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ECPE

Advanced Three-Phase PFC-Rectifiers

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– ECPE Cluster-Seminar –

"Power Factor Correction (PFC)" und "Active Frontend" Schaltungen, Bauelemente, Regelung

21-22th May 2019, Innovationspark Augsburg

Advanced Three-Phase PFC-Rectifiers

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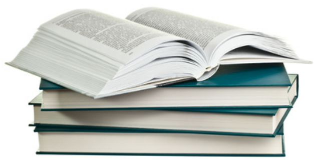
► Workshops/Tutorials on 3ϕ Rectifier Systems from ETH/PES

- **ECPE Workshop 2011:**

M. Hartmann „Three-Phase Unity Power Factor Mains Interfaces of High Power EV Battery Charging Systems"

- **Tutorial IECON 2012:**

J. W. Kolar „Essence of Three-Phase PFC Rectifier Systems"



- **Keynote APEC 2018:**

J. W. Kolar „Vienna Rectifier & Beyond..."

- **International Forum on Recent Trends in Power Electronics 2018:**

J. W. Kolar „Latest Findings in Three-Phase AC/DC Converter Research"

Available @ http://www.pes.ee.ethz.ch/publications.html

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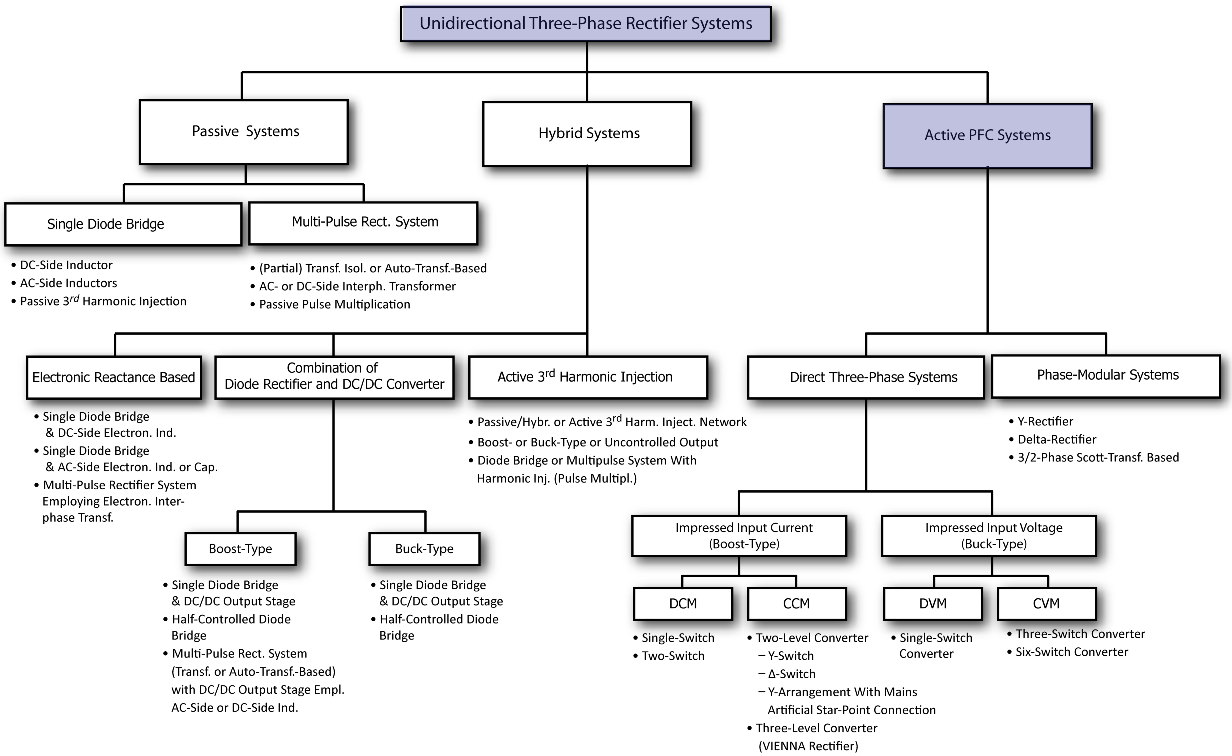
► *Wide Varity of 3ϕ Rectifier Topologies*

▶ Classification of Unidirectional 3ϕ Rectifier Systems

- Basic Classification of 3ϕ Rectifier didn't really change in the *Last Decade*
- The Most Attractive Active PFC Rectifiers at that Time are *still among the Best in Class.*



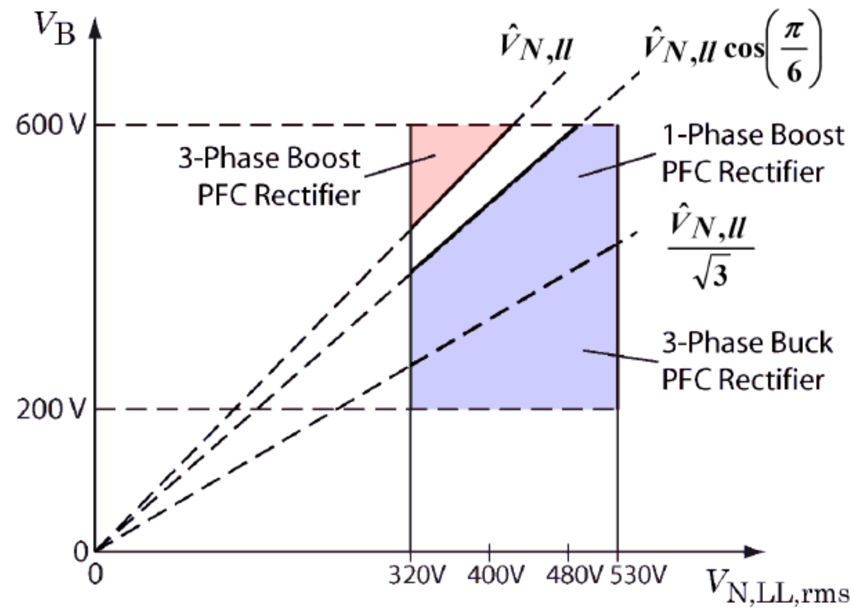
▶ However, several *Advanced 3ϕ Rectifier Topologies* appeared on the Stage

Outline

- *Still Best in Class*
  - *Boost-Type Rectifiers*
  - *Buck-Type Rectifiers*
- *Advanced 3ϕ Rectifier Topologies*
  - *1/3 and 2/3 Concepts*
  - *Phase-Modular Concepts*

▶ Features of 3ϕ Active PFC Rectifier Systems

- Mains Side Sinusoidal Current Shaping
- Wide Input/Output Voltage Range
- High Efficiency / High Power Density
- Low Complexity



▶ Topology Selection mainly Depends on Voltage Range,
▶ *Boost-Type* and *Buck-Type* Rectifiers

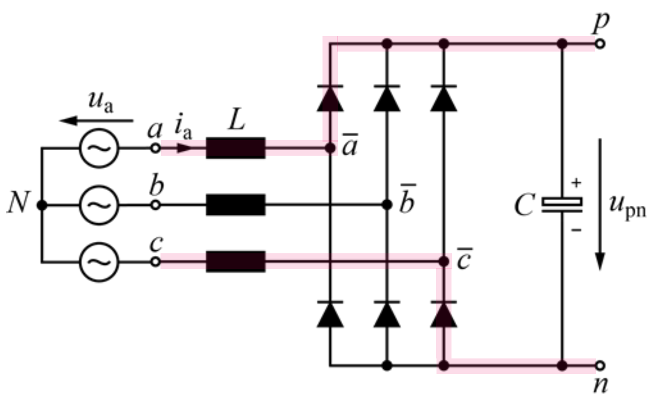
Boost-Type PFC Rectifier

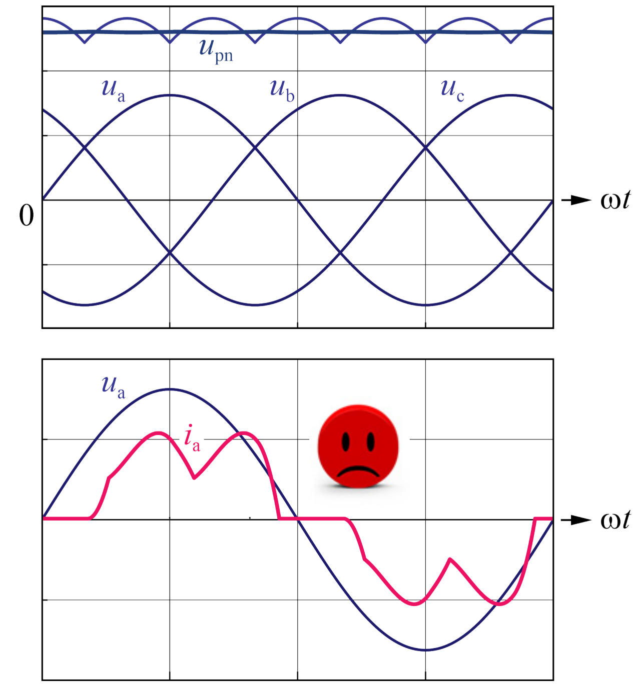
6-Switch Boost Rectifier
Vienna Rectifier

6-Switch Boost Rectifier

3-Φ Diode Bridge Rectifier

- Conduction States and Blocking Voltage Defined by *Line-to-Line* Mains Voltages
- Intervals with *Zero Current* / LF Harmonics
- No Output Voltage Control

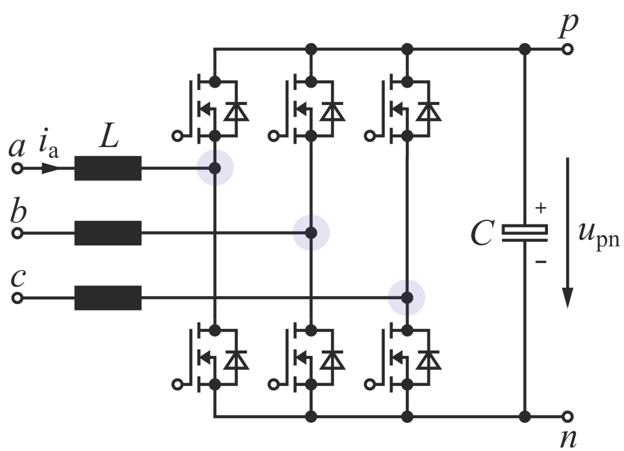


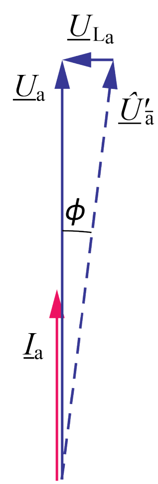


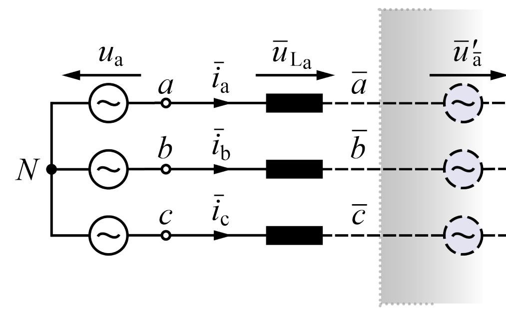
► Modulation of Diode Bridge Input Voltages

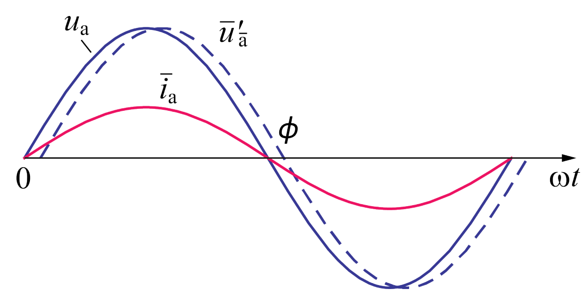
6-Switch Boost PFC Rectifier (1)

- *Active Control of Switch Node Voltages due to Replacement of Diodes by Switches*
- 2-Level Topology with Boost-Functionality
- *Input Current Impressed by Difference of Mains & Bridge Input Voltage*
- Blocking Voltage of Switches Defined by DC-Voltage $u_{pn} > u_{in,line-line}$





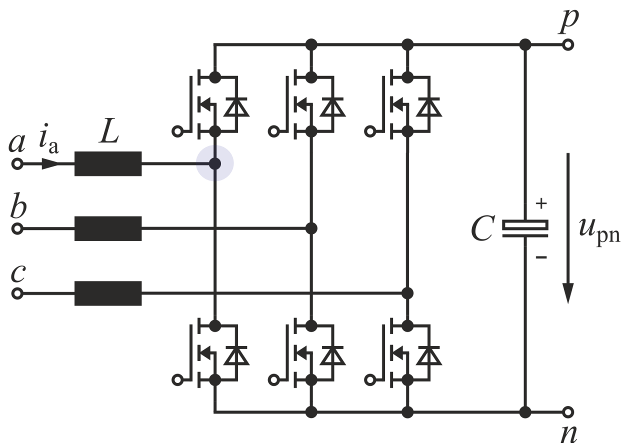


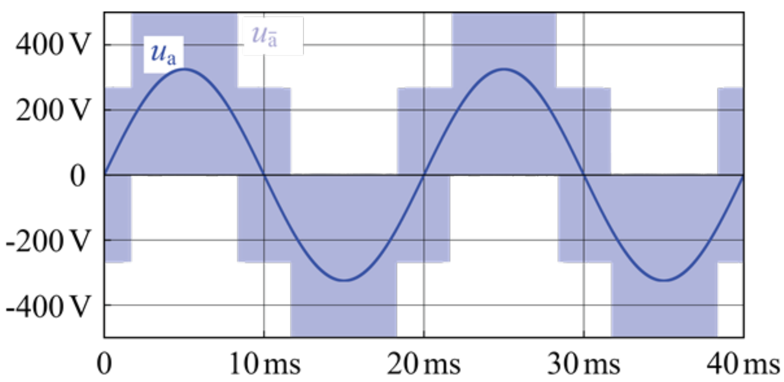


▶ Time Behavior of PWM Voltages

6-Switch Boost PFC Rectifier (2)

- *2-Level Bridge Leg Characteristic / 5-Level Phase Voltage with open Star-Point*



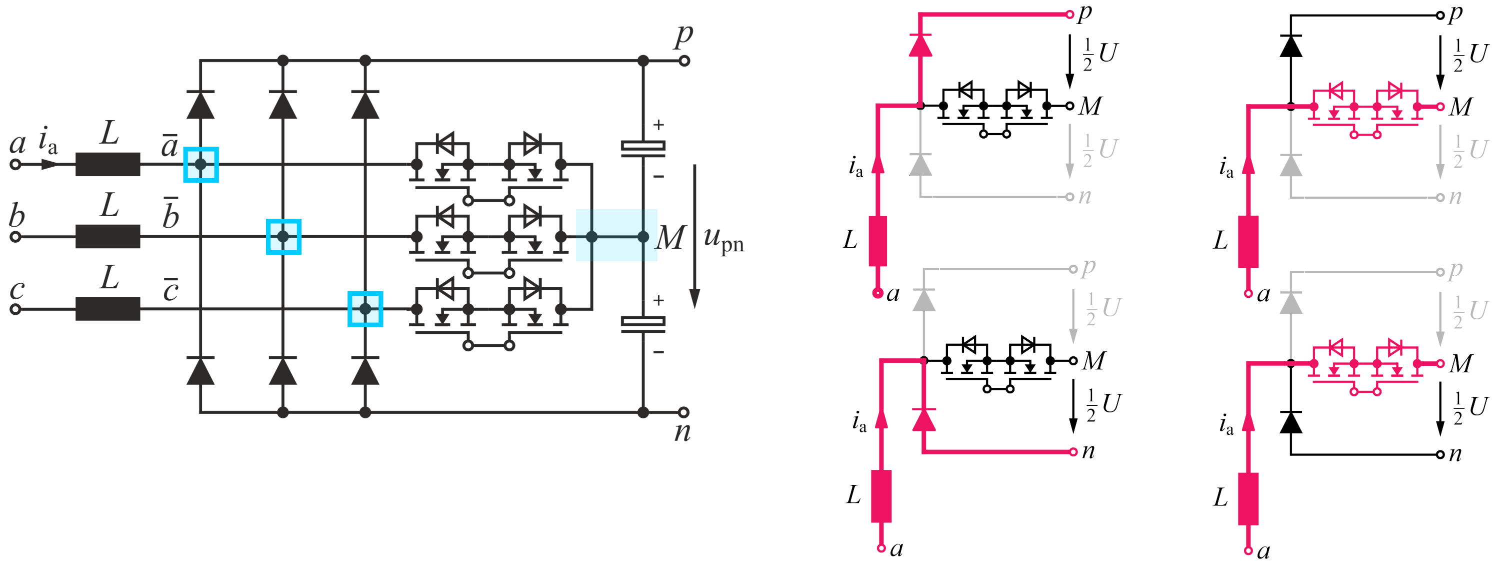


▶ **Multi-Level Topologies → Lower Switching Losses and Smaller Inductors**

Vienna Rectifier
(3L-Topology)

Vienna Rectifier (1)

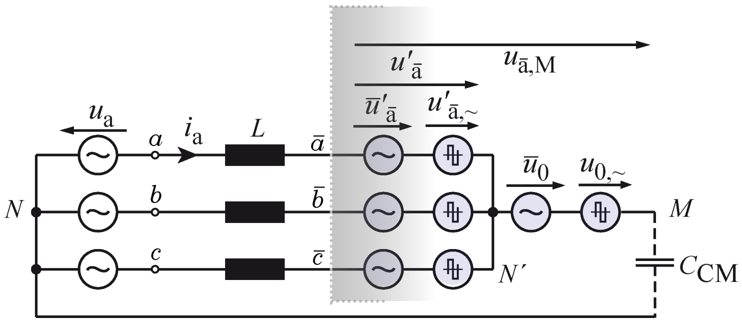
- *Active Control of Diode Bridge Conduction State / Input Voltages*
- 3-Level Topology with Boost-Functionality
- Bridge Leg Topologies with Different Voltage Stresses / Cond. Losses (u_{pn}/2 for Switches)



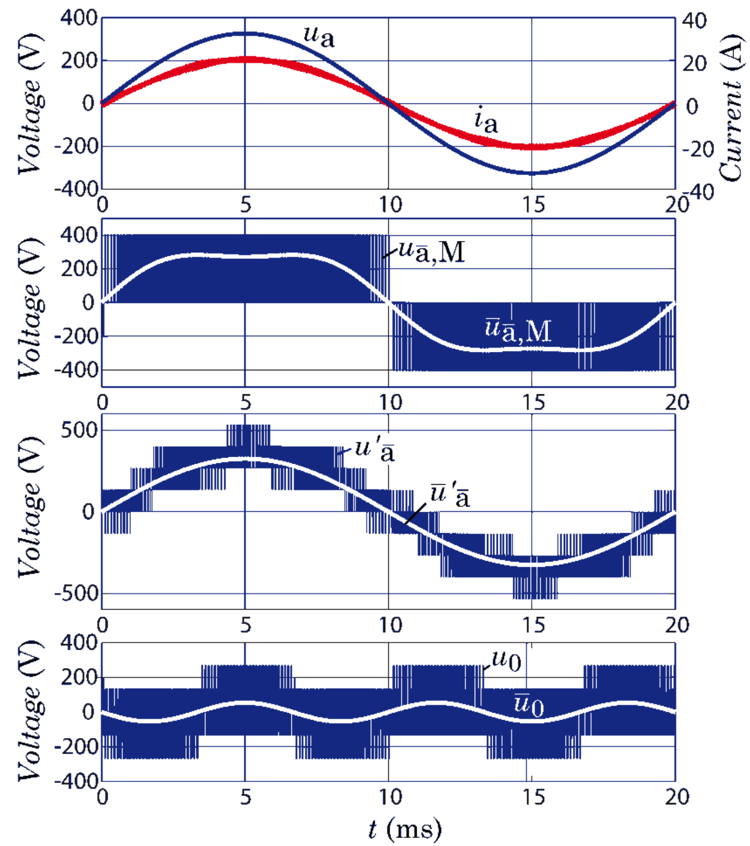
▶ *Diode Bridge Input Voltage Formation Dependent on Current Direction*
▶ Φ = (-30°,+30°) *Limit* Due to Current Dependent Voltage Formation

Vienna Rectifier (2)

- *3-Level Bridge Leg Characteristic / 9-Level Phase Voltage*
- Low Input Current Ripple / *Low Inductance L*



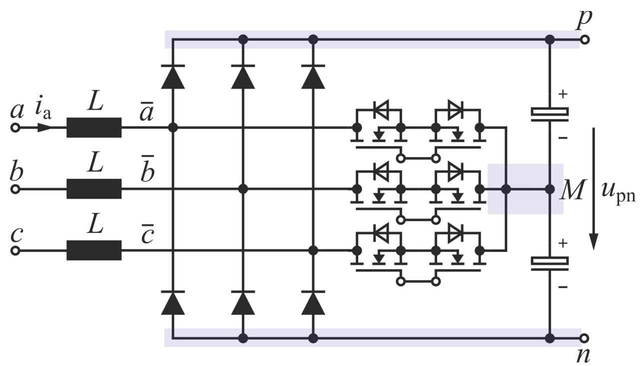
$$u_{NN'} = 0$$

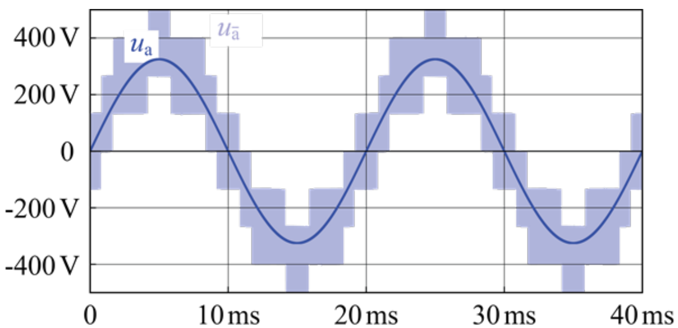


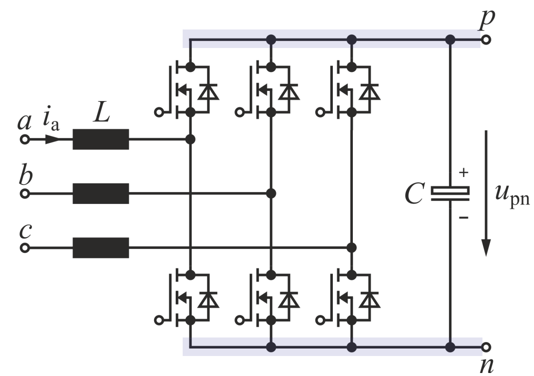
▶ Comparison between 2-Level and 3-Level

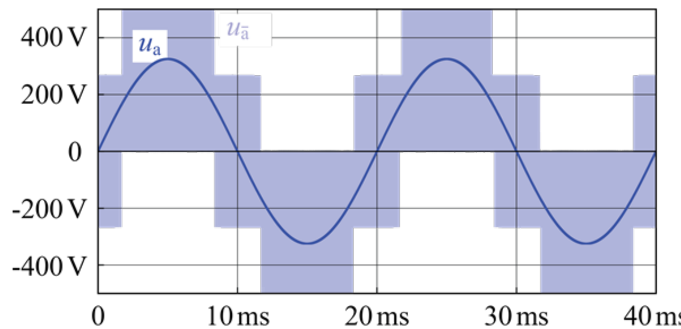
Comparative Evaluation (1)

- Comparison between *3-Level* Vienna Rectifier to Standard *2-Level* PWM Rectifier
- *9 vs. 5 Volt. Levels & Factor 2…3 Lower Sw. Losses → Factor 4…6 (!) Lower L*





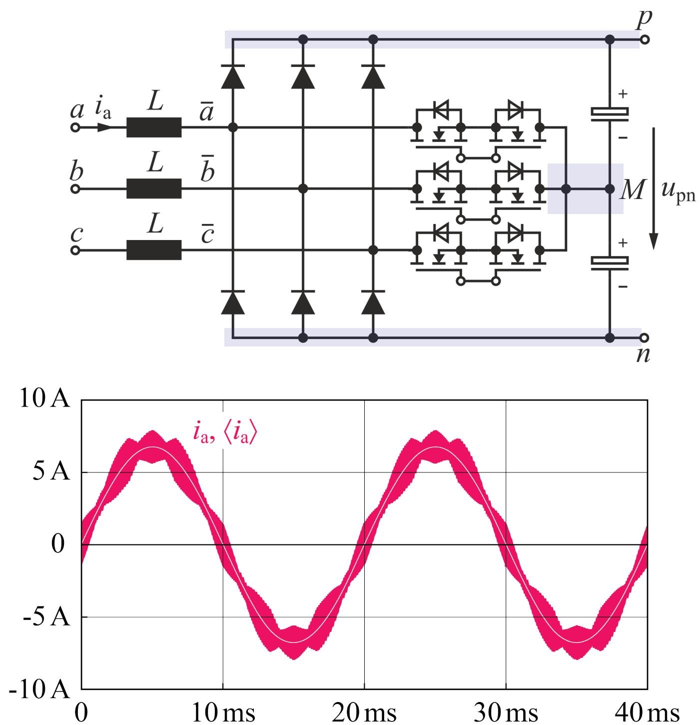




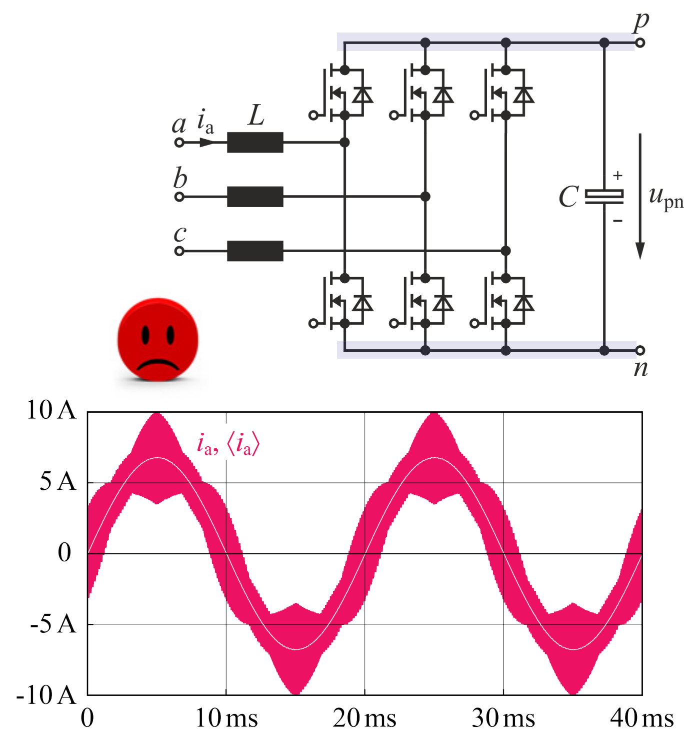
- Vienna Rectifier
- Standard PWM Rectifier

Comparative Evaluation (2)

- Comparison between *3-Level* Vienna Rectifier to Standard *2-Level* PWM Rectifier
- *9 vs. 5 Volt. Levels & Factor 2…3 Lower Sw. Losses → Factor 4…6 (!) Lower L*



- **Vienna Rectifier**



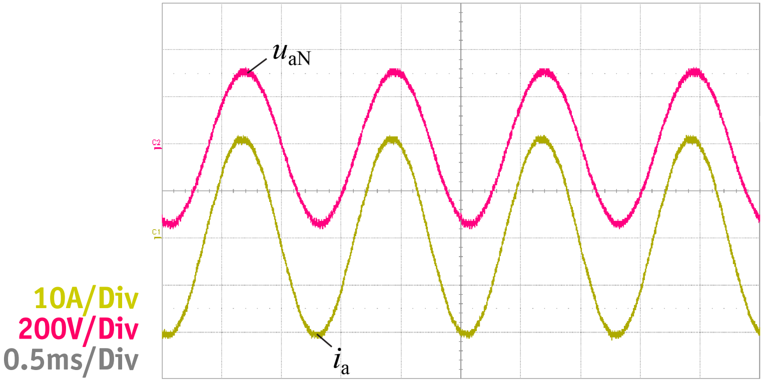
- **Standard PWM Rectifier**

Vienna Rectifier Demonstrator

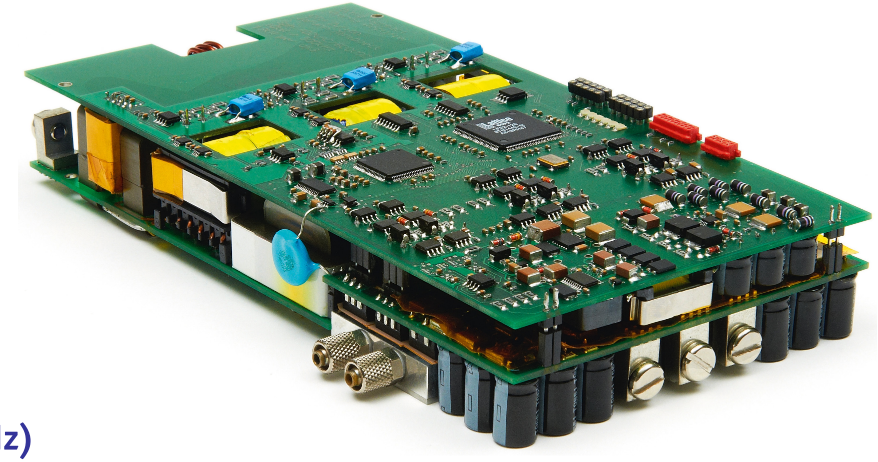
- Highly-Compact Demonstrator System
- CoolMOS & SiC Diodes
- Coldplate Cooling

P_O = 10 kW
U_N = 400V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_O = 800V_{DC}

η = 96.8%



★ ρ = 10 kW/dm³



▶ THD_i = 1.6% @ f_N = 800Hz (f_P = 250kHz)

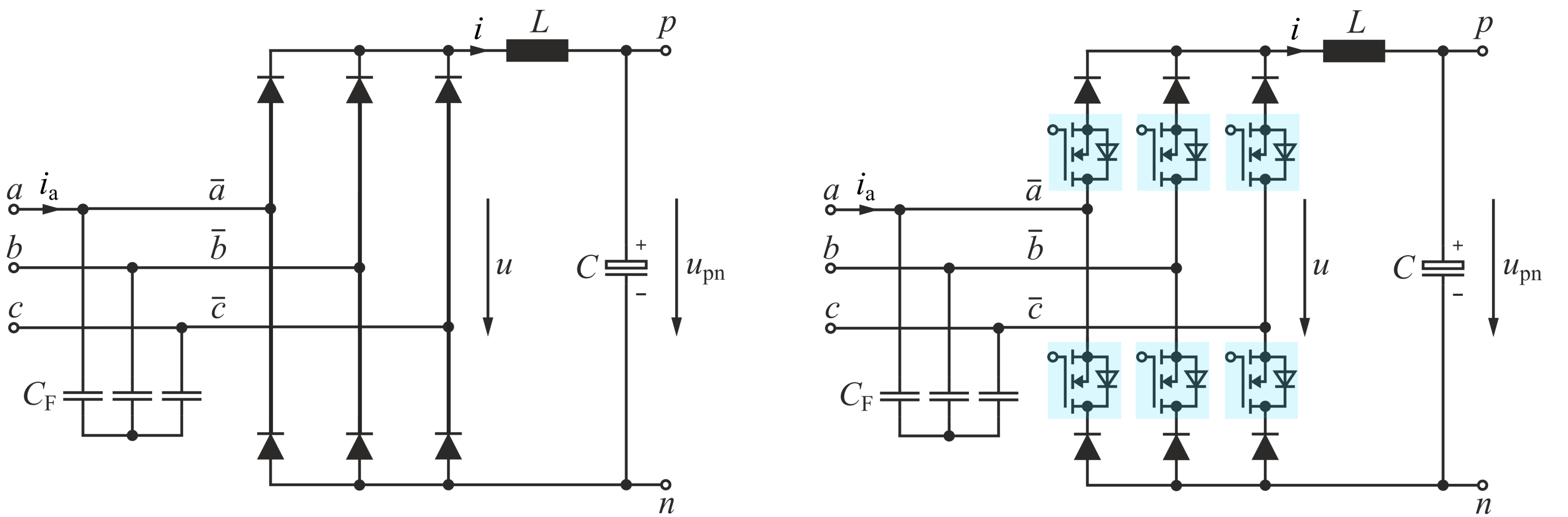
Buck-Type

6-Switch Buck Rectifier
Integr. Active Filter PFC Rectifier
SWISS Rectifier

6-Switch Buck PFC Rectifier

6-Switch Buck PFC Rectifier (1)

- Buck-Operation ($u_{pn} < 3/2\, U_{line\text{-}line,rms}$) → Insertion of Switches in Series to Diodes
- Active Control of Cond. States → Avg. Voltage u defined by selected Line-to-Line Volt.
- *DC Current Impressed by Difference of Bridge u & Output Voltage u_{pn}*

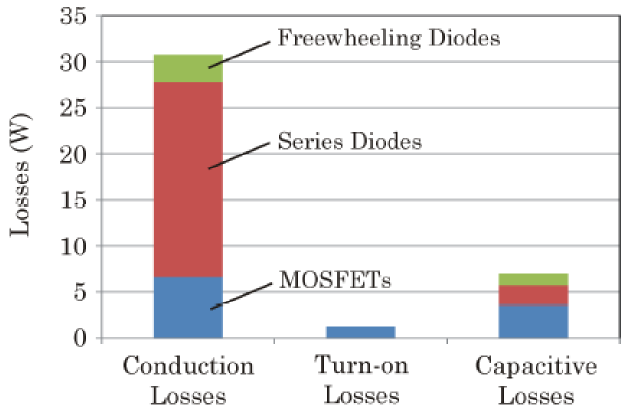


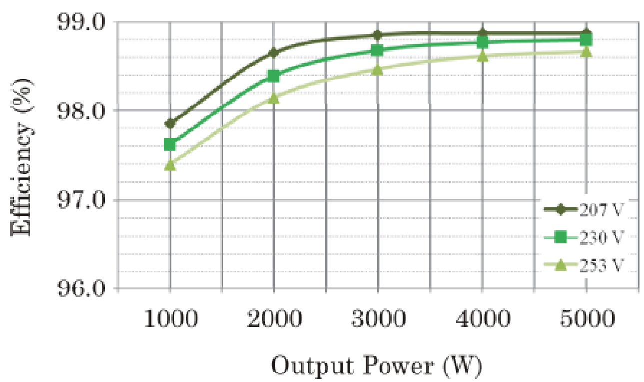
- ▶ *No Line-Inductors* : Pulsating Input Currents
- ▶ Relatively High Conduction Losses

6-Switch Buck PFC Rectifier Demonstrator

- Efficiency η > 98.8% (Calorimetrically Measured)

P_0= 5 kW
U_N= 400V_{AC} → U_0= 400V_{DC}
f_S = 18kHz
L = 2 x 0.65mH

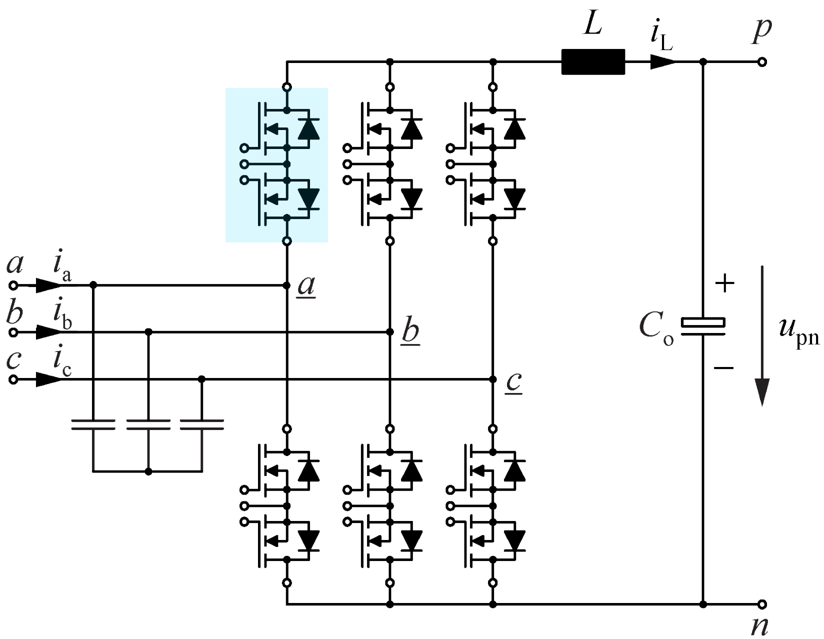


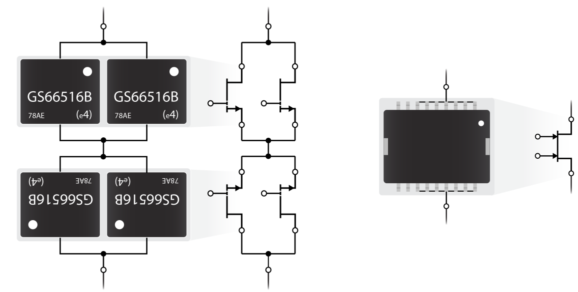


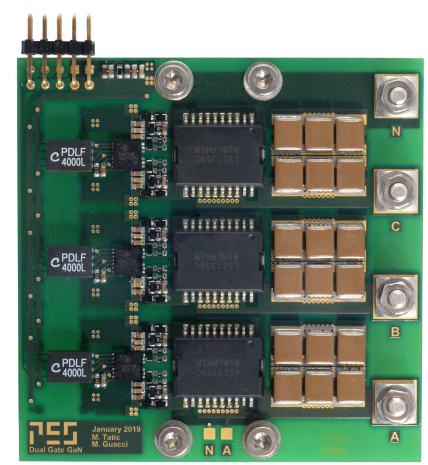
▶ Biggest Share of Losses in Series Diodes
▶ Substitution by Dual-Gate Monolithic Bidirectional GaN e-FETs

6-Switch Buck PFC Rectifier Demonstrator

- New Panasonic "Dual-Gate Monolithic Bidirectional GaN e-FETs", ±600V, 26mΩ
- 4 x lower Conduction Losses than Best in Class 650V GaN Switches (GaN Systems GS6651B)





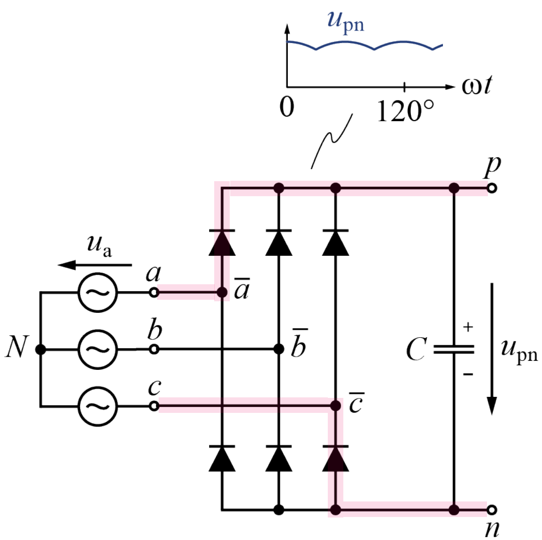


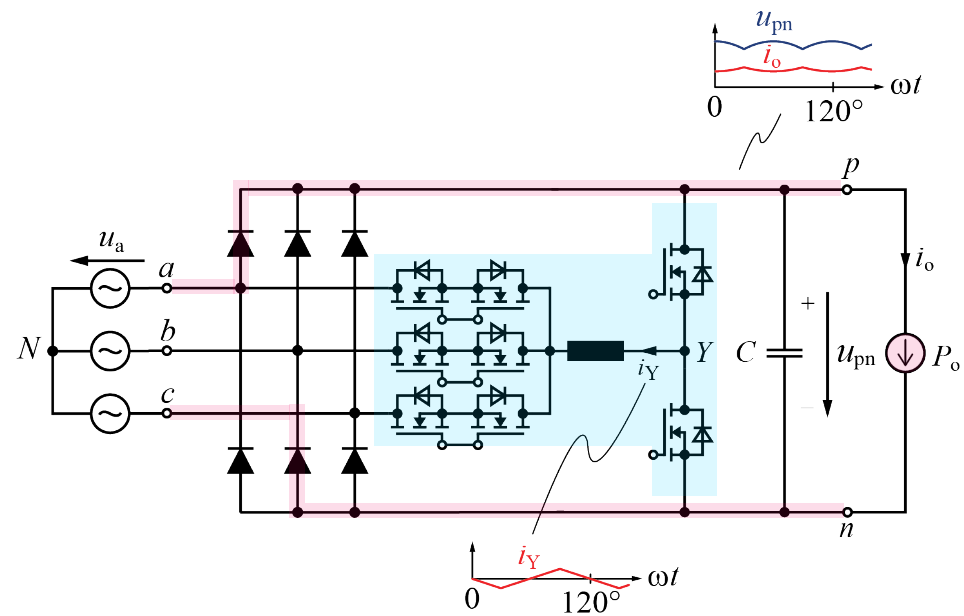
▶ Switching Loss Measurements under Investigation
▶ Bidirectional Power Transfer possible

Integrated Active Filter PFC Rectifier

Integr. Active Filter (*IAF*) PFC Rectifier (1)

- **No Line-Inductors** : Output Voltage defined by largest Line-to-Line Input Voltage
- Always Diodes of most Positive and most Negative Input Voltage conducting

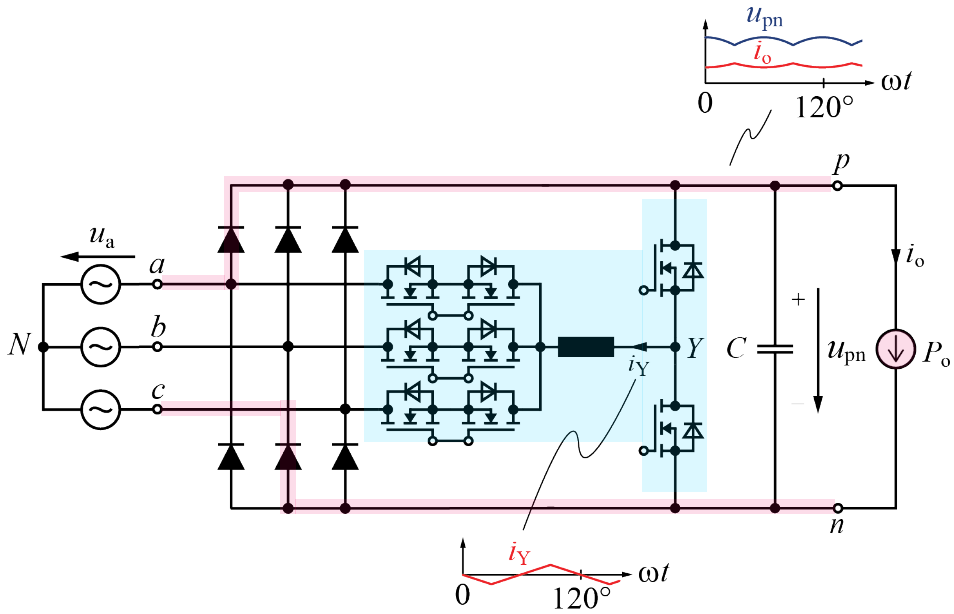


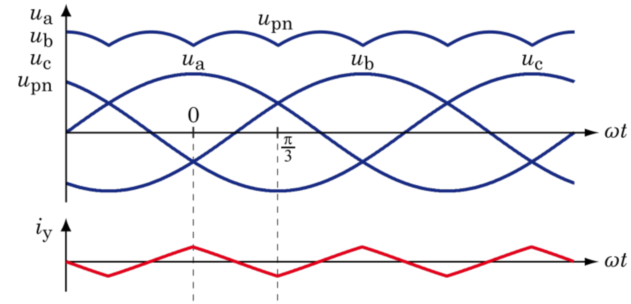


▶ 3rd Harm. Injection into "Middle" Phase → *Basic Idea: M. Jantsch, 1997 (for PV Inv.)*

Integr. Active Filter (*IAF*) PFC Rectifier (2)

- Only *One Inductor* conducting the Smallest Phase Current → *Low Switching Losses*
- High Efficiency, Low Complexity
- Bidirectional Phase-Selector Switches conducting within 60° Intervals



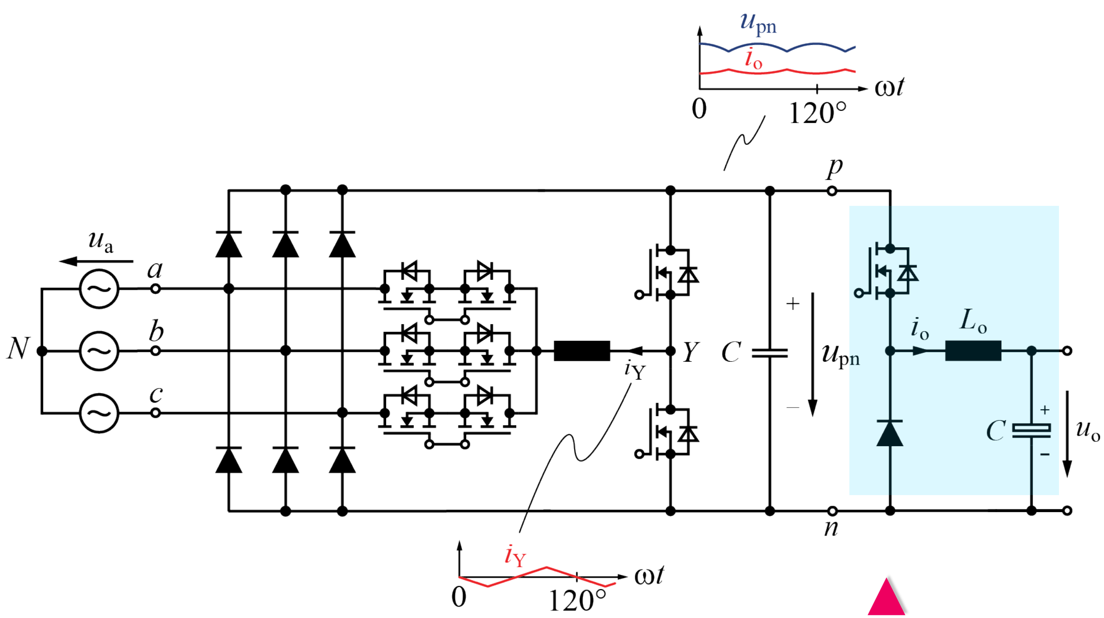


▶ Sinusoidal Current in All Phases

→ P_0= const. Required
→ *NO (!) Output Voltage Control*

Integr. Active Filter (*IAF*) PFC Rectifier (3)

- *Buck-Output Stage* for P_0= const. & *Outp. Voltage Control*

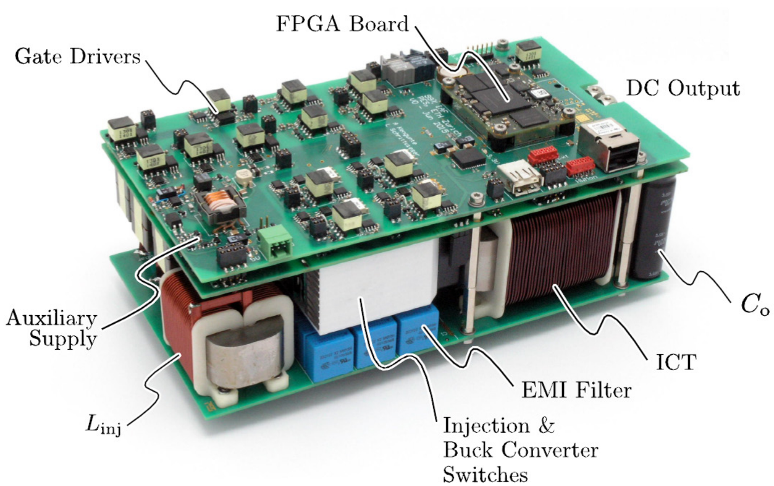


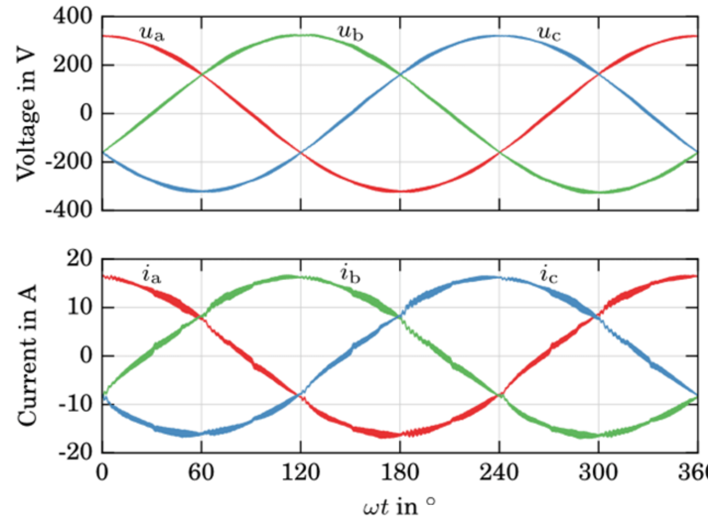
▶ Buck-Stage Could be Replaced by *Boost-Stage, Isol. DC/DC Conv.* or Inverter

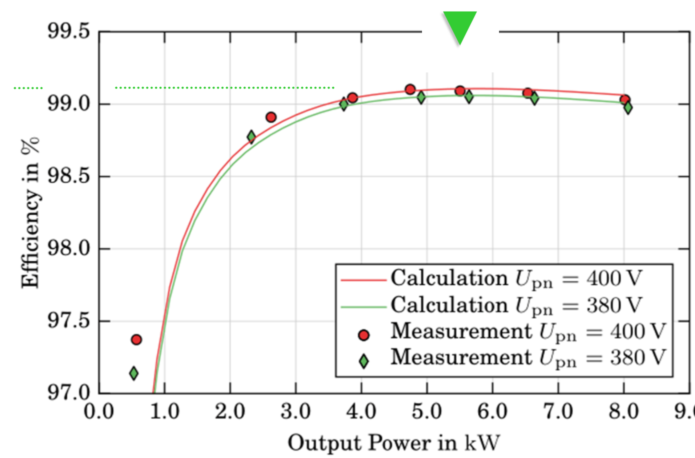
IAF Rectifier Demonstrator

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

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





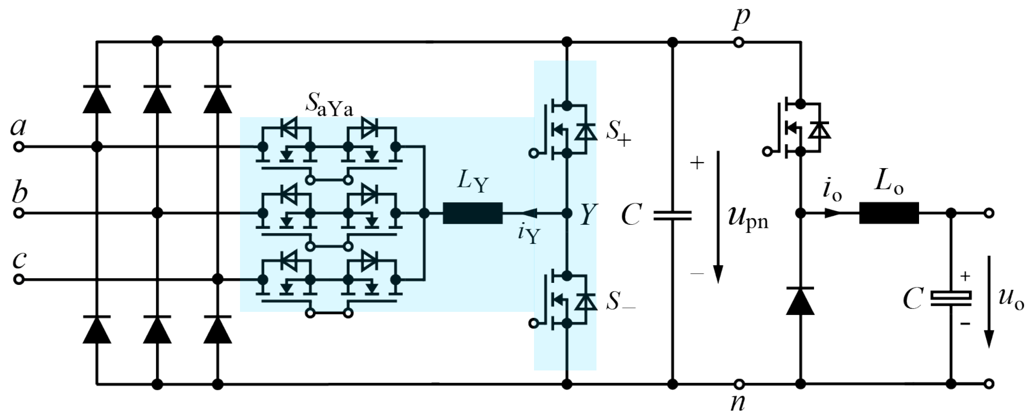


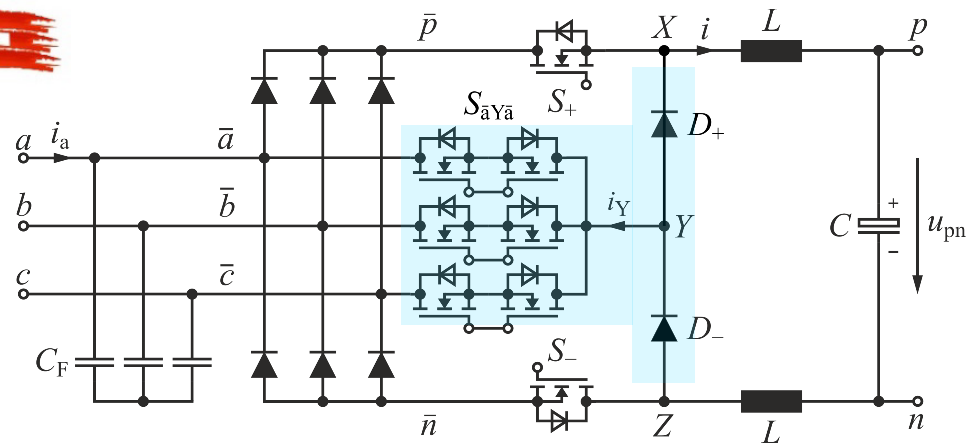
- ▶ SiC Power MOSFETs & Diodes
- ▶ 2 Interleaved Buck Output Stages

SWISS Rectifier

Swiss Rectifier (1)

- Integration of Buck-Stage into IAF Rectifier
- Low Complexity / High Efficiency

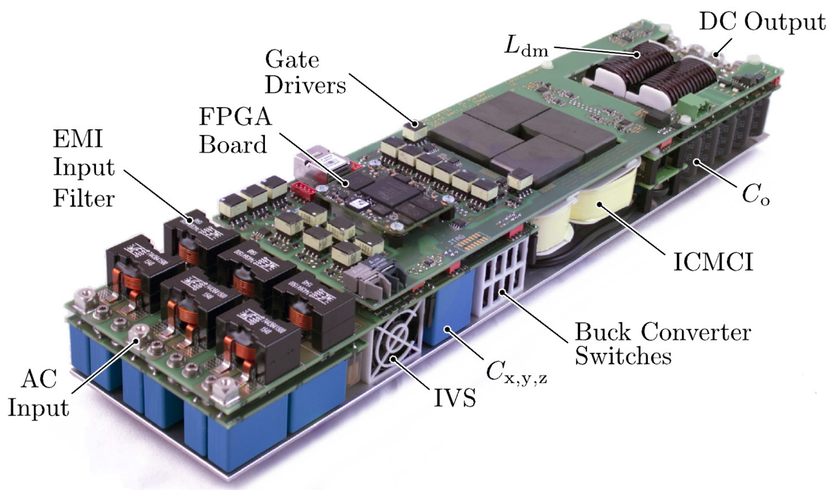


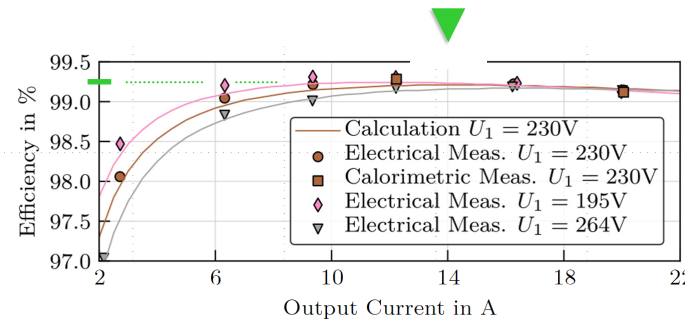


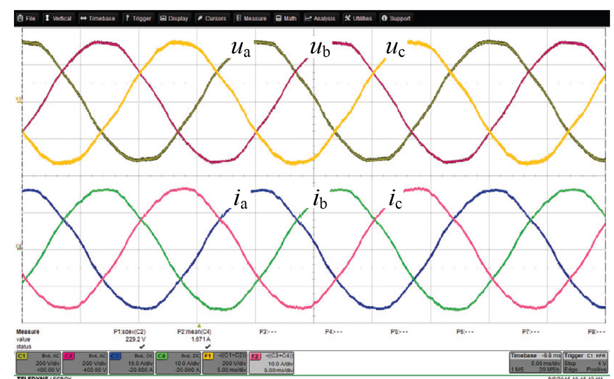
Swiss Rectifier Demonstrator

- Efficiency η = 99.26% @ 60% Rated Load
- Mains Current $THD_I \approx 0.5\%$ @ Rated Load
- Power Density $\rho \approx 4\text{kW/dm}^3$

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







- SiC Power MOSFETs & Diodes
- Integr. CM Coupled Output Inductors (ICMCI)

Boost-Buck
AND
Buck-Boost-Type PFC Rectifier

1/3 and 2/3 Concepts
Phase-Modular Concepts

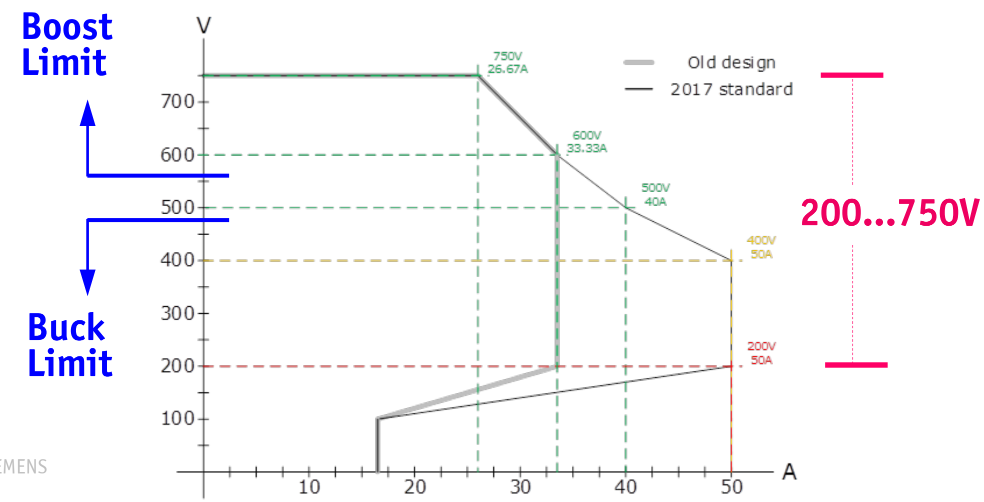
▶ Advanced 3ϕ Active PFC Rectifier Systems

- Mains Side Sinusoidal Current Shaping
- *Extremely Wide and Overlapping Voltage Ranges*
- High Efficiency / High Power Density
- Low Complexity

Source: Porsche Mission-E Project

High-Power EV Batter Charging

Source: SIEMENS



▶ **Buck-Boost Functionality needed**

1/3 and 2/3 Concepts

1/3 Rectifier
1/3 Vienna-Rectifier
2/3 Current Source Rectifier

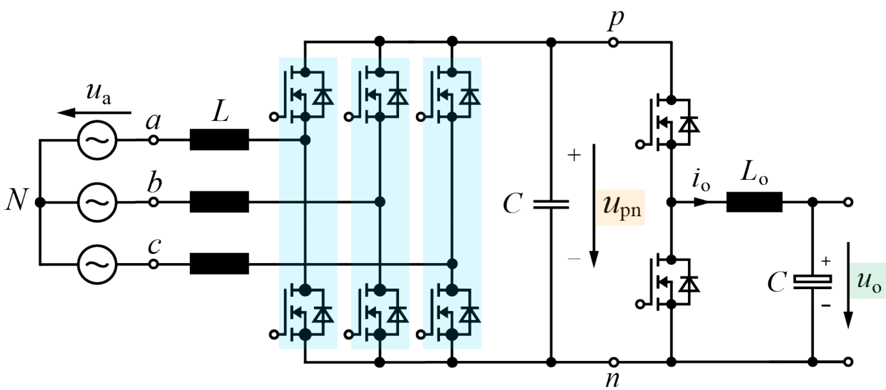
1/3 Rectifier

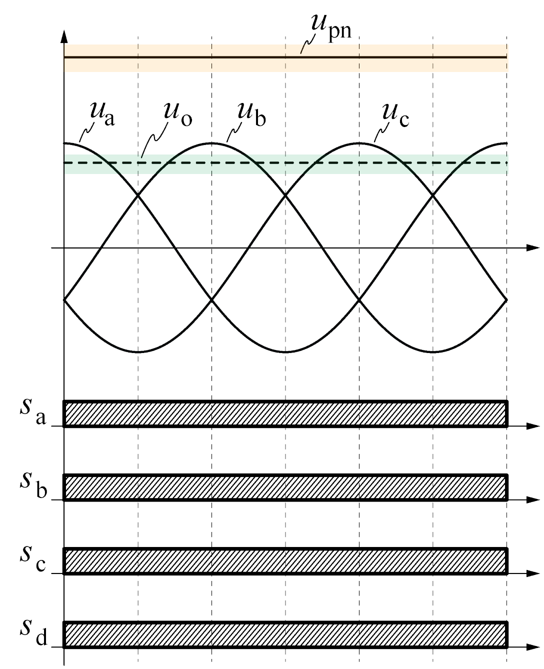
Reference

[1] D. Menzi, D. Bortis and J.W. Kolar,
"*Three-Phase Two-Phase-Clamped Boost-Buck Unity Power Factor Rectifier Employing Novel Variable DC Link Voltage Input Current Control*",
Proceedings of the 2nd IEEE International Power Electronics and Application Conference and Exposition (PEAC 2018), Shenzhen, China, November 4-7, 2018.

1/3 PWM *Boost & Buck* PFC Rectifier (1)

- Conventional 3Φ-Boost PFC Rectifier with subsequent DC/DC Buck-Stage
- Control of *Sinusoidal* Input Currents and *Constant* DC-Link Voltage u_{pn}

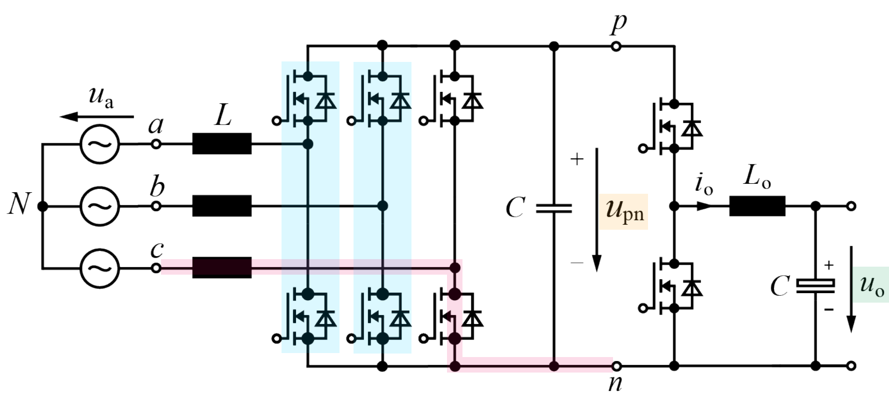


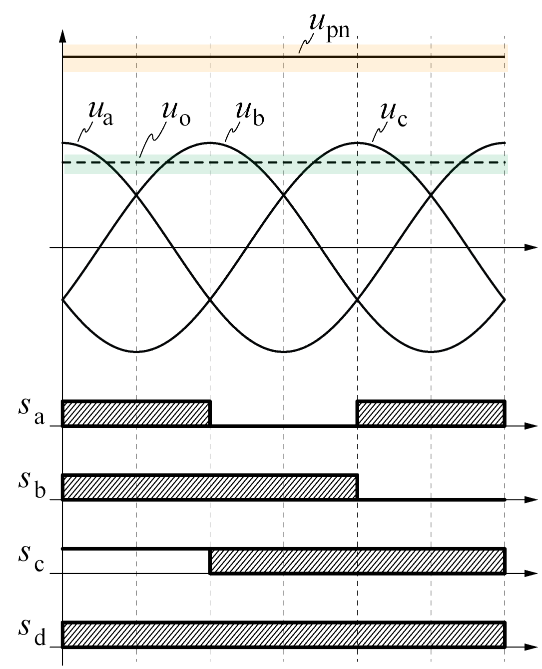


- ▶ *PWM* - Operation of *Three* Rectifier-Bridges
- ▶ *DPWM* - Operation of *Two* Rectifier-Bridges - One Phase Clamped

1/3 PWM *Boost & Buck* PFC Rectifier (2)

- Conventional 3Φ-Boost PFC Rectifier with subsequent DC/DC Buck-Stage
- Control of *Sinusoidal* Input Currents and *Constant* DC-Link Voltage u_{pn}

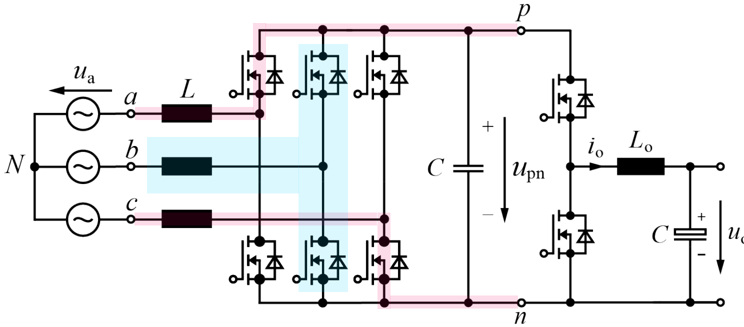


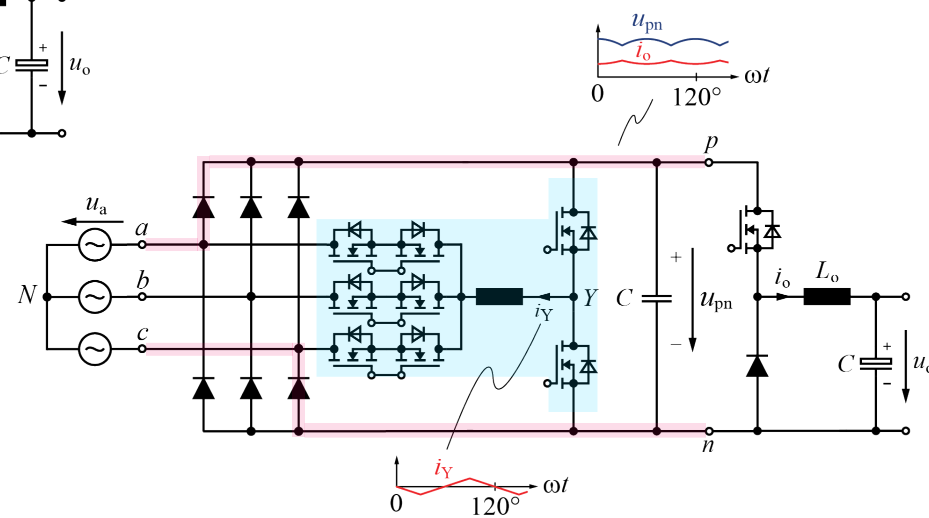


- ▶ DC/DC Buck-Stage steps u_{pn} down
- ▶ No Need to kept DC-Link Voltage u_{pn} constant

1/3 PWM *Boost & Buck* PFC Rectifier (3)

- Clamping of two Phases → *Pulsating DC-Link Voltage like IAF Rectifier*
- Current Injection in "Middle" Phase → *Sinusoidal Input Currents*

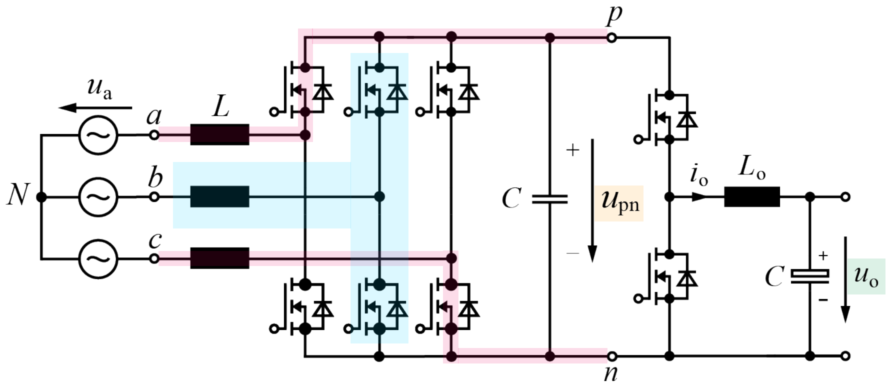


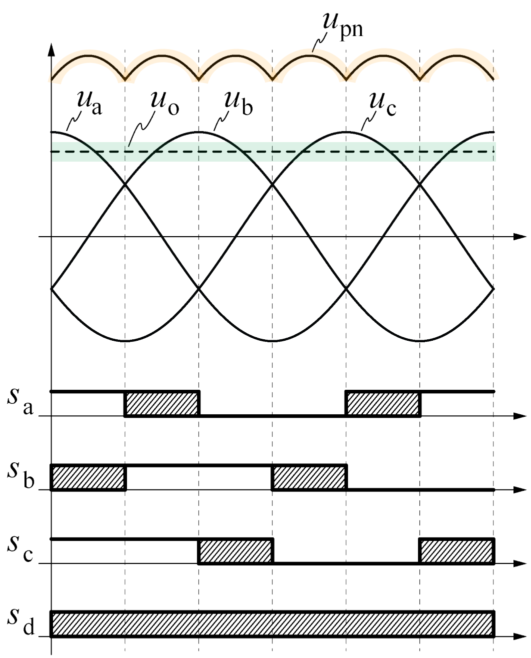


▶ *Similar Concept: D. Neacsu, 2012*

1/3 PWM *Boost & Buck* PFC Rectifier (4)

- *Buck-Stage Utilized for DC Link Voltage Shaping / Control of 2 Mains Phase Currents*
- *Low Switching Losses* / High Efficiency
- Cont. Input & Output Currents



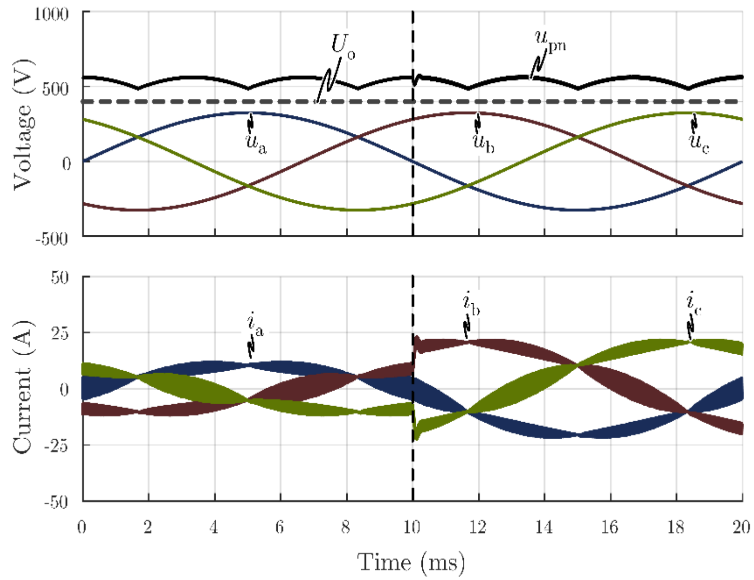


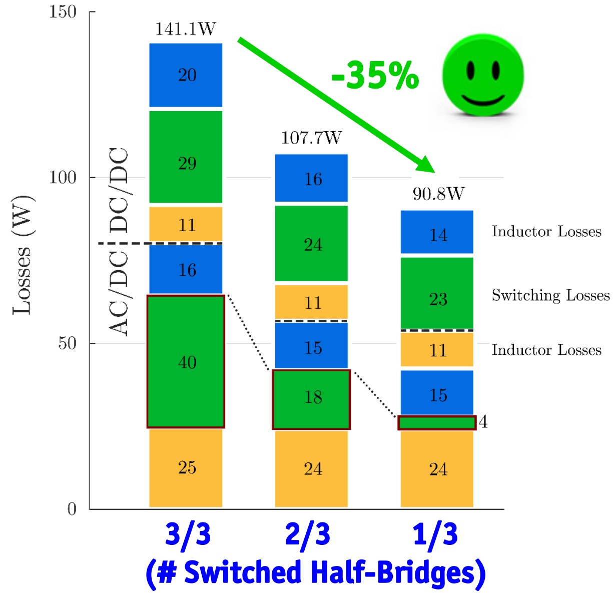
- *Buck-* or *Boost & Buck-Operation possible*
- Bidirectional / Inv. Operation
- Conventional Cascaded Control Structure of PFC Rectifiers

1/3 PWM *Boost & Buck* PFC Rectifier (5)

- Simulated Waveforms (Load Step)
- Theoretical Loss Calculation

- 48kHz Switching Frequency
- 10kW Operation
- 400V Output Voltage
- 25A Output Current





▶ Rectifier Switching Loss Reduction by x 10 → Allows for higher Switching Freq.

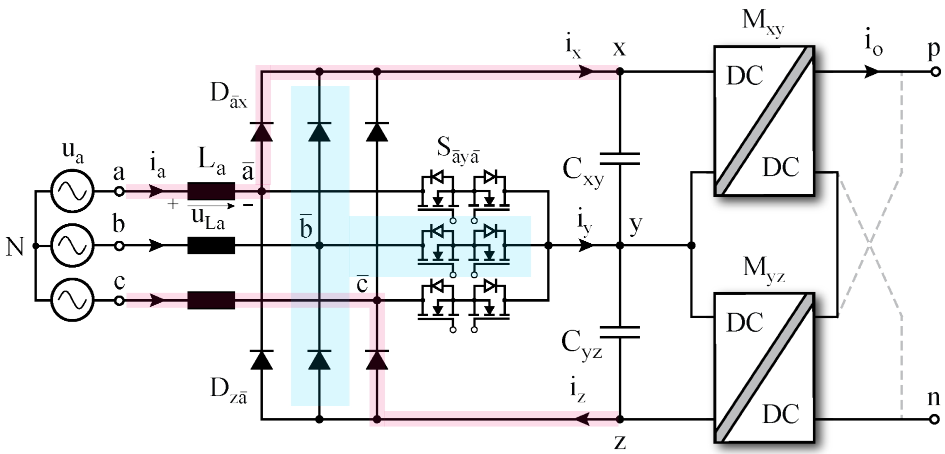
1/3 Vienna Rectifier

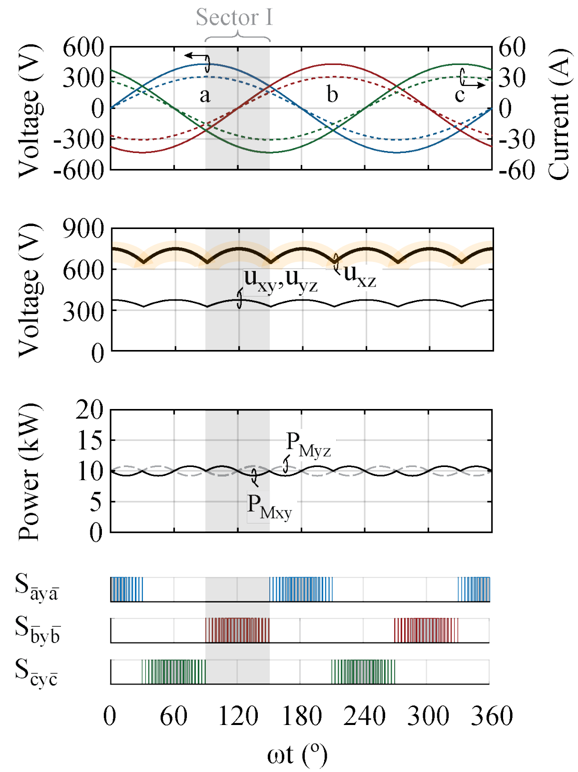
REFERENCE

[1] J. Azurza, D. Bortis and J.W. Kolar,
"*20kW EV Battery Charger Employing New Synergetic Control of Three-Phase/Level PFC Rectifier Mains Interface and Isolated Split DC/DC Converter Output Stage*",
COMPEL 2019, 17rd-20th June 2019, Toronto, Canada.

1/3 Isolated Vienna Rectifier (1)

- Application of *1/3-Modulation* on *Two-Stage Isolated Vienna Rectifier*
- 3-Level Topology → Lower Current Ripple and Blocking Voltage Requirements
- Lower Switching Losses → Higher Efficiency





- DC-Midpoint Voltage balanced by Isolated DC/DC Stage
- Also Non-Isolated DC/DC Converters applicable
- Presentation in upcoming COMPEL 2019

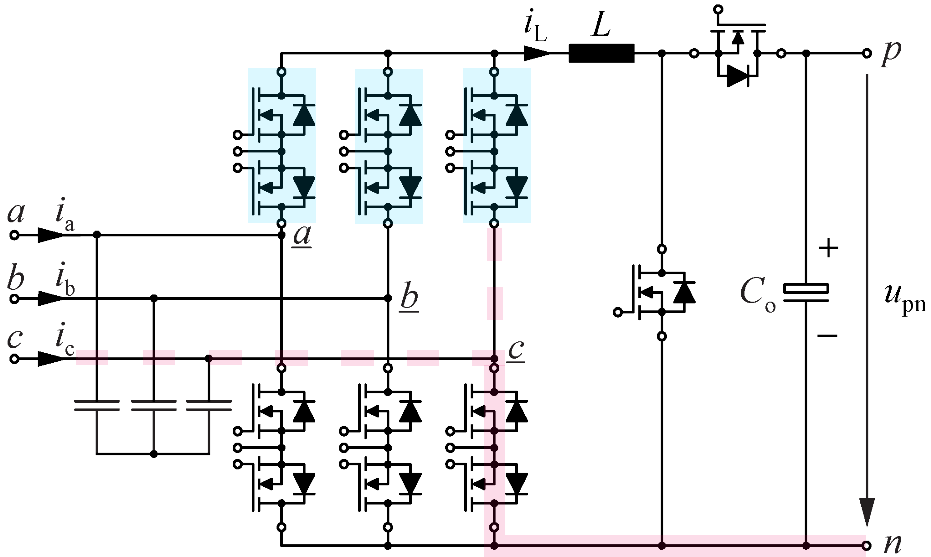
2/3 Current Source Rectifier

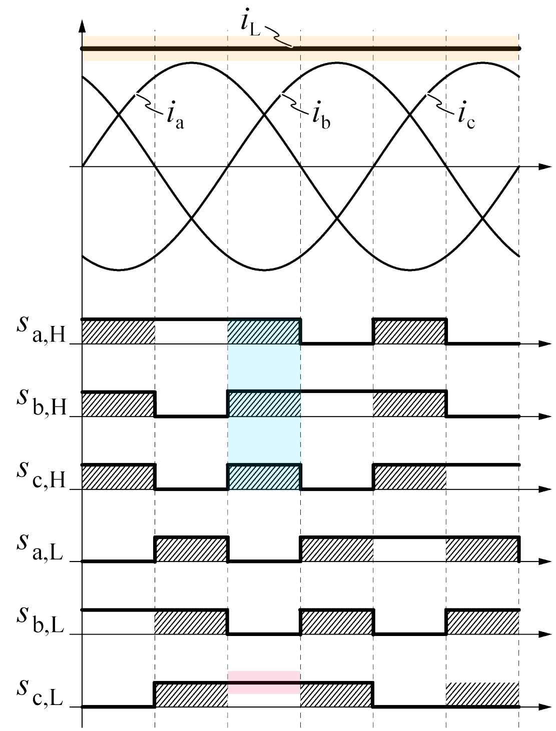
REFERENCE

[1] M. Guacci, M. Tatic, D. Bortis, J.W. Kolar, Y. Kinoshita and H. Ishida,
"*Novel Three-Phase Two-Third-Modulated Buck-Boost Current Source Inverter System Employing Dual-Gate Monolithic Bidirectional GaN e-FETs*", PEDG 2019, 3rd-6th June 2019, Xi'an, China.

2/3 PWM *Buck & Boost* Current Source Rectifier (1)

- Conventional 3Φ-Buck PFC Rectifier with subsequent DC/DC Boost-Stage
- Control of *Sinusoidal* Input Currents and *Constant* DC-Link Inductor Current i_L

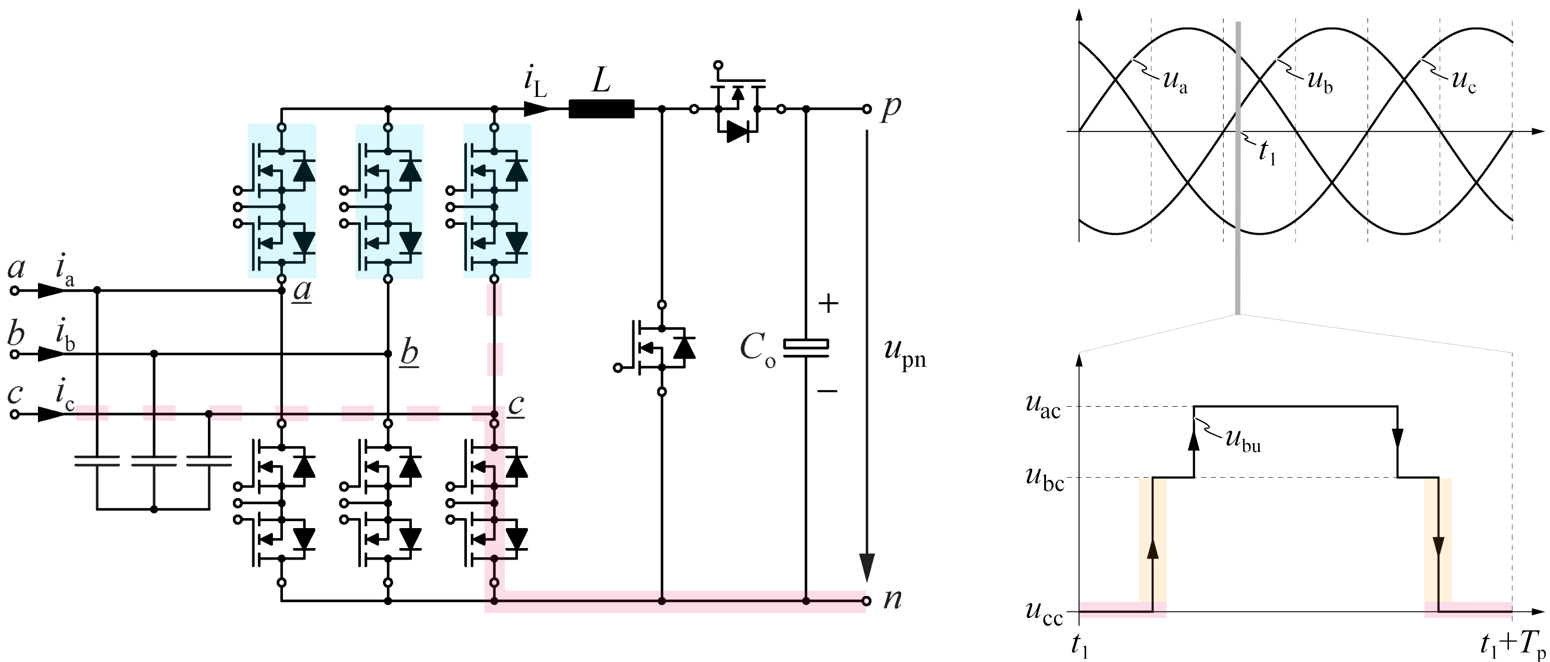




▶ Either All Three High-Side or Low-Side Switches must be Pulse-Width modulated
▶ Freewheeling Interval for Bridge with largest Phase Current needed

2/3 PWM *Buck & Boost* Current Source Rectifier (2)

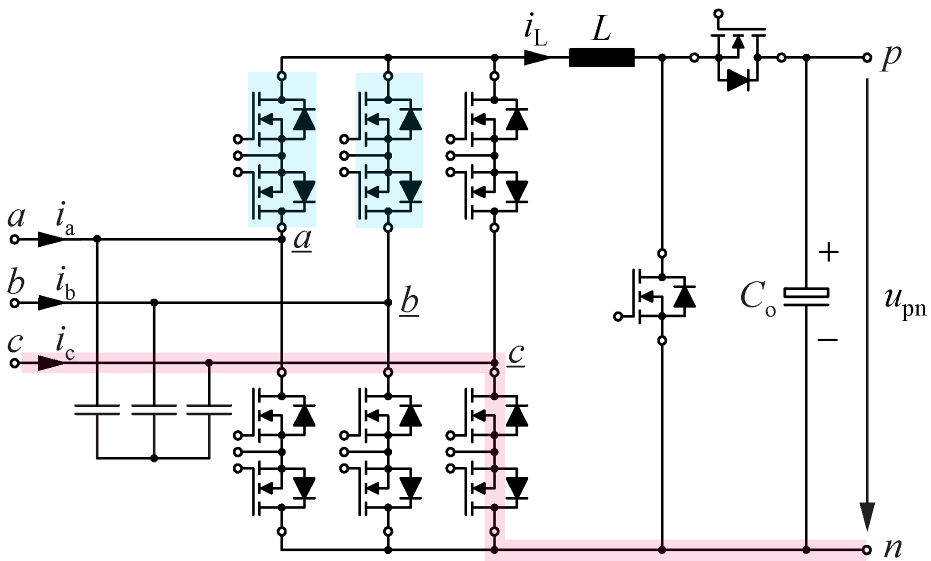
- On-Time / Freewheeling Time defined by Ratio betw. max. Phase and Inductor Current
- On-Times of other Phases given by Current Ratios with respect to max. Phase Current

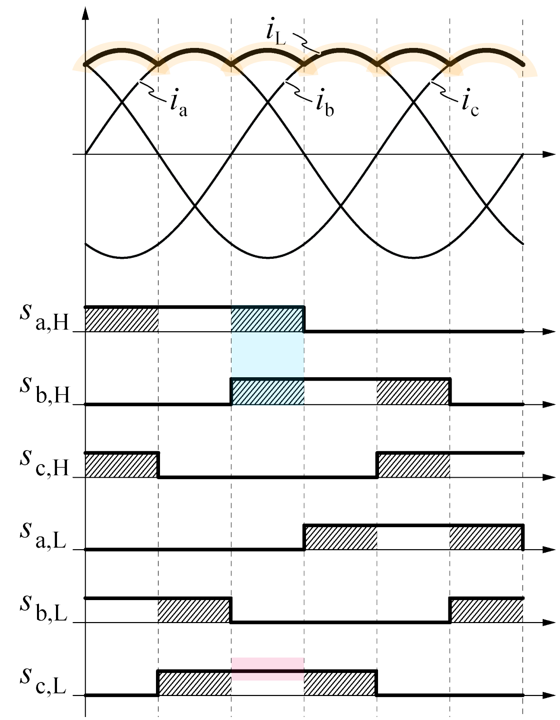


▶ Transition from/into Short-Circuit Interval → largest Voltage switched (PFC Op.)
▶ *Constant* DC-Link Inductor Current i_L actually not needed

2/3 PWM *Buck & Boost* Current Source Rectifier (3)

- Shape DC-Link Inductor Current i_L to equal Absolute Value of max. Phase Current
- Only two High-Side or Low-Side Switches Pulse-Width modulated

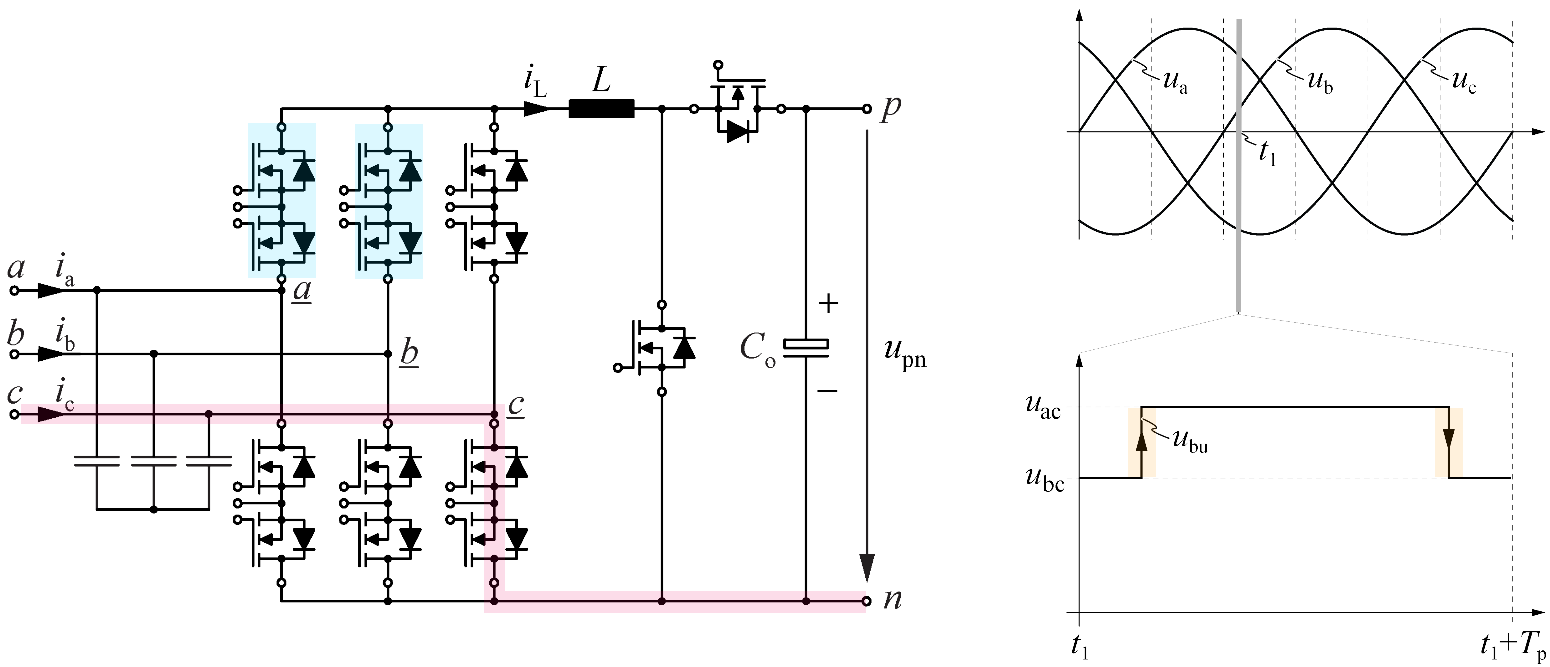




▶ NO (!) Freewheeling-Interval needed

2/3 PWM *Buck & Boost* Current Source Rectifier (4)

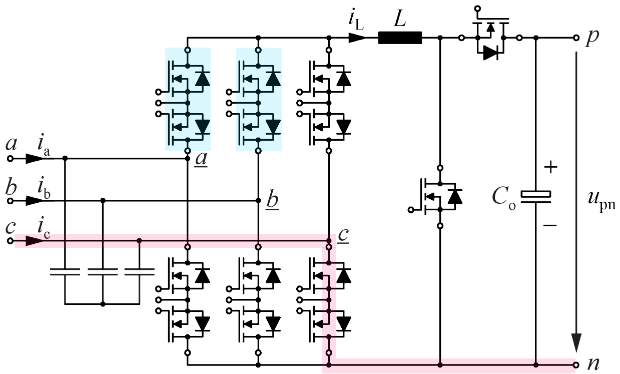
- Transition from/into Short-Circuit Interval eliminated → 2/3 Modulation

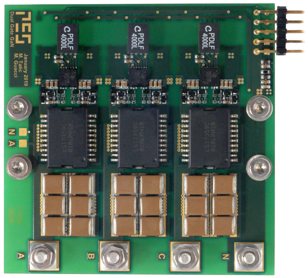


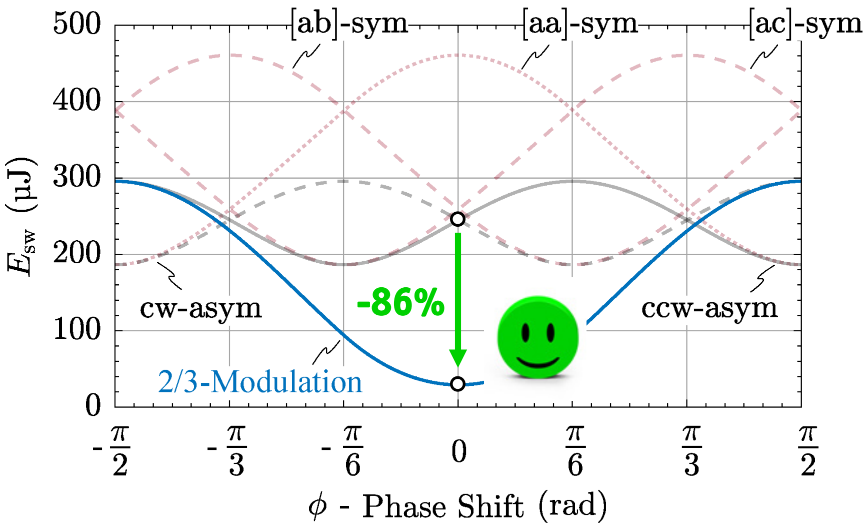
► Only small Voltages switched for PFC Operation
► Ultra Low Switching Losses expected

2/3 PWM *Buck & Boost* Current Source Rectifier (5)

- Loss Reduction of -86% for PFC Operation calculated
- Realization with Monolithic Bidirectional GaN e-FETs under Investigation







► Also applicable for Variable Speed Drive or Back-to-Back Configurations

Phase-Modular Concepts

Trident Rectifier

Y- Rectifier

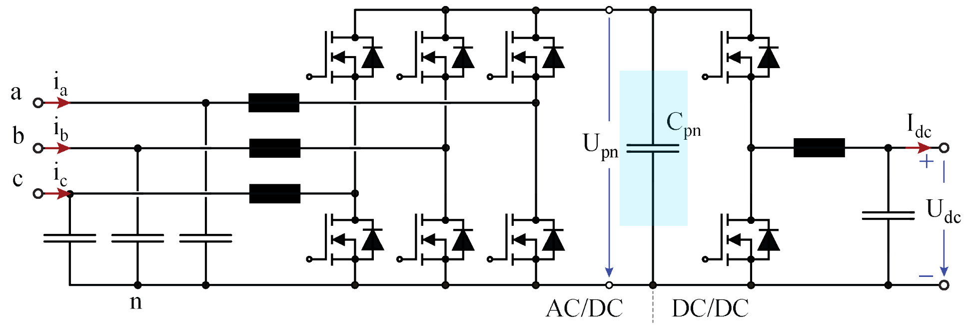
Trident-Rectifier

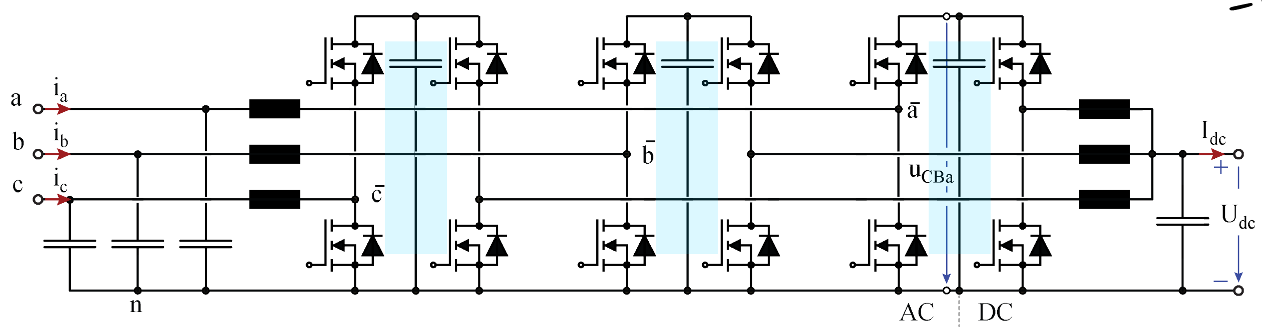
Reference

[1] D. Menzi, D. Bortis and J.W. Kolar,
"*A New Bidirectional Three-Phase Phase-Modular Boost-Buck AC/DC Converter*",
Proceedings of the 2nd IEEE International Power Electronics and Application Conference and Exposition (PEAC 2018), Shenzhen, China, November 4-7, 2018.

Trident Rectifier (1)

- Deduced from Conventional 3Φ-Boost PFC Rectifier & DC/DC Buck-Stage
- *Individual DC-Link Voltages* → Three Indep. DC/DC Boost & Buck Conv. Op. as AC/DC
- Realization of 3-Φ Inverter Using 3 DC/DC Converter (Phase) Modules — S. Cuk/1982

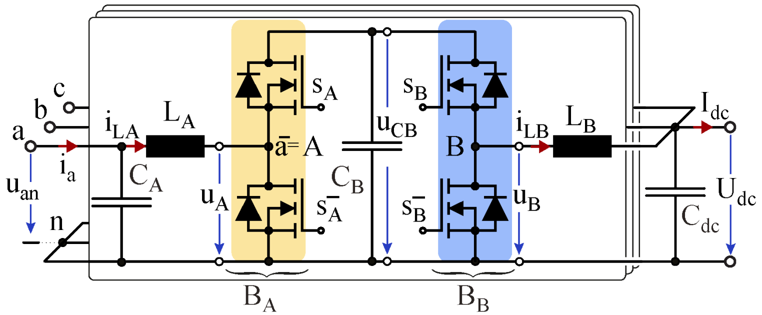


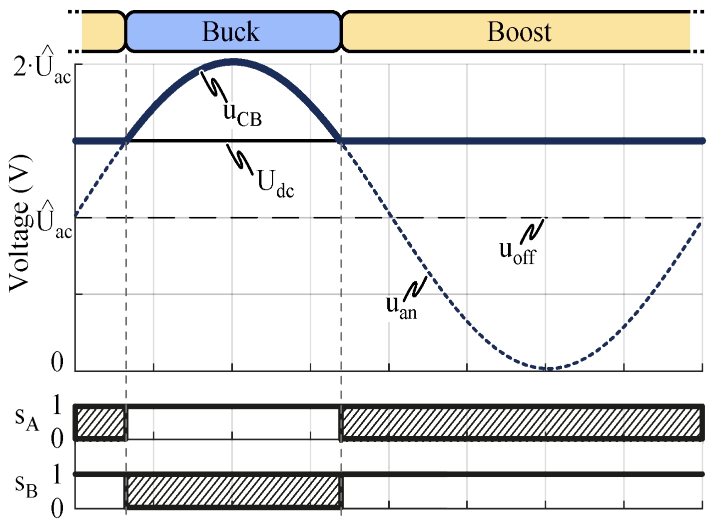


- ▶ *Phase Modular Structure* with Phase Voltages Referenced to *DC-Minus*
- ▶ DC Link Voltages Adapted to Required AC Input Phase Voltage

Trident Rectifier (2)

- Clamping of either Boost or Buck Bridge Leg of Phase Module → High Efficiency

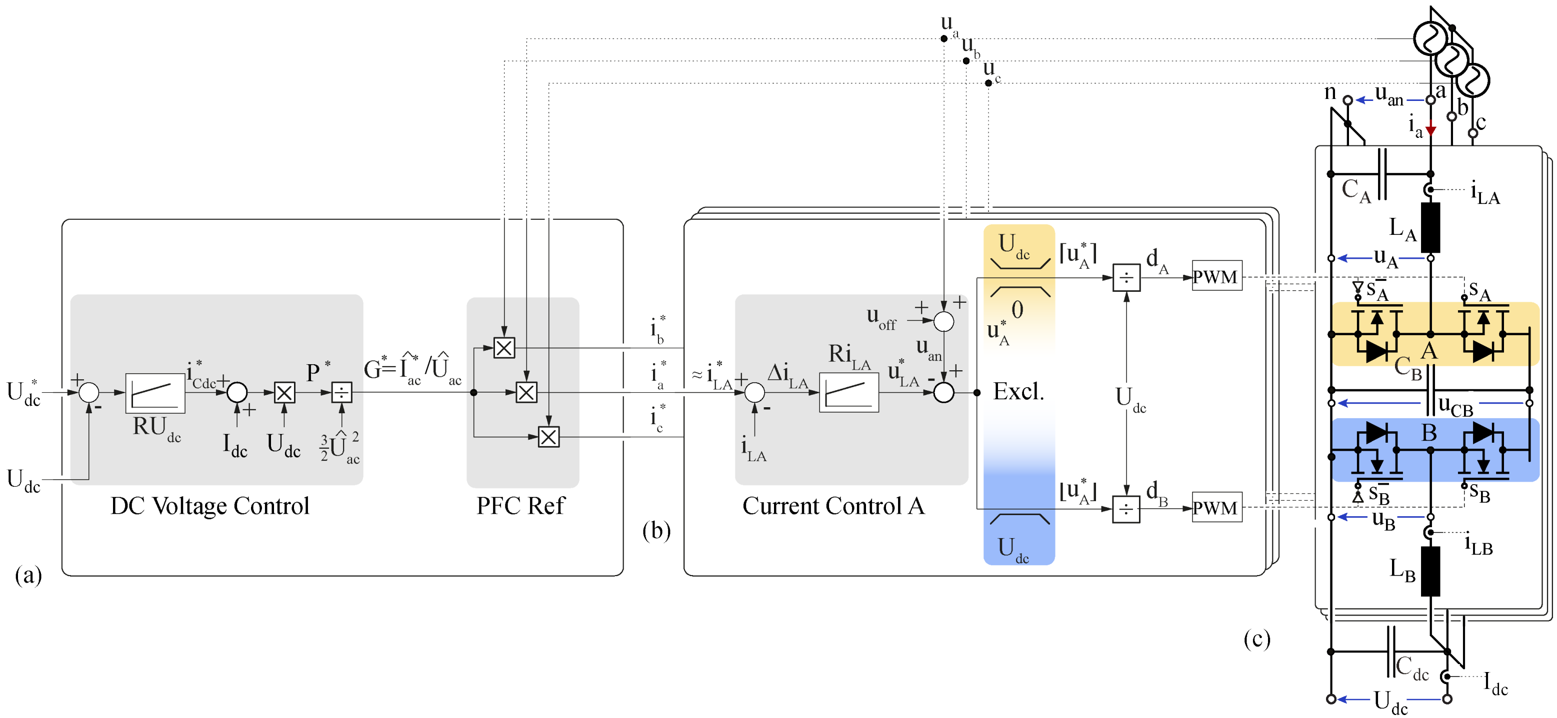




- Seamless Transition between Boost- & Buck-Mode → "Democratic" Control

Trident Rectifier (3)

- Clamping of either Boost or Buck Bridge Leg of Phase Module



- ▶ Continuous Input and Output Currents
- ▶ Applicable to Variable-Speed Motor Drives with unshielded Cables

Y-Rectifier

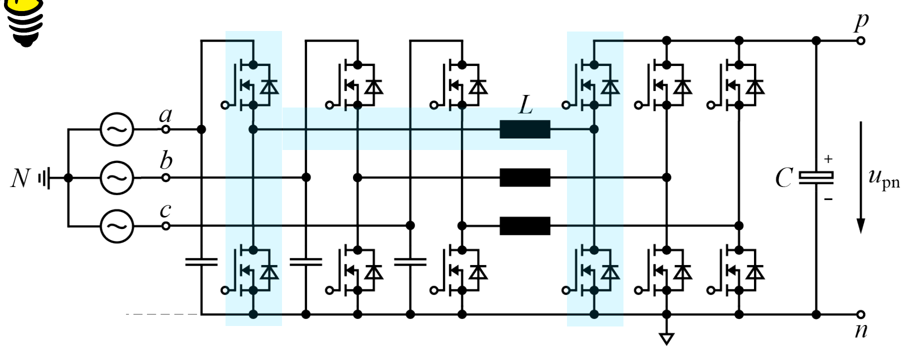
References

[1] M. Antivachis, D. Bortis, L. Schrittwieser and J.W. Kolar,
"*Three-Phase Buck-Boost Y-Inverter with Wide DC Input Voltage Range*",
Proceedings of the 33rd Applied Power Electronics Conference and Exposition (APEC 2018), San Antonio, Texas, USA, March 4-8, 2018.

[2] M. Antivachis, D. Bortis, D. Menzi and J.W. Kolar,
"*Comparative Evaluation of Y-Inverter against Three-Phase Two-Stage Buck-Boost DC-AC Converter Systems*",
Proceedings of the International Power Electronics Conference (ECCE Asia 2018), Niigata, Japan, May 20-24, 2018.

Y-Rectifier (1)

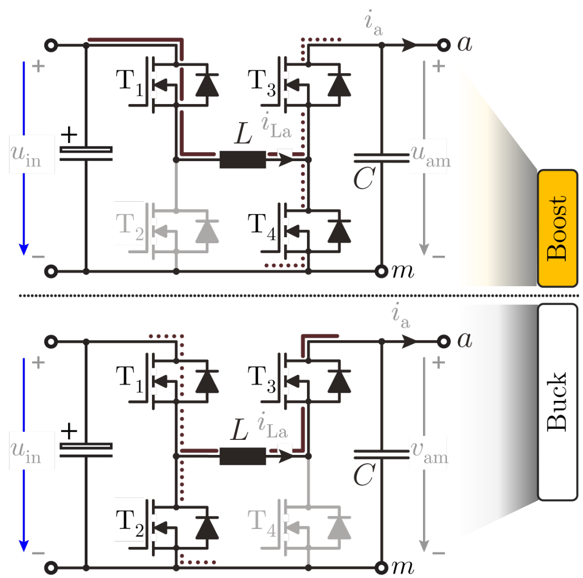
- *"Buck-Boost" Instead of "Boost-Buck" Phase Modules*
- No Intermediate DC Link Voltages → Intermediate DC Link Currents

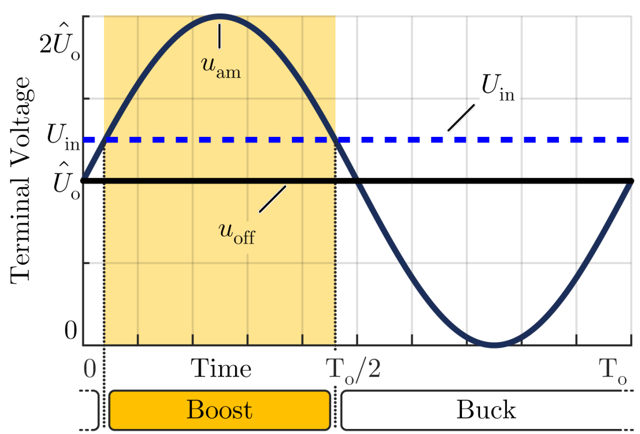


- ▶ Low Number of Ind. Components → High Power Density
- ▶ Converter Integrated Filter Inductors → Continuous Input/Output Voltages

Y-Rectifier (2)

- Clamping of Boost or Buck Bridge Leg → Low Switching Losses

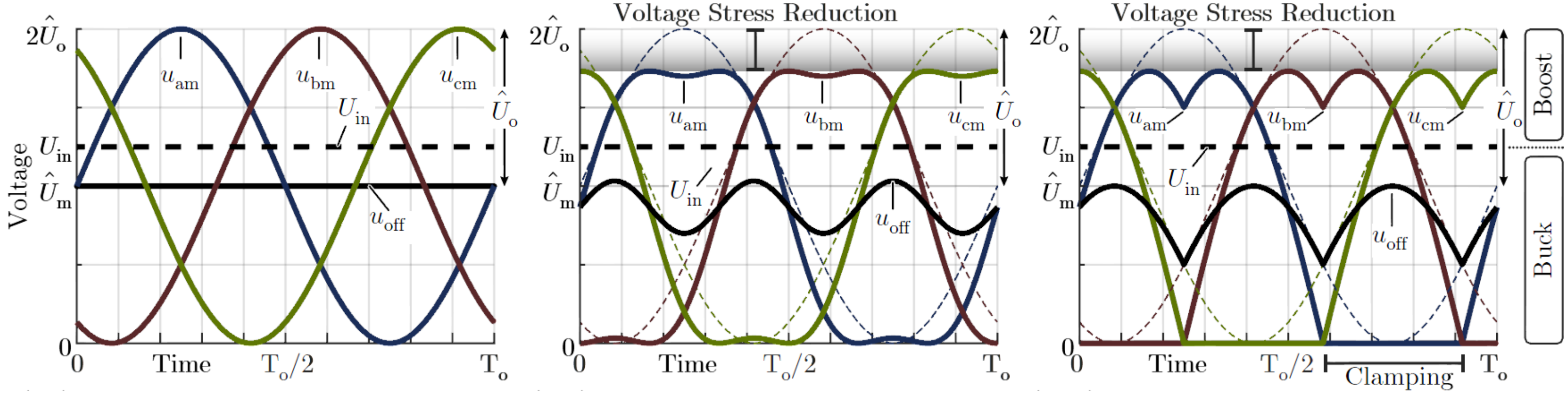




- ▶ Seamless Transition between Boost- & Buck-Mode → "Democratic" Control
- ▶ Improved Modulation Schemes Applicable → Only 2-of-6 Bridges-Legs switched

Y-Rectifier (3)

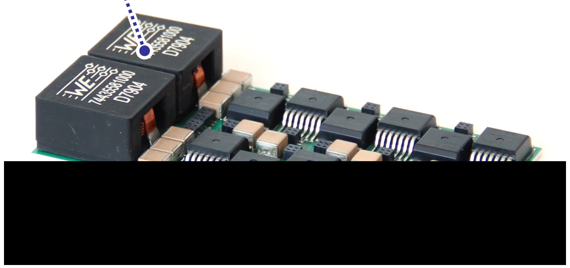
- *Sinusoidal Modulation* → *Variable Output Voltage DC Offset for Low Mod. Index*
- *3rd Harmonic Injection*
- *Phase Clamping as Alternative Concepts*

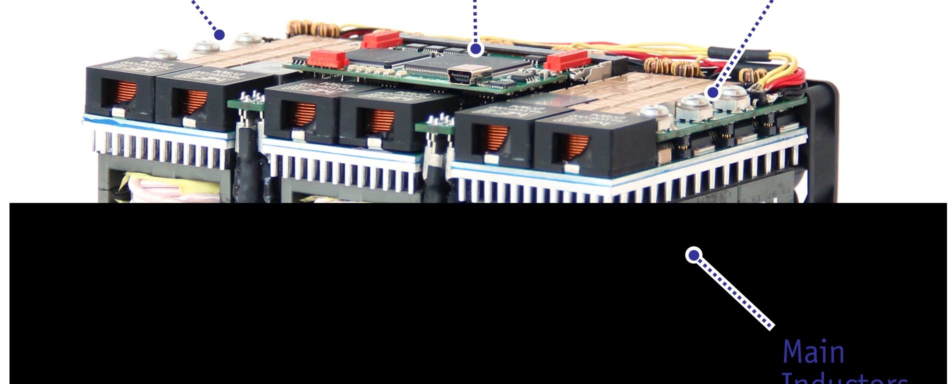


- **Adv. of Reduced Output Voltage Amplitude & Reduction of Sw. Losses**
- **Demonstrator Realized as Variable-Speed Drive**

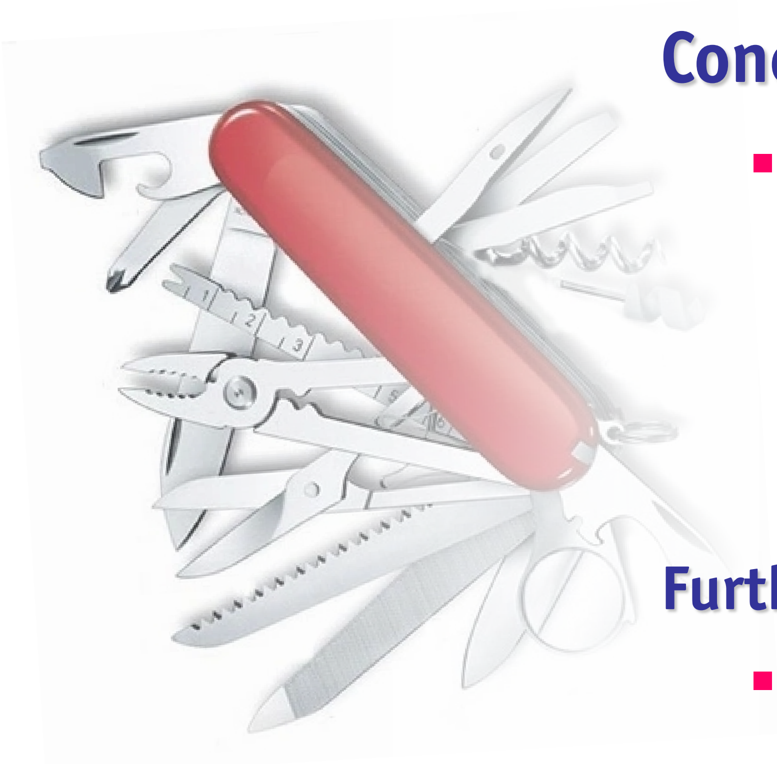
Y-Inverter Demonstrator

- DC Voltage Range 400…750V_{DC}
- Max. Input Current ± 15A
- Output Voltage 0…230V_{rms} (Phase)
- Output Frequency 0…500Hz
- Sw. Frequency 100kHz
- 3x SiC (75mΩ)/1200V per Switch
- IMS Carrying Buck/Boost-Stage Semicond. & Comm. Caps & 2nd Filter Ind.





■ **Dimensions** → 160 x 110 x 42 mm³ (15kW/dm³, 245W/in³)



Conclusions

- Several *"SWISS Knife"* PFC Rectifier Topologies
  → Wide Input / Output Voltage Range
  → Bidirectional Power Transfer
  → Standard Building Blocks / Modular
  → High Efficiency
  → High Power Density
  → Low Complexity

Further Improvements

- Isolated Topologies
  → Not Discussed here

- Higher Number of Levels? (Flying Cap. Converter)
  → Higher Complexity
  → Lower Reliablilty?

Thank You !


BACKUP

ETH Zurich

21 Nobel Prizes
509 Professors
5800 T&R Staff

2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages

150th Anniv. in 2005

Departments

ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	Information Technology and Electrical Eng.
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

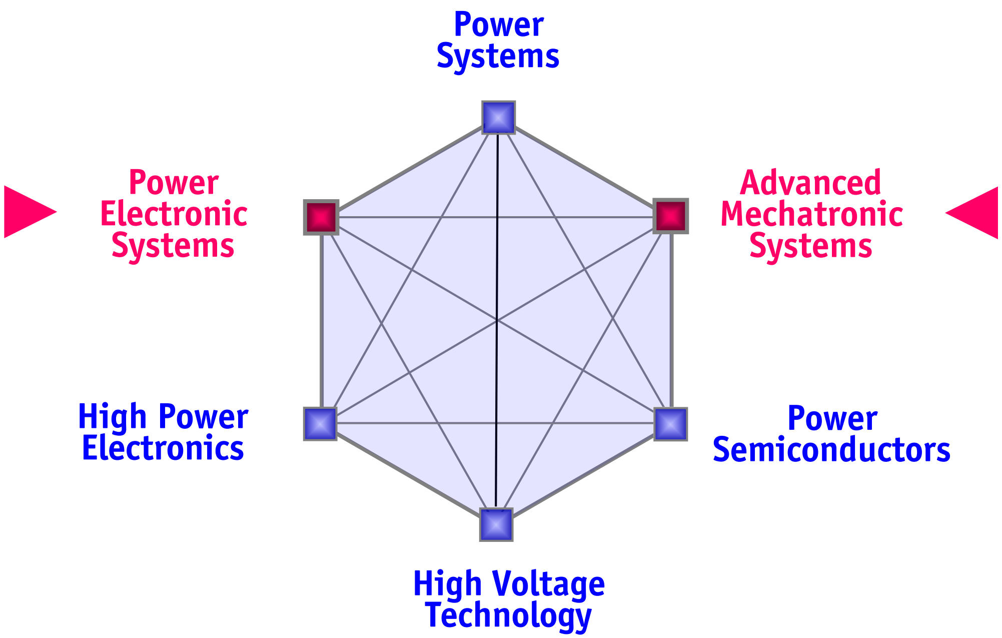
Students ETH in total

14’500	B.Sc.+M.Sc.-Students
4’500	Doctoral Students

ITET – Research in E-Energy

Systems

Technologies



- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	**D. Bortis**	**F. Krismer**		**D. Bortis**	**D. Bortis**
M. Heller D. Menzi D. Neumayr J. Schäfer	J. Azurza P. Czyz	P. Bezerra T. Guillod G. Knabben	M. Antivachis J. Böhler M. Guacci M. Haider	P. Papamanolis	P. Niklaus	E. Hubmann	Th. Holenstein P. Püntener S. Miric

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

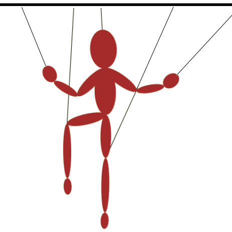
19 Ph.D. Students
2 Sen. Researchers

ECPE Competence Centre

EPSMA

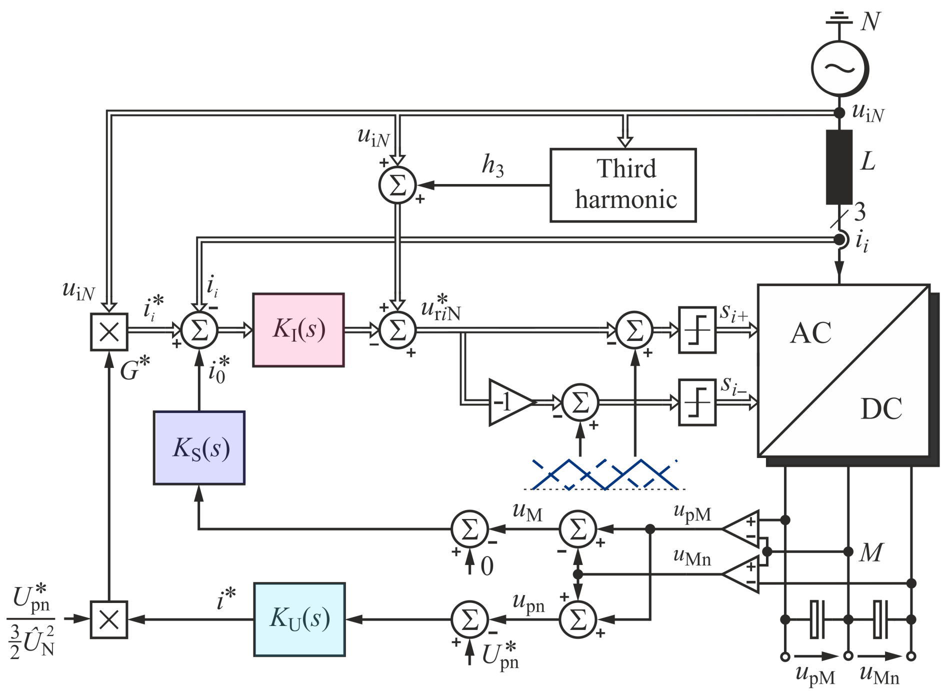
Leading Univ. in Europe

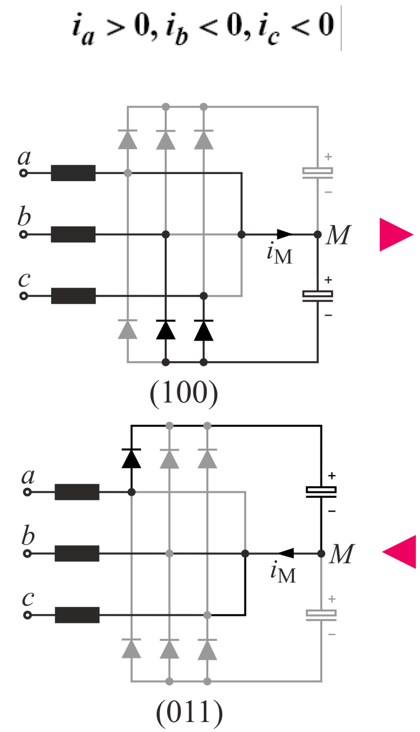
Cluster Leistungselektronik ECPE



Vienna Rectifier (5)

- *Output Voltage Control / Inner Mains Current Control*
- Add. Control Loop for DC Midpoint Balancing
- Redundant Sw. States Utilized for DC Midpoint Balancing

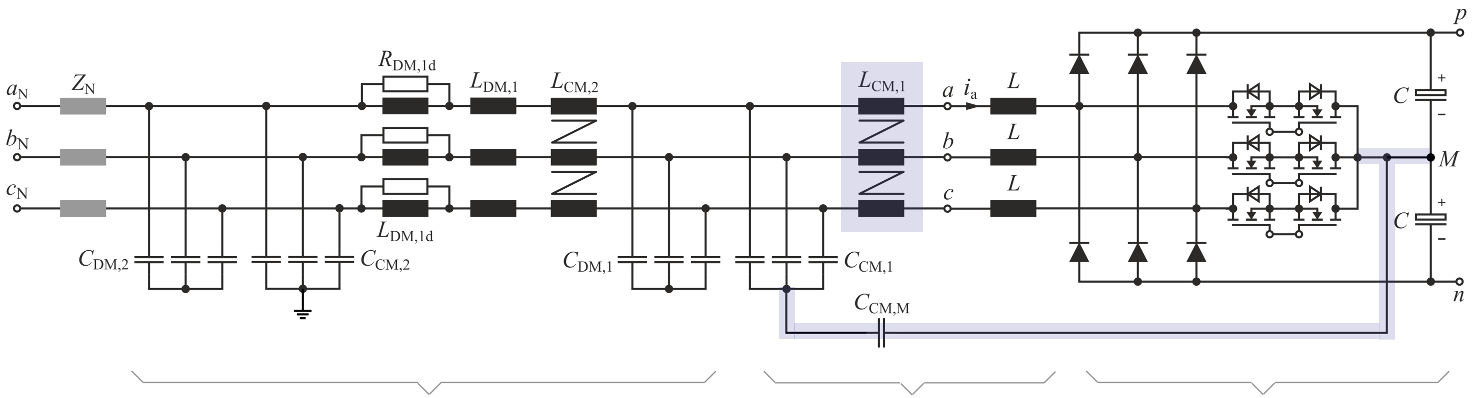




▶ Multi-Stage Diff. Mode & Common Mode *EMI Filter*

Vienna Rectifier (6)

- *CM EMI Filtering Utilizing Internal Cap. Connection to Virtual Star Point*
- No Limit of CM Capacitance by Max. Leakage Current
- CM Filter Stage(s) on DC-Side as Alternative

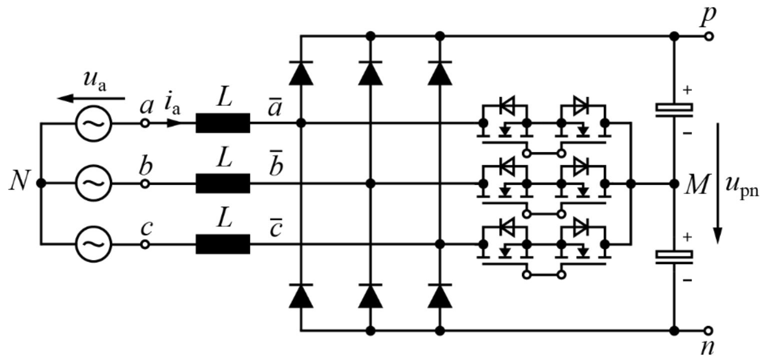


33% 33% 33%

► Number of Filter Stages Dependent on Sw. Frequency

Vienna Rectifier (7)

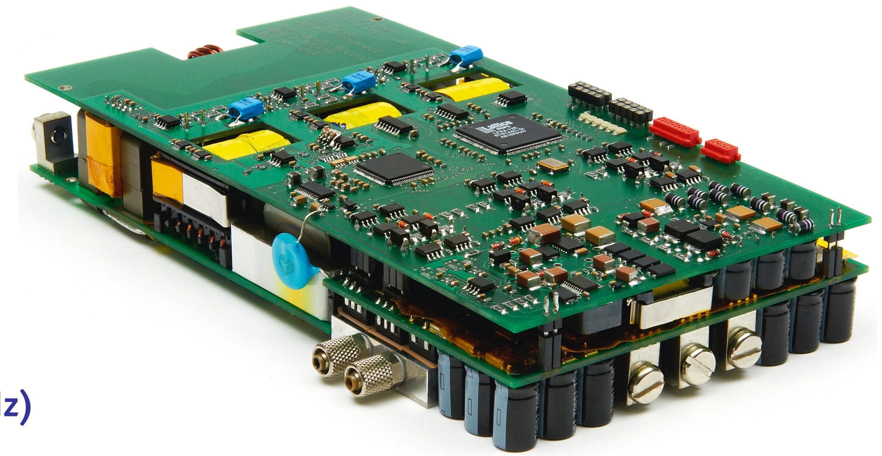
- Highly-Compact Demonstrator System
- CoolMOS & SiC Diodes
- Coldplate Cooling



P_O = 10 kW
U_N = 400V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_O = 800V_{DC}

η = 96.8%

★ ρ = 10 kW/dm^3



► THD_i = 1.6% @ f_N = 800Hz (f_P = 250kHz)

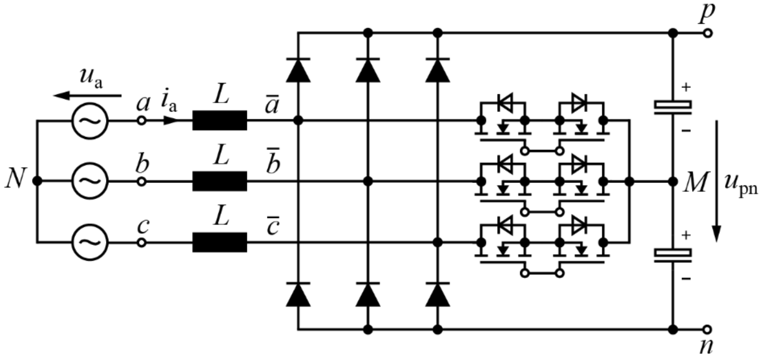
Vienna Rectifier (8)

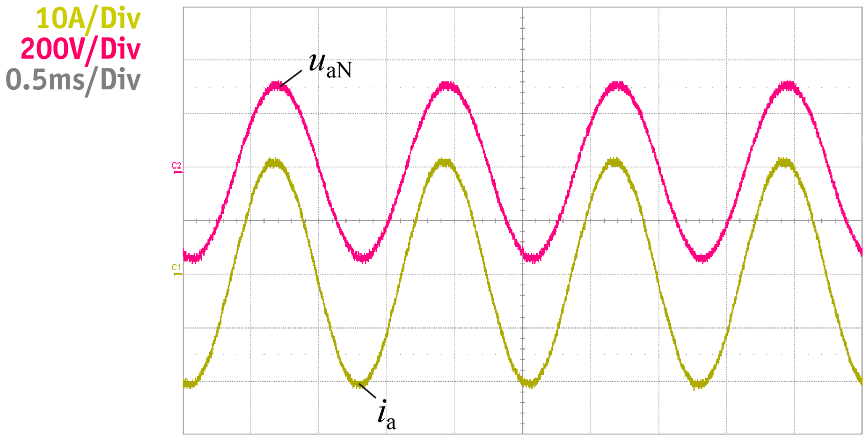
- Highly-Compact Demonstrator System
- CoolMOS & SiC Diodes
- Coldplate Cooling

P_0= 10 kW
U_N= 400V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_0= 800V_{DC}

η =96.8%
ρ =10 kW/dm^3
f_P= 250kHz

▶ THD_i = 1.6% @ f_N = 800Hz
▶ System Allows 2-Φ Operation

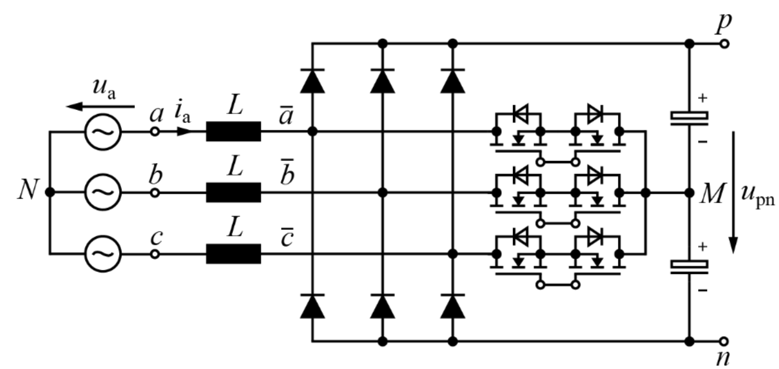


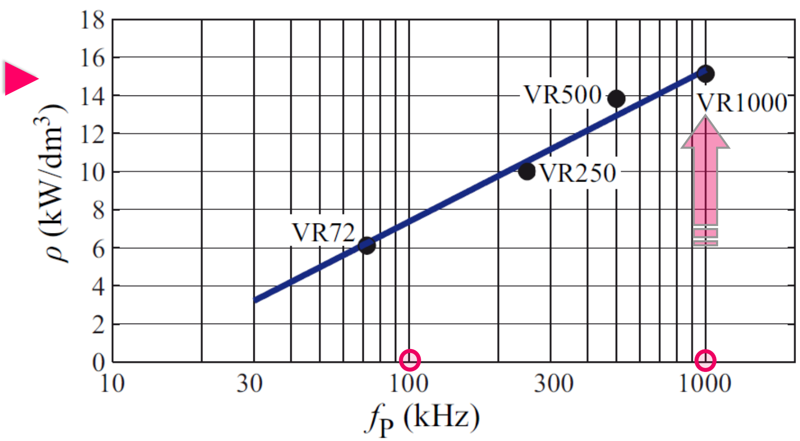


Vienna Rectifier (9)

- Dependency of Power Density on Sw. Frequency f_P
- CoolMOS & SiC Diodes
- Coldplate Cooling

P_O= 10 kW
U_N= 230V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_O= 800V_{DC}

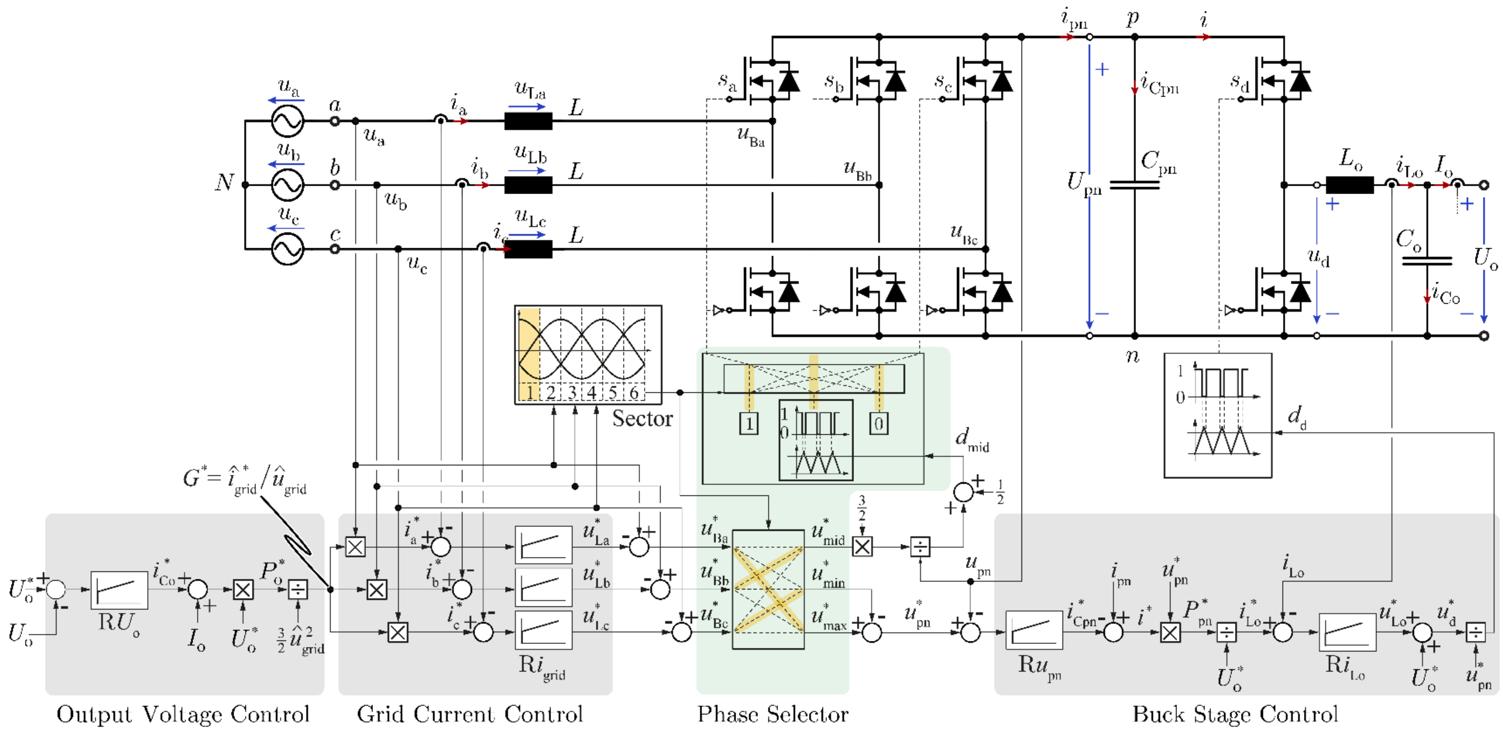




- ▶ Factor 10 in f_P → Factor 2 in Power Density
- ▶ Systems with f_P= 72/250/500/1000kHz

1-of-3 PWM Boost+Buck Rectifier

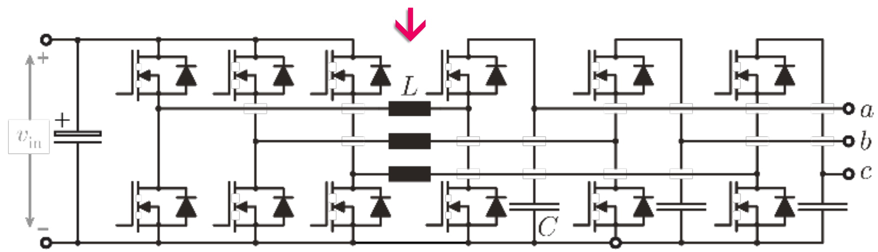
- Outer *Output Voltage Control Loop* and Inner *Input Current Control Loop*
- Only Phase Selector Block to be introduced → Applicable to Existing Systems

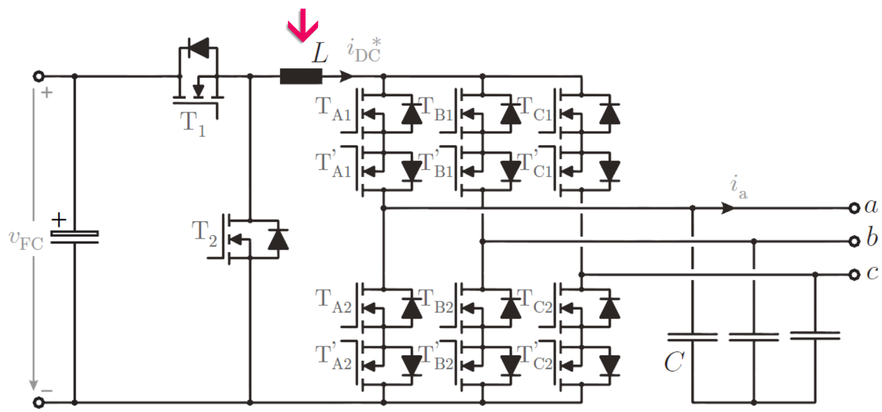


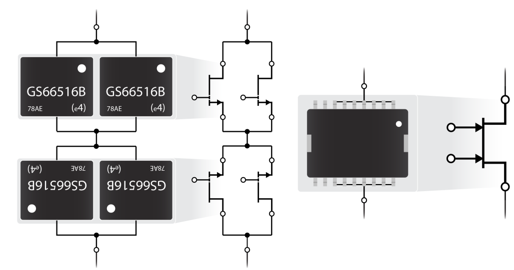
▶ Option → Operation as *Conv. Boost-Type Const. DC-Link Voltage* PWM Rectifier

► Current Source Inverter (CSI) Topologies

- *Phase Modular Concept → Y-Inverter (Buck-Stage / Current Link / Boost-Stage)*
- *3-Φ Integrated Concept → Buck-Stage & Current DC Link Inverter*



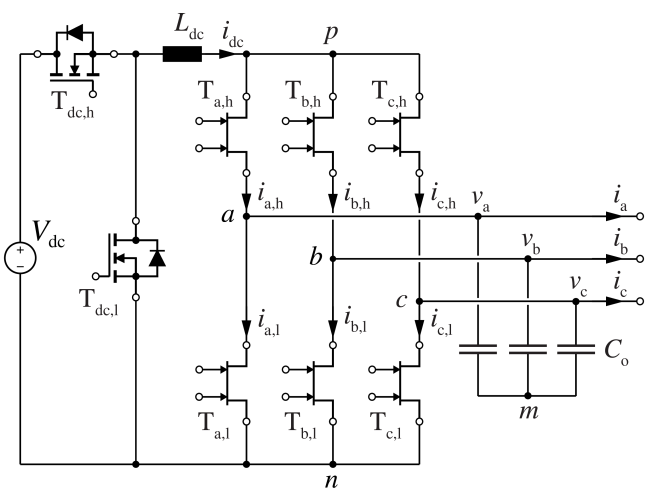


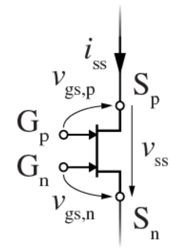


→ Low Number of Ind. Components & Utilization of Bidir. GaN Semicond. Technology

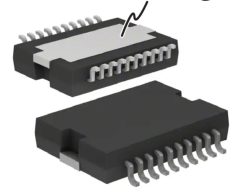
▶ 3-Φ –Integrated Buck-Boost CSI (1)

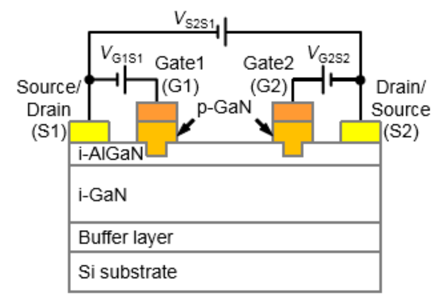
- Basic Topology Proposed in 1984 / Ph.D. Thesis of K.D.T Ngo
- Bidir./Bipolar Switches → Positive DC-Side Voltage for Both Directions of Power Flow





Source: Panasonic

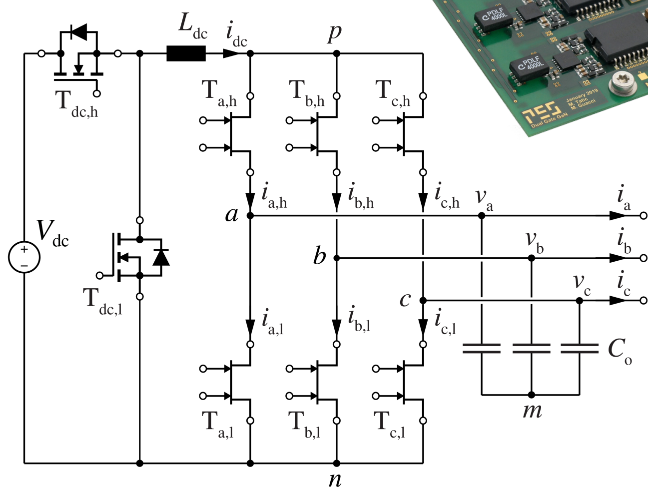


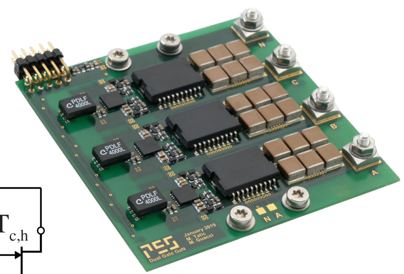


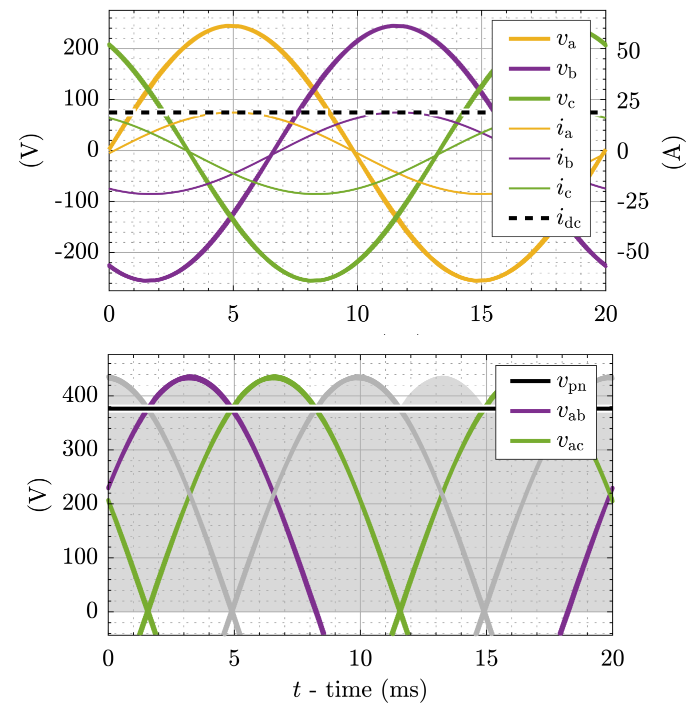
→ Monol. GaN Switches → Factor 4 Improvement in Chip Area Comp. to Discrete Realiz.
→ Also Beneficial for Matrix Converter Topologies

▶ 3-Φ –Integrated Buck-Boost CSI (2)

- *Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates / Full Controllability*
- *Buck-Stage for Const. DC Current / PWM CSI for Output Voltage Control*



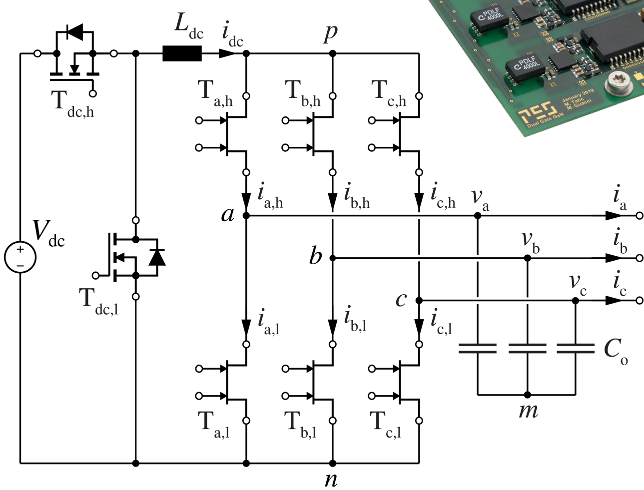


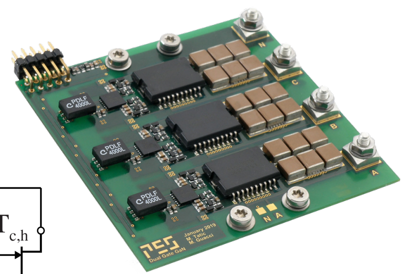


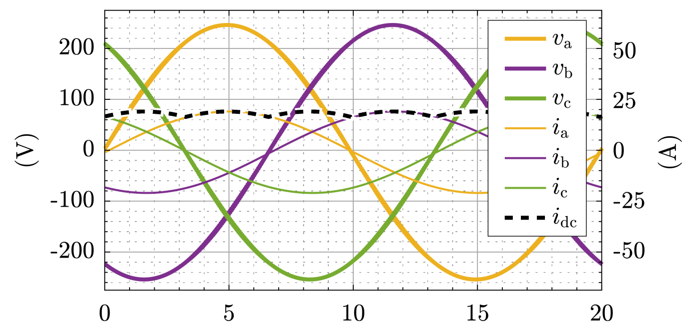
→ *"Synergetic Control" of Buck & Inverter Stage for Red. of Sw. Losses*

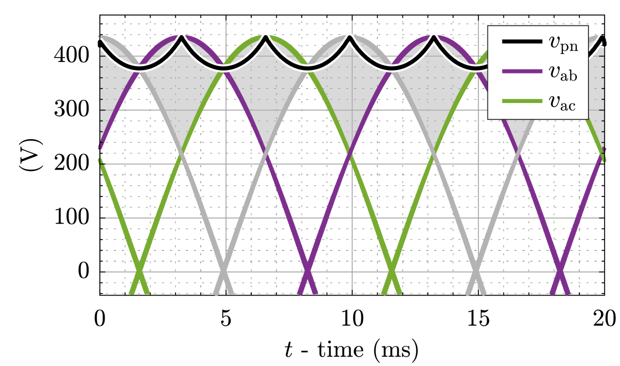
► 3-Φ –Integrated Buck-Boost CSI (3)

- *Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates / Full Controllability*
- *"Synergetic" Variable DC Current Control of Buck Stage & Inverter Stage Clamping*







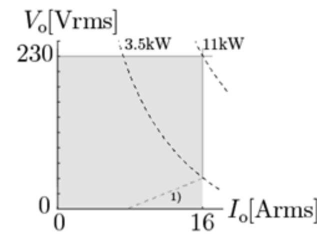


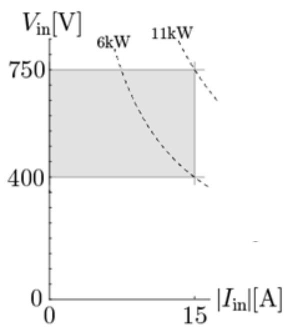
→ *Experimental Analysis in Progress (Upcoming Publication @ PEDG 2019)*

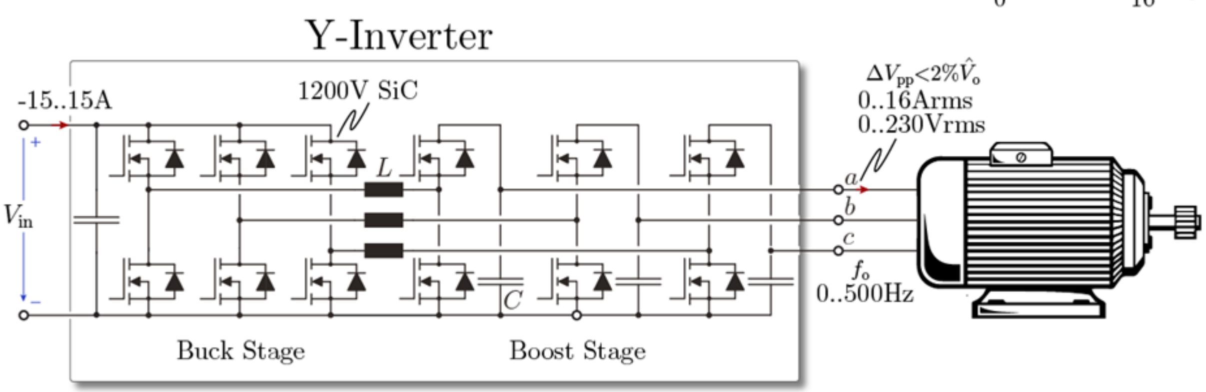
▶ Y-Inverter Prototype (a)

- *Demonstrator Specifications*

- Wide Input Voltage Range → 400…750V_{DC}
- Max. Input Current → ± 15A







- Max. Output Power → 6…11 kW
- Output Frequency Range → 0…500Hz
- Output Voltage Ripple → 3.2V Peak-to-Peak (incl. Add. Output Filter)

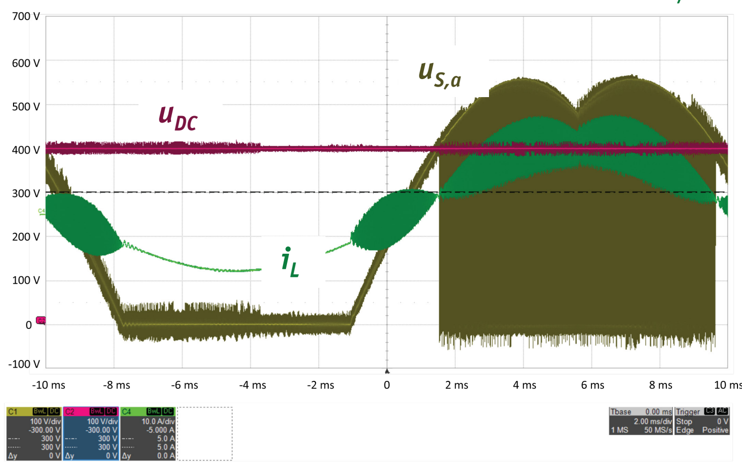
▶ Y-Inverter Prototype (c)

- *Measurement Results*

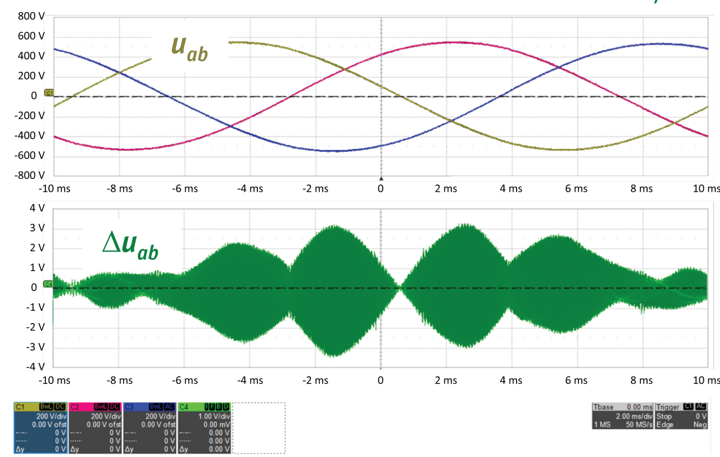
U_{DC}= 400V
U_{AC}= $400V_{rms}$ (Motor Line-to-Line Voltage)
f_0= 50Hz
f_S = 100kHz / DPWM

P = 6.5kW

100V/div
10A/div



200V/div
1V/div

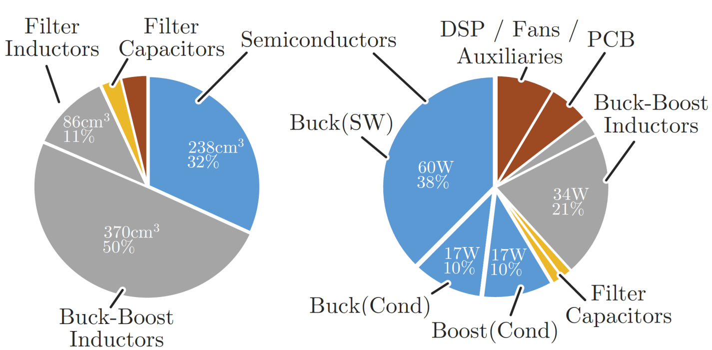


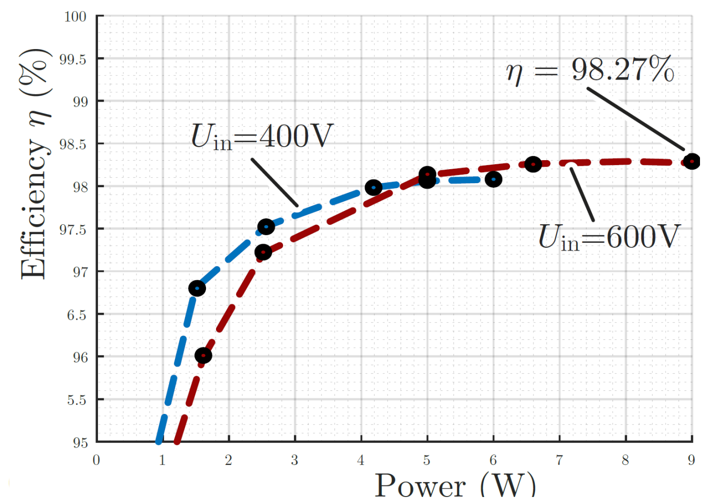
→ *Line-to-Line Output Voltage Ripple < 3.2V*

▶ Y-Inverter Prototype (d)

- **Demonstrator Performance – Efficiency over Output Power @ Given Input Voltage**

U_{DC} = 400V / 600V
U_{AC} = 230V_{rms} (Motor Phase Voltage, rms)
f_S = 100kHz

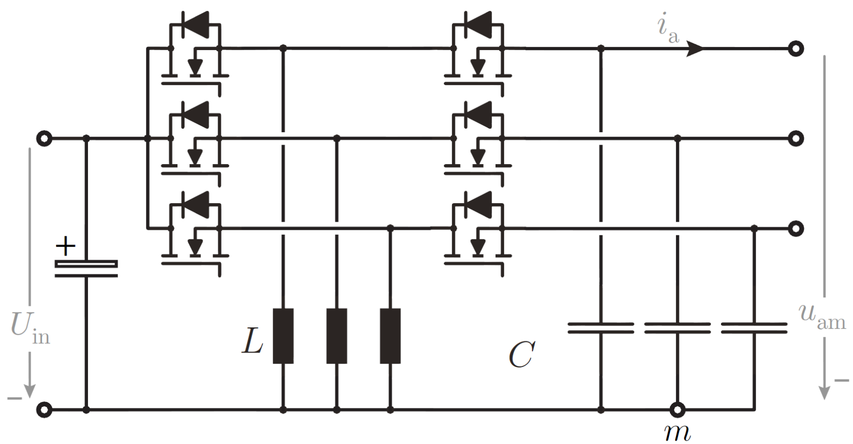




→ *Multi-Level Bridge Leg Structure for Ind. Comp. Volume Reduction*

▶ Alternative Topology

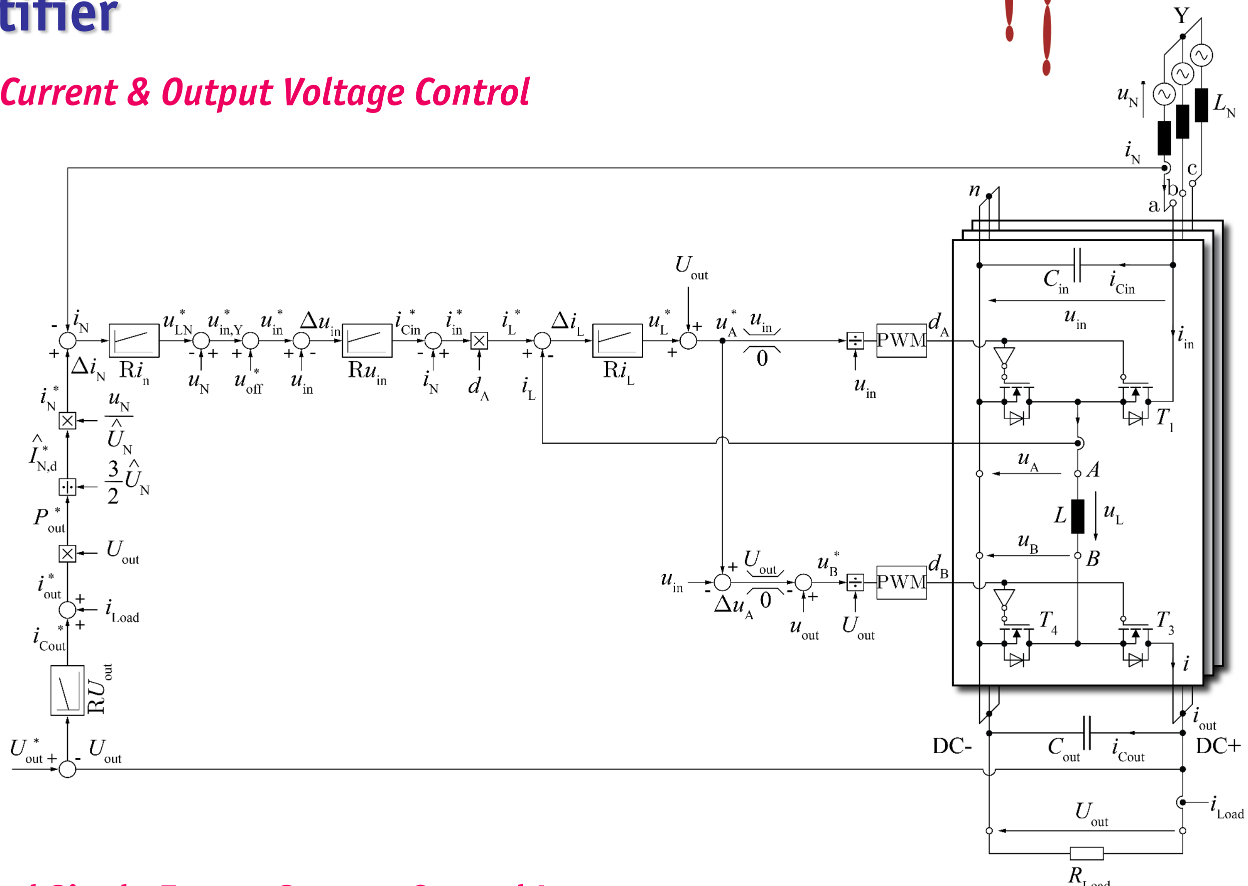
- *Phase Modules Based on 2-Switch Buck+Boost Topology*



■ Lower Number of Switches / Higher Component Stresses → *Low Power Applications*

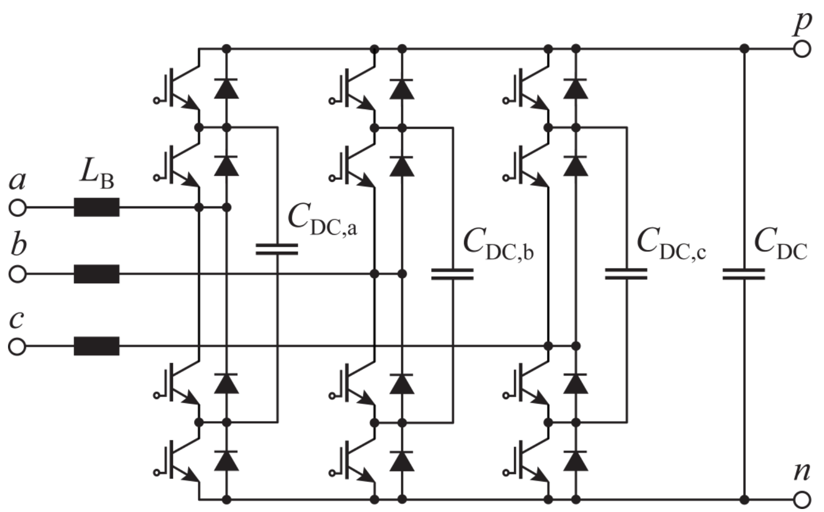
Y - Rectifier

- *Input Current & Output Voltage Control*



- Cascaded Single Energy Storage Control Loops
- Seamless Transition between Boost- & Buck-Mode → "Democratic" Control

▶ Three-Level Flying Capacitor (FC) Boost-Type Rectifier System



+ Lower Number of Components (per Voltage Level)
+ For Three-Level Topology only Two Output Terminals

− Volume of Flying Capacitors
− No Standard Industrial Topology