ETH zürich

Power Electronic Systems Laboratory

Synergetically Controlled Three-Phase Boost-Buck Ultra-Wide Output Voltage Range Isolated EV Battery Charger

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In collaboration with:

Infineon

Acknowledgements: J. Azurza, J. Schäfer

Introduction

▶ Motivation

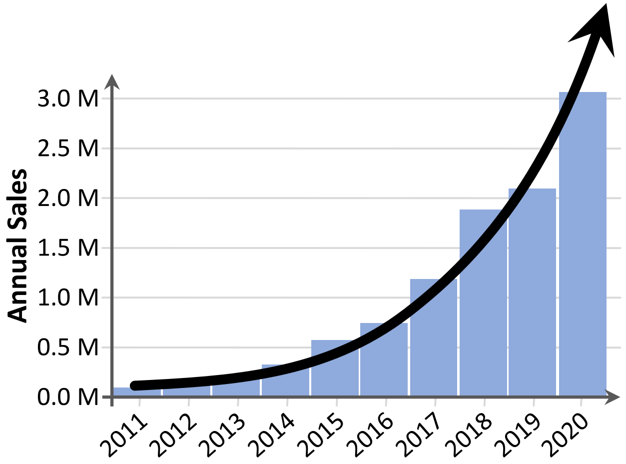
- Growing sales of EVs
- High power density and high efficiency of the charging system

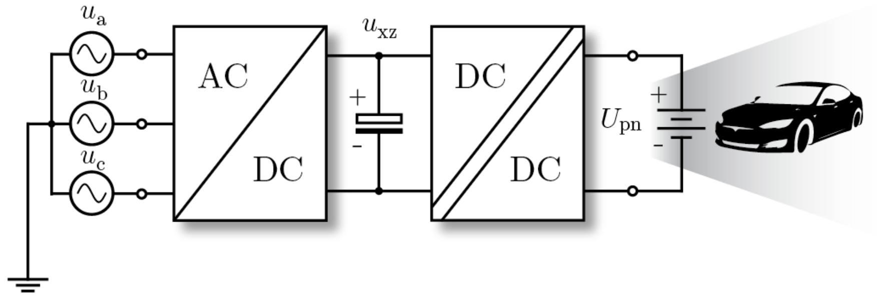
▶ Future Fast EV Charger Specifications

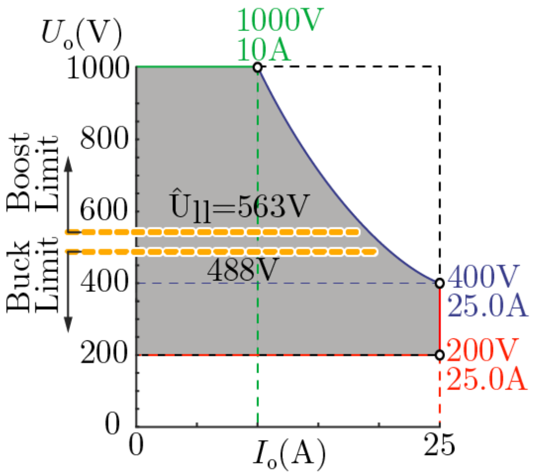
- Extremely wide input-output voltage range
- Buck-boost capability

▶ Two-Stage EV Charging System

- AC/DC front-end + isolated DC/DC converter







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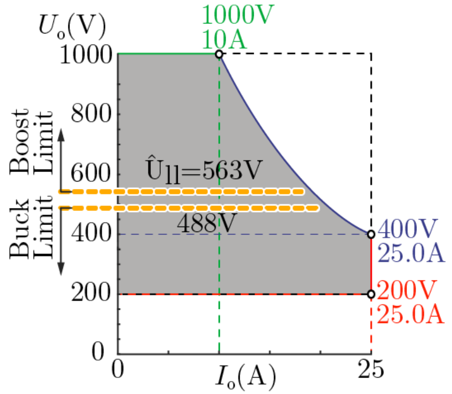
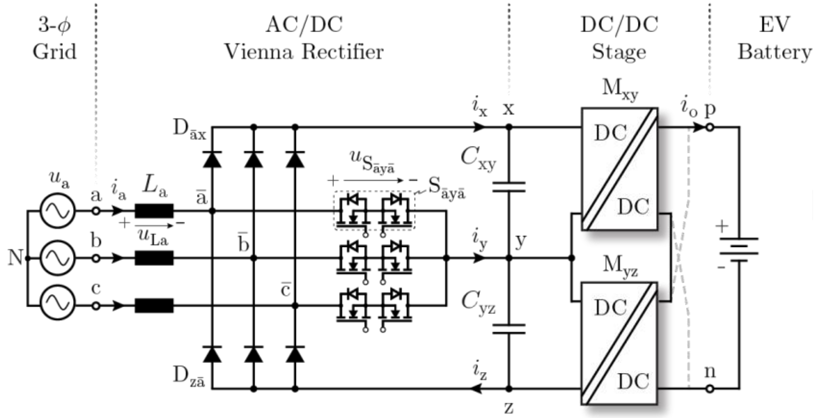


▶ Two-Stage EV Charging System

- Vienna Rectifier front-end (VR)



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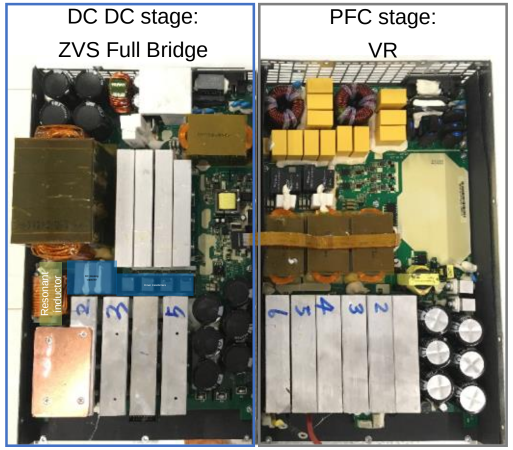
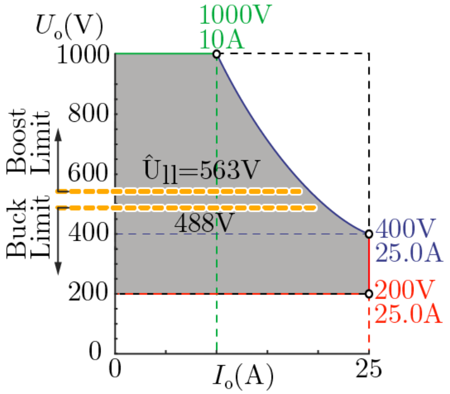
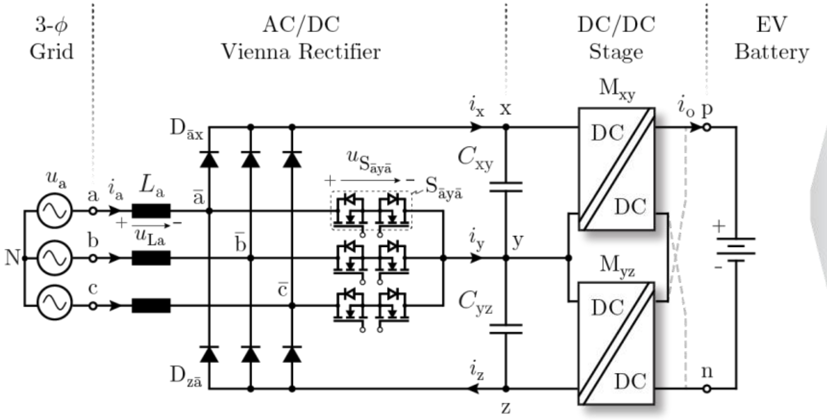
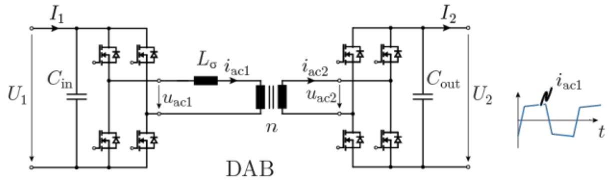
- Vienna Rectifier front-end (VR)
- Isolated DC/DC converters
  - Phase-shifted converters
    - ZVS full bridge, DAB etc.



Source: INFY 20kW EV Charger Module







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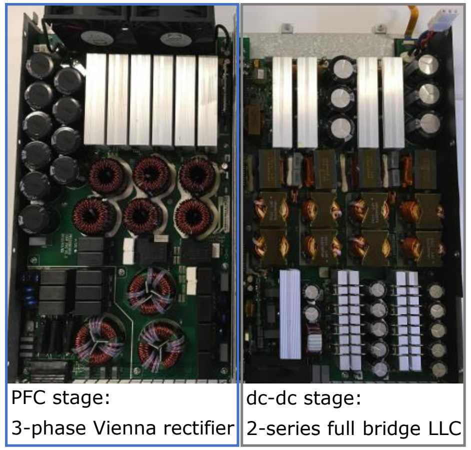
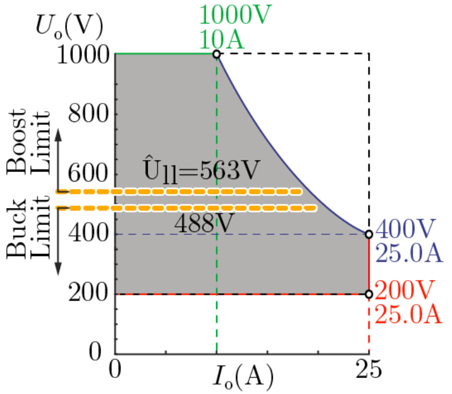
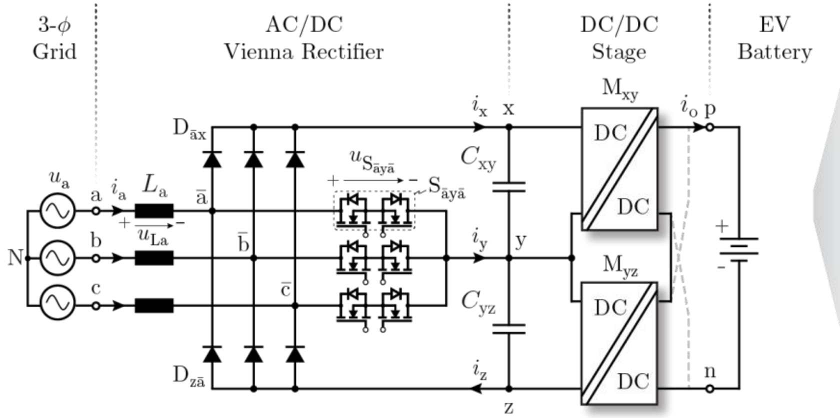
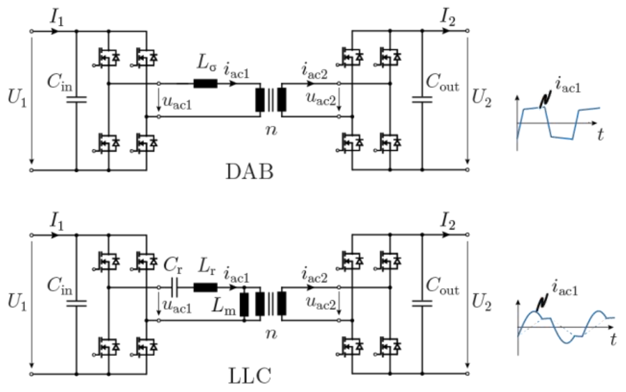
  - Phase-shifted converters
  - Resonant converters
    - LLC



Source: UU Green 15kW EV Charger Module







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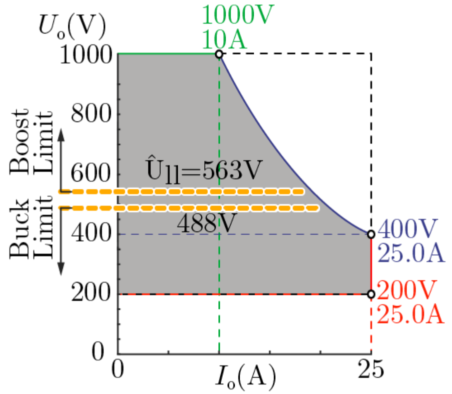

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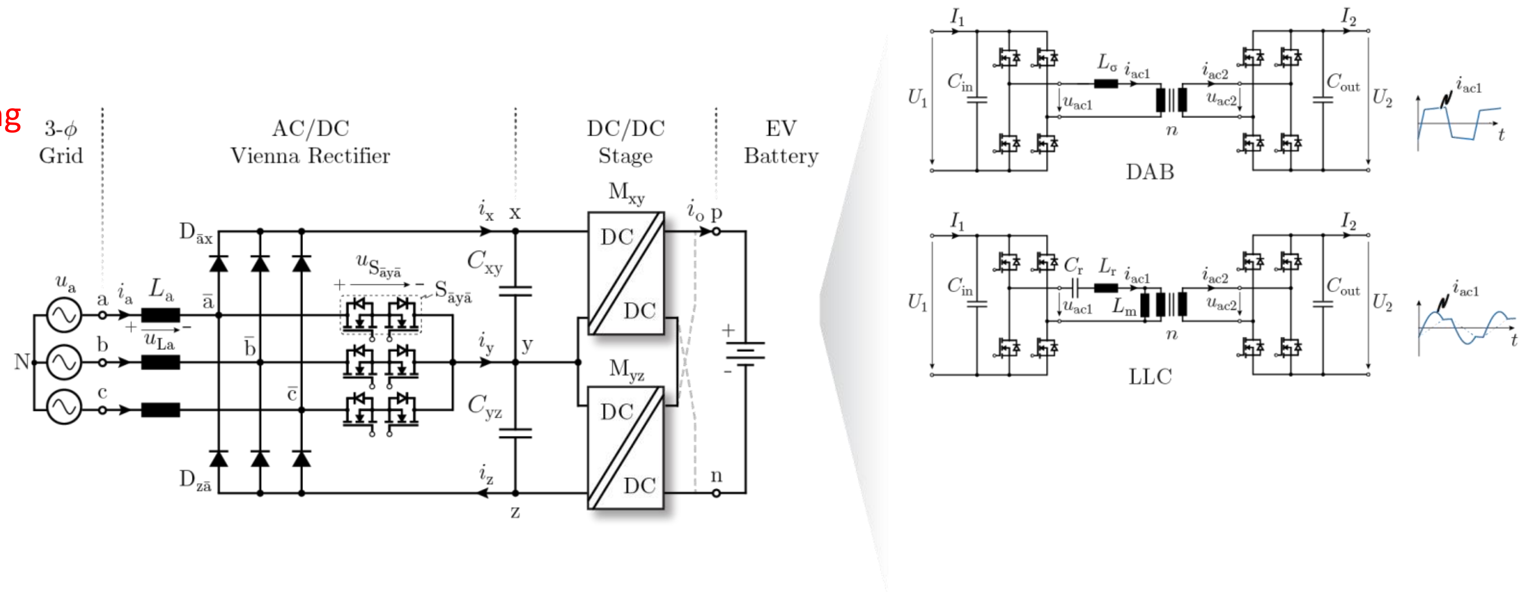
▶ Future Fast EV Charger Specifications

- Extremely wide input-output voltage range
- Buck-boost capability

▶ Two-Stage EV Charging System: Challenges

- Vienna Rectifier front-end (VR)
- Isolated DC/DC converters
  - Phase-shifted converters
    - Reactive power / RMS current, soft-switching
  - Resonant converters
    - High f_{sw}, losses of magnetic components



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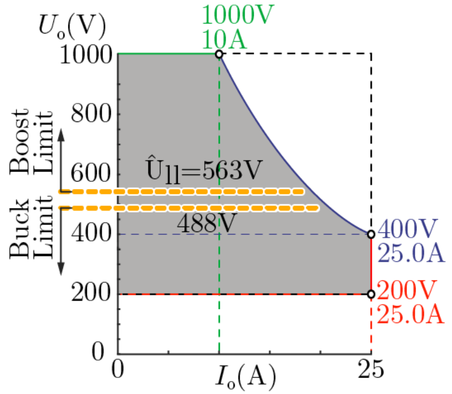
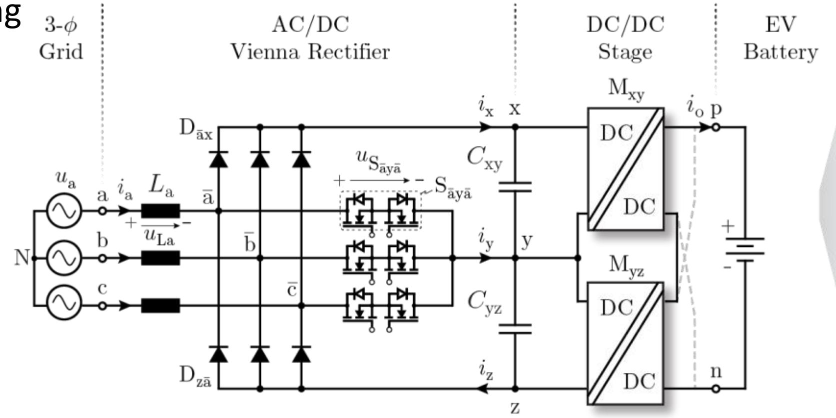


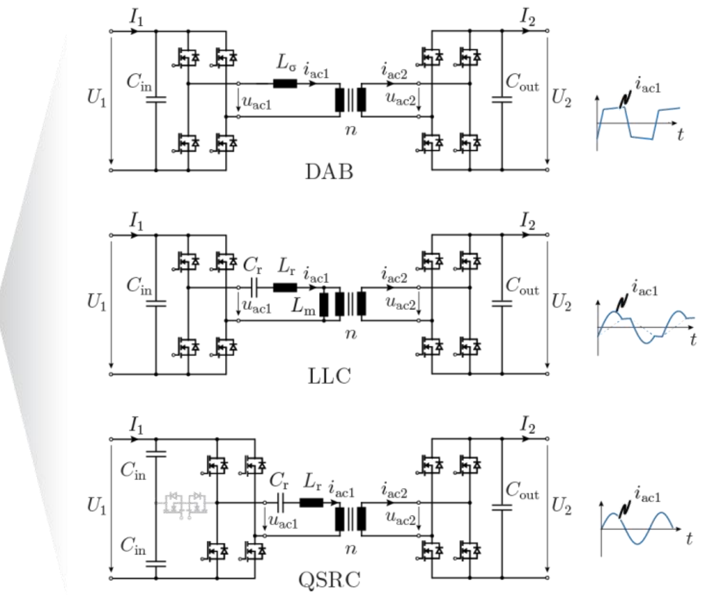
▶ Future Fast EV Charger Specifications

- Extremely wide input-output voltage range
- Buck-boost capability

▶ Two-Stage EV Charging System: Solutions

- Vienna Rectifier front-end (VR)
- Isolated DC/DC converters
  - Phase-shifted converters
    - Reactive power / RMS current, soft-switching
  - Resonant converters
    - High f_{sw}, losses of magnetic components
    - QSRC (Quantum Series Resonant Converter)
    - Constant f_{sw}, sinusoidal currents
    - Buck-boost capability
    - Currently in investigation





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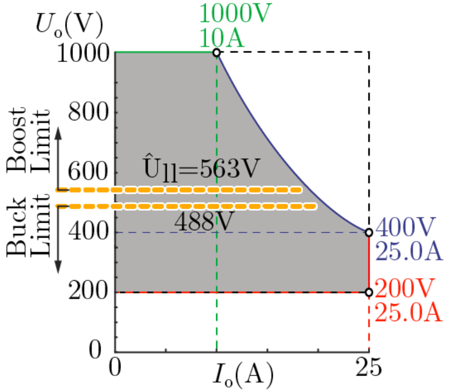

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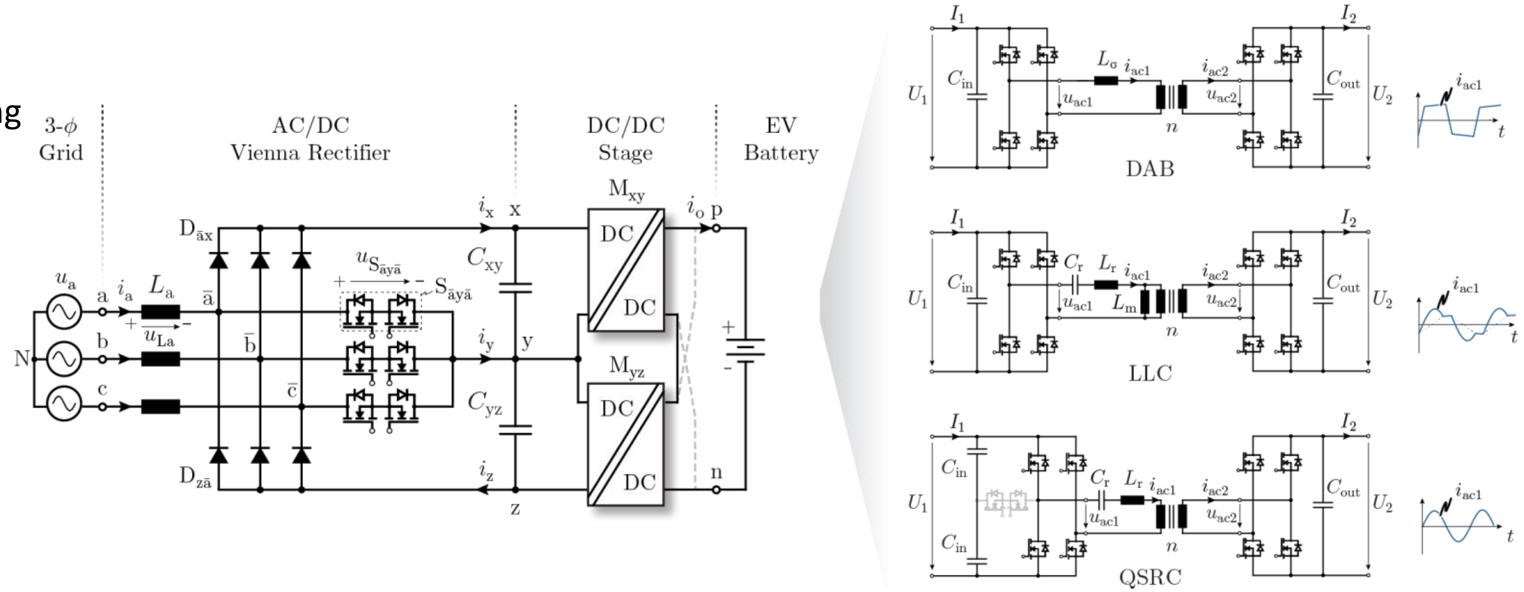
  - Resonant converters
    - High f_{sw}, losses of magnetic components
    - QSRC
- Decoupled control? Synergetic control!



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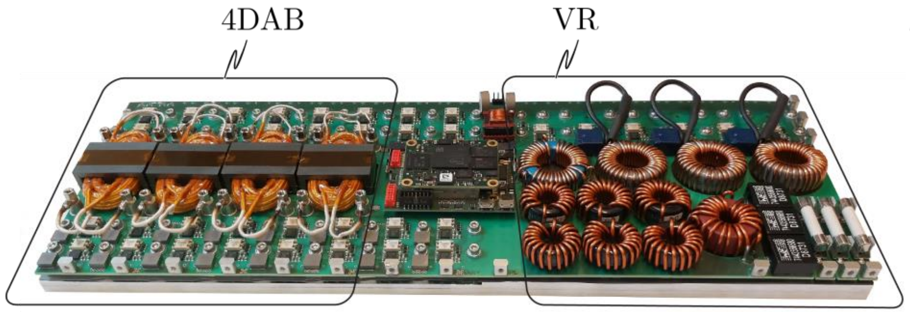
▶ Two-Stage EV Charging System

▶ 10kW Demonstrator System

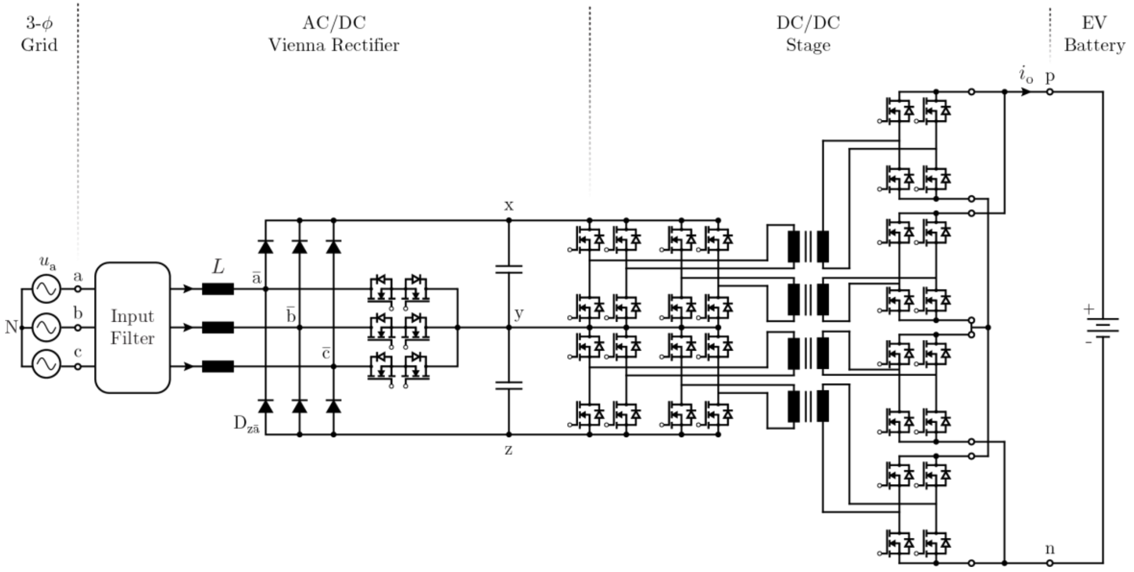
- Vienna Rectifier front-end
- 4DAB: 2 in parallel, 2 in series both input/output

▶ Semiconductors

- 600V GaN Switches (Infineon, IGOT60R070D1)
- 1200V SiC Schottky Diodes (Infineon, IDM10G120C5)



Parameters	Value
Rated Power	10 kW
Input Voltage Range	320-530 V_{rms}
Output Voltage Range	250-1000 V_{dc}
Power Density	10 kW/dm^3 (2x 20 kW/dm^3)
Size	400 x 140 x 18 mm^3
Efficiency (Target)	95 %
Switching Frequency	560kHz (VR) 140kHz – 400kHz (DAB)



External Hw. Design: J. Miniböck

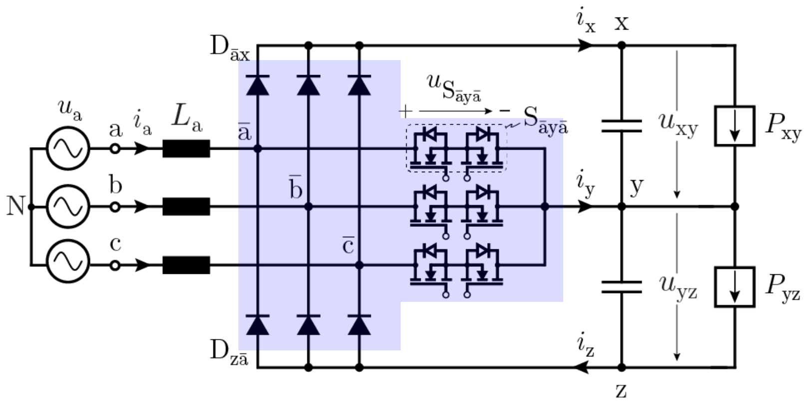
Outline

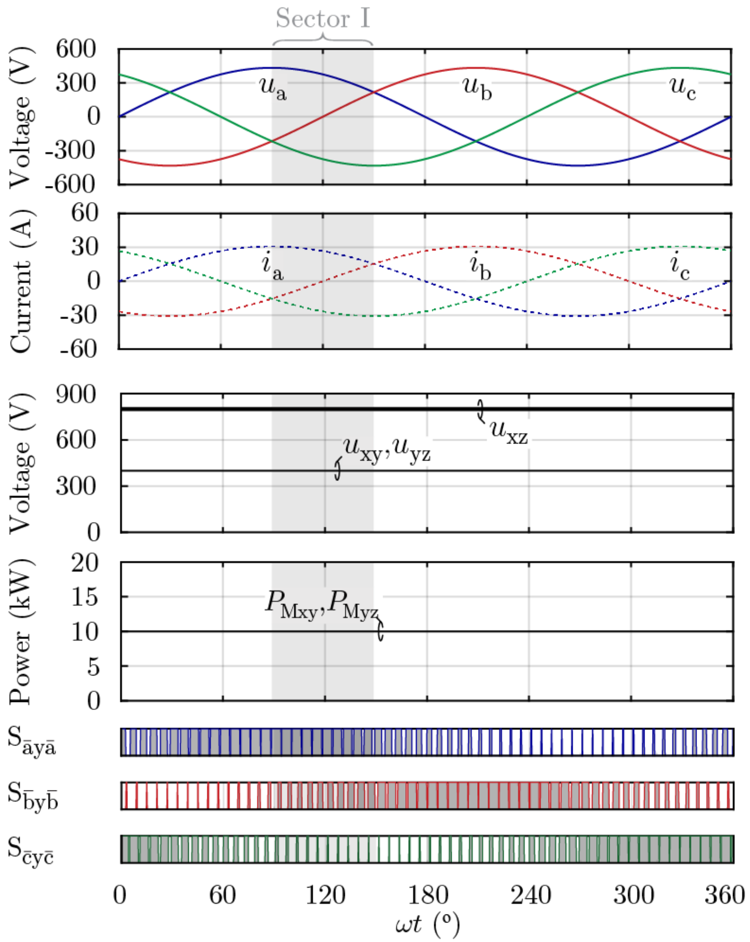
- Introduction
- Operating Principle of the Two-Stage Charger System
- Firmware Structure
- Measurements of DAB Test System
- Measurements of the 10kW VR + DAB Demonstrator System
- Conclusions

Operating Principle of the Two-Stage Charger System : Vienna Rectifier

▶ Conventional modulation (3/3 - PWM)

- 3/3 Phases pulse width modulated
- Constant DC voltage (equal splitting)
- Decoupled AC/DC and DC/DC





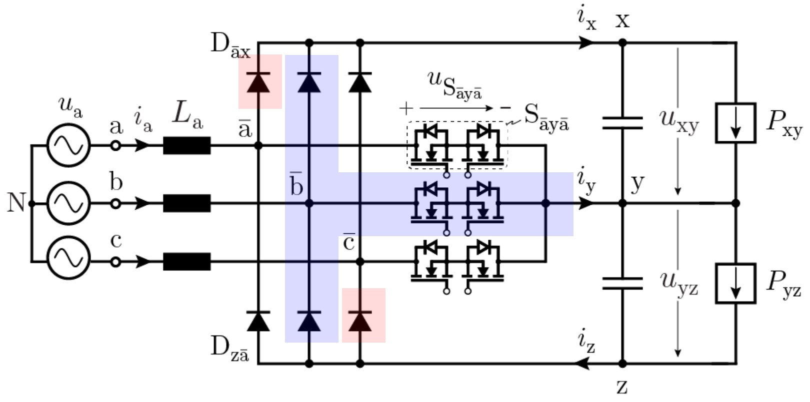
Operating Principle of the Two-Stage Charger System : Vienna Rectifier

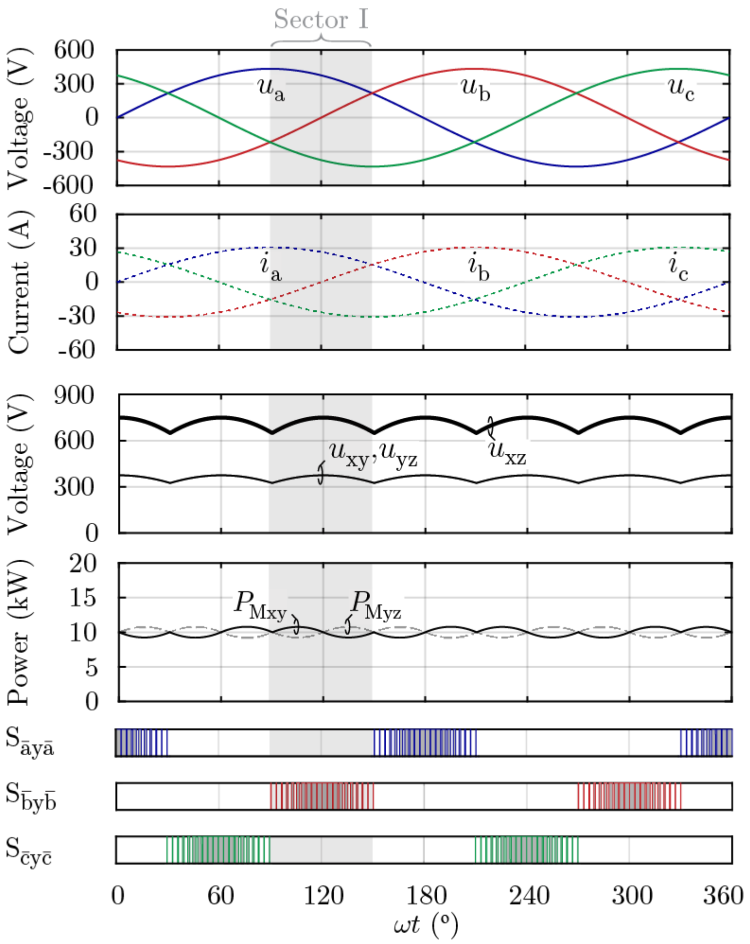
▶ Conventional modulation (3/3 - PWM)

- 3/3 phases are pulse width modulated
- Constant DC voltage (equal splitting)
- Decoupled AC/DC and DC/DC

▶ 1/3 Modulation

- Only the phase with lowest current is switched
- Sinusoidal PFC currents
- Achieved by Synergetic Control scheme
- Significant switching loss saving
  - Performance improvement: efficiency/power density
  - Cost reduction: cheaper switches

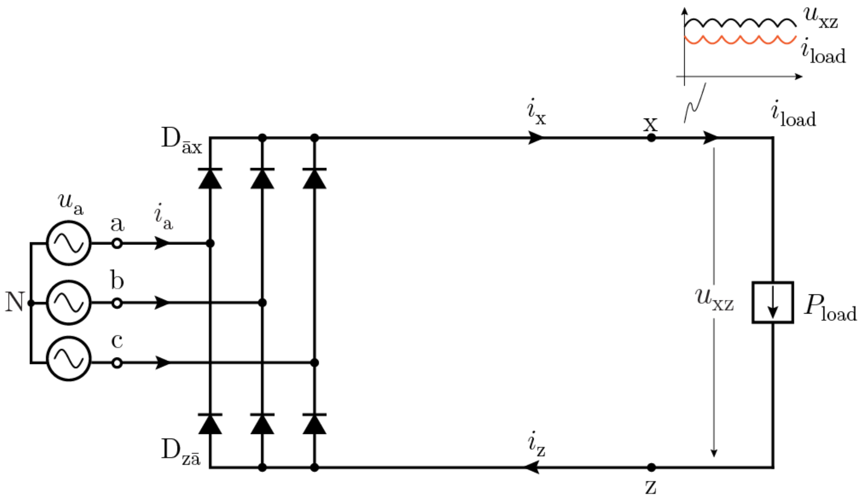


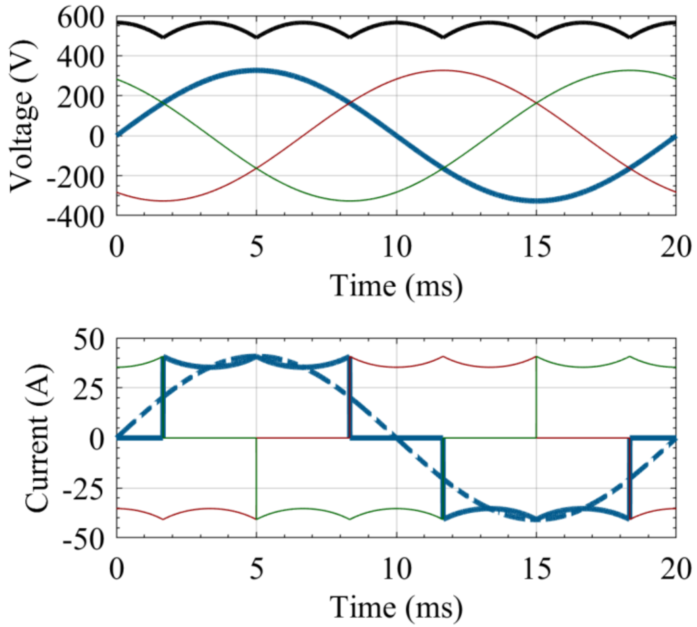


Operating Principle of the Two-Stage Charger System : Vienna Rectifier

▶ Diode Rectifier

- Constant power load
- Simple realization
- Minimum DC-link voltage – six-pulse shape
- Block-shaped input currents: low freq. harmonics

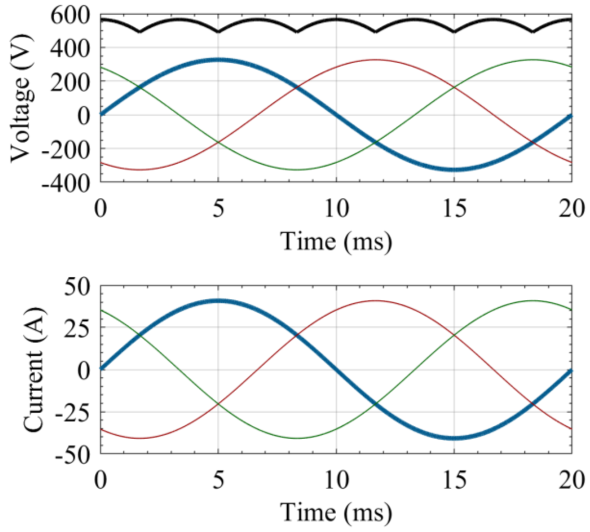


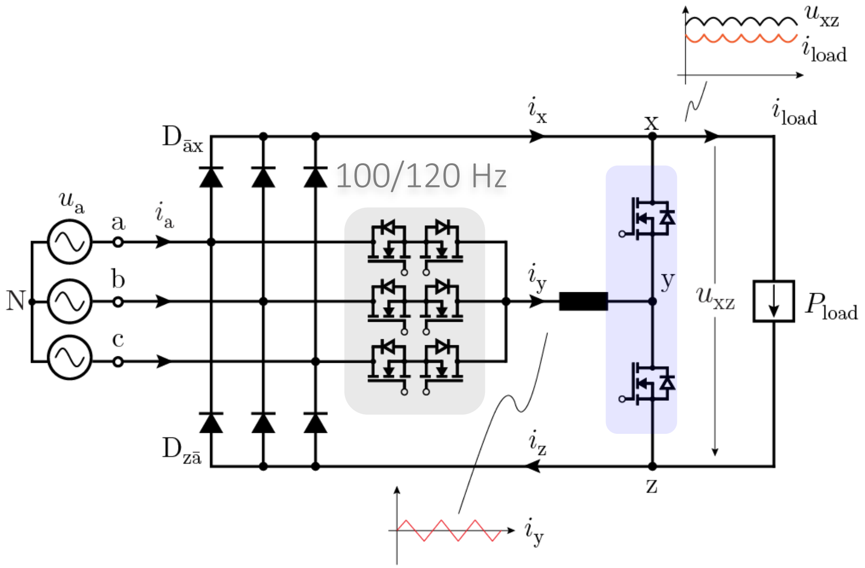


Operating Principle of the Two-Stage Charger System : Vienna Rectifier

▶ Integrated Active Filter (IAF)

- Only 1 bridge leg PWM
- Insert a current prop. to smallest voltage in the “middle phase”
- “Phase-selector” 100/120 Hz switches
- Achieve sinusoidal input currents
- No boost capability





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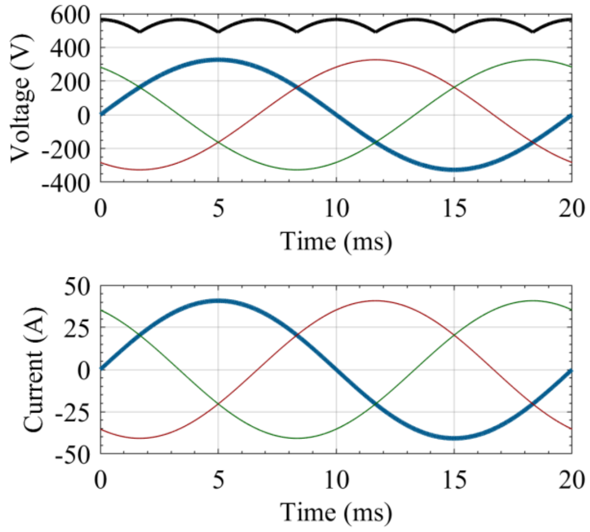

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- Only 1 bridge leg PWM
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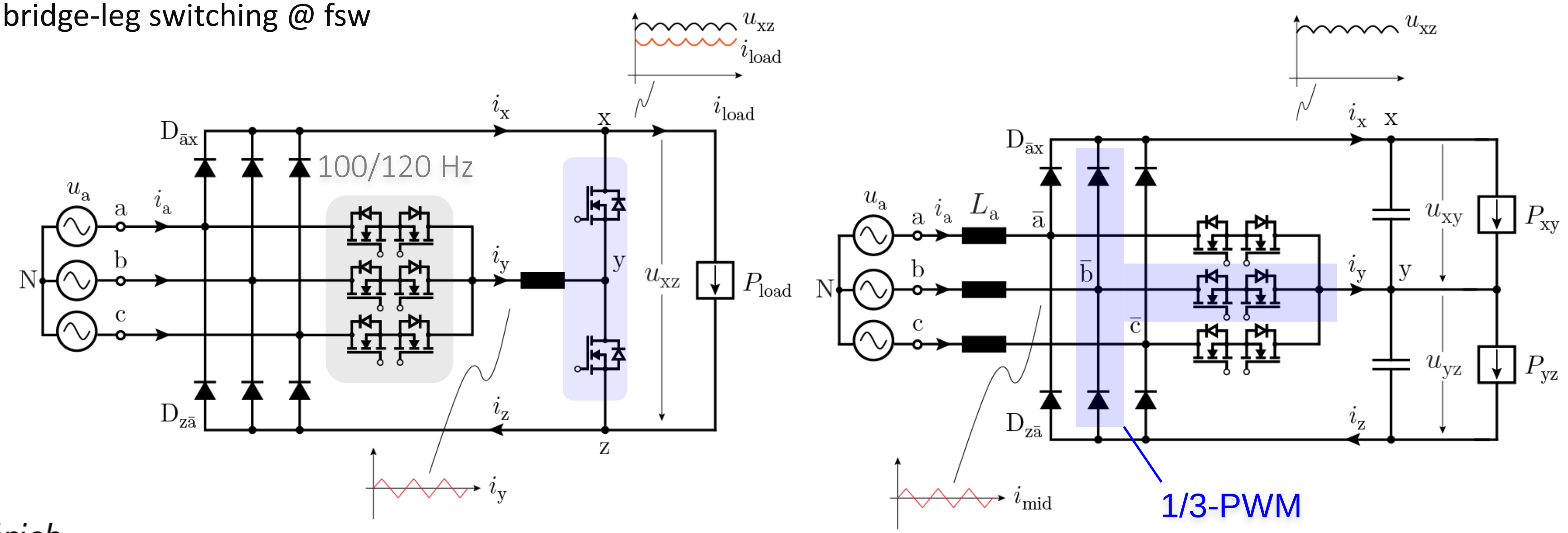
▶ IAF vs. VIENNA – Similar Structures

- 1x inductor in IAF -> 3x inductors in VIENNA
- Less semiconductors
- VIENNA can boost
- 1/3 bridge-leg switching @ fsw



Operating Principle of the Two-Stage Charger System : Vienna Rectifier

▶ 3/3 PWM vs 1/3 PWM

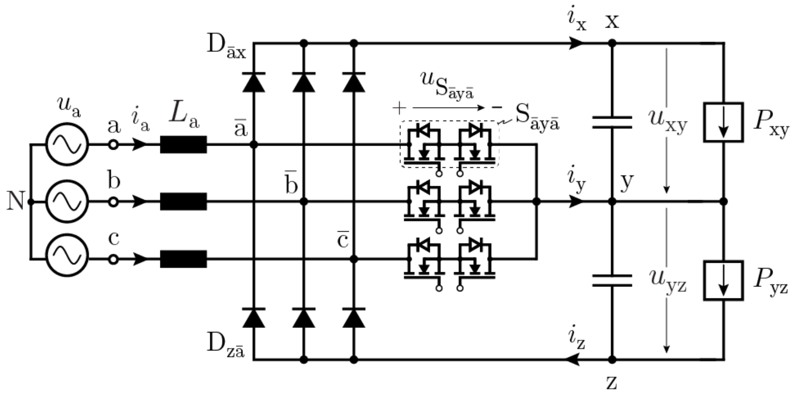
- Reduced switching transitions

▶ Coupled Control of AC/DC and DC/DC

- Implementation effort: one-time

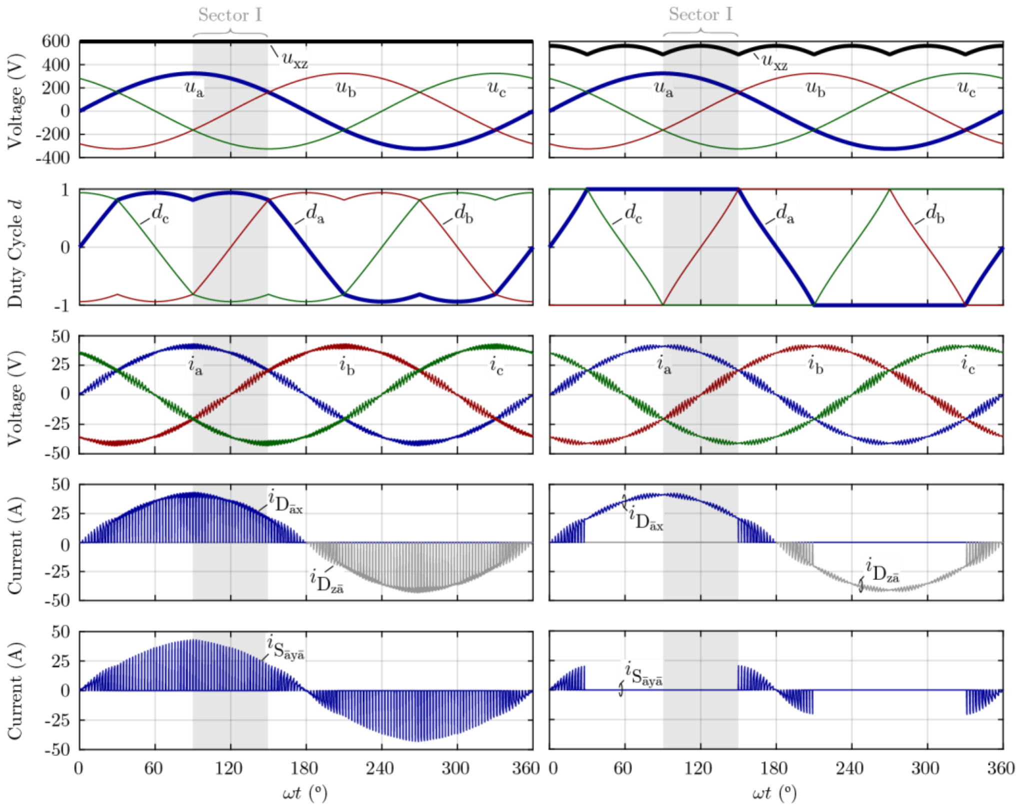
▶ DC link Capacitance Reduction

- Space saving
- Potential surge protection devices



3/3 PWM (20 kW , 400 $V_{rms,ll}$, 600 V_{dc})

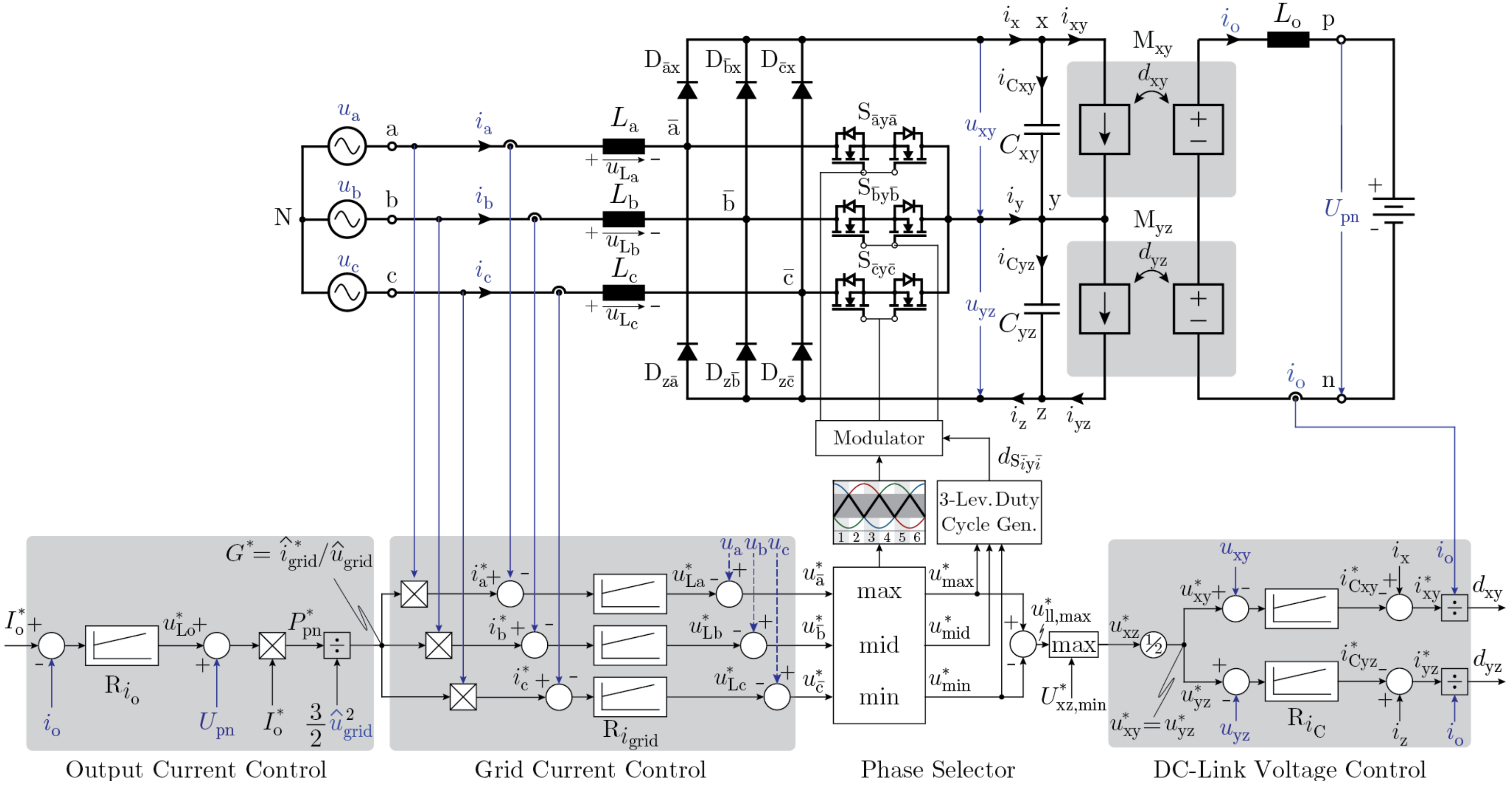
1/3 PWM (20 kW , 400 $V_{rms,ll}$)



Operating Principle of the Two-Stage Charger System : Vienna Rectifier

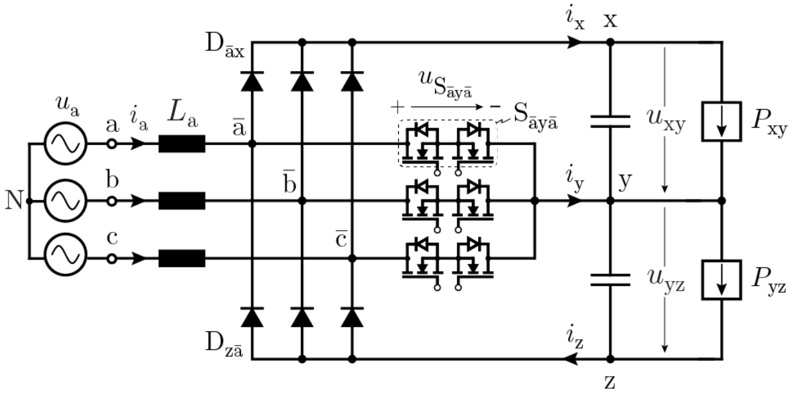
▶ Synergetic Control Structure

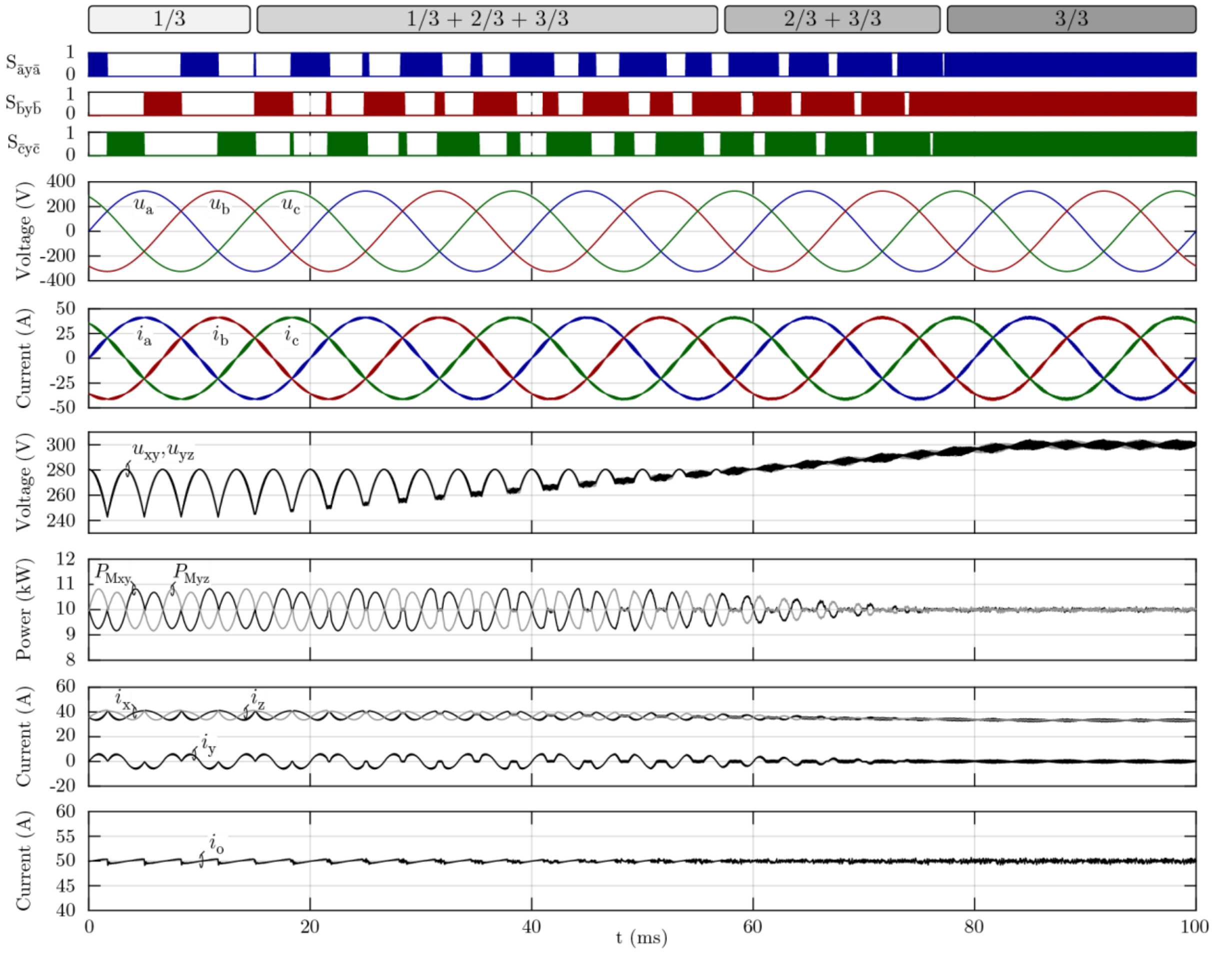
- Synergetic cascaded control structure



Operating Principle of the Two-Stage Charger System : Vienna Rectifier

► **Simulation Results : DC-Link Voltage Transition**

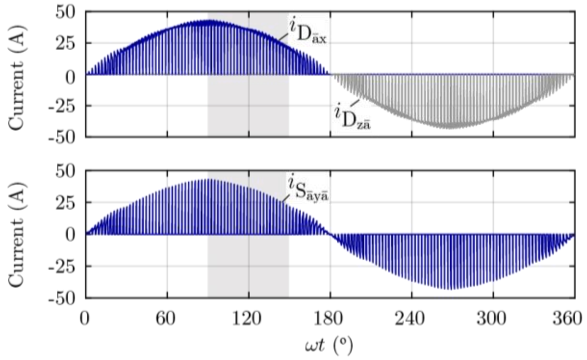




Operating Principle of the Two-Stage Charger System : Vienna Rectifier

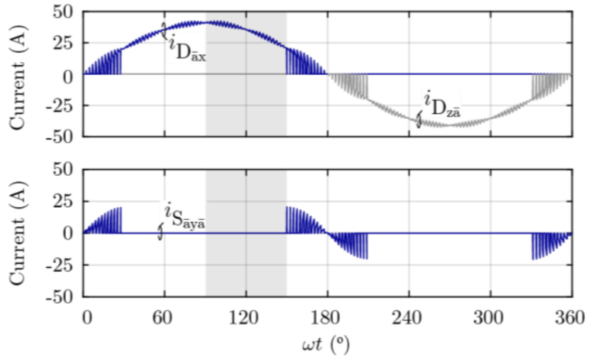
▶ Semiconductor Loss Savings

- Switching Losses Esw = Constant Term + Current Dep. (Linear) Term
- 3/3-PWM: $P_{sw,3/3} = \left(E_{sw,0} + E_{sw,1} \cdot I_{avg}\right) f_{sw}$
- 1/3-PWM: $P_{sw,1/3} = \left(\underbrace{\frac{E_{sw,0}}{3}}_{-66\%} + \underbrace{\left(1 - \frac{\sqrt{3}}{2}\right) E_{sw,1} \cdot I_{avg}}_{-86\%}\right) f_{sw}$



- Conduction losses

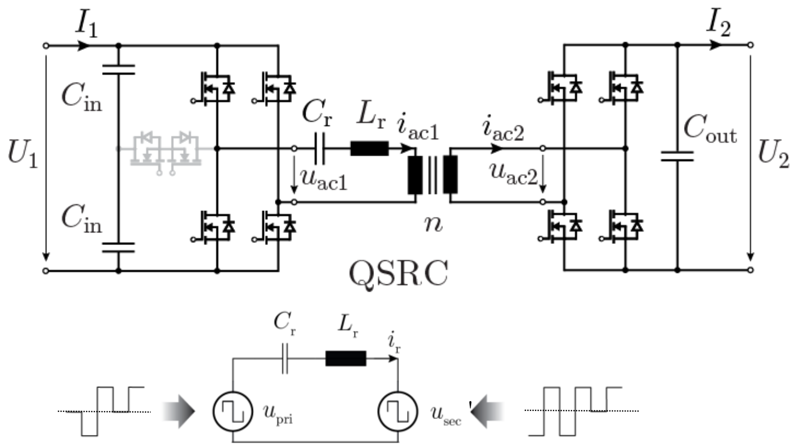
		3/3-PWM	1/3-PWM	Diff.
Switches	RMS	10.2 A	3.7 A	- 63.4 %
Diodes	RMS	19.3 A	20.4 A	+ 5.5 %
	AVG	11.1 A	12.44 A	+ 12.3 %

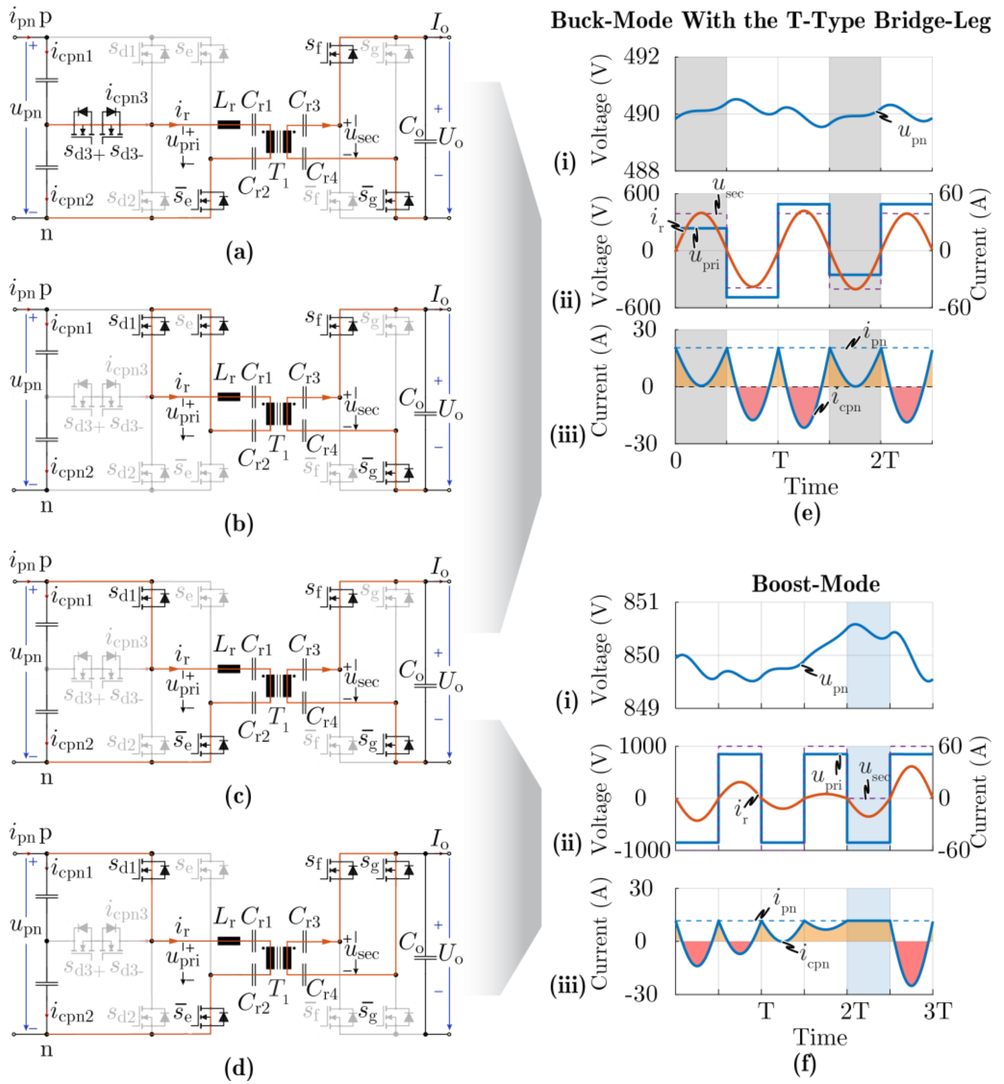


Operating Principle of the Two-Stage Charger System : DC/DC Stage

▶ Isolated DC/DC Converters

- Phase-shifted converters
  - DAB
    - Complexity
    - Reactive power (high RMS current)
    - Trapezoidal currents: EMI unfriendly
    - Active switches on the secondary side
- Resonant converters
  - LLC
    - High f_{sw}, losses of magnetic components
  - QSRC (Quantum Series Resonant Converter)
  - Constant f_{sw}, sinusoidal currents
  - Buck-boost capability

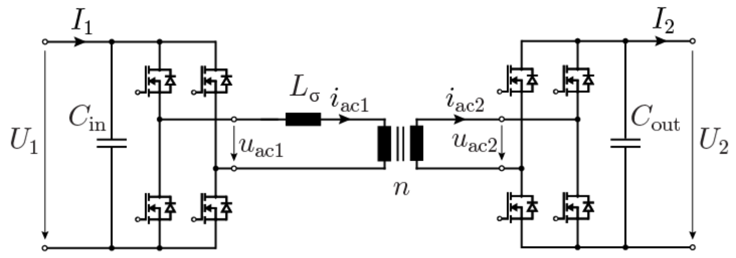


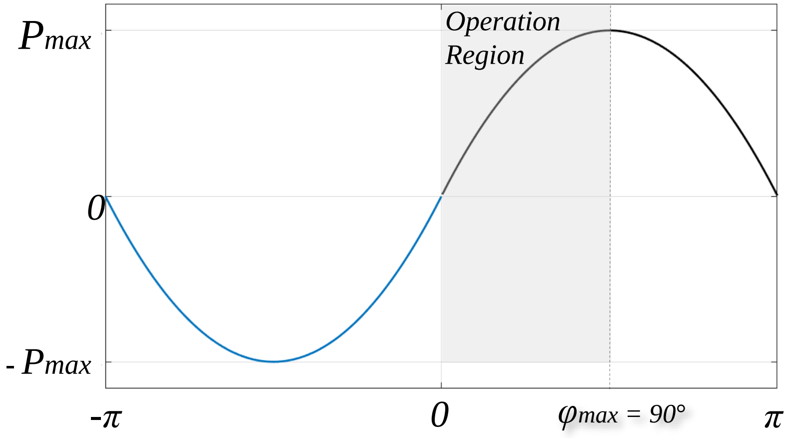


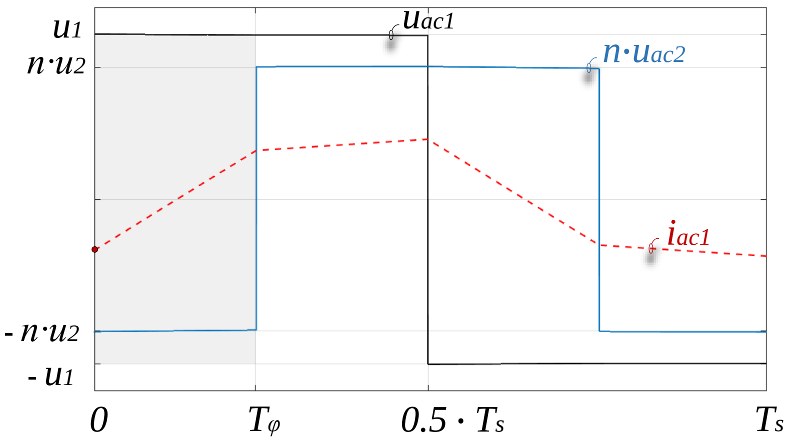
Operating Principle of the Two-Stage Charger System : Dual-Active-Bridge Converter

▶ Phase-Shift Modulation (PSM)

- Phase-shift between the primary & secondary side full bridge
- Buck & Boost capability
- Bidirectional (on-board chargers)







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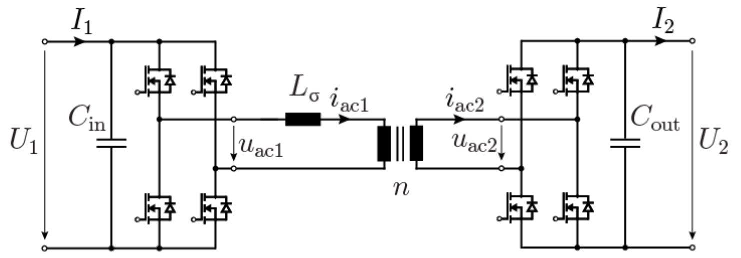
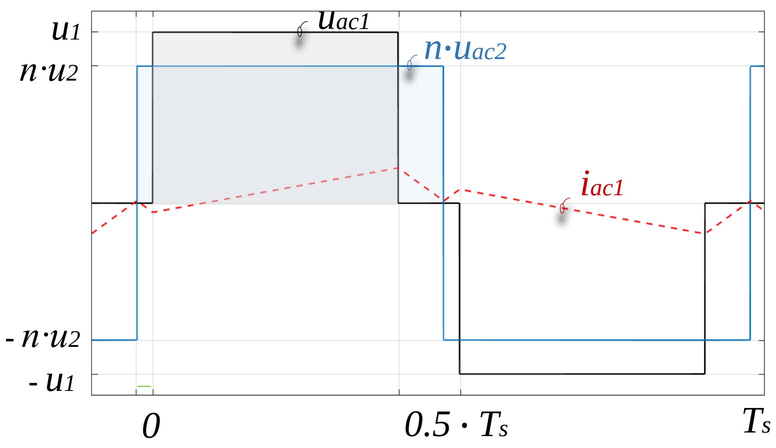
▶ Advanced Modulation

- More degrees of freedom
  - d_1, d_2, f_{sw}
- Simple & straightforward implementation
- Different operating regions
  - Buck ($U_1 > nU_2$)
    - $d_1 = nU_2/U_1$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
  - Transition ($U_1 = nU_2$): PSM
    - $d_1 = 0.5$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
  - Boost ($U_1 < nU_2$)
    - $d_1 = nU_2/U_1$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
    - High switching losses due to high voltage and f_{sw}



Buck ($U_1 > nU_2$)



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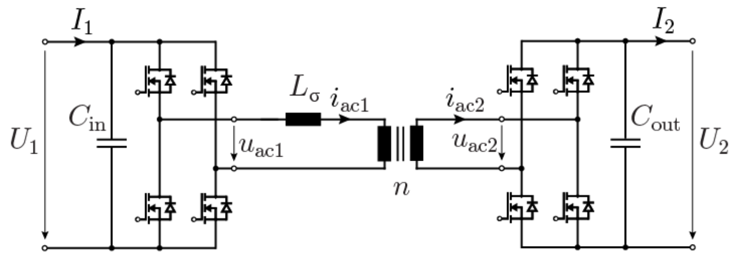
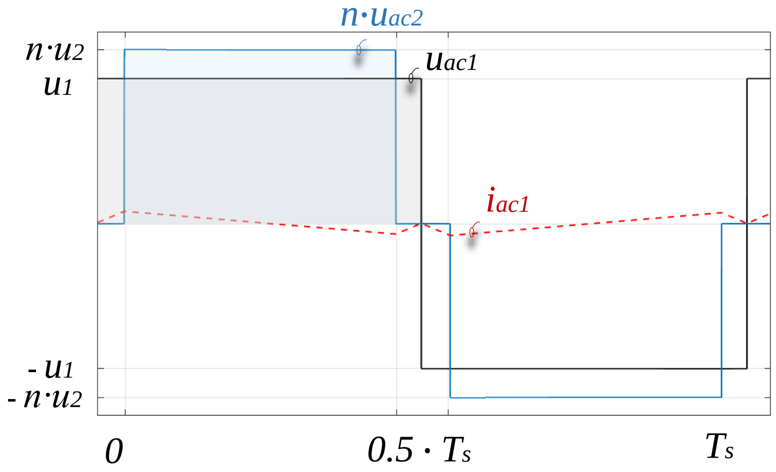
  - Boost (U_1<nU_2)
    - $d_1 = nU_2/U_1$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
    - High switching losses due to high voltage and f_{sw}
    - $d_1 = 0.5$, d_2, f_{sw} optimized to ensure soft switching



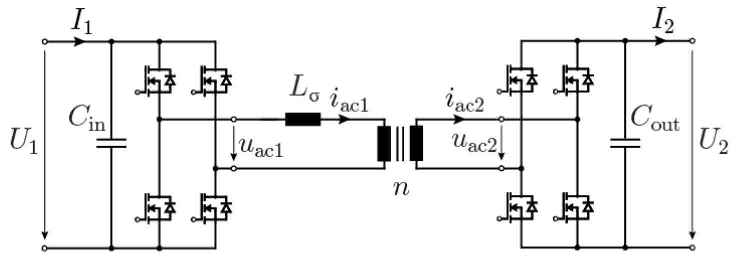
Boost (U1<nU2)



Operating Principle of the Two-Stage Charger System : Dual-Active-Bridge Converter

▶ Basic Modulation

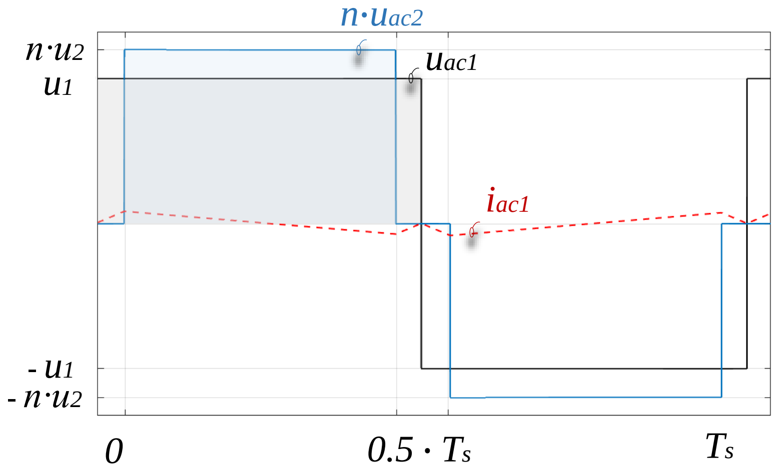
- Phase-shift between the primary & secondary side full bridge
- Buck & Boost capability
- Bidirectional



▶ Advanced Modulation

- More degrees of freedom
  - d_1, d_2, f_{sw}
- Simple & straightforward implementation
- Different operating regions
  - Buck ($U_1>nU_2$)
    - $d_1 = nU_2/U_1$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
  - Transition ($U_1 = nU_2$)): PSM
    - $d_1 = 0.5$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
  - Boost ($U_1<nU_2$)
    - $d_1 = nU_2/U_1$, $d_2 = 0.5$, f_{sw} increases with U_1 to keep the same V·s
    - High switching losses due to high voltage and f_{sw}
    - d_1, f_{sw} optimized, $d_2 = 0.5$, to ensure soft switching
- Possible improvements
  - Minimum I_{lrms}
  - Soft switching
  - Refer to Dr. Florian Krismer's PhD Thesis

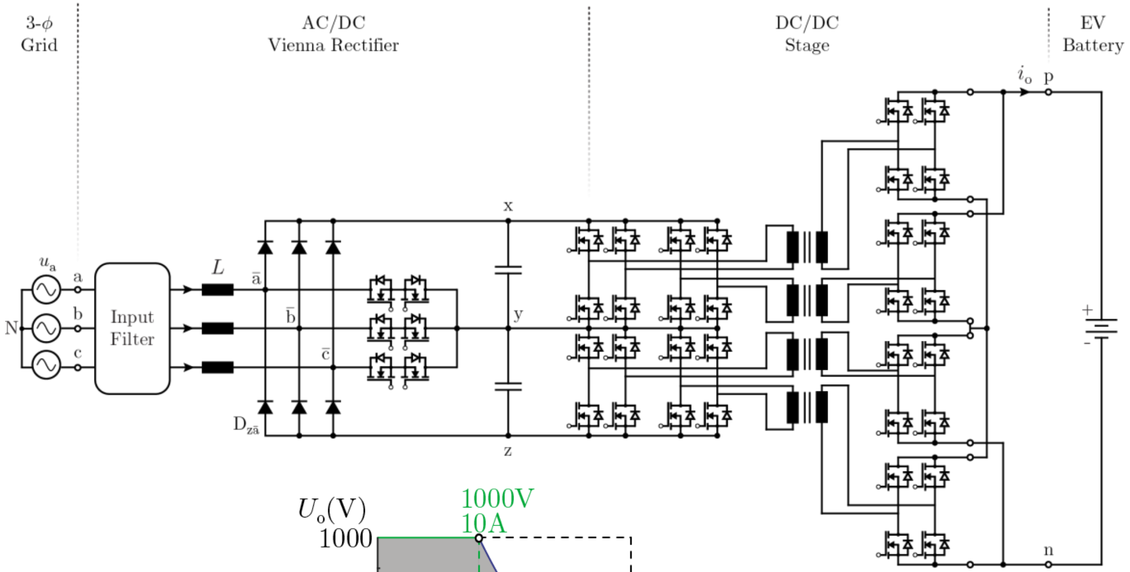
Boost (U1<nU2)

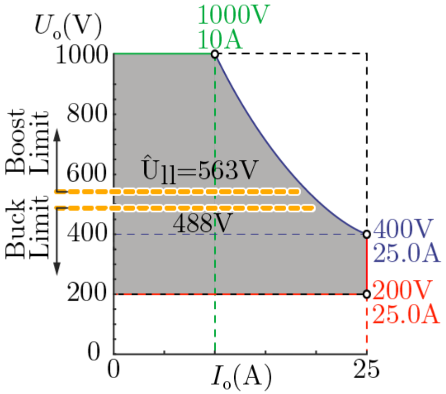


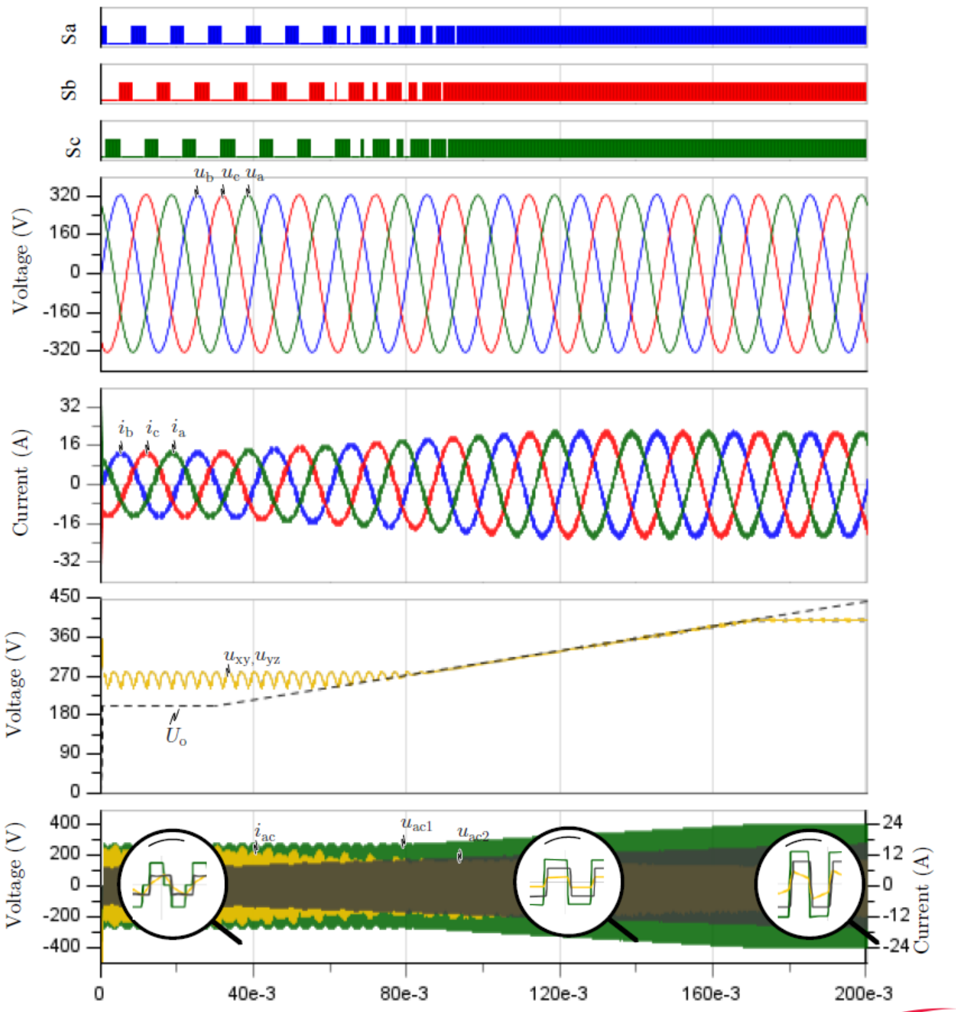
Operating Principle of the Two-Stage Charger System

▶ Simulation Results : DC-Link Voltage Transition

- VR + 4DABs







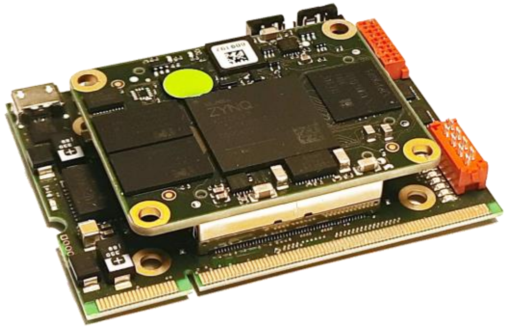
Firmware Structure

▶ Controller

- Zynq®-7000 from **Xilinx**
  - An FPGA + A dual core ARM® processor with peripherals
- SoC Module XC7Z020 from Trenz Electronic
- Custom designed development board
  - 16x external ADCs (AD7274 – 12 bits – 3MSPS)
  - Isolated UART communication
  - Debug interface

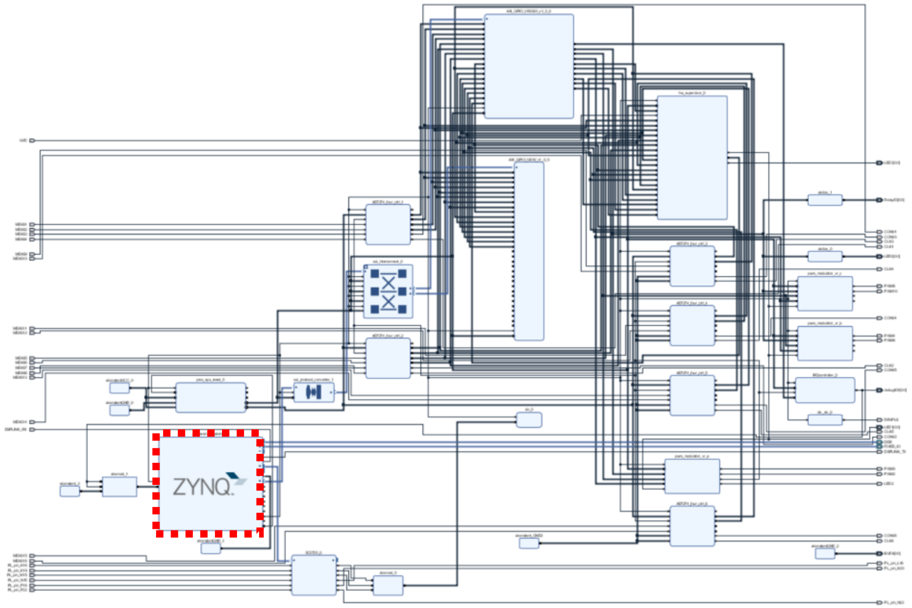
Trenz Electronic SoC Module

Ad-hoc Custom Control Board



▶ Development Environment

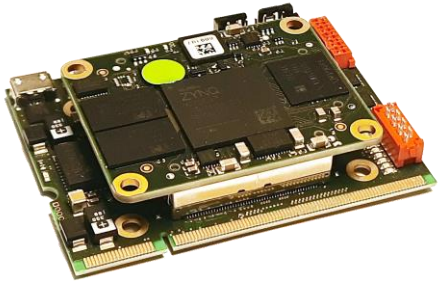
- Vivado® Design Suite / IP Integrator
  - Design environment for configuration of Processing system (DSP)
  - Hardware design for programmable logic (FPGA)
- Software Development Kit (SDK)
  - Software application / debugging

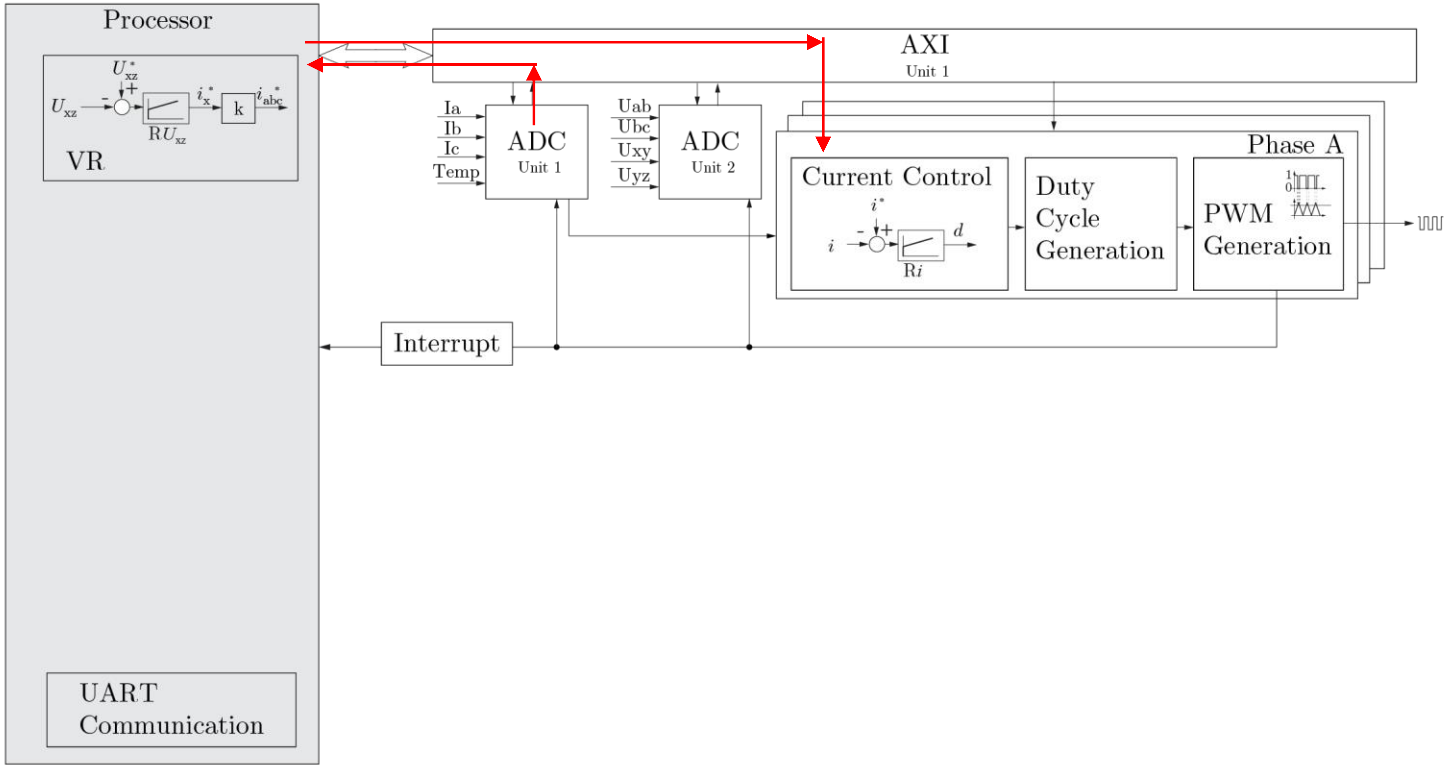


Firmware Structure

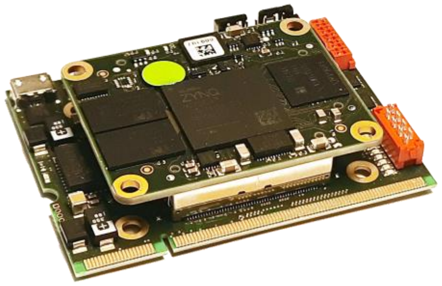
▶ Decoupled Control of VR & DAB

- Communication between the processor and FPGA
  - AXI (Advanced eXtensible Interface) protocol
- Communication between controller and laptop
  - UART
- VR
  - Output voltage control
    - 30kHz,
    - implemented in C
  - Input current Control
    - 560kHz
    - implemented in VHDL





Firmware Structure



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- DAB
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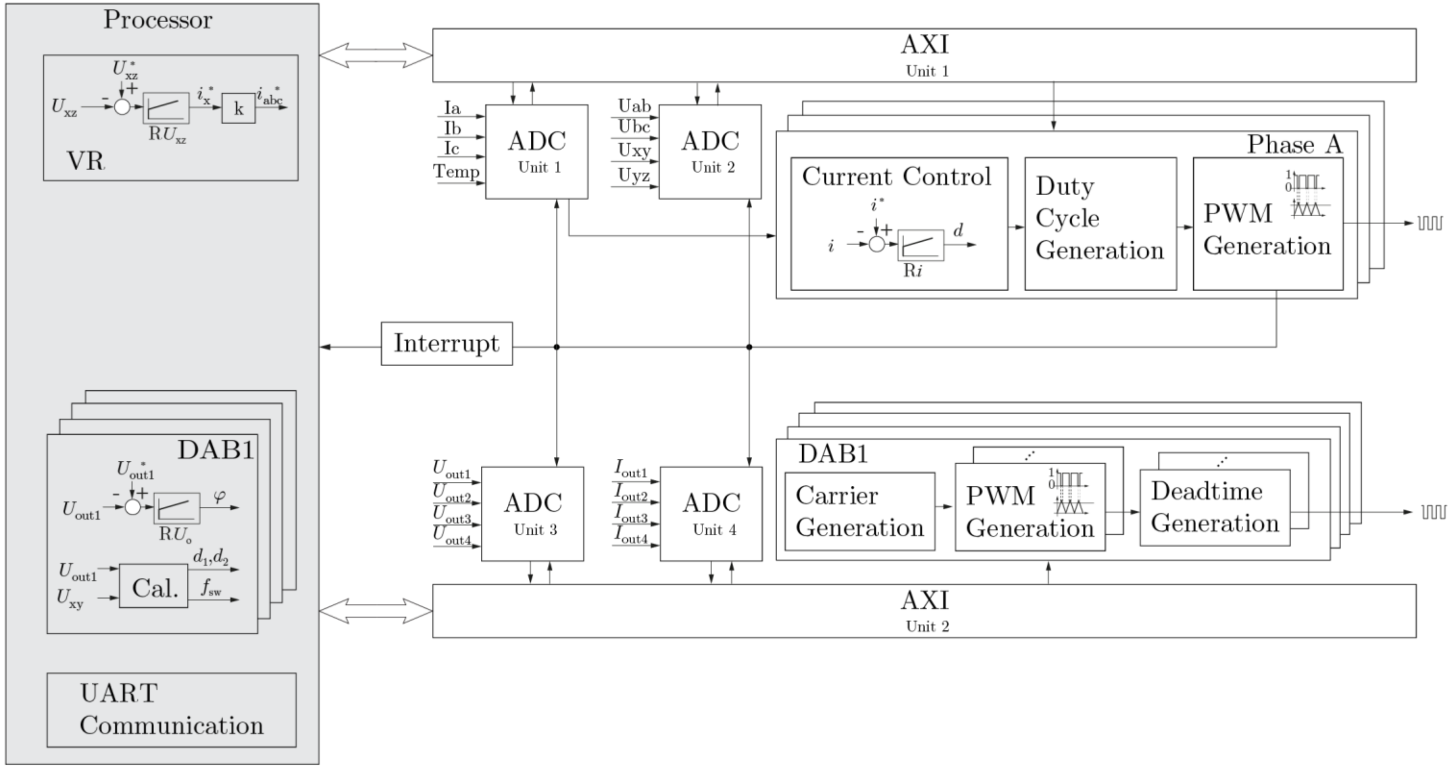
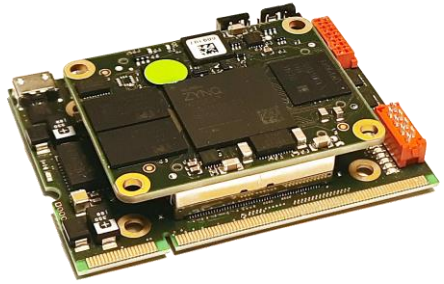
    - 30kHz
    - implemented in C



Firmware Structure



▶ Decoupled Control of VR & DAB

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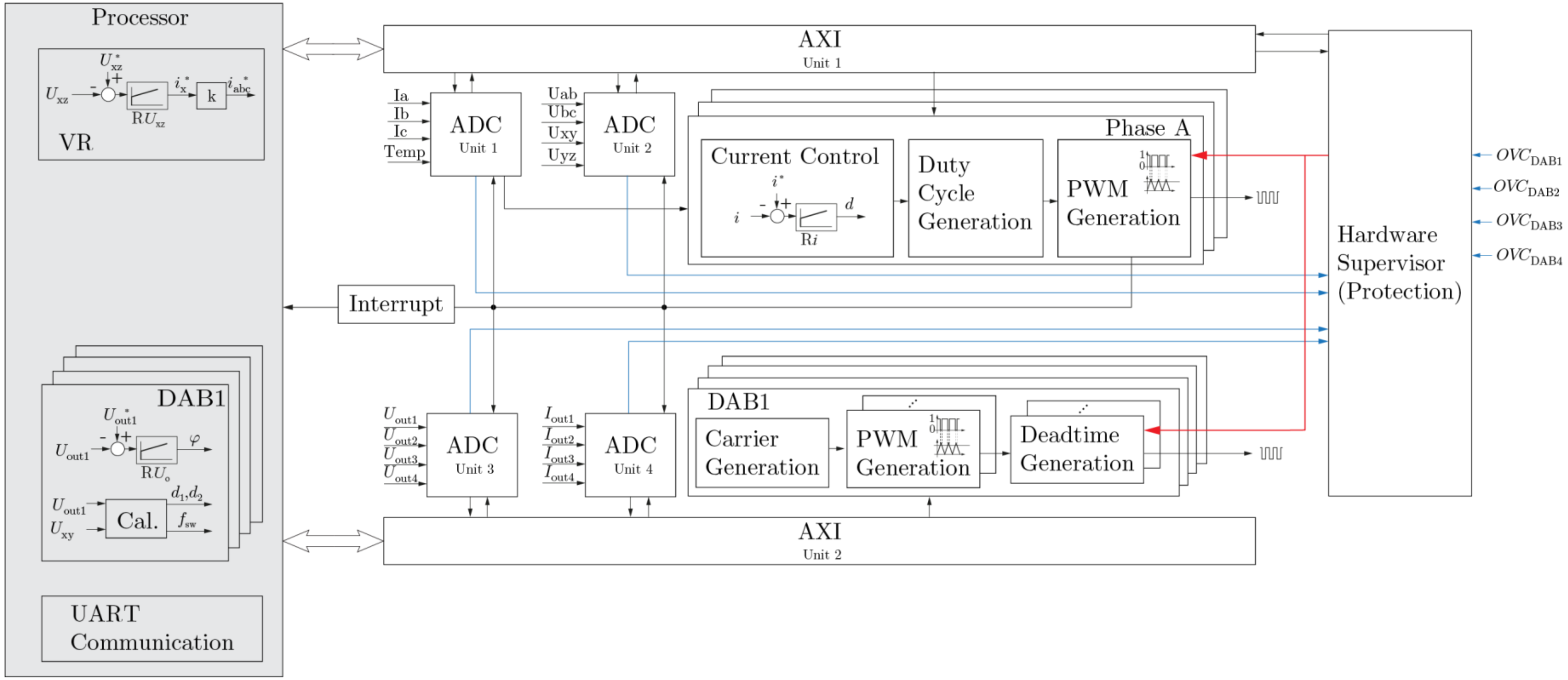
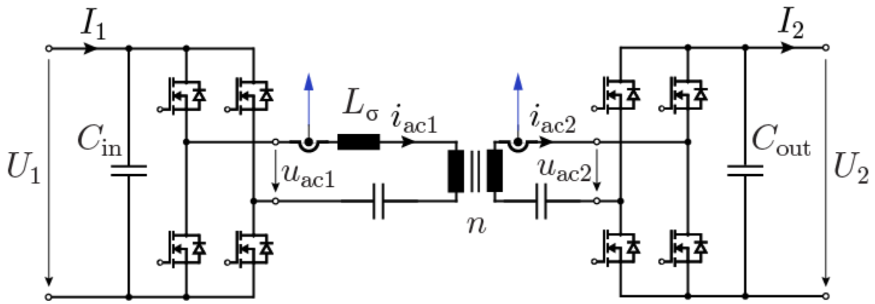
  - AXI (Advanced eXtensible Interface) protocol
- Communication between controller and laptop
  - UART
- VR
  - Output voltage control
    - 30kHz,
    - implemented in C
  - Input current Control
    - 560kHz
    - implemented in VHDL
- DAB
  - Output voltage control
    - 30kHz
    - implemented in C
- Hardware Supervisor
  - Protection

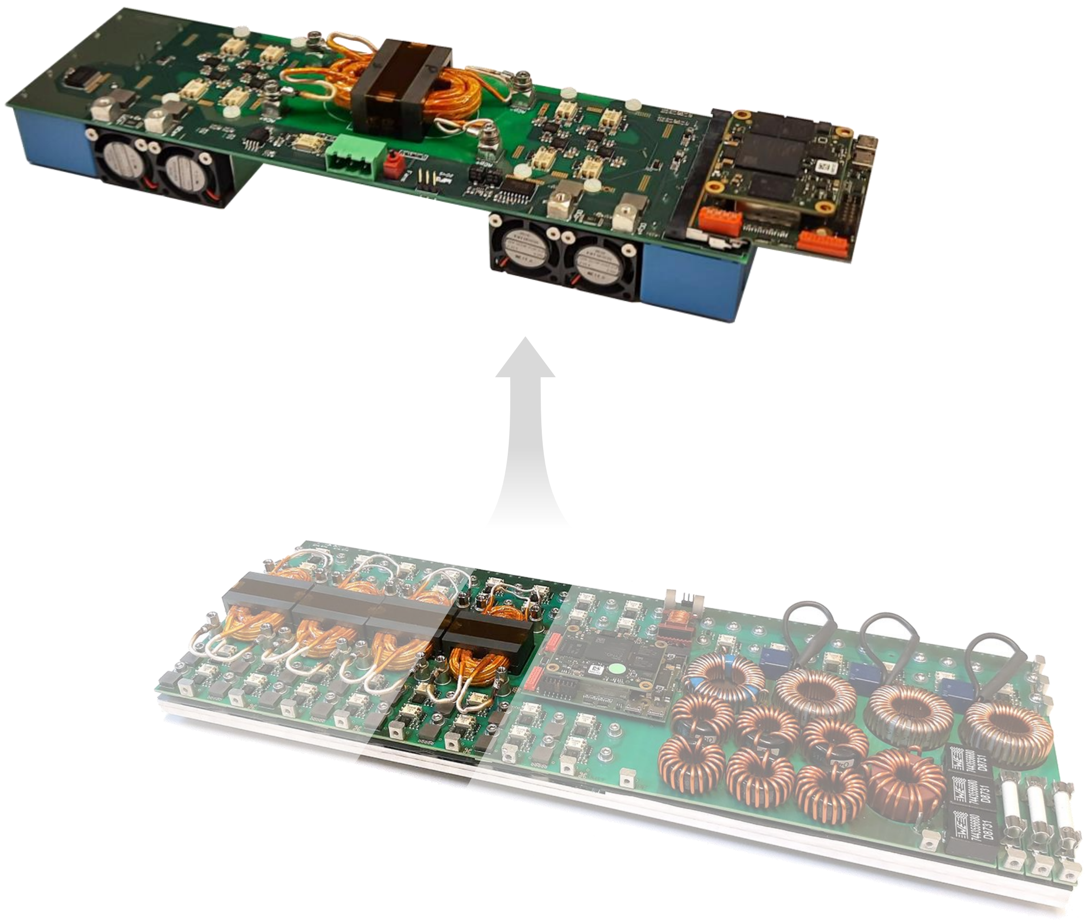


Measurements of the DAB Test System

▶ Topology & Specifications



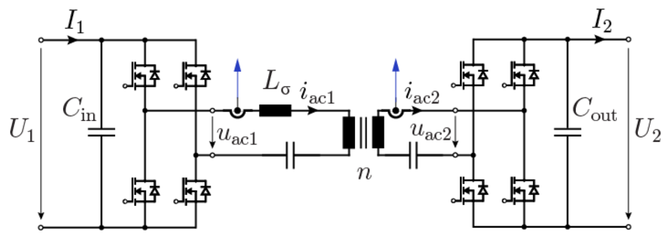
Parameters	Value
Rated Power	2.5 kW
Input Voltage Range	280-400 V_{dc}
Output Voltage Range	125-500 V_{dc}
Turns Ratio	16:10
Leakage Inductance	12uH
Switching Frequency	140kHz – 400kHz



▶ Commissioning and Measurements

- Same components

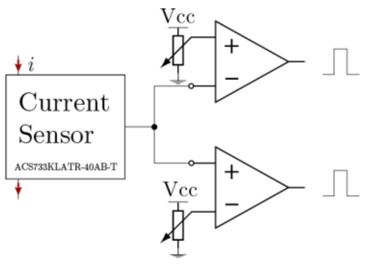
Measurements of the DAB Test System



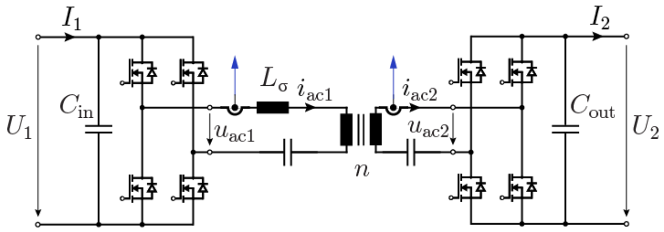
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
  - Current sensors + comparators -> digital signals to FPGA
  - Delay around 100-200ns: fast reaction



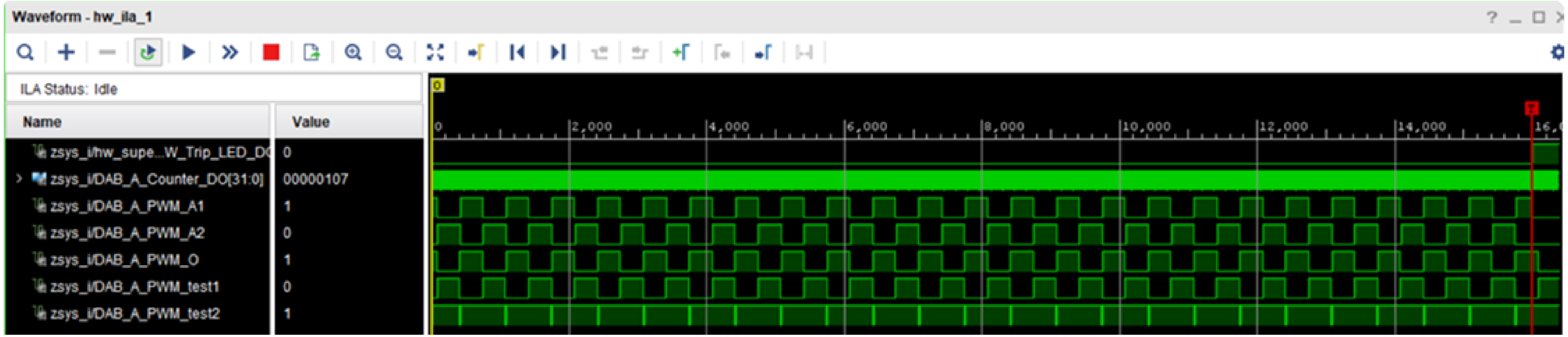
Measurements of the DAB Test System



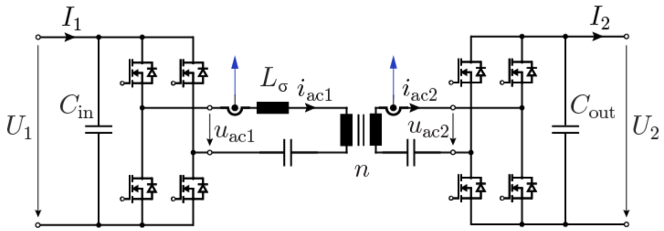
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of the Zynq platform
  - Up 64 probes per block
  - Up to 4096 bits per probe



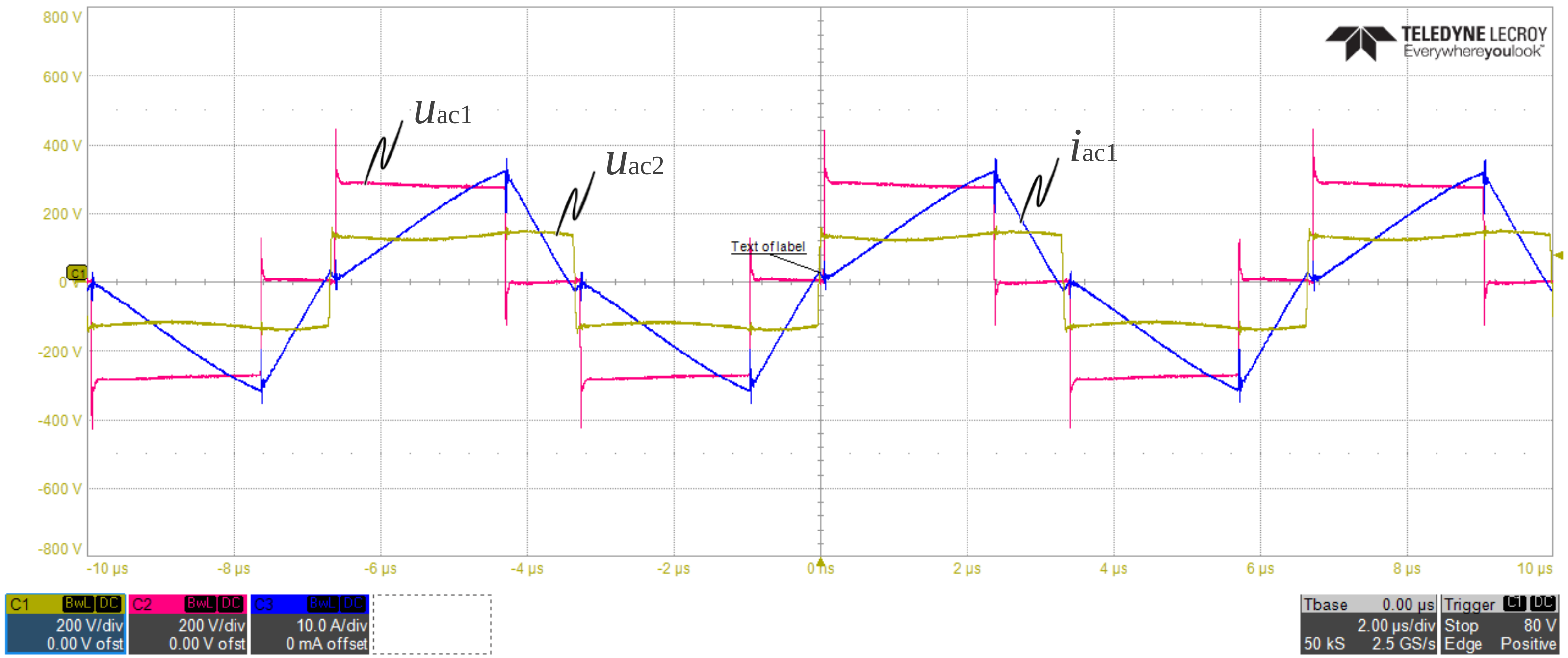
Measurements of the DAB Test System



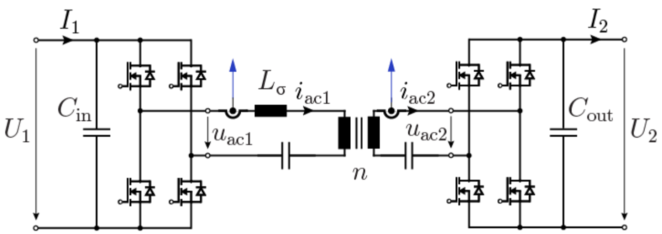
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of the Zynq platform
- Waveforms
  - 125V out (280V in)
    - Soft switching of 3 half-bridges, hard-switching of 1 half-bridge



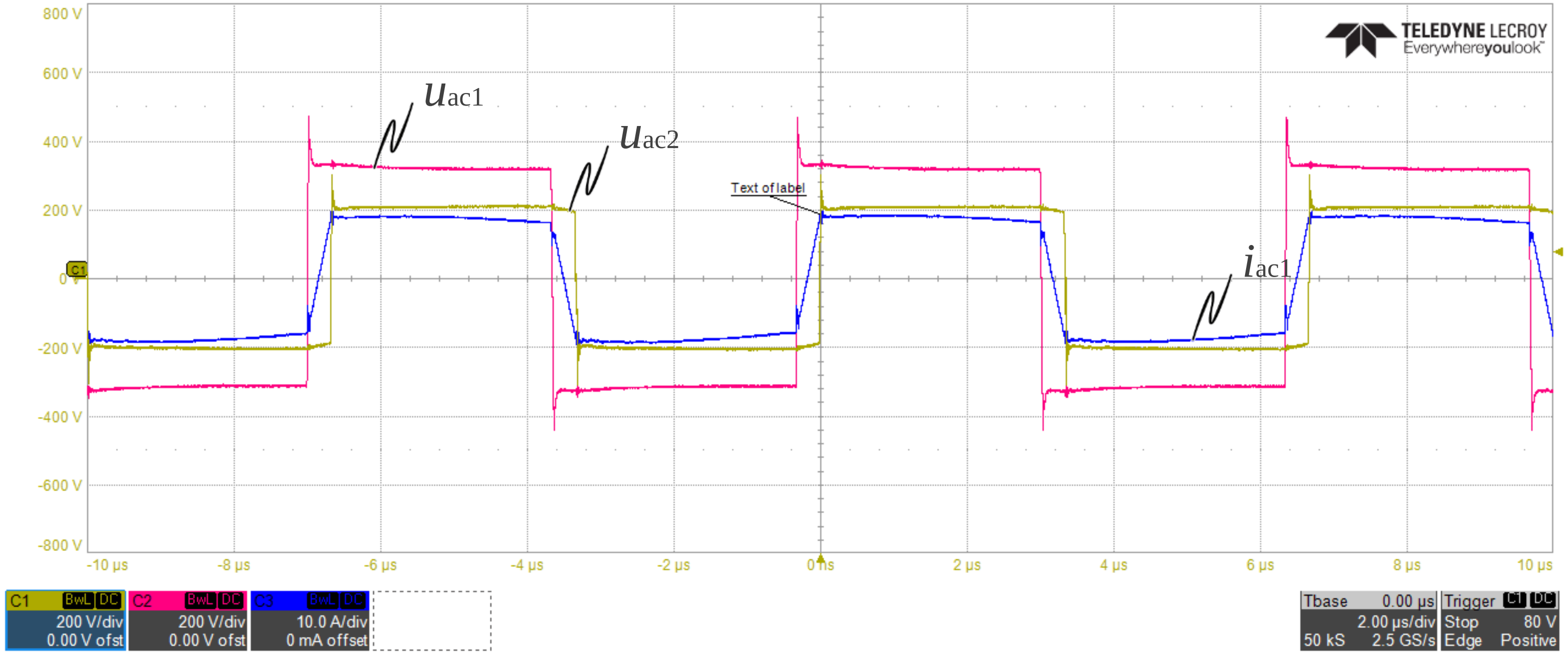
Measurements of the DAB Test System



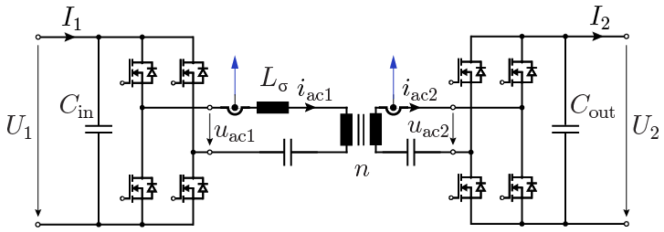
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of the Zynq platform
- Waveforms
  - 125V out
  - 200V out(320V in)
    - Soft switching for all half-bridges



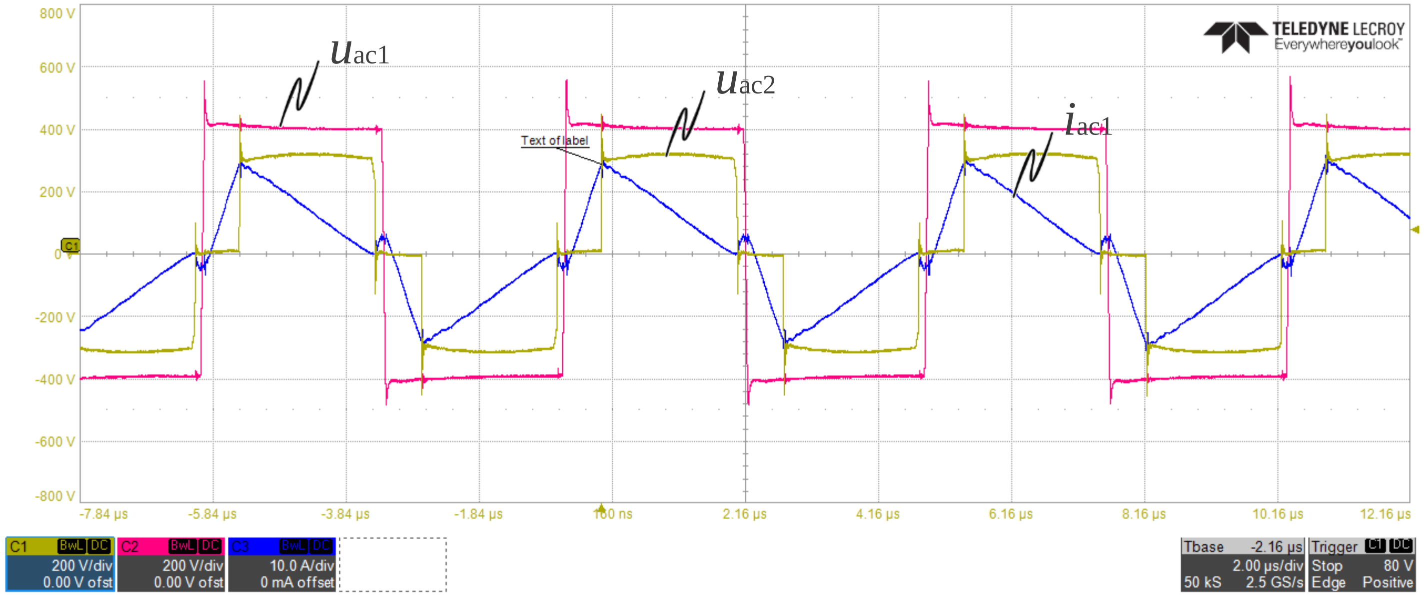
Measurements of the DAB Test System



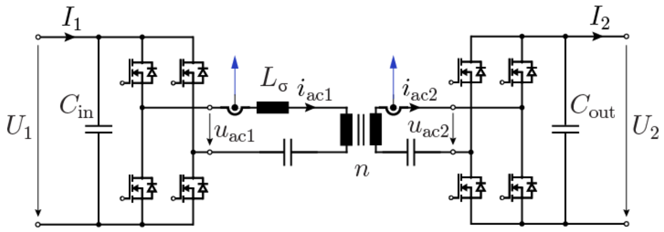
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of the Zynq platform
- Waveforms
  - 125V out
  - 200V out
  - 300V out (400V in)
    - Soft switching of 3 half-bridges, hard-switching of 1 half-bridge



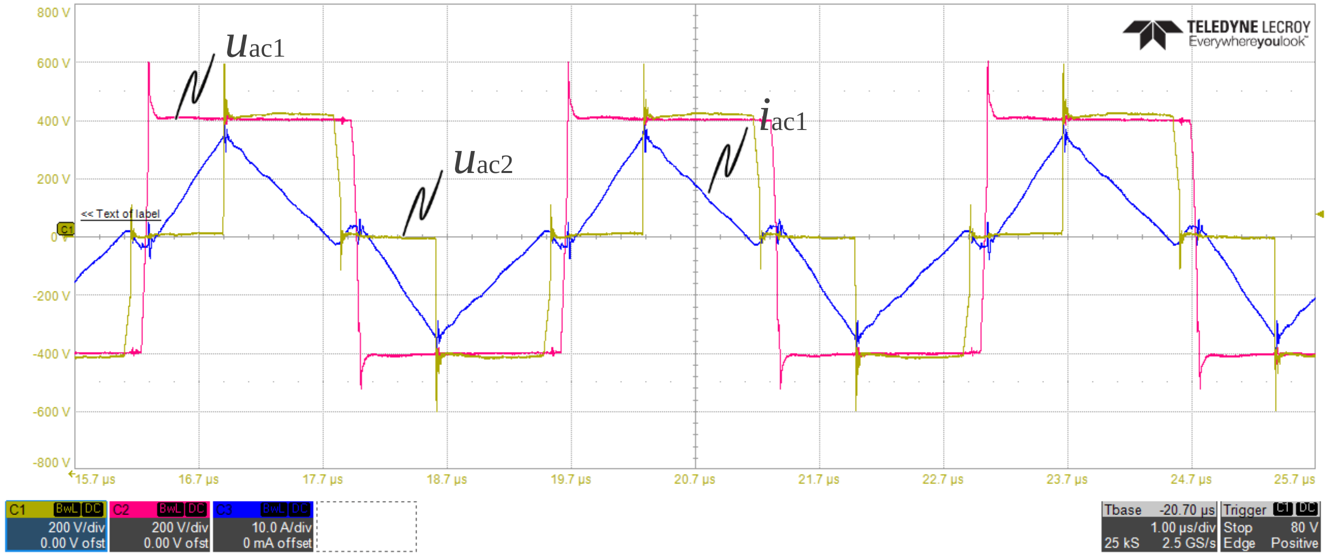
Measurements of the DAB Test System



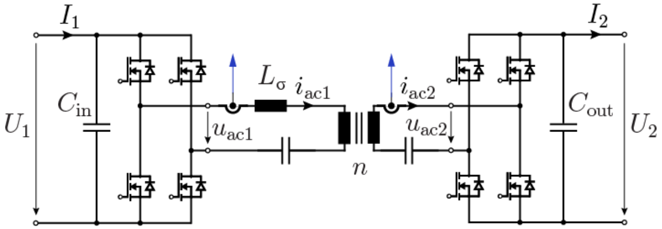
▶ Topology & Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of the Zynq platform
- Waveforms
  - 125V out
  - 200V out
  - 300V out
  - 400V out (400V in)
    - Partial-soft switching of 3 half-bridges(considering RMS current), soft-switching of 1 half-bridge



Measurements of the DAB Test System

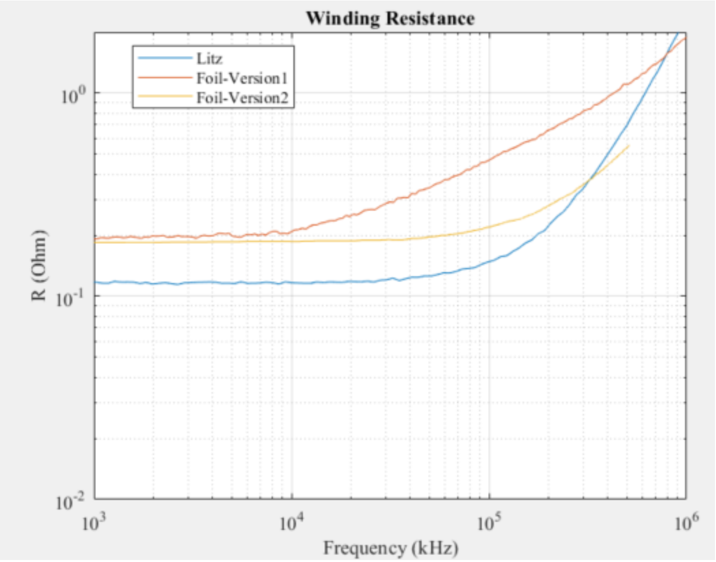


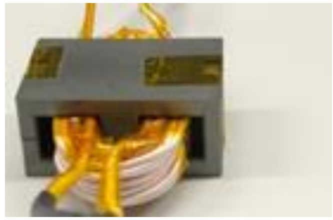
▶ Topology

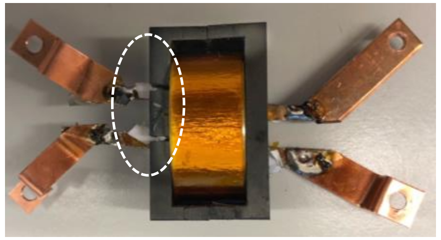
▶ Specifications

▶ Commissioning and Measurements

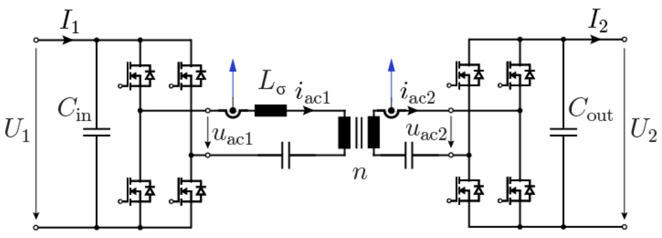
- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of Zynq platform
- Waveforms
- Transformer Design
  - Litz wire
    - Much higher R_{ac} due to integrated leakage inductance
  - Foil windings
    - In Parallel with the vertical magnetic field → lower losses
    - Easy cooling
  - Non-idealities
    - Wrinkles in the foils: eddy currents (vertically penetrating field)
    - Air gaps in the custom-made core.
    - Terminals
      - Extra air gaps to cancel the field: difficult to fix the windings in lab environment







Measurements of the DAB Test System

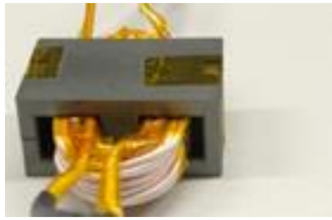


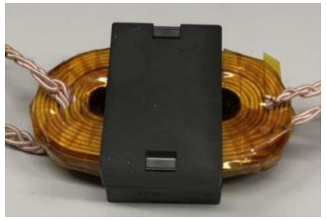
▶ Topology

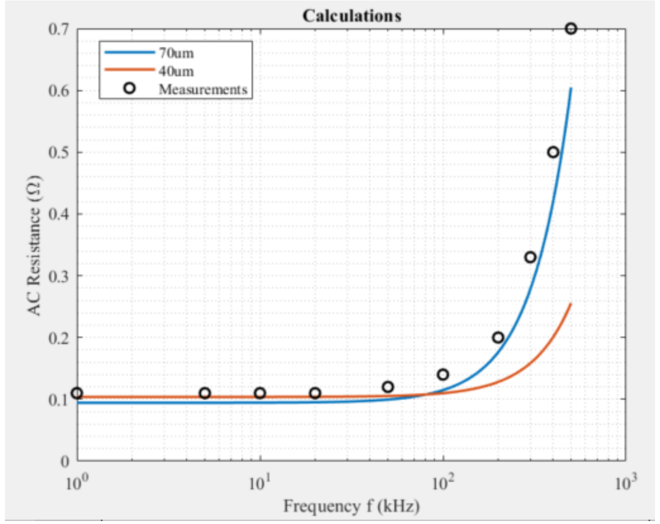
▶ Specifications

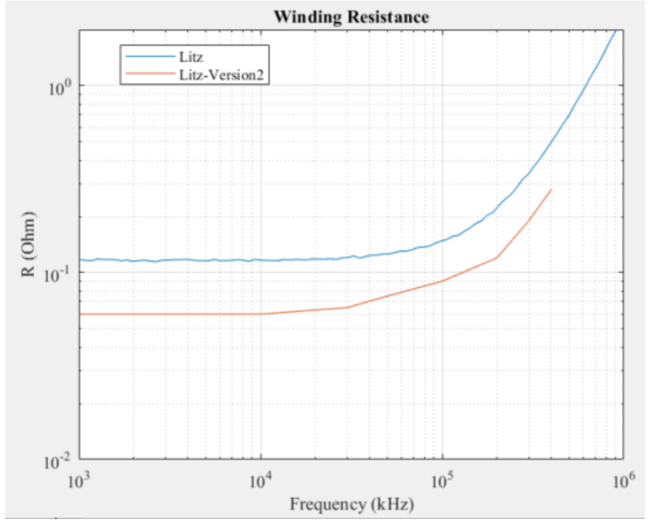
▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of Zynq platform
- Waveforms
- Transformer Design
  - Litz wire loss modeling: 70um Vs. 40um, R_{ac} decrease
  - Fully utilized winding window → lower R_{dc}
  - Parallel windings
  - Further improvements with custom-made litz wire of the appropriate number of strands

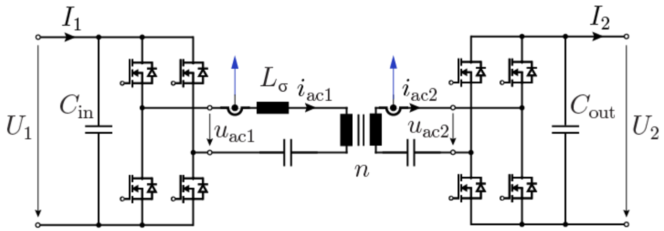








Measurements of the DAB Test System

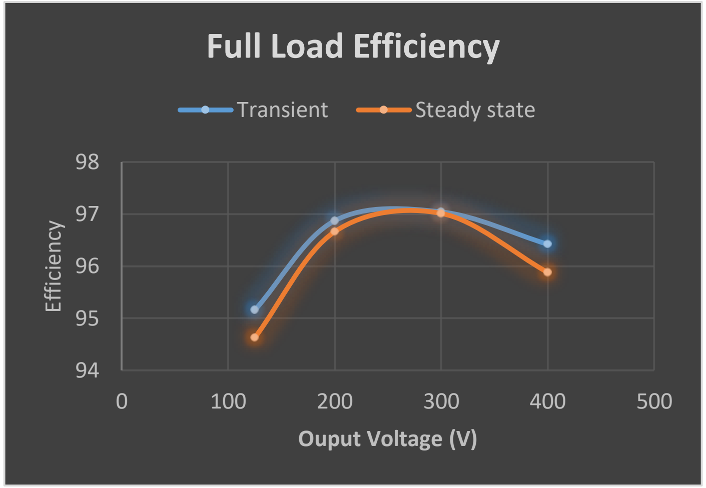


▶ Topology

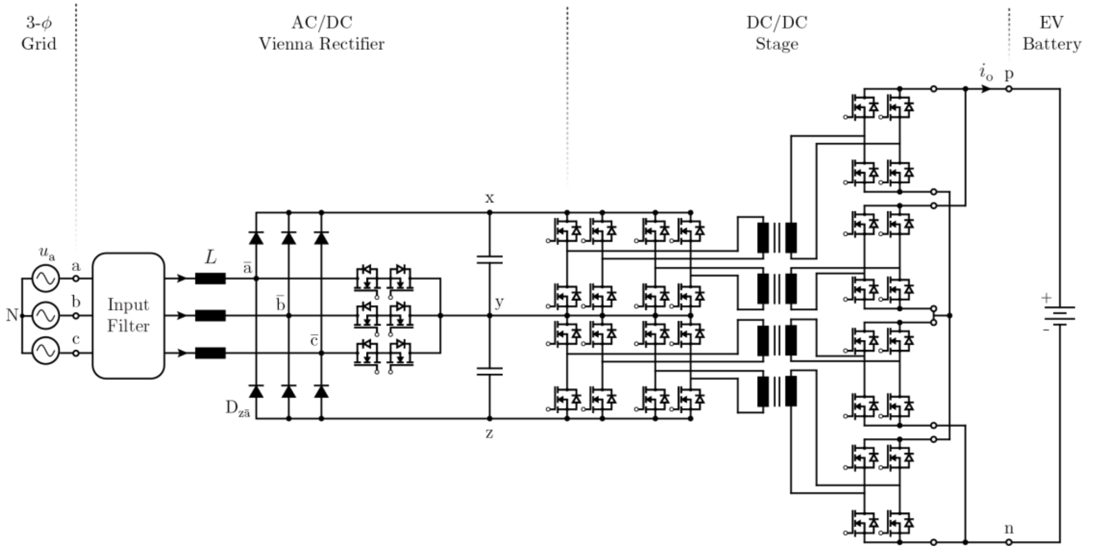
▶ Specifications

▶ Commissioning and Measurements

- Protection Circuits
- Integrated Logic Analyzer(ILA Core) of Zynq platform
- Waveforms
- Transformer Design
- Efficiency measurements
  - Peak efficiency 97%
- Temperature measurements (NTCs)
  - Core Temperature ≤ 100°C, winding Temperature ≤ 80°C



Measurements of the 10kW Demonstrator System

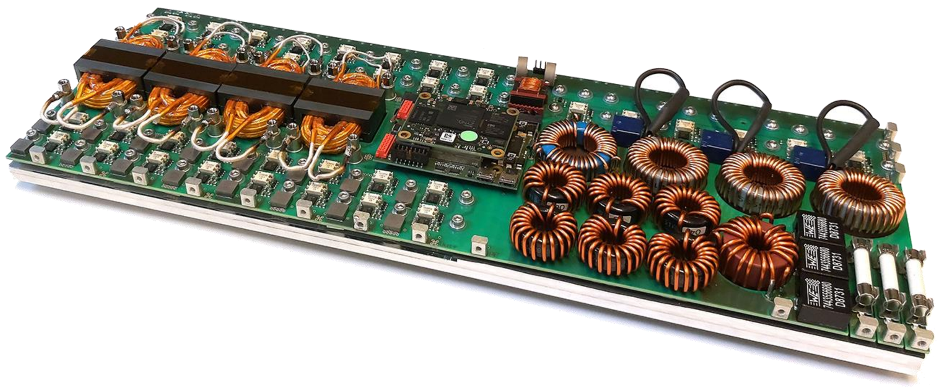


▶ Topology

- Vienna Rectifier Front-end
- 4DAB: 2 in parallel, 2 in series both input/output

▶ Specifications

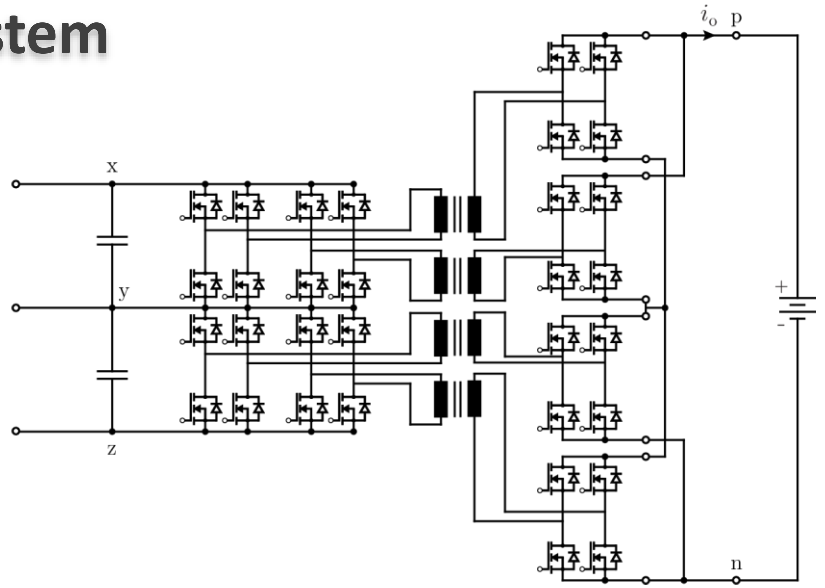
Parameters	Value
Rated Power	10 kW
Input Voltage Range	320-530 V_{rms}
Output Voltage Range	250-1000 V_{dc}
Power Density	10 kW/dm^3 (2x 20 kW/dm^3)
Size	400 x 140 x 18 mm^3
Efficiency (Target)	95 %
Switching Frequency	560kHz (VR) 140kHz – 400kHz (DAB)



▶ Semiconductors

- 600V GaN Switches (Infineon, IGOT60R070D1)
- 1200V SiC Schottky Diodes (Infineon, IDM10G120C5)

Measurements of the 10kW VR + DAB Demonstrator System



▶ Topology

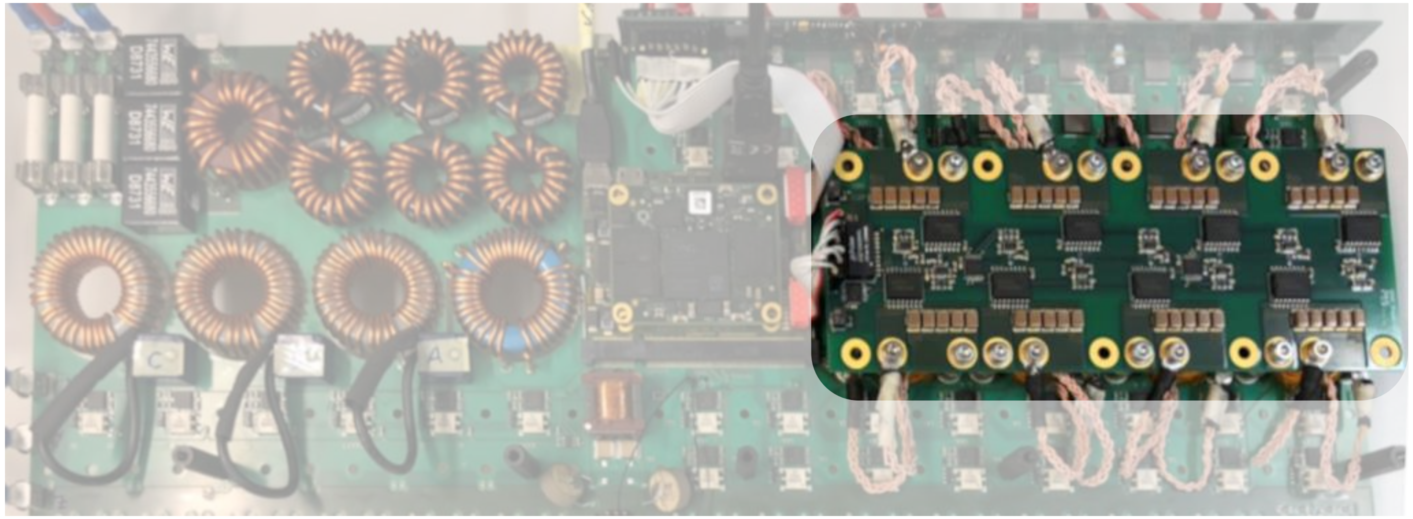
- Vienna Rectifier Front-end
- 4DAB: 2 in parallel & series, both input/output

▶ Specifications

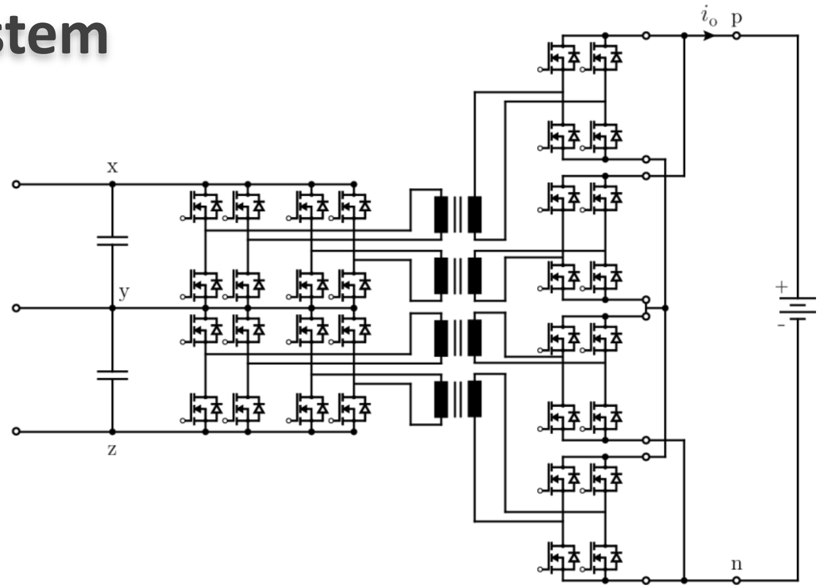
▶ Measurements of the VR

▶ Measurements of the DABs

- Protection board
  - 4 channels for each DAB, both primary & secondary sides



Measurements of the 10kW VR + DAB Demonstrator System



▶ Topology

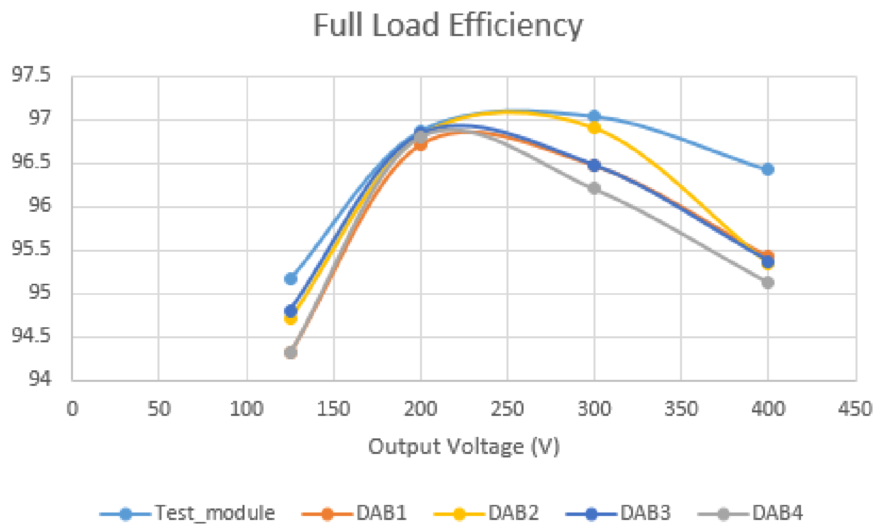
- Vienna Rectifier Front-end
- 4DAB: 2 in parallel & series, both input/output

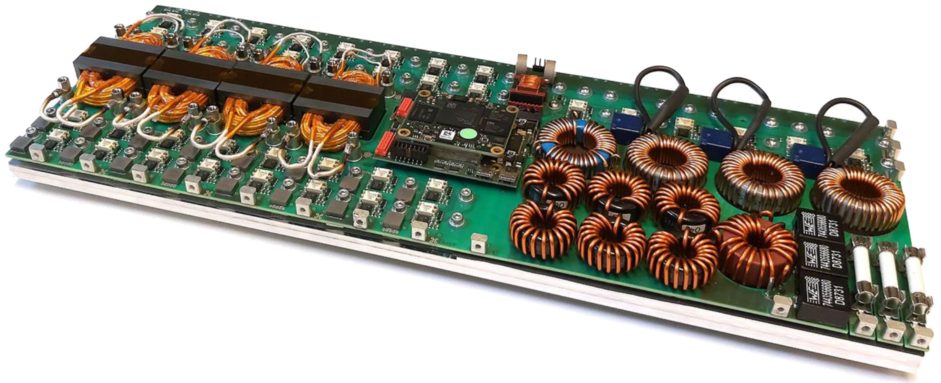
▶ Specifications

▶ Measurements of the VR

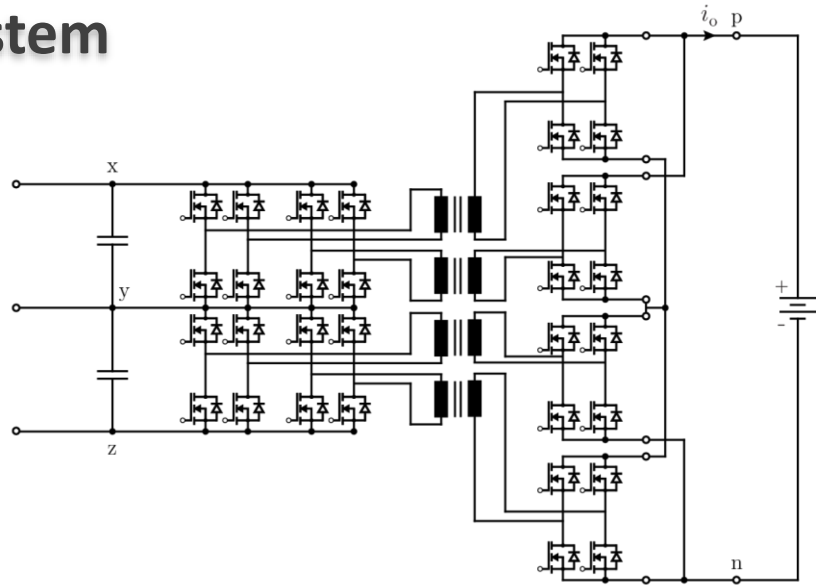
▶ Measurements of the DABs

- Protection board
- Efficiency measurements of 4 individual modules
  - Transformer terminals close to PCB traces → magnetic field & eddy currents
  - Layout





Measurements of the 10kW VR + DAB Demonstrator System



▶ Topology

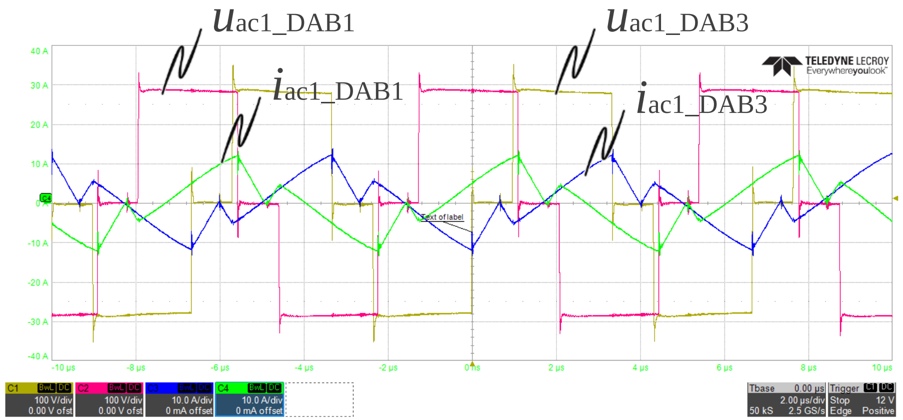
- Vienna Rectifier Front-end
- 4DABs: 2 in parallel & series, both input/output

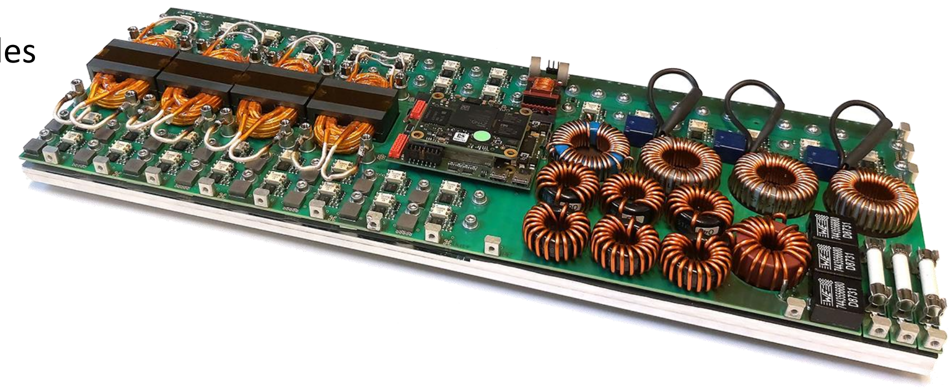
▶ Specifications

▶ Measurements of the VR

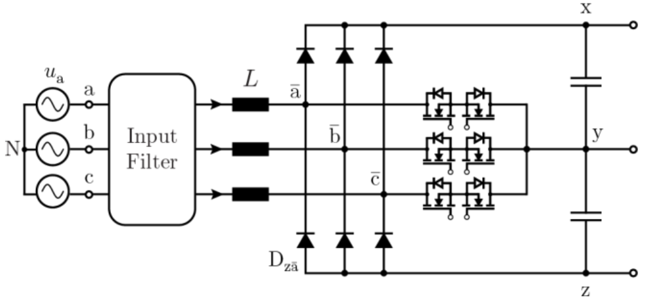
▶ Measurements of the DABs

- Protection board
- Efficiency measurements of 4 individual modules
- Operation of 2 modules (125V out)
  - Input in series, output in parallel
  - Balanced currents
  - Random phase-shift: possible to be synchronized to minimize output voltage ripples



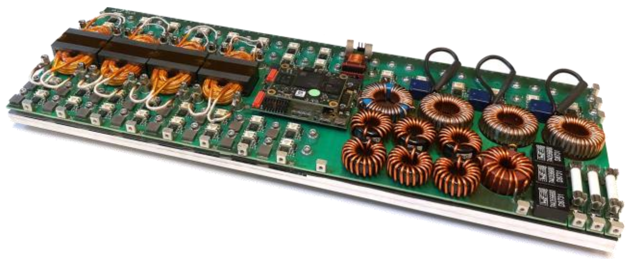


Measurements of the 10kW VR + DAB Demonstrator System



▶ Topology

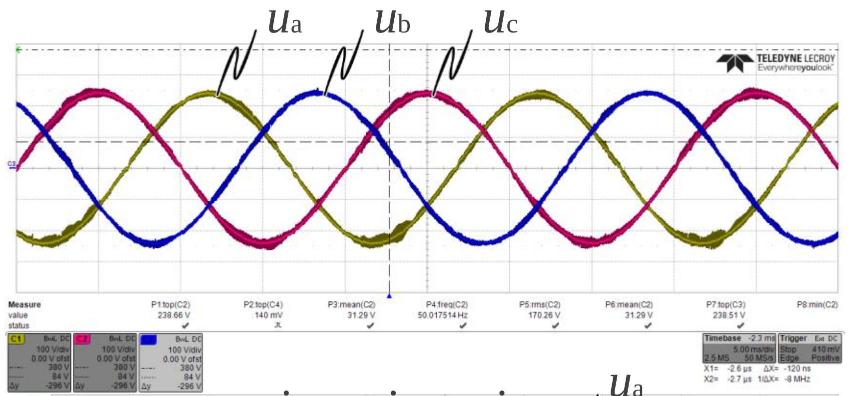
- Vienna Rectifier Front-end
- 4DABs: 2 in parallel, 2 in series both input/output

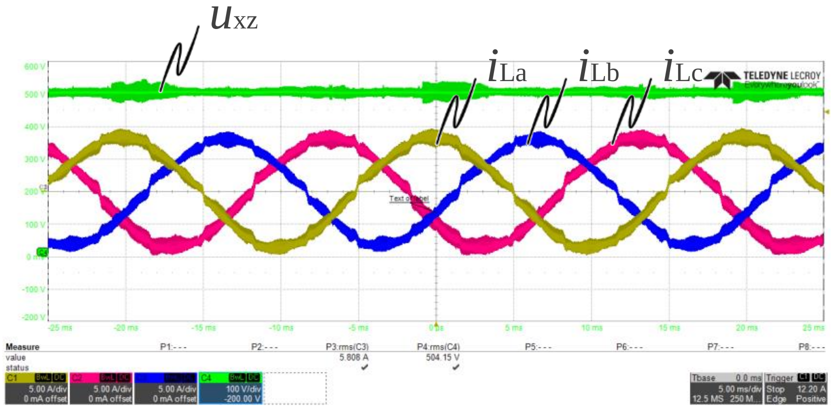


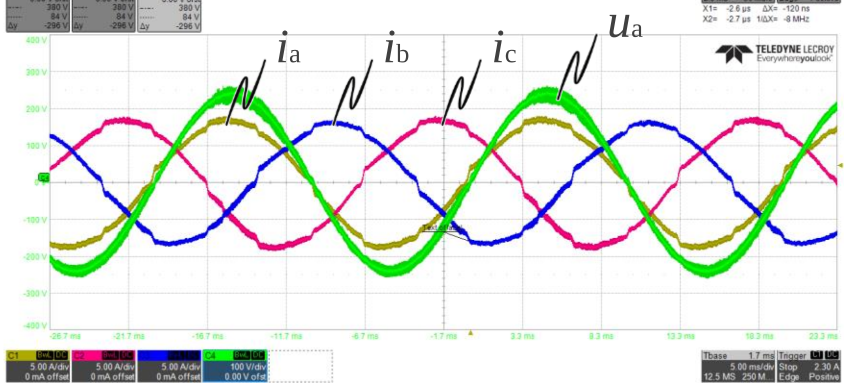
▶ Specifications

▶ Measurements of the VR

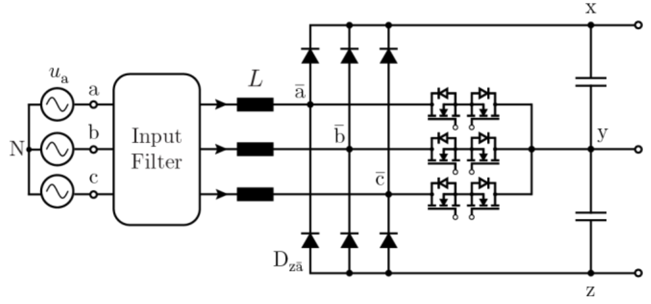
- 500V DC link voltage, 3kW
- Three-phase sinusoidal input currents Vs. voltages
- THD: 5.37%
- Currents in the boost inductors







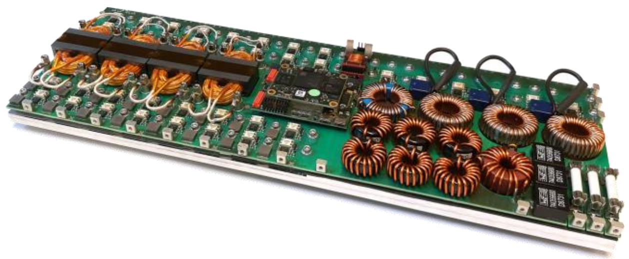
Measurements of the 10kW VR + DAB Demonstrator System



▶ Topology

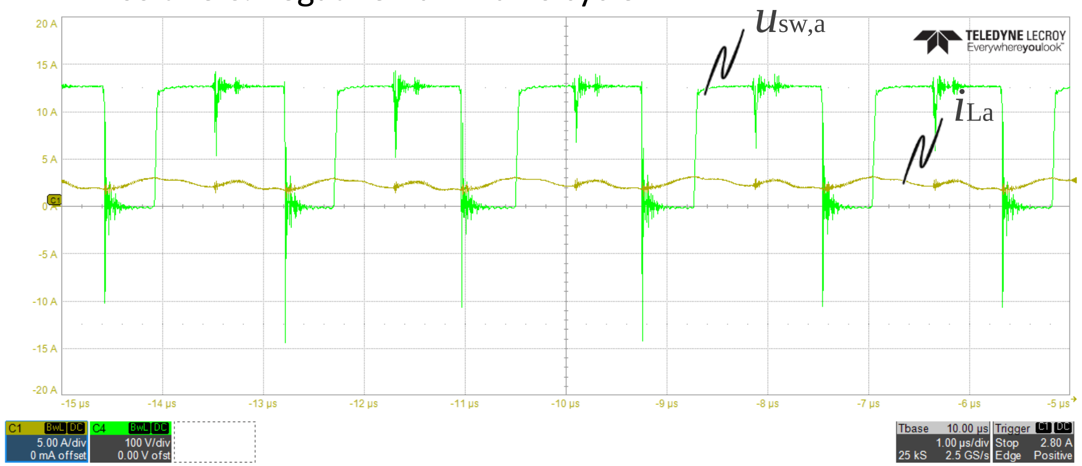
- Vienna Rectifier Front-end
- 4DABs: 2 in parallel & series, both input/output

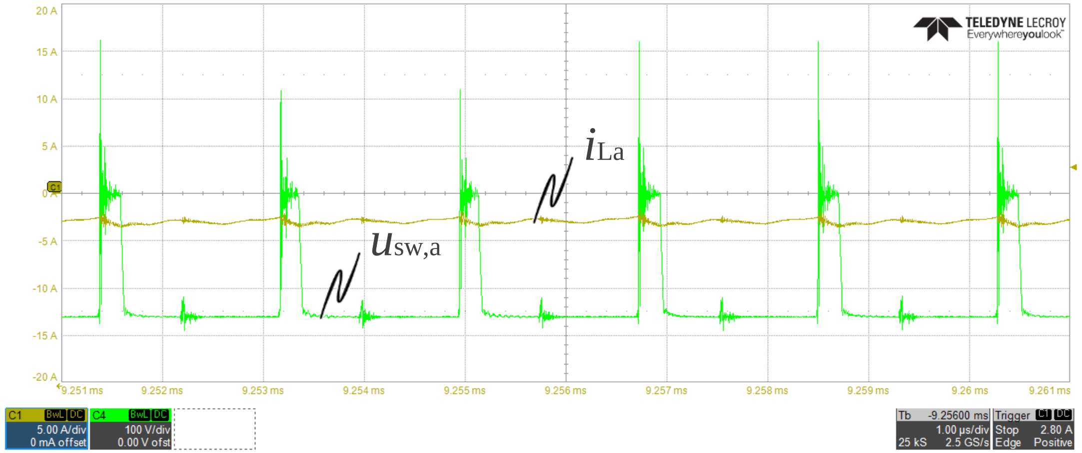
▶ Specifications



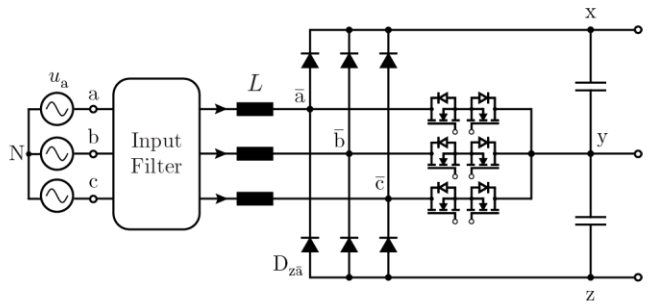
▶ Measurements of the VR

- 500V DC link voltage, 3kW
- Three-phase sinusoidal input currents Vs. voltages
- THD: 5.37%
- Currents in the boost inductors
- Switching node voltages
  - Positive & negative half mains cycle





Measurements of the 10kW VR + DAB Demonstrator System



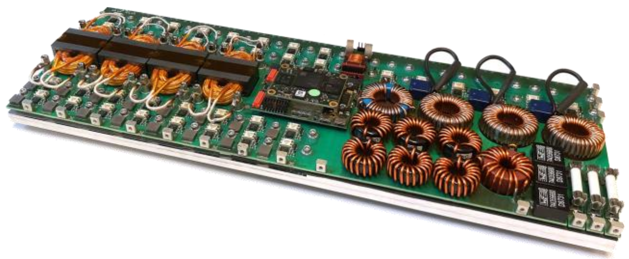
▶ Topology

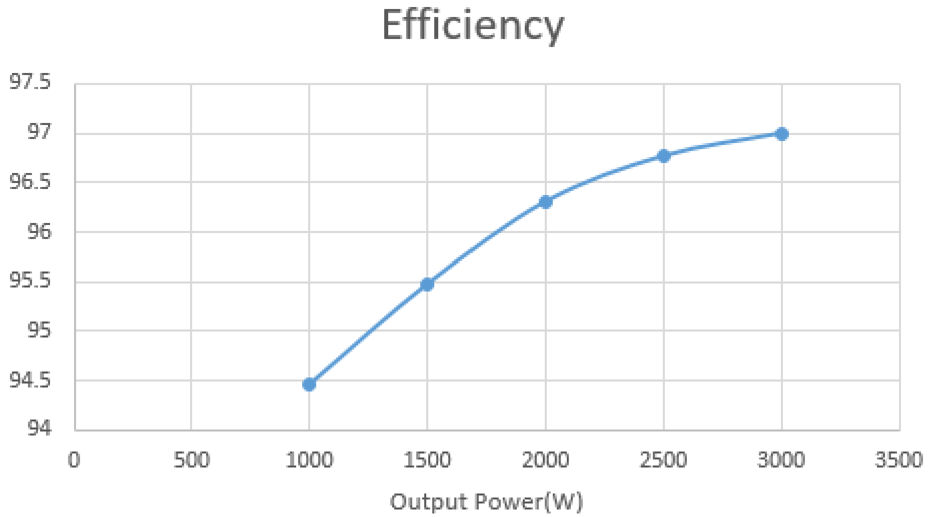
- Vienna Rectifier Front-end
- 4DABs: 2 in parallel & series, both input/output

▶ Specifications

▶ Measurements of the VR

- 500V DC link voltage, 3kW
- Three-phase sinusoidal input currents Vs. voltages
- THD: 5.37%
- Currents in the boost inductors
- Efficiency measurements (Yokogawa 3000WT, 500V)
- 700V, 5kW, 97%
- Higher Efficiencies expected for full-load
- Further improvement with 1/3 modulation





Measurements of the 10kW VR + DAB Demonstrator System

▶ **Topology**

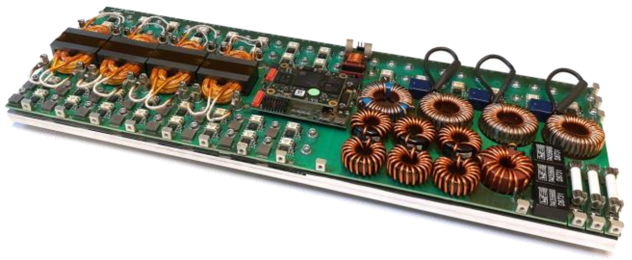
- Vienna Rectifier Front-end
- 4DABs: 2 in parallel & series, both input/output

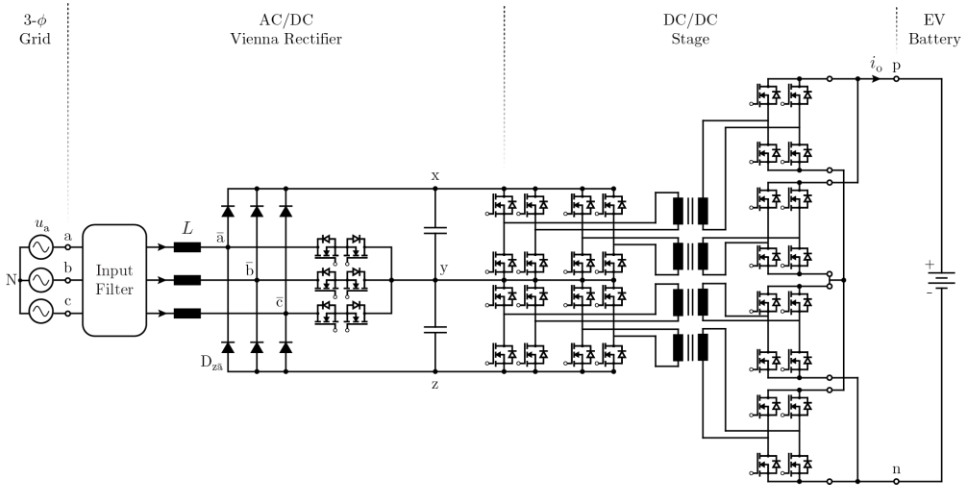
▶ **Specifications**

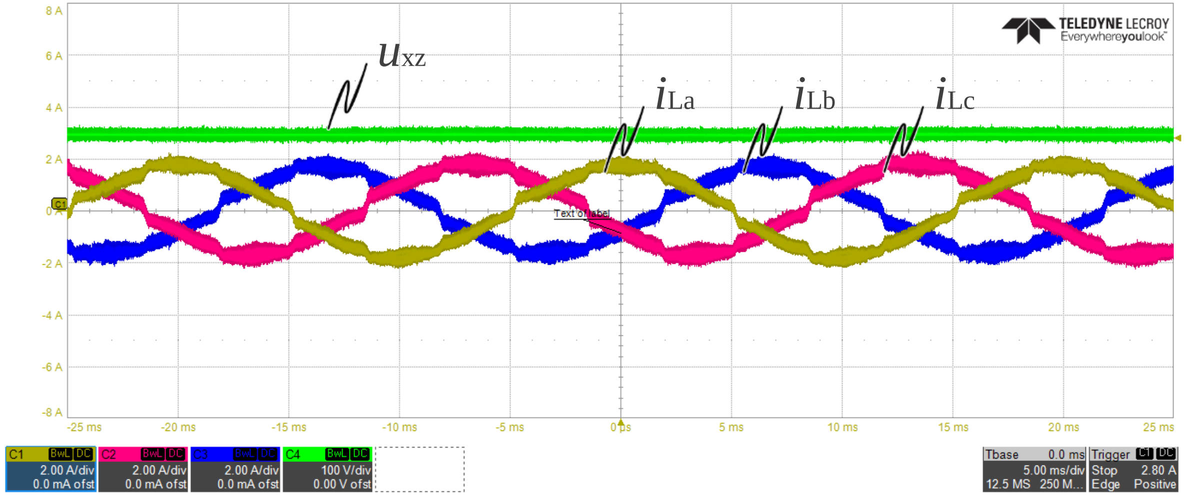
▶ **Measurements of the VR**

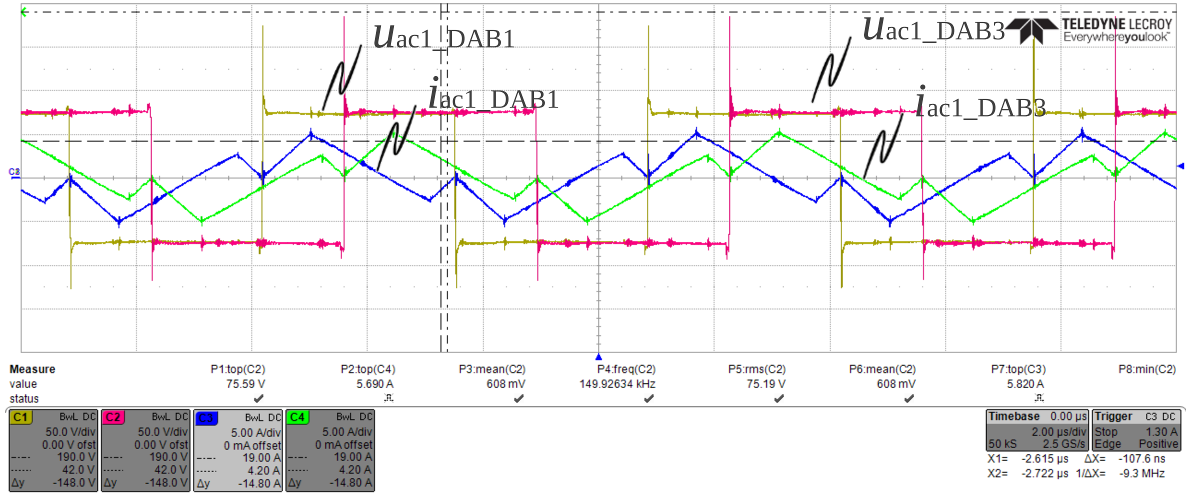
▶ **Measurements of the DABs**

▶ **Measurements of the VR + 2xDABs**









Measurements of the 10kW VR + DAB Demonstrator System

▶ Topology

- Vienna Rectifier Front-end
- 4DABs: 2 in parallel & series, both input/output

▶ Specifications

▶ Measurements of the VR

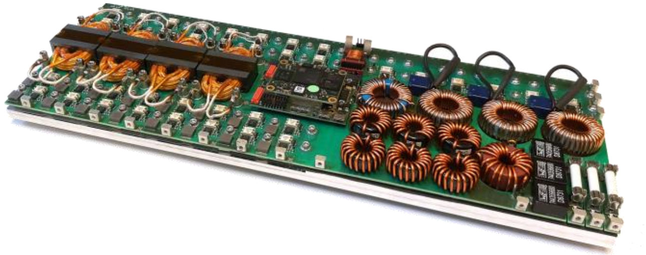
▶ Measurements of the DABs

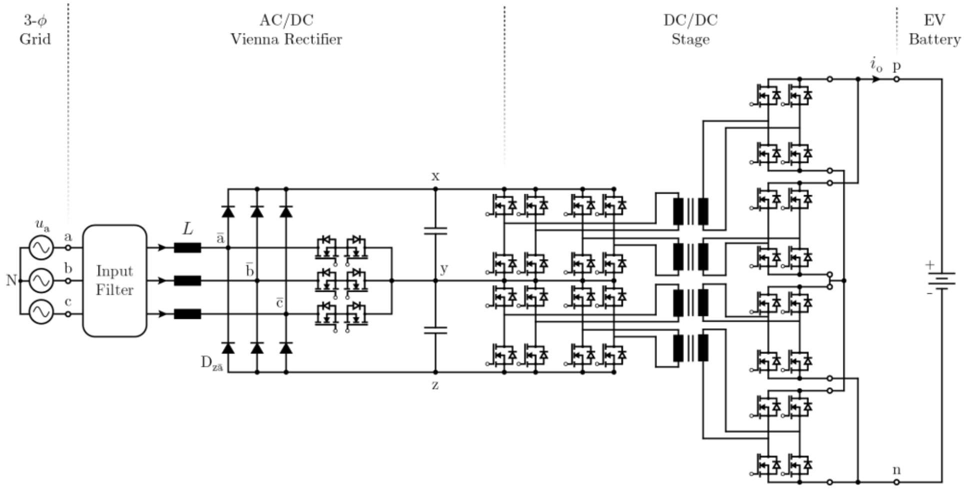
▶ Measurements of the VR + 2xDABs

- Missing Pulses at higher voltages

▶ Next Steps

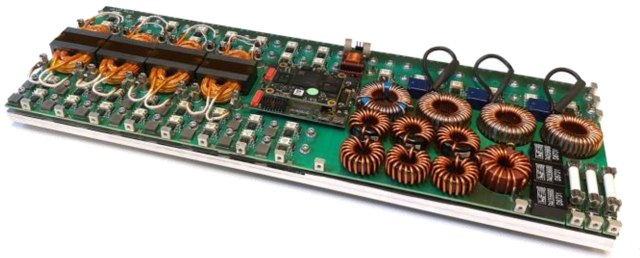
- Test VR at higher voltages & power
- Looking into the missing-pulse problem
- Possible redesign of the system





Conclusions and Takeaways

- ▶ Proposed Solutions for EV Charger: 1/3 VIENNA Rectifier + Isolated DC/DC Converter
- ▶ Principle Verification
- ▶ Firmware Implementation
- ▶ Protection Circuits for Complex Systems
- ▶ Transformer Design
- ▶ Commissioning of the Isolated DC/DC Stage: Test System
- ▶ Commissioning of the Isolated DC/DC Stage: 4 Individual Modules
- ▶ Commissioning of the VR
- ▶ Combination Operation of Both Stages: in Progress
- ▶ Noise Suppression in Layout Design



Thank You !