The Path Towards 10kW 3-Phase On-Board Chargers

Featuring 600V CoolGaN^{TM} GIT HEMT Technology

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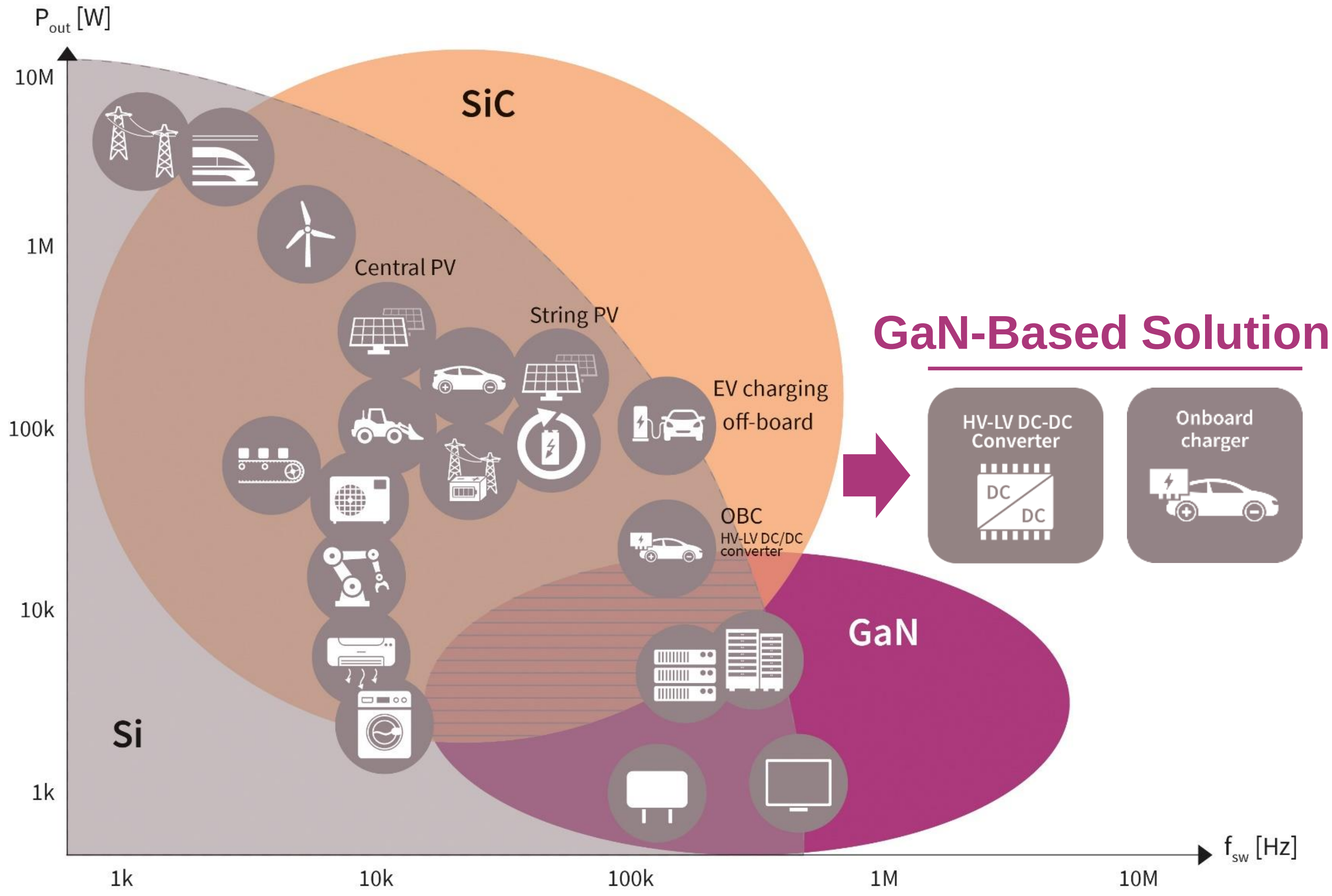
GaN has the potential to redefine automotive OBC and DCDC applications when moving towards high switching frequency

Comparison of technologies



Si

- Si remains the mainstream technology
- Targeting 25 V – 6.5 kV
- Suitable from low to high power

SiC

- SiC complements Si in many applications and enables new solutions
- Targeting 650 V – 3.3 kV
- High power – high switching frequency

GaN

- GaN enables new horizons in power supply applications and audio fidelity
- Targeting 80 V – 600 V
- Medium power – highest switching frequency

GaN has the potential to revolutionize On Board Chargers, as enabler of ultra high power density designs beyond 6 kW/L

2020
2 kW/L

Si → SiC

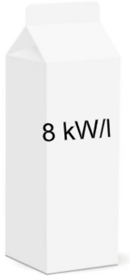
Double power density

2024
4 kW/L

SiC → GaN

Ultra dense design

>2025
>6 kW/L



Ultimate Goal

Cost effective solutions
Si / SiC based

- Up to 96% Efficiency
- High cost – performance ratio
- 400V and 800V capable

Evolution

High power density / Integration

- Merged functionalities (OBC + DCDC + more)
- Top Side Cooling packaging technology
- 400V and 800V capable

Revolution

Ultra high power density requires full system approach

- Ultra low loss designs possible
- Ultra high power density

Challenges...

- Wide input/output voltage range
- Buck-Boost capability
- 1-Φ & 3-Φ op. w/o 1/3 derating
- Bi-Directionality

System Introduction of an EV Charging Unit

Paving the Path towards Ultra-Compact OBC

- **Wide EV Battery Voltage Range**
  - **$400V_{rms,in}$ → $250...1000\ V_{dc,out}$**
- **AC/DC: 3-Φ Vienna Rectifier**
  - **550 kHz:** CoolGaN™ GIT + CoolSiC™ Schottky
  - Novel Synergetic Control: **1/3 PWM**
- **DC/DC: 4x D**ual **A**ctive **B**ridges (DABs)
  - **140...400 kHz:** CoolGaN™ GIT HEMT

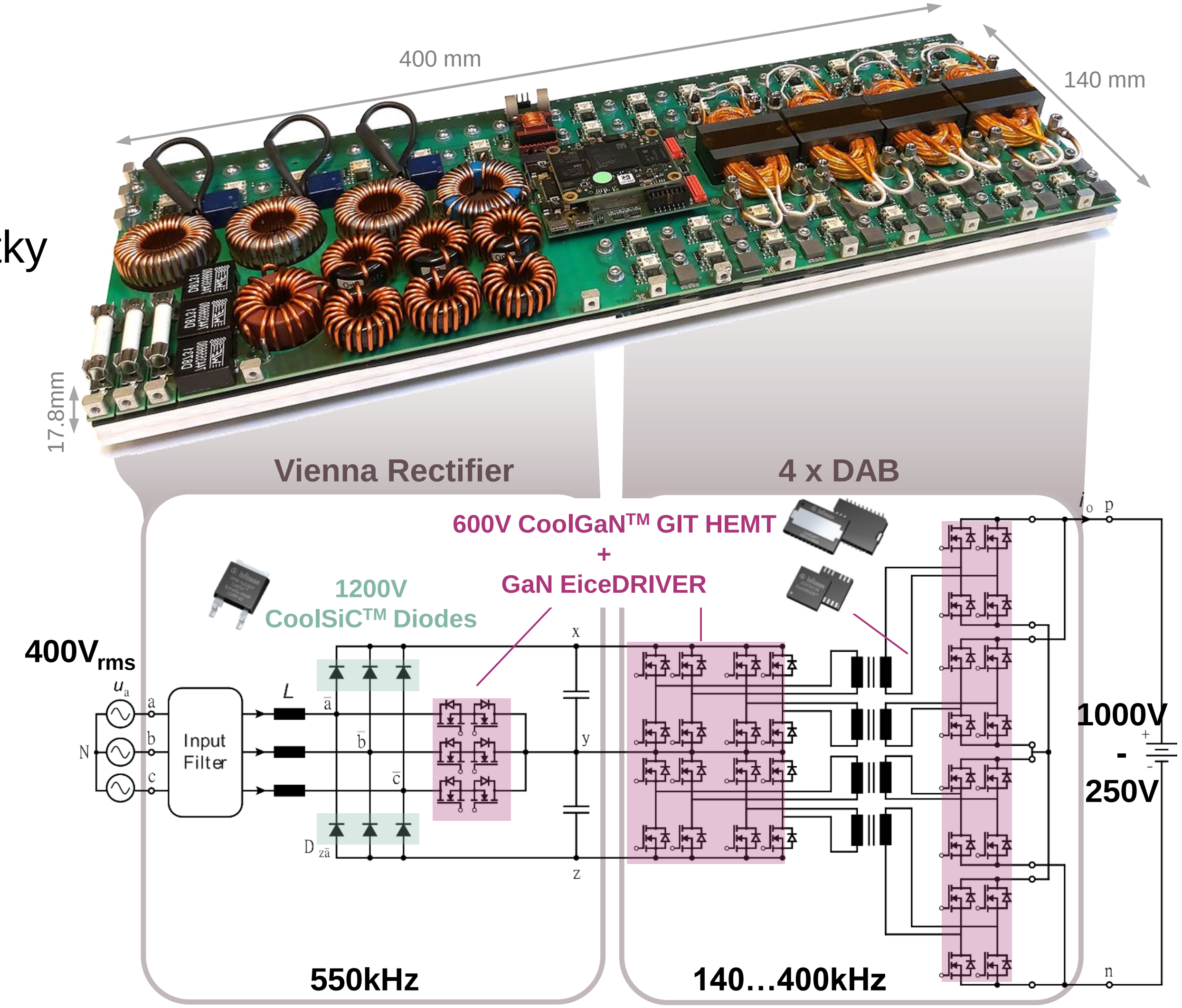
Power Density
10 kW/L*

* Casing/cooling not included

Efficiency
94.8%*

* Measured at 5kW, $400V_{out}$, more measurements pending

- How do we achieve such power density?



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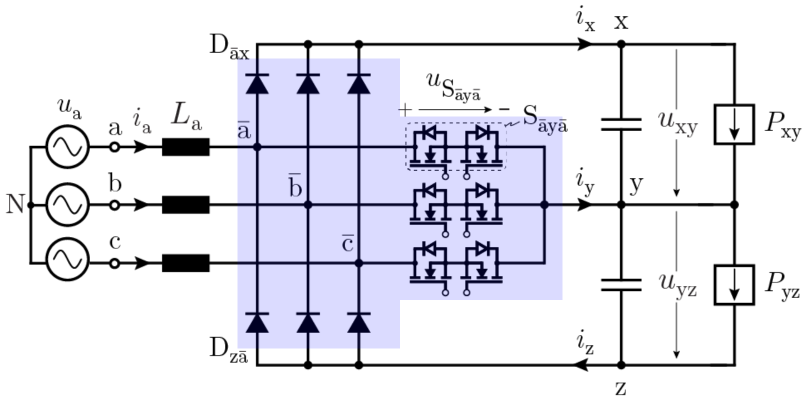
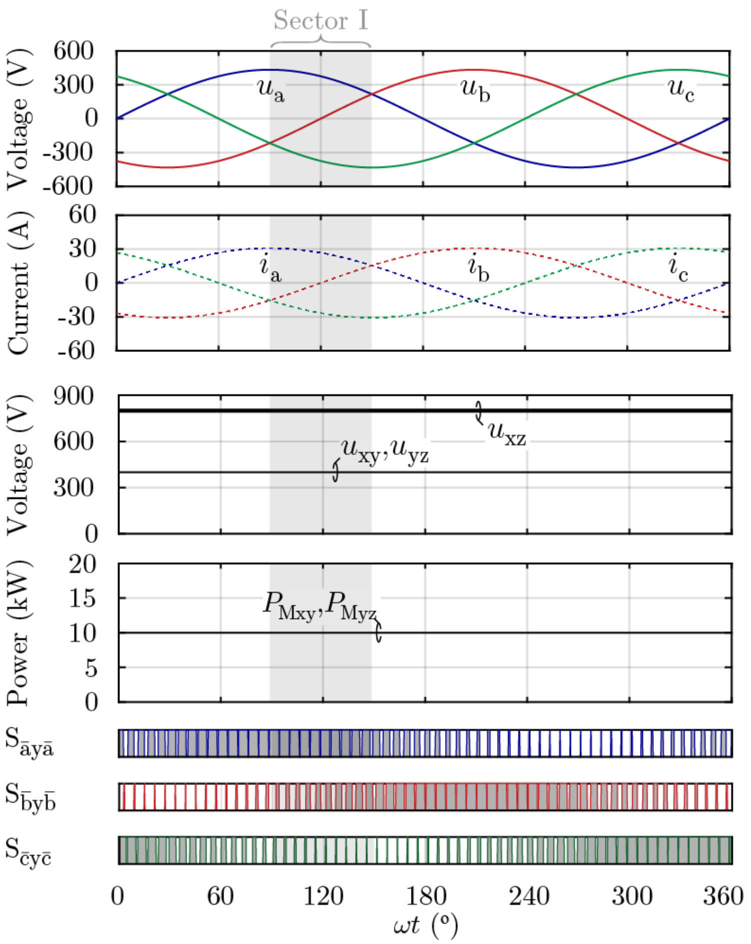
AC/DC Stage: Vienna Rectifier

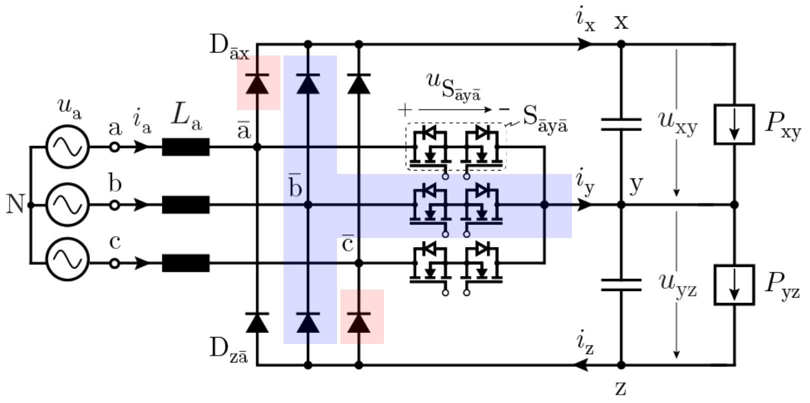
- **Conventional Modulation**
  - **3/3 PWM**: 3 out of 3 phases pulse-width modulated
  - **Constant** DC Voltage: 800V
  - **Decoupled** AC/DC and DC/DC: Large DC Link Caps

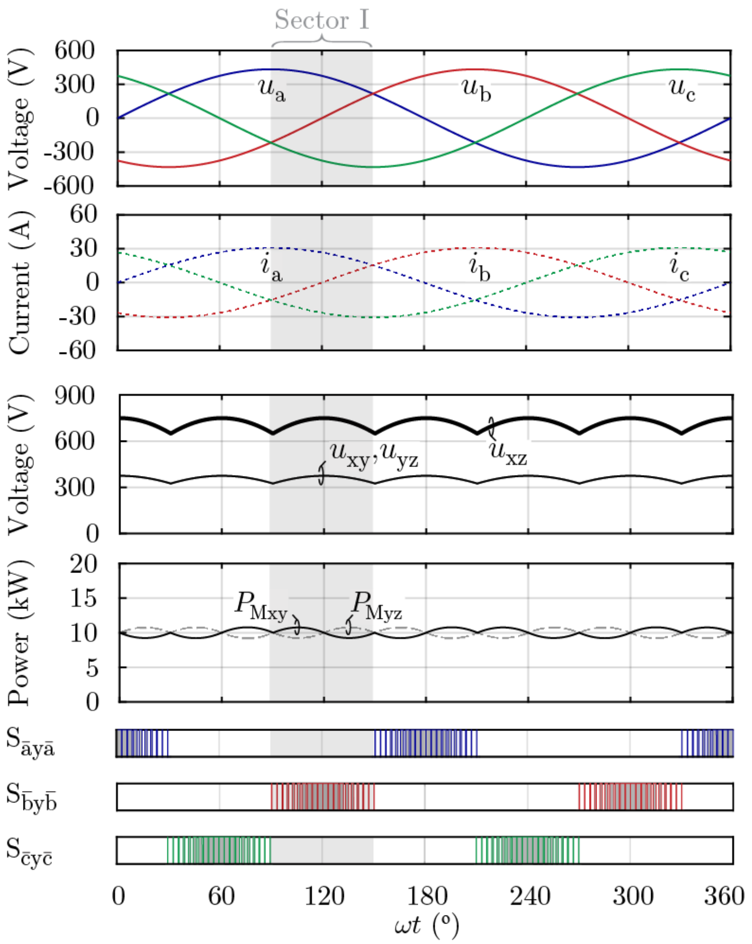




AC/DC Stage: Vienna Rectifier

- **Novel Modulation**
  - **1/3 PWM**: 1 out of 3 phases pulse-width modulated
    - a.k.a. "**Synergetic Control**"
  - **Variable** DC Voltage
  - **Coupled** AC/DC and DC/DC: Small DC Link Caps
  - Significant **Switching Loss Saving**
    - Performance improvement: efficiency/power density
    - Cost reduction: higher R_{dson} devices if always in 1/3 PWM operation

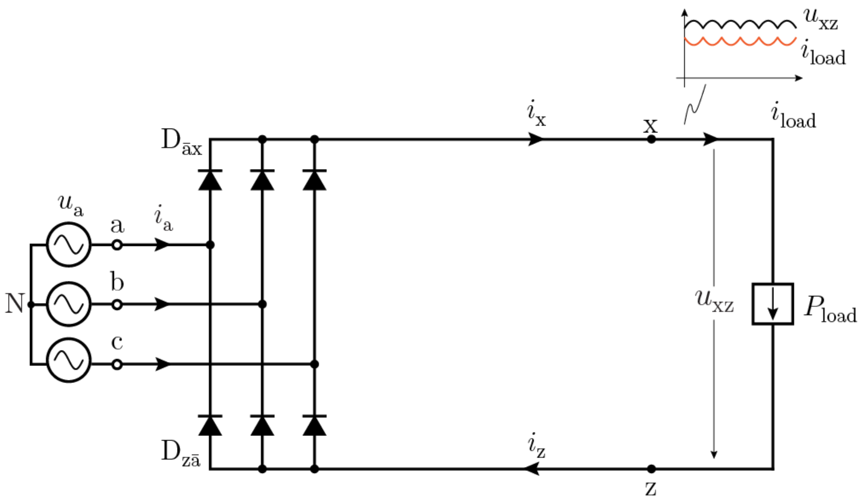


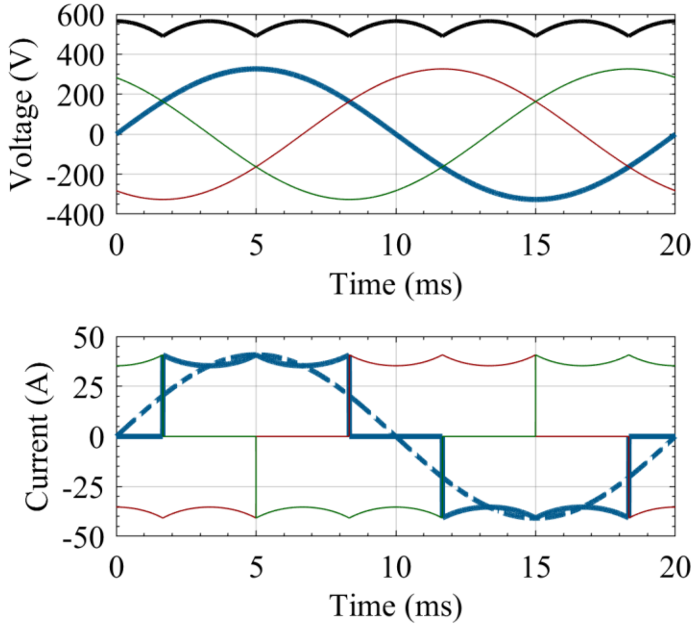


AC/DC Stage

Operation Principle of the 1/3 PWM

- **Diode Rectifier**
  - **Constant Power Load**
  - Simple Realization
  - Minimum DC-Link Voltage → Six Pulse Shape
  - **Block-Shaped Input Currents** → Low Freq. Harmonics / No PFC

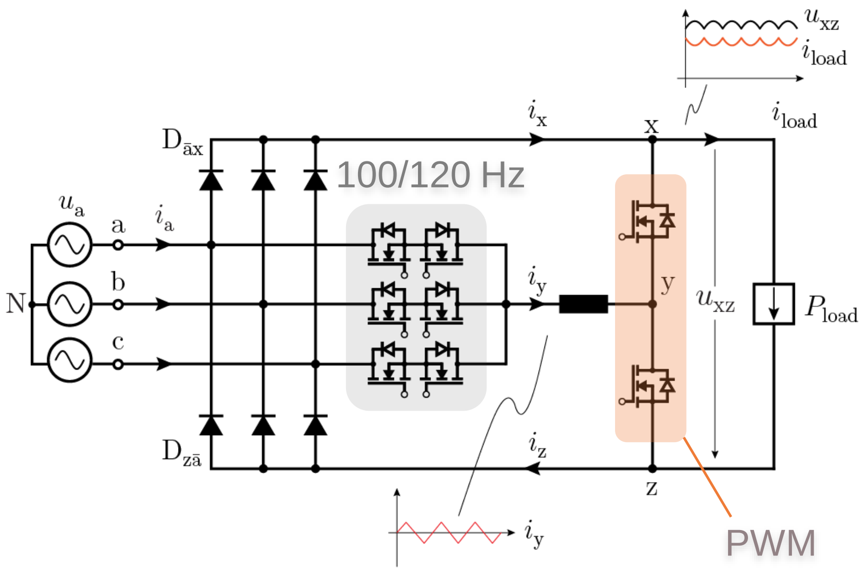


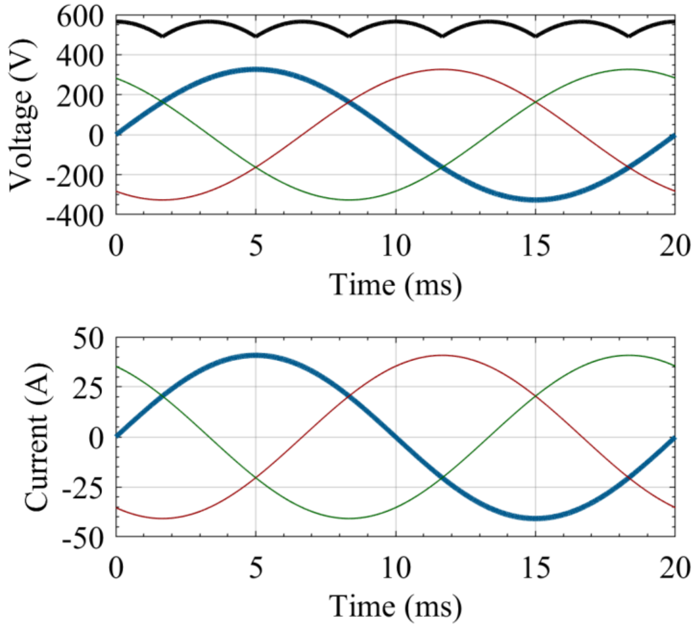


AC/DC Stage

Operation Principle of the 1/3 PWM

› **Integrated Active Filter (IAF)**
  – Only 1 Bridge Leg PWM
  – Insert a Current Prop. To Smallest Voltage in the "Middle Phase"
  – "Phase-Selector" 100/120Hz Switches
  – Active Sinusoidal Input Currents
  – No Boost Capability 😐

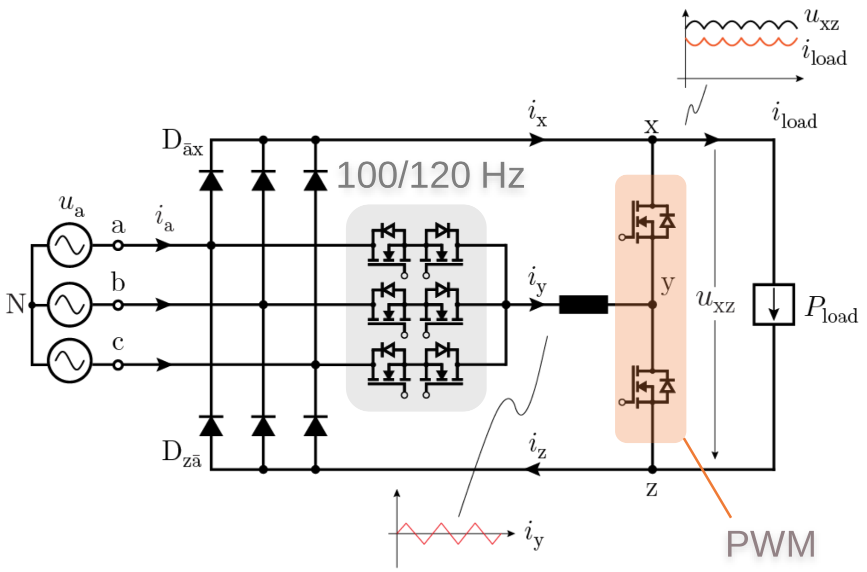


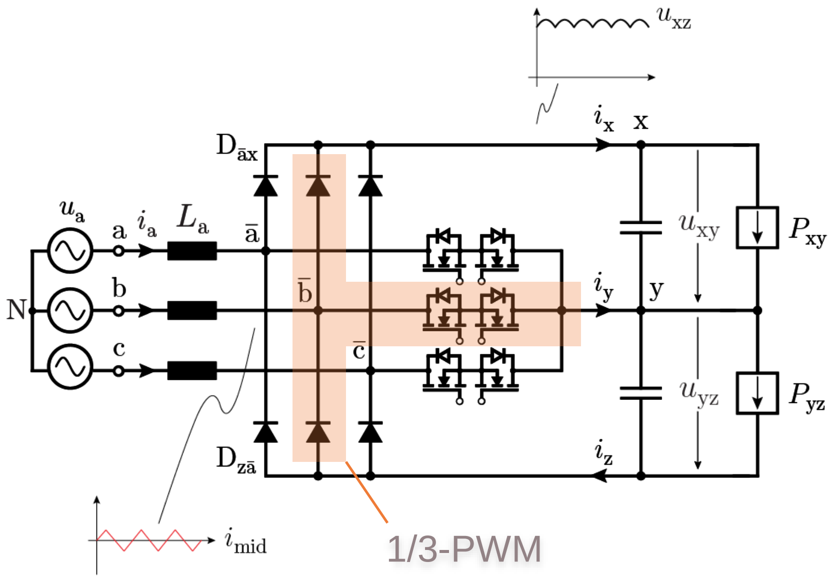


AC/DC Stage

Operation Principle of the 1/3 PWM

- **Integrated Active Filter (IAF) vs. Vienna Rectifier**
  - 3-Φ PFC Rectification is achieved with both
  - 1x Inductor in the IAF → 3x Inductors in the Vienna Rectifier
  - Vienna Rectifier has less semiconductors
  - Vienna Rectifier can boost



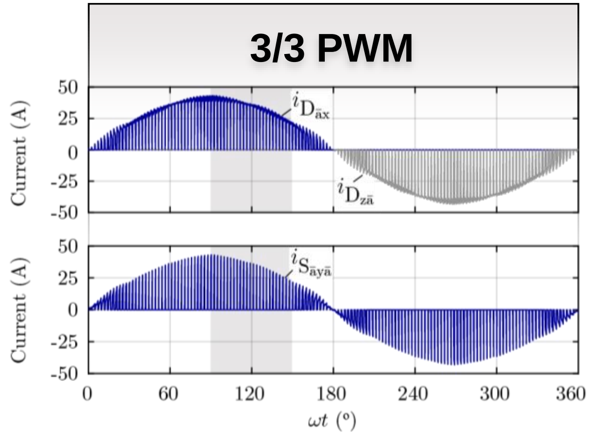


1/3 PWM Semiconductor Loss Savings

› **Switching Losses**

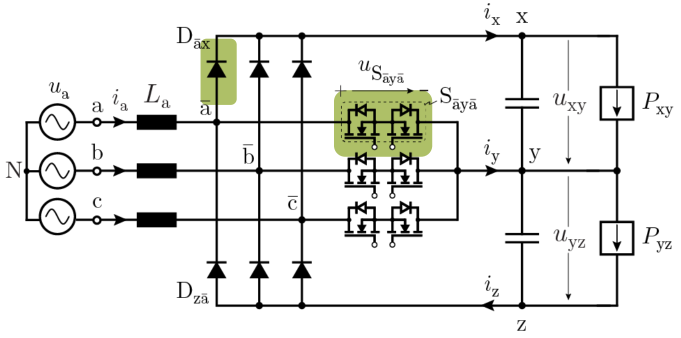
– 3/3 PWM: $P_{\mathrm{sw},3/3} = \left(E_{\mathrm{sw},0} + E_{\mathrm{sw},1} \cdot I_{\mathrm{avg}}\right) f_{\mathrm{sw}}$

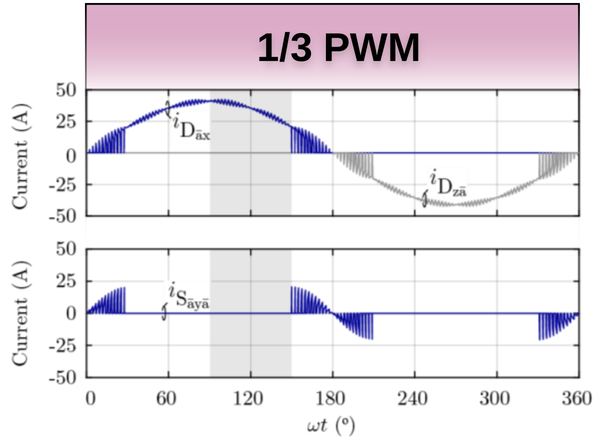
– 1/3 PWM: $$P_{\mathrm{sw},1/3} = \left(\underbrace{\frac{E_{\mathrm{sw},0}}{3}}_{-66\%} + \underbrace{\left(1 - \frac{\sqrt{3}}{2}\right) E_{\mathrm{sw},1} \cdot I_{\mathrm{avg}}}_{-86\%}\right) f_{\mathrm{sw}}$$



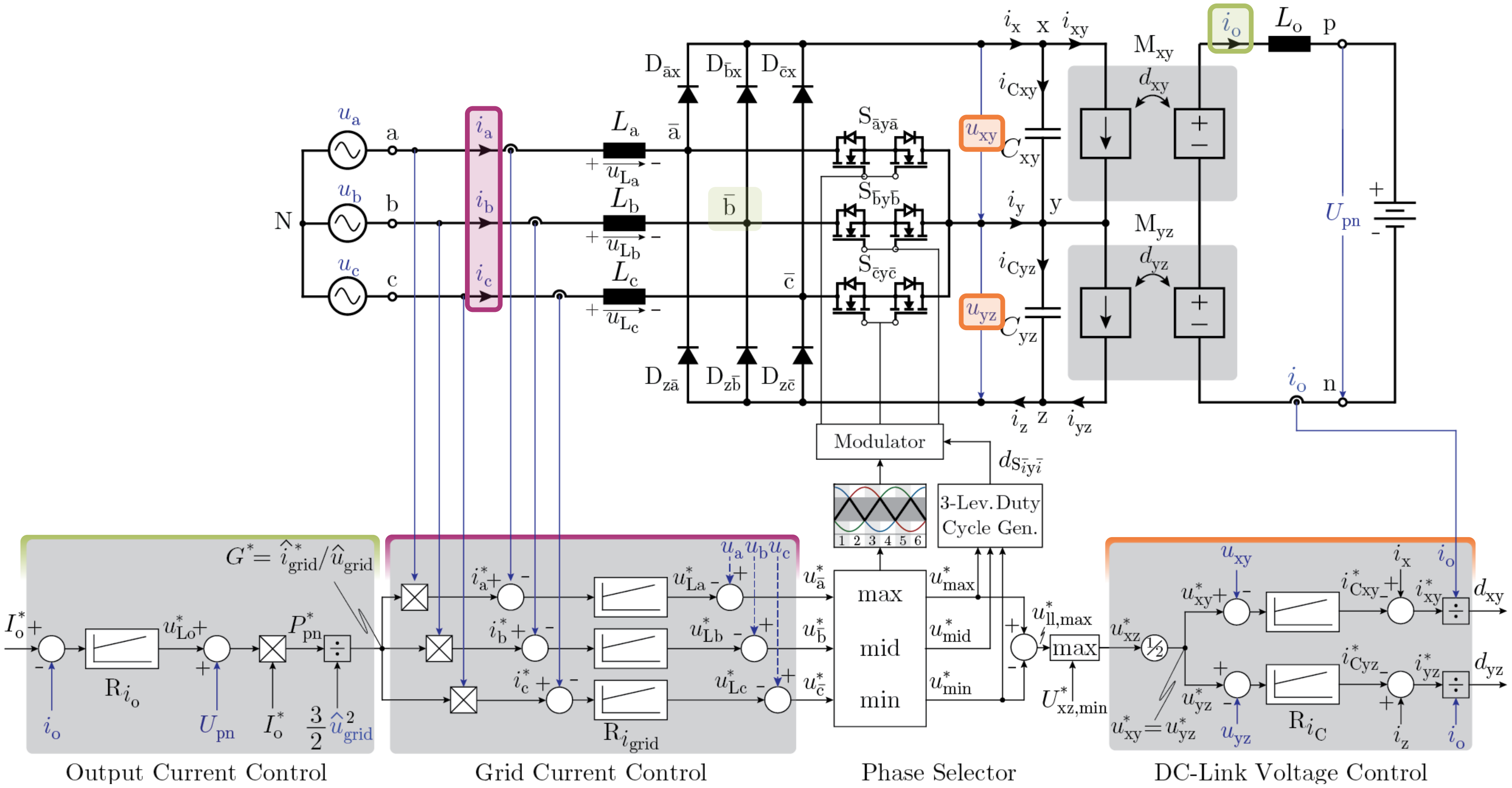
› **Conduction Losses**

		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 %





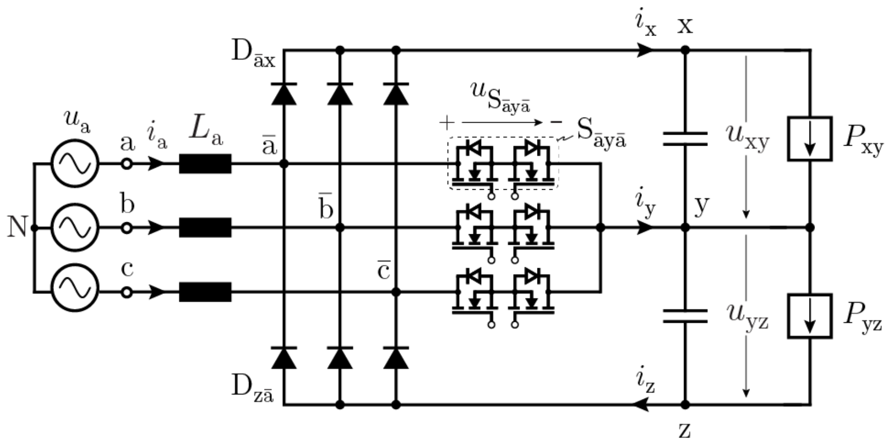
Synergetic (1/3 PWM) Control Structure

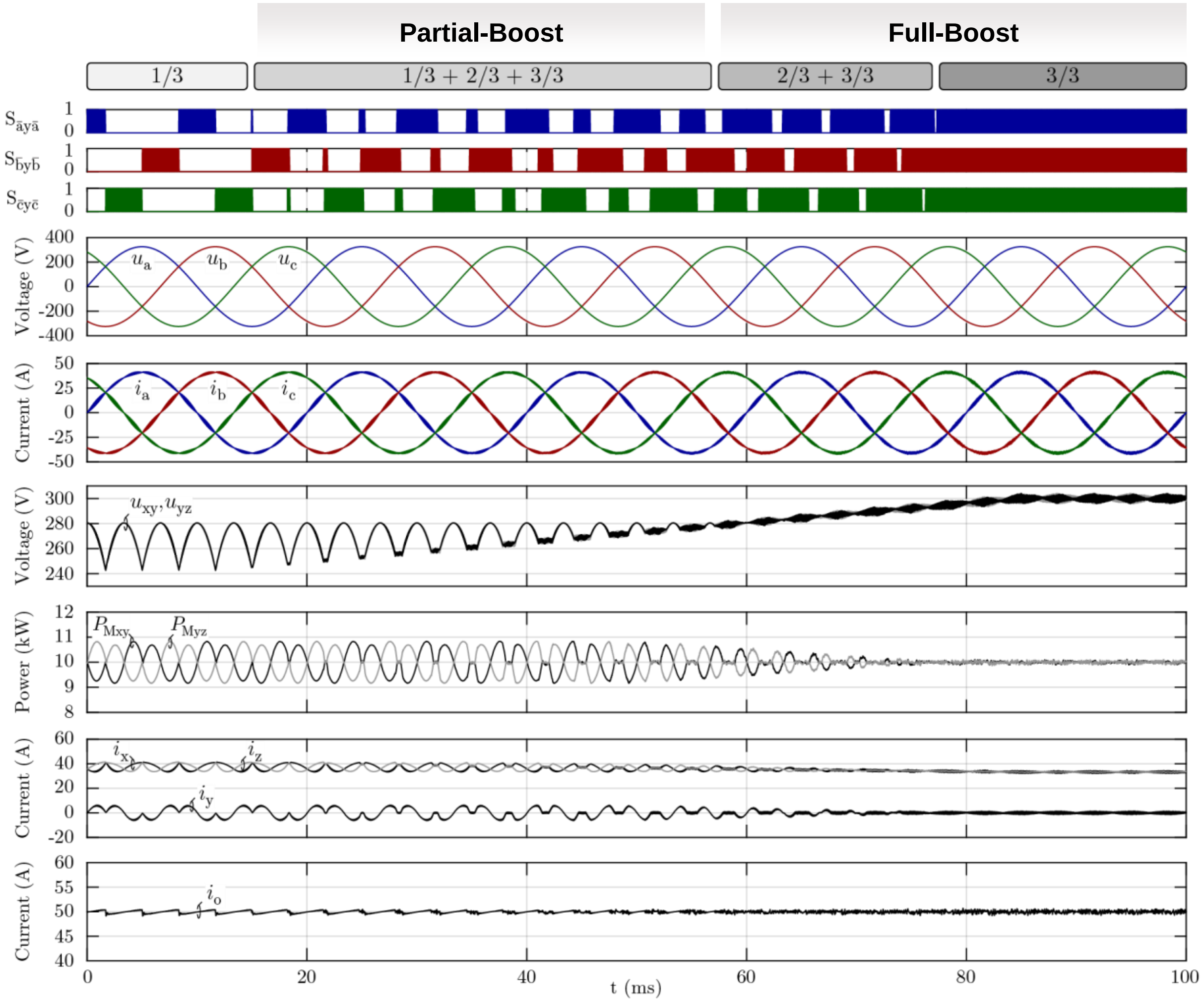


- **Synergetic Cascaded Control Structure**
- **Valid for 1/3 PWM and (!) 3/3 PWM**

System Simulation

Synergetic (1/3 PWM) Control Validation





Further Reading: J. Azurza, M. Haider, D. Bortis and J. W. Kolar, “New Synergetic Control of a 20kW Isolated VIENNA Rectifier Front-End EV Battery Charger”, IEEE COMPEL, 2019

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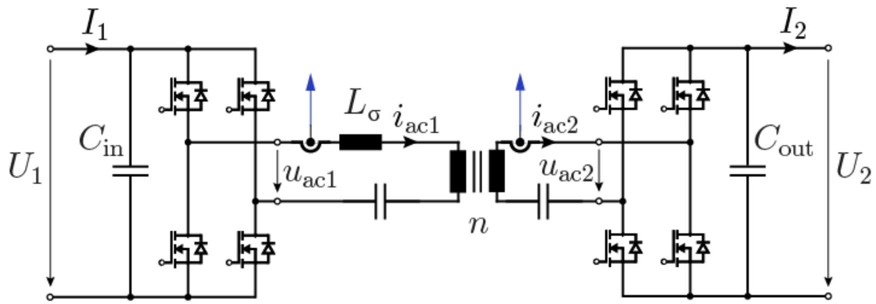
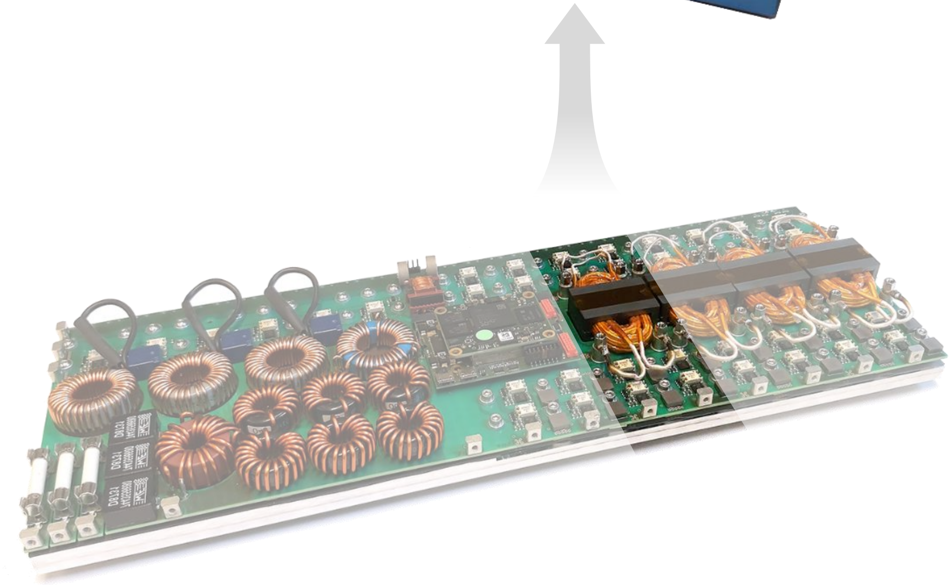
Dual Active Bridge (DAB)

› 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	12.3 µH
Switching Frequency	140 - 400 kHz

› Ad-Hoc DAB Test Module



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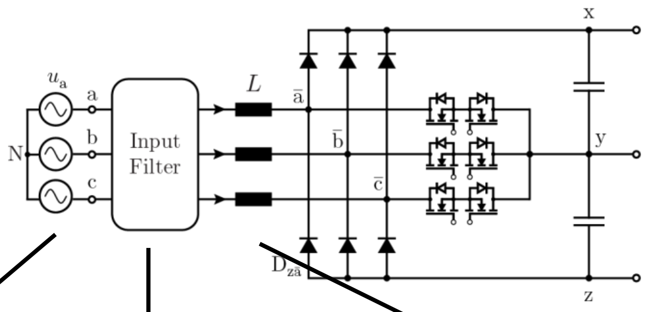
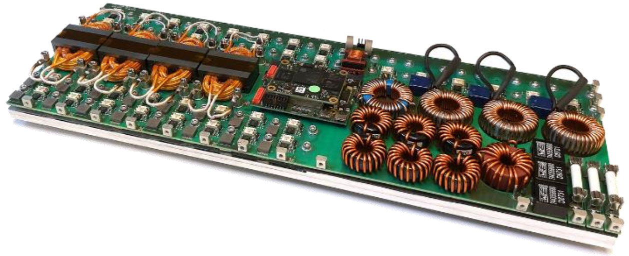
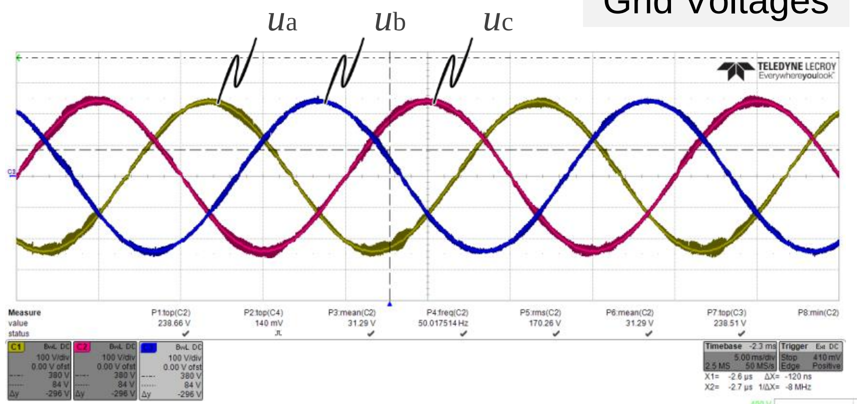
Vienna Rectifier Measurements (3/3 PWM)

- 3kW, 500 V_{dc}
- THD: 5.37%
- f_{sw} = 550kHz
  - 1.1MHz Current Control Loop

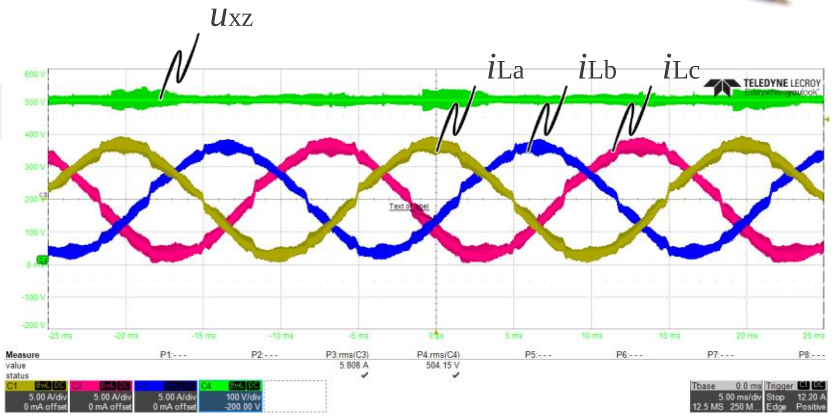




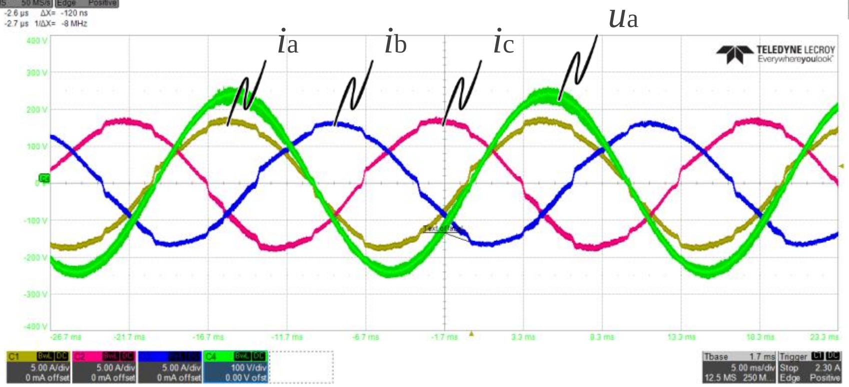
Grid Voltages



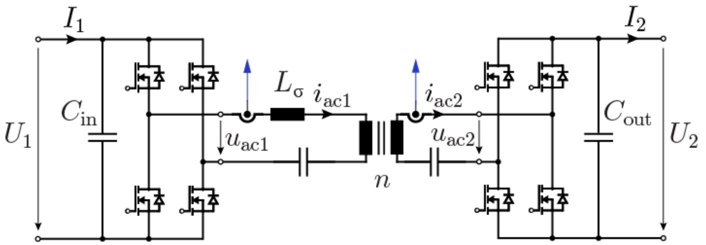
Inductor Currents

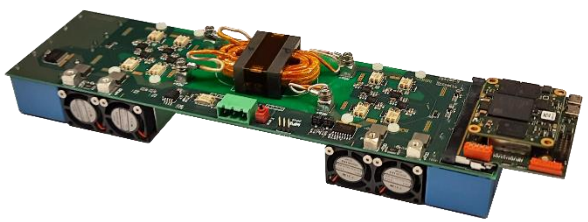


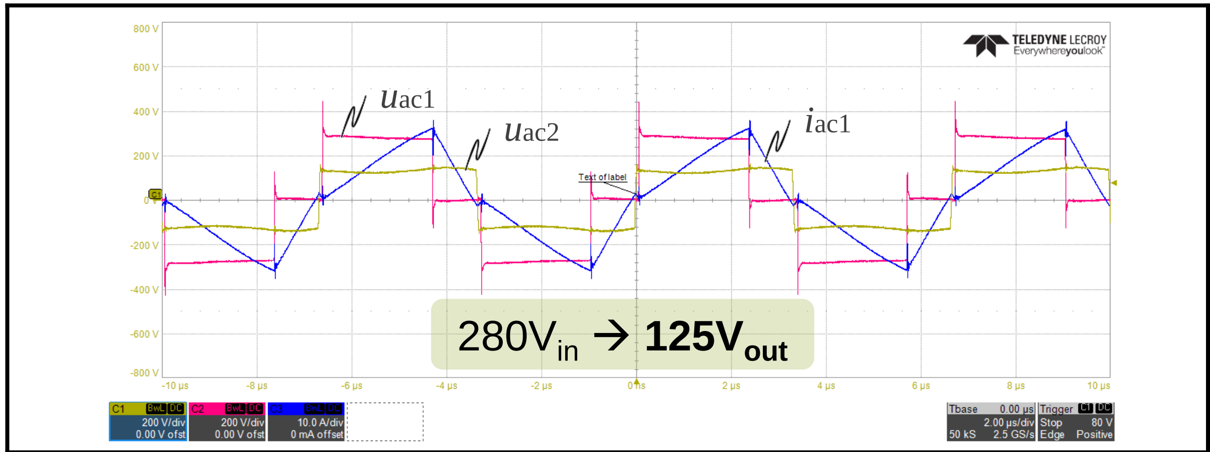
Grid Currents

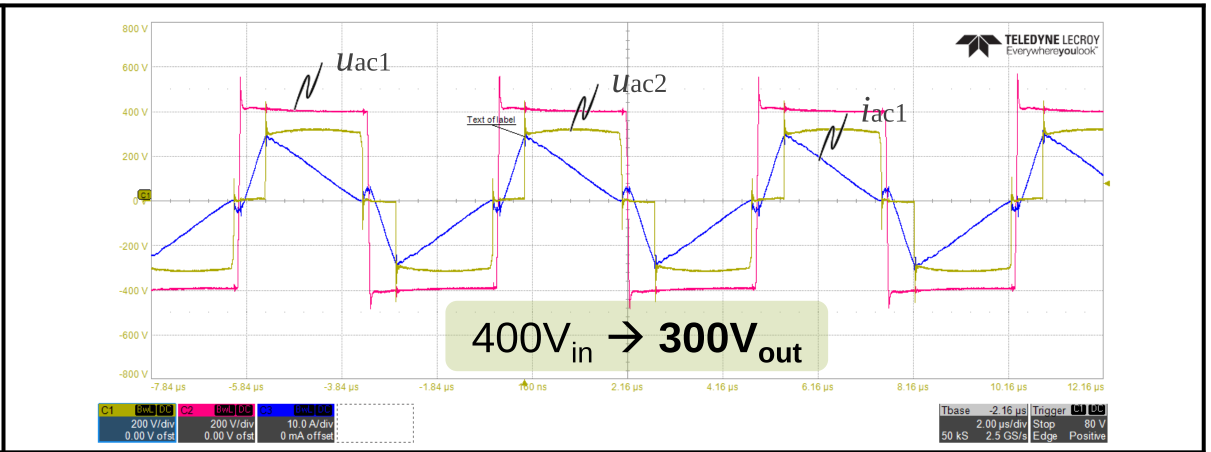


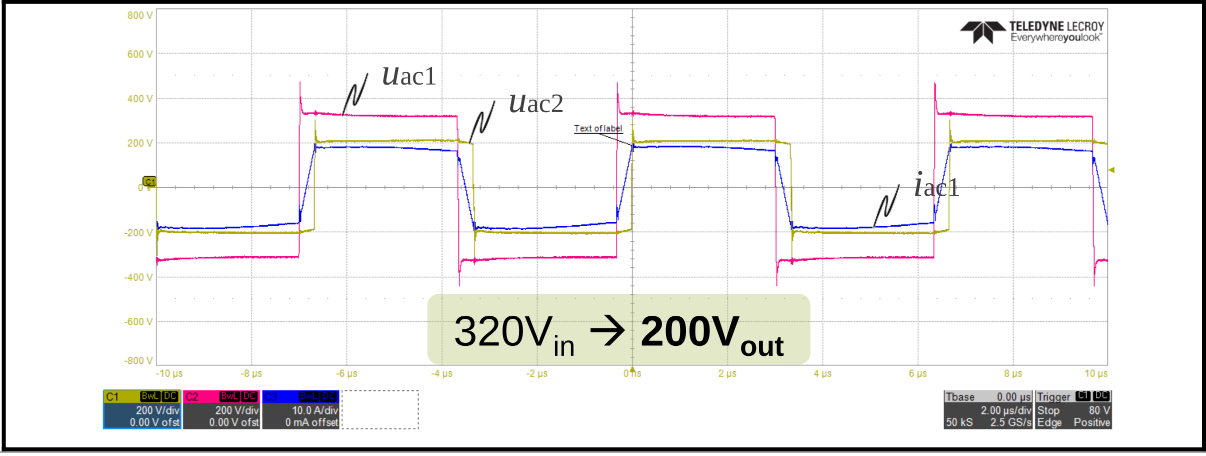
DAB Measurements @ max (12.5A, 2.5kW)

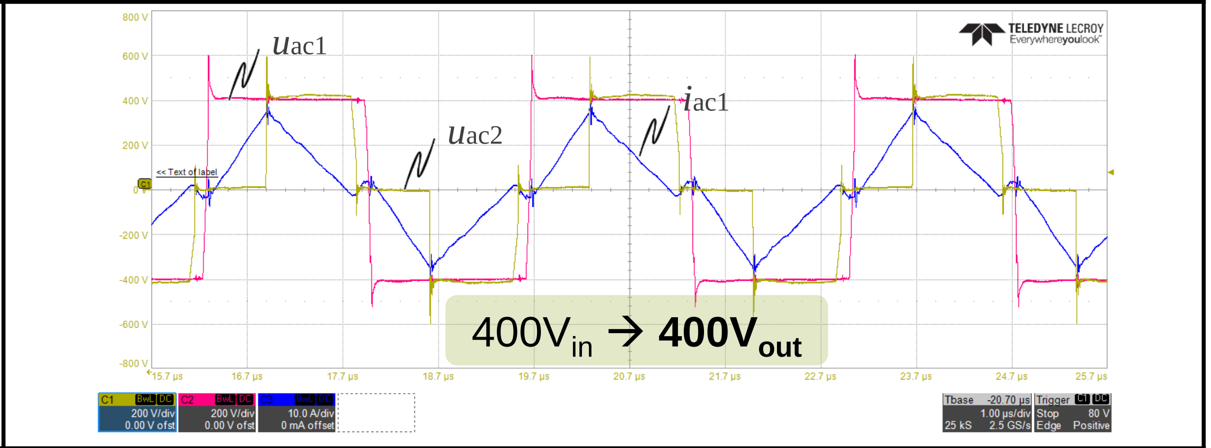












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Conclusion & Next Steps

› **Next Level of Power-Density Achieved**

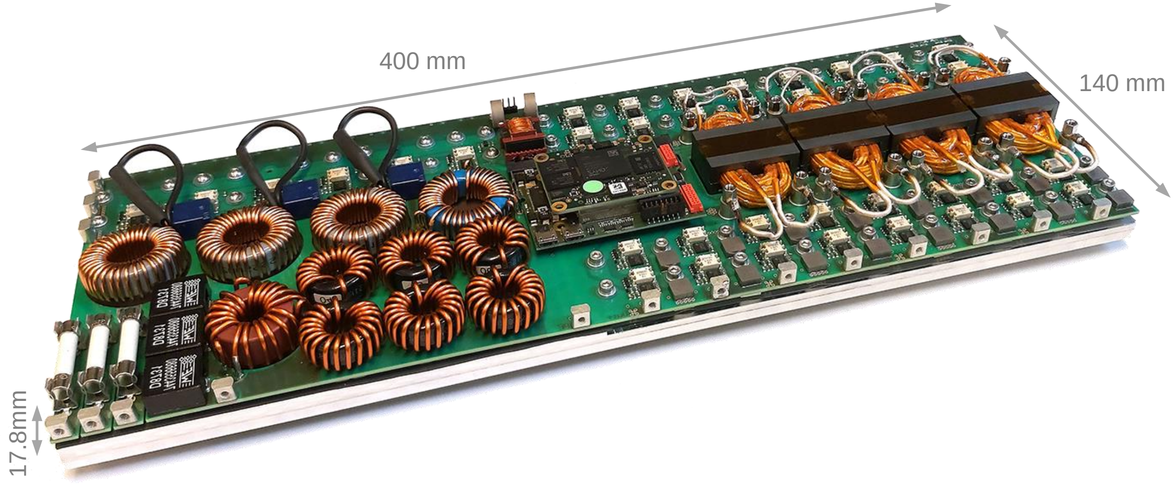
› **Enabled by:**

– **Synergetic Control** of AC/DC & DC/DC Stages
– **DAB Stage** for Wide Output Voltage Regulation
– **Infineon CoolGaN™ GIT**
– f_{sw} up to **550kHz** → Flat Mag. Profile

› **Next Steps**

– Full Power Testing
– Hardware Verification of:
  – 3/3 PWM
  – 1/3 PWM w/ Synergetic Control

Let's Team Up to Redefine On-Board Chargers!



Power Density
☆ **10 kW/L***

* Casing/cooling not included

Efficiency
☆ **94.8%***

* Measured at 5kW, 400V_{out}, more measurements pending

Part of your life. Part of tomorrow.