ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Three-Phase Unity Power Factor Mains Interfaces of High Power EV Battery Charging Systems

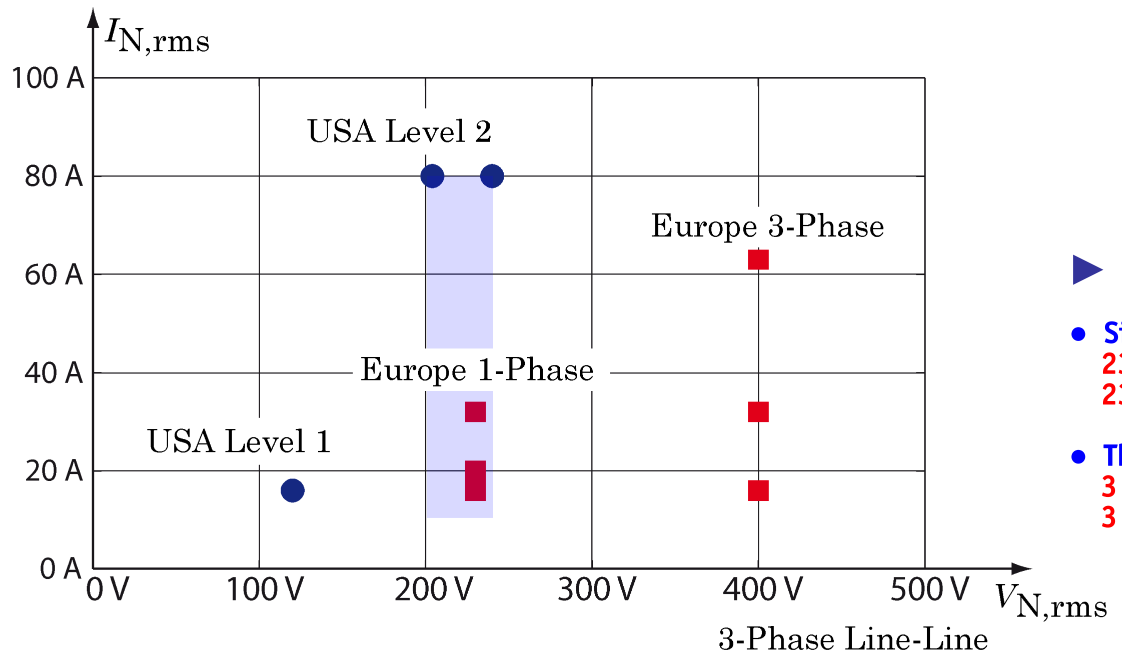
M. Hartmann, T. Friedli and J. W. Kolar
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
hartmann@lem.ee.ethz.ch, www.pes.ee.ethz.ch

Outline

Electrical Ratings of EV Chargers

▶ USA (SAE J1772 Definition)

- **Level 1 Charging**
  - Single-Phase AC Connection
  - On-Board Charger
  - 120 VAC, 16 A → 1.92 kW
- **Level 2 Charging**
  - Single-Phase AC Connection
  - On-Board Charger
  - 204 – 240 VAC, ≤ 80 A → 19.2 kW
- **Level 3 Charging**
  - DC Connection
  - Three-Phase Off-Board Charger
  - 300 – 600 V_{DC}, ≤ 80 A → 240 kW



▶ Europe On-Board Charger

- Single-Phase AC Connection
  230 VAC, 16 / 32 A → 3.68 / 7.4 kW
  230 VAC, 20 A → 4.6 kW
- Three-Phase AC Connection
  3 x 400 VAC, 16 / 32 A → 11 / 22 kW
  3 x 400 VAC, 63 A → 44 kW

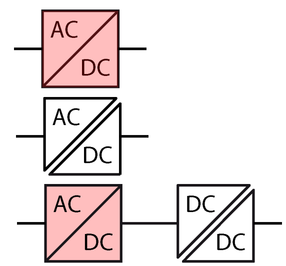
EV Charging – Power Electronics Topologies (I)

■ Basic Requirements

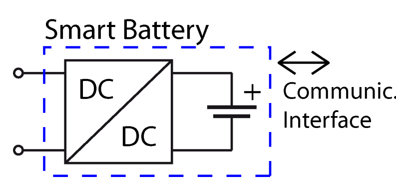
- Wide Input/Output Voltage Range – Voltage Adaption
- Mains Side Sinusoidal Current Shaping
- Isolation of Mains and Battery (?)
- Output Battery Current Control
- Maintainability (No Inverter/Motor Integration)

■ Basic Topologies

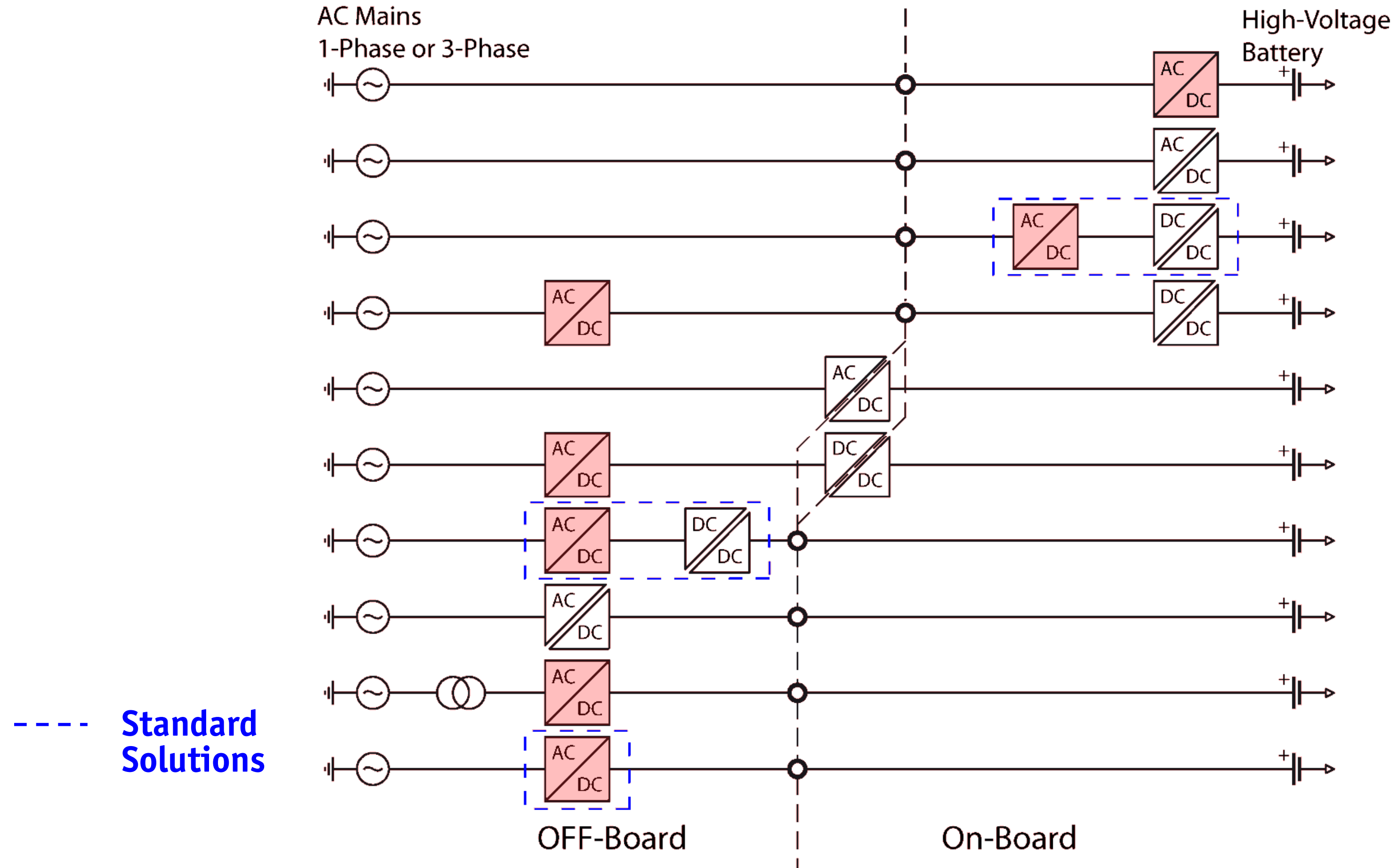
- Non-Isolated
- Isolated Single-Stage (Matrix-Type)
- Isolated Two-Stage



- Battery could Integrate a DC/DC Conv. & Communication Interface (Monitoring, Distributed Control – *SMART Battery*)

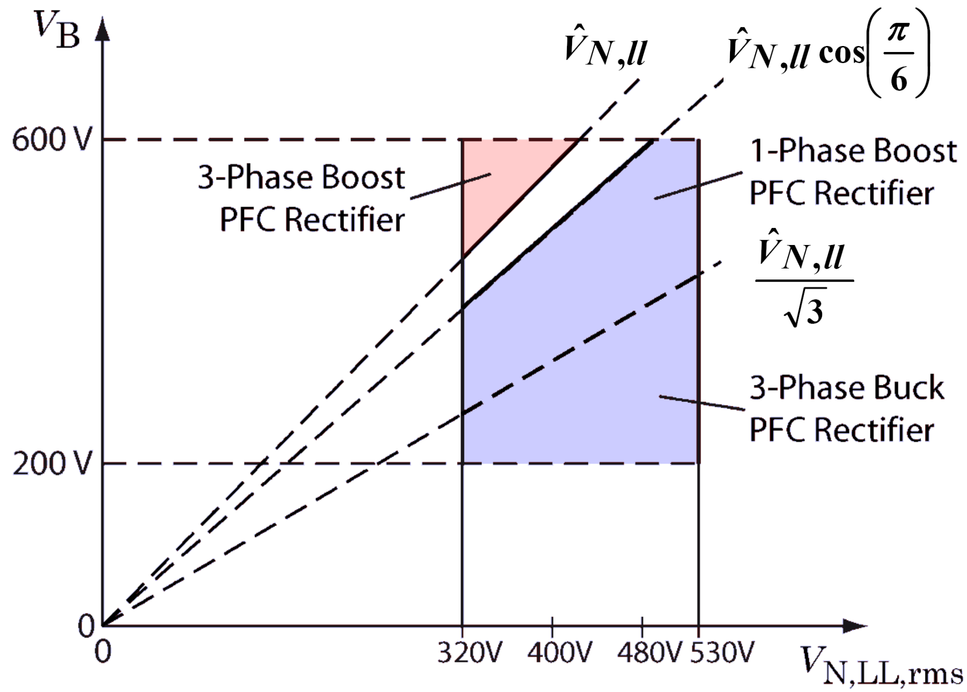


EV Charging – Power Electronics Topologies (II)



Operating Range of 3-Phase PFC Rectifier Systems

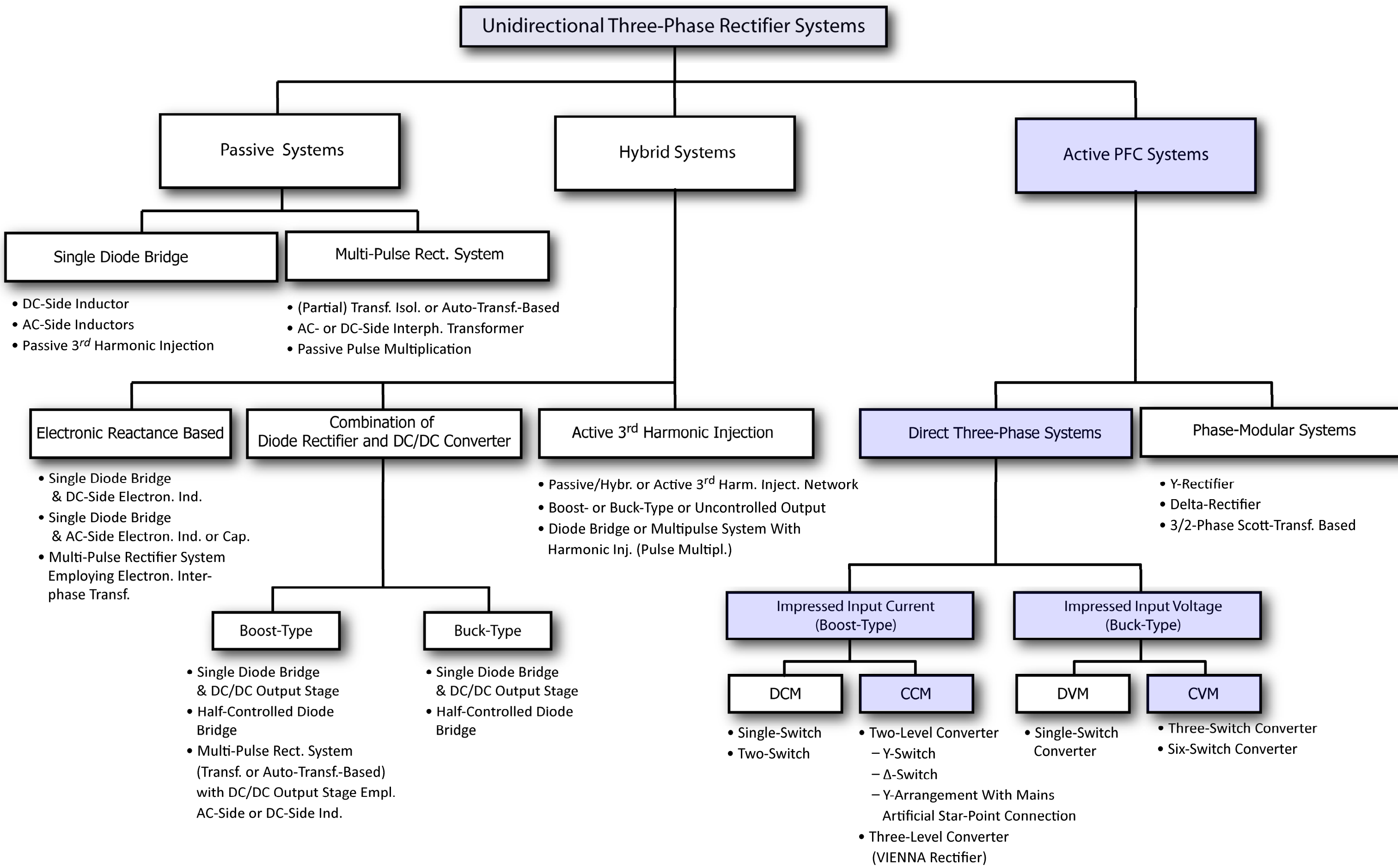
- Boost Type
- Buck Type



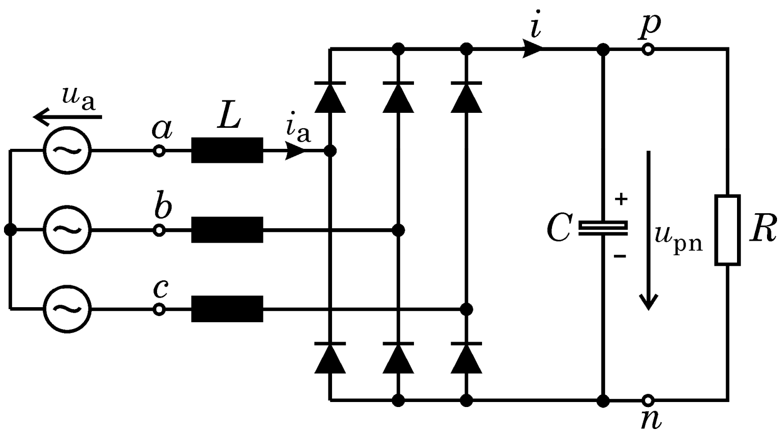
V_B .... Battery Voltage
$V_{N,ll,rms}$ ... RMS Value of Mains Line-to-Line Voltage

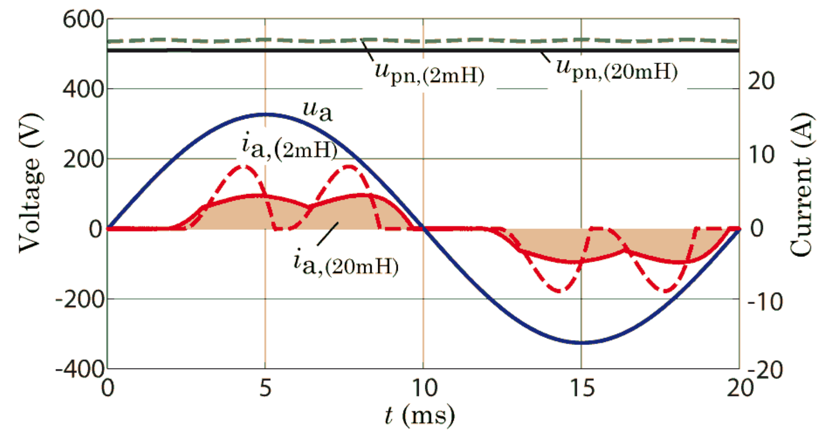
3ph. PFC Rectifier Topologies

Classification of Unidirectional 3ph. Rectifier Systems



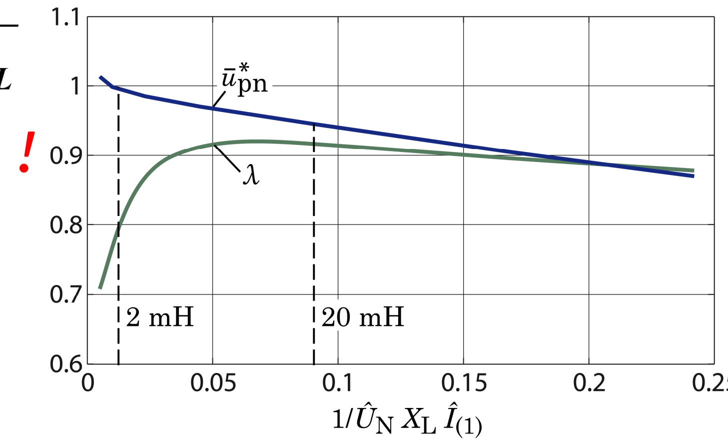
Diode Bridge Rectifier / AC-Side Inductor & Output Capacitor





U_{LL} = 3 x 400 V
f_N = 50 Hz
P_o = 2.5 kW (R=125 Ω)
C = 1 mF
L = 2 mH; 20 mH

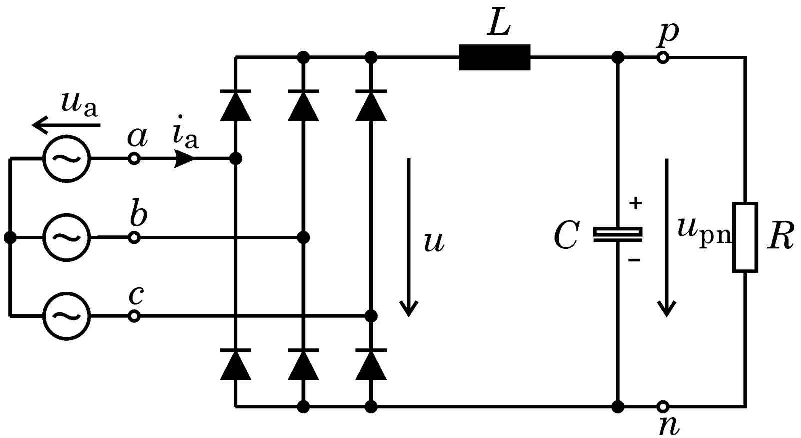
$$\bar{u}^*_{pn} = \frac{\bar{u}_{pn}}{\frac{\pi}{3}\hat{U}_{N,LL}}$$

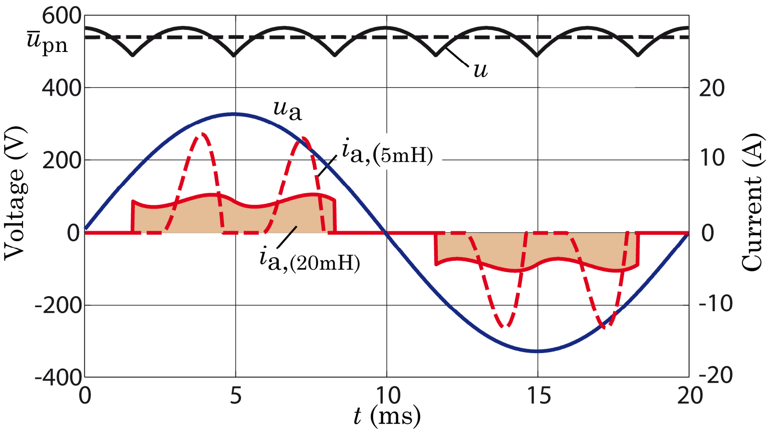


▶ Power Factor

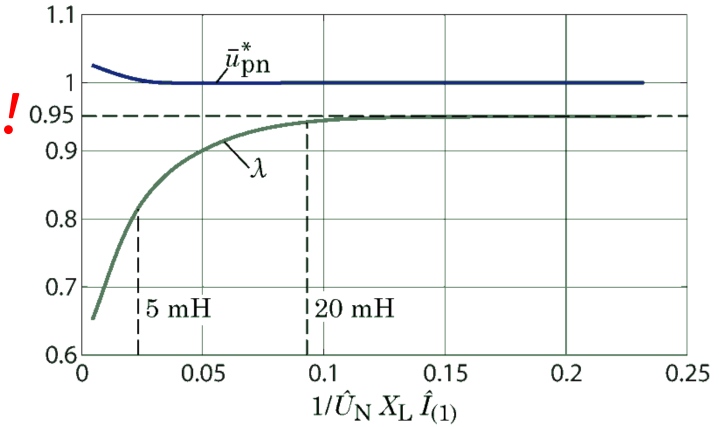
$$\lambda = \frac{P}{S} = \frac{I_{(1)}}{I}\cos(\varphi_1) = \frac{1}{\sqrt{1+THD_I{}^2}}\cos(\varphi_1)$$

Diode Bridge Rectifier / DC-Side Inductor & Output Capacitor



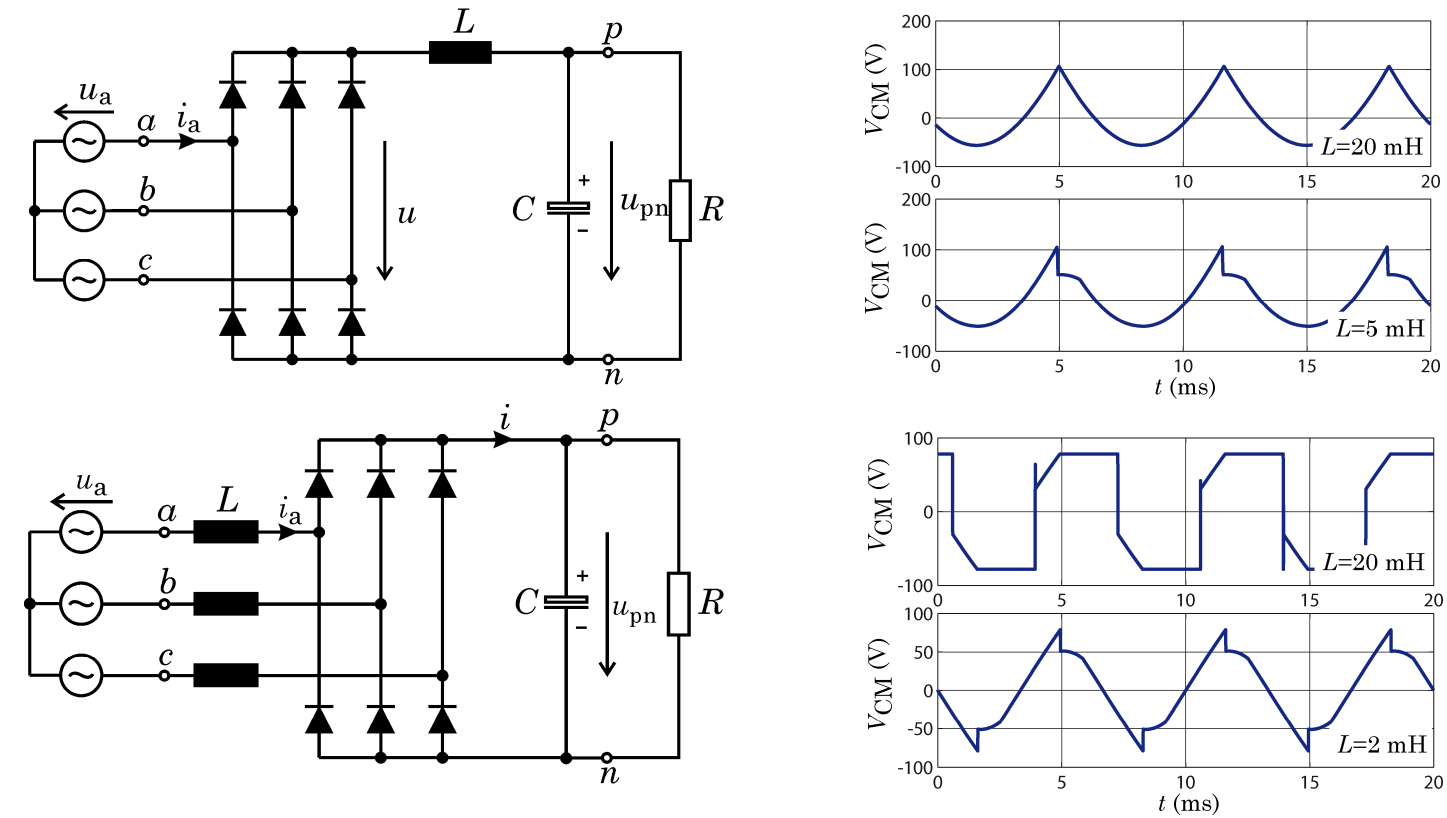


$$\bar{u}^*_{pn} = \frac{\bar{u}_{pn}}{\frac{\pi}{3}\hat{U}_{N,LL}}$$!



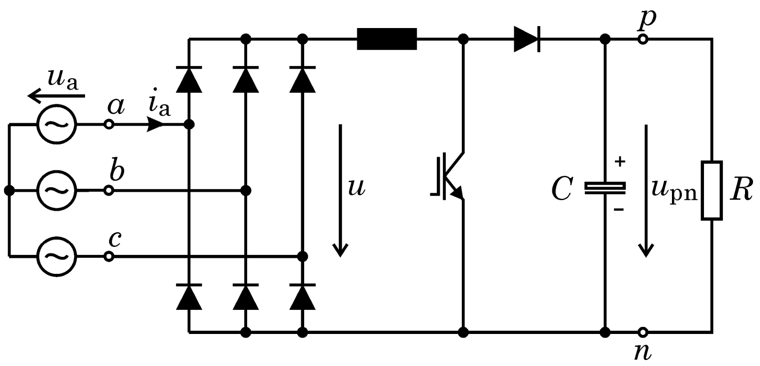
U_{LL} = 3 x 400 V
f_N = 50 Hz
P_o = 2.5 kW (R=125 Ω)
C = 1 mF
L = 5 mH; 20 mH

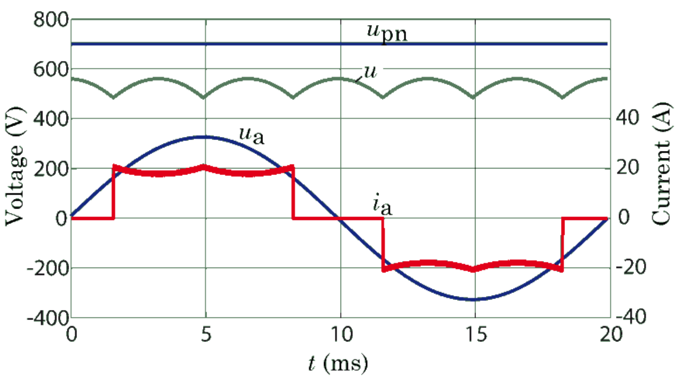
3-ph. Rectifier Common Mode Output Voltage



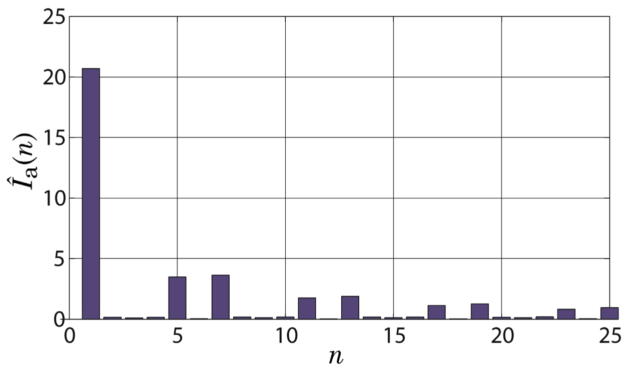
- **Output shows Low-Frequency Common Mode Voltage; Load / Battery cannot be Connected to Ground (Isolation Required)**

Improvement I - Controlled Output Voltage





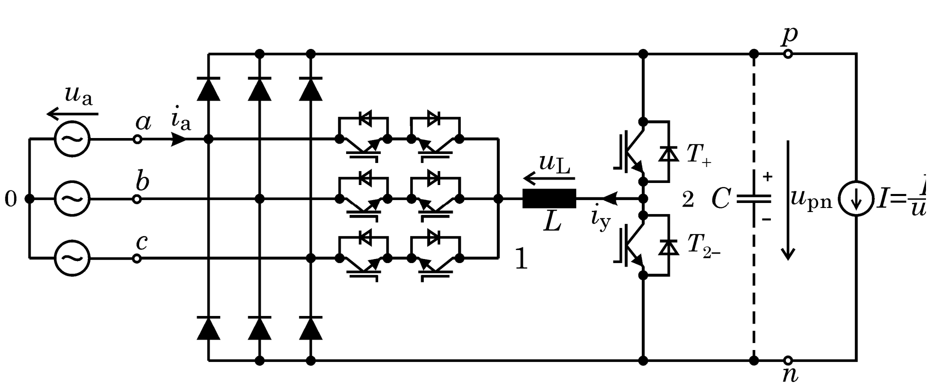
U_{LL} = 3 x 400 V
P_{out} = 10 kW



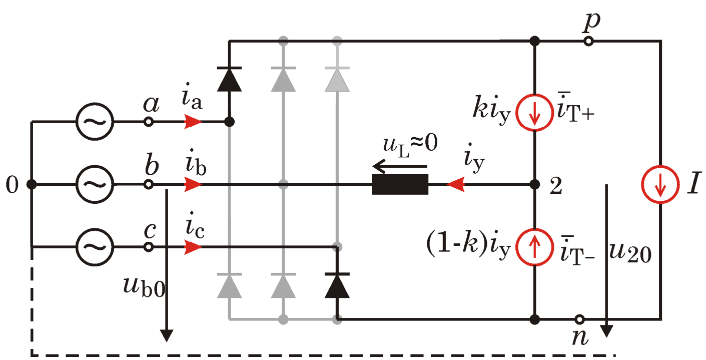
▶ Remaining Disadvantages

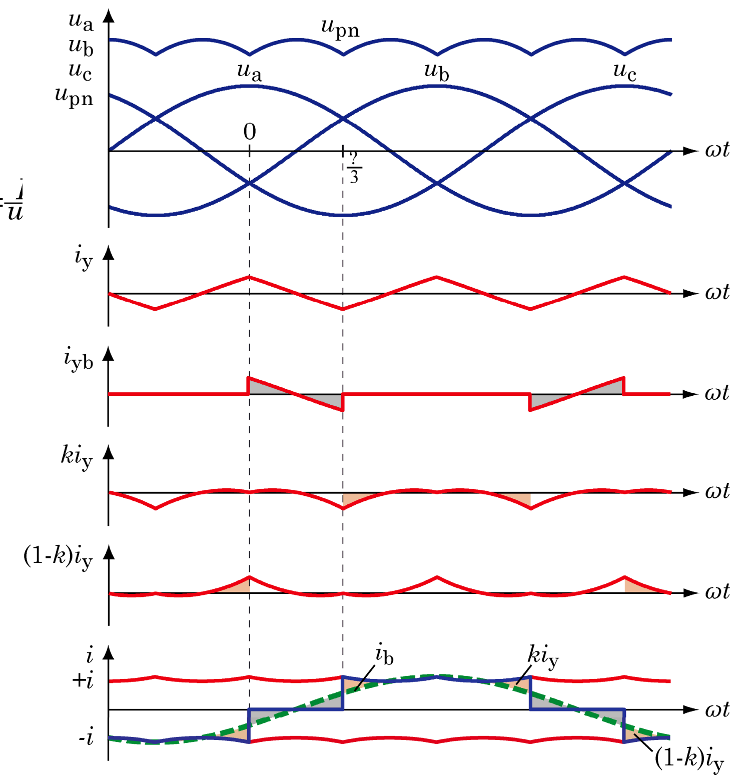
- Block Shaped Mains Currents
- Maximum Power Factor λ = 0.952
- Input Current Distortion THD = 32 %

Improvement II - Purely Sinusoidal Mains Current



$$\omega t \in \left[0, \frac{\pi}{3}\right]$$

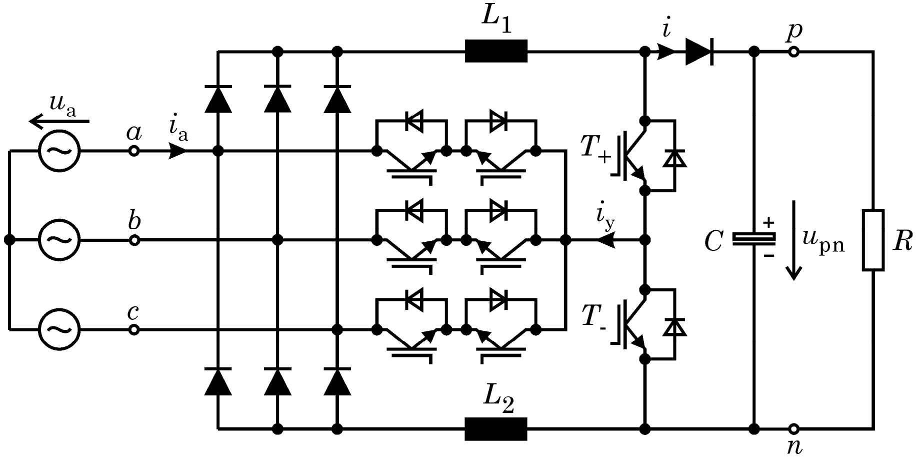


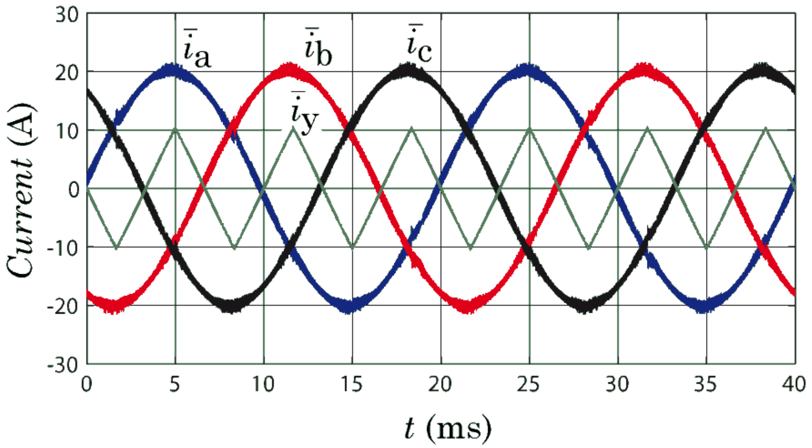


▶ **Remaining Disadvantage** - **No Output Voltage Control**

Combination of *Improvements I & II*

- Boost-Type Topology





+ Controlled Output Voltage
+ Purely Sinusoidal Mains Current

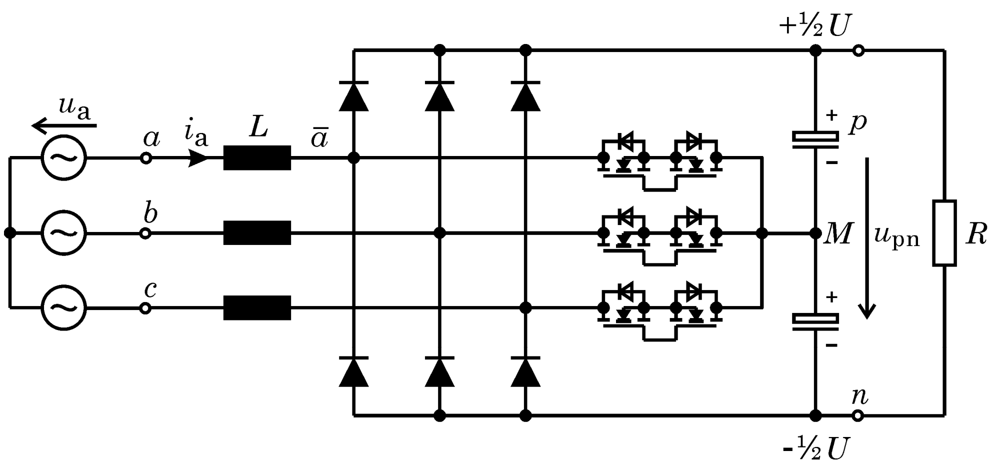
- Power Semiconductors Stressed with Line-to-Line and/or Full Output Voltage

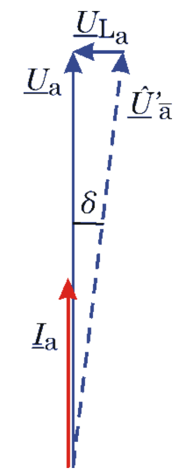
Boost-Type PFC Rectifier System

- VIENNA Rectifier
- Δ–Switch Rectifier

VIENNA Rectifier

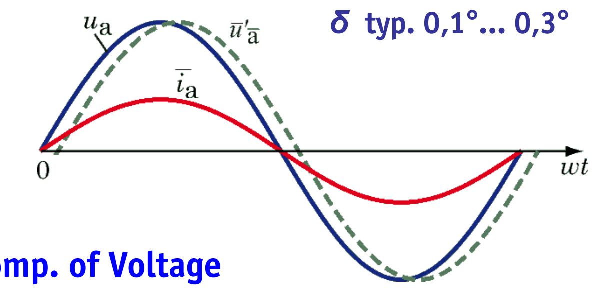
▶ Three-Level Characteristic





- \+ Low Input Inductance Requ.
- \+ Low Switching Losses,
- \+ Low EMI

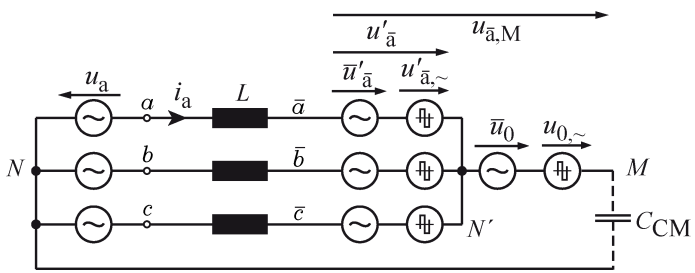
- – Higher Circuit Complexity
- – Control of Output Voltage Center Point Required

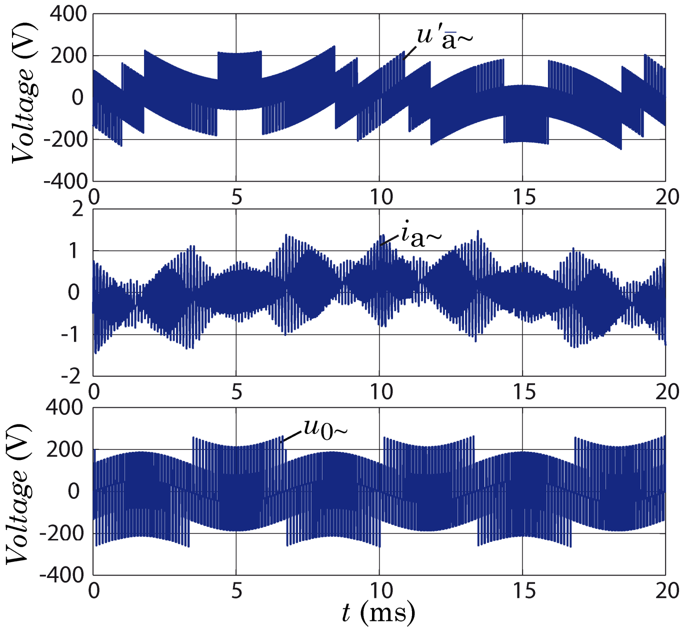


δ typ. 0,1°... 0,3°

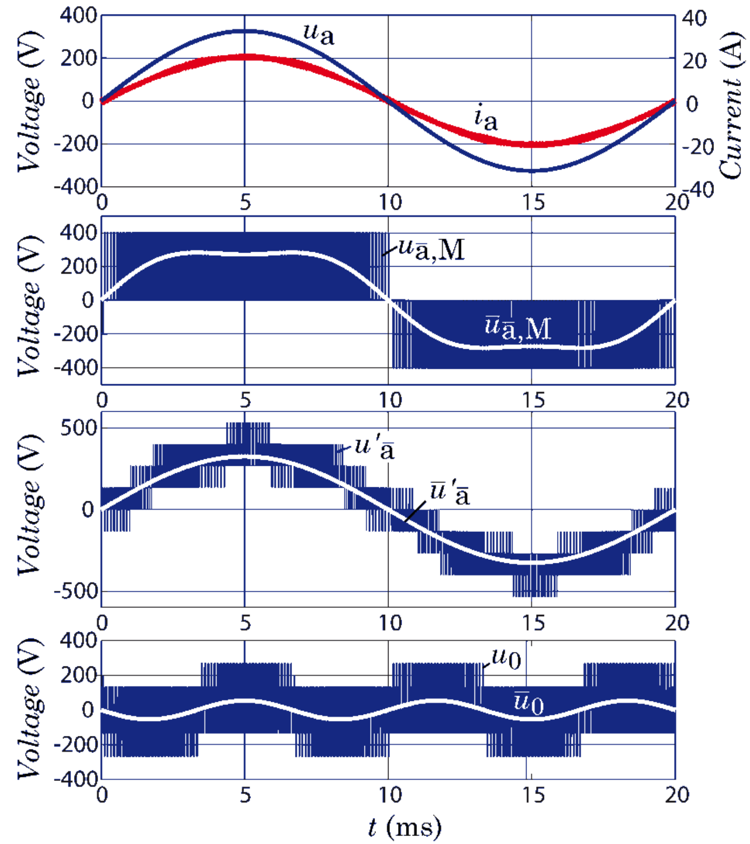
▶ Difference of Mains Voltage (e.g. u_a) and Mains Frequency Comp. of Voltage Formed at Rectifier Bridge Input (e.g. $\bar{u}'_{\bar{a}}$) Impresses Mains Current (e.g. i_a)

Time Behavior of the Components of Voltages $u_{\bar{a}}, u_{\bar{b}}, u_{\bar{c}}$





$$i_a = \bar{i}_a + i_{a\sim}$$

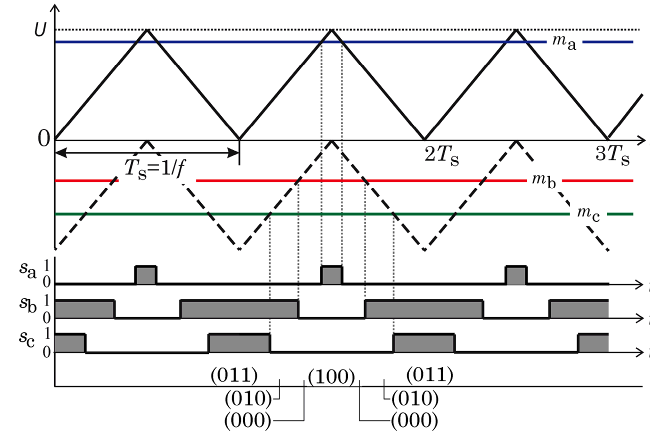


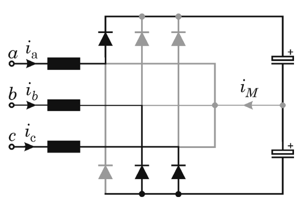
Cond. States within a Pulse Period / i_M-Formation

- Consider e.g. $i_a > 0, i_b < 0, i_c < 0$

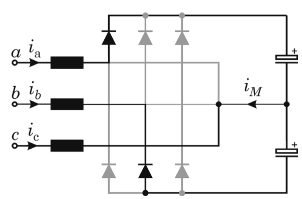
- Switching States (100), (011) are Forming Identical Voltages u'_a, u'_b, u'_c but Inverse Centre Point Currents i_M

- Control of i_M by Changing the Partitioning of Total On-Times of (100) and (011)

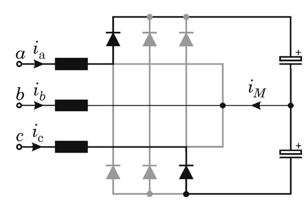




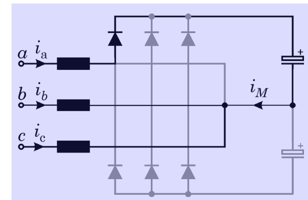
(000), $i_M = 0$



(001), $i_M = i_a$

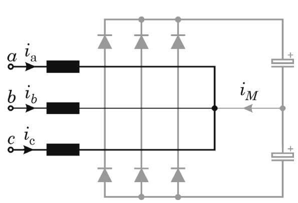


(010), $i_M = -i_b$

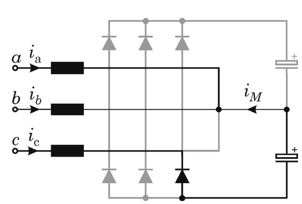


(011), $i_M = i_a$

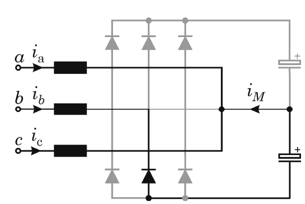
- Corresponding Switching States and Resulting Currents Paths



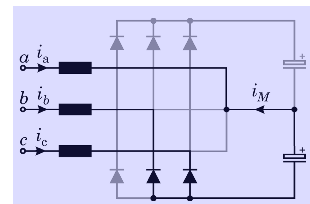
(111), $i_M = 0$



(110), $i_M = i_c$



(101), $i_M = i_b$

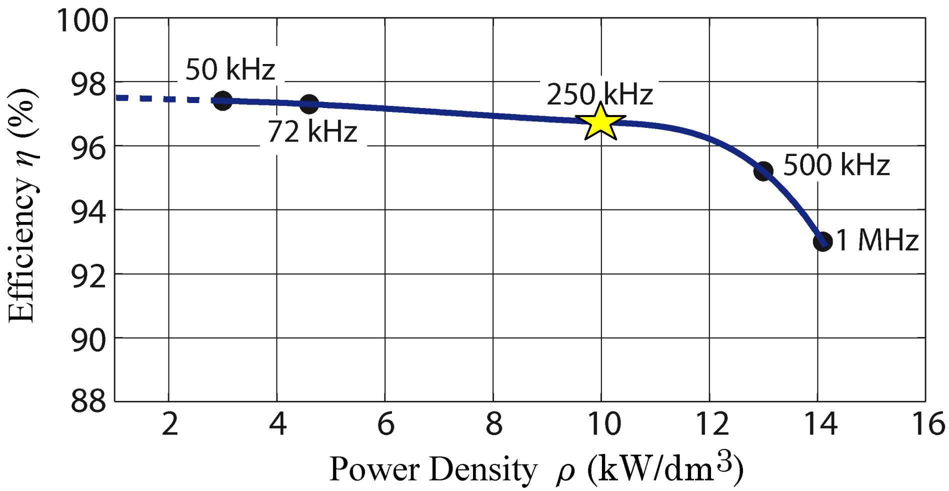


(100), $i_M = -i_a$

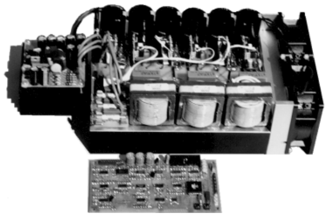
▶ Experimental Analysis

■ Generation 1 – 4 of VIENNA Rectifier Systems

- Switching Frequency of f_S = 250 kHz offers a Good Compromise Concerning Power Density, Weight, Efficiency, and Input Current THD



f_S = 50 kHz
ρ = 3 kW/dm^3



f_S = 72 kHz
ρ = 4.6 kW/dm^3

f_s = 250 kHz
ρ = 10 kW/dm^3
(164 W/in^3)
Weight = 3.4 kg

f_S = 1 MHz
ρ = 14.1 kW/dm^3
Weight = 1.1 kg

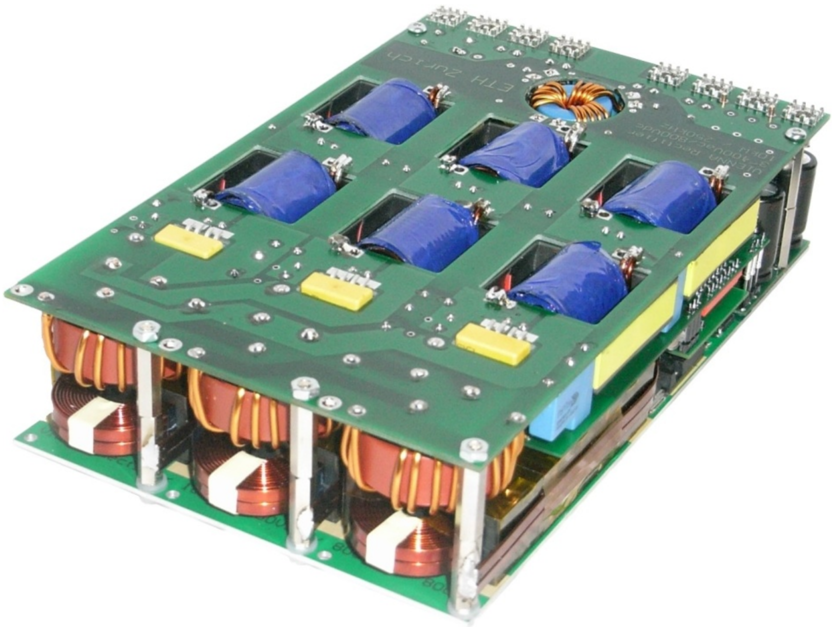
▶ Demonstrator – VR250 (1)

- **Specifications**

  U_{LL} = 3 x 400 V
  f_N = 50 Hz ... 60 Hz or 360 Hz ... 800 Hz
  P_o = 10 kW
  U_o = 2 x 400 V
  f_s = 250 kHz

- **Characteristics**

  η = 96.8 %
  THD_i = 1.6 % @ 800 Hz
  10 kW/dm3
  3.3 kg (≈3 kW/kg)



Dimensions: 195 x 120 x 42.7 mm^3

▶ Demonstrator – VR250 (2)

- **Specifications**

  U_{LL} = 3 x 400 V
  f_N = 50 Hz ... 60 Hz or 360 Hz ... 800 Hz
  P_o = 10 kW
  U_o = 2 x 400 V
  f_s = 250 kHz

- **Characteristics**

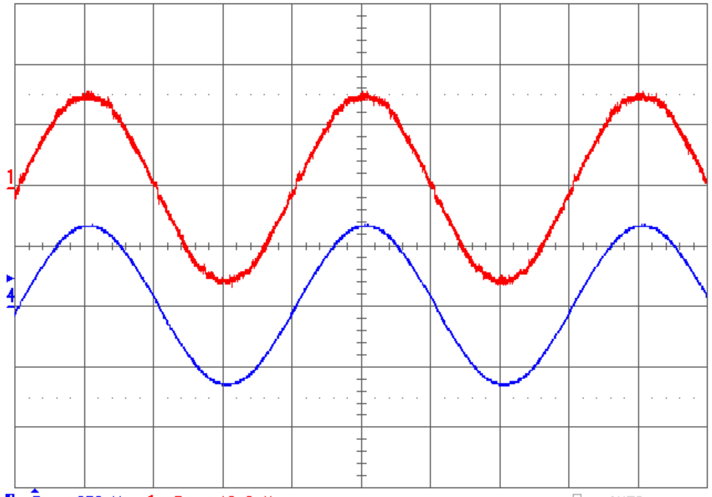
  η = 96.8 %
  THD_i = 1.6 % @ 800 Hz
  10 kW/dm3
  3.3 kg (≈3 kW/kg)

Dimensions: 195 x 120 x 42.7 mm^3

▶ Mains Behavior @ f_N = 50 Hz

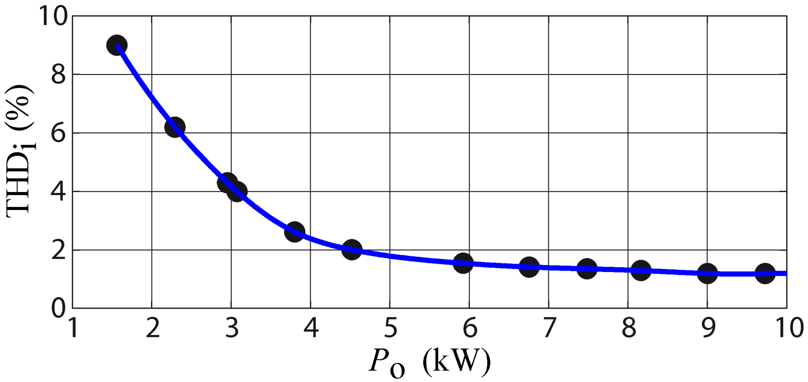
P_0 = 4kW
U_N = 230V
f_N = 50Hz
U_0 = 800V
THD_i = 1.1%

5A/Div
200V/Div
5ms/Div

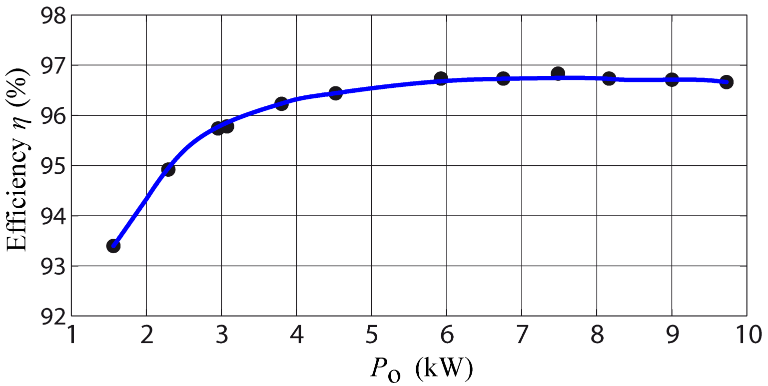


▶ Demonstrator Performance (VR250)

- **Input Current Quality @ f_N = 800 Hz**

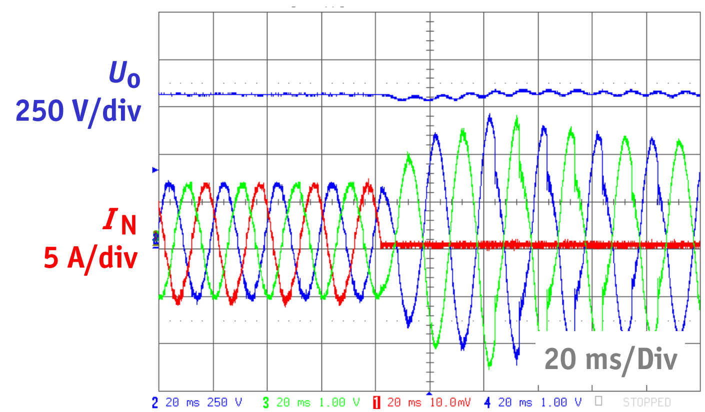


- **Efficiency @ f_N = 800 Hz**

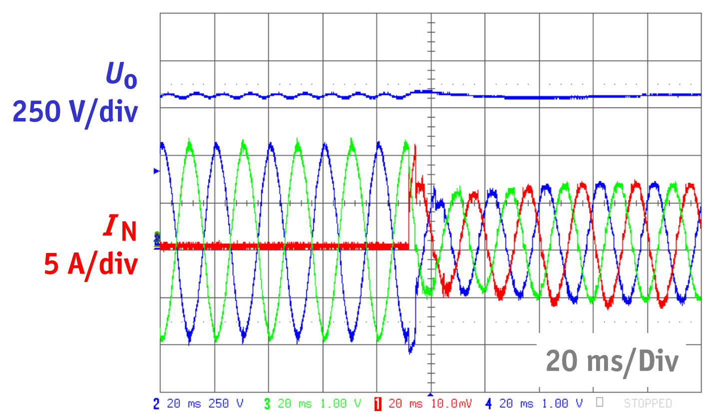


▶ Demonstrator (VR250) Control Behavior

- **Mains Phase Loss**

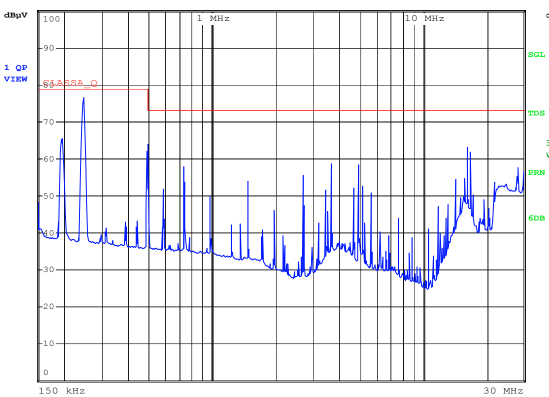


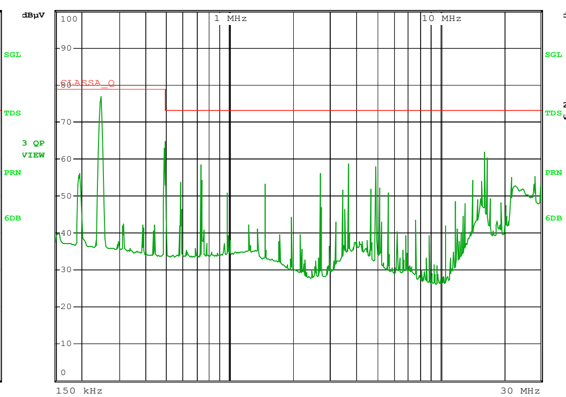
- **Mains Phase Return**

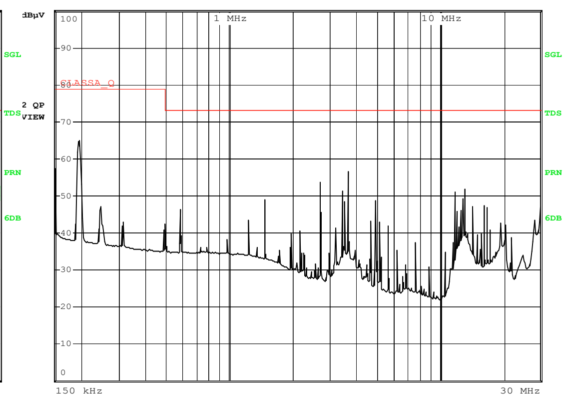


▶ Demonstrator (VR250) EMI Analysis

- **Total Emissions**
- **DM Emissions**
- **CM Emissions**

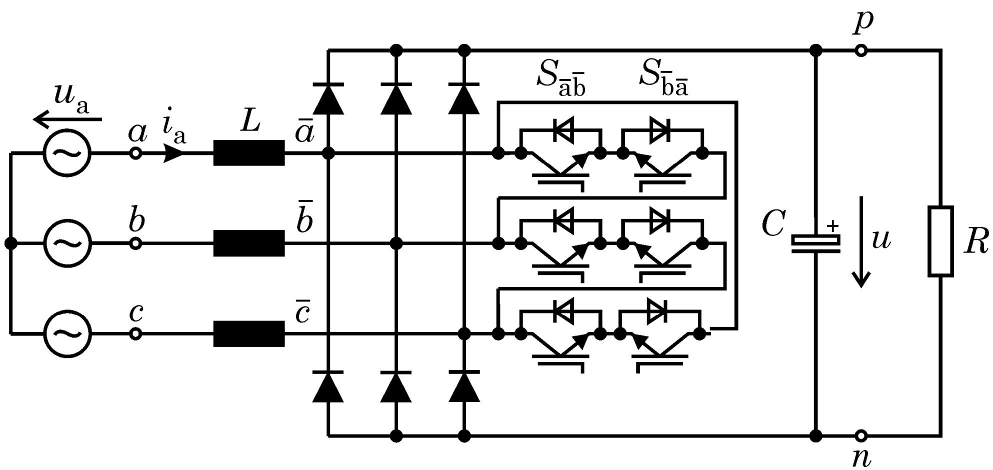




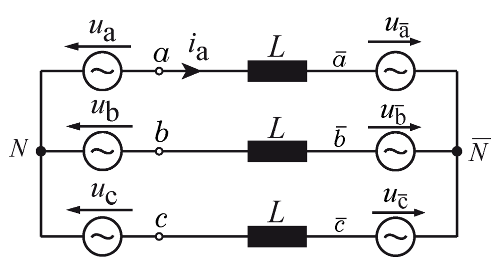


Δ-Switch Rectifier

- **2-Level Characteristic**



AC Side Equivalent Circuit



$$\overline{u}_{\bar{a}\bar{b}} = \overline{u}_{\bar{a}} - \overline{u}_{\bar{b}}$$

$$\overline{u}_{\bar{b}\bar{c}} = \overline{u}_{\bar{b}} - \overline{u}_{\bar{c}}$$

$$\overline{u}_{\bar{c}\bar{a}} = \overline{u}_{\bar{c}} - \overline{u}_{\bar{a}}$$

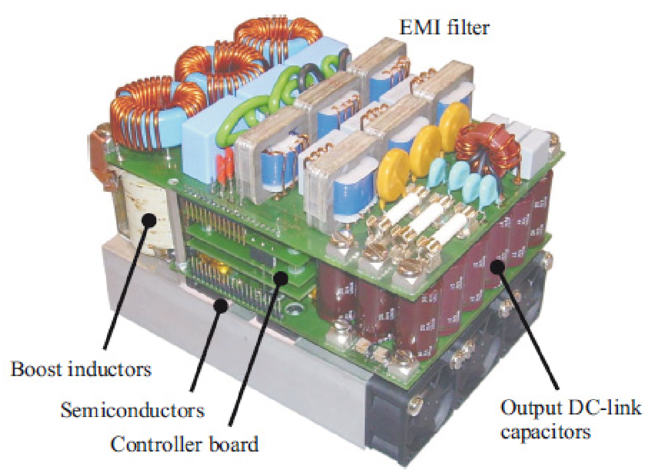
- **Phase Current Control:** Output of the Phase Current Controllers are Transformed into Δ-Quantities

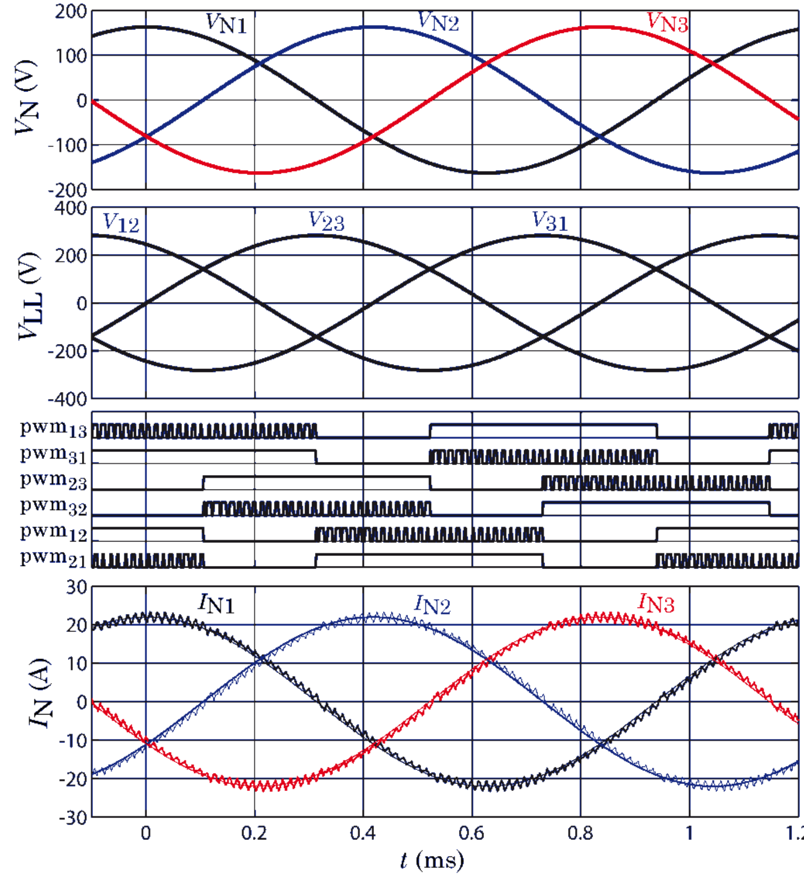
Δ-Switch Rectifier

▶ Modulation

U_{LL} = 115 V (400Hz)
P_o = 5 kW
U_o = 400 V
f_S = 72 kHz

Power Density: 2.35 kW/dm³





Δ-Switch Rectifier

▶ Experimental Analysis

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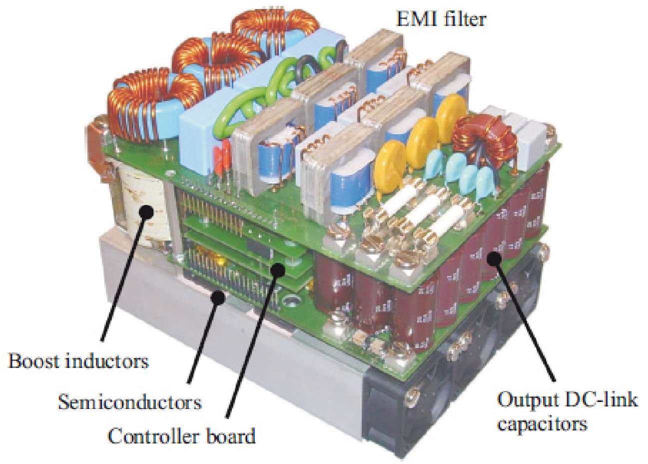
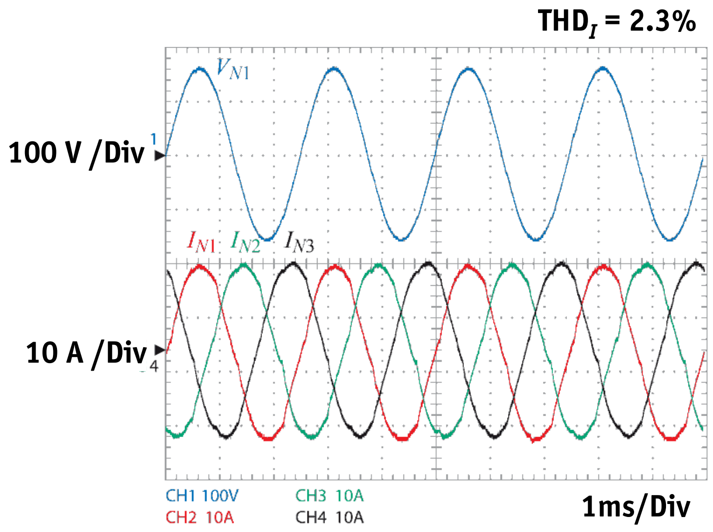


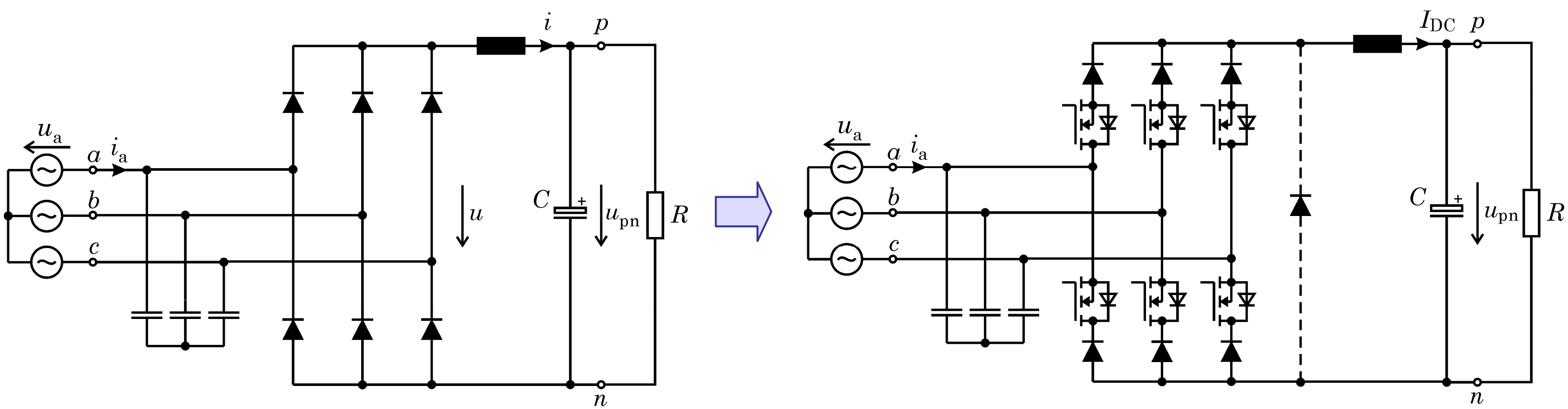


Buck-Type PFC Rectifier System

- *6S-Buck Rectifier*
- *SWISS Rectifier*

6S-Buck Rectifier

► **Derivation of the Circuit Topology - Insertion of Switches in Series to the Diodes**



+ DC Current Distribution to Phases *a*, *b*, *c* can be Controlled
+ Control of Output Voltage $0 \leq u \leq \frac{3}{2}\hat{U}$

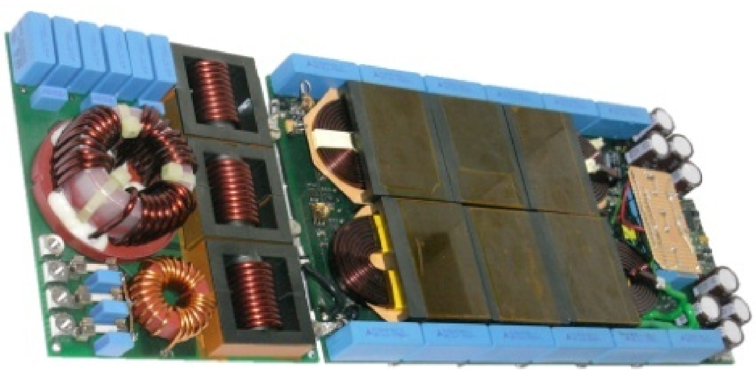
– Pulsating Input Currents / EMI Filtering Requ.
– Relatively High Conduction Losses

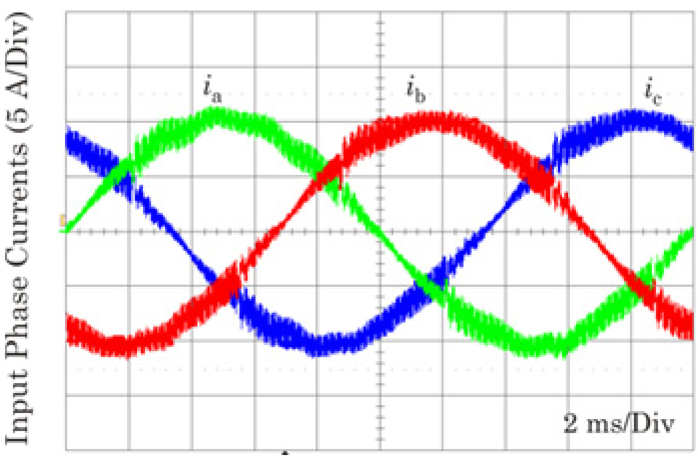
Experimental Results

▶ Ultra-Efficient Demonstrator System

U_{LL} = 3 x 400 V (50 Hz)
P_o = 5 kW
U_o = 400 V
f_s = 18 kHz
L = 2 x 0.65 mH

η = 98.8% (Calorimetric Measurement)





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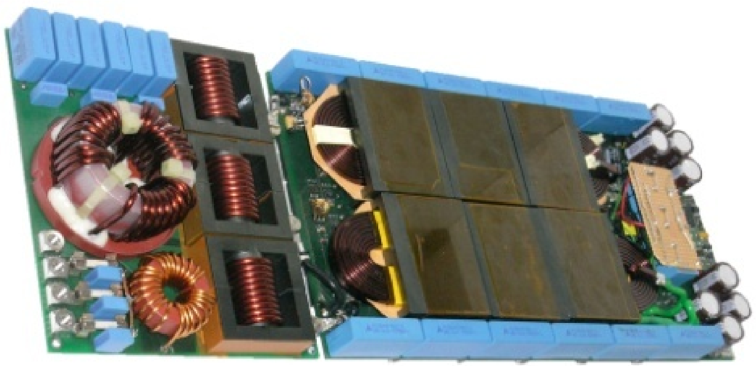
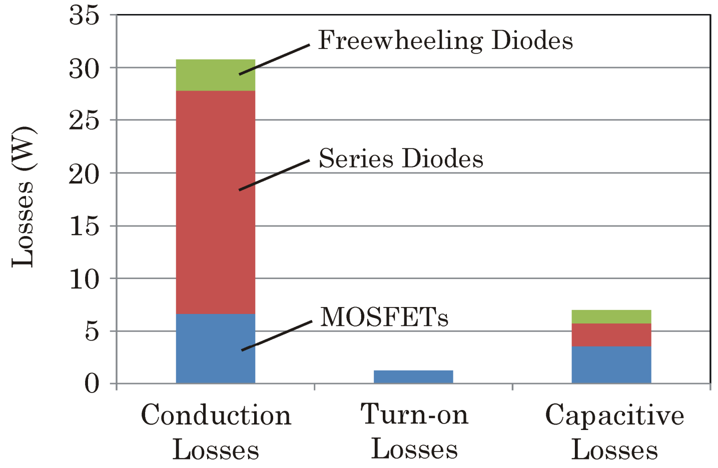
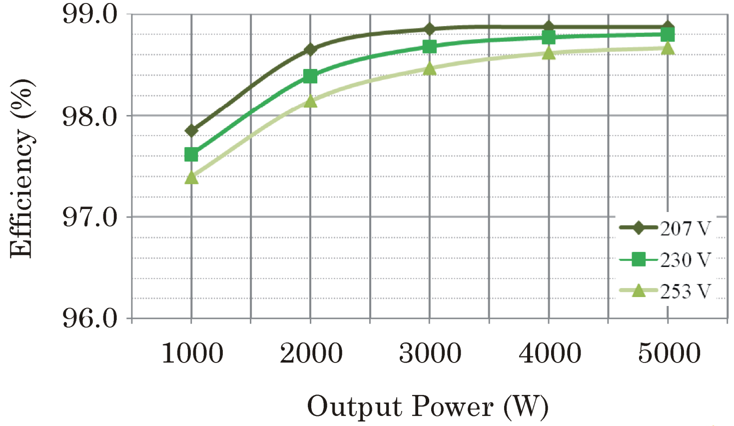
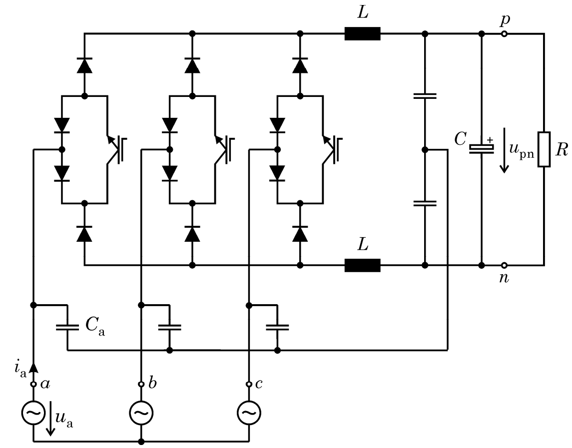




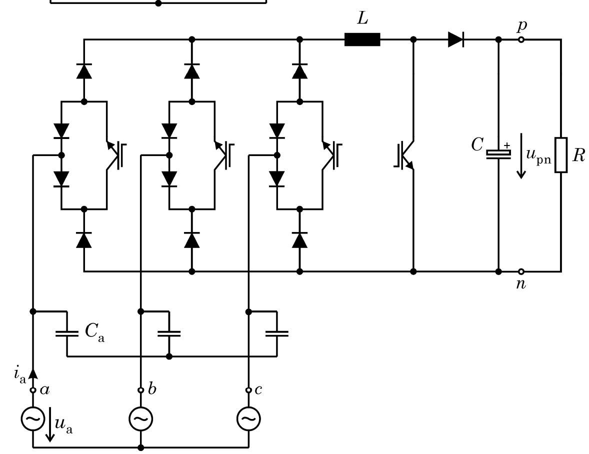


Extensions / Modifications of 6S-Buck Circuit Topology

▶ 3S-Buck / Buck+Boost Topology



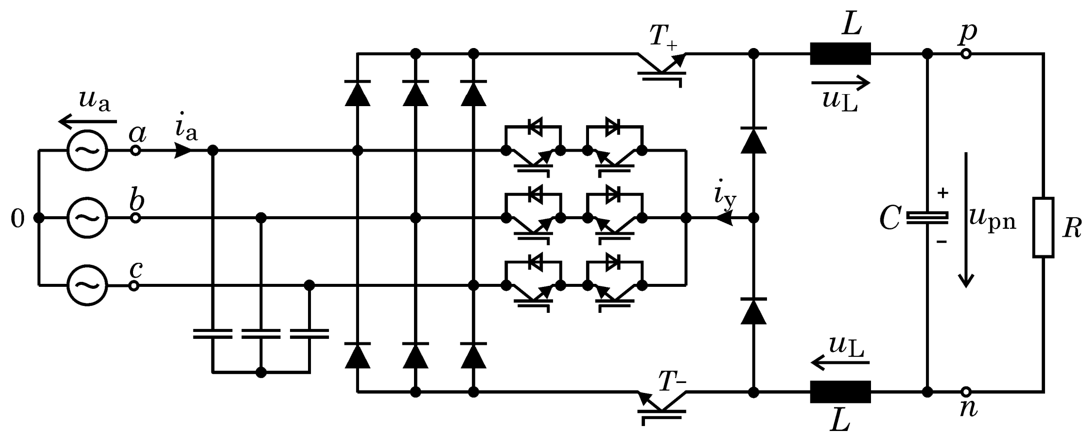
- Internal Filtering of CM Output Voltage Component



- Integration of Boost-Type Output Stage
- Wide Output Voltage Range, i.e. also $U > \frac{3}{2}\hat{U}$
- Sinusoidal Mains Current also in Case of Phase Loss

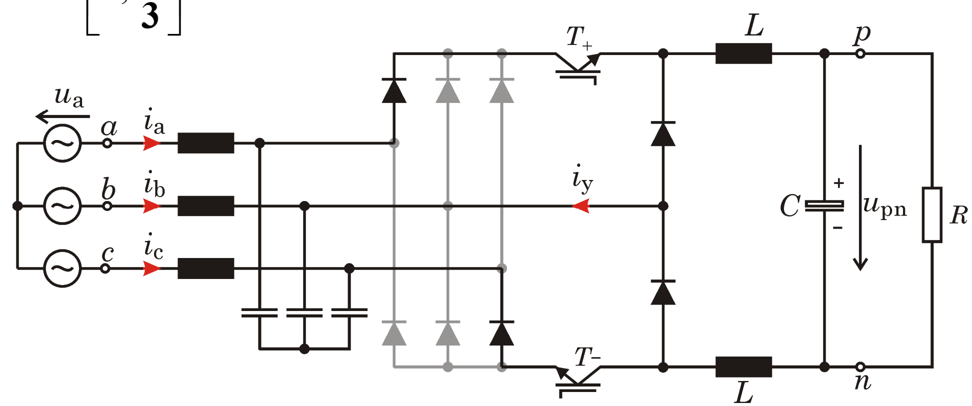
▶ Modifications also for 6-Switch Topology

SWISS Rectifier



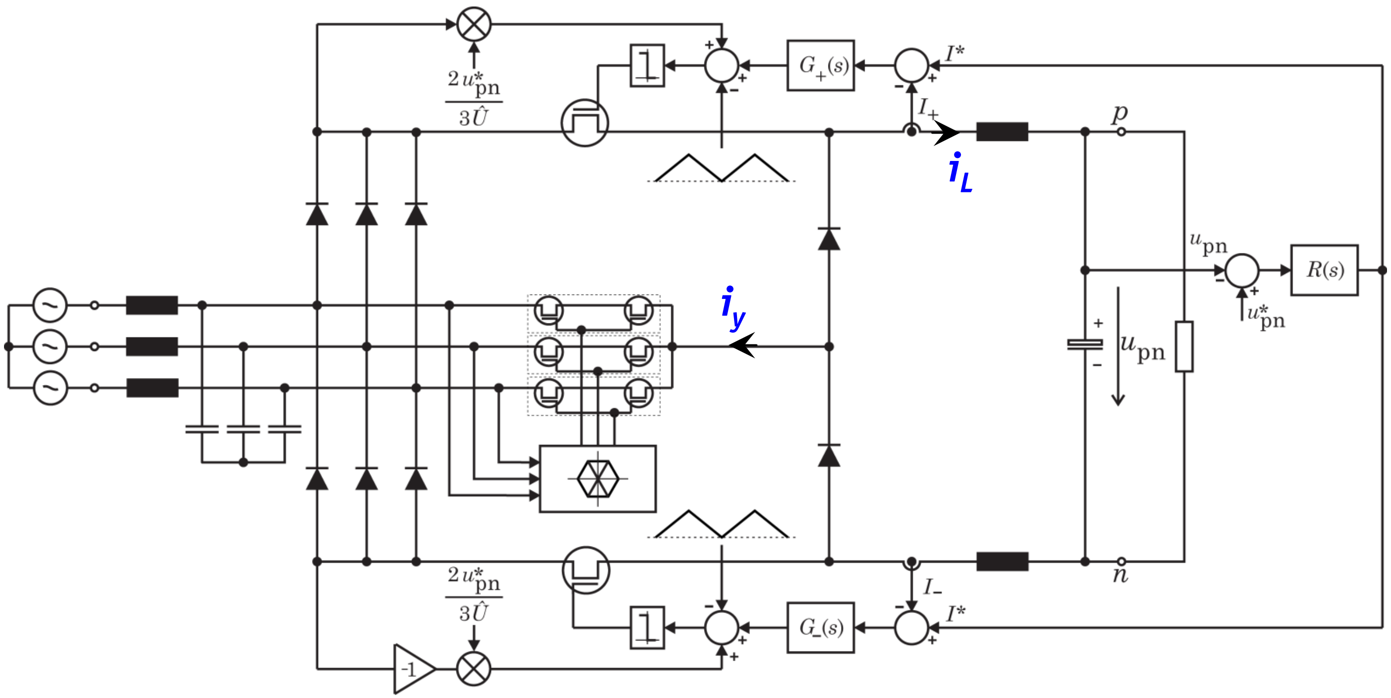
- + Controlled Output Voltage
- + Purely Sinusoidal Mains Current
- + Low Current Stress on the Inj. Current Distribution Power Transistors / High Eff.
- + Low Control Complexity
- - Higher Number of Active Power Semiconductors than Active Buck-Type PWM Rect. (but Only T_+, T_- Operated with Switching Frequency)

$$\omega t \in \left[0, \frac{\pi}{3}\right]$$



SWISS Rectifier

▶ Control Structure

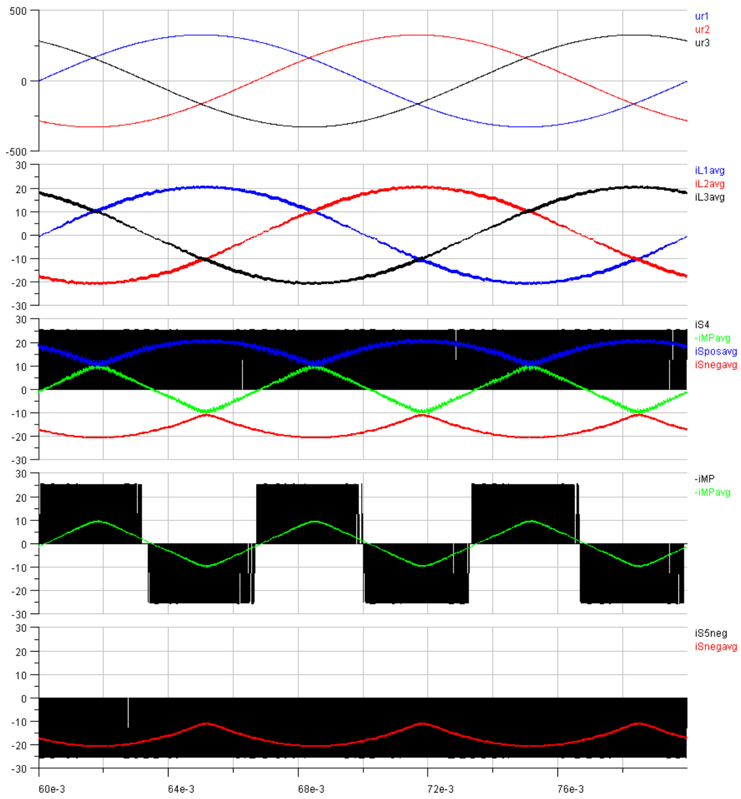


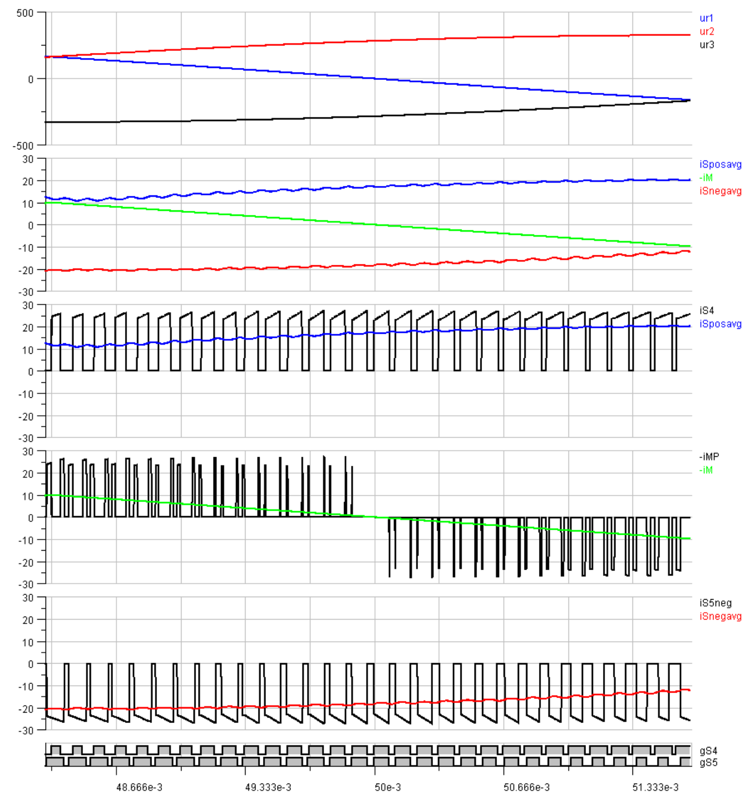
▶ Gating of T_+, T_-: - Synchronous Control Minimizes i_y-Ripple / Maximizes Ripple of i_L
- Interleaving Minimizes Ripple of i_L / Maximizes i_y-Ripple

SWISS Rectifier

$U_{N,LL} = 400\ V_{rms}$
$U_{pn} = 400\ V_{DC}$
$P = 10\ kW$

▶ Simulation Results – Mains Period and 60°-Wide Section





Comparative Evaluation

- VIENNA / Δ-Switch Rectifier
- SWISS / 6S-Buck Rectifier

Performance Indices

▶ Diodes

$$\text{Diode VA - Rating} = \frac{1}{\mu_D} = \frac{\sum_n V_{D,\max,n} I_{D,\max,n}}{P_o}$$

$$\text{Diode Conduction Losses} = \frac{\sum_n I_{D,avg,n}}{I_o}$$

▶ Transistors

$$\text{Transistor VA - Rating} = \frac{1}{\mu_T} = \frac{\sum_n V_{T,\max,n} I_{T,\max,n}}{P_o}$$

$$\text{Transistor Conduction Losses} = \frac{\sum_n I_{T,rms,n}}{I_o}$$

$$\text{Transistor Sw. Losses Boost} = \frac{\sum_n I_{T,avg,n} V_{T,n}}{P_o}$$

$$\text{Transistor Sw. Losses Buck} = \frac{\sum_n I_{T,n} V_{T,avg,n}}{P_o}$$

▶ Power Passives

$$\text{Percentage Reactance} = \frac{2\pi f_N I_N L_N}{V_N}$$

$$\text{Rated Inductor Power} = \frac{I_L \Delta I_{L,pkpk} L f_s}{P_o}$$

$$\text{Capacitive Current Stress} = \frac{\sum_n I_{C,rms,n}}{I_o}$$

▶ Conducted Noise (DM, CM)

$$V_{Noise} = V_{DM} + V_{CM} \qquad V_{CM} = \frac{V_a + V_b + V_c}{3}$$

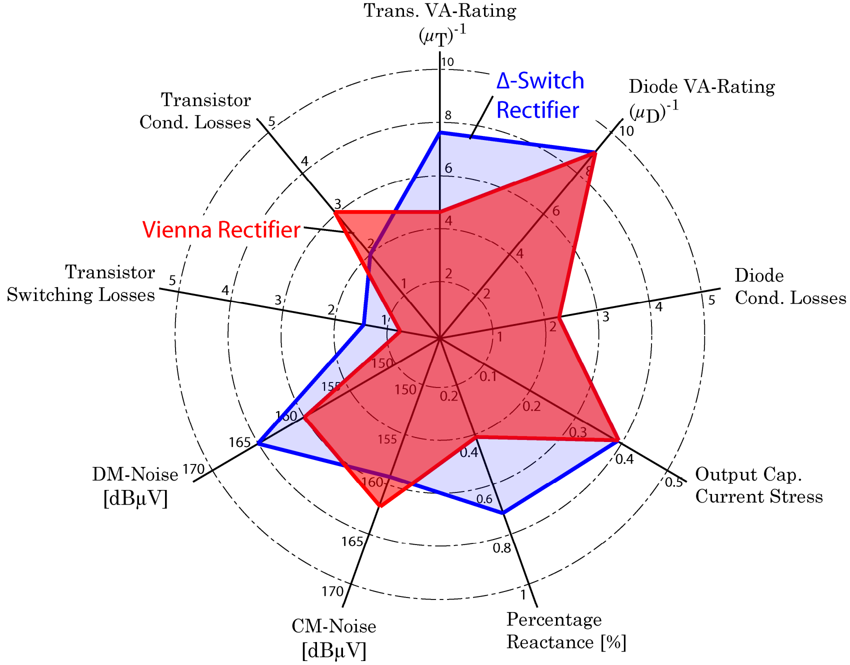
$$V_{DM}^2 = V_{DM,tot}^2 - V_{N,rms}^2$$

$$V_{CM}^2 = V_{CM,tot}^2 - V_{CM,LF}^2$$

Comparative Evaluation (I)

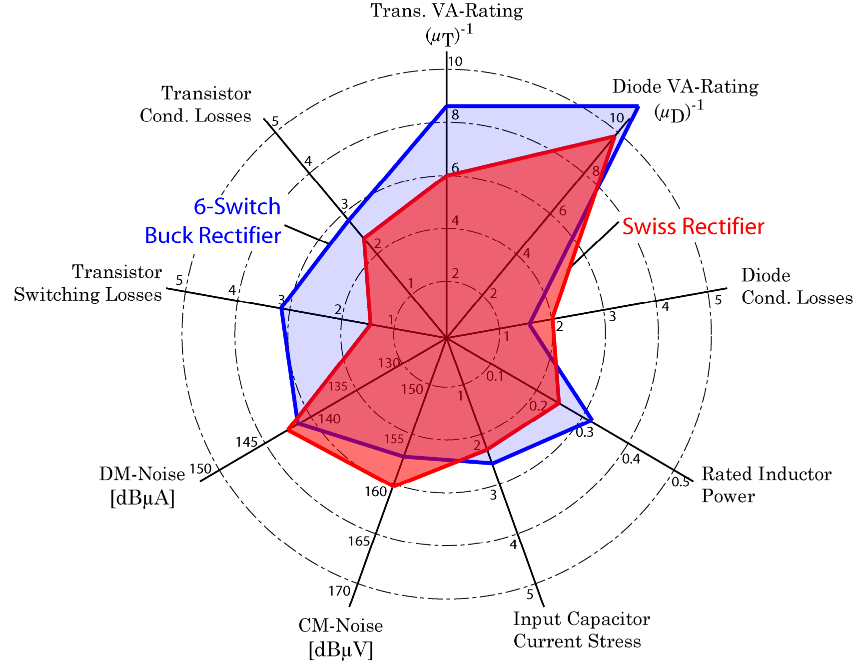
▶ Boost-Type
VIENNA / Δ−Switch Rectifier

V_{LL} = 400 V (50 Hz)
P_o = 10 kW
U_o = 720 V
f_s = 72 kHz



▶ Buck-Type
SWISS/ 6-Switch Rectifier

V_{LL} = 400 V (50 Hz)
P_o = 10 kW
U_o = 360 V
f_s = 72 kHz



Comparative Evaluation (II)

▶ Design Space

- Semiconductor Type, Data
- Thermal Properties
- EMI Specifications
- Converter Topologies, Load
- Modulation Scheme
- Control Scheme
- etc.

▶ Specifications

- Operating Range (e.g. U_i, U_o)
- Mission (Charging) Profile
- Limit Values
- etc.

Virtual PFC Rectifier Evaluation Platform

▶ Outputs (Post-Processing)

- Performance Indices
- Operating Efficiency
- Mission Efficiency
- Volume, Weight, Power Density
- Costs
- etc.

■ Comprehensive Evaluation of PFC Rectifier Systems Based on *Required Total Chip Area*, *Total Volume / Weight* of Power Passives and *Conversion Efficiency*

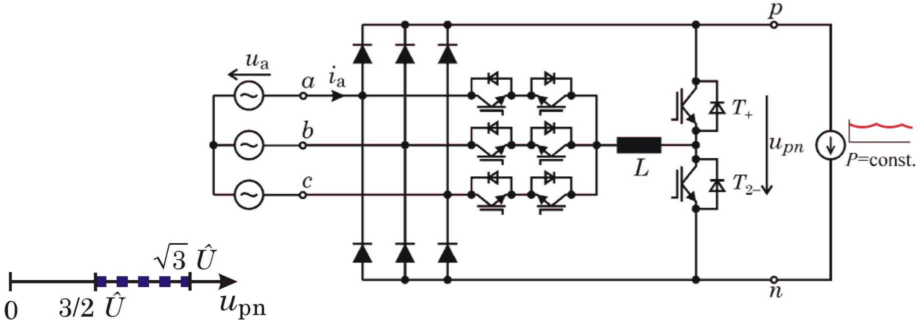
Conclusions (1)

► 3 Decades of Research have Identified the most Advantageous 3ph. PFC Rectifier Topologies

■ Unregulated Output / Sinusoidal Input Current (KOREA Rectifier)

+ Low Current Stress on Power Semicond.
+ In Principal No DC-Link Cap. Required
+ Control Shows Low Complexity

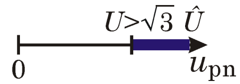
− Sinusoidal Mains Current Only for Const. Power Load
− Power Semicond. Stressed with Full Output Voltage
− Does Not Tolerate Mains Phase Loss

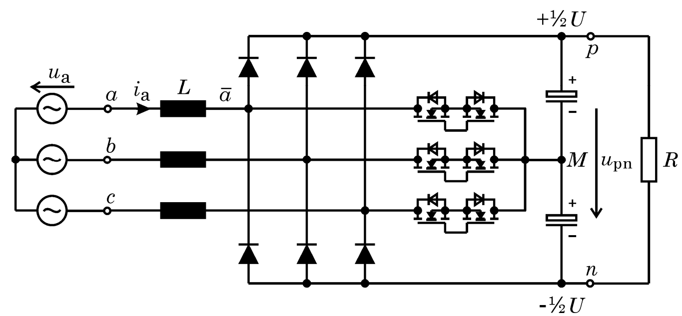


Conclusions (2)

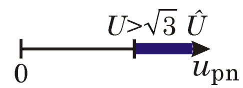
■ Boost-Type PFC Rectifier Systems

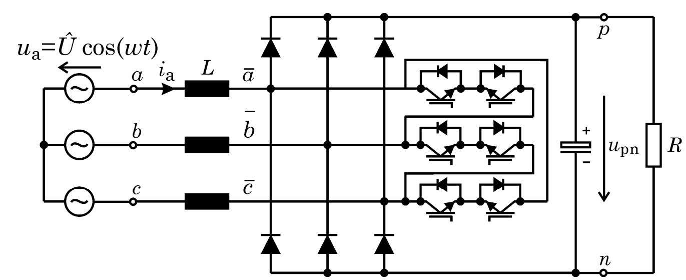
- \+ Controlled Output Voltage
- \+ 3-Level Characteristic
- \+ Tolerates Mains Phase Loss
- \+ Power Semicond. Stressed with Half Output Voltage
- – Higher Control Complexity





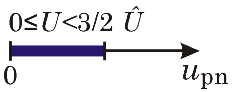
- \+ Controlled Output Voltage
- \+ Relatively Low Control Complexity
- \+ Tolerates Mains Phase Loss
- – 2-Level Characteristic
- – Power Semiconductors Stressed with Full Output Voltage

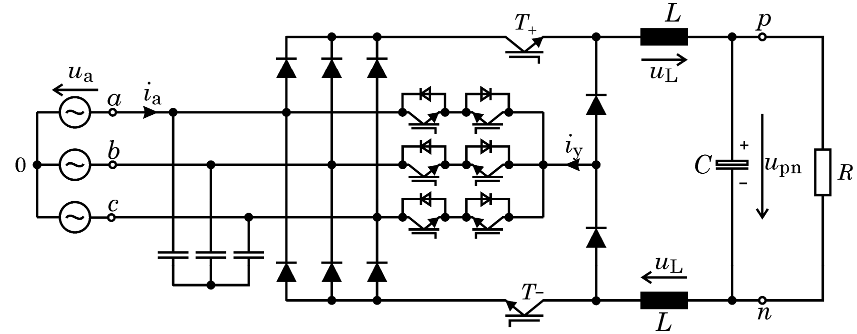




Conclusions (3)

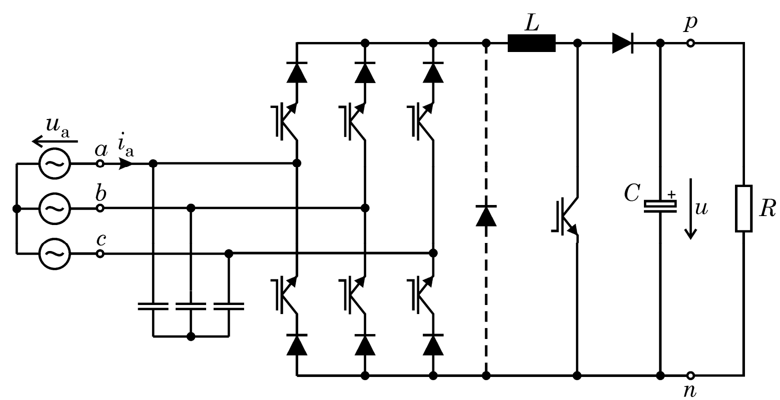
Buck-Type PFC Rectifier System





- + Allows to Generate Low Output Voltages
- + Short Circuit Current Limiting Capability
- – Power Semicond. Stressed with LL-Voltages
- – AC-Side Filter Capacitors / Fundamental Reactive Power Consumption

Buck+Boost-Type PFC Rectifier System



- + See Buck-Type Converter
- + Wide Output Voltage Range
- + Tolerates Mains Phase Loss, i.e. Sinusoidal Mains Current also for 2-Phase Operation
- – See Buck-Type Converter (6-Switch Version of Buck Stage Enables Compensation of AC-Side Filter Cap. Reactive Power)

Thank You !

Appendix A

Design Equations

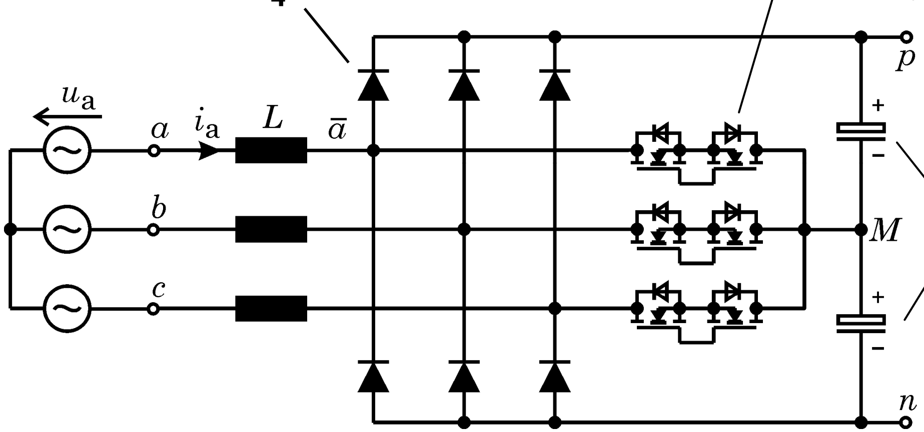
Current Stresses – VIENNA Rectifier

$$I_{DF,rms} = \hat{I}_a \sqrt{\frac{2M}{3\pi}}$$

$$I_{DF,avg} = \hat{I}_a \frac{M}{4}$$

$$I_{S,avg} = \hat{I}_a \left(\frac{1}{\pi} - \frac{M}{4} \right)$$

$$I_{S,rms} = \hat{I}_a \sqrt{\frac{1}{4} - \frac{2M}{3\pi}}$$



$$I_{C,rms} = \hat{I}_a \sqrt{\frac{5\sqrt{3}M}{4\pi} - \frac{9M^2}{16}}$$

Modulation Index: $M = \frac{\hat{U}_a}{(U_{pn}/2)}$

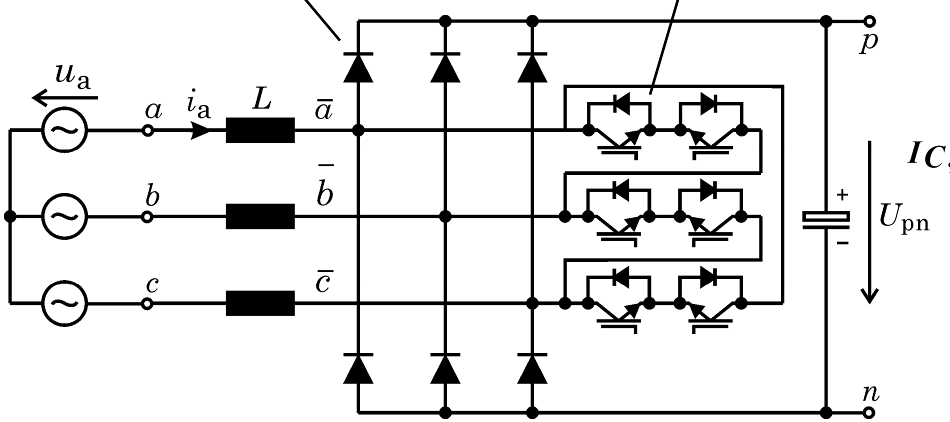
Current Stresses – Δ–Switch Rectifier

$$I_{DF,avg} = \hat{I}_a \frac{M}{2\sqrt{3}}$$

$$I_{DF,rms} = \hat{I}_a \sqrt{\frac{M(5+2\sqrt{3})}{12\pi}}$$

$$I_{\frac{D}{S},avg} = \hat{I}_a \left(\frac{1}{2\pi} - \frac{M}{4\sqrt{3}} \right)$$

$$I_{\frac{D}{S},rms} = \hat{I}_a \sqrt{\left(\frac{1}{6} - \frac{\sqrt{3}}{8\pi} \right) - \frac{M}{2\sqrt{3}\pi}}$$



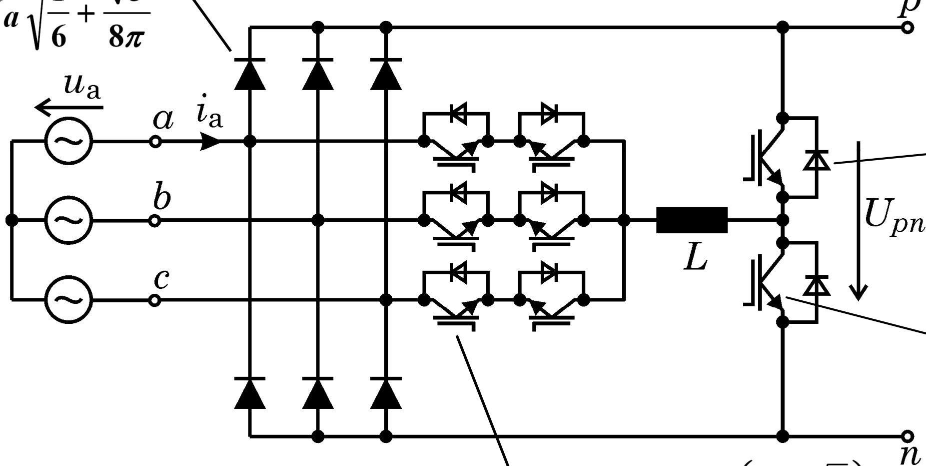
$$I_{C,rms} = \hat{I}_a \sqrt{\frac{5M}{2\pi} - \frac{3M^2}{4}}$$

Modulation Index: $M = \frac{\sqrt{3}\hat{U}_a}{U_{pn}}$

Current Stresses – KOREA Rectifier

$$I_{D,avg} = \hat{I}_a \frac{\sqrt{3}}{2\pi}$$

$$I_{D,rms} = \hat{I}_a \sqrt{\frac{1}{6} + \frac{\sqrt{3}}{8\pi}}$$



$$I_{D,avg} \approx \hat{I}_a \frac{3}{2\pi}\left(1 + \frac{3}{\pi} - \sqrt{3}\right)$$

$$I_{D,rms} = \hat{I}_a \sqrt{\frac{1}{8} + \frac{3\sqrt{3}}{4\pi}\left(\ln\left(\frac{4}{3}\right) - \frac{1}{2}\right)}$$

$$I_{S,avg} = \hat{I}_a \frac{3}{4\pi}\left(2 + \sqrt{3}\ln\left(\frac{1}{3}\right)\right)$$

$$I_{S,rms} = \hat{I}_a \sqrt{\frac{1}{8} + \frac{3\sqrt{3}}{4\pi}\ln\left(\frac{3}{4}\right)}$$

$$I_{\frac{D}{S},avg} = \hat{I}_a \left(\frac{2 - \sqrt{3}}{2\pi}\right)$$

$$I_{\frac{D}{S},rms} = \hat{I}_a \sqrt{\frac{1}{12} - \frac{\sqrt{3}}{8\pi}}$$

Modulation Index: $M = \frac{\sqrt{3}\hat{U}_a}{U_{pn}}$

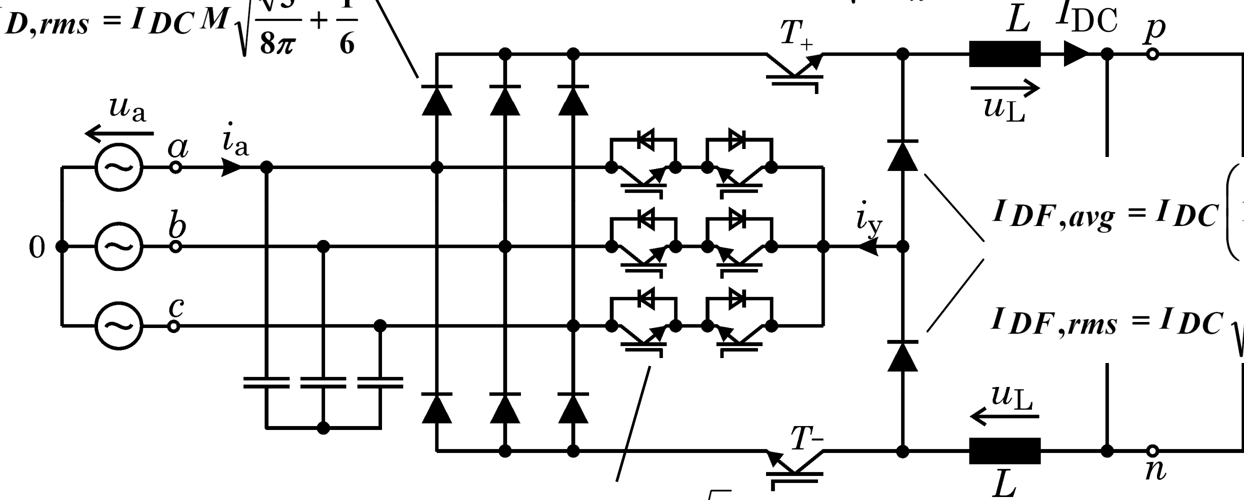
Current Stresses – SWISS Rectifier

$$I_{D,avg} = I_{DC} M \frac{\sqrt{3}}{2\pi}$$

$$I_{D,rms} = I_{DC} M \sqrt{\frac{\sqrt{3}}{8\pi} + \frac{1}{6}}$$

$$I_{S,avg} = I_{DC} M \frac{3\sqrt{3}}{2\pi}$$

$$I_{S,rms} = I_{DC} \sqrt{\frac{3\sqrt{3}M}{2\pi}}$$



$$I_{DF,avg} = I_{DC} \left(1 - \frac{3\sqrt{3}}{2\pi} M\right)$$

$$I_{DF,rms} = I_{DC} \sqrt{1 - \frac{3\sqrt{3}}{2\pi} M}$$

$$I_{\frac{D}{S},avg} = I_{DC} M \frac{2-\sqrt{3}}{2\pi}$$

$$I_{\frac{D}{S},rms} = I_{DC} M \sqrt{\frac{1}{12} - \frac{\sqrt{3}}{8\pi}}$$

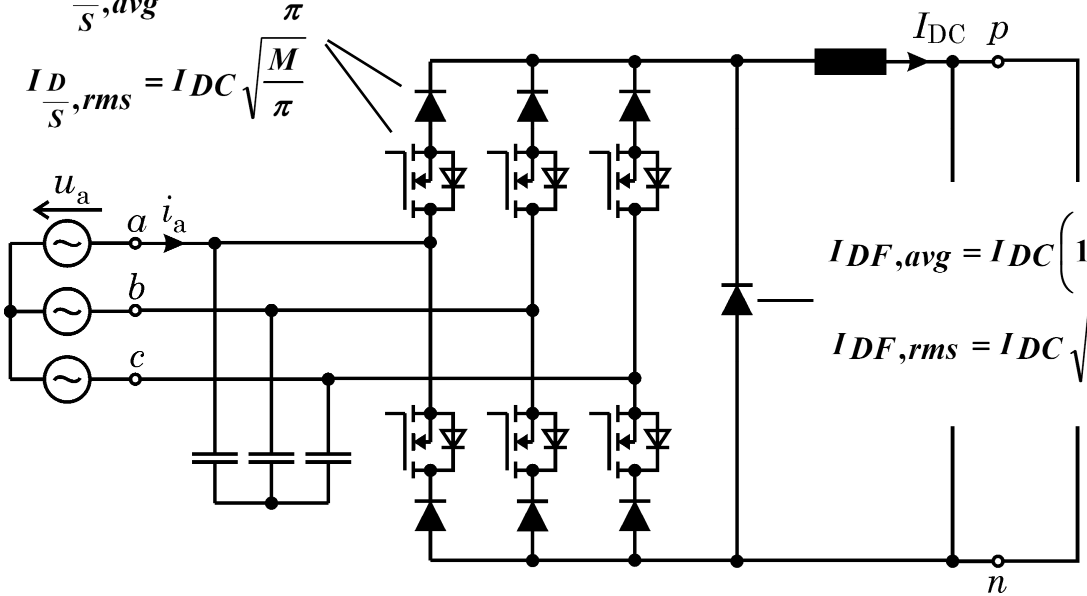
Modulation Index:

$$M = \frac{\hat{I}_a}{I_{DC}}$$

Current Stresses – 6S Buck Rectifier (1)

$$I_{\frac{D}{S},avg} = I_{DC}\frac{M}{\pi}$$

$$I_{\frac{D}{S},rms} = I_{DC}\sqrt{\frac{M}{\pi}}$$

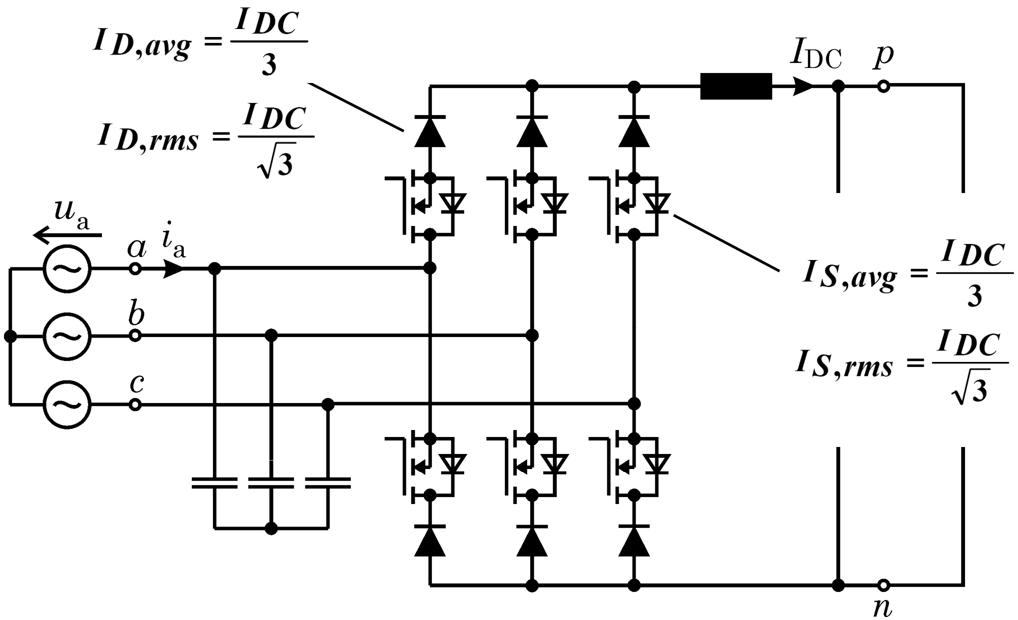


$$I_{DF,avg} = I_{DC}\left(1-\frac{3M}{\pi}\right)$$

$$I_{DF,rms} = I_{DC}\sqrt{1-\frac{3M}{\pi}}$$

Modulation Index: $M = \frac{\hat{I}_N}{I_{DC}}$

Current Stresses – 6S Buck Rectifier (2)



Modulation Index: $M = \frac{\hat{I}_N}{I_{DC}}$

Appendix B

References

Hybrid Rectifier Systems (Electronic Reactance Based)

[1] **H. Ertl, J.W. Kolar, and F.C. Zach,** *“A Constant Output Current Three-Phase Diode Bridge Employing a Novel Electronic Smoothing Inductor,”* Proc. of the 40th Intern. Conf. on Power Conversion, Nuremberg, June 22-24, pp. 645–651 (1999).

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Hybrid Rectifier Systems (Active 3rd Harmonic Injection) (1)

[7] **H. Ertl, J.W. Kolar, and F.C. Zach,** *"A Constant Output Current Three-Phase Diode Bridge Employing a Novel Electronic Smoothing Inductor,"* Proc. of the 40th Intern. Conf. on Power Conversion, Nuremberg, June 22-24, pp. 645–651 (1999).

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