ETH zürich

Power Electronic Systems Laboratory

A Three-Phase Synergetically Controlled Buck-Boost Current DC-Link EV Charger

Daifei Zhang

Swiss Federal Institute of Technology (ETH) Zurich

Power Electronic Systems Laboratory

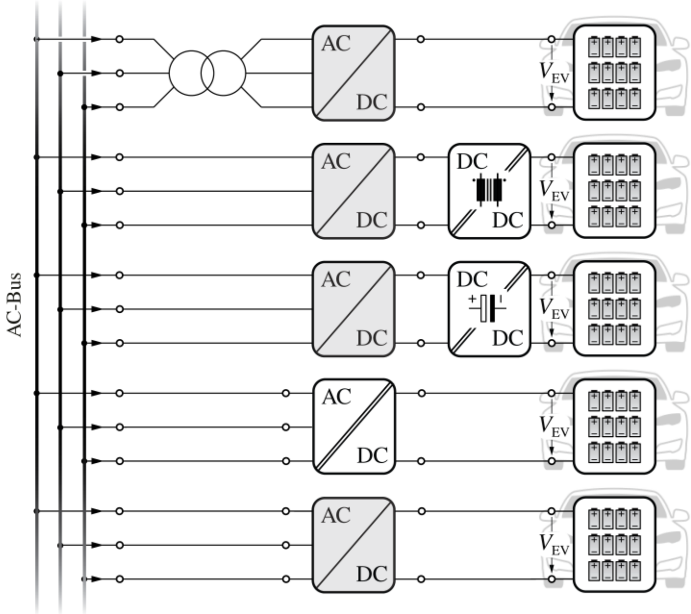
ECCE 2023

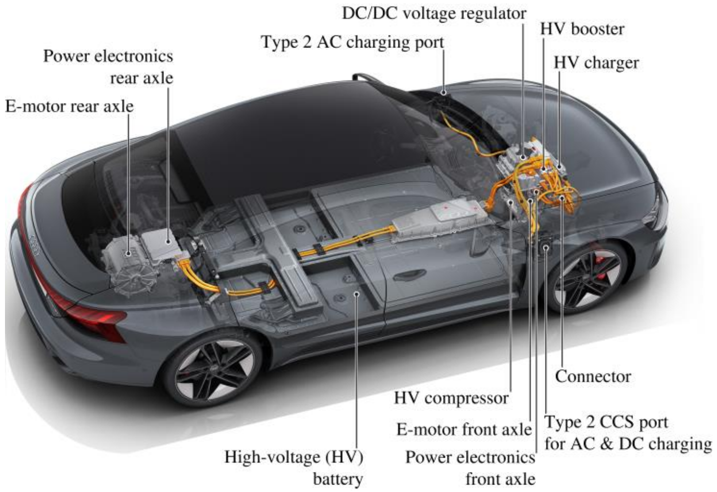
IEEE ENERGY CONVERSION CONGRESS & EXPO Nashville, TN | OCT.29-Nov.2

Research Background

- *Transportation : 25% of World Energy & CO2 Emission*
- *Sustained Transportation Electrification*
- *More Compact & Efficient EV Chargers*

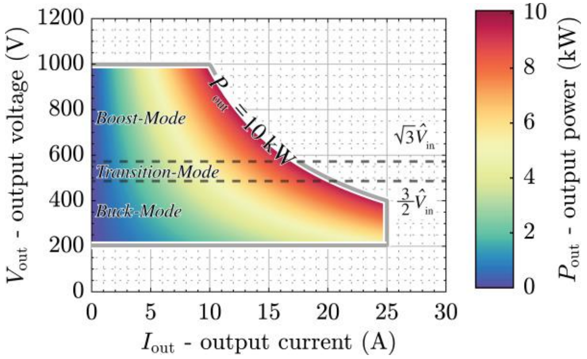
❖ *Typical Structures of Isolated or Non-Isolated EV Charger*





Source:Electrichasgoneaudi.net

❖ *Typical Operating Range of 10kW Charger Module*

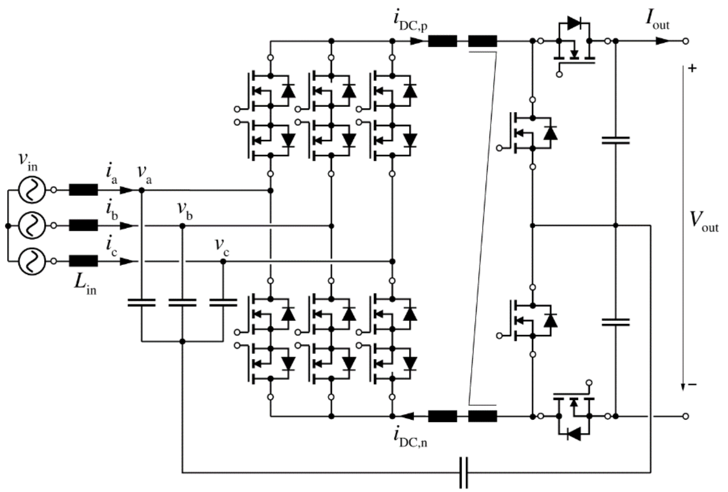


- *3-Φ Non-Isolated Bidirectional AC/DC Converter System → Standard Building Block*
- *Buck-boost Capability : 200V to 1000V*

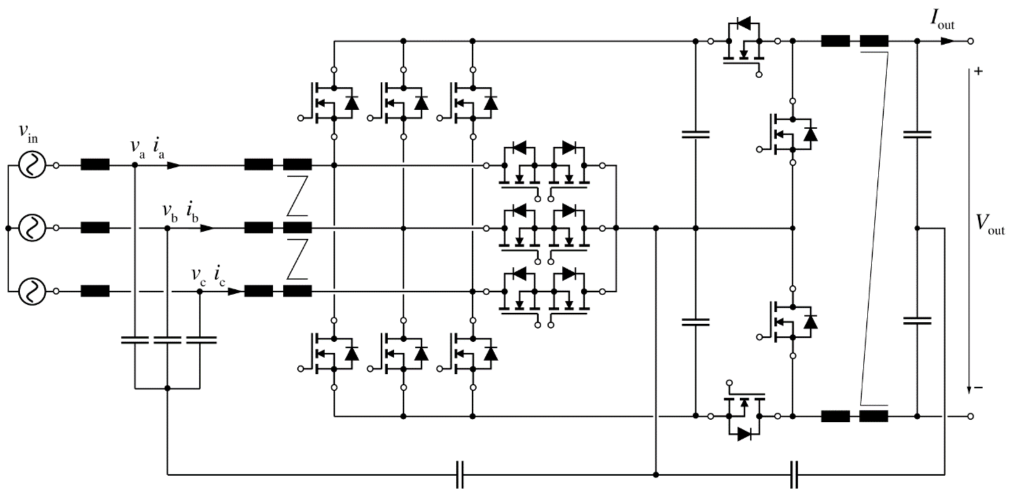
Bidirectional *Buck-Boost* AC/DC Converter System

- *Buck-Boost (bB) OR Boost-Buck (Bb) Combination*
- *Shared Current (Inductive) OR Voltage (Capacitive) DC-Link*

❖ *3-Φ bB Current DC-Link PFC AC/DC Converter System*



❖ *3-Φ Bb Voltage DC-Link PFC AC/DC Converter System*

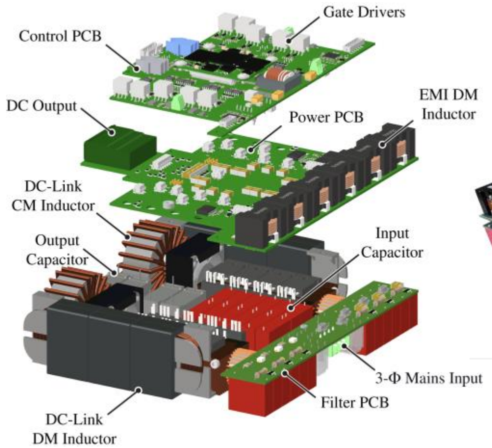


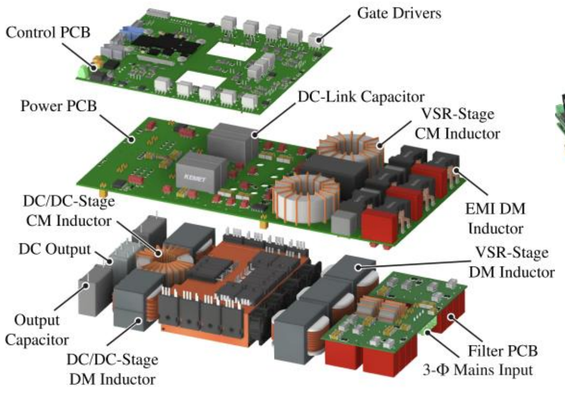
- *Advanced PWM Schemes Enabling Optimal Clamping Operation w/ Significantly Reduced Losses*
- *"Synergetic Control" of AC/DC and DC/DC Converter Stage*
- *Comprehensive Comparison based on Realized Demonstrator Systems*

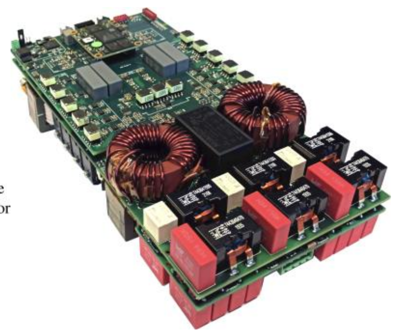
Buck-Boost | *Boost-Buck* Demonstrator Systems

- ***Buck-Boost** Current DC-Link AC/DC Converter*
  - 10 kW @ 400…1000 V_{DC} @ 3-Φ 400 V_{rms} *Mains*
  - U_{out} = 200 … 1000 V_{DC}
  - η = 98.8% @ 6.4 kW/dm^3
  - *AC/DC* — f_{sw} = 100 kHz
  - *DC/DC* — f_{sw} = 2x 50 kHz/100 kHz *eff.*

- ***Boost-Buck** Voltage DC-Link AC/DC Converter*
  - 10 kW @ 400…800 V_{DC} @ 3-Φ 400 V_{rms} *Mains*
  - U_{out} = 200 … 800 V_{DC}
  - η = 98.8% @ 5.4 kW/dm^3
  - *AC/DC* — f_{sw} = 100 kHz
  - *DC/DC* — f_{sw} = 2x 100 kHz/200 kHz *eff.*

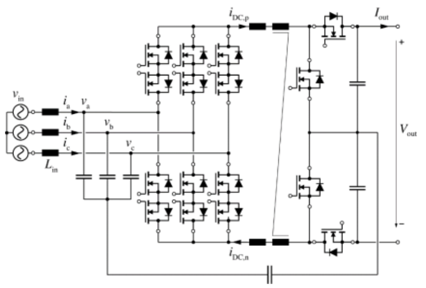


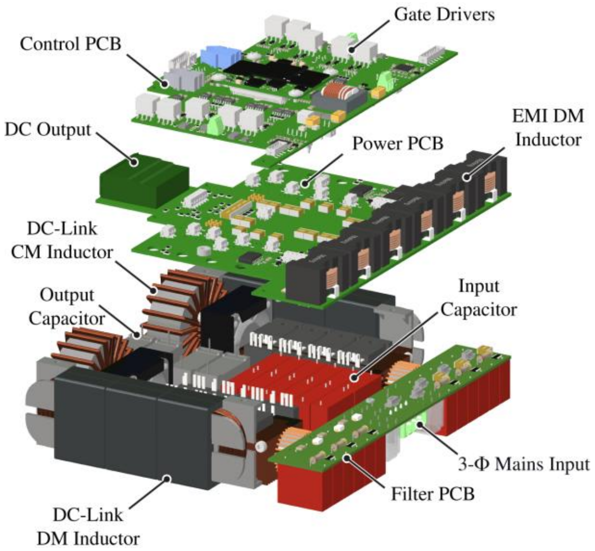




- *Min. # of Inductive Components → AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor*
- *Reduced Hardware Manufacture Cost & Complexity*
- *Reduced Control/Firmware Implementation Efforts*

3-Φ bB Current DC-link PFC AC/DC Converter System

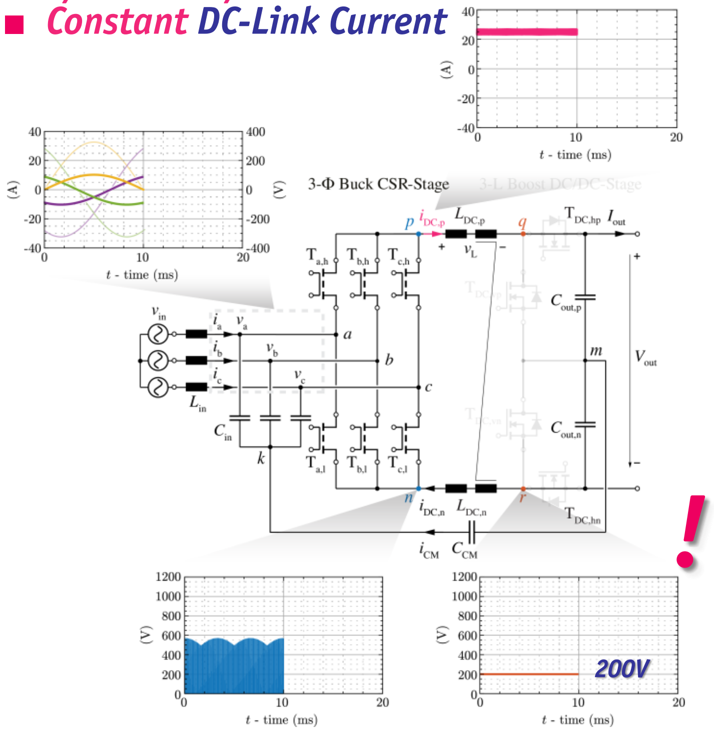




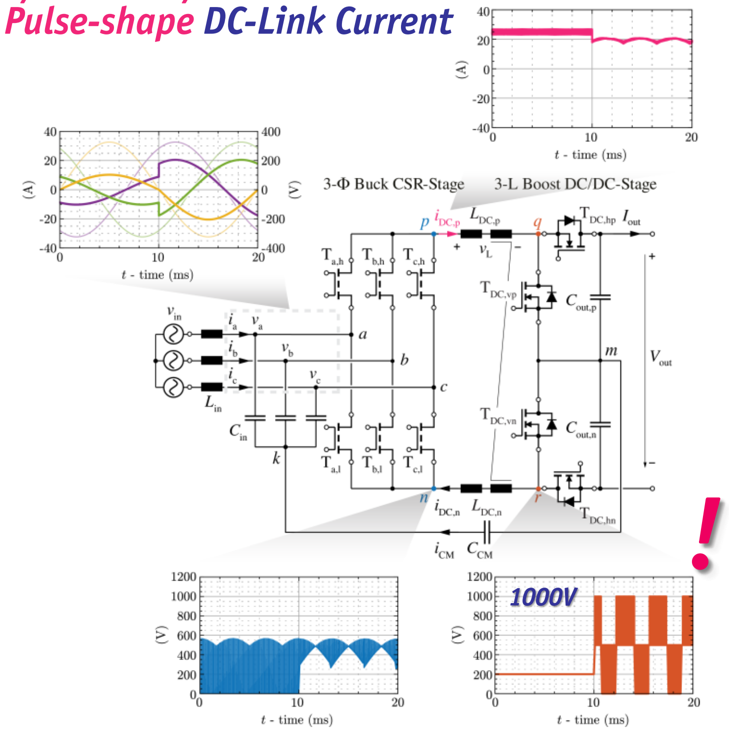
200 … 1000 V_{DC} | 10 kW 98.8% | 6.4 kW/L

Loss-Optimal Operating Principles

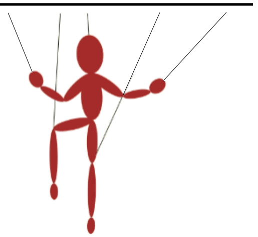
- *Buck-Mode Operation*
- *3/3-PWM w/ Zero State*
- *Constant DC-Link Current*



- *Boost-Mode Operation*
- *2/3-PWM w/o Zero State*
- *Pulse-shape DC-Link Current*

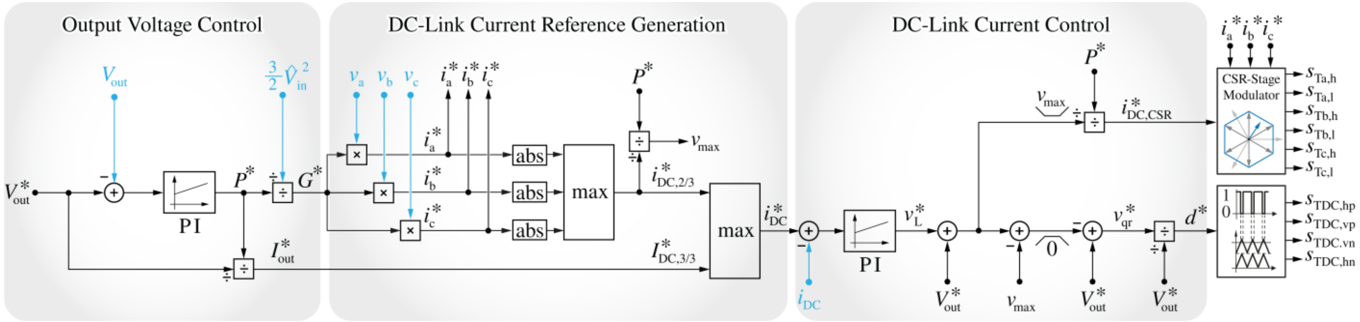


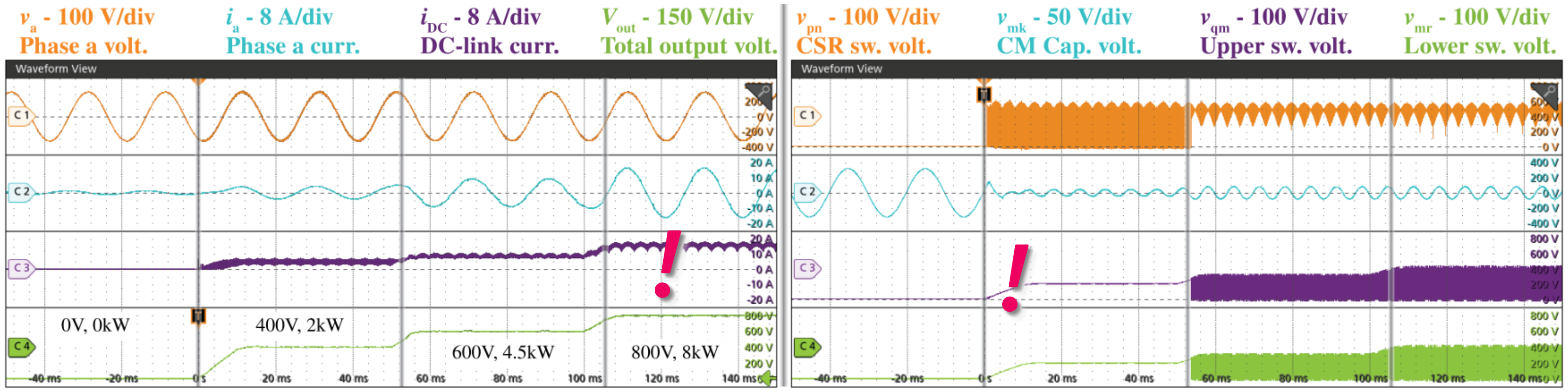
- *Min. # of Switching Instants & Reduced Sw. Voltage → App. 77% Reduction of Switching Losses*
- *Min. DC-Link Current → 8% Reduction of Conduction Losses*



Synergetic Control Strategy

- *Enable 2/3-PWM with Variable DC-Link Current*
- *Collaborative Operation of AC/DC & DC/DC Converter Stages*



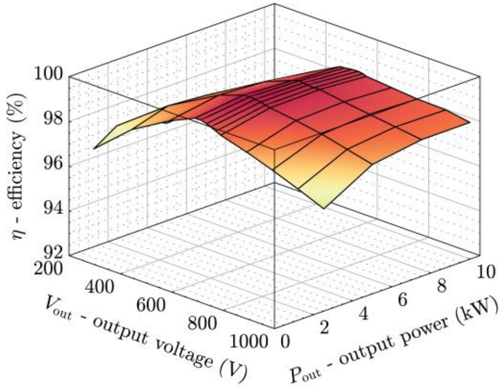


- *Ensure Seamless / Democratic Transitions between Proposed Loss-Optimal Modes*

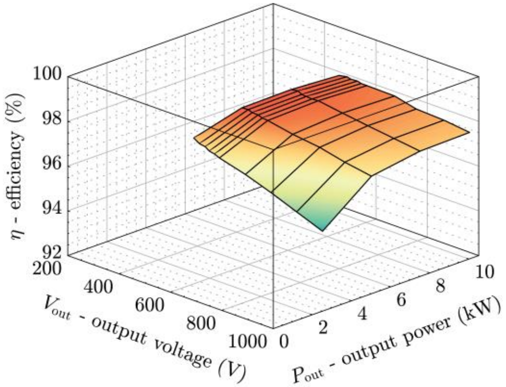
Efficiency Measurement Results

- *Measurements Covering 200V to 1000V & 25% Load to Full Load*

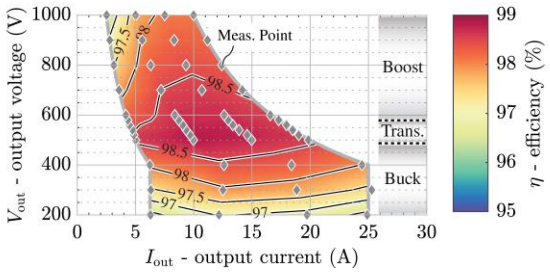
Loss-Optimal Operation



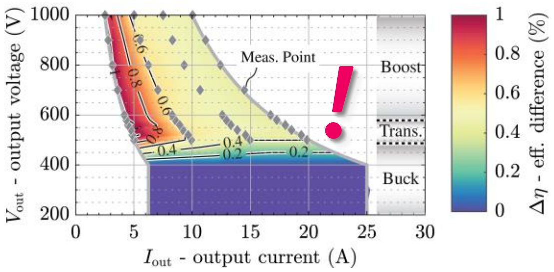
Benchmark Operation



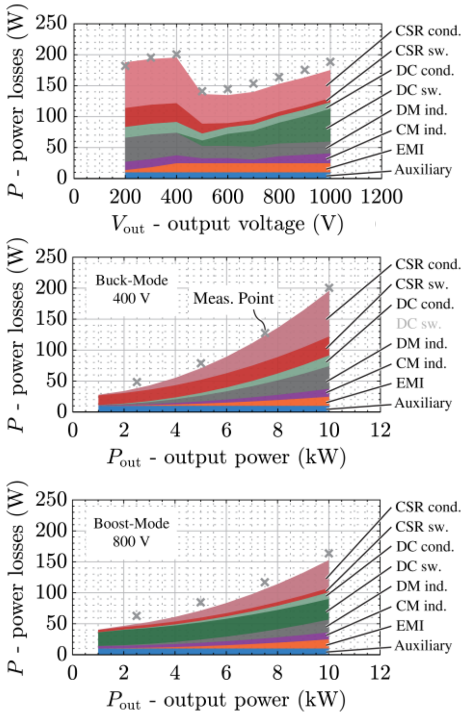
Loss-Optimal Operation (2D)



Efficiency Improvement



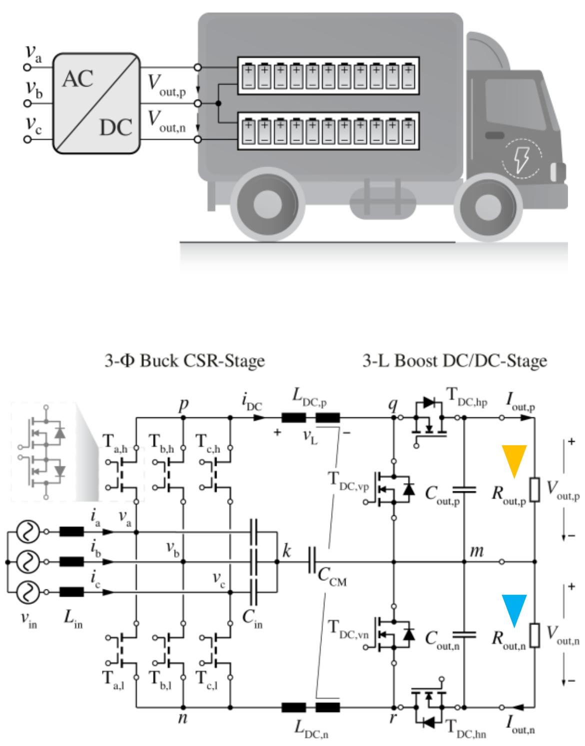
Loss Breakdown

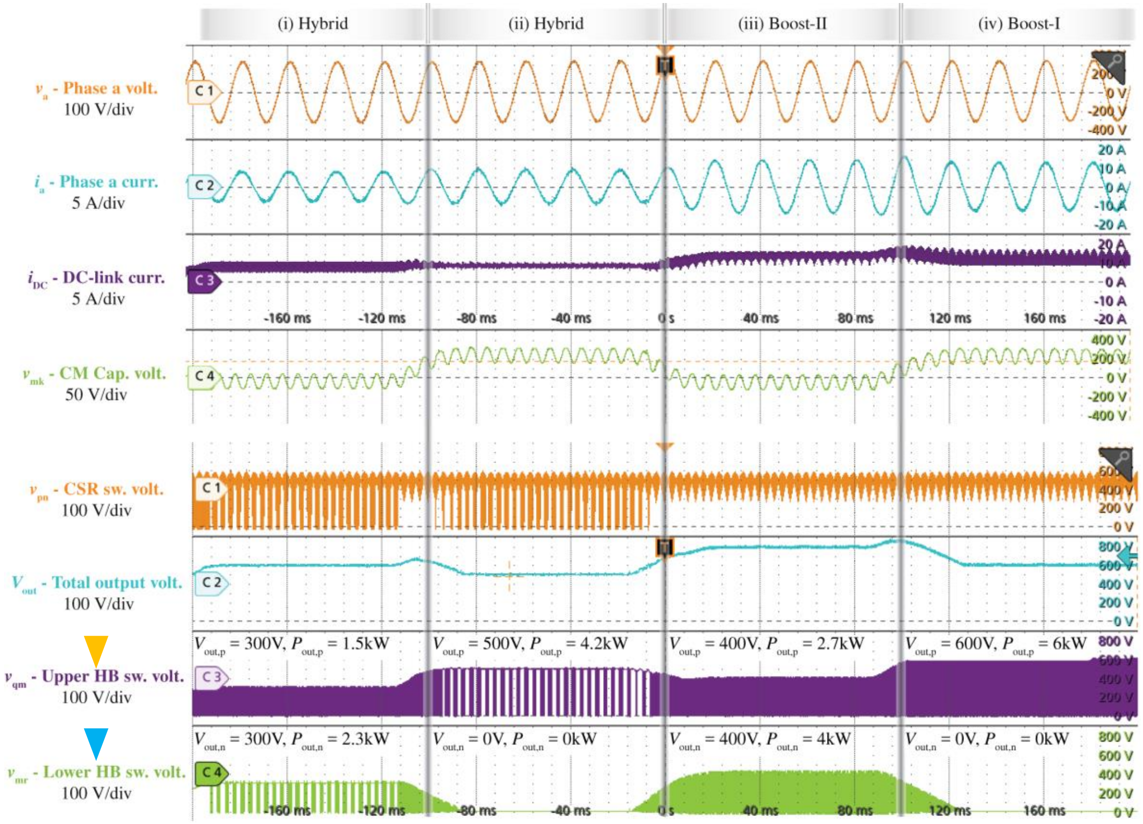


- *Peak Efficiency of 98.8%*
- *Flat Efficiency Characteristic -- Above 98% in Most Area*
- *Up to 1% Efficiency Improvement in Boost-Mode Operation*

Two *Independently* Regulated DC Outputs

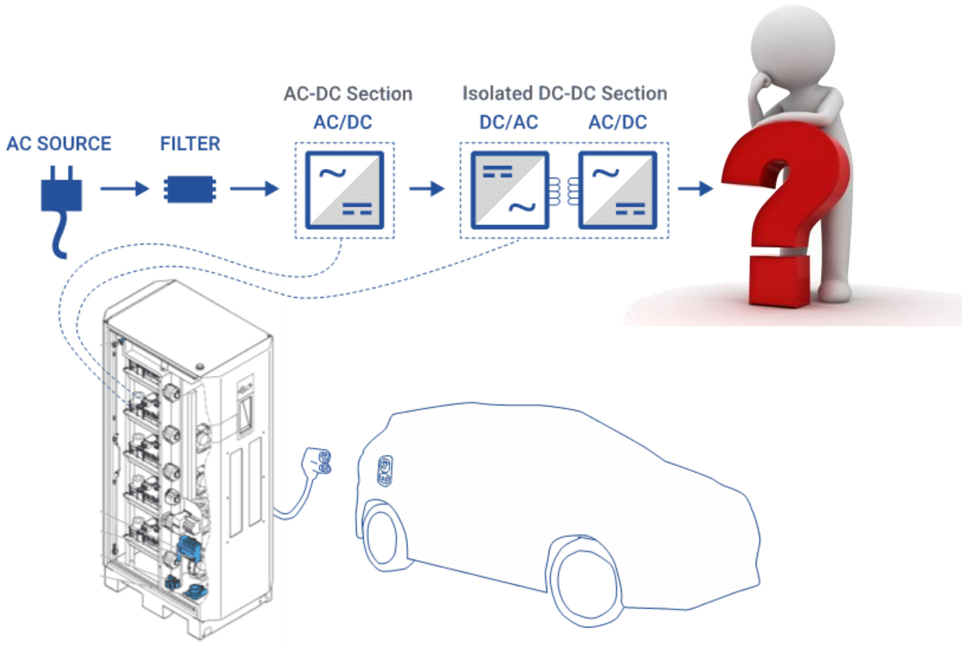
- *Extended Synergetic Control Allows Independent Regulation of V_{out} or P_{out}*
- *Heavy-Duty EV Battery Charging*





- *Loss-Optimal Operation Modes & 2/3-PWM are Still Maintained*

Future RCD-Based Non-Isolated EV Charger

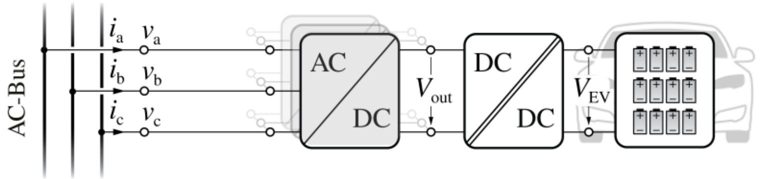


Source: www.wolfspeed.com

3-Φ AC/DC Converter in EV Chargers

- Galvanic Isolated EV charger
- Multi-Stage Structure

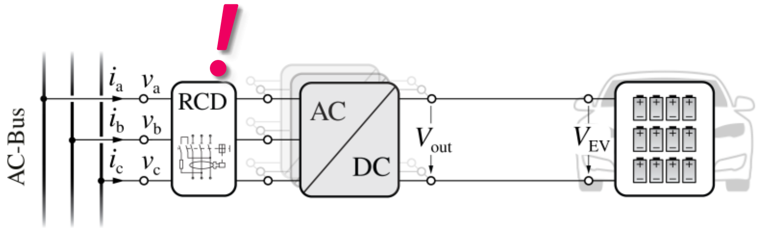
- 50 Hz Or HF Transformer (DAB, LLC, DCX…)
- Small Ground Current → End-User Safety
- Bulky & Low Power Efficiency & High Cost



- Non-Isolated EV charger

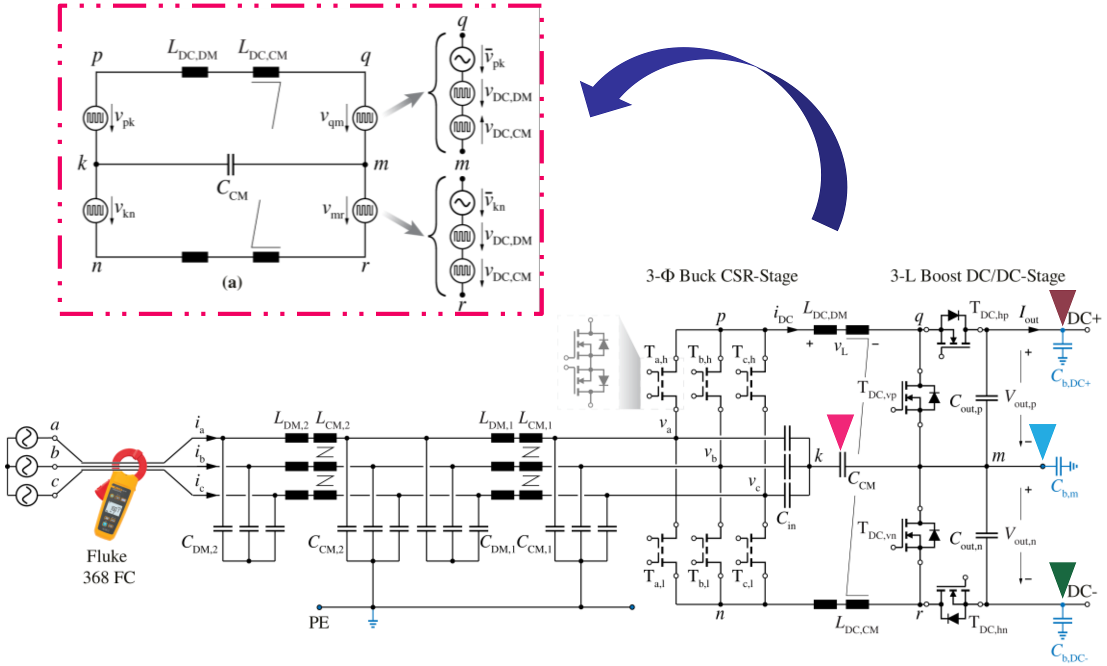
- Residual Current Device (RCD) → End-User Safety
- Battery Package Parasitic Cap. up to Several uFs
- Min. Ground Current → Avoid Nuisance Tripping
- Conv. EMI Filter Suppress HF Ground Current

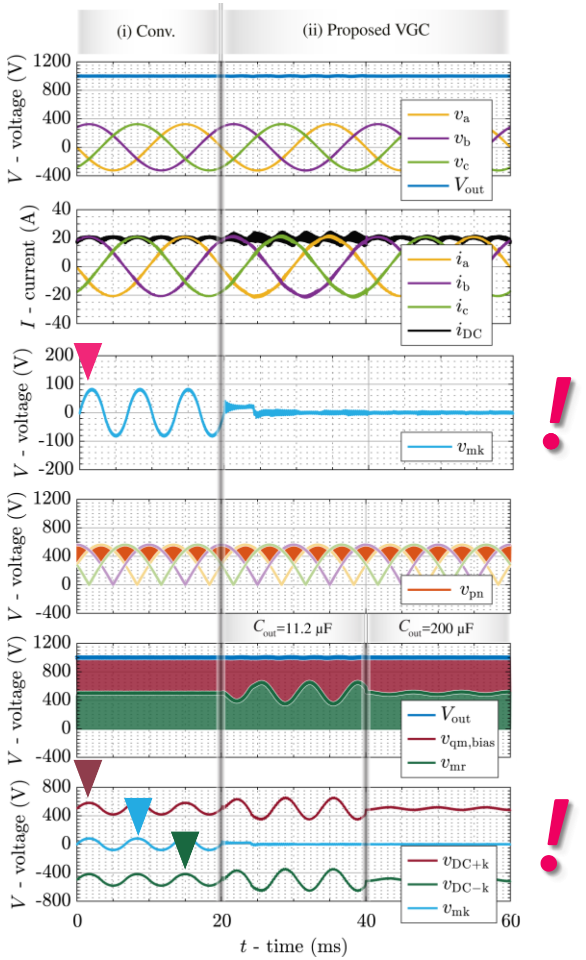
- PV Inverter → 1% More Efficiency w/ Half Volume
- Enable High Power On-Board Charger (OBC)



Virtual Grounding Control (VGC)

- *Current DC-Link Rectifier Stage Generates LF CM Voltage*
- *Use DC/DC to Actively Compensate LF CM of AC/DC*

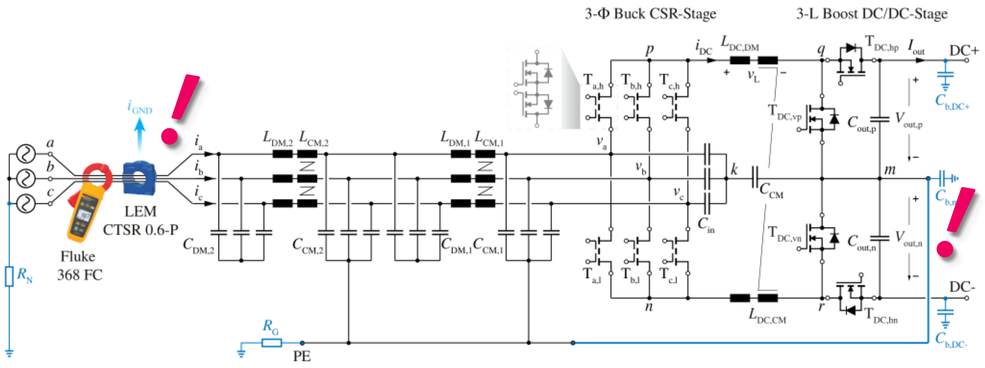


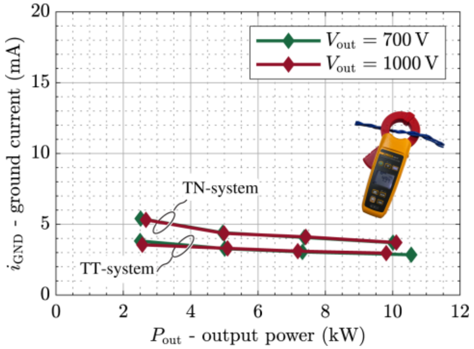


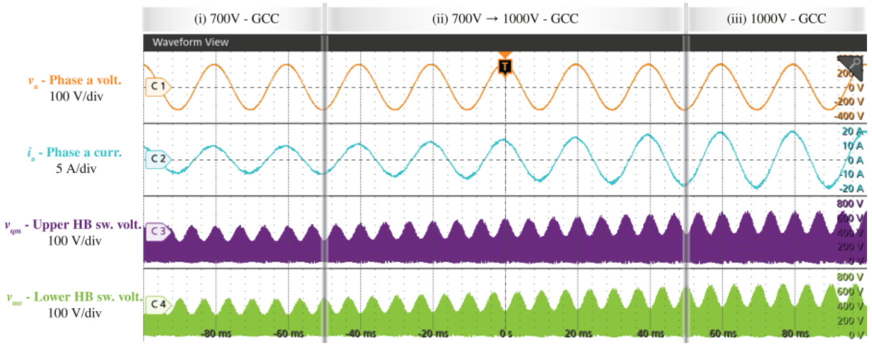
- *Reduced LF CM Noise Emission → Time-Varying (150 Hz) Output Capacitor Voltage*
- *Similar DM Operations → Constant Output Voltage & 2/3-PWM*

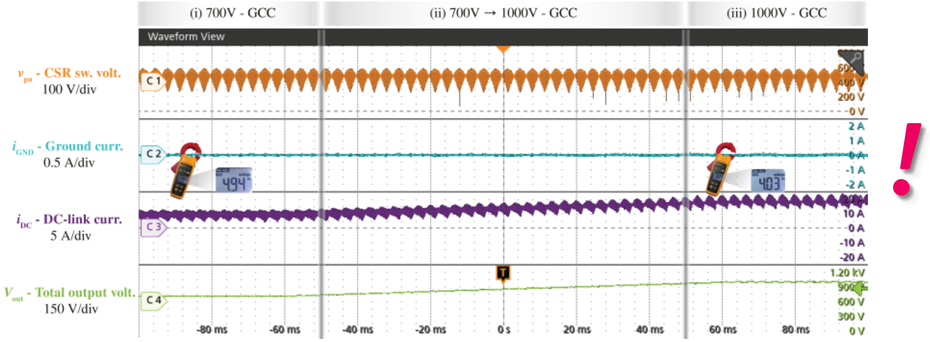
Ground *Current* Control (GCC)

- *Hard Connection between Output Midpoint & PE*
- *Direct Measure & Feedback Regulate Ground Current*



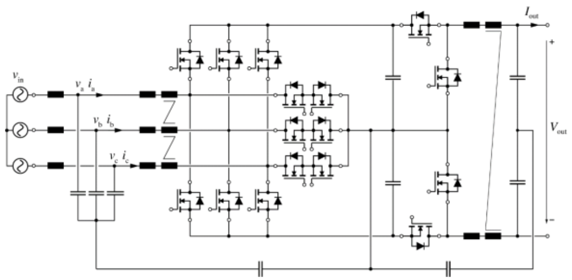


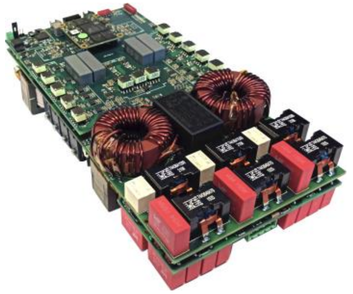


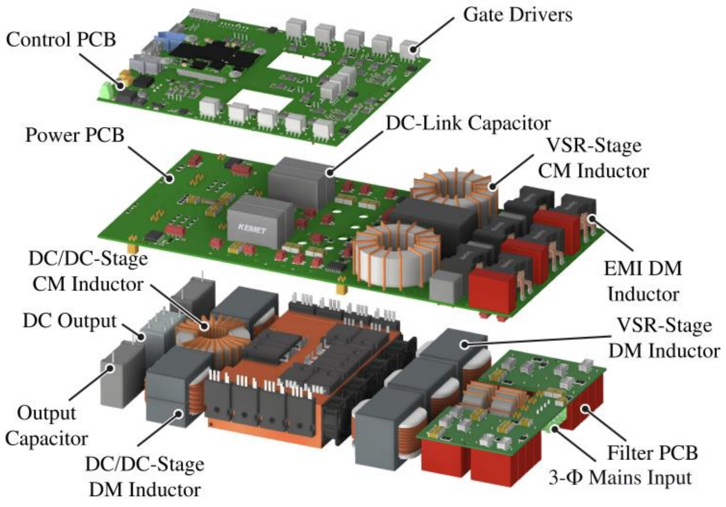


- *Ground Current : < 6 mA, Far Below 30 mA Limit*
- *Pre-Compliance Test Accord. to UL 2202 & IEC 61851 Considering TT & TN Systems*

3-Φ Bb Voltage DC-link PFC AC/DC Converter System





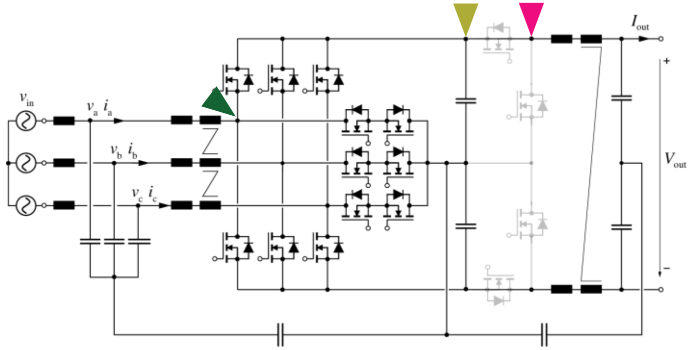


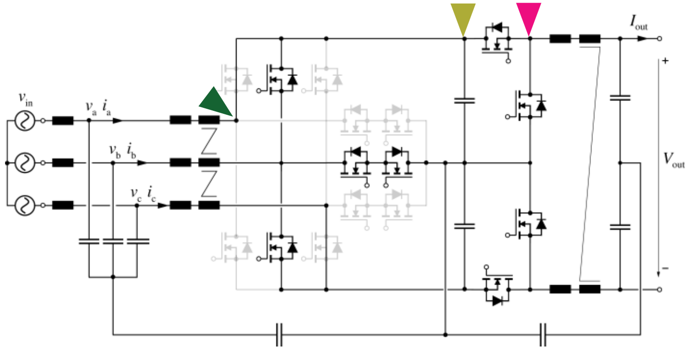
200 … 800 V_{DC} | 10 kW 98.8% | 5.4 kW/L

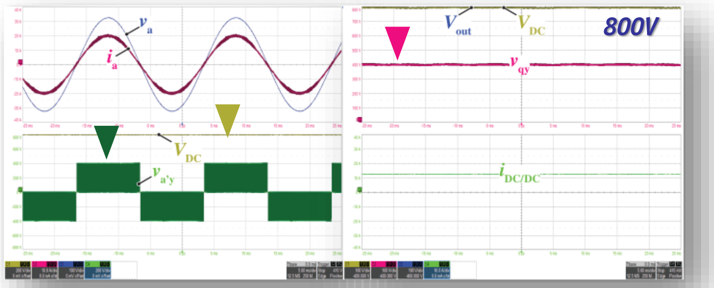
Loss-Optimal Operating Principles

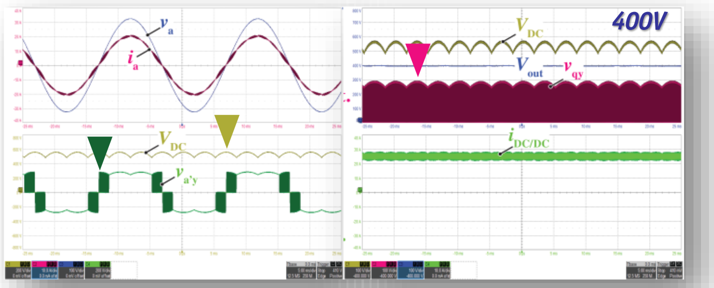
- *Boost-Mode Operation*
- *3/3-PWM*
- *Constant DC-Link Voltage*

- *Buck-Mode Operation*
- *1/3-PWM*
- *Pulse-shape DC-Link Voltage*





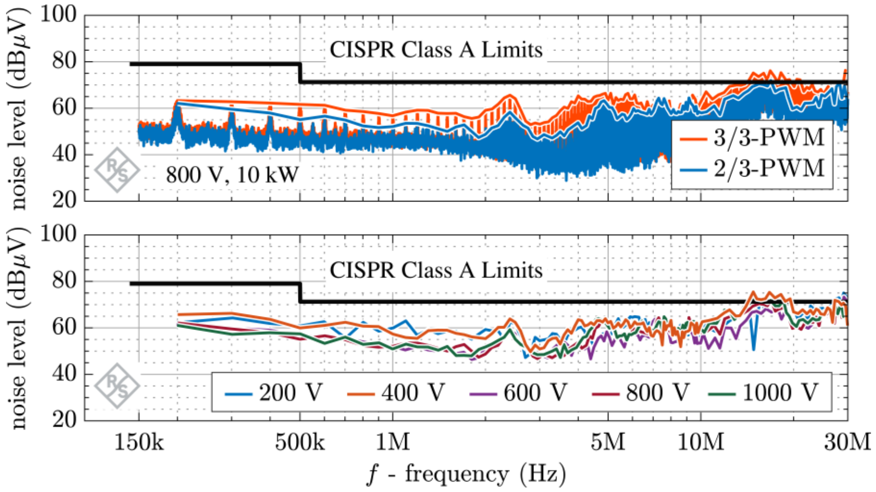




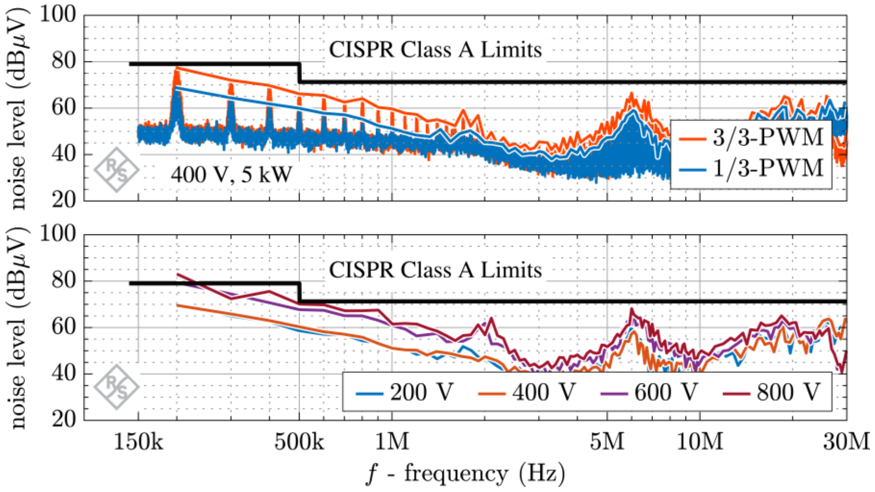
- *Min. # of Switching Instants & Min. Amplitude of Switched Current*
- *App. 70% Reduction of Switching Losses*

Conducted EMI Pre-Compliance Tests

- Buck-Boost Current DC-Link AC/DC Converter



- Boost-Buck Voltage DC-Link AC/DC Converter



- Lower EMI Noise Emission Achieved by Advanced PWM Schemes

- Current DC-Link : Output Voltage Independent but Power Dependent
- Voltage DC-Link : DC-Link Voltage and Output Voltage Dependent

- EMI Filter Redesign is Not Needed When Applying the Advanced PWM Schemes

Conclusion & Contribution

■ *Advanced PWM Schemes*

- *Current DC-Link : 2/3-PWM*
- *Voltage DC-Link : 1/3-PWM & 2/3-PWM-OPT*
- *Enables Optimal Clamping Operation*

■ *Synergetic Control Strategies*

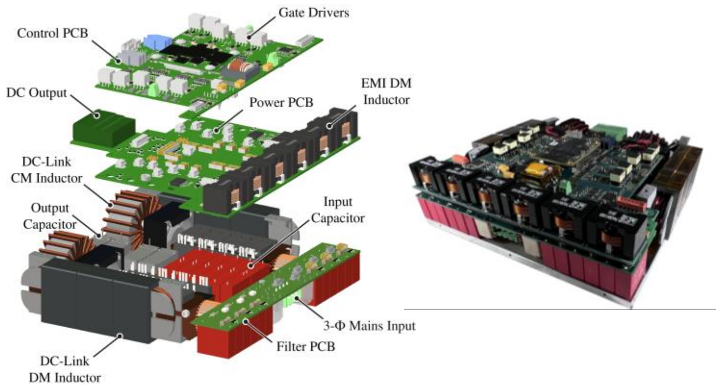
- *Loss-Optimal Buck-Boost Operation*
- *Seamless & Smooth Transitions Between Different Modes*

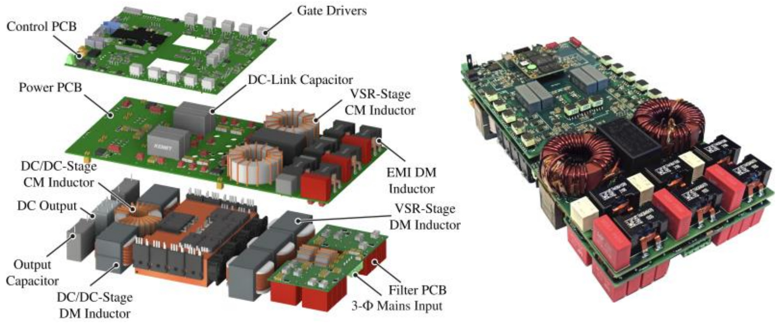
■ *Independent Output Voltage/Power Control*

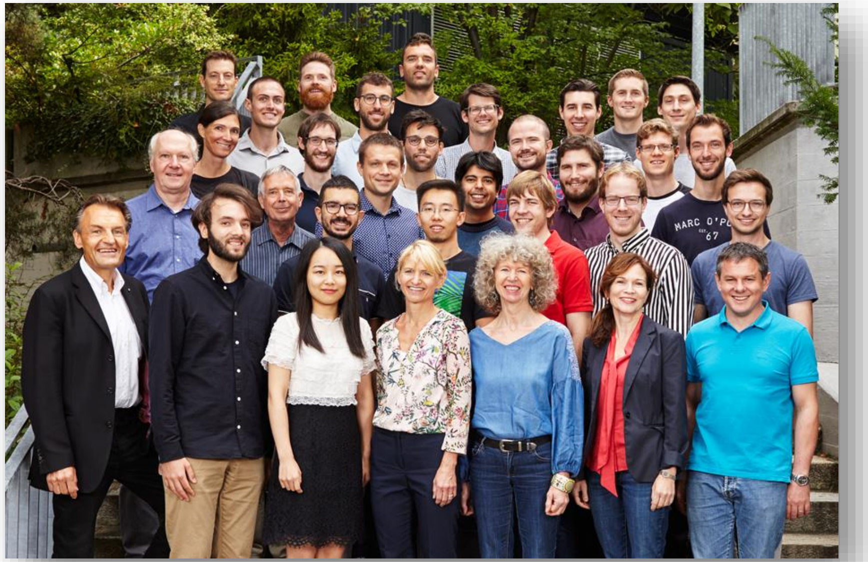
- *Fully Leverage Hardware Capacity*
- *Allow Loss-optimal Operation for Voltage or Power Asymmetry*

■ *Ground Current Control Strategy*

- *Target Future RCD-Based Non-Isolated EV Chargers*
- *Closed-Loop Regulation of Ground Current*
- *More Compact & Efficient EV Chargers*







Thank you!