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Synergetic Control of Non-Isolated 3-Φ Voltage & Current DC-Link EV Chargers

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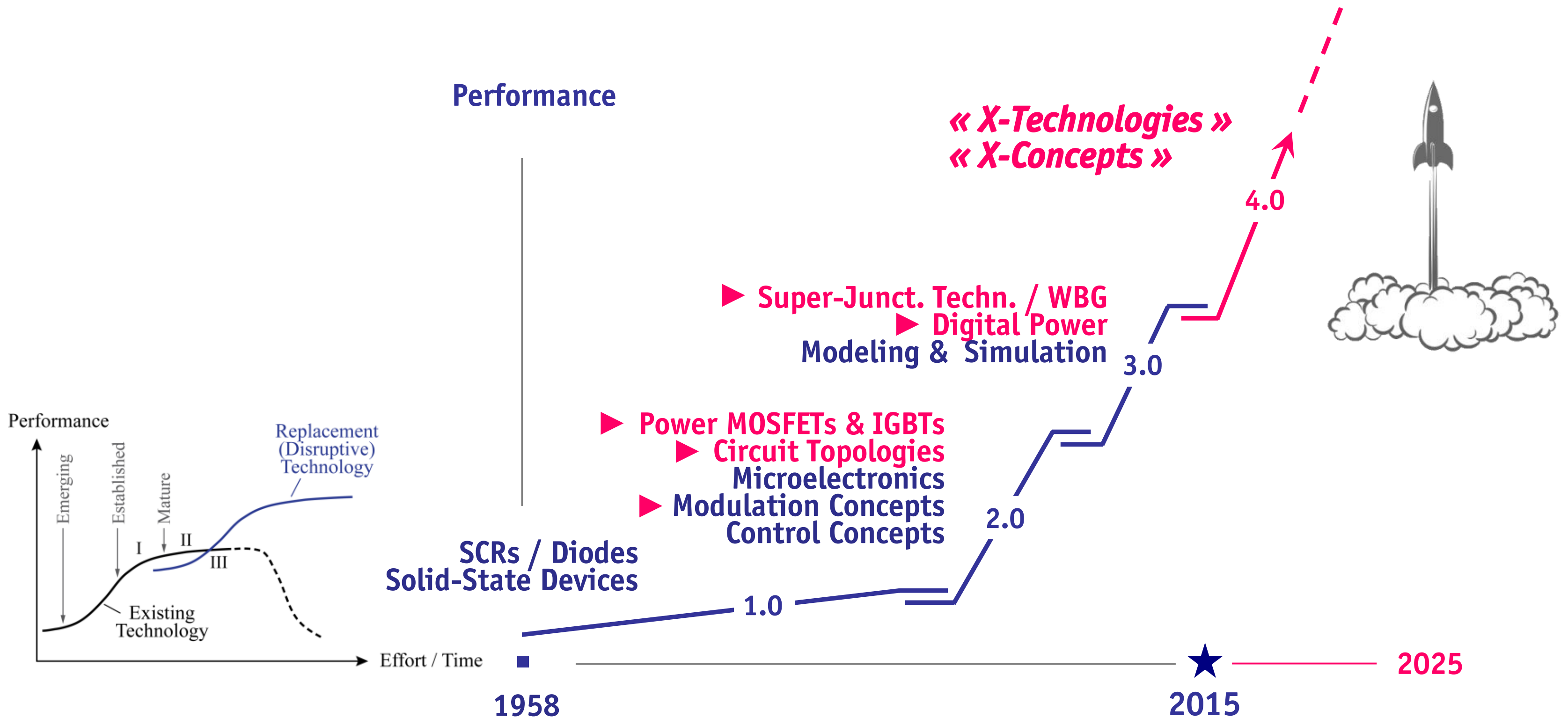
Abstract — The presentation first identifies Modularization, Functional Integration, Decentralization, Hybridization, and Synergetic Association as key concepts (**«**X-Concepts**»**) for future performance improvements of power electronics converters. Next, latest research results of the Power Electronic Systems Laboratory of ETH Zurich in the area of bidirectional three-phase AC/DC converter systems with voltage or current DC-link, i.e., boost-buck or buck-boost functionality, are discussed. The realization of both systems is based on "Synergetic Control" of the PFC rectifier input stage and DC/DC converter output stage and considers 400V line-to-line input, a very wide output voltage range of 200V to 1000V, and 10kW of rated power. The described hardware demonstrators are featuring high efficiency and power density and accordingly could serve as standard building blocks of galvanically isolated EV chargers. Moreover, as documented with the results of comprehensive experimental analyses, both systems are ideally suited as future RCD-based *non-isolated* EV chargers. The talk concludes with remarks on the urgency of a transition from a Linear Economy to a Circular Economy, which also needs to be considered for future power electronics converter designs in order to ensure that the 2050 Net-Zero-CO_2 target is reached on a sustainable basis.

Outline

S-Curve of Power Electronics

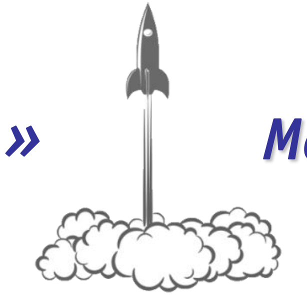
- « X-Technologies » / "Moon-Shot" Technologies
- « X-Concepts » → Full Utilization of Basic Scaling Laws & X-Technologies
- Power Electronics 1.0 → Power Electronics 4.0



« X-Concepts »

Modularization
Functional Integration
Decentralization
Hybridization
Synergetic Association

« X-Concept »



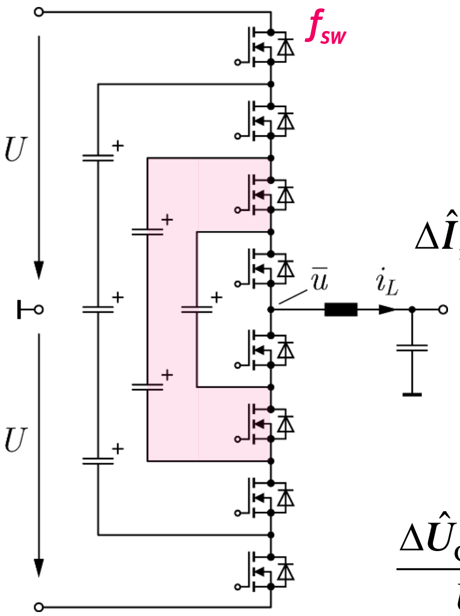
Modularization

Scaling of Multi-Cell/Level Concepts

- *Reduced Ripple @ Same (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage*
- *Application of LV Technology to HV*

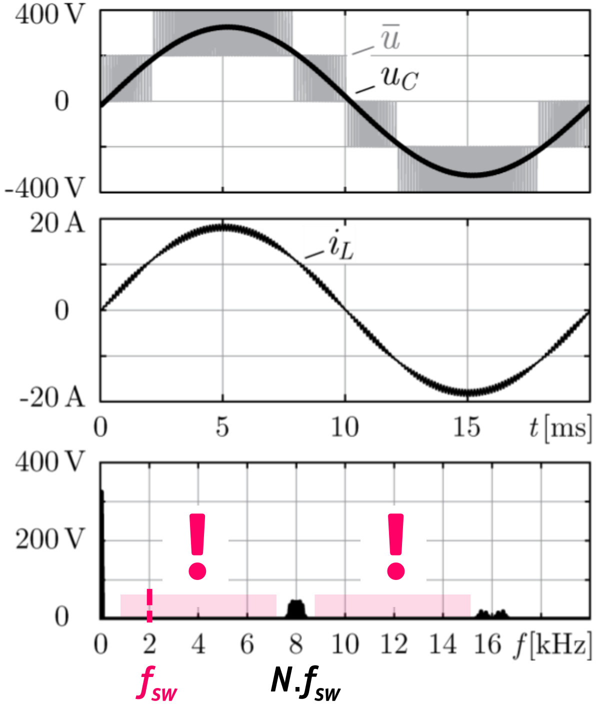
Source: R. Pilawa

Integrated Dual-Sided Half-Bridge Flying Capacitor Converter Switching Cell



$$\Delta\hat{I}_{max,N} = \frac{1}{N^2}\Delta\hat{I}_{max,N=1}, \quad \Delta\hat{I}_{max,N=1} = \frac{U}{8 f_s L}$$

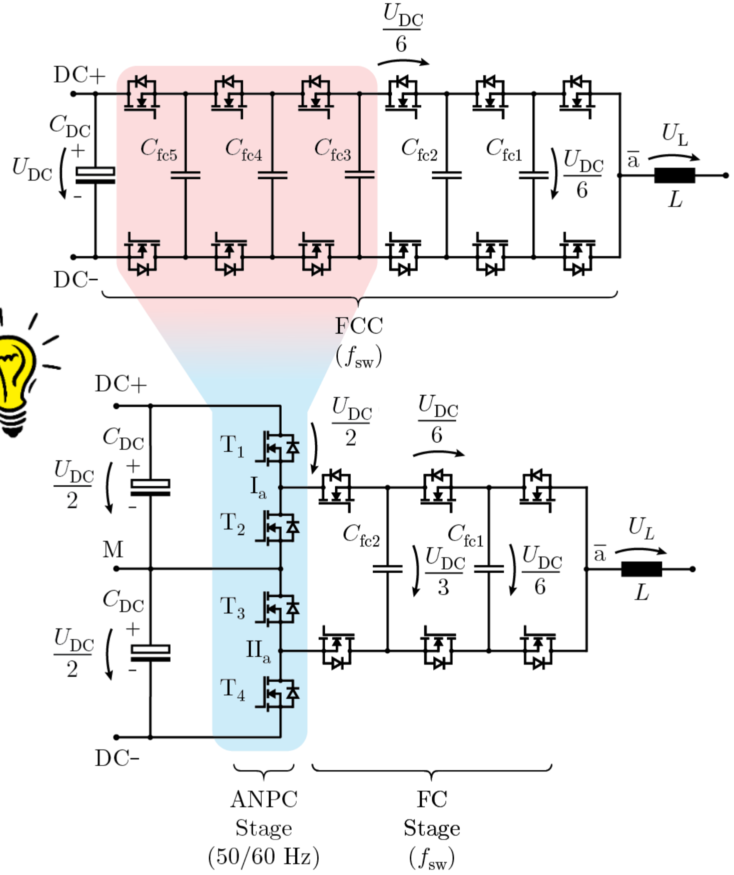
$$\frac{\Delta\hat{U}_{C,max,N}}{U} = \frac{\pi^2}{32}\left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$

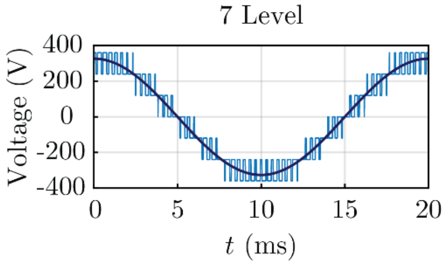


- *Scalability / Manufacturability / Standardization / Redundancy*

3-Φ Hybrid Multi-Level Inverter

- *Realization of a 99%++ Efficient 10kW 3-Φ 400$V_{rms,ll}$ Inverter System*
- *7-Level Hybrid Active NPC Topology / LV Si-Technology*

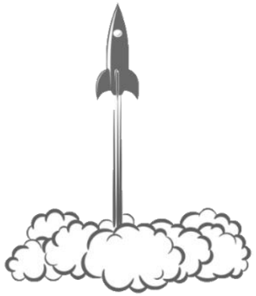




99.35%
2.6kW/kg
56 W/in³

- *200V Si → 200V GaN Technology Results in 99.5% Efficiency*

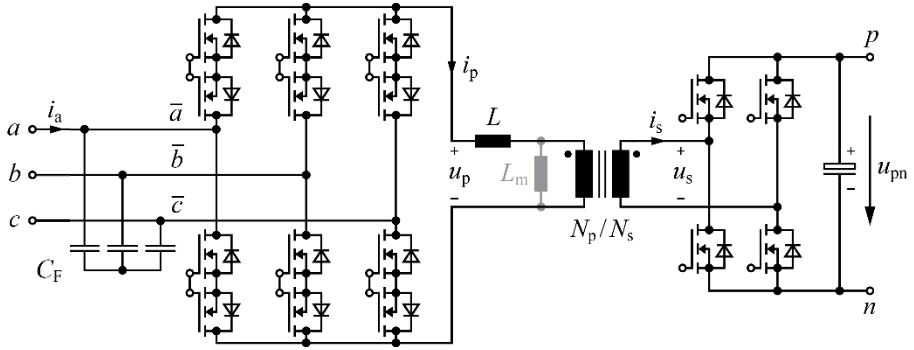
« X-Concept »

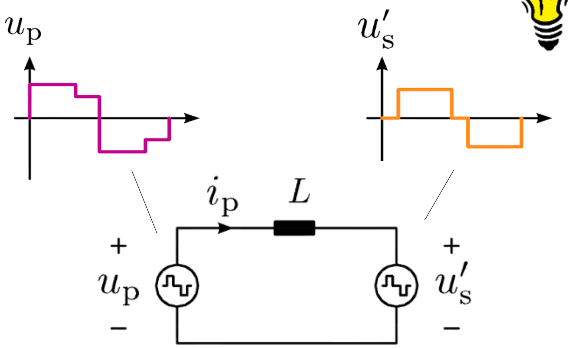


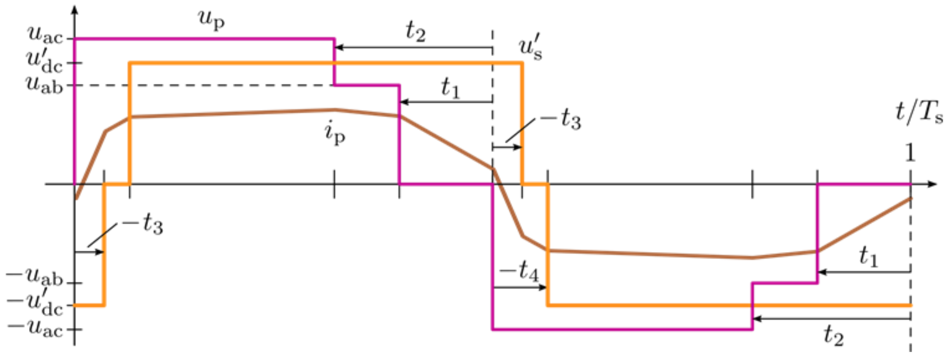
Functional Integration

Isolated Matrix-Type 3-Φ PFC Rectifier (1)

- *Based on Dual Active Bridge (DAB) Concept*
- *Ingegration of 3-Φ PFC Rectifier & DC/DC Converter Stage*
- *Opt. Modulation (t_1...t_4) for Min. Transformer RMS Curr. & ZVS or ZCS*
- *Allows Buck-Boost Operation*





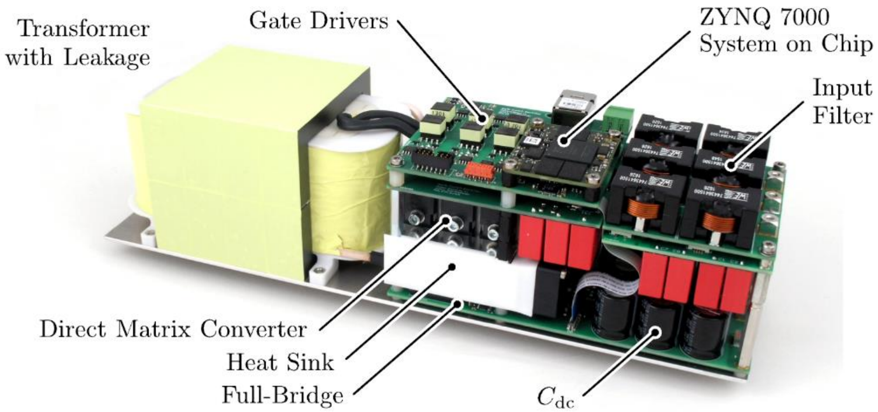


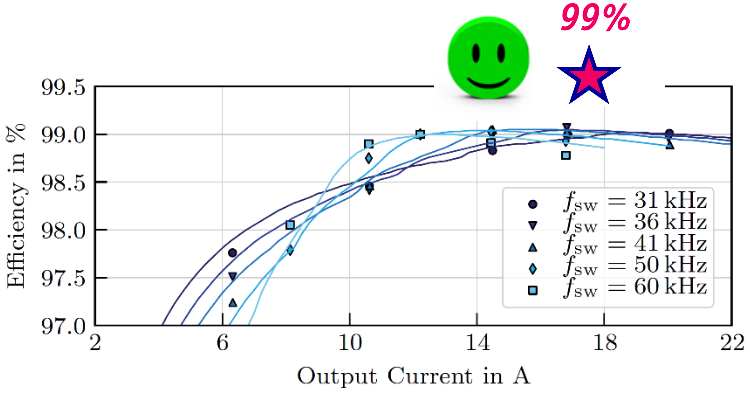
- *Equivalent Circuit*
- *Transformer Voltages / Currents*

Isolated Matrix-Type 3-Φ PFC Rectifier (2)

- Efficiency η = 99% @ 60% Rated Load (ZVS)
- Mains Current $THD_I \approx 4\%$ @ Rated Load
- Power Density $\rho \approx 4 kW/dm^3$

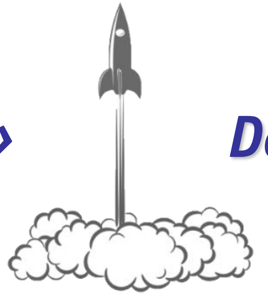
P_O = 8 kW
U_N = $400V_{AC}$ → U_O = $400V_{DC}$
f_S = 36kHz





- 900V / 10mΩ SiC Power MOSFETs
- Opt. Modulation Based on 3D Look-Up Table

« X-Concept »



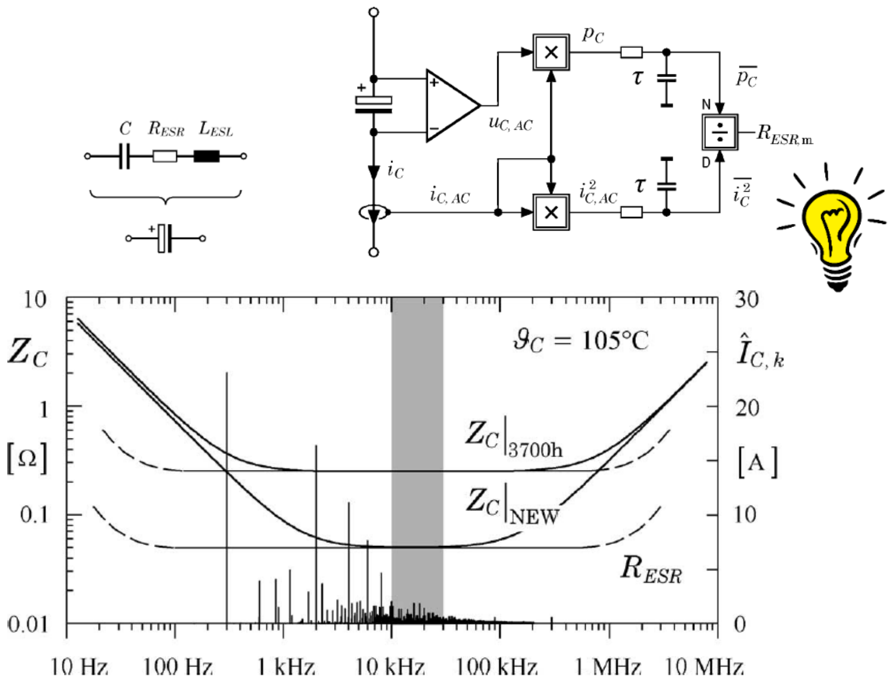
Decentralization

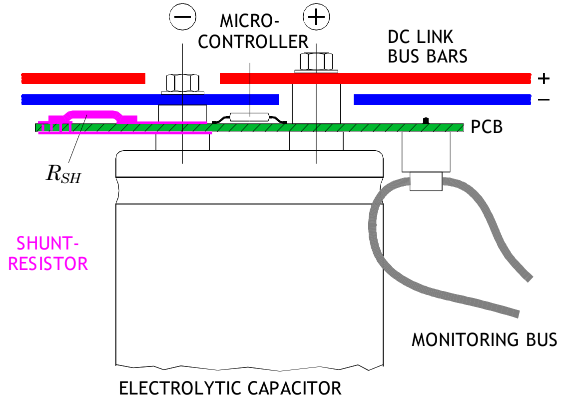
IIoT Starts with Sensors (!)

- *Condition Monitoring of DC Link Capacitors*
- *On-Line Measurement of the ESR in "Frequency Window" (Temp. Compensated)*
- *Data Transfer by Optical Fibre or Near-Field RF Link*

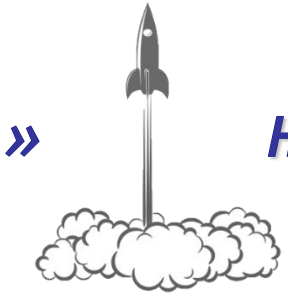
TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

Source: Prof. Ertl
TU Vienna, 2011



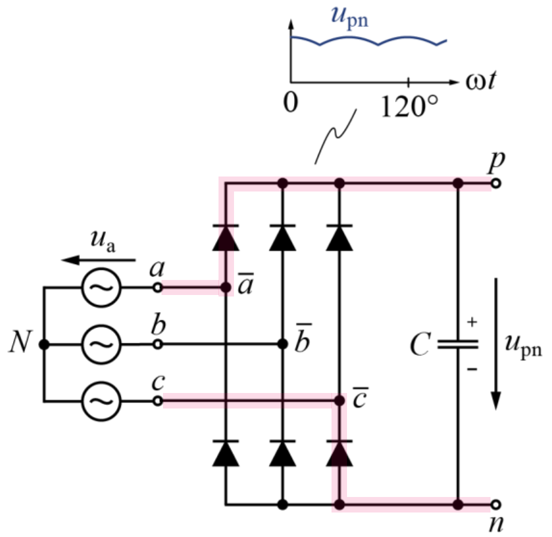


- *Possible Integration into Capacitor Housing or PCB*
- *Additionally features Series Connect. Voltage Balancing*

« X-Concept »  *Hybridization*

Integrated Active Filter (IAF) PFC Rectifier

- Hybrid Combination of Mains- and Forced-Commutated Converter
- 3rd Harmonic Current Injection into Phase with Lowest Voltage
- Phase Selector AC Switches Operated @ Mains Frequency — 3-Φ Unfolder



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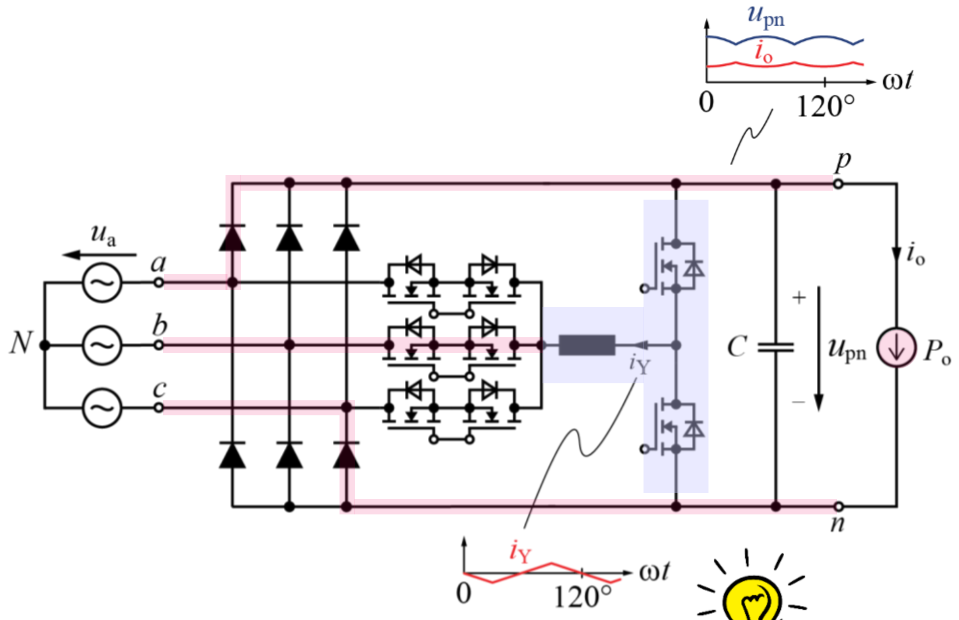


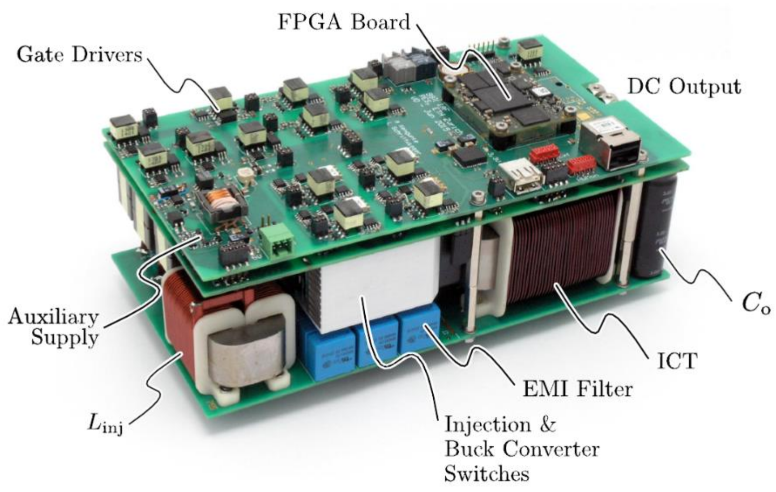
- Non-Sinusoidal Mains Current

→ P_0= const. Required
→ Sinusoidal Mains Current
→ NO (!) DC Voltage Control

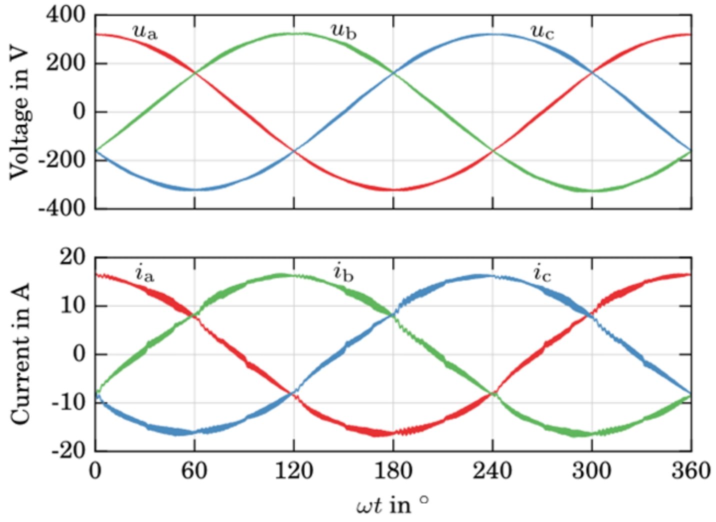
IAF PFC Rectifier & Buck Converter Demonstrator

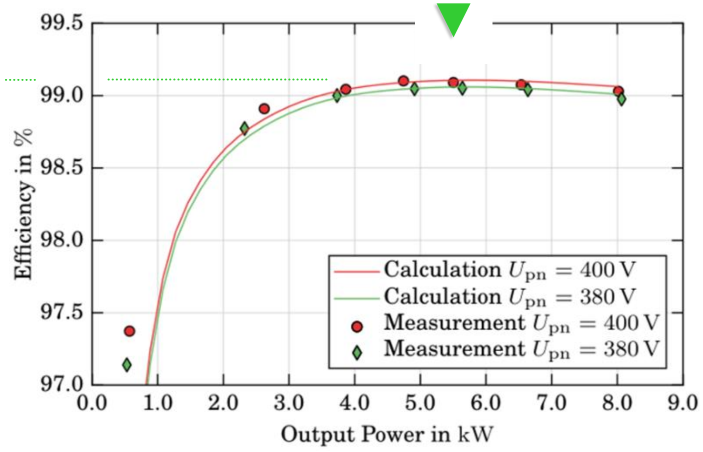
- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current $THD_I \approx 2\%$ @ Rated Load*
- *Power Density $\rho \approx 4 kW/dm^3$*

P_O = 8 kW
U_N = 400V_{AC} → U_O = 400V_{DC}
f_S = 27kHz

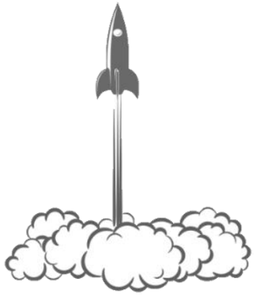


- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck Output Stages*
- *Controlled Output Voltage*





« X-Concept »

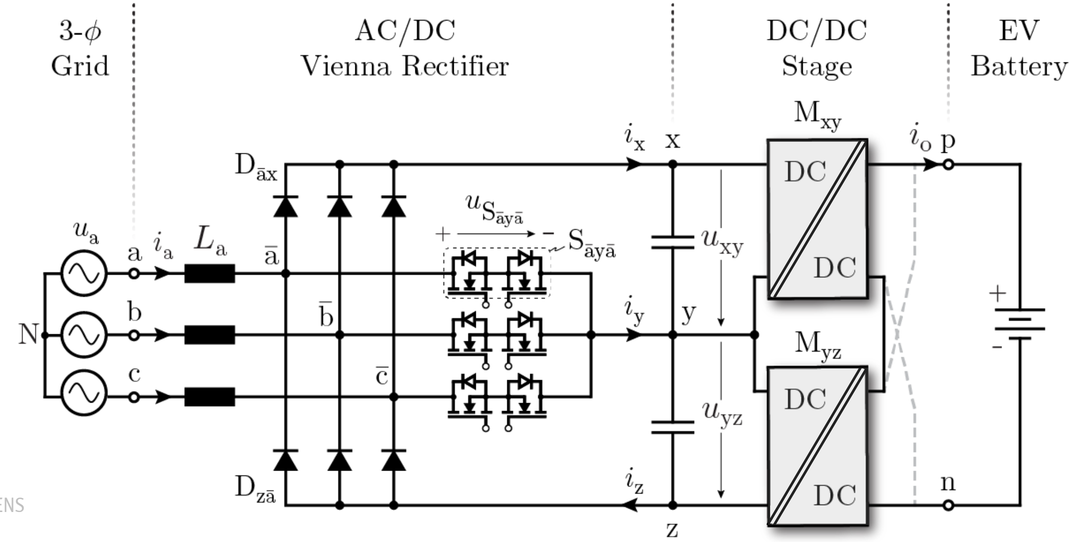


Synergetic Association

3-Φ EV-Charger Topology

- Isolated Controlled Output Voltage
- Buck-Boost Functionality & Sinusoidal Input Current
- *Applicability of 600V GaN Semiconductor Technology*
- *High Power Density / Low Costs*

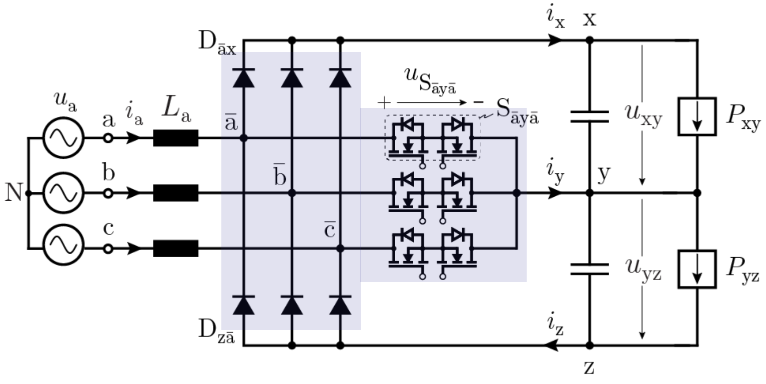
Source: SIEMENS

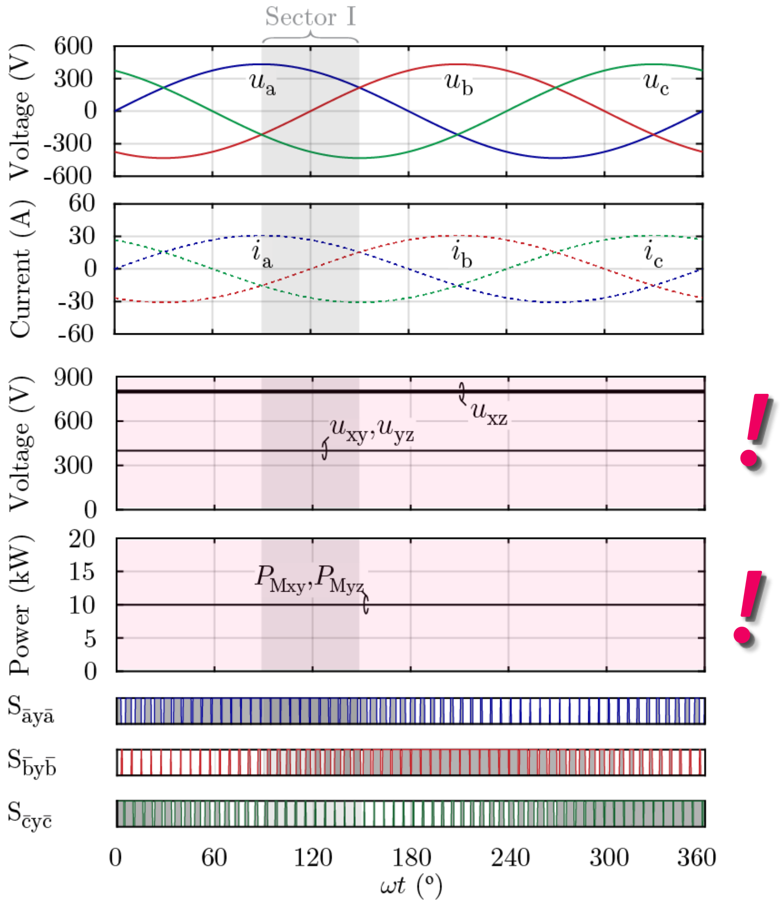


→ *Conventional / Independent OR "Synergetic Control" of Input & Output Stage*

Conventional Control — 3/3-PWM

- *Decoupled Control of AC/DC & DC/DC-Stage*
- *Constant DC-Link Voltage (Equally Splitted)*
- *Cont. Sw. of All 3 Phases → 3/3 PWM*

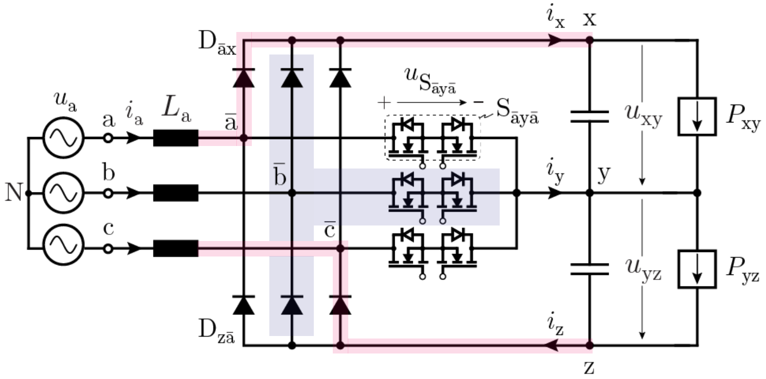


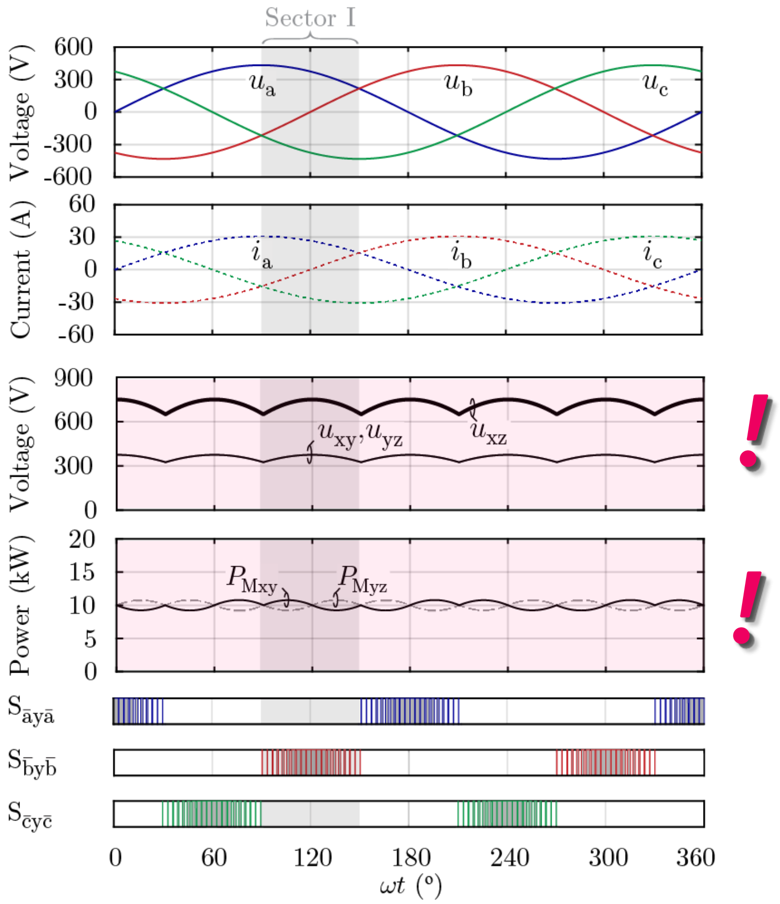


→ Control Capability & Control DOFs NOT Fully Utilized (!)

"Synergetic" Control — 1/3-PWM

- *Only Phase with Lowest Current Switched*
- *Control of 2 Phase Currents by DC/DC-Stage*
- *Conduction Losses of the Switches ≈ -80%*
- *Switching Losses ≈ -70%*
- *600V GaN HEMTs Can be Used (!)*



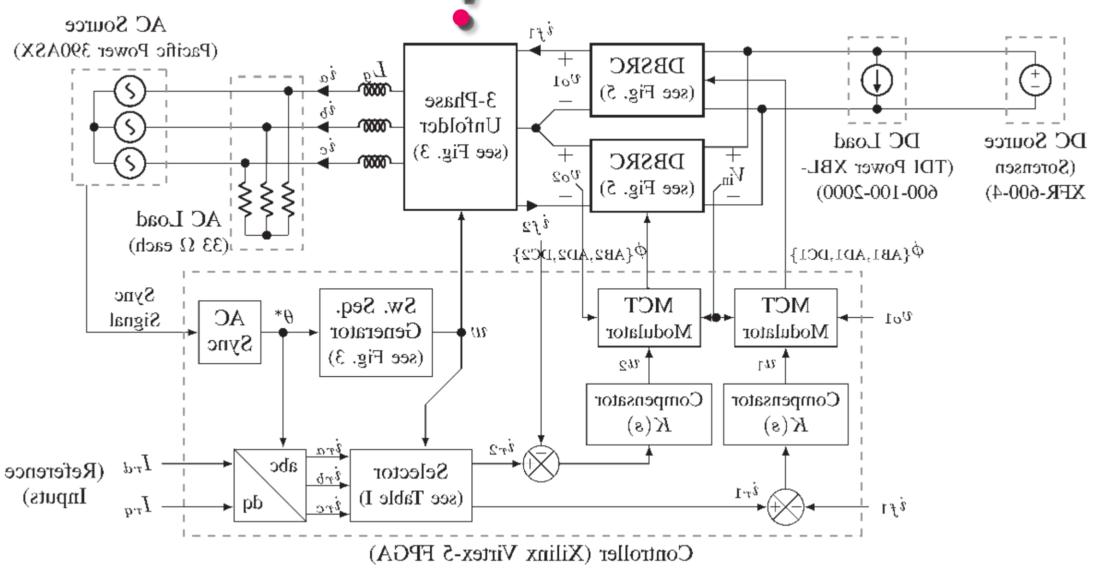


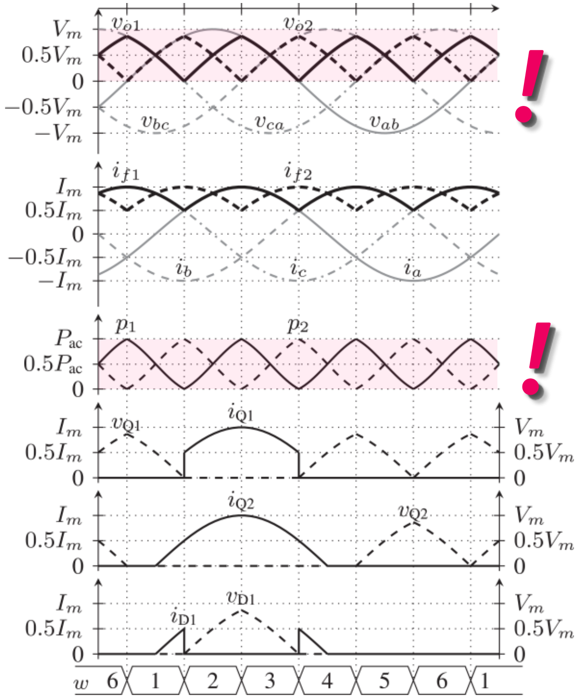
→ *Boost Capability Maintained (Transition from 1/3 to 3/3-PWM)*

"Synergetic" Control — 3-Φ Unfolder

- *Mains-Frequency Commutated NPCC Unfolder Cascaded by Dual-Bridge SRC*
- *DBSRC Regulates DC-Link Currents & Ultimately 3-Φ AC currents*
- *93% @ 1.2 kW Bidirectional Power Flow*

Source: W. W. Chen, R. Zane and L. Corradini (2017)





- *Negligible Unfolder Switching Loss*
- *Large DC-Link Voltage & Power Fluctuations*

1/3-PWM — Analytical Derivation

- ***KVL of All Three Phases :***

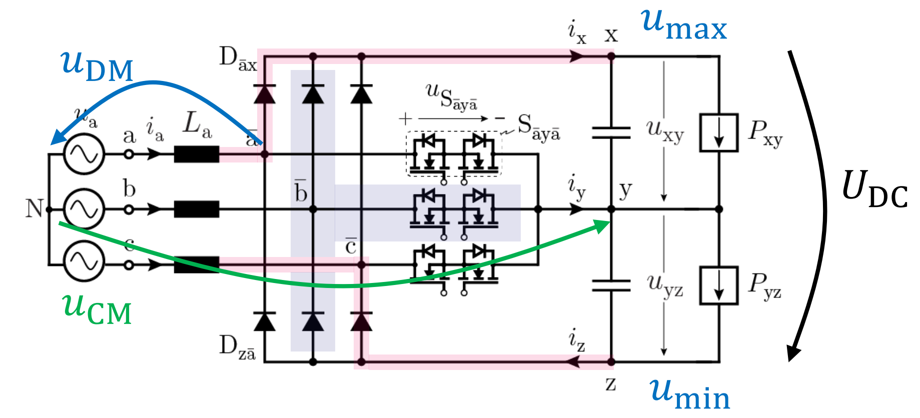
$$-\frac{1}{2}U_{\mathrm{DC}} = u_{\mathrm{yz}} \leq u_{\bar{\mathrm{a}}\mathrm{N}} + u_{\mathrm{CM}} \leq u_{\mathrm{xy}} = \frac{1}{2}U_{\mathrm{DC}}$$
$$-\frac{1}{2}U_{\mathrm{DC}} = u_{\mathrm{yz}} \leq u_{\bar{\mathrm{b}}\mathrm{N}} + u_{\mathrm{CM}} \leq u_{\mathrm{xy}} = \frac{1}{2}U_{\mathrm{DC}}$$
$$-\frac{1}{2}U_{\mathrm{DC}} = u_{\mathrm{yz}} \leq u_{\bar{\mathrm{c}}\mathrm{N}} + u_{\mathrm{CM}} \leq u_{\mathrm{xy}} = \frac{1}{2}U_{\mathrm{DC}}$$

- ***CM Voltage Boundary :***

$$-\frac{1}{2}U_{\mathrm{DC}} - u_{\mathrm{min}} \leq u_{\mathrm{CM}} \leq \frac{1}{2}U_{\mathrm{DC}} - u_{\mathrm{max}}$$
$$u_{\mathrm{min}} = \min\left(u_{\bar{\mathrm{a}}\mathrm{N}}, u_{\bar{\mathrm{b}}\mathrm{N}}, u_{\bar{\mathrm{c}}\mathrm{N}}\right)$$
$$u_{\mathrm{max}} = \max\left(u_{\bar{\mathrm{a}}\mathrm{N}}, u_{\bar{\mathrm{b}}\mathrm{N}}, u_{\bar{\mathrm{c}}\mathrm{N}}\right)$$

- ***1/3-PWM when Satisfying Two Equalities :***

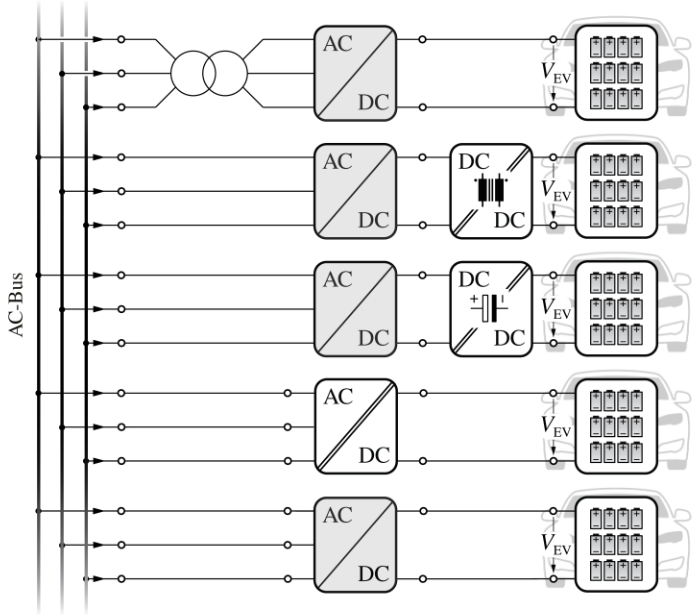
$$U_{\mathrm{DC},1/3} = u_{\mathrm{max}} - u_{\mathrm{min}}$$
$$u_{\mathrm{CM}} = -\frac{1}{2}\left(u_{\mathrm{max}} + u_{\mathrm{min}}\right)$$

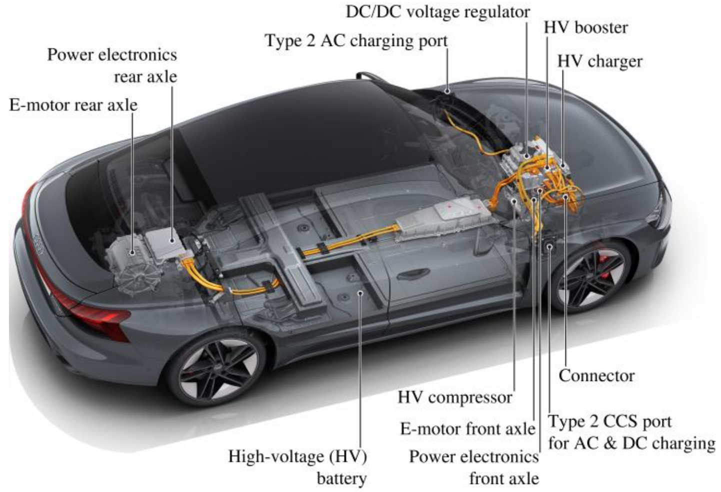


Typical EV Charger Structures

- *Sustained Transportation Electrification*
- *More Compact & Efficient EV Chargers*

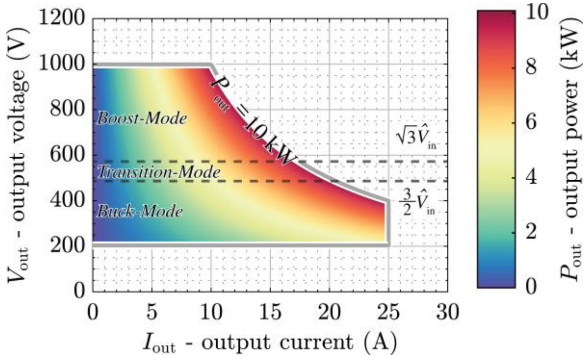
❖ *Typical Structures of Isolated or Non-Isolated EV Charger*





Source:Electrichasgoneaudi.net

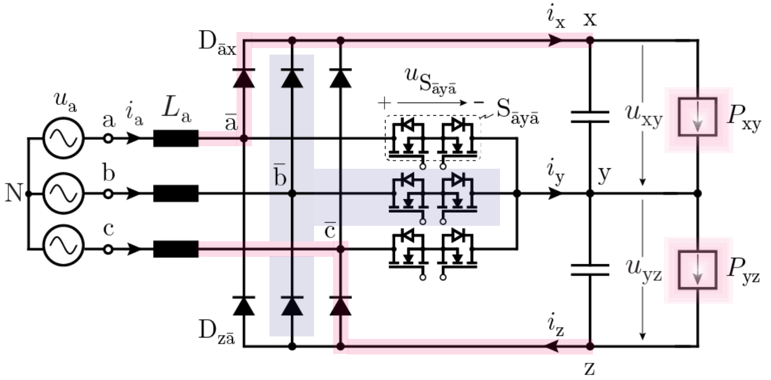
❖ *Typical Operating Range of 10kW Charger Module*



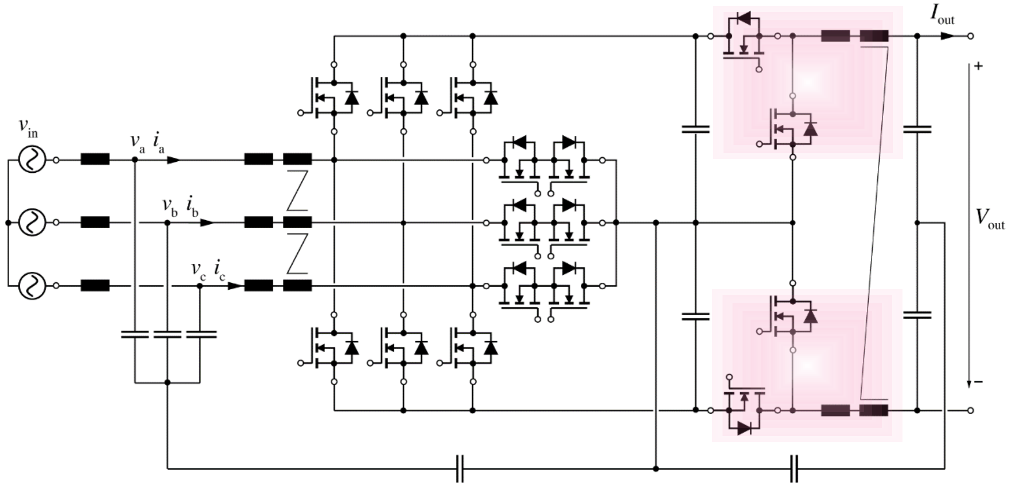
- *3-Φ Non-Isolated Bidirectional AC/DC Converter System → Standard Building Block*
- *Buck-boost Capability : 200V to 1000V*

3-Level DC/DC Buck Converter Stage

- *Simple & Non-Isolated Three-level Rare-End*

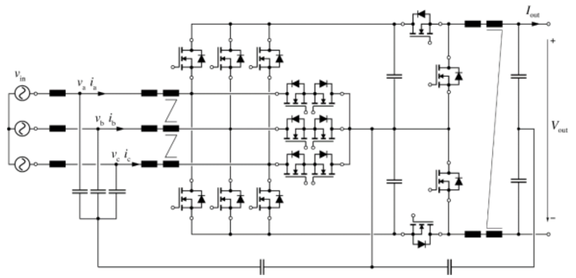


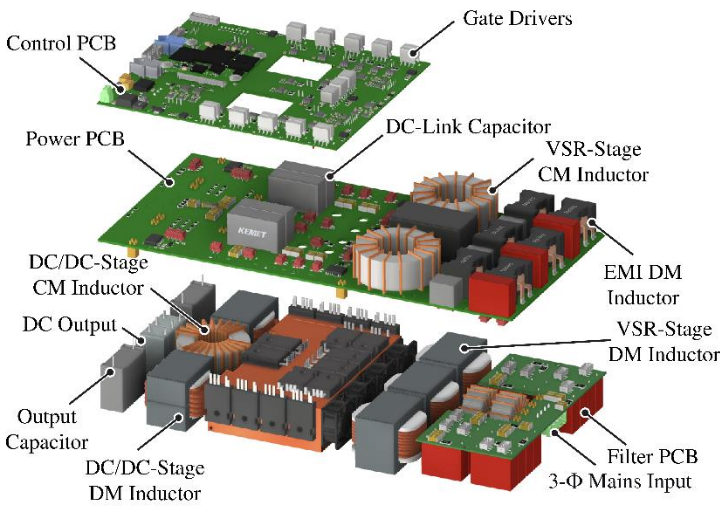
❖ *3-Φ Bb Voltage DC-Link PFC AC/DC Converter System*

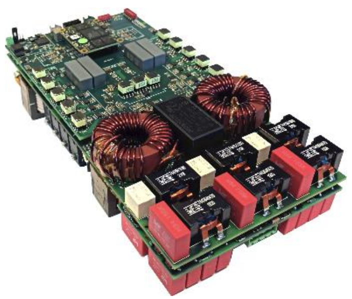


- *High Effective Sw. Frequency → Small Passive Components Volume*
- *Less Sw. Voltage → High Efficiency Operation*
- *Extended Output Voltage Range → 900V Devices for 1200V DC Output*

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



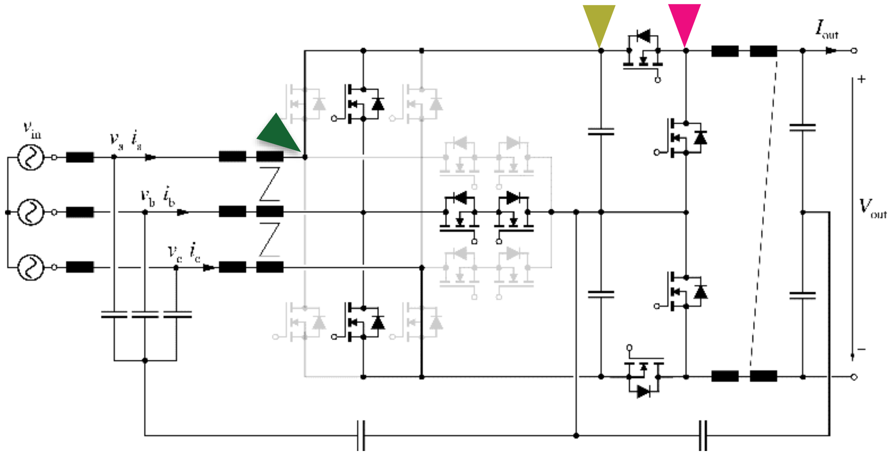


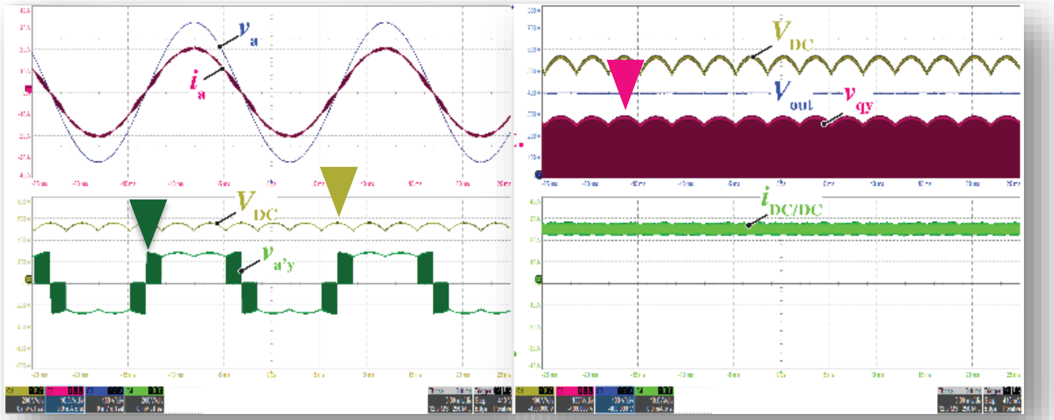


200 ... 800 V_{DC} | 10 kW @ 98.8% | 5.4 kW/L

Loss-Optimal Operating Principles

- *Buck-Mode Operation - 400V*
- *1/3-PWM*
- *Pulse-Shape DC-Link Voltage*

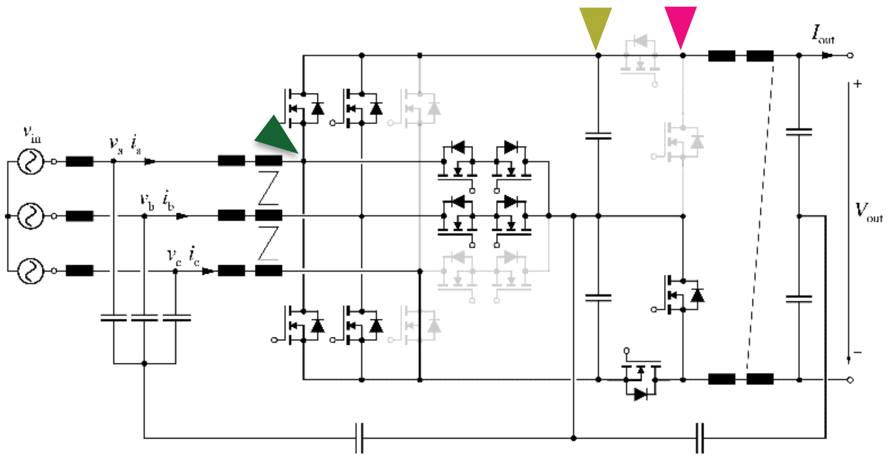


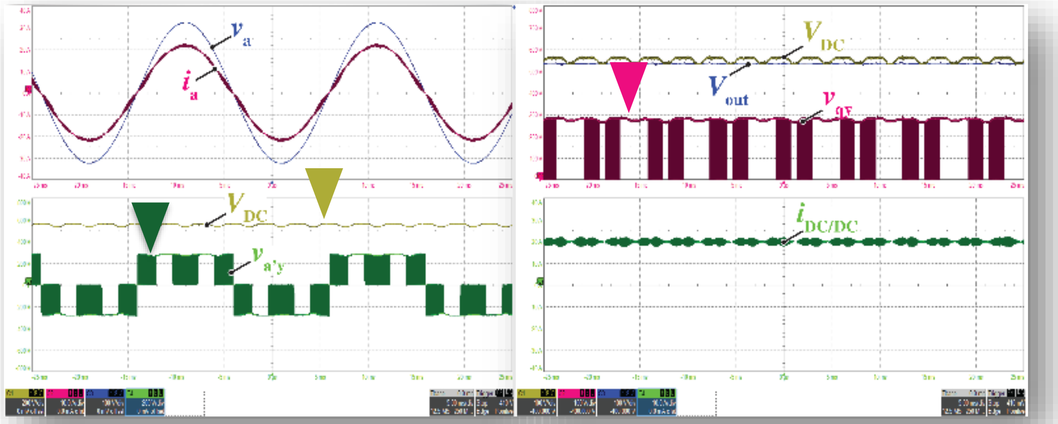


- *Min. # of Switching Instants & Min. Amplitude of Switched Current*
- *App. 70% Reduction of Switching Losses*

Loss-Optimal Operating Principles

- *Transition-Mode Operation - 540V*
- *Optimal 2/3-PWM*
- *Time-Varying DC-Link Voltage*

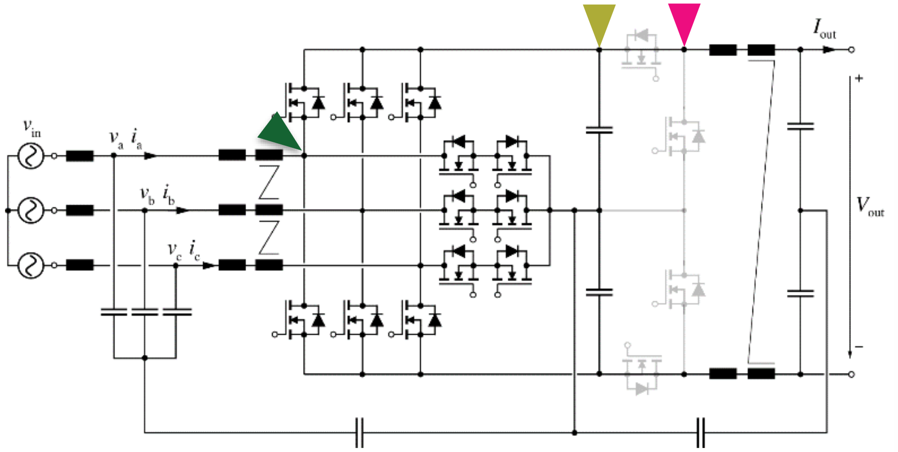


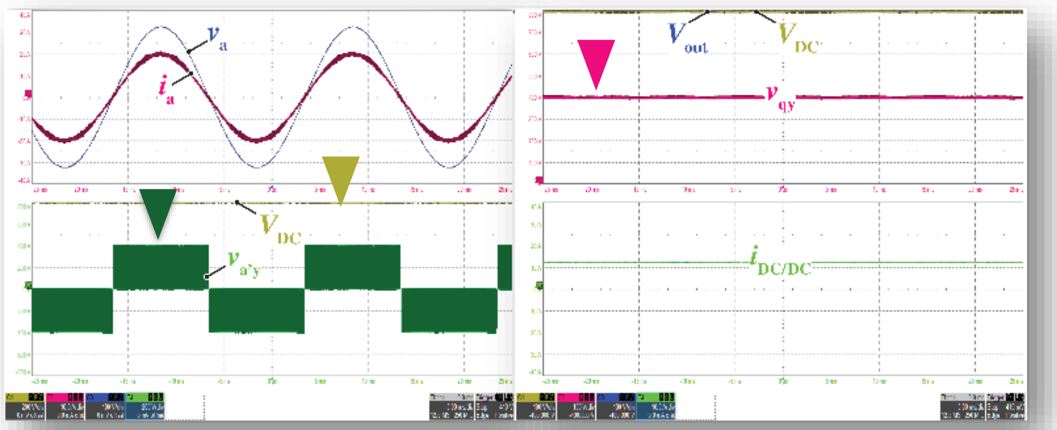


- *Seamless & Smooth Transition Between 1/3-PWM & 3/3-PWM*
- *Fully Utilize DC-Link Voltage Shape*
- *Avoid LF Current Flowing Through DC-Link Capacitors*

Loss-Optimal Operating Principles

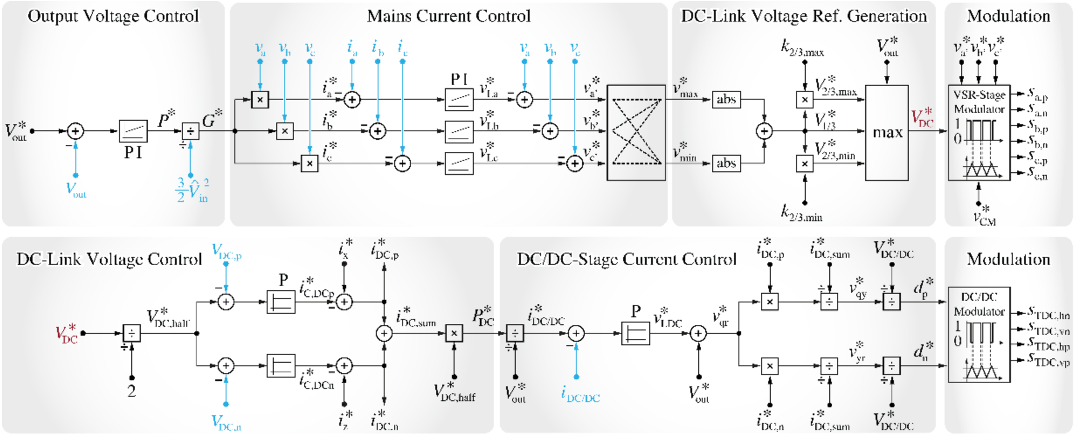
- *Boost-Mode Operation – 800V*
- *3/3-PWM*
- *Constant DC-Link Voltage*

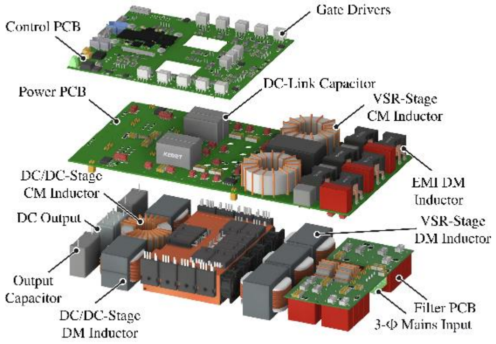




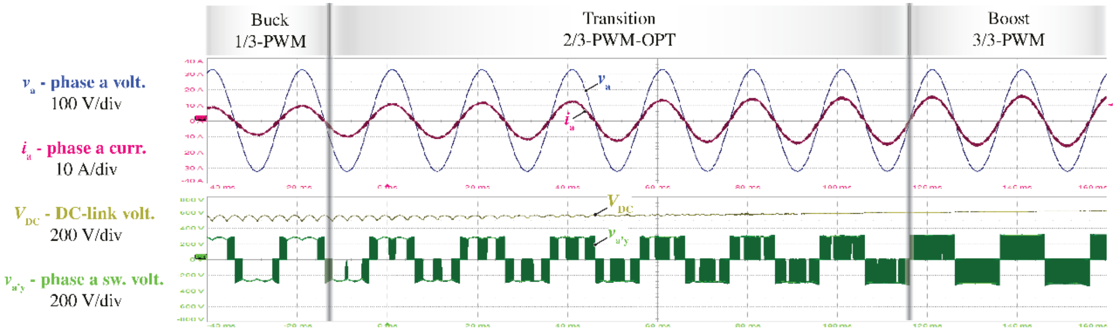
- *Only Require Boost Functionality*
- *Permanently Turn DC/DC-Stage On → Avoid Sw. Losses*

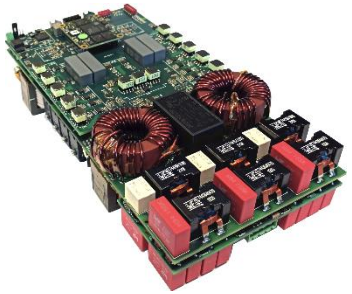
Synergetic Control Strategy





❖ *Output Voltage : 460V → 600V w/ 50 Ohm Load*

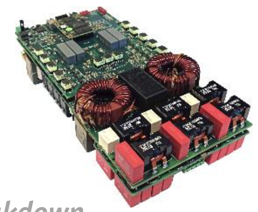




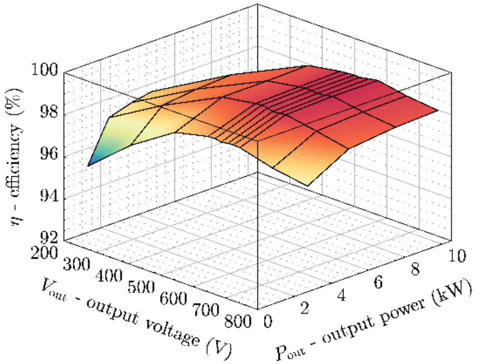
- *Collaborative Operation of AC/DC & DC/DC Converter Stage*
- *Ensure Seamless / Democratic Transitions between Loss-Optimal Modes*

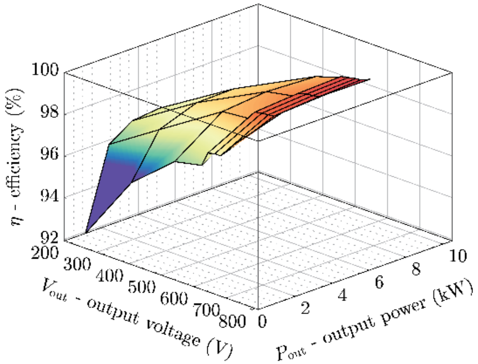
Efficiency Measurement Results

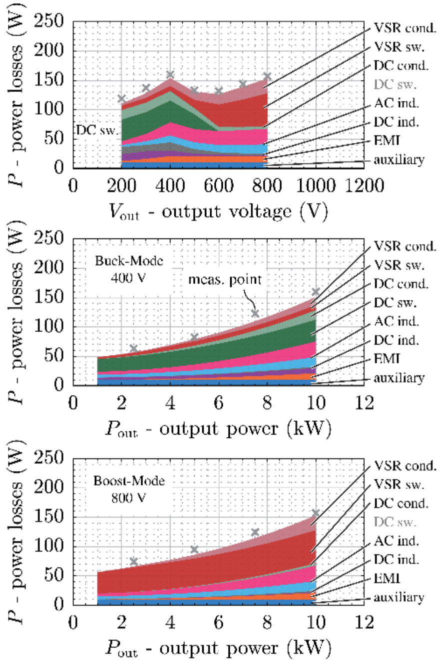
- *Measurements Covering 200V to 800V & 25% Load to Full Load*



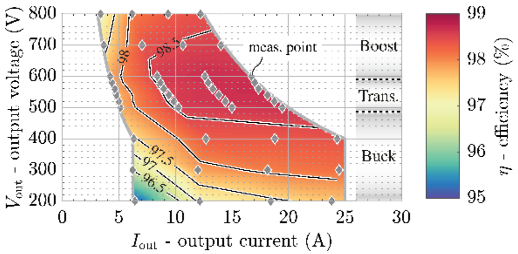
- Loss-Optimal Operation
- Benchmark Operation
- Loss Breakdown

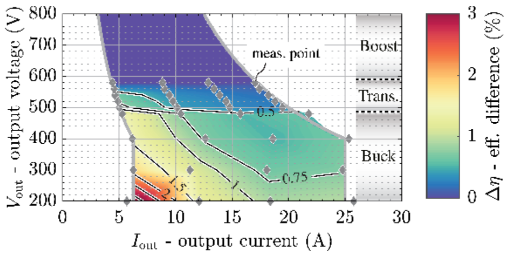




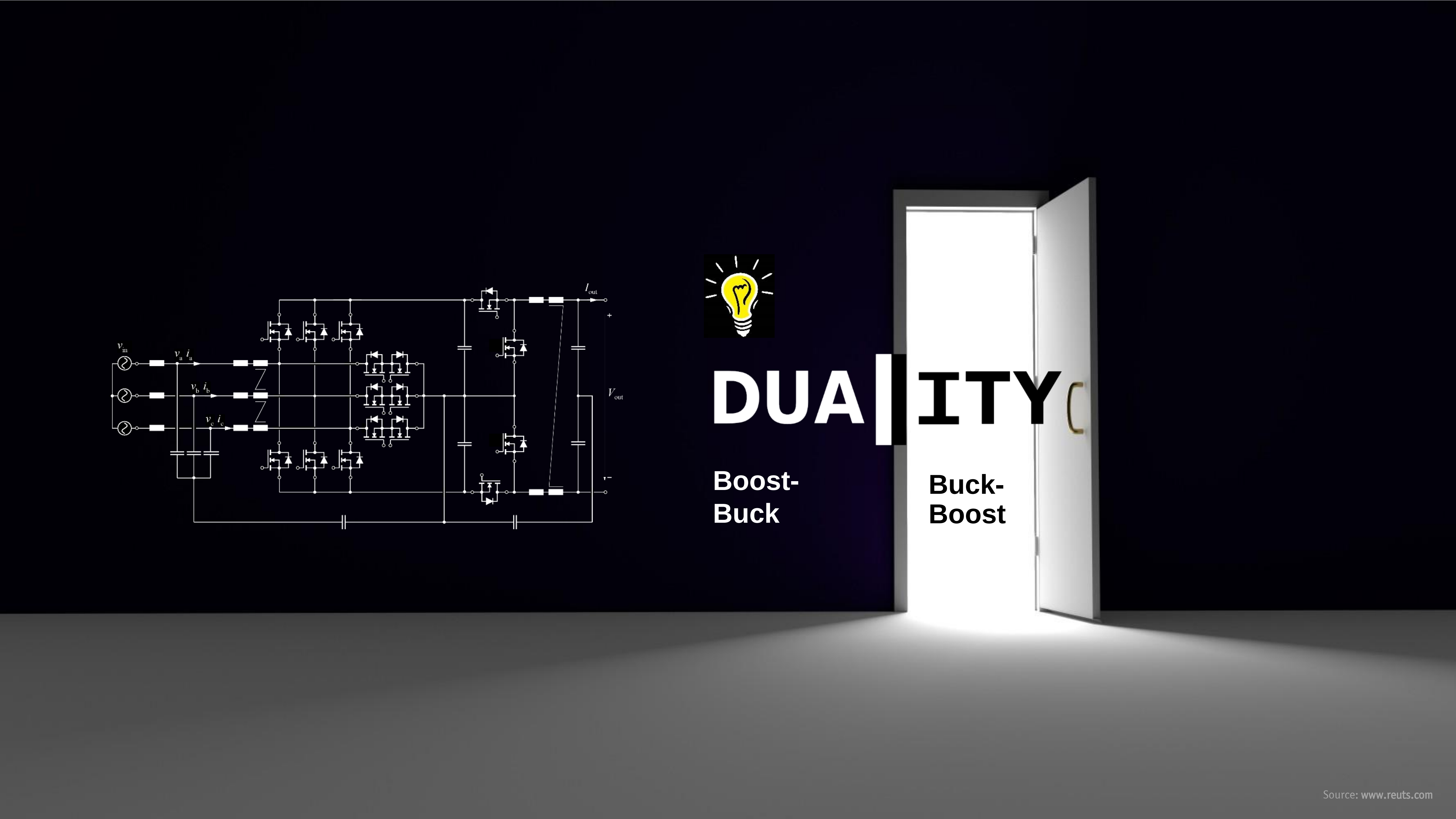


- Loss-Optimal Operation (2D)
- Efficiency Improvement





- *Peak Efficiency of 98.8%*
- *Up to 3.2% / 0.8% Efficiency Improvement in Buck-Mode / Transition-Mode Operations*


DUALITY
Boost-
Buck
Buck-
Boost
Source: www.reuts.com

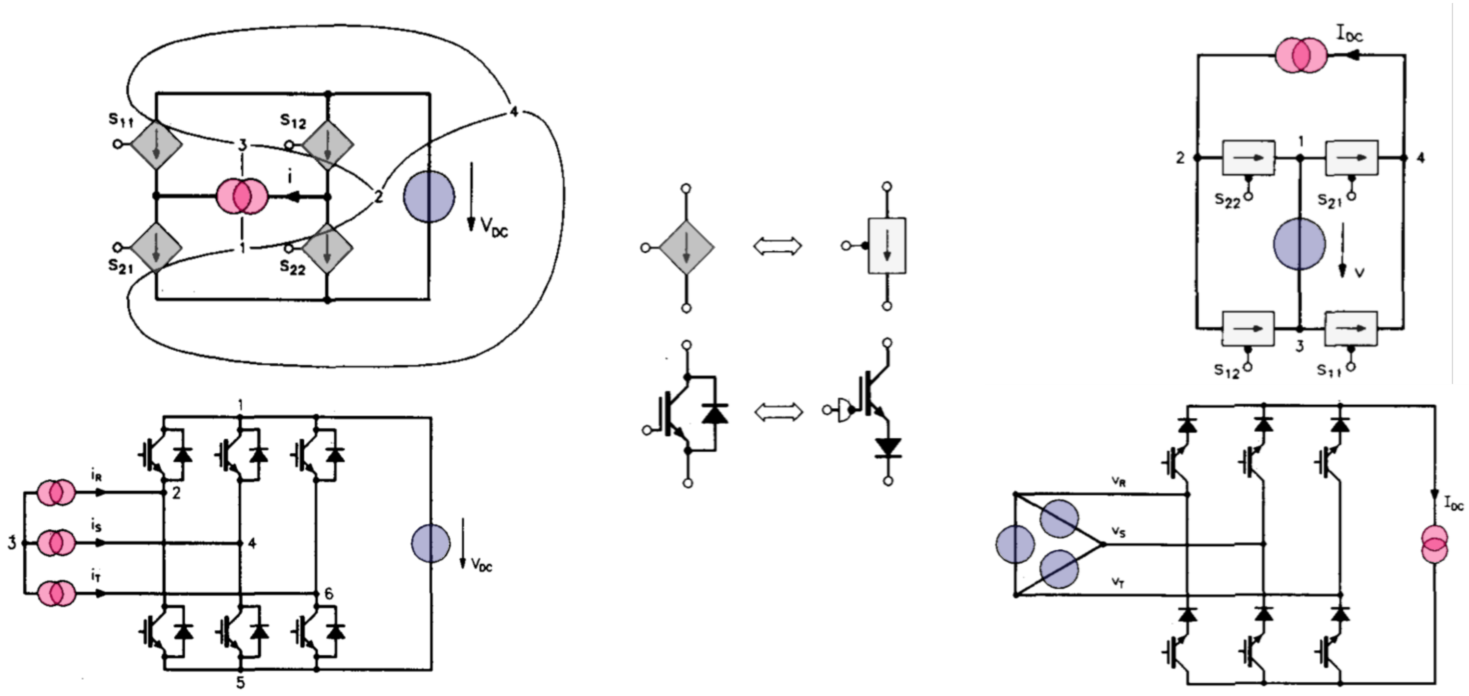
DUALITY

IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 29, NO. 2, MARCH/APRIL 1993

Quasi-Dual Modulation of Three-Phase PWM Converters

Johann W. Kolar, *Member, IEEE*, Hans Ertl, *Member, IEEE*, and Franz Zach, *Member, IEEE*

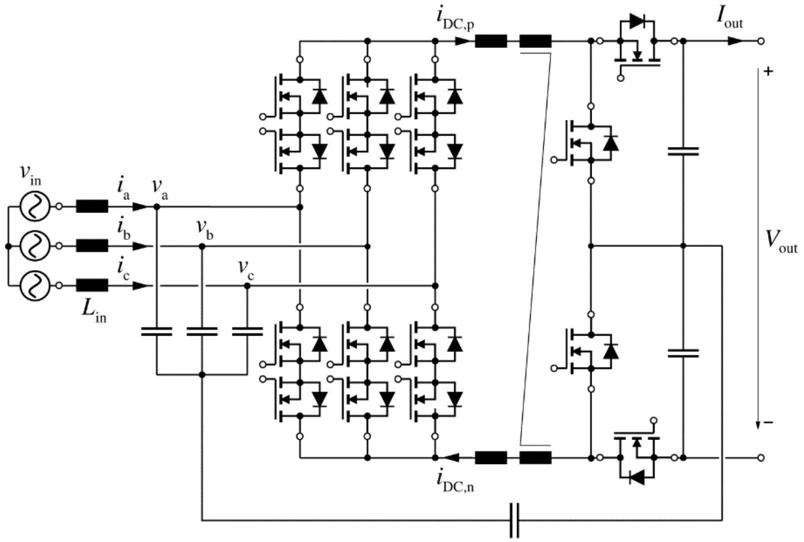
- *Duality of Voltage DC-Link & Current DC-Link Converter Circuits*
- *Unipolar Blocking / Bidir. Current → Bipolar Blocking Unidir. Switches → Appl. of M-BDSs (!)*



- *"Boost-Buck" Translated into "Buck-Boost" Functionality / Lower # of Ind. Components*

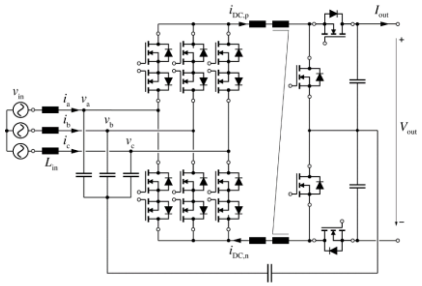
Bidirectional *Buck-Boost* PFC Rectifier Concepts

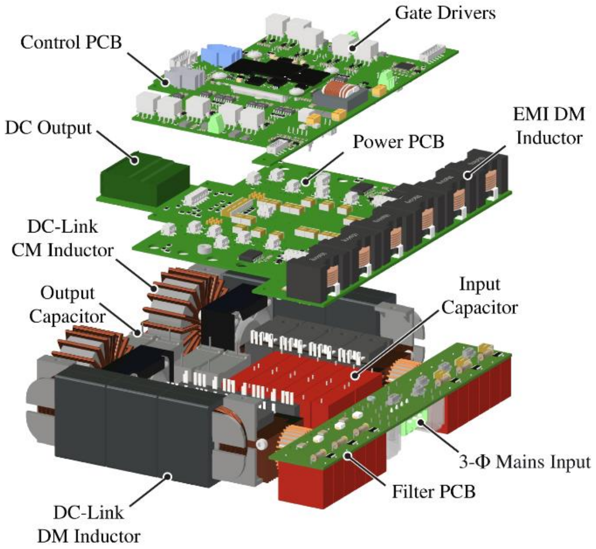
- *Boost—Buck* ***OR*** *Buck—Boost Combination*
- *"Synergetic Control" of AC/DC and DC/DC Converter Stage*



- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

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

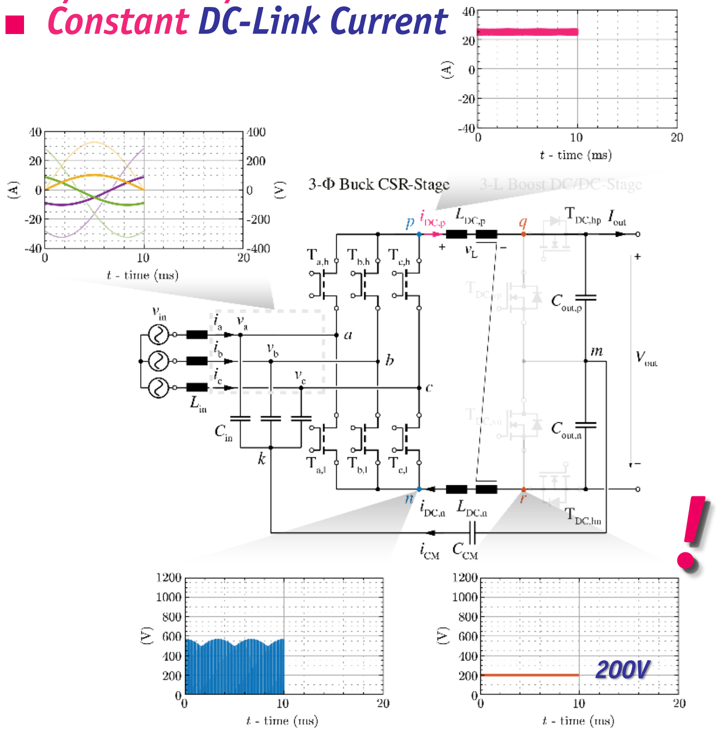




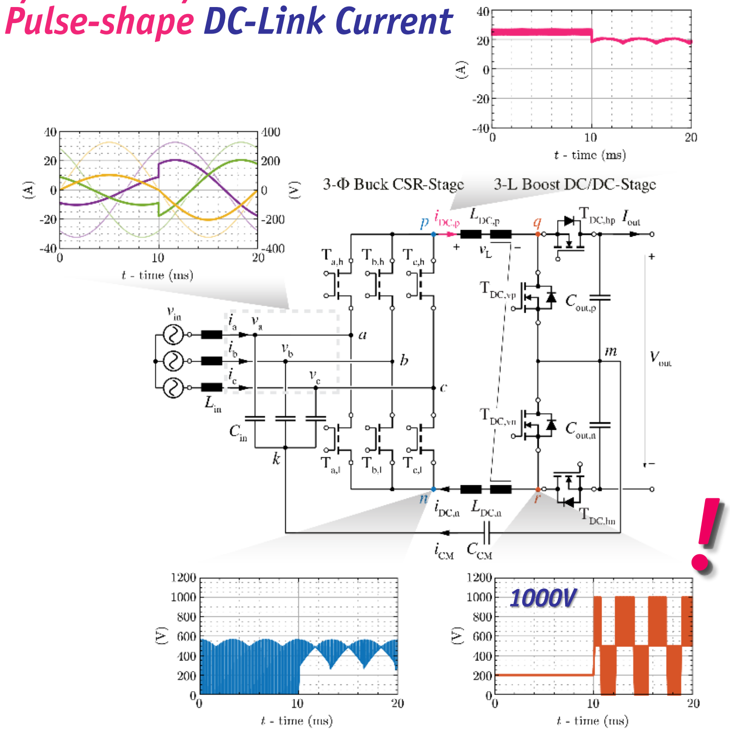
200 ... 1000 V_{DC} | 10 kW @ 98.8% | 6.4 kW/L

Loss-Optimal Operating Principles (1)

- *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*

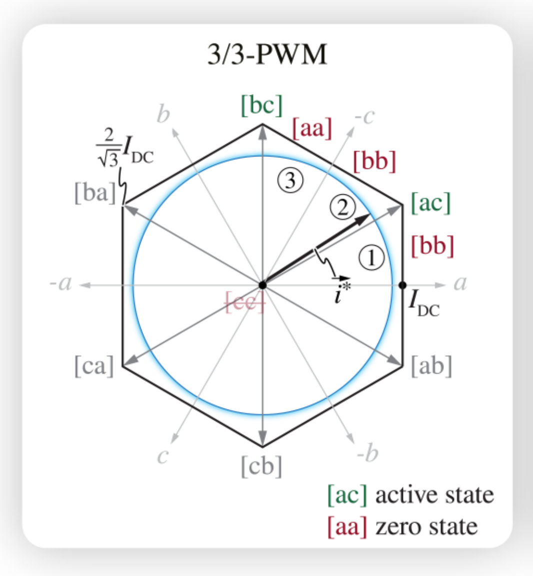


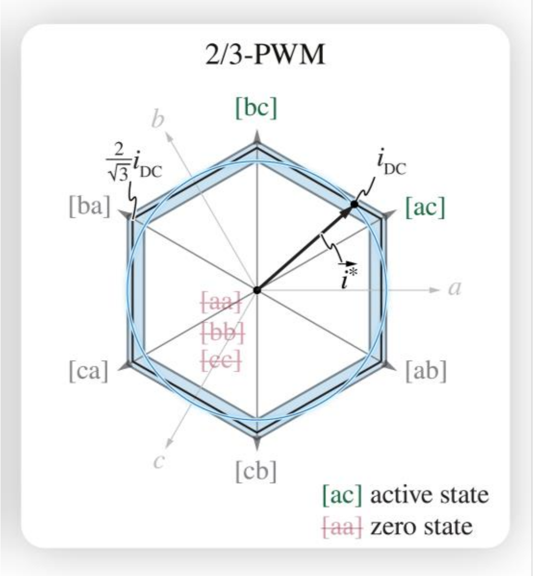
- *Min. # of Switching Instants & Reduced Sw. Voltage → App. 77% Reduction of Switching Losses*
- *Min. DC-Link Current → 8% Reduction of Conduction Losses*

Loss-Optimal Operating Principles (2)

- *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*

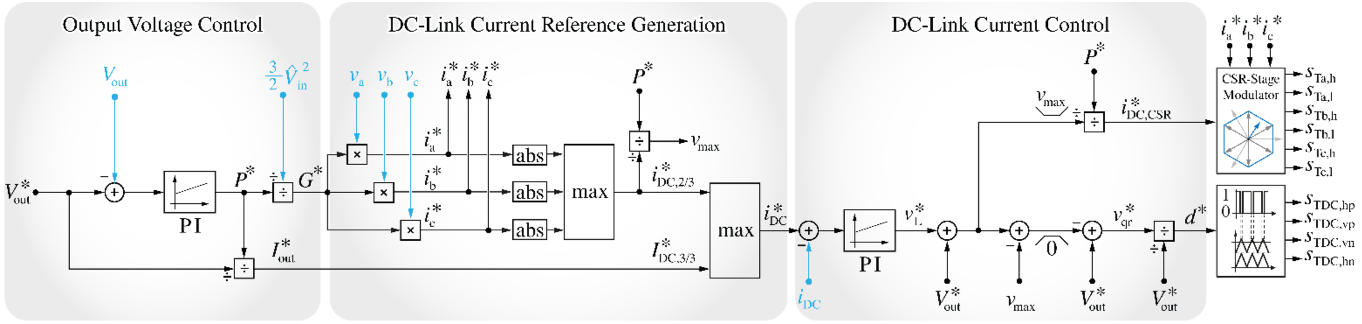


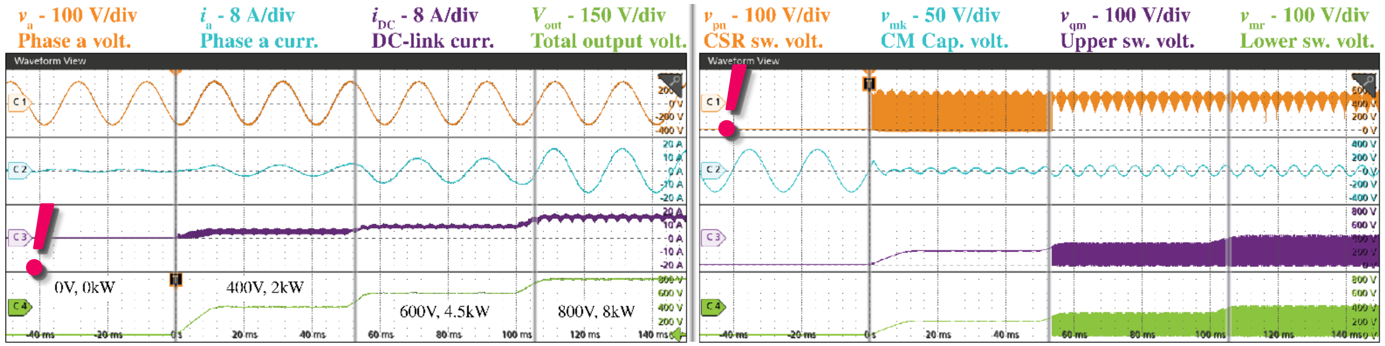


- *Min. # of Switching Instants & Reduced Sw. Voltage → App. 77% Reduction of Switching Losses*
- *Min. DC-Link Current → 8% Reduction of Conduction Losses*

Synergetic Control Strategy

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



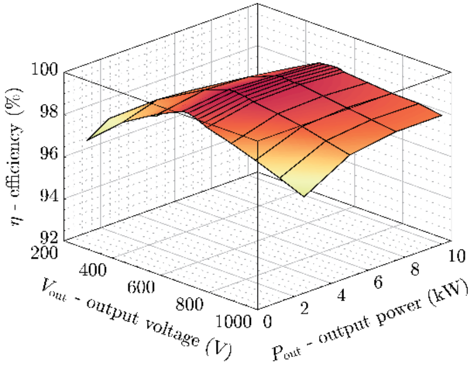


- *Ensure Seamless / Democratic Transitions between Proposed Loss-Optimal Modes*

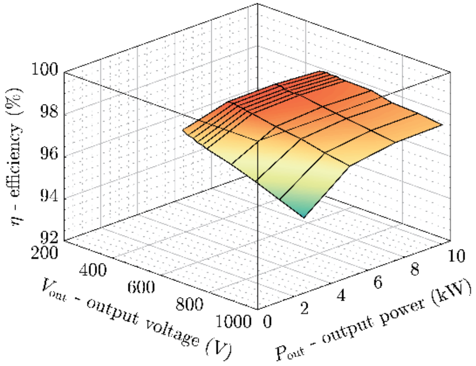
Efficiency Measurement Results

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

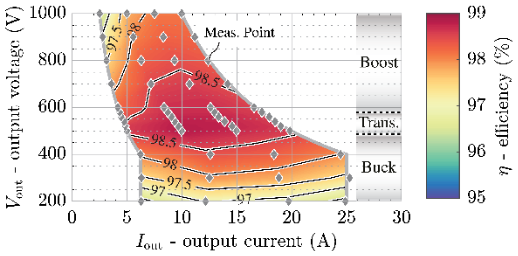
Loss-Optimal Operation



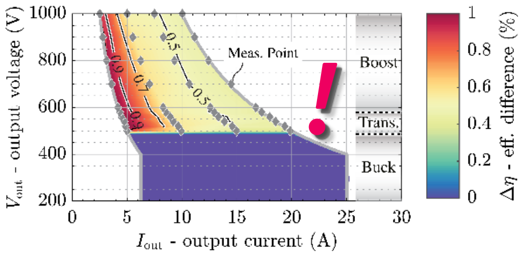
Benchmark Operation



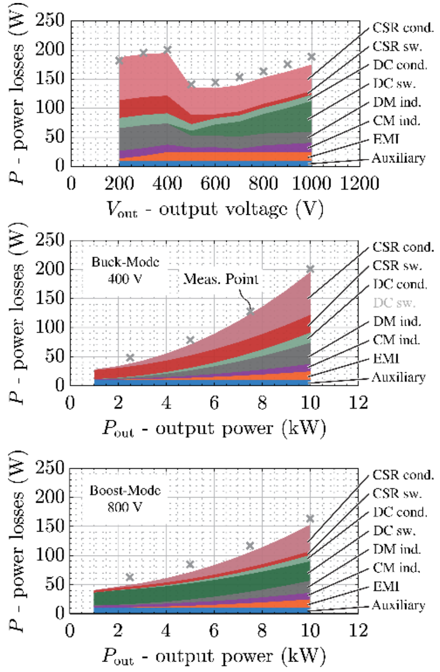
Loss-Optimal Operation (2D)



Efficiency Improvement

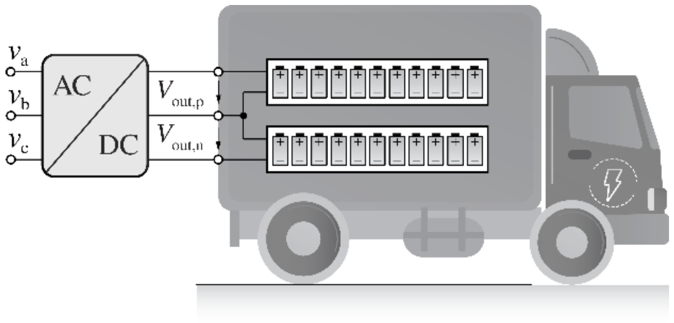


Loss Breakdown



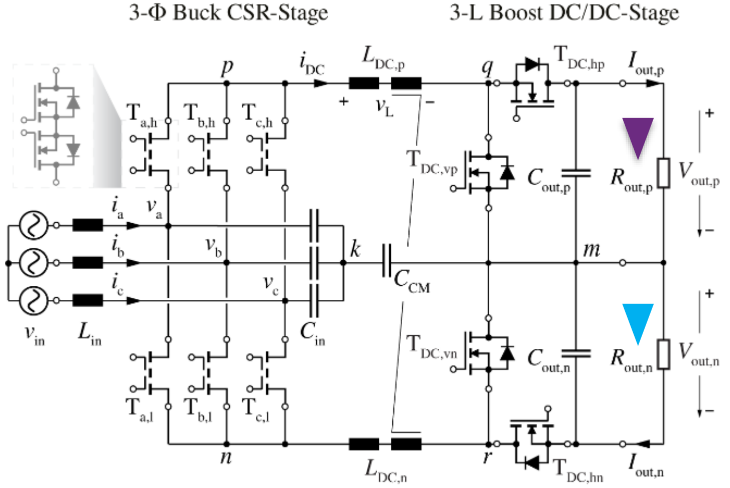
- *Peak Efficiency of 98.8%*
- *Flat Efficiency Characteristic -- Above 98% in Most Area*
- *Up to 1% Efficiency Improvement in Boost-Mode Operation*

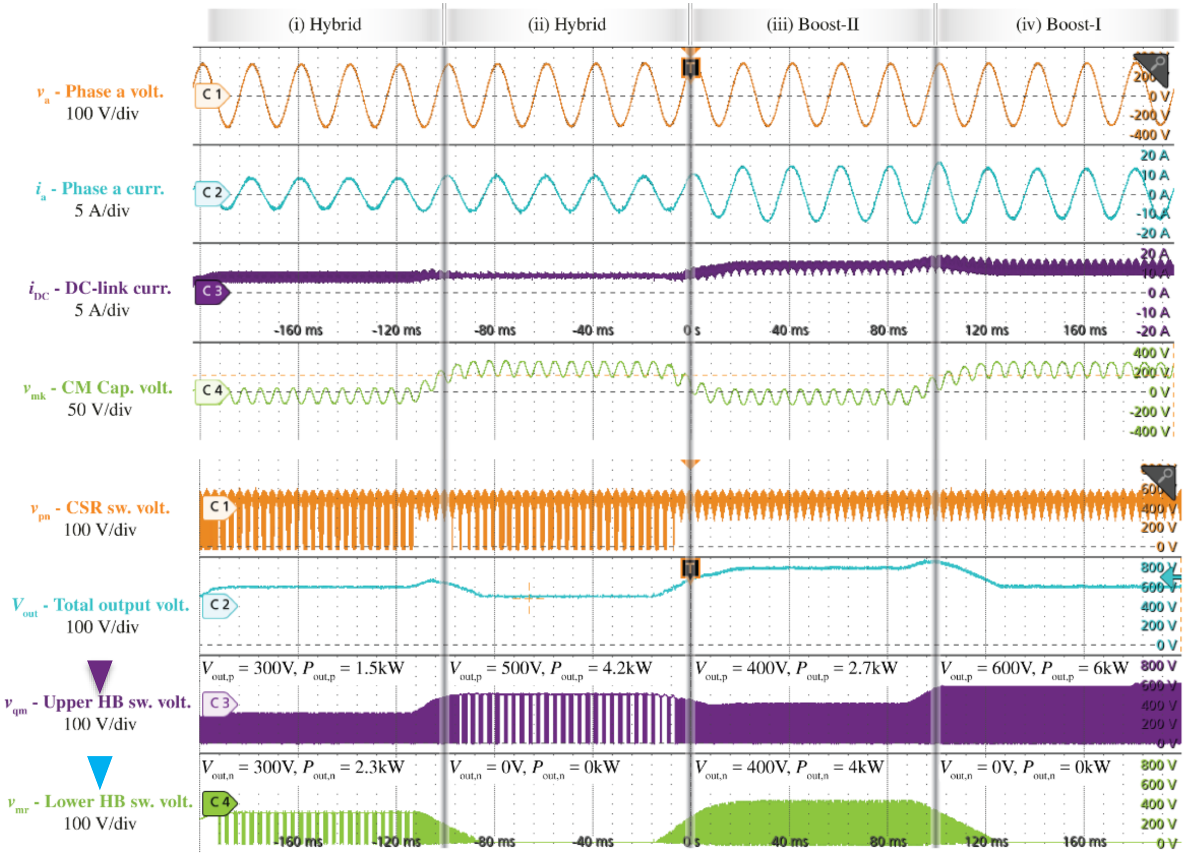
Extended Synergetic Control



Two *Independently* Regulated DC Outputs

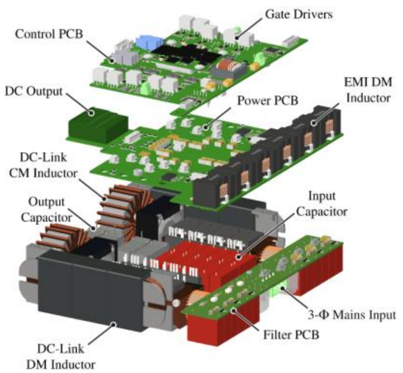
- *Independent Regulation of* V_{out} *or* P_{out}
- *Heavy-Duty EV Battery Charging*
- *Battery Swapping*

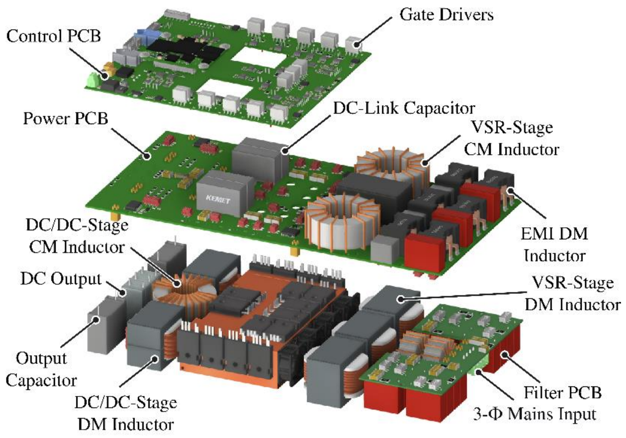




- *2/3-PWM are Still Maintained*

Experimental Comparison

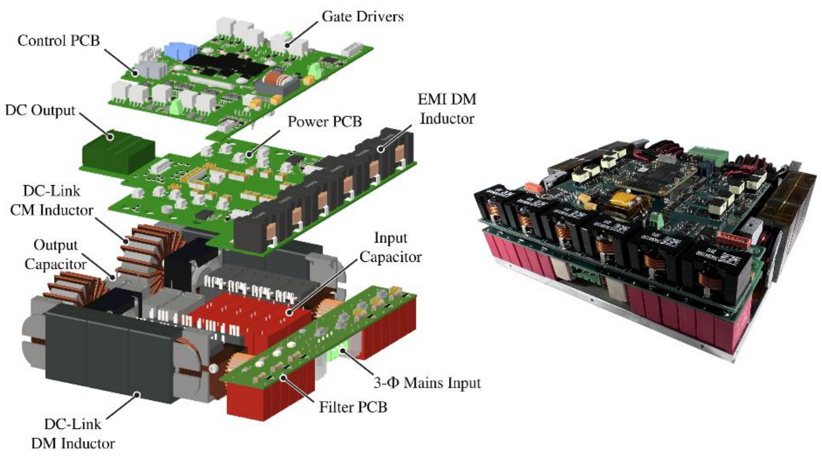


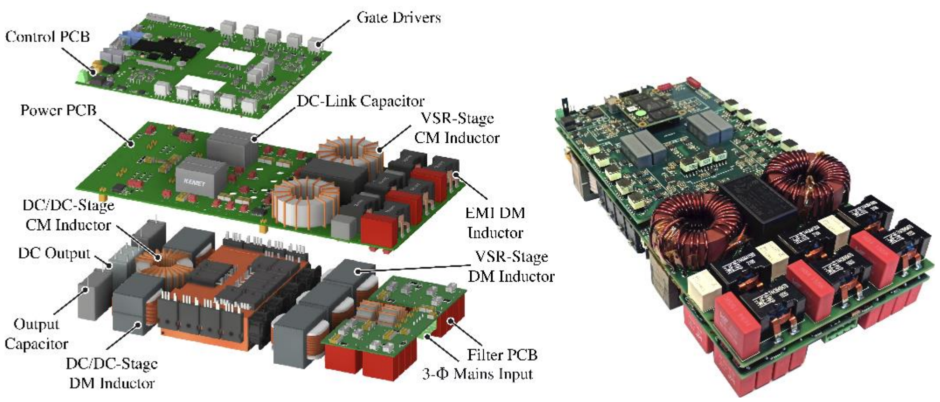


Buck-Boost | *Boost-Buck* Demonstrator Systems

- 10 kW @ 400...1000 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 1000 V_{DC}
- η = 98.8% @ 6.4 kW/dm³
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 50 kHz/100 kHz *eff.*

- 10 kW @ 400...800 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 800 V_{DC}
- η = 98.8% @ 5.4 kW/dm³
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 100 kHz/200 kHz *eff.*

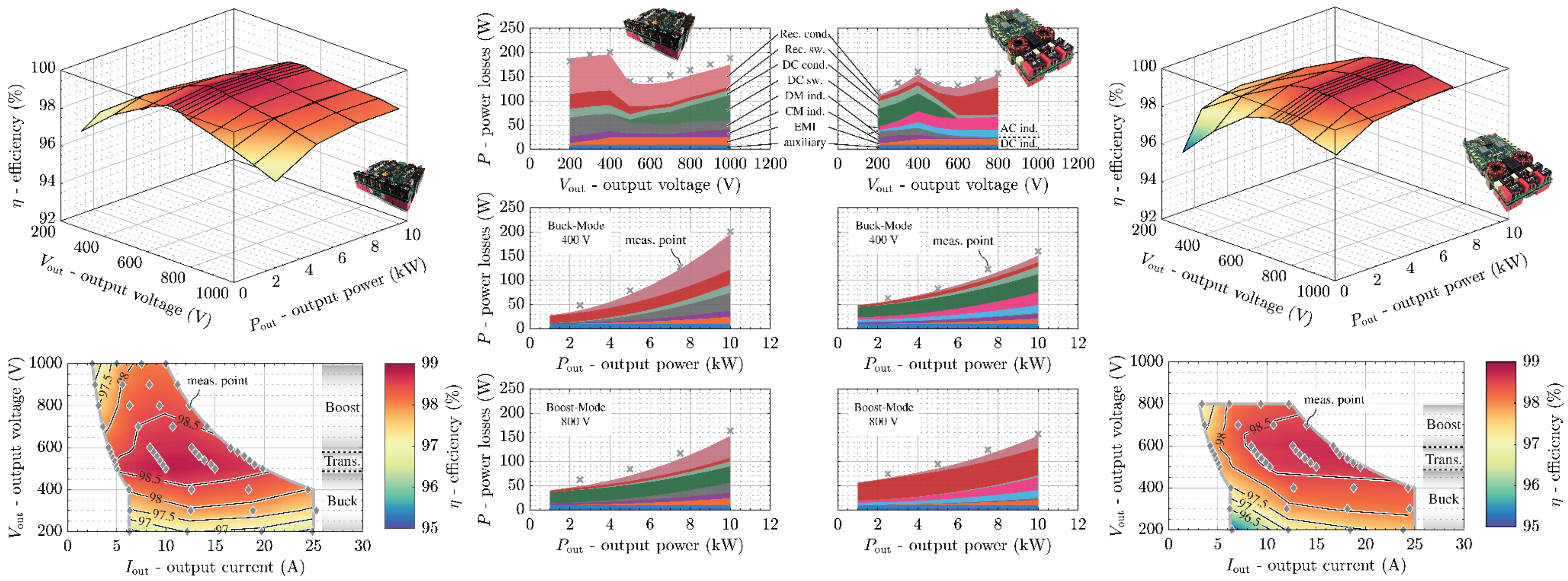




- *Min. # of Inductive Components* → *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor*
- *Reduced Hardware Manufacture Cost & Complexity*
- *Reduced Control/Firmware Implementation Efforts*

Demonstrator Systems *Measured Efficiency*

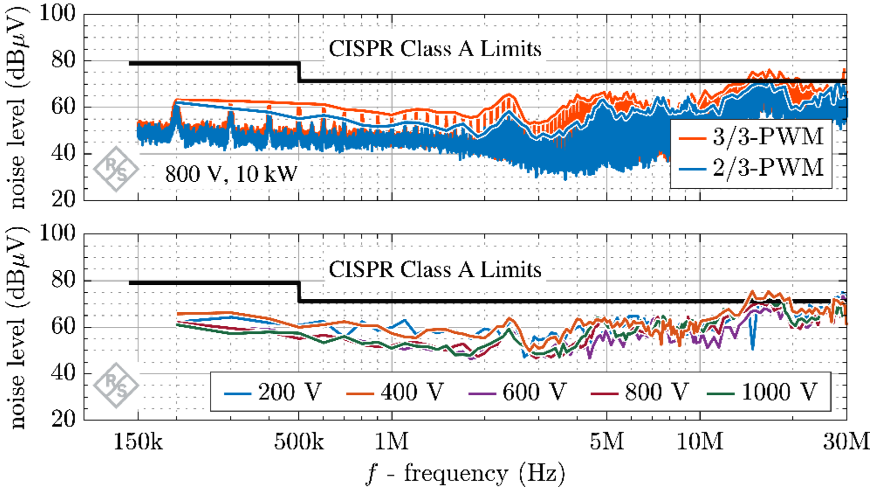
- *Buck-Boost Current DC-Link AC/DC Converter*
- *Boost-Buck Voltage DC-Link AC/DC Converter*

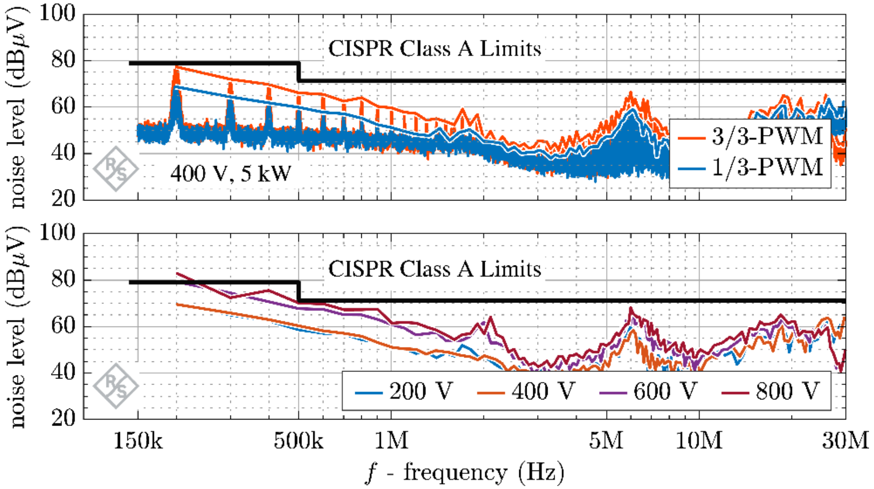


- *Same # of Power Semiconductors & Similar Blocking Voltage Rating*
- *Current DC-Link : Dominant Cond. Losses → Flat Eff. Characteristic & High Partial-Load Eff.*
- *Voltage DC-Link : 3-L Front-End → High Full-Load Eff.*

Conducted EMI Pre-Compliance Tests

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



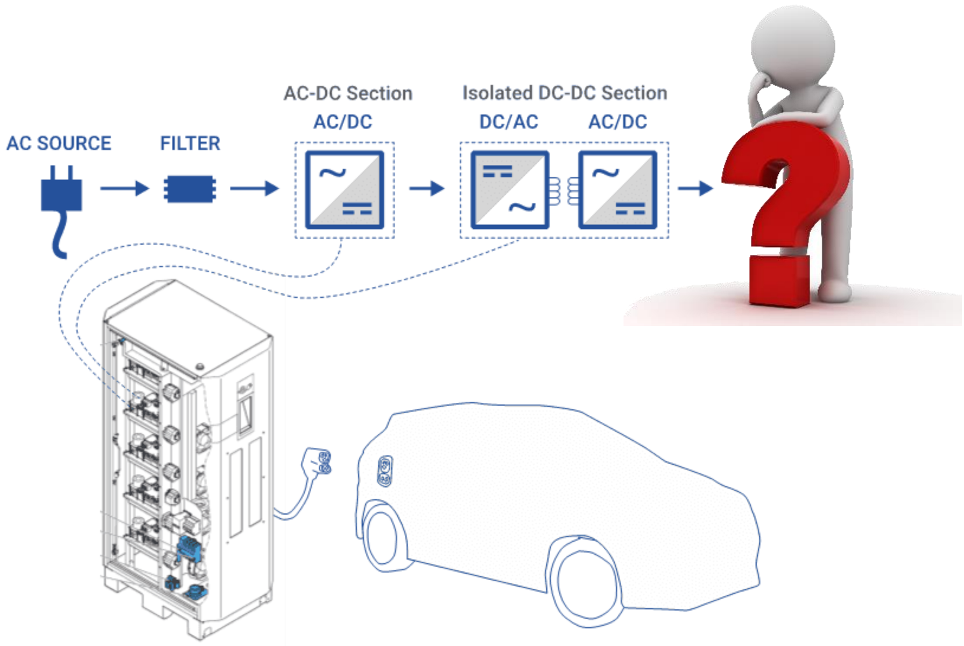


- Lower EMI Noise Emission Achieved by Advanced PWM Schemes

- 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

Future RCD-Based Non-Isolated EV Charger

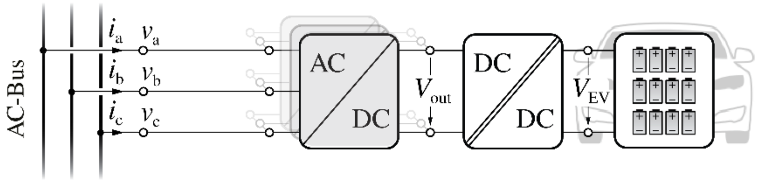


Source: www.wolfspeed.com

3-Φ AC/DC Converter in EV Chargers

- *Galvanically Isolated EV Charger*
- *Multi-Stage Structure*

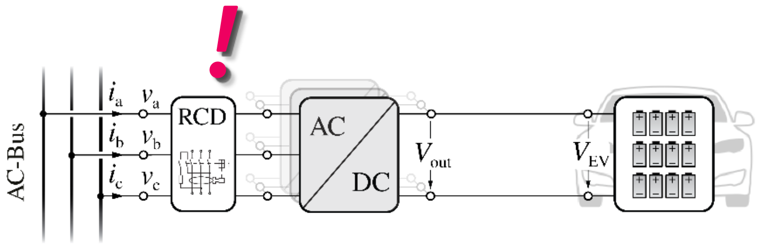
- *50 Hz Or HF Transformer (DAB, LLC, DCX...)*
- *Small Ground Current → End-User Safety*
- *Bulky & Low Power Efficiency & High Cost*



- *Non-Isolated EV charger*

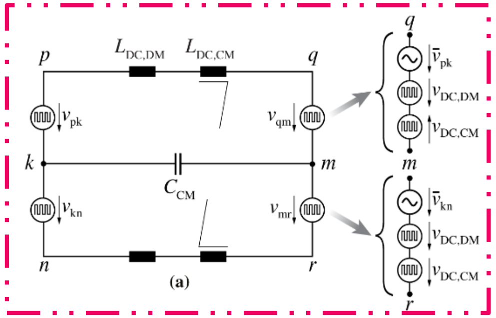
- *Residual Current Device (RCD) → End-User Safety*
- *Battery Package Parasitic Cap. up to Several uFs*
- *Min. Ground Current → Avoid Nuisance Tripping*
- *Conv. EMI Filter Suppress HF Ground Current*

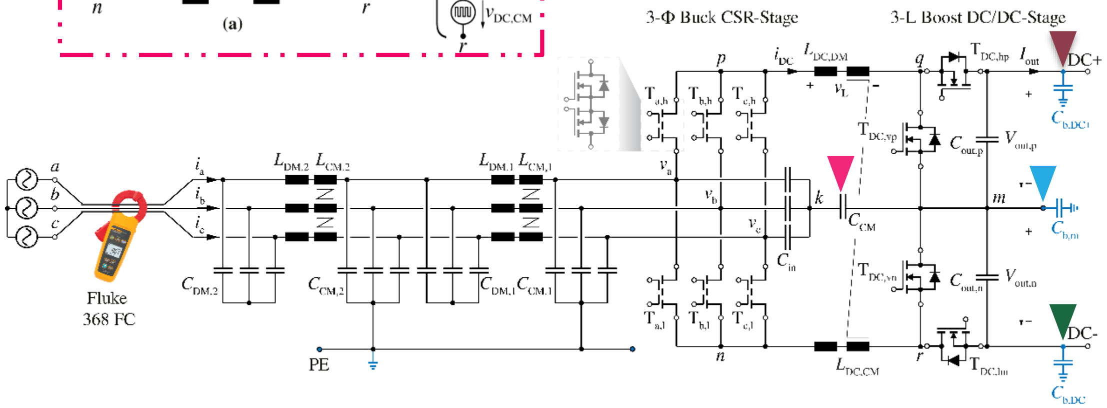
- *PV Inverter → 1% More Efficiency w/ Half Volume*
- *Enable High Power On-Board Charger (OBC)*

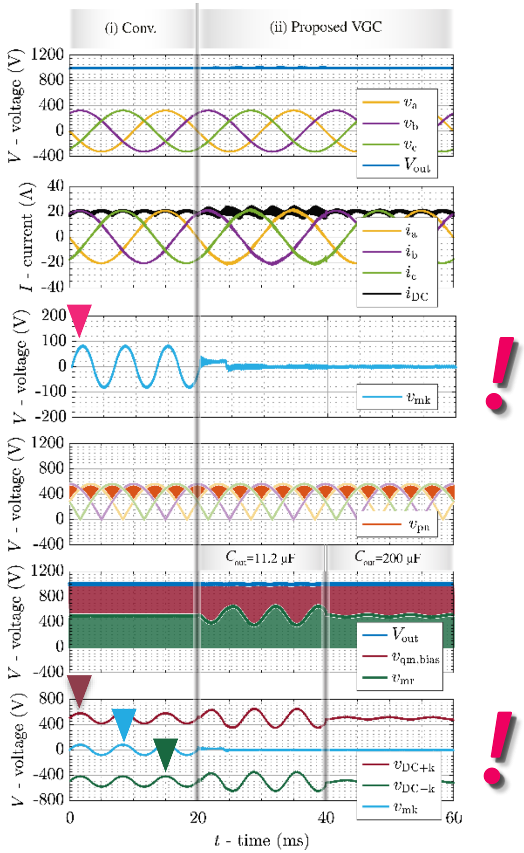


Virtual Grounding Control (VGC)

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





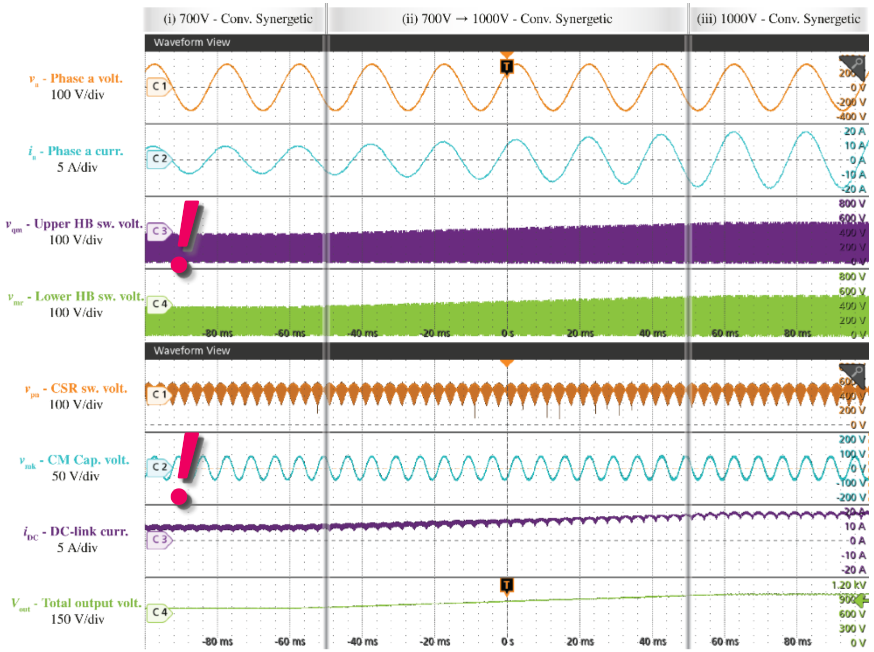


- *Reduced LF CM Noise Emission → Time-Varying (150 Hz) Output Capacitor Voltage*
- *Similar DM Operations → Constant Output Voltage & 2/3-PWM*

Experimental Verification

- Output Midpoint Virtually Grounded to Input Capacitor Neutral & Mains PE
- Increased Output Capacitance → High Cost & Low Power Density

❖ Conventional Synergetic Control

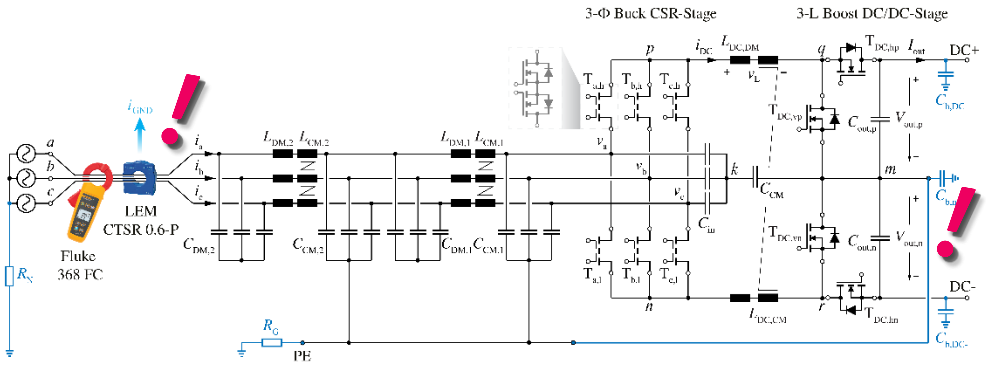


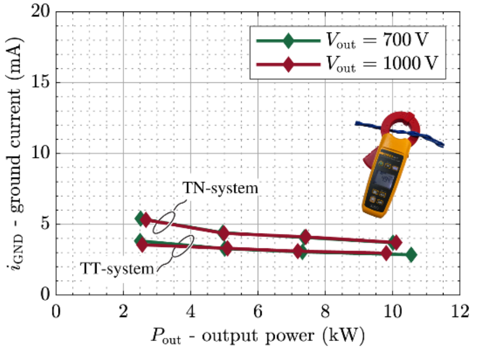
❖ Proposed Virtual Ground Control

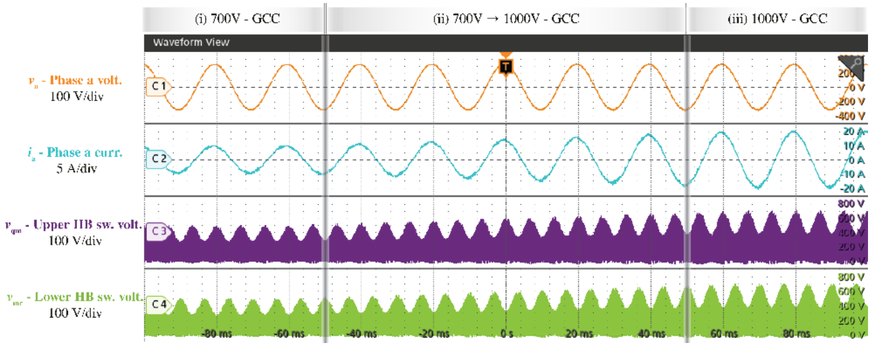
- Closed-Loop Regulation of the Ground Current

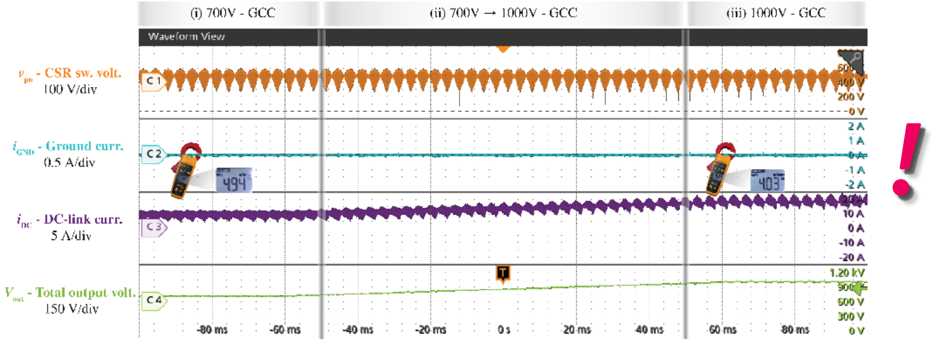
Ground *Current* Control (GCC)

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





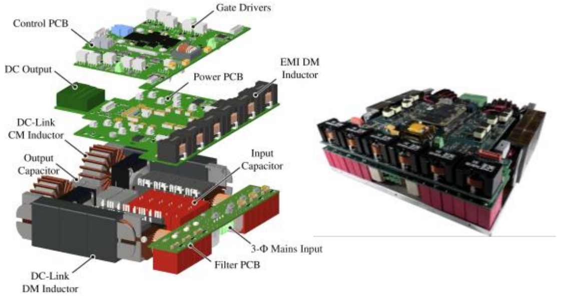


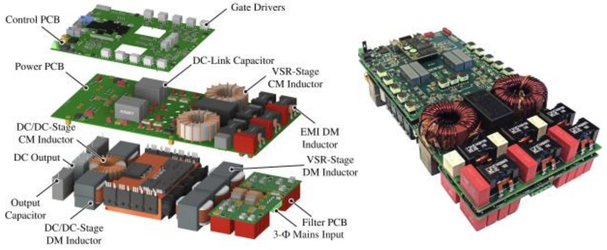


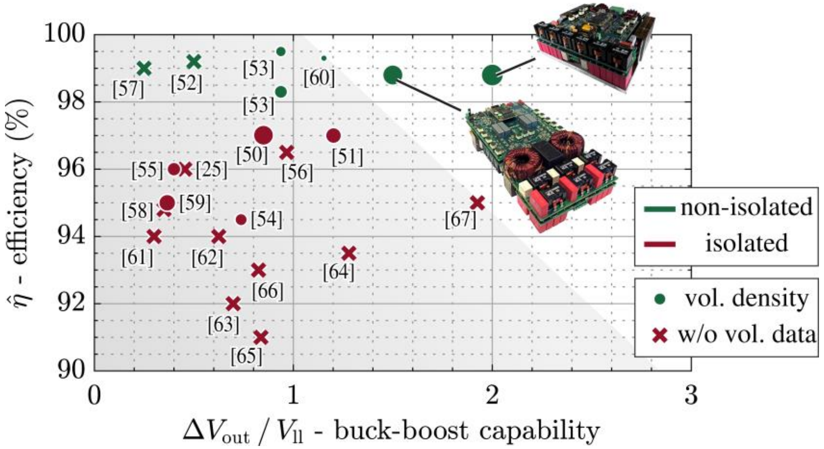
- *Ground Current: < 6 mA, Far Below 30 mA Limit*
- *Pre-Compliance Test Accord. to UL 2202 & IEC 61851 Considering TT & TN Systems*

Conclusion & Summary

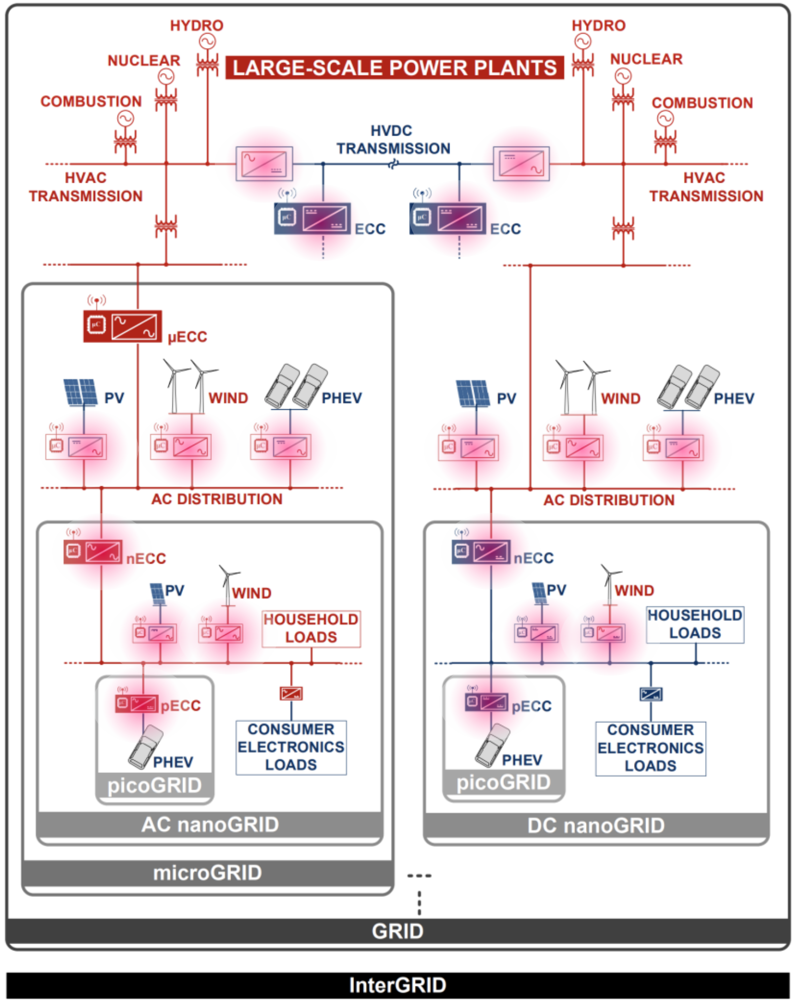
- **Advanced PWM Schemes**
  - Current DC-Link: 2/3-PWM
  - Voltage DC-Link: 1/3-PWM & 2/3-PWM-OPT
  - Enables Optimal Clamping Operation
- **Synergetic Control Strategies**
  - Loss-Optimal Buck-Boost Operation
  - Seamless & Smooth Transitions Between Different Modes
- **Independent Output Voltage/Power Control**
  - Fully Leverage Hardware Capacity
  - Allow Loss-Opt. 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







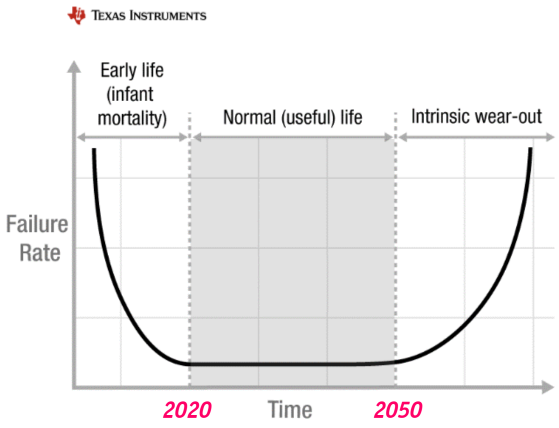
Source: D. Boroyevich (2010)



Remark — All-Electric Society

- 25´000 GW of Installed Renewable Gen. & 15´000 GWh Batt. Storage
- 4x Power Electronics Conversion Stages btw Generation → Load
- 100´000 GW of Installed Converter Power
- 20 Years of Useful Life

- 5´000 GW_{eq} = 5´000´000´000 kW_{eq} of Electronic Waste / Year (!)

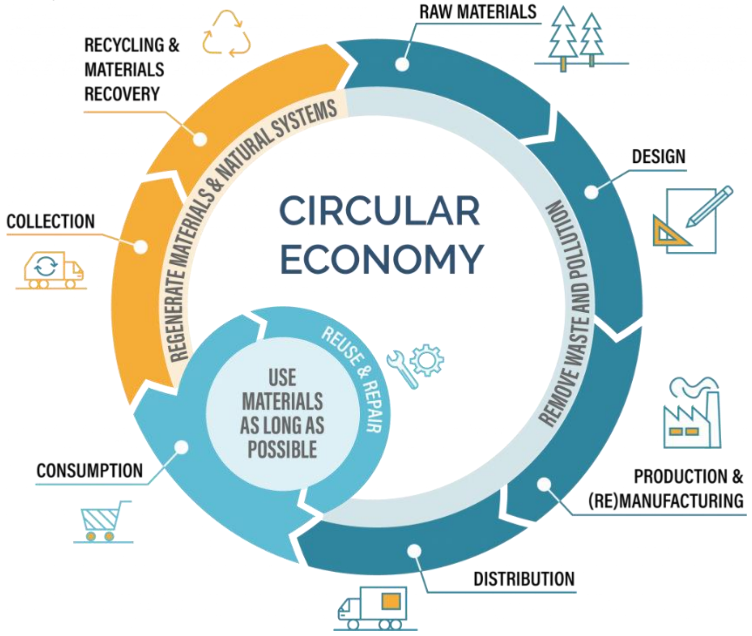


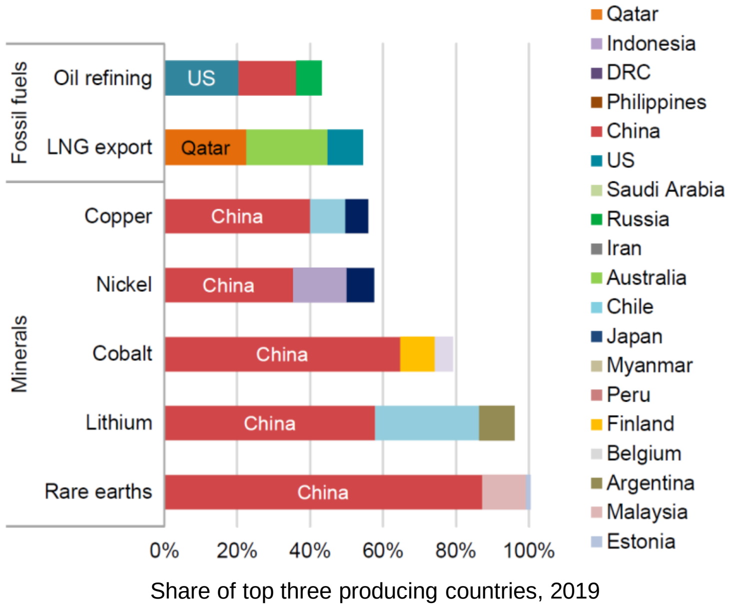
Source: www.e-waste-recyclers.co.in

The Paradigm Shift

- *"Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources*
- *Resources Returned into the Product Cycle at the End of Use*

Source: https://circularphiladelphia.org



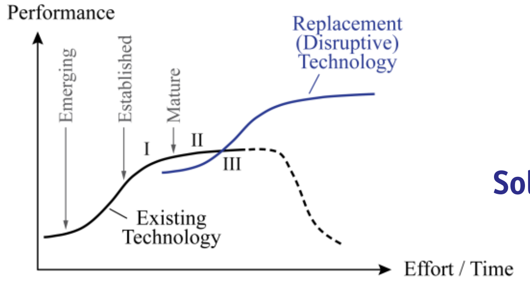


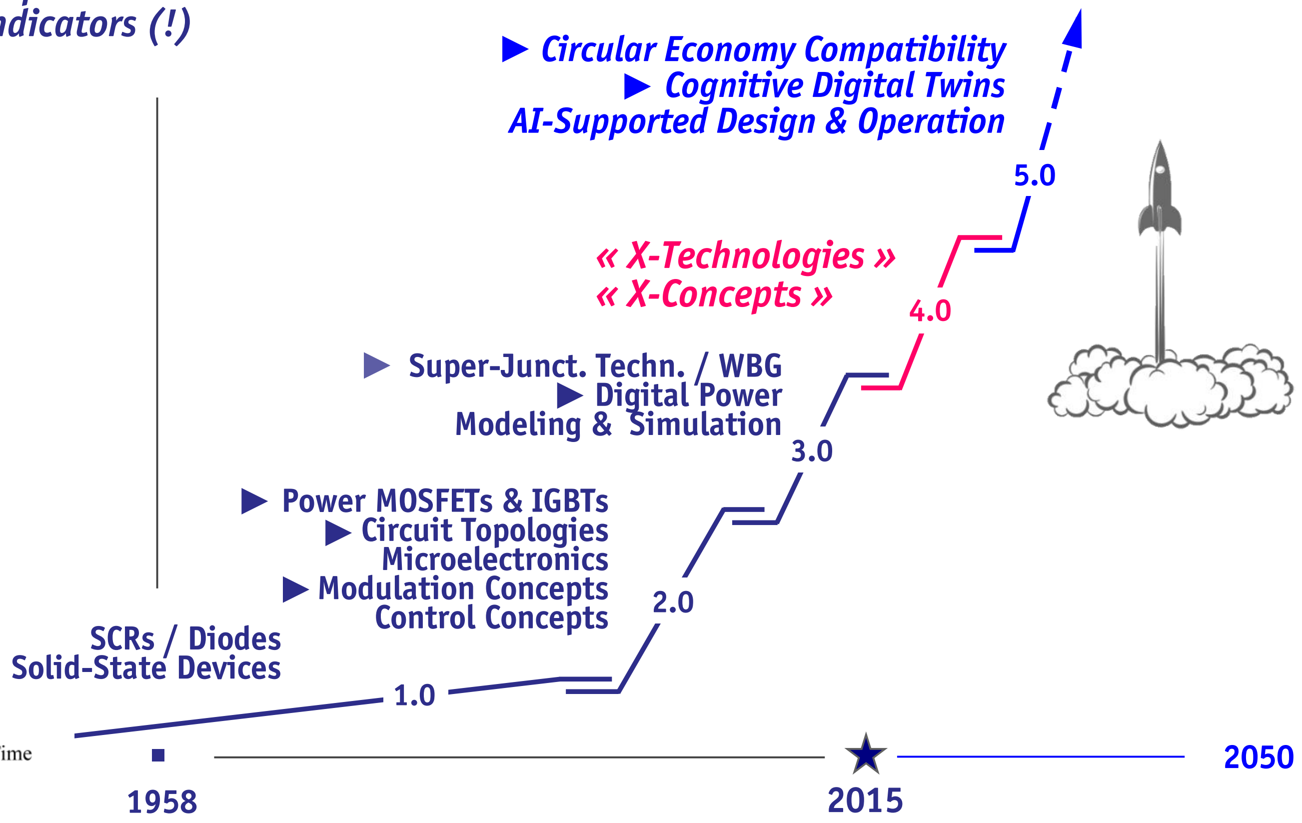
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

- *Geographically Concentrated Production of Many Energy Transition Critical Minerals*

Power Electronics 5.0

- *Power Electronics 1.0 → Power Electronics 5.0*
- *X-Technologies & X-Concepts*
- *New Main Performance Indicators (!)*





Further Reading

- D. Zhang, C. Leontaris, J. Huber, and J. W. Kolar, “Optimal Synergetic Control of High-Efficiency Three-Phase/Level Boost-Buck Voltage DC-Link Very Wide Output Voltage Range EV Charger,” IEEE J. Emerg. Sel. Topics Power Electron. (Under Review). TechRxiv Preprint. DOI: https://doi.org/10.36227/techrxiv.22227889.v1
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Thank you!