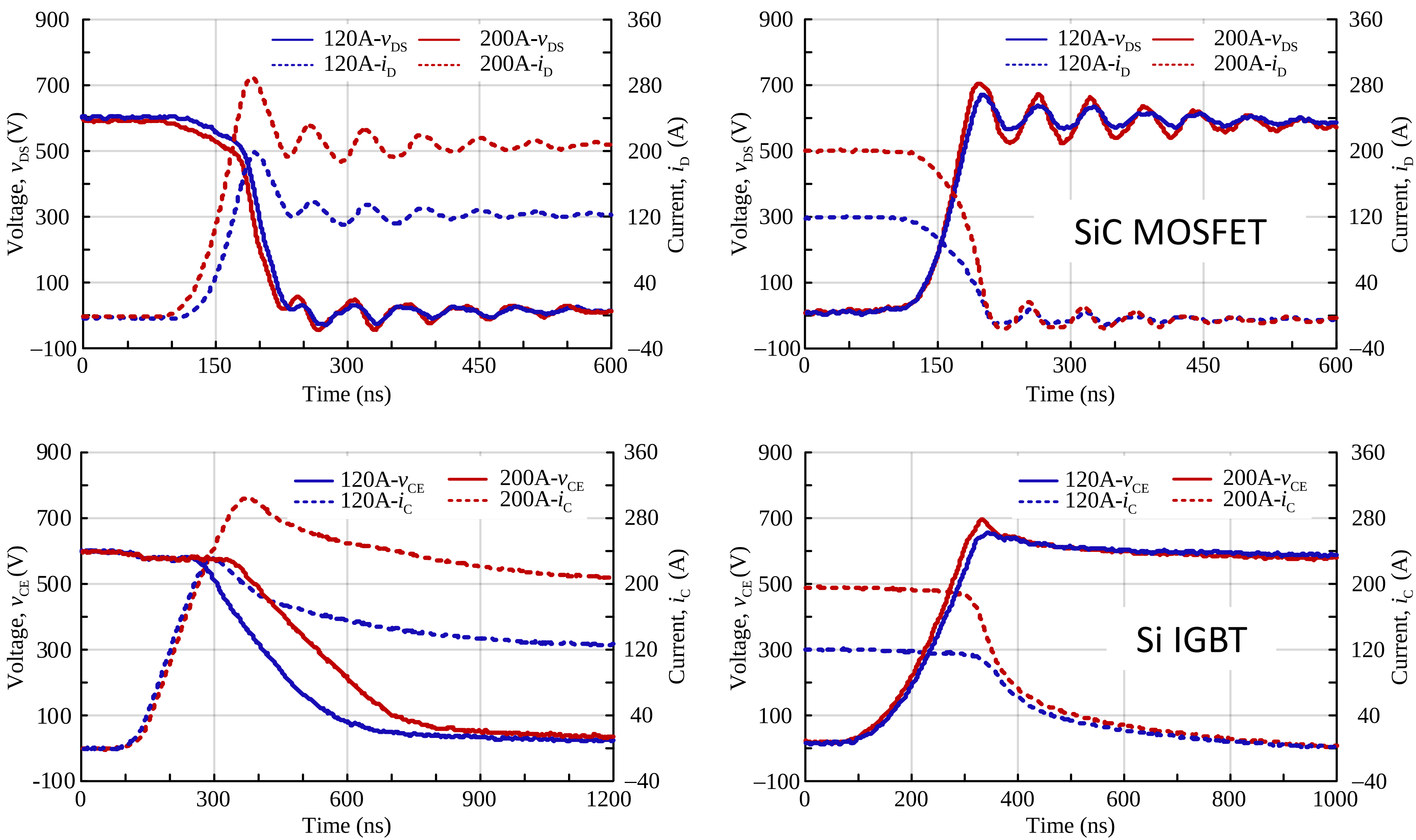
Speed

Voltage

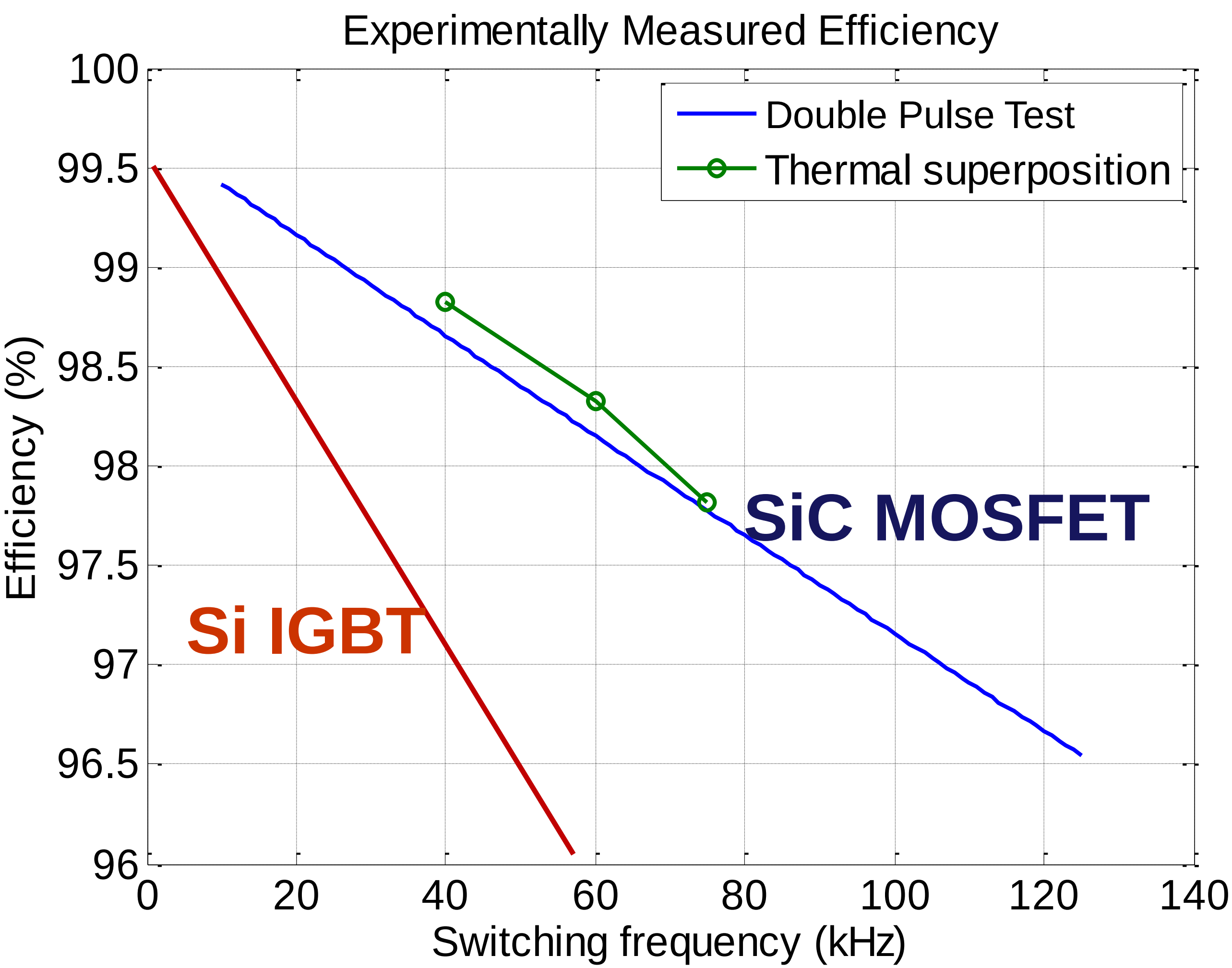
Temperature

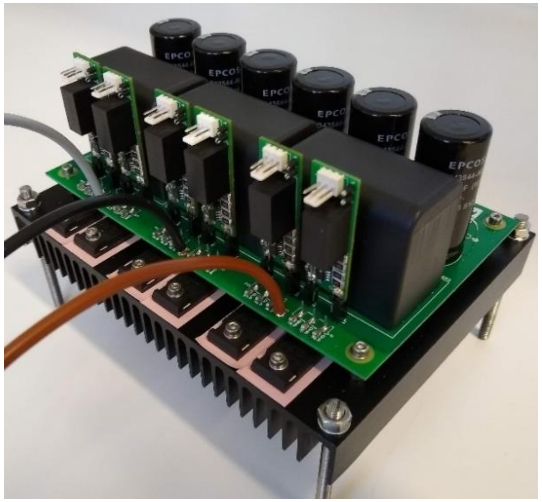
X. Yuan, I. Laird, S. Walder, “Opportunities, Challenges and Potential Solutions in the Application of Fast-Switching Silicon Carbide (SiC) Power Devices and Converters”, *IEEE Transactions on Power Electronics*, vol.36, no.4, pp. 3925-3945, Apr. 2021.

High Power Module (1700V, 300A) Switching



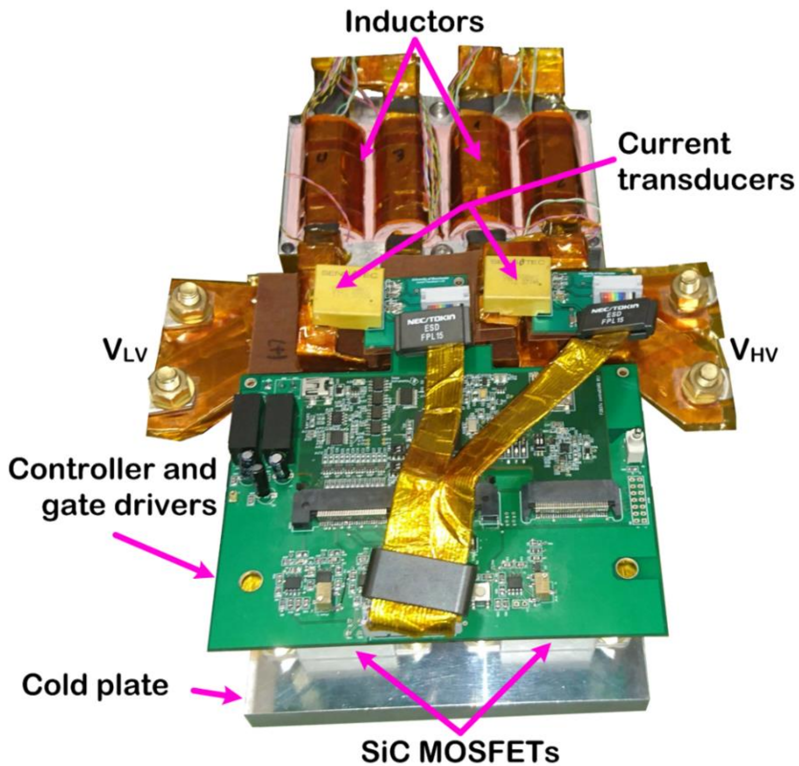
Opportunities: Efficiency Improvement

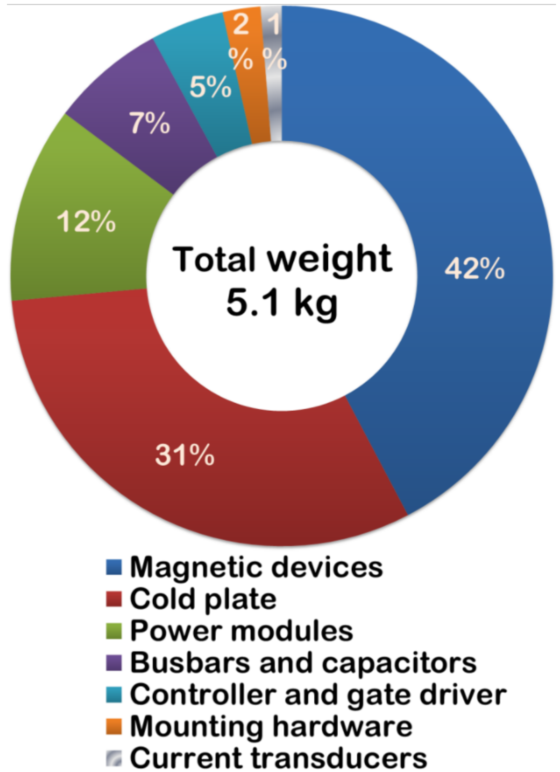




- Reduce harmonic-induced losses
- Reduce filtering components (inductors, dc-link caps)
- High fundamental frequency drives

High Power Density DC/DC Converter

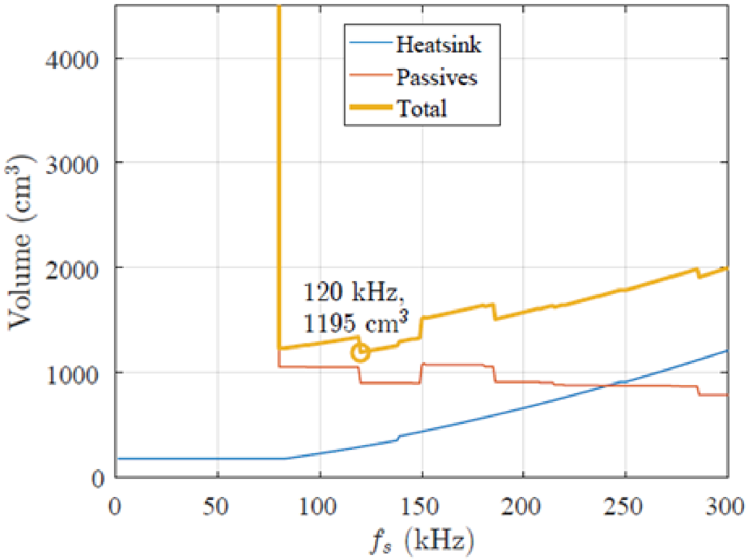




80 kW dual bi-directional interleaved DC/DC converter and its breakdown of weight, 300-750 V, 115 kHz, 5.1 kg, 256×142×70 mm
2.6 L, 31.5 kW/L ,15.7 kW/kg

G. Lopez, J. Scoltock, Y. Wang, I. Laird, X. Yuan, A. Forsyth, "Power-dense Bi-directional DC-DC Converters with High Performance Inductors", *IEEE Transactions on Vehicular Technology*, vol.68, no.12, pp. 11439-11448, Dec. 2019.

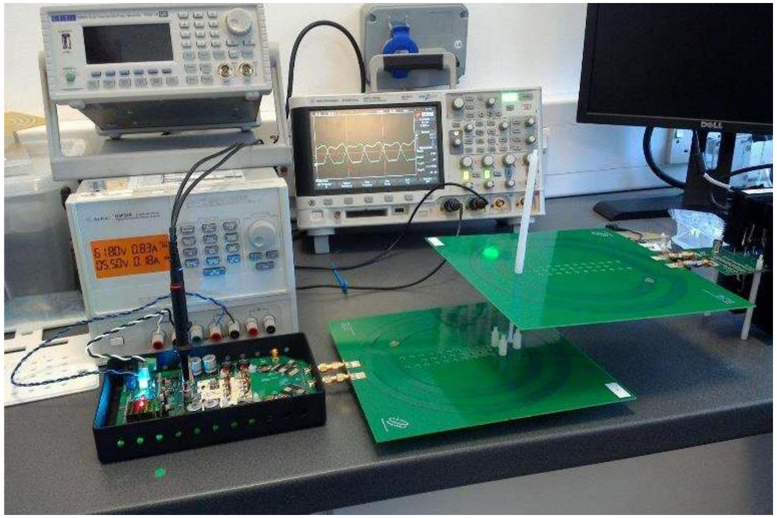
High Temperature SiC BJT Converter

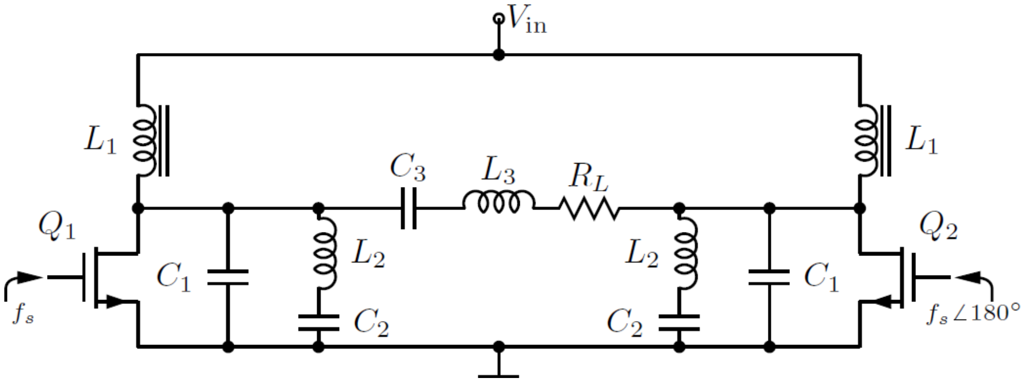


A 5kW 'high-temperature' (180°C junction temperature) SiC BJT based three-phase converter optimised holistically using a proposed design optimisation tool (EMI and line filters are not shown here).

I. Laird, X. Yuan, B. Jin, N. McNeill, "High Temperature Design Optimization of DC/AC Power Converters Using SiC BJTs", in Proc. IEEE ECCE'18 Conf., pp.1-7, Sept. 2018.

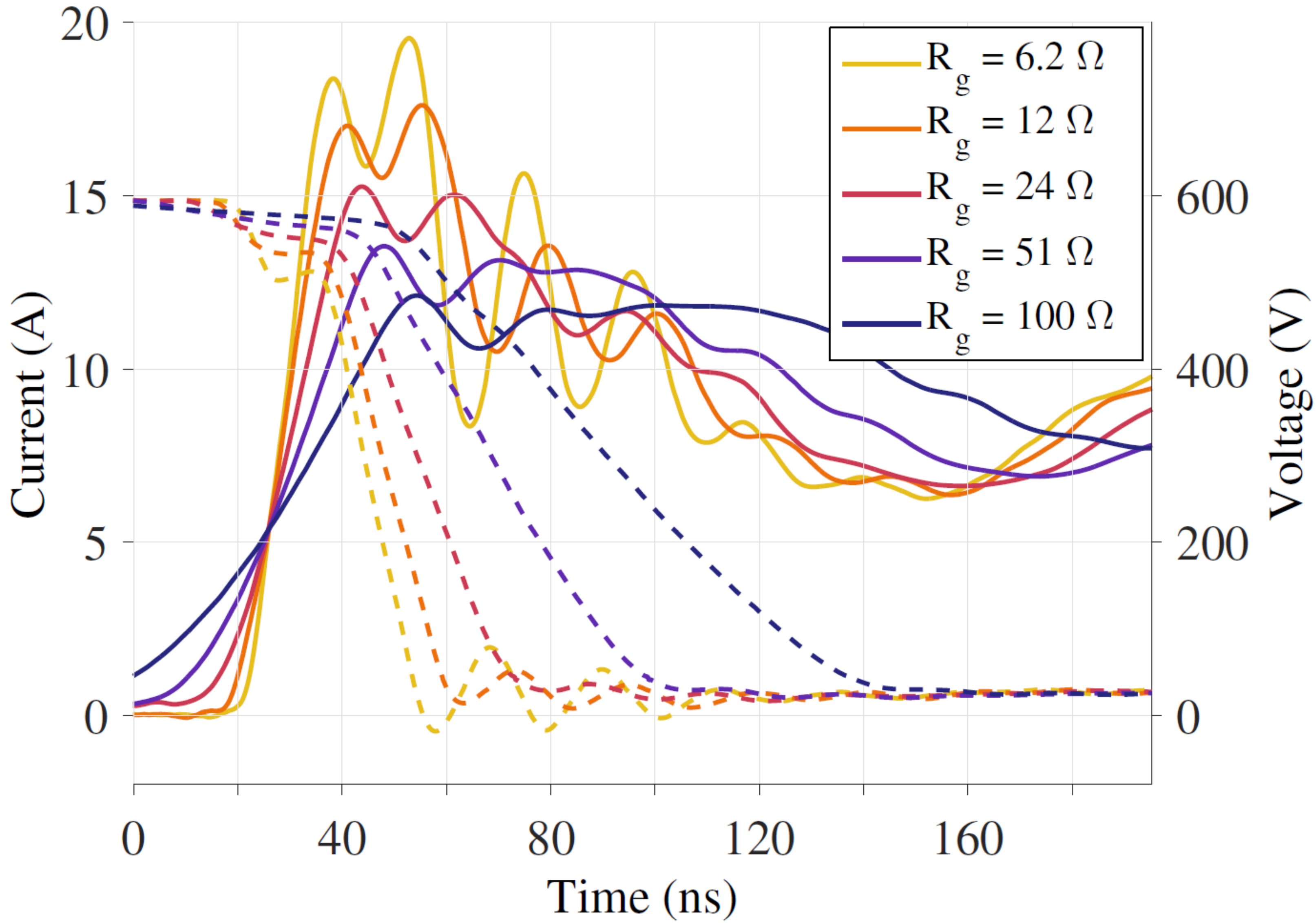
Class EF Push Pull Inverter, 13.56MHz, 500W



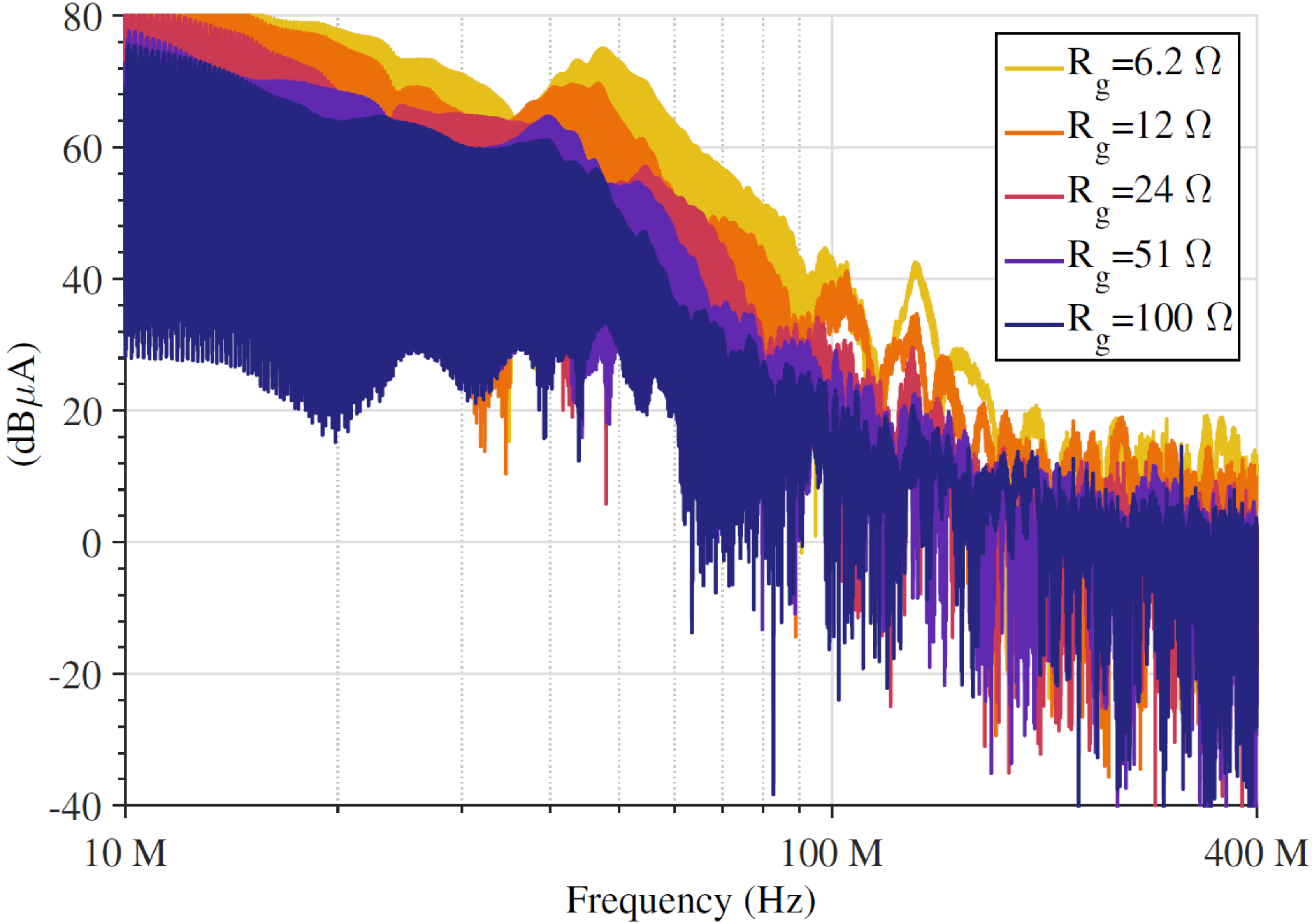


Wireless Power Transfer

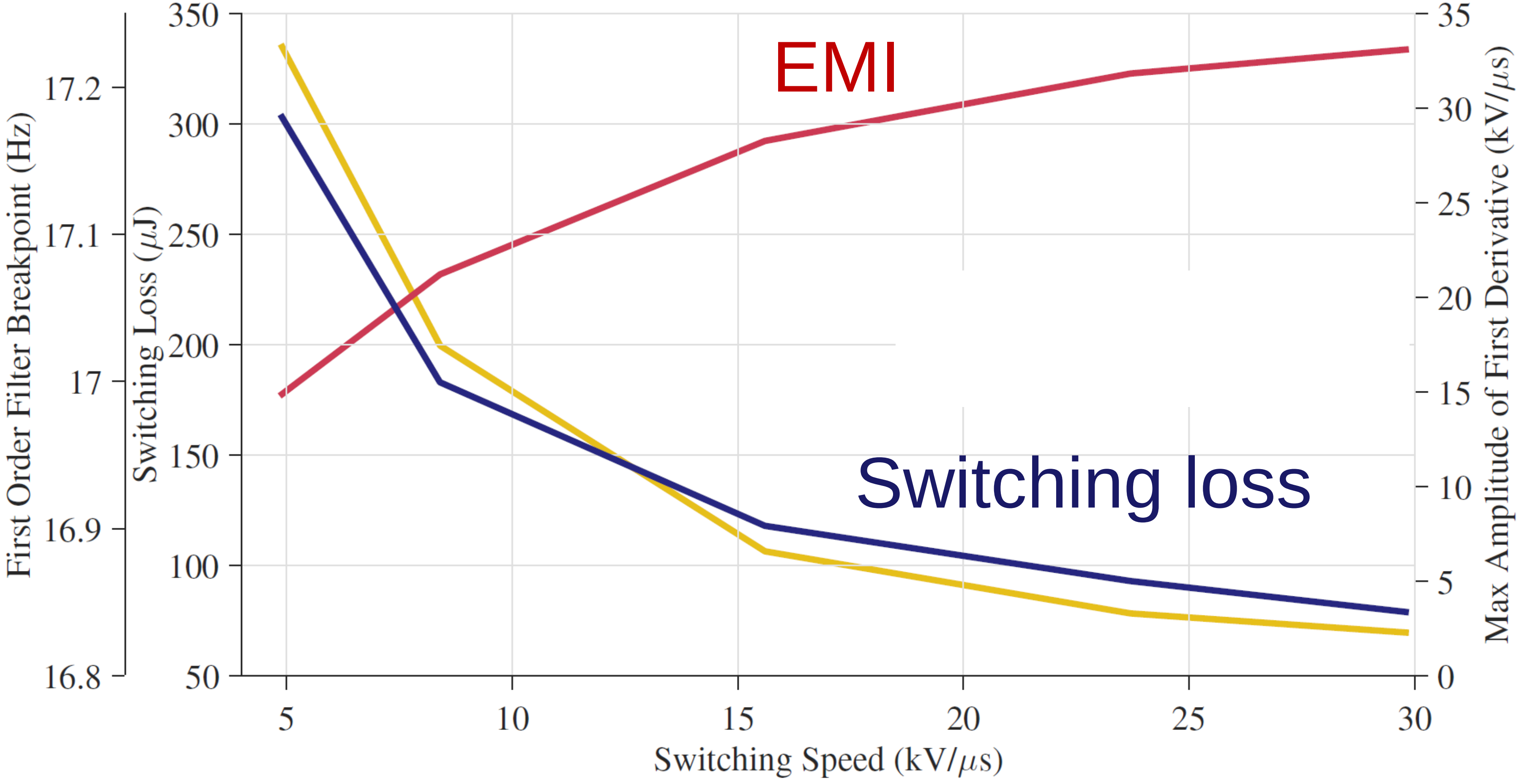
Challenges with High Switching Speed (high dv/dt)
Overshoot, Oscillation, Losses, Cross-talk



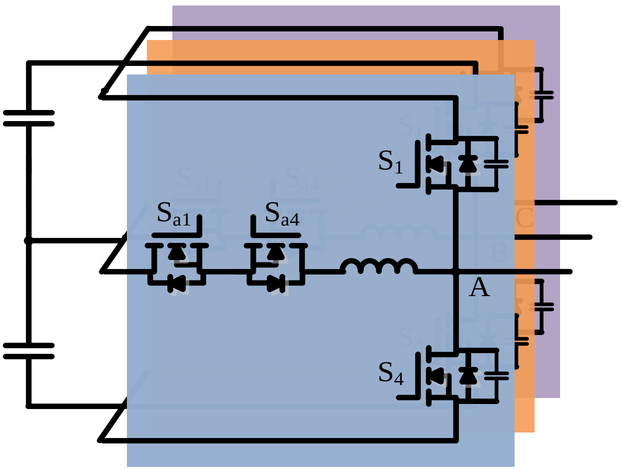
Challenges: Increased Level of EMI

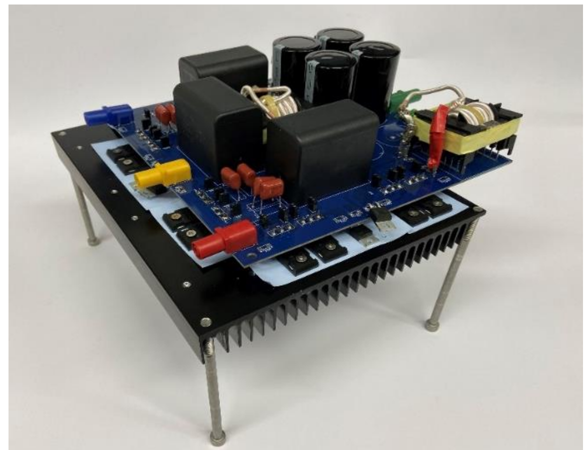


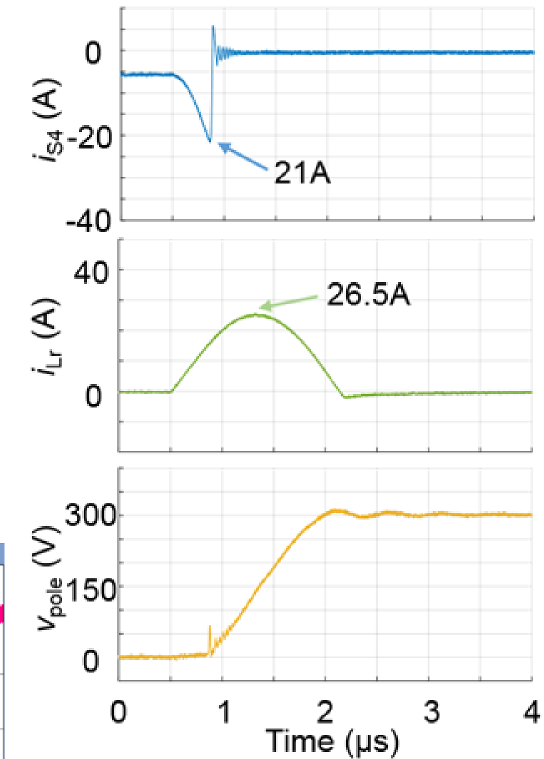
Challenges: Trade-off of EMI and Switching Loss

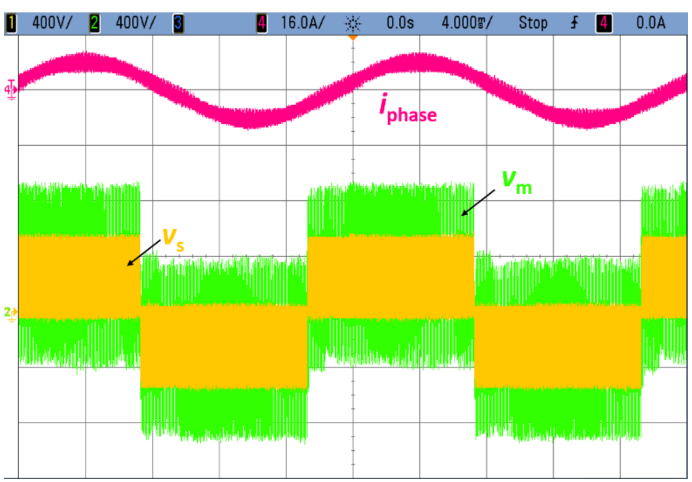


Potential Solutions: Soft-switching

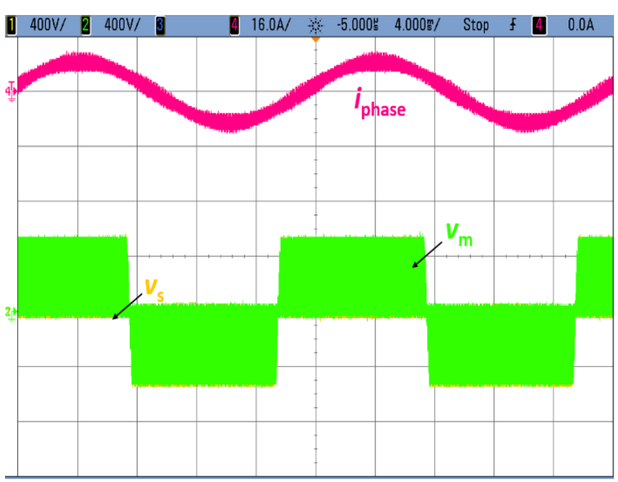








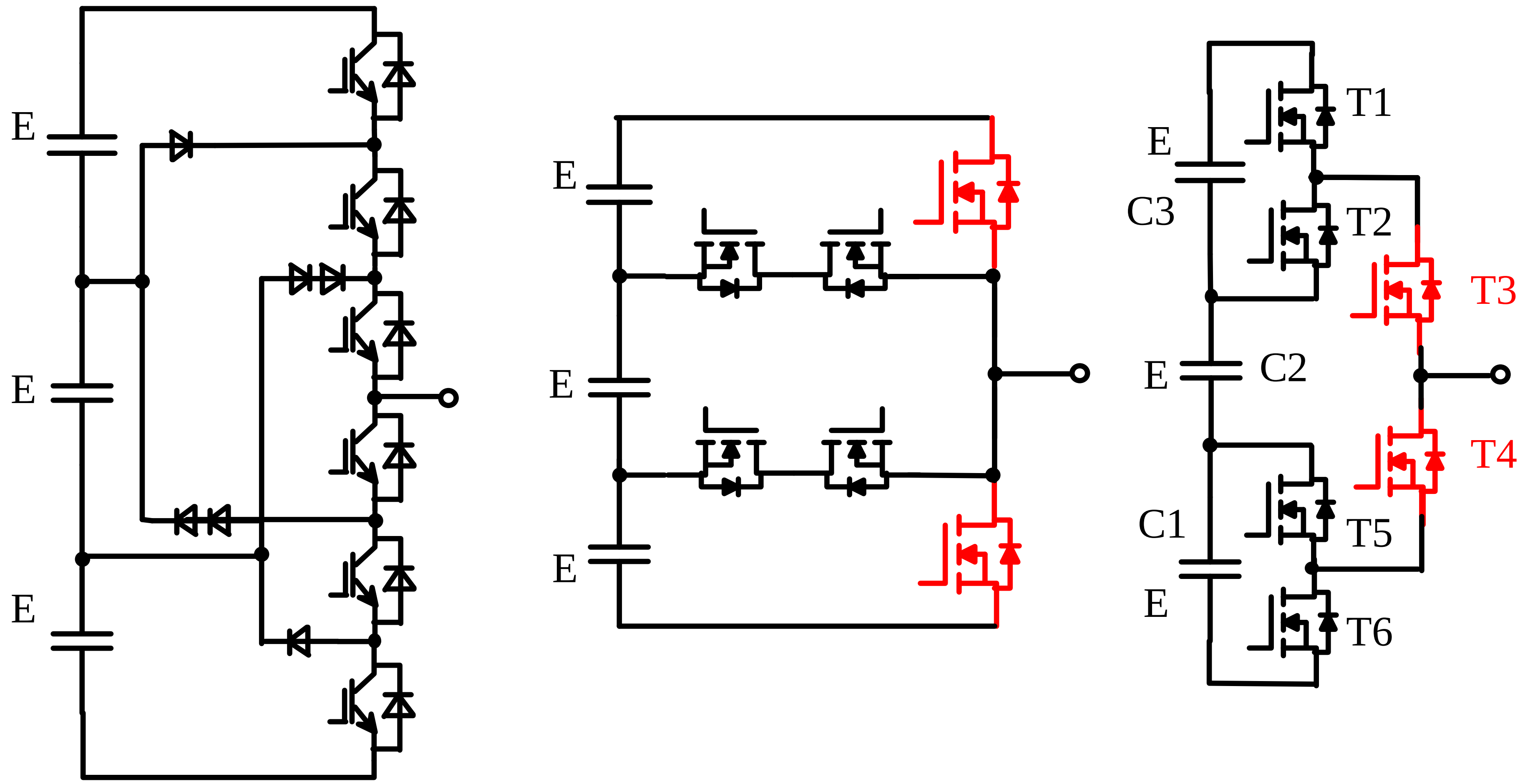
Hard switching
$t_r = t_f \approx 50ns$



Soft switching
$t_r = t_f \approx 200\text{ns}$

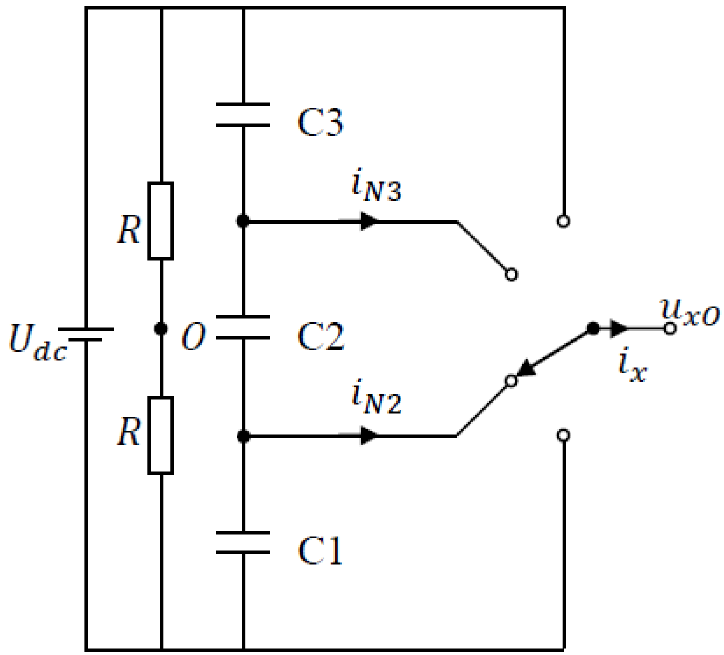
WBG devices can achieve an ideal soft-switching operation with mitigated dv/dt

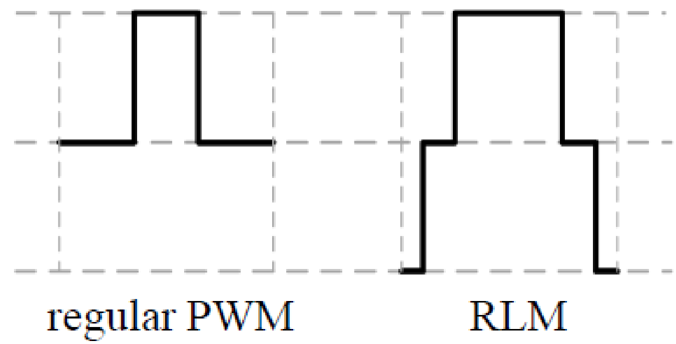
Great Opportunity for WBG Device based Simplified Multilevel Converter Topologies

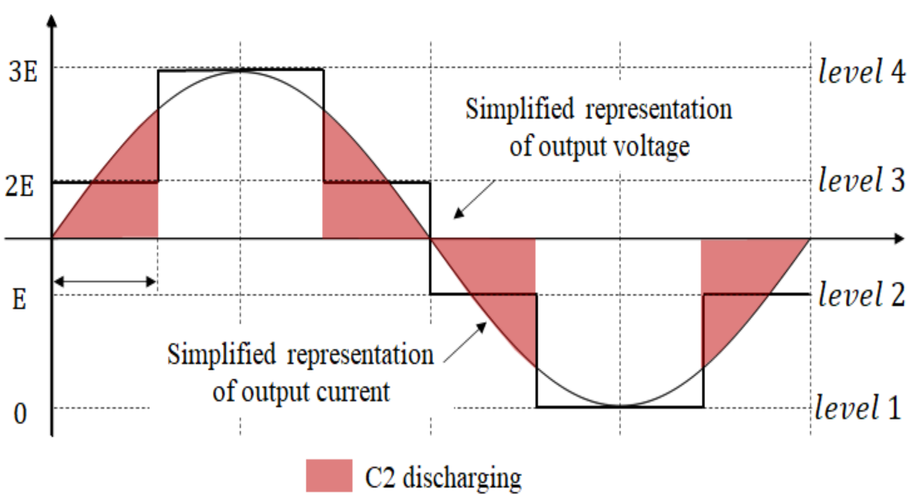


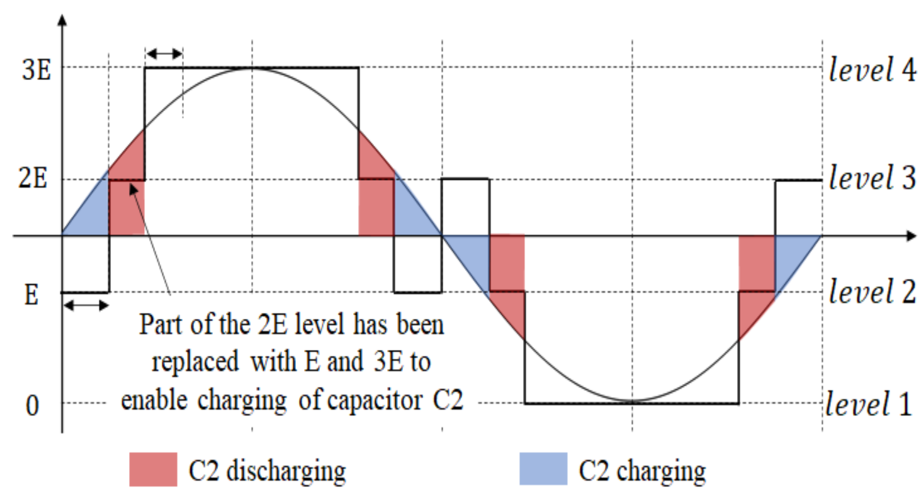
X. Yuan, J. Wang, I. Laird, W. Zhou, "Wide-bandgap Device Enabled Multilevel Converters with Simplified Structures and Capacitor Voltage Balancing Capability", *IEEE Open Journal of Power Electronics*, July 2021.

Redundant Level Modulation for Multilevel Converters





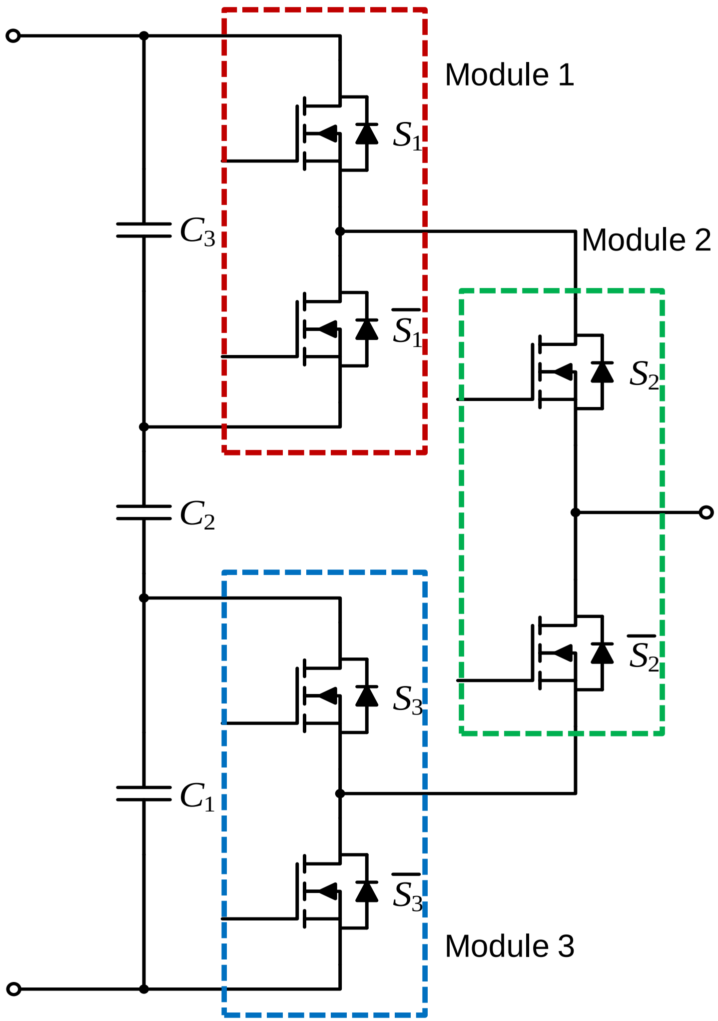


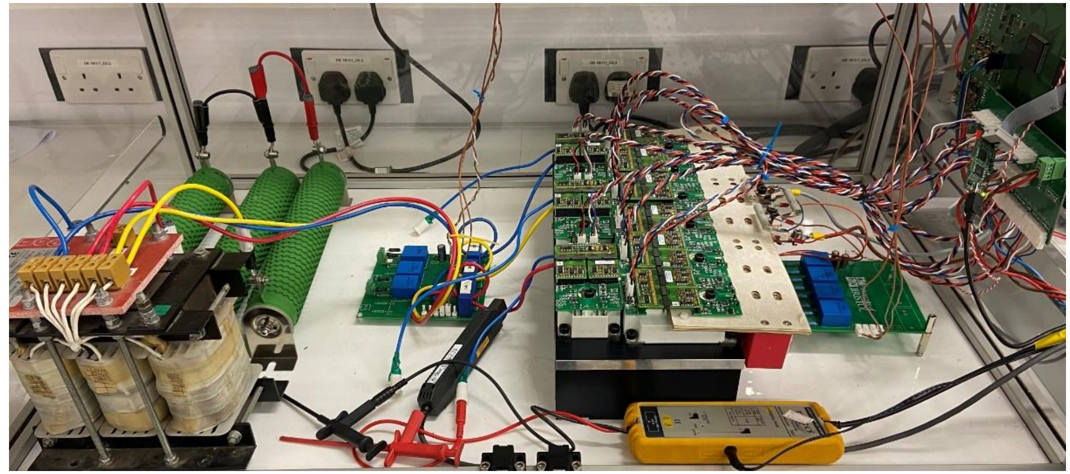


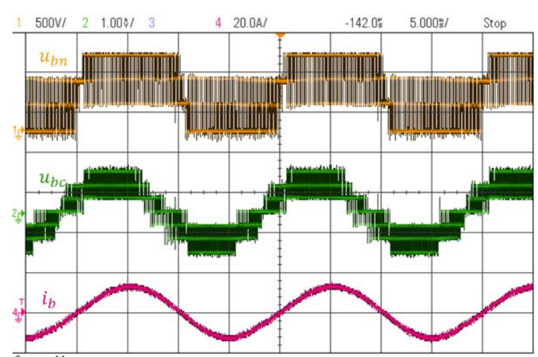
With conventional modulation

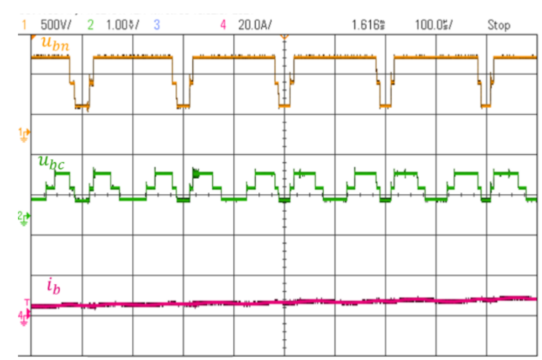
With redundant level modulation

Simplified Multilevel Topologies with SiC MOSFETs



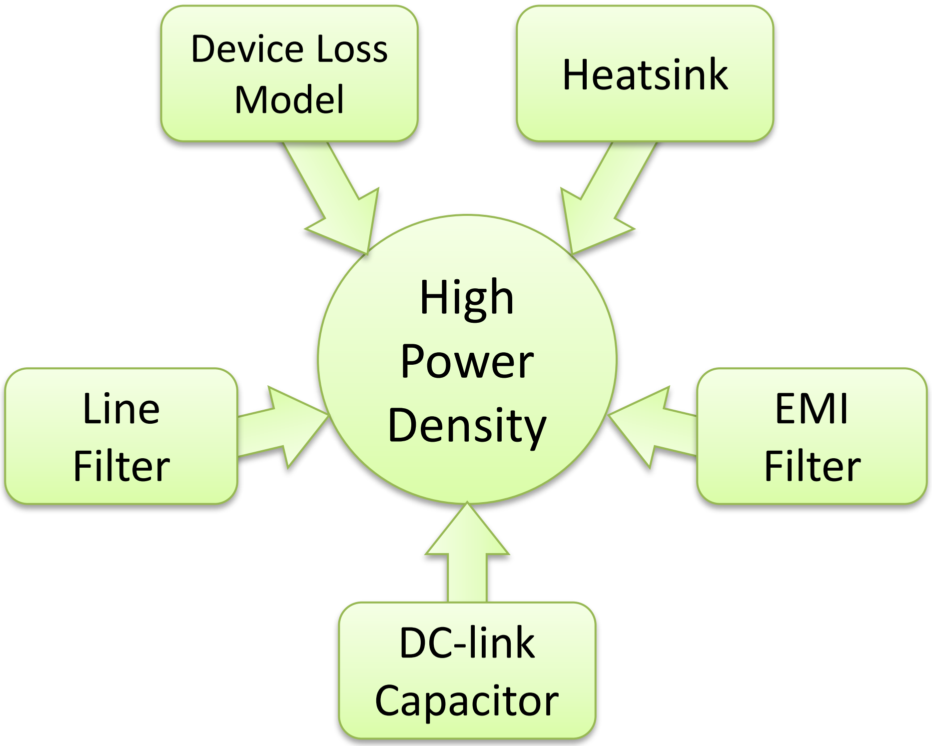


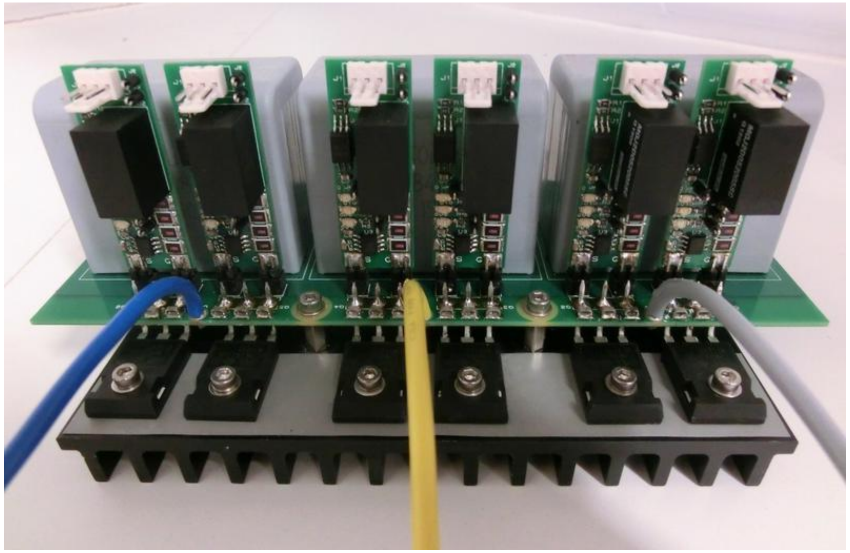




- 1kV dc voltage, 100kW
- Conduction loss = 456 W
- Switching loss = 150.6 W @ fsw = 5 kHz; 99.4% efficiency. 98% @ fsw = 50 kHz

Holistic Optimisation of Wide-bandgap Converters

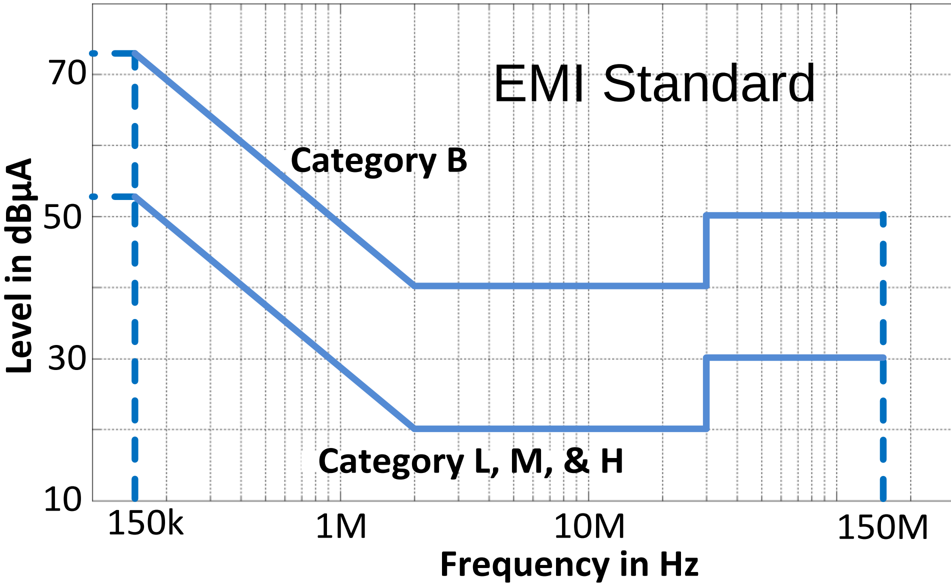




5kW, three-phase SiC DC/AC converter

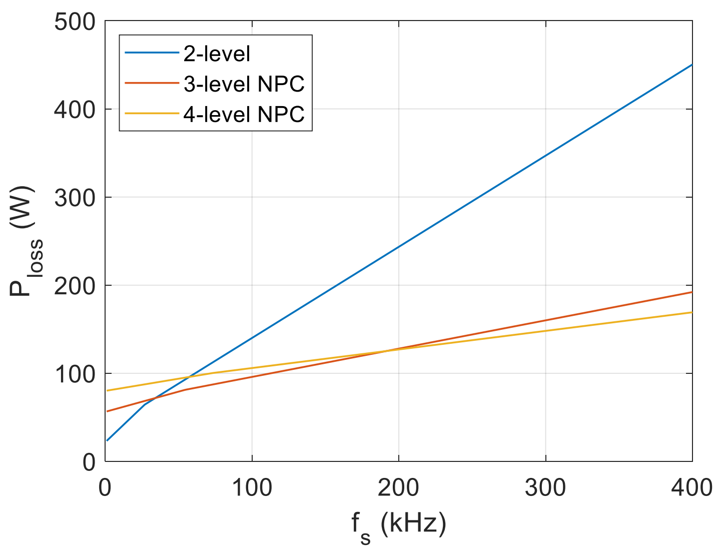
A holistic design optimisation tool has been developed.

The developed SiC converters have been used by several companies and universities.

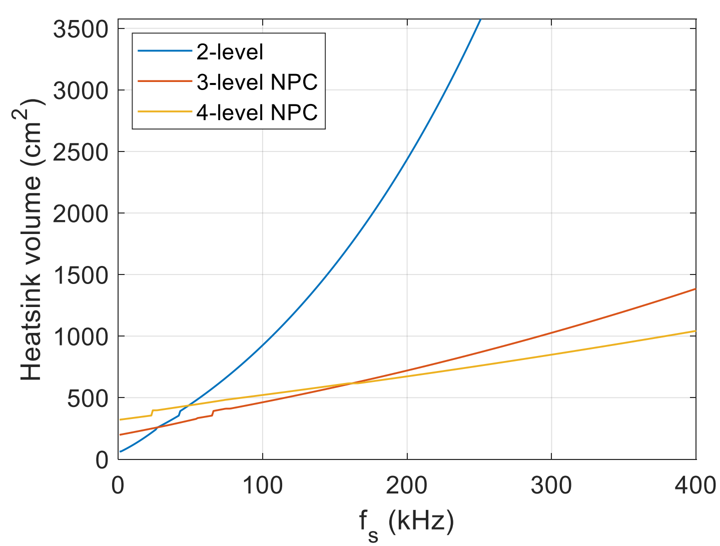


Multi-Level Design Tool

- Tool simulates a range of switching frequencies, calculating power losses and its impact on component volumes (switching devices, cooling system, filters etc.)
- Facilitates side-by-side comparison of converters with differing
  - topologies
  - number of levels
  - device technology

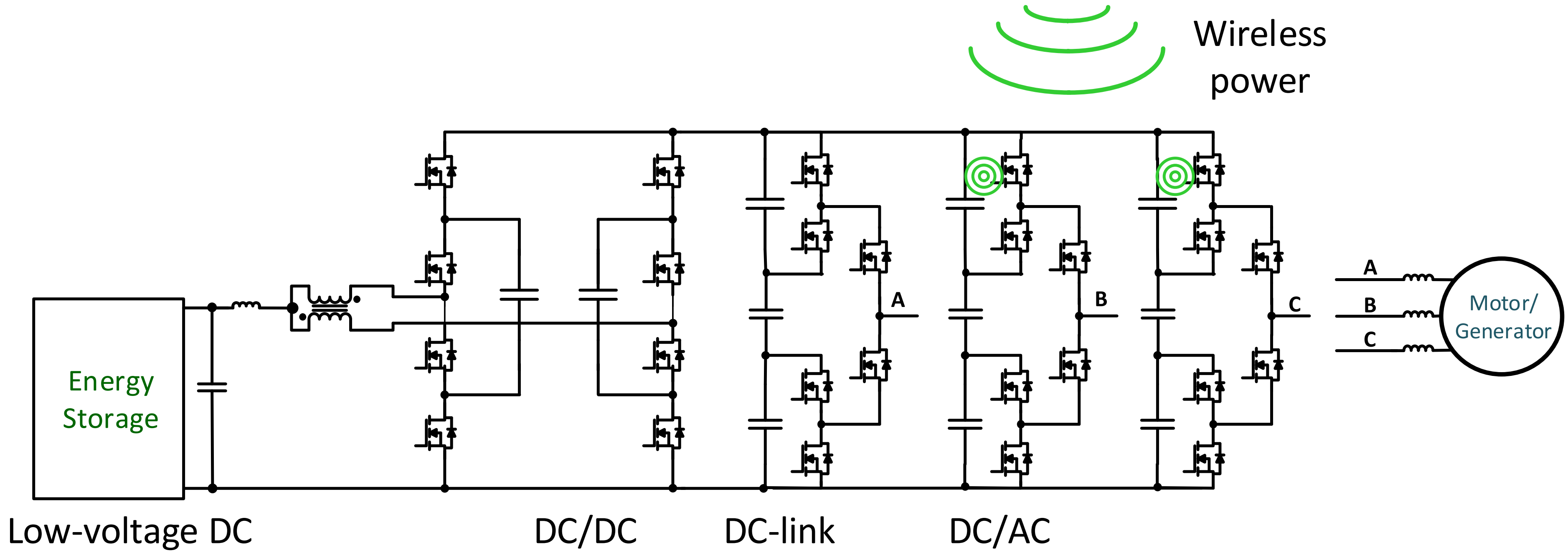


Switching device P_{loss} vs Switching frequency

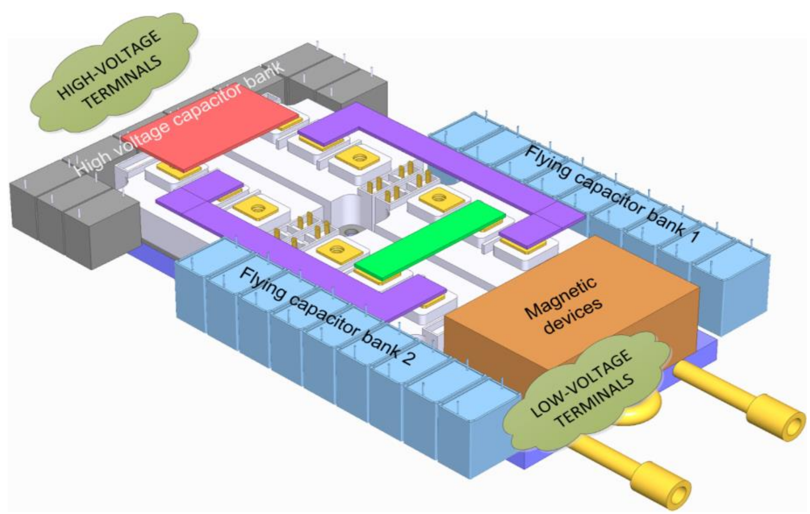


Heatsink volume vs Switching frequency

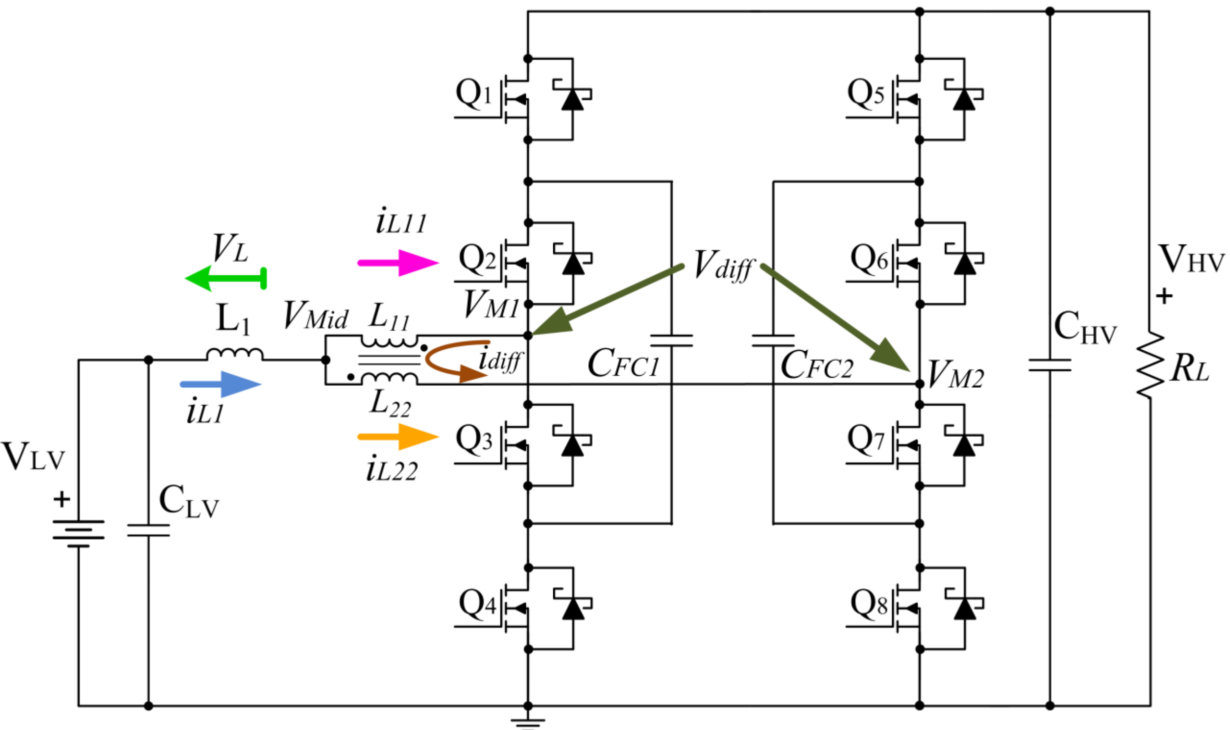
Project Demonstrator



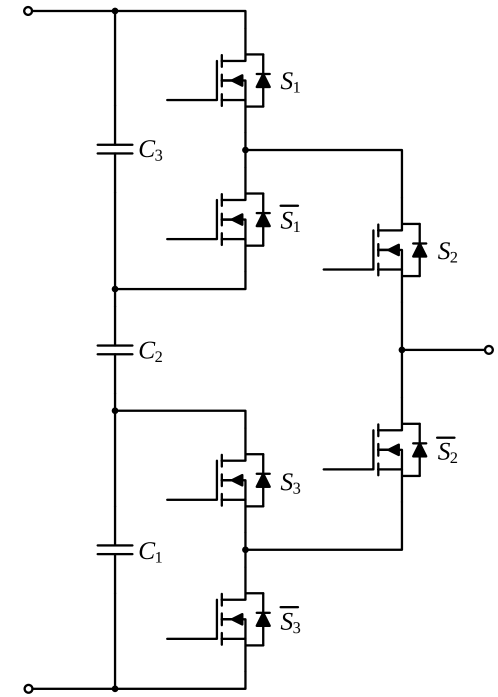
Rated at 1200V, 100kW



High Power DC/DC and DC/AC Converters

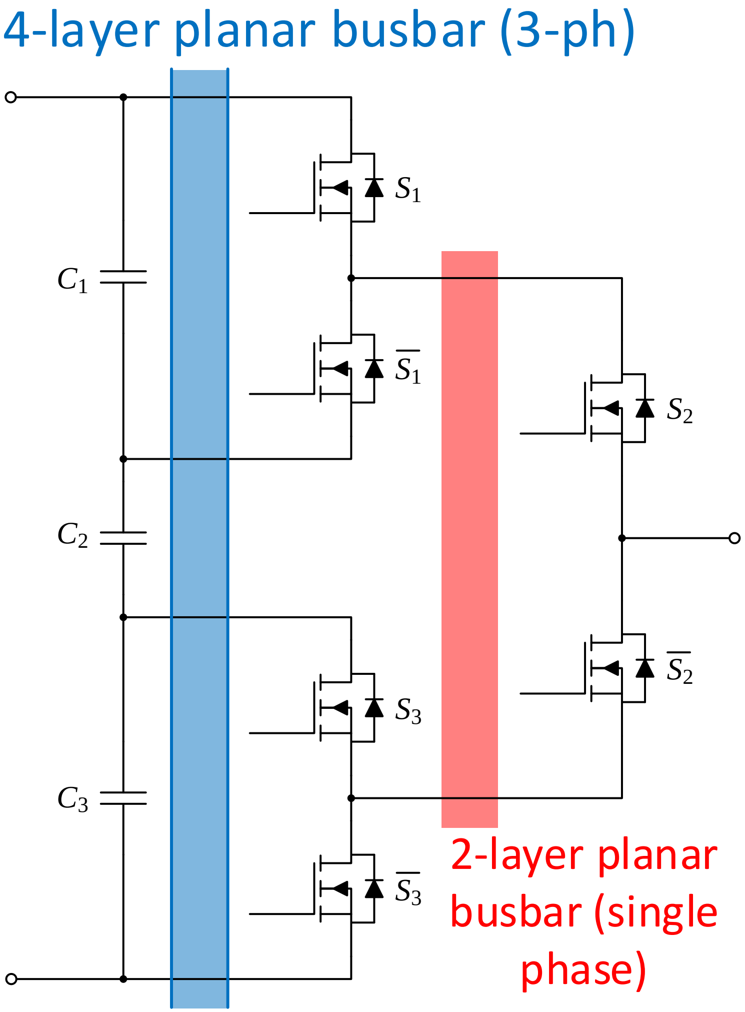


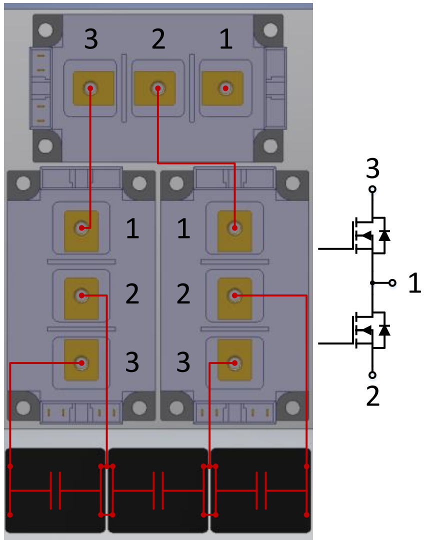
Three-level flying capacitor based dc/dc converter

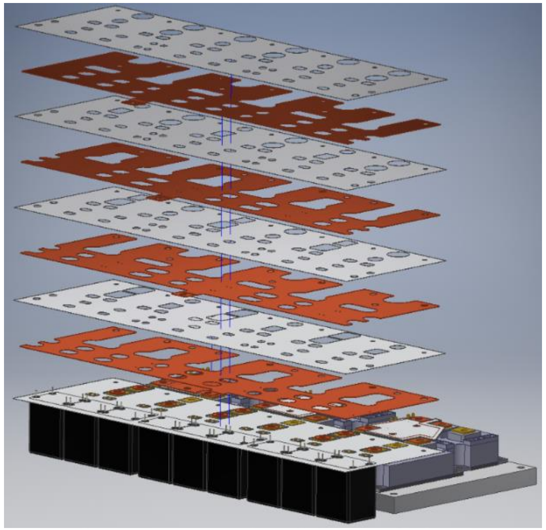


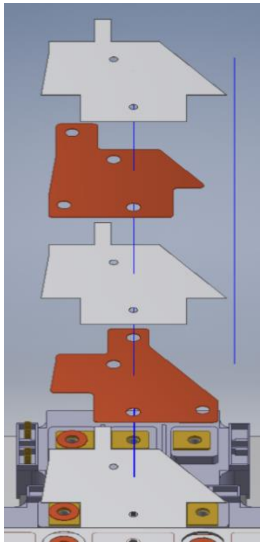
Four-level dc/ac converter

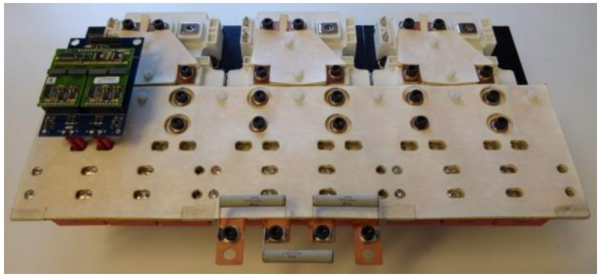
Four-level DC/AC Converter





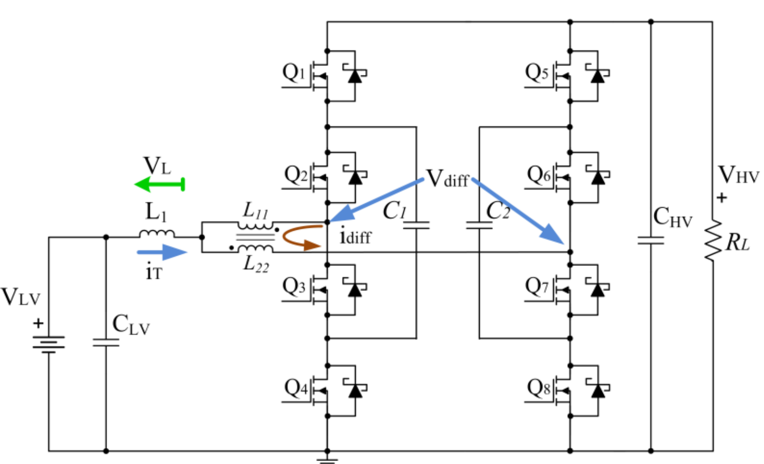


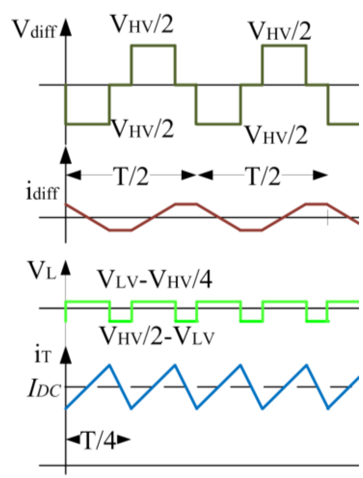


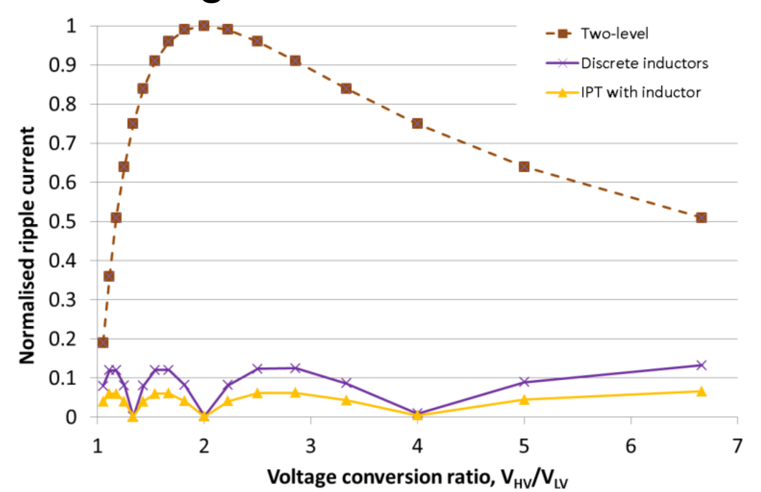


High Performance DC-DC Conversion

- Aiming to increase voltage and power and reduce overall size
  - Interleaved (90º) flying capacitor legs
  - Device voltages $V_{HV}/2$
  - Leg output voltages at $2f_{switching}$ with reduced voltage steps
  - With two separate inductors the overall input ripple is almost 10x smaller compared with a single two level converter
  - Interphase transformer and one inductor reduces ripple by almost 20x and inductor operates at $4f_{switching}$ → small size
  - Active balancing of phases and capacitor voltages needed

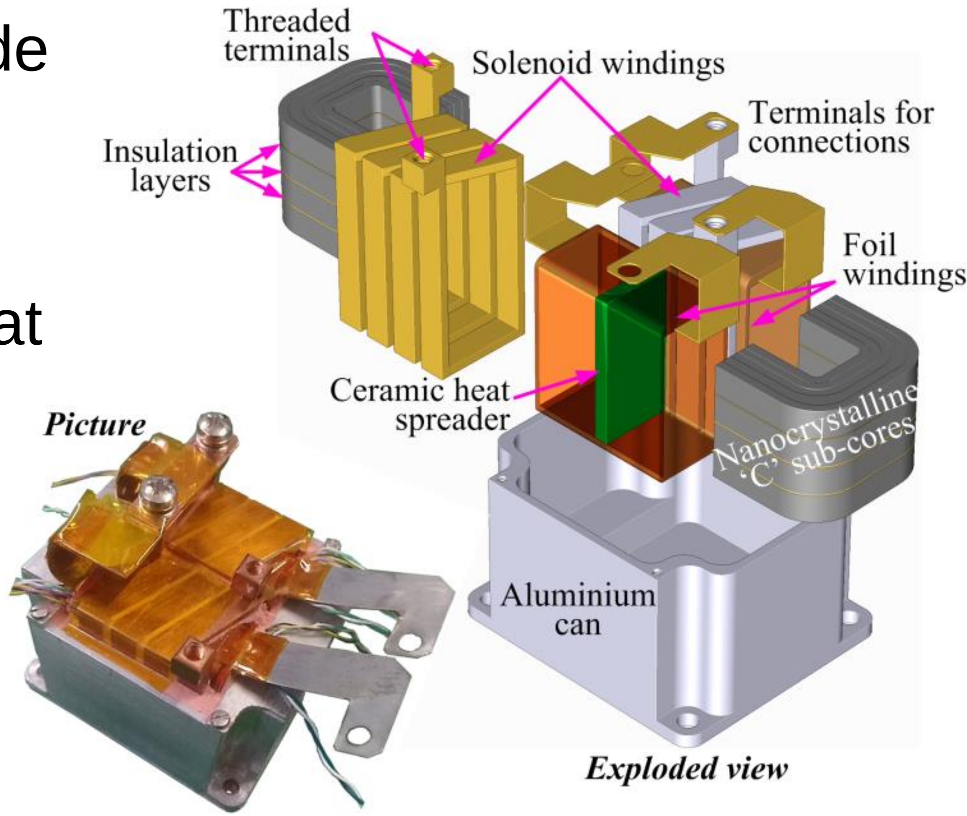






Reducing the size of DC inductors

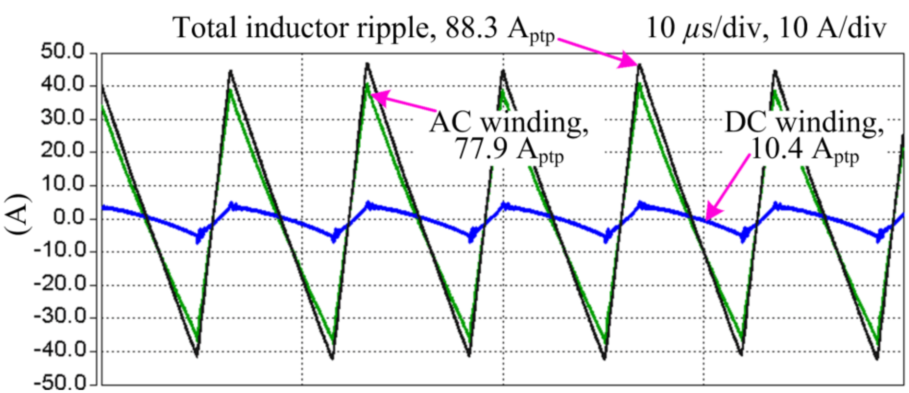
- To reduce gap losses in tape-wound, nano-crystalline cores, stack smaller cores side-by-side
  - 50% reduction with three cores
- To improve heat flow in potted components place ceramic heat spreaders in the airgaps
- To reduce copper losses combine solenoidal winding (low DC resistance) with foil winding (low AC resistance)

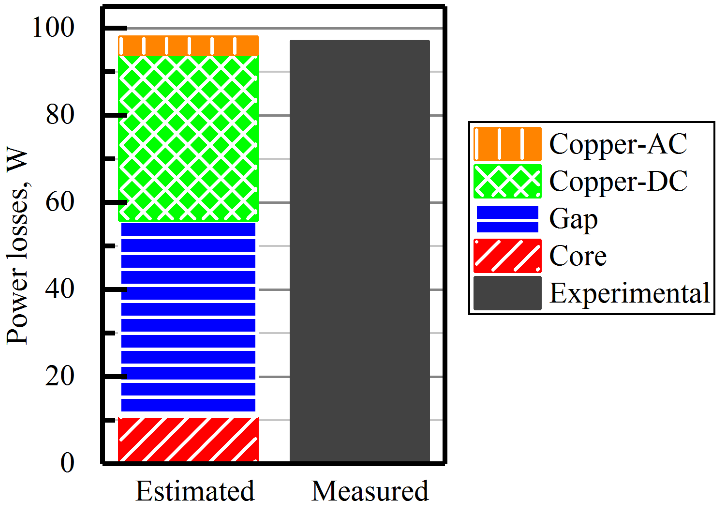


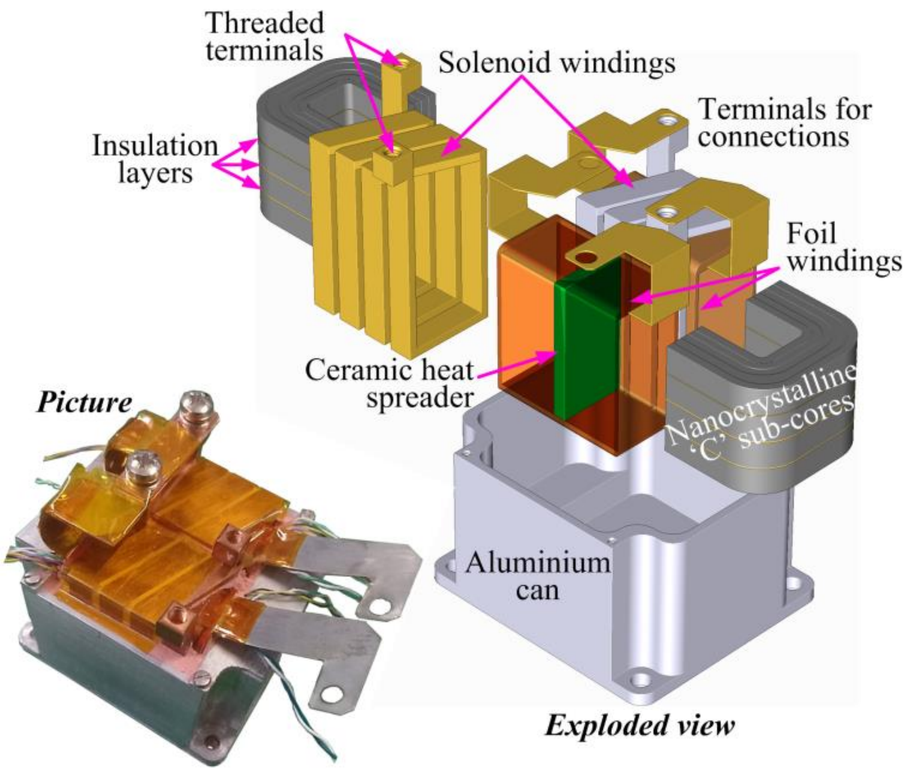
G. Calderon-Lopez, R. Todd, A. Forsyth, J. Wang, X. Yuan, S. Aldhaher, C. H. Kwan, D. Yates, P. Mitcheson, "**Towards Lightweight Magnetic Components for Converters with Wide-bandgap Devices**", in *Proc. IEEE ECCE-Asia (IPEMC)'20 Conf.*, pp. 1-6, November, 2020.

Reducing the size of DC inductors

- 50% weight and volume reduction in a 5µH, 200 A, 150 kHz inductor



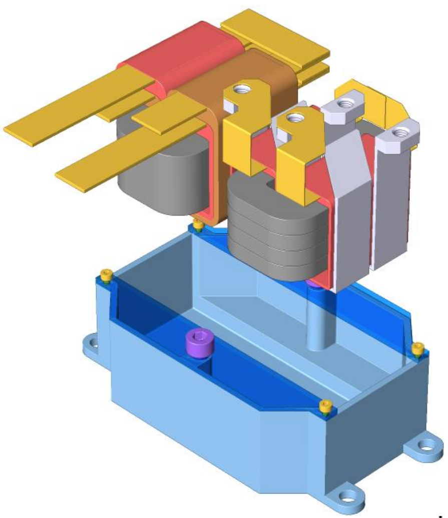


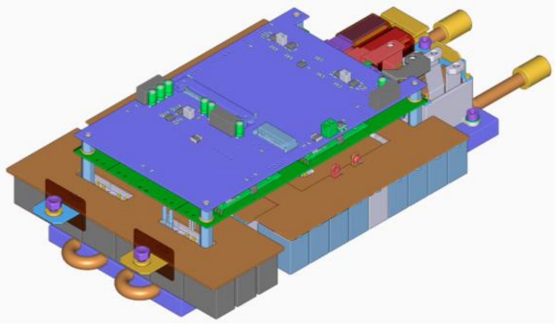


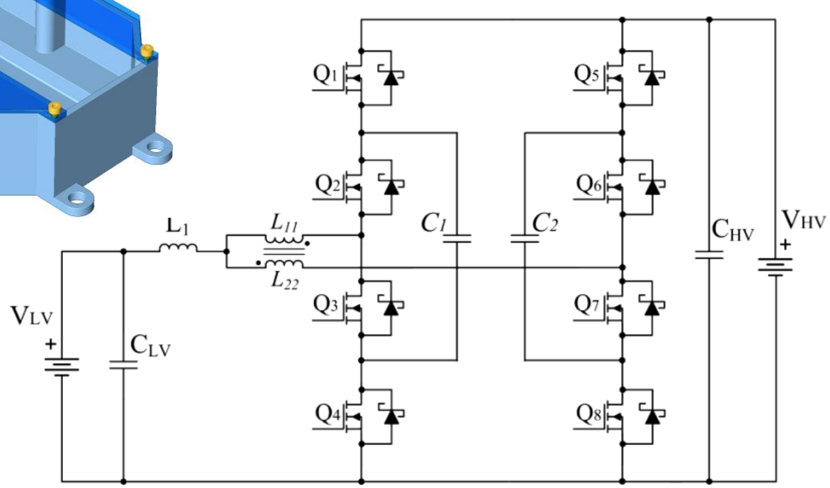
Measured AC current sharing, and estimated and measured losses: I_{DC}= 160 A, ΔI_L= 88.3 A, ~148 kHz.

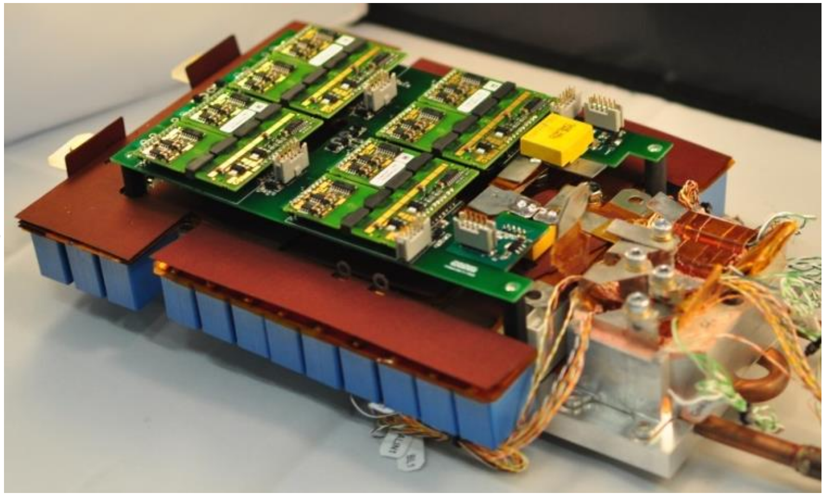
Demonstrator

- 100 kW, 1200 V DC-DC converter demonstrator
  - SiC MOSFETs, 80 kHz switching, 320 kHz inductor ripple
  - Overall weight 4.2 kg, (potted magnetics 0.7 kg)
  - 23.8 kW/kg and 31.8 kW/litre
  - Efficiency 96.8%









HF-IPT to power gate drives

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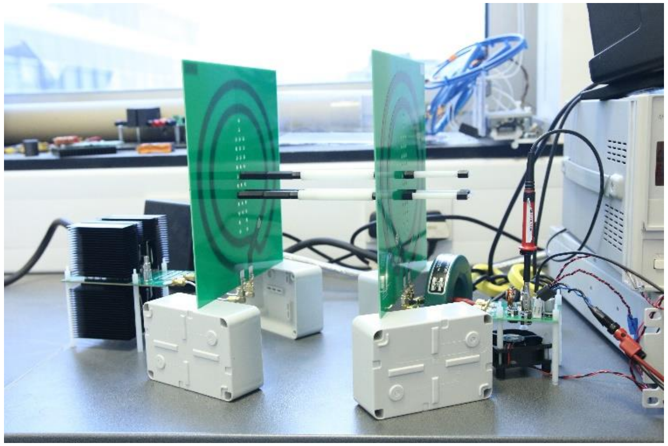
Underpinning Research



- Wireless power is extended from work in Tranche 1
  - We demonstrated a one-to-one system with 80%+ efficiency
  - Constant current transmitter gives a starting point for multiple receivers

- Advantages of using high-frequency inductive power transfer systems to power floating gate drives:
  - Provides very large isolation for applications such as HVDC
  - Minimises the mass of the magnetic components
  - Multiple receivers at very different voltage levels can be powered from a single power source
  - Common-mode transient immunity

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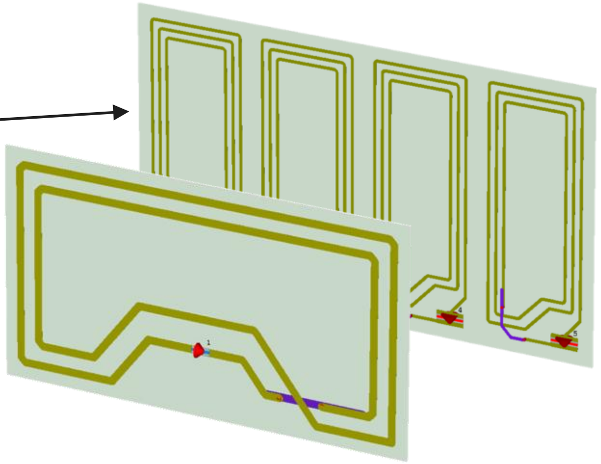
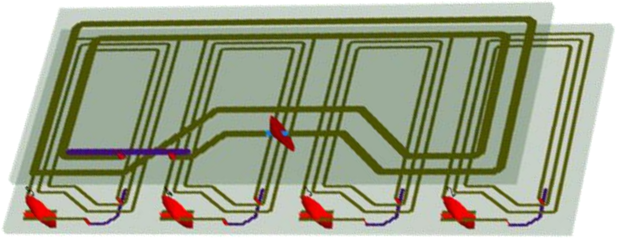
HF-IPT to power gate drives

- Design 1
  - 4 identical receiver coils
  - 1 transmitter coil
  - Metal shield around system
  - Distance between TX and RX PCBs is varied from 5mm to 50mm in steps of 5mm
  - FR4: Thickness of 1.6mm
  - Copper: 35 um (1oz)
  - CST simulations of the link one to four link





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System optimisation

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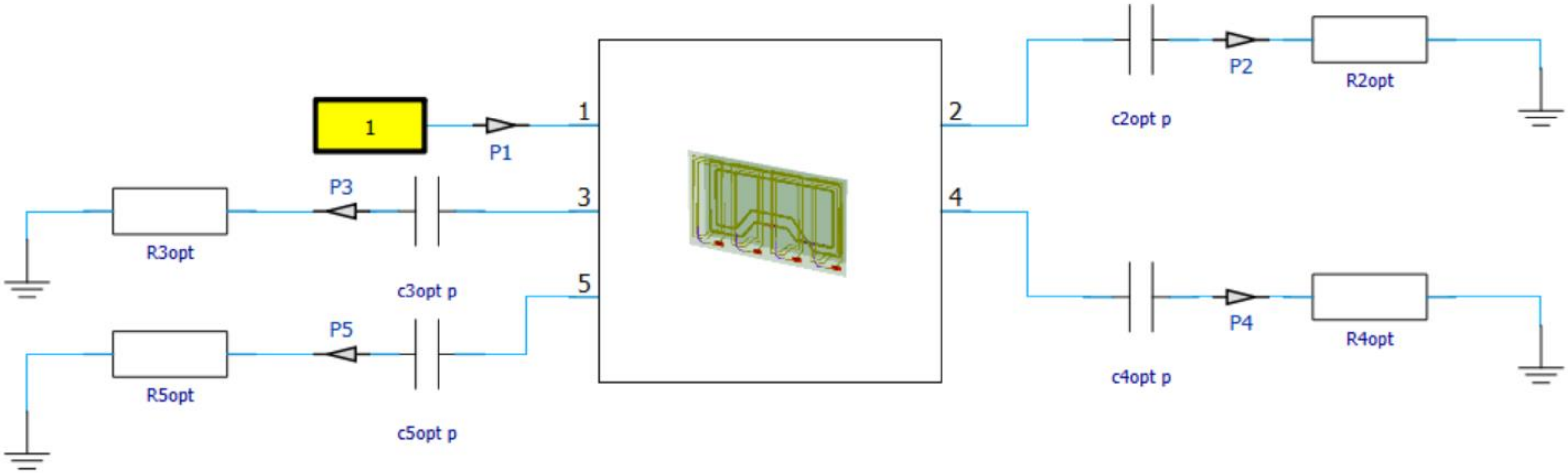
- Tuning the link with series capacitances
  - Using CST Studio Suite’s Circuit Optimiser
  - Algorithms: Trust Region Framework, Nelder Mead Simplex Algorithm, Interpolated Quasi Newton
  - Design parameters: Receiver loads, receiver tuning capacitances, transmitter (P1) current



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LTSpice vs experiments

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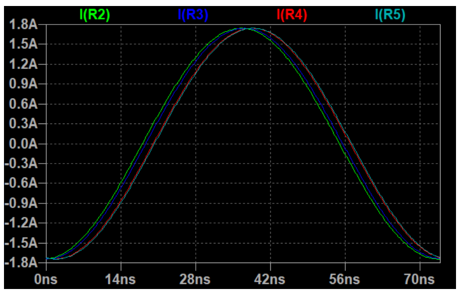
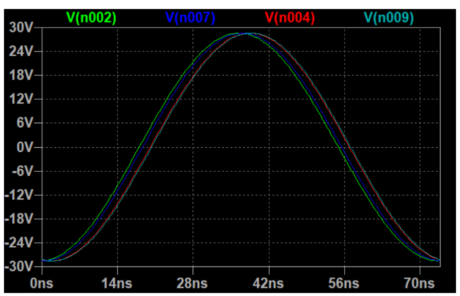
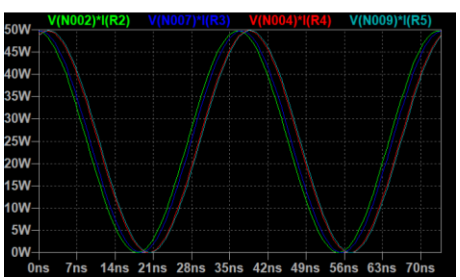
Underpinning Research

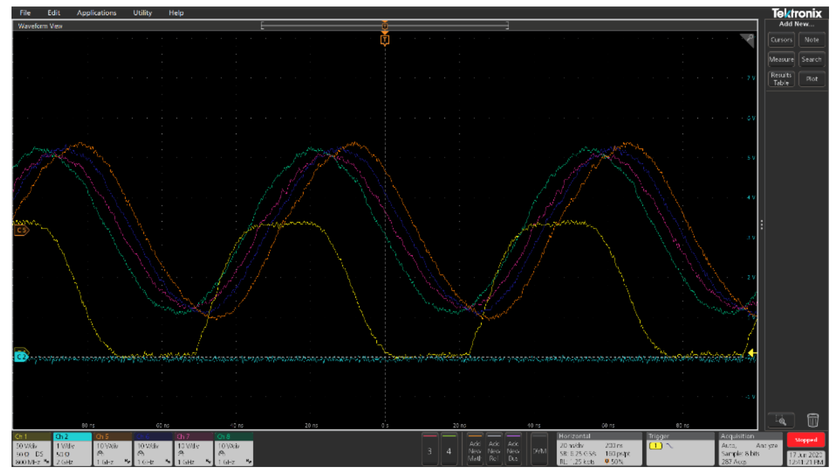
- Spice simulations from the design obtained from CST
  - The loads are evenly distributed







- Tuning the receivers with the design 1
- Waveforms are similar yet there is a slight unbalance



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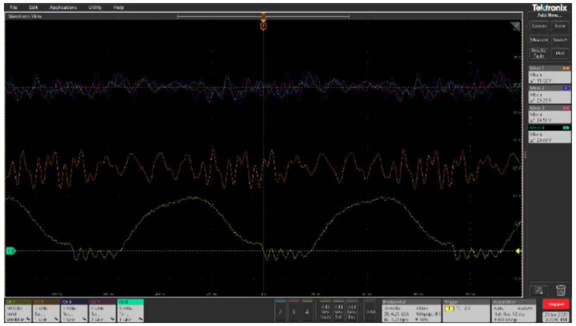
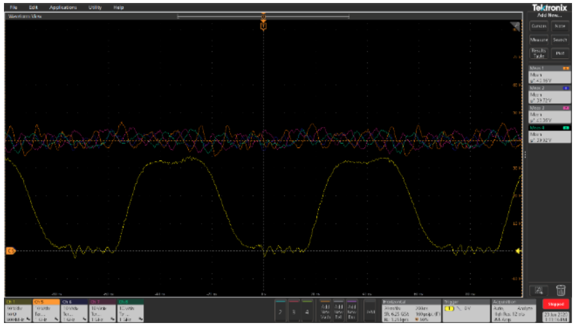
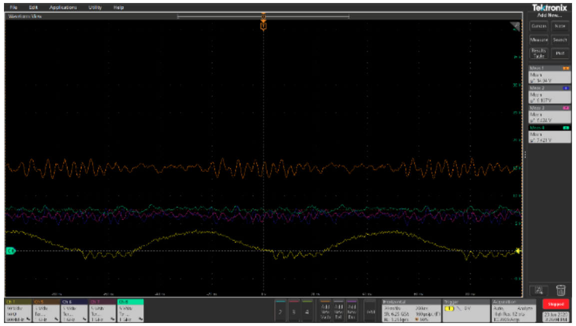
Design 1 in operation

- Powering independent regulated loads using design 1
  - When the dc loads are the same, they are balanced
  - When the primary current is regulated to keep one voltage at 15V and the loads differ, there is a large difference between the receive voltages making the system unpractical







Re-spin of the receiver coils

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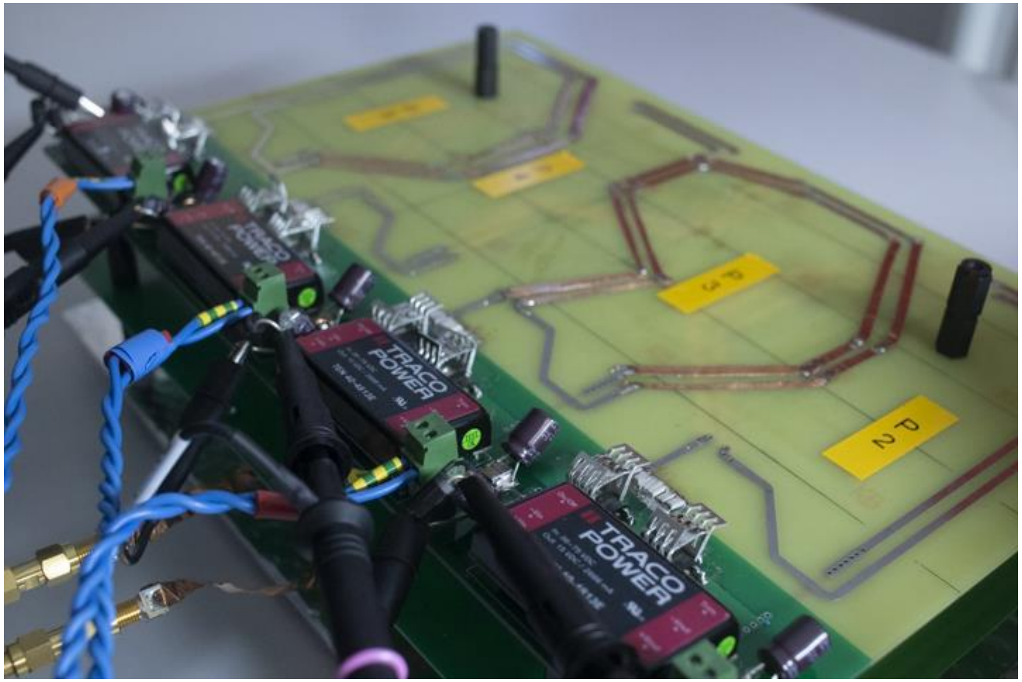
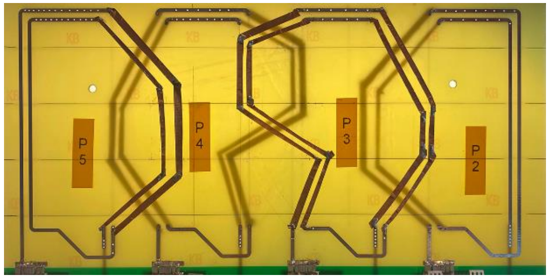
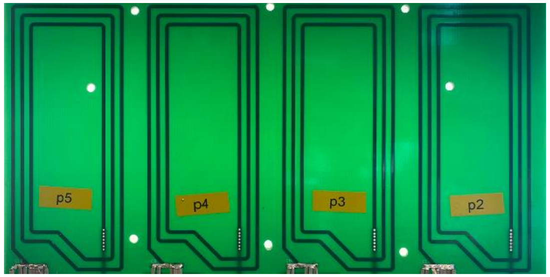
- Design 2
  - Minimises the coupling factor between the receivers
  - Avoids the loading effects from secondary to secondary
  - We manage to get 12.5W at each output, load independent







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Synchronous rect./ Bidirectionality

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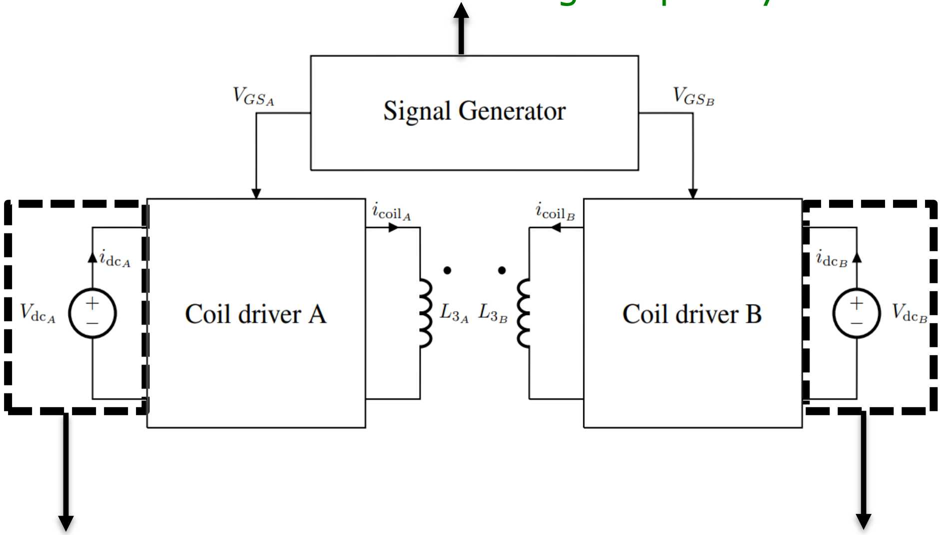
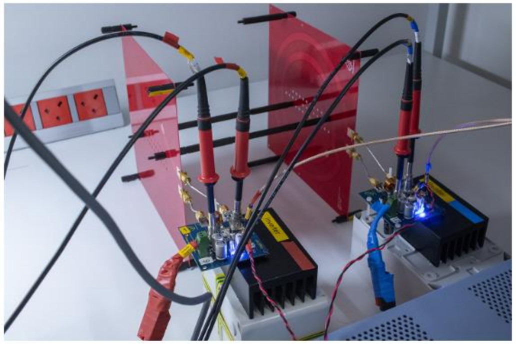
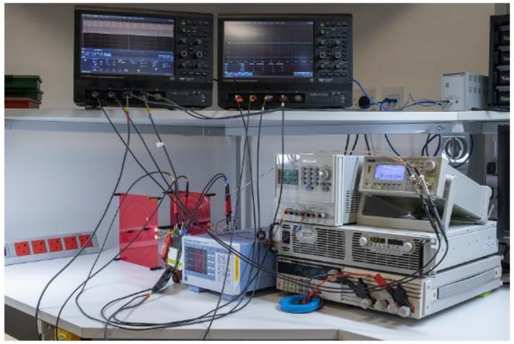
- For the first time we showed a load independent Class EF transceiver as bidirectional coil driver!
- Active control of power flow
- Correction of tuning mismatches
- Low coupling operation
- Fully autonomous environments operation
- Powering systems in low accessibility areas

Control switching frequency and θ



Source-sink configuration of CV electronic load to keep a fixed dc voltage





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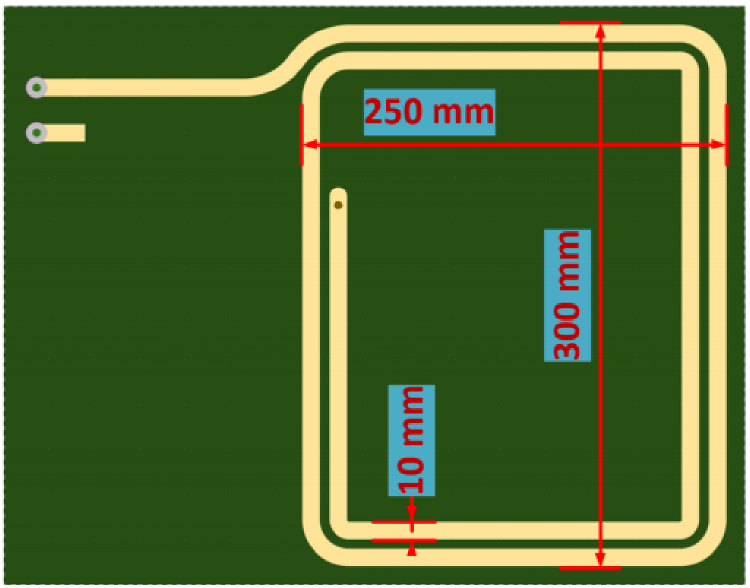
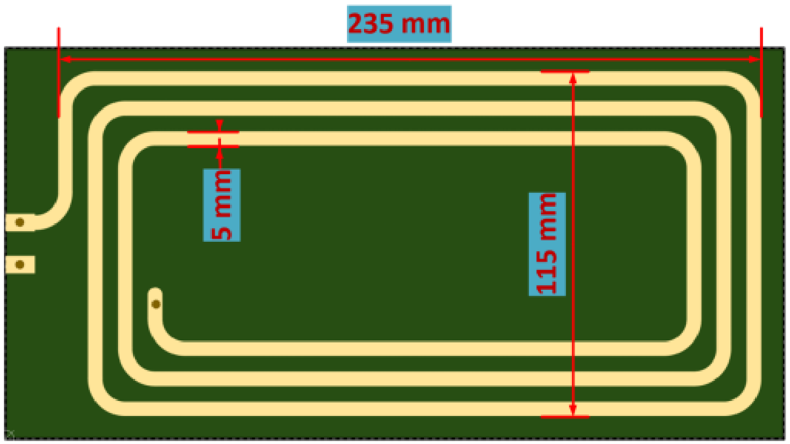
E-Scooter Wireless Charger

- Transmit pad



- Receive unit



Wurth Electronik 364003 flexible ferrite sheets

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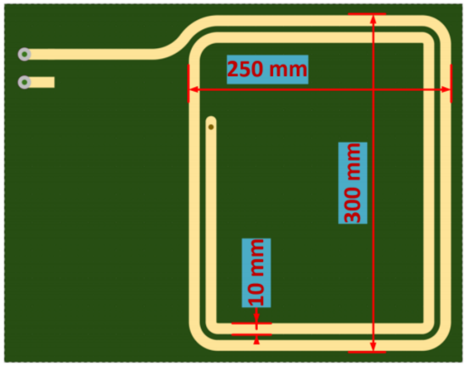
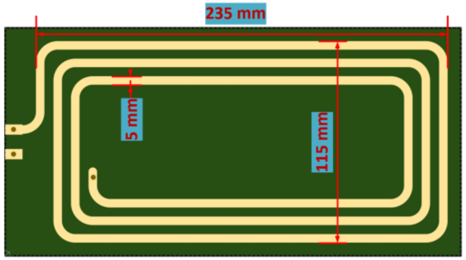
E-Scooter Wireless Charger

- Integration of receive unit in bottom of e-scooter
- Distance 65 mm to 80 mm from transmit pad

- Transmit pad



- Receive unit



Wurth Electronik 364003 flexible ferrite sheets

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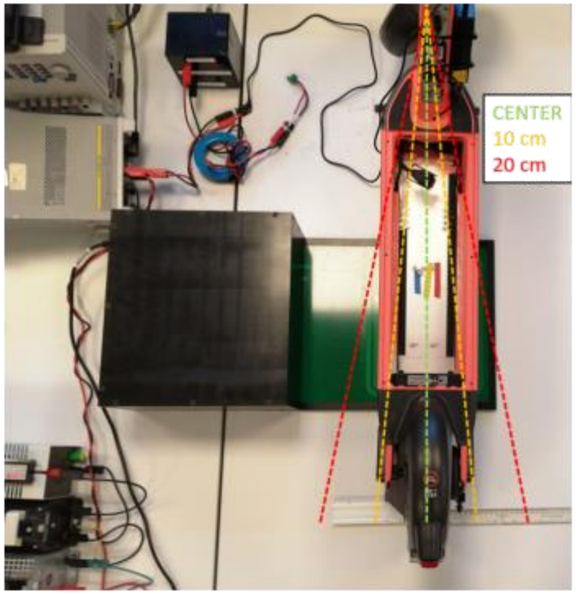
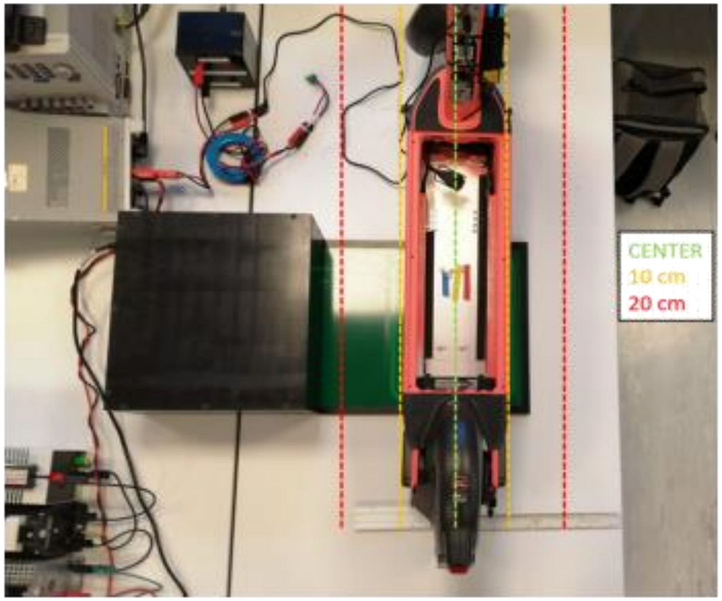
E-Scooter Wireless Charger

- Back-wheel



Lateral



- A 6.78 MHz, 110 W wireless charging system with DC-DC IPT efficiency of 69%-75% was successfully integrated into an E-scooter.
- Ferrite shielding, PCB coils, and high frequency resonant power converters were used.

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Integration into applications

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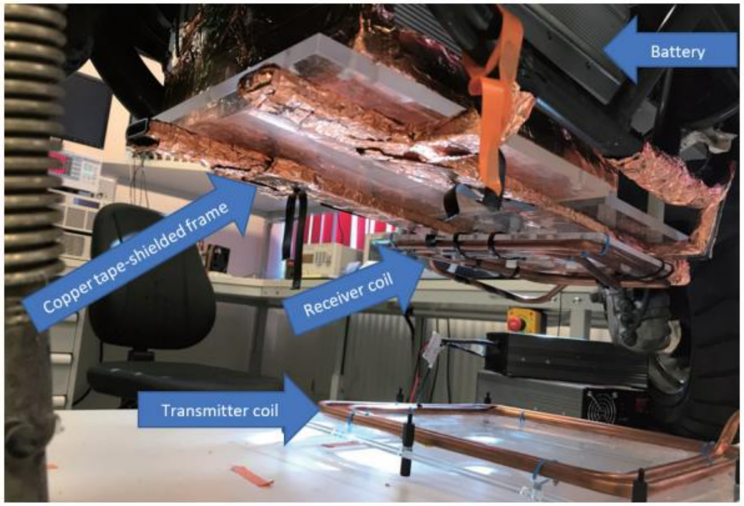
- A 6.78 MHz, 100 W wireless charging system with DC-DC IPT efficiency of 70% was successfully integrated into an M100 DJI drone

Wireless Power Lab drone landing

- A 6.78 MHz, 600 W wireless charging system with DC-DC IPT efficiency of 85% was successfully integrated into Govecs E scooter



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Outreach

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- We hosted IEEE Wireless Power Week
  - We held a session on the future of WBG devices with participation of the Converter Architectures Theme

WPW 2019

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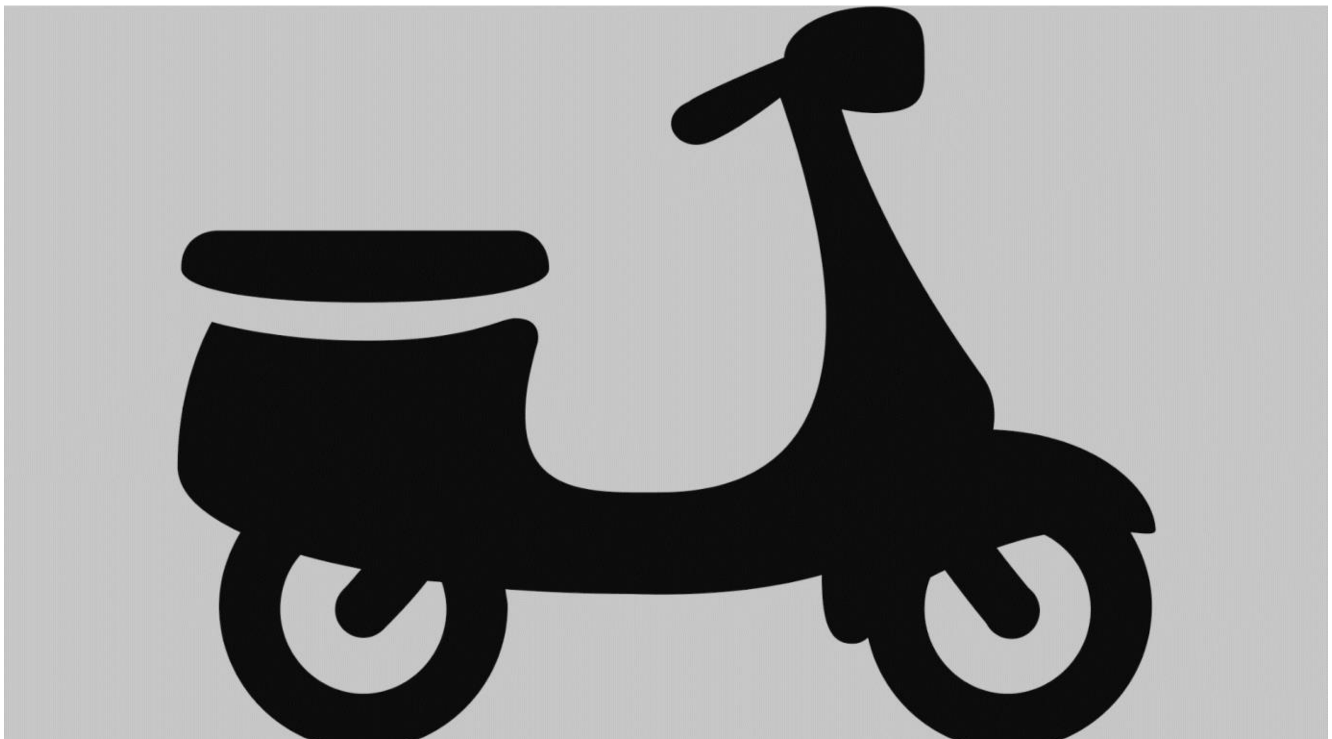
Bumblebee Power

- We spun out a company called Bumblebee Power to commercialise the HF-IPT technology developed during the period of the Centre for Power Electronics



Thank you!