ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The Essence of Three-Phase PFC Rectifier Systems

J. W. Kolar, J. Mühlethaler
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Schedule / Outline

14:00 — ▶ Introduction

▶ Passive and Hybrid Rectifier Systems

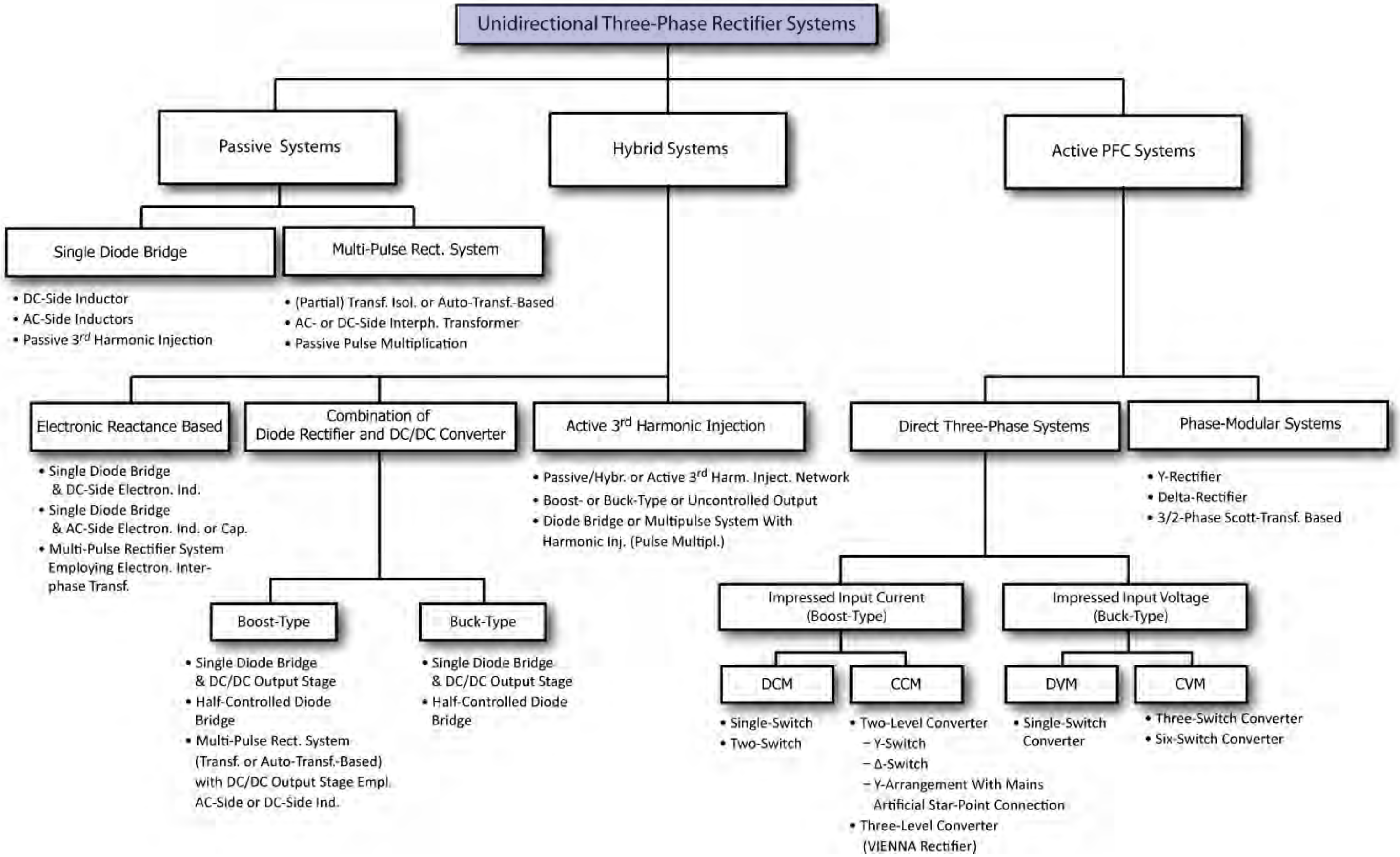
15:10 — ▶ Phase-Modular Active PFC Rectifier Systems

15:30 — ▶ Boost-Type Active PFC Rectifier Systems

▶ Buck-Type Active PFC Rectifier Systems

17:00 — ▶ Conclusions / Questions / Discussion

▶ Classification of Unidirectional Rectifier Systems



Unidirectional Three-Phase Rectifier Systems

Passive Systems

Single Diode Bridge

- DC-Side Inductor
- AC-Side Inductors
- Passive 3rd Harmonic Injection

Multi-Pulse Rect. System

- (Partial) Transf. Isol. or Auto-Transf.-Based
- AC- or DC-Side Interph. Transformer
- Passive Pulse Multiplication

Hybrid Systems

Electronic Reactance Based

- Single Diode Bridge & DC-Side Electron. Ind.
- Single Diode Bridge & AC-Side Electron. Ind. or Cap.
- Multi-Pulse Rectifier System Employing Electron. Interphase Transf.

Combination of Diode Rectifier and DC/DC Converter

Boost-Type

- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge
- Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.

Buck-Type

- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge

Active 3rd Harmonic Injection

- Passive/Hybr. or Active 3rd Harm. Inject. Network
- Boost- or Buck-Type or Uncontrolled Output
- Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)

Active PFC Systems

Direct Three-Phase Systems

Impressed Input Current (Boost-Type)

DCM

- Single-Switch
- Two-Switch

CCM

- Two-Level Converter
  - Y-Switch
  - Δ-Switch
  - Y-Arrangement With Mains Artificial Star-Point Connection
- Three-Level Converter (VIENNA Rectifier)

Impressed Input Voltage (Buck-Type)

DVM

- Single-Switch Converter

CVM

- Three-Switch Converter
- Six-Switch Converter

Phase-Modular Systems

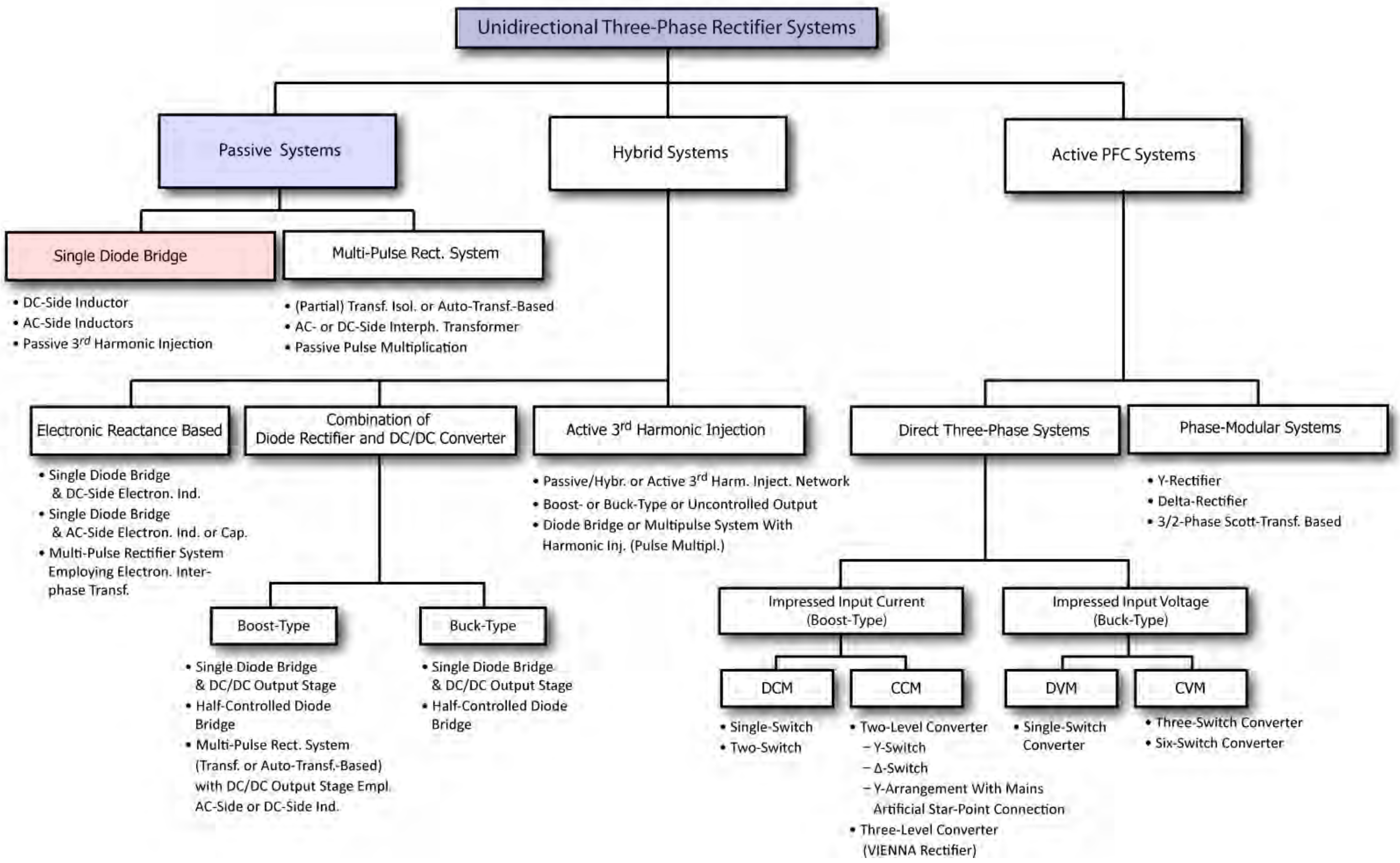
- Y-Rectifier
- Delta-Rectifier
- 3/2-Phase Scott-Transf. Based

► Classification of Unidirectional Rectifier Systems

■ Definitions and Characteristics

● Passive Rectifier Systems	- Line Commutated Diode Bridge/Thyristor Bridge - Full/Half Controlled - Low Frequency Output Capacitor for DC Voltage Smoothing - Only Low Frequency Passive Components Employed for Current Shaping, No Active Current Control - No Active Output Voltage Control
● Hybrid Rectifier Systems	- Low Frequency and Switching Frequency Passive Components and/or - Mains Commutation (Diode/Thyristor Bridge - Full/Half Controlled) and/or Forced Commutation - Partly Only Current Shaping/Control and/or Only Output Voltage Control - Partly Featuring Purely Sinusoidal Mains Current
● Active Rectifier Systems	- Controlled Output Voltage - Controlled (Sinusoidal) Input Current - Only Forced Commutations / Switching Frequ. Passive Components
■ Phase-Modular Systems	- Phase Rectifier Modules of Identical Structure - Phase Modules connected in Star or in Delta - Formation of Three Independent Controlled DC Output Voltages
■ Direct Three-Phase Syst.	- Only One Common Output Voltage for All Phases - Symmetrical Structure of the Phase Legs - Phase (and/or Bridge-)Legs Connected either in Star or Delta

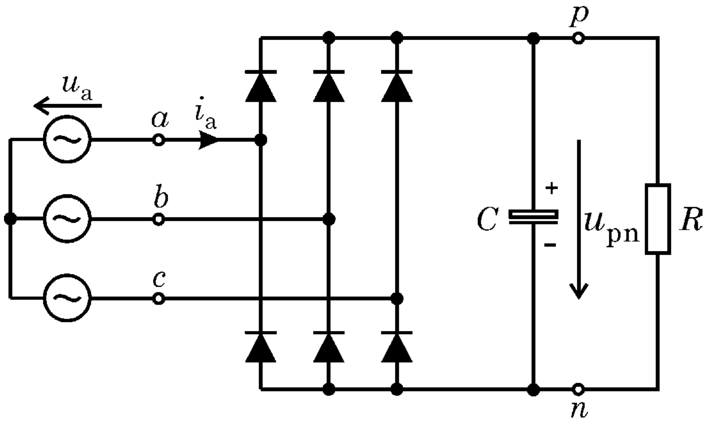
► Classification of Unidirectional Rectifier Systems

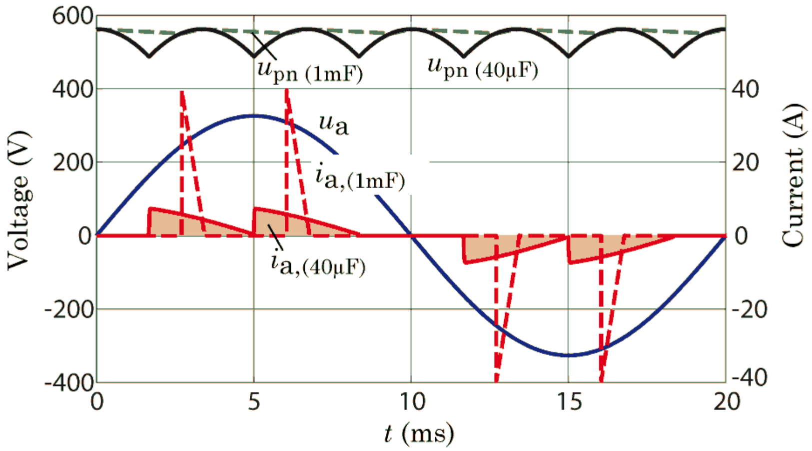


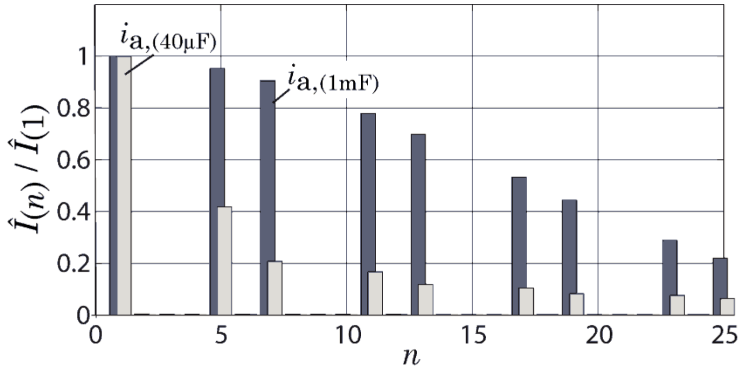
Unidirectional Three-Phase Rectifier Systems

- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3rd Harmonic Injection
  - Multi-Pulse Rect. System
    - (Partial) Transf. Isol. or Auto-Transf.-Based
    - AC- or DC-Side Interph. Transformer
    - Passive Pulse Multiplication
- Hybrid Systems
  - Electronic Reactance Based
    - Single Diode Bridge & DC-Side Electron. Ind.
    - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
    - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
  - Combination of Diode Rectifier and DC/DC Converter
    - Boost-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
      - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
    - Buck-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
  - Active 3rd Harmonic Injection
    - Passive/Hybr. or Active 3rd Harm. Inject. Network
    - Boost- or Buck-Type or Uncontrolled Output
    - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
- Active PFC Systems
  - Direct Three-Phase Systems
    - Impressed Input Current (Boost-Type)
      - DCM
        - Single-Switch
        - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - Δ-Switch
          - Y-Arrangement With Mains Artificial Star-Point Connection
        - Three-Level Converter (VIENNA Rectifier)
    - Impressed Input Voltage (Buck-Type)
      - DVM
        - Single-Switch Converter
      - CVM
        - Three-Switch Converter
        - Six-Switch Converter
  - Phase-Modular Systems
    - Y-Rectifier
    - Delta-Rectifier
    - 3/2-Phase Scott-Transf. Based

▶ Diode Bridge Rectifier with Capacitive Smoothing

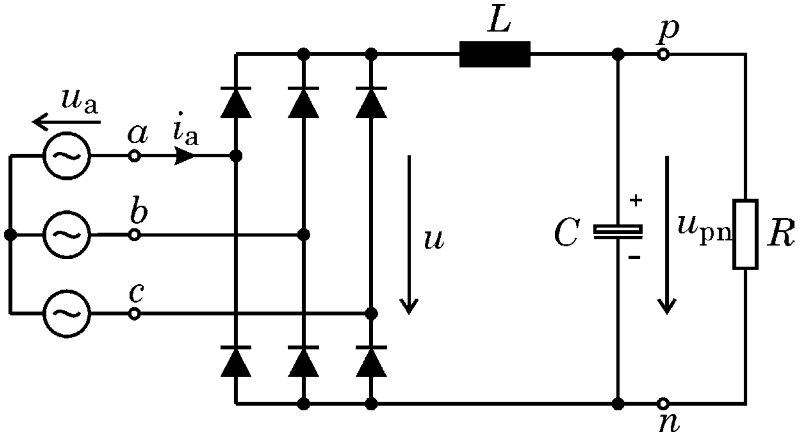


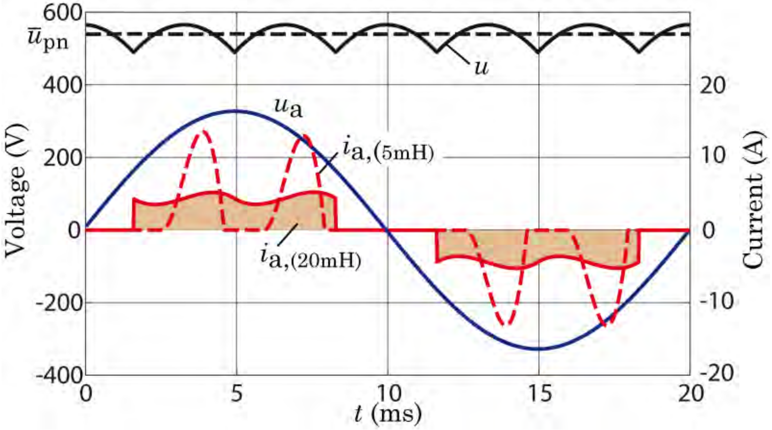




U_{LL} = 3 x 400 V
f_N = 50 Hz
P_{out} = 2.5 kW (R=125 Ω)
C = 1 mF; 40 µF
X_c/R = 0.025; 0.636

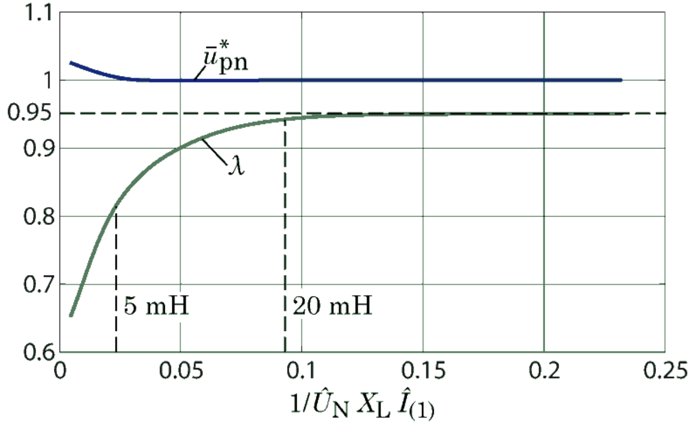
► Diode Bridge Rectifier / DC-Side Inductor and Output Capacitor



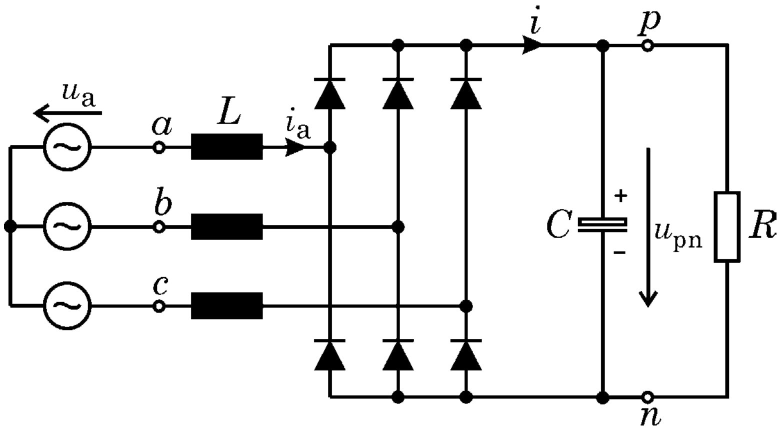


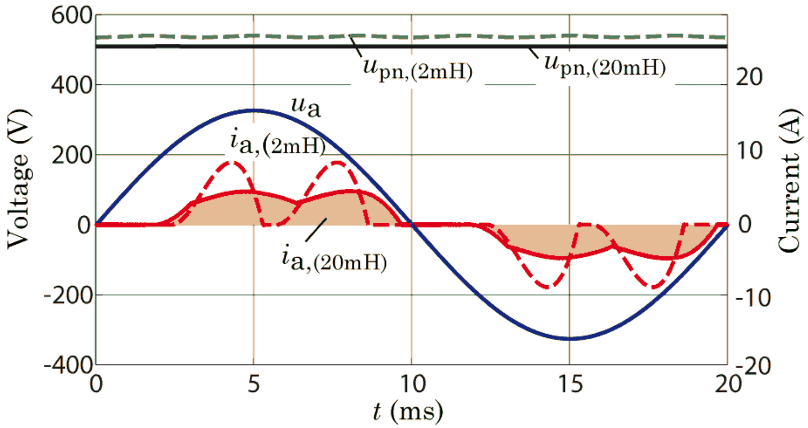
$$\bar{u}^*_{pn} = \frac{\bar{u}_{pn}}{\frac{\pi}{3}\hat{U}_{N,LL}}$$

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

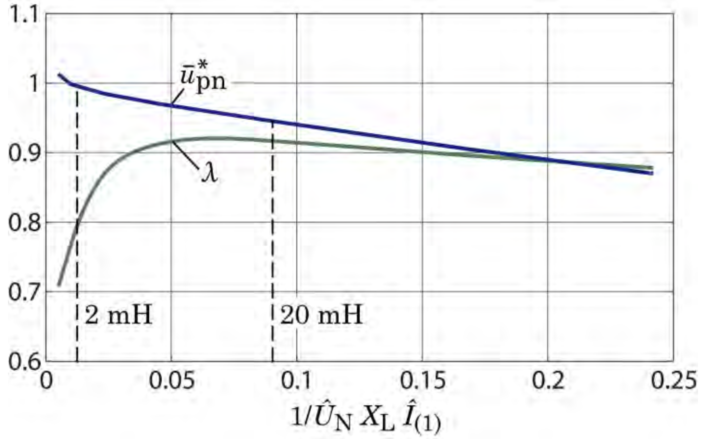


▶ Diode Bridge Rectifier / AC-Side Inductor and Output Capacitor



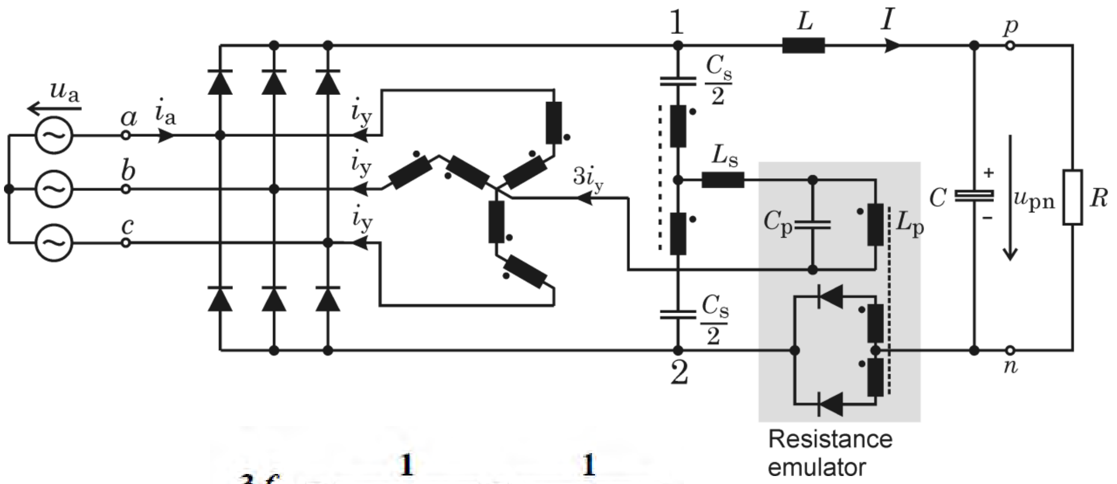


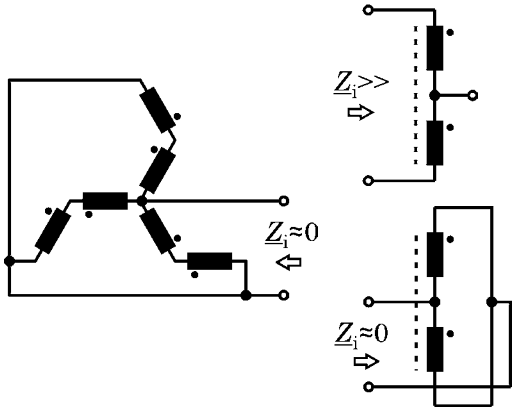
$$\bar{u}^*_{pn} = \frac{\bar{u}_{pn}}{\frac{\pi}{3}\hat{U}_{N,LL}}$$



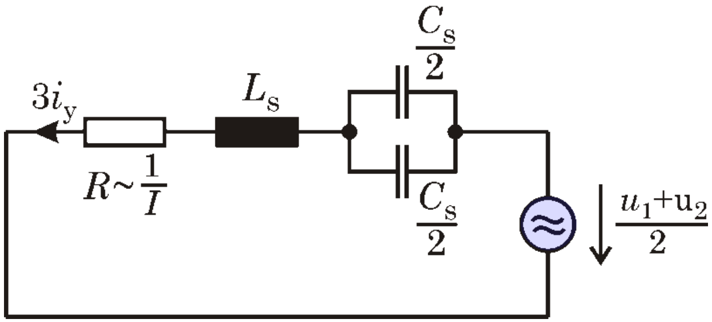
U_{LL} = 3 x 400 V
f_N = 50 Hz
P_{out} = 2.5 kW (R=125 Ω)
C = 1 mF
L = 2 mH; 20 mH

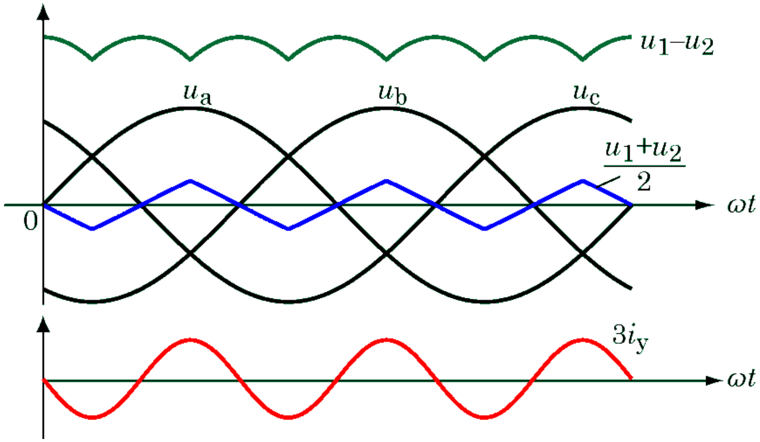
▶ Passive 3rd Harmonic Injection



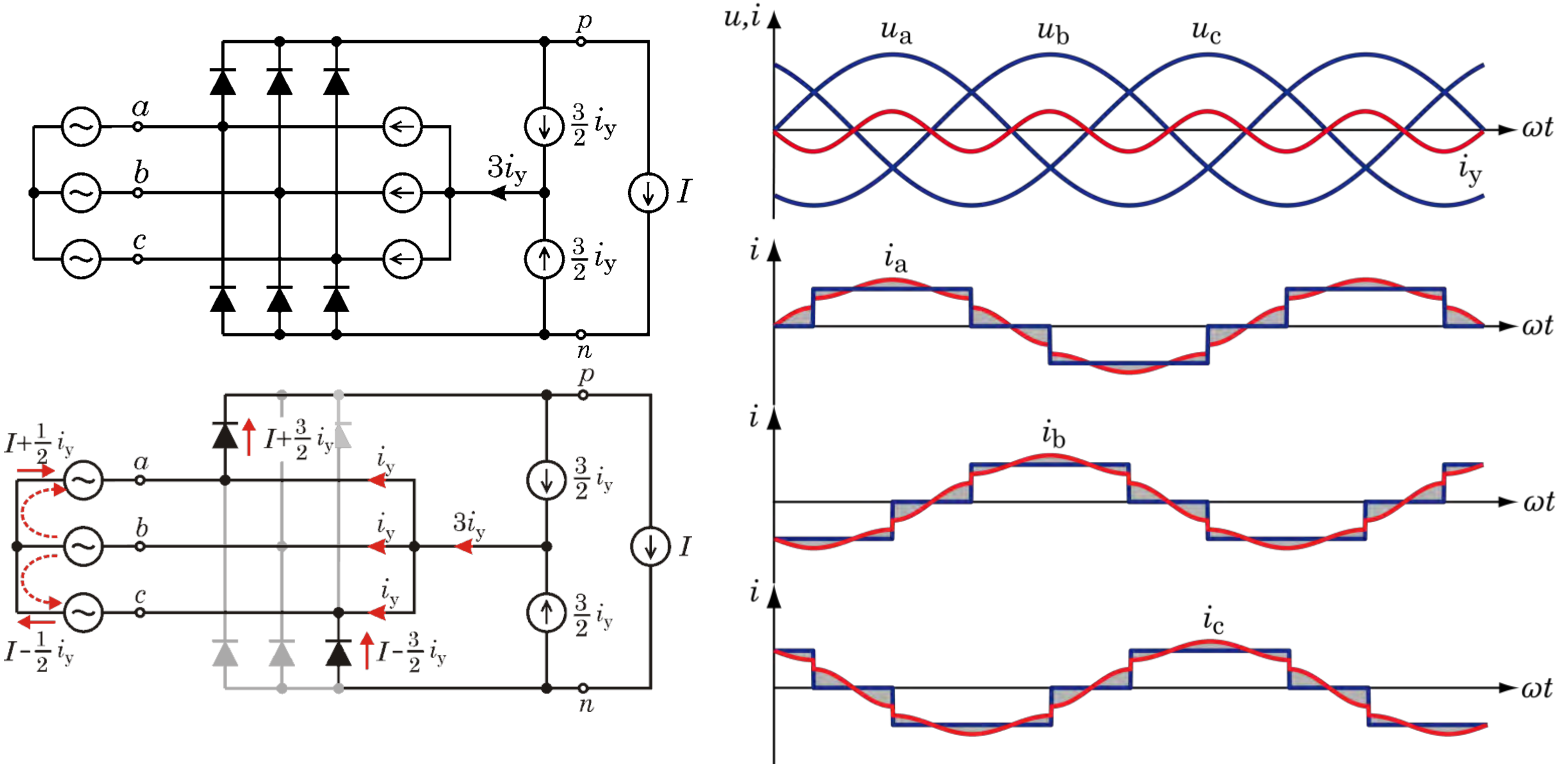


$$3f_N = \frac{1}{2\pi\sqrt{L_s C_s}} = \frac{1}{2\pi\sqrt{L_p C_p}}$$



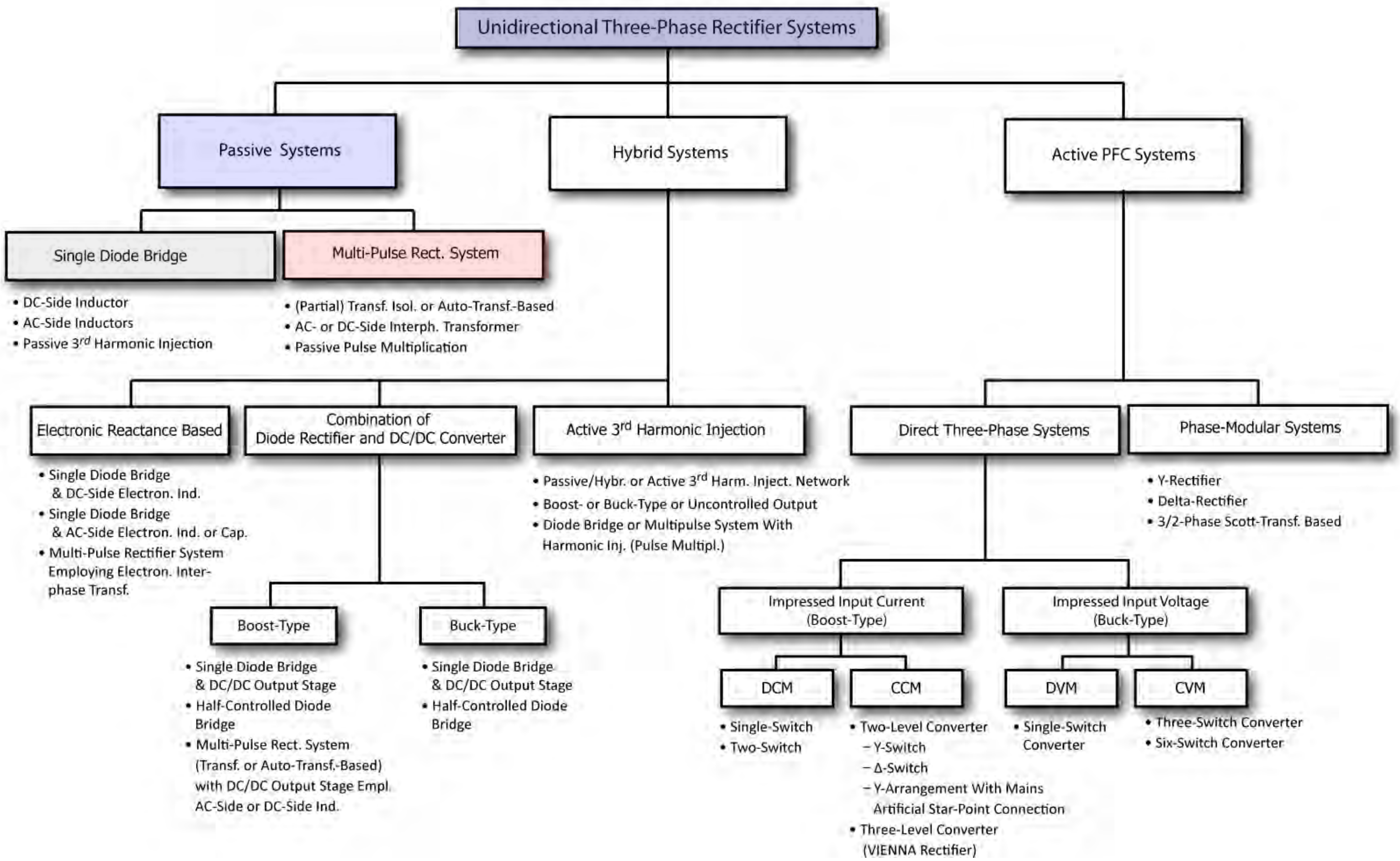


▶ Passive 3rd Harmonic Injection



- Minimum THD of Phase Current for $i_y = 1/2\, I$
- $\text{THD}_{\text{min}} = 5\ \%$

▶ Classification of Unidirectional Rectifier Systems

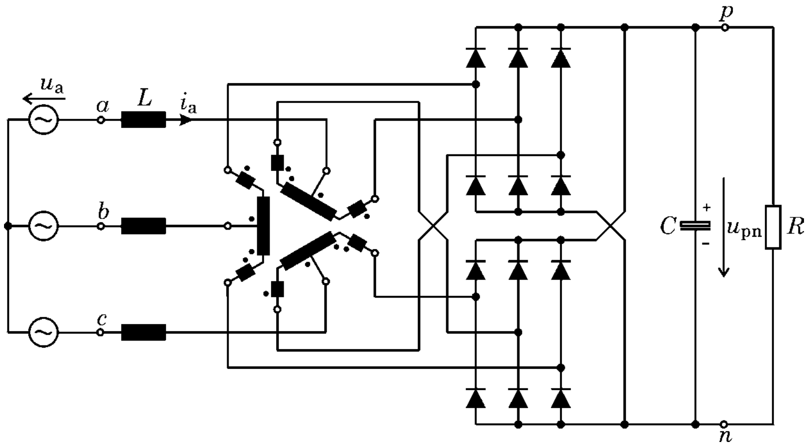


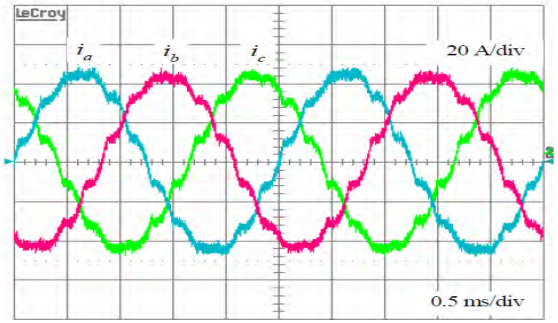
Unidirectional Three-Phase Rectifier Systems

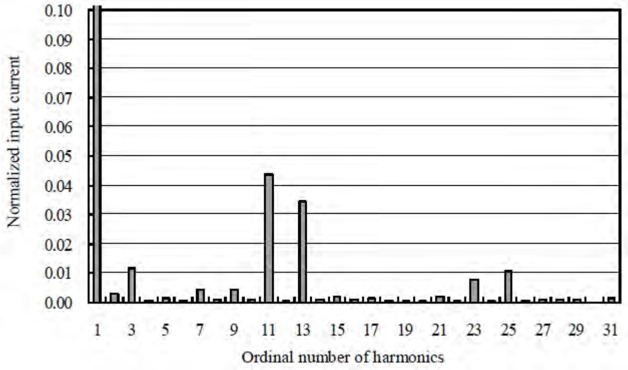
- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3rd Harmonic Injection
  - Multi-Pulse Rect. System
    - (Partial) Transf. Isol. or Auto-Transf.-Based
    - AC- or DC-Side Interph. Transformer
    - Passive Pulse Multiplication
- Hybrid Systems
  - Electronic Reactance Based
    - Single Diode Bridge & DC-Side Electron. Ind.
    - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
    - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
  - Combination of Diode Rectifier and DC/DC Converter
    - Boost-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
      - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
    - Buck-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
  - Active 3rd Harmonic Injection
    - Passive/Hybr. or Active 3rd Harm. Inject. Network
    - Boost- or Buck-Type or Uncontrolled Output
    - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
- Active PFC Systems
  - Direct Three-Phase Systems
    - Impressed Input Current (Boost-Type)
      - DCM
        - Single-Switch
        - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - Δ-Switch
          - Y-Arrangement With Mains Artificial Star-Point Connection
        - Three-Level Converter (VIENNA Rectifier)
    - Impressed Input Voltage (Buck-Type)
      - DVM
        - Single-Switch Converter
      - CVM
        - Three-Switch Converter
        - Six-Switch Converter
  - Phase-Modular Systems
    - Y-Rectifier
    - Delta-Rectifier
    - 3/2-Phase Scott-Transf. Based

▶ Auto-Transformer-Based-12-Pulse Rectifier Systems

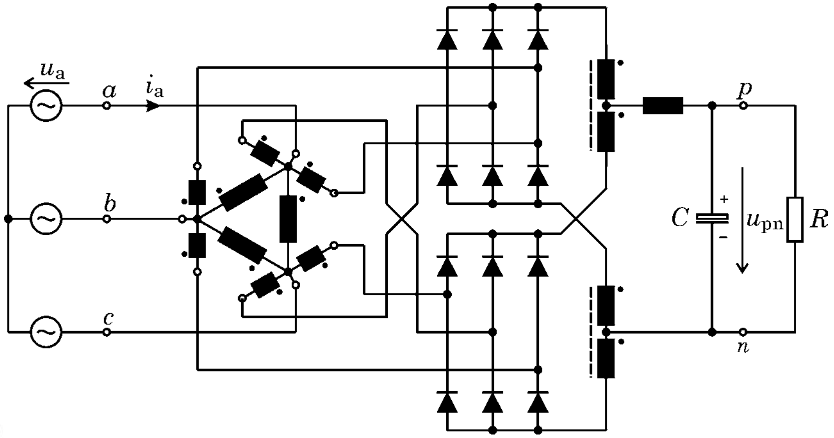
■ AC-Side Interphase Transf. (Impr. DC Voltage)





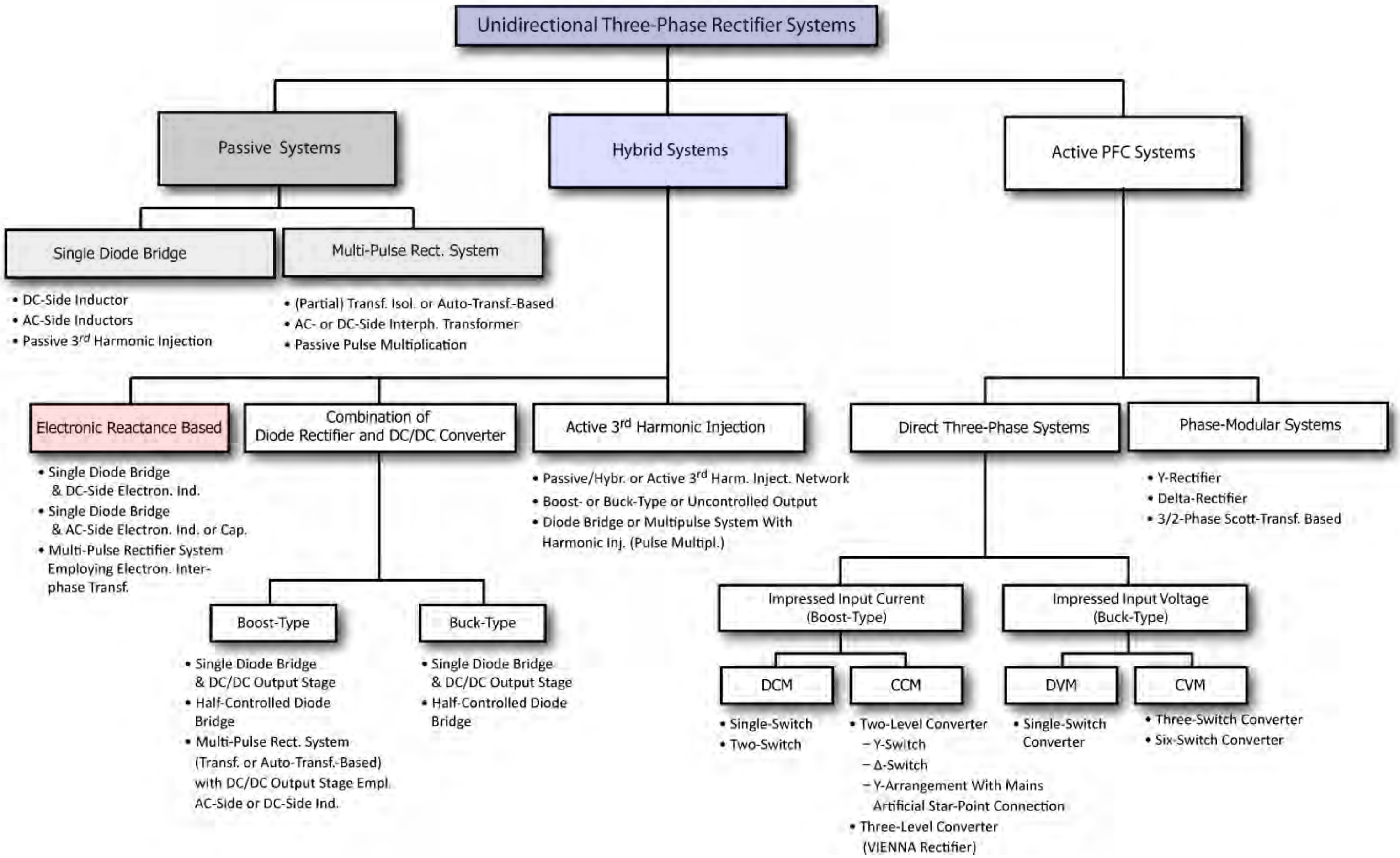


■ DC-Side Interphase Transf. (Impr. DC Current)



DC-Side Interphase Transformer can be omitted in Case of Full Transformer Isolation of Both Diode Bridges

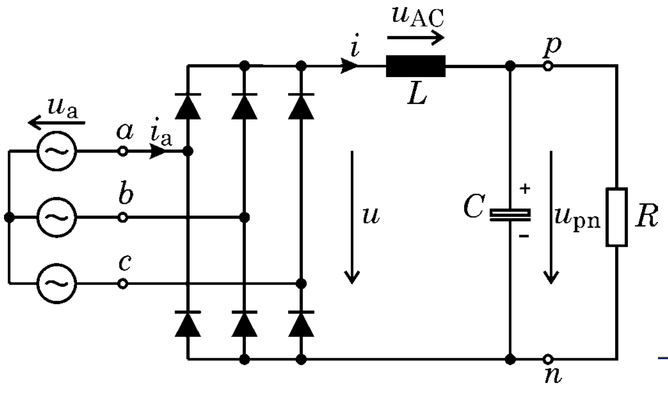
► Classification of Unidirectional Rectifier Systems

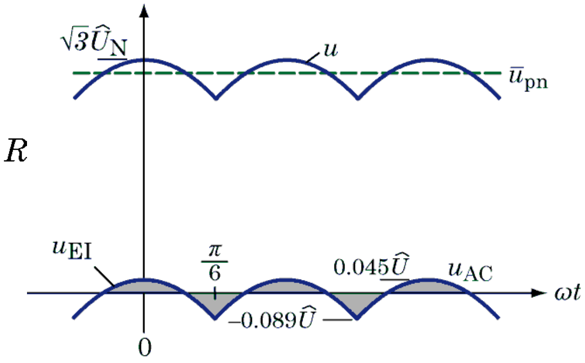


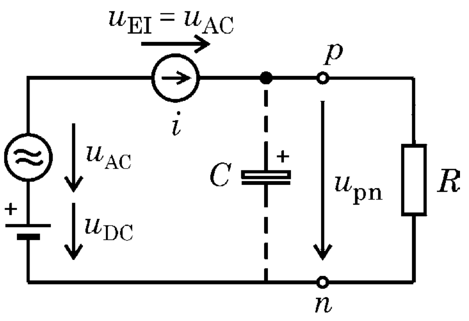
Unidirectional Three-Phase Rectifier Systems

- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3rd Harmonic Injection
  - Multi-Pulse Rect. System
    - (Partial) Transf. Isol. or Auto-Transf.-Based
    - AC- or DC-Side Interph. Transformer
    - Passive Pulse Multiplication
- Hybrid Systems
  - Electronic Reactance Based
    - Single Diode Bridge & DC-Side Electron. Ind.
    - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
    - Multi-Pulse Rectifier System Employing Electron. Interphase Transf.
  - Combination of Diode Rectifier and DC/DC Converter
    - Boost-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
      - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
    - Buck-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
  - Active 3rd Harmonic Injection
    - Passive/Hybr. or Active 3rd Harm. Inject. Network
    - Boost- or Buck-Type or Uncontrolled Output
    - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
- Active PFC Systems
  - Direct Three-Phase Systems
    - Impressed Input Current (Boost-Type)
      - DCM
        - Single-Switch
        - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - Δ-Switch
          - Y-Arrangement With Mains Artificial Star-Point Connection
        - Three-Level Converter (VIENNA Rectifier)
    - Impressed Input Voltage (Buck-Type)
      - DVM
        - Single-Switch Converter
      - CVM
        - Three-Switch Converter
        - Six-Switch Converter
  - Phase-Modular Systems
    - Y-Rectifier
    - Delta-Rectifier
    - 3/2-Phase Scott-Transf. Based

▶ Diode Bridge and DC-Side Electronic Inductor (EI)

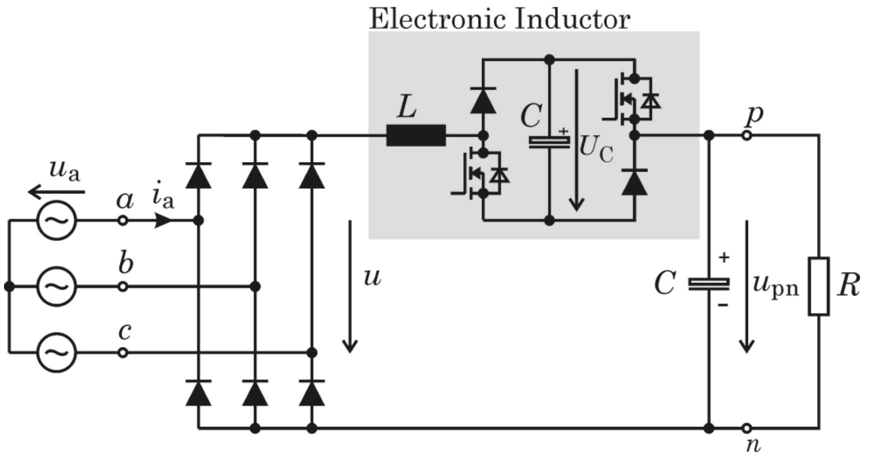






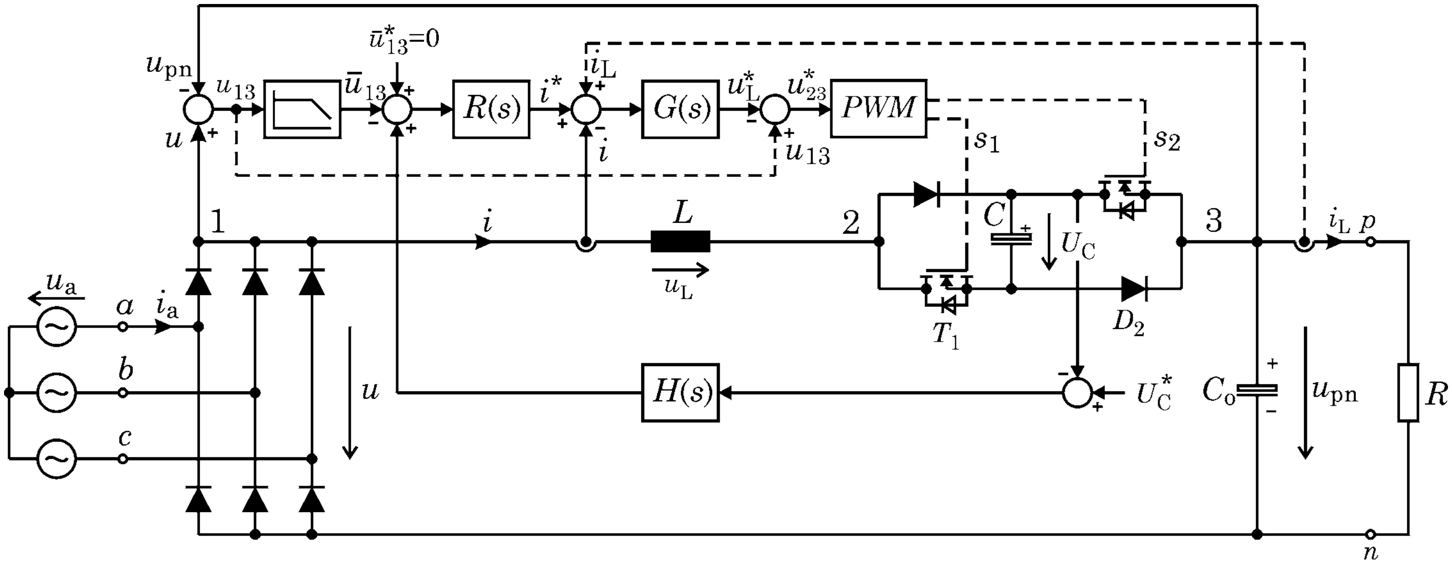
- **+ Only Fract. of Output Power Processed**
- **+ High Efficiency and Power Density**

- **− Not Output Voltage Control**
- **− EMI Filtering Required**



▶ Diode Bridge and DC-Side Electronic Inductor (EI)

■ Control Structure

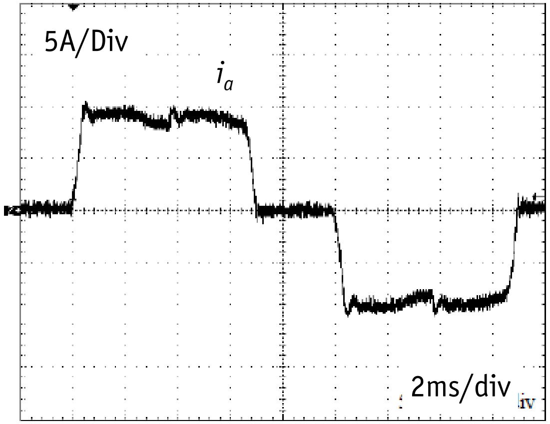


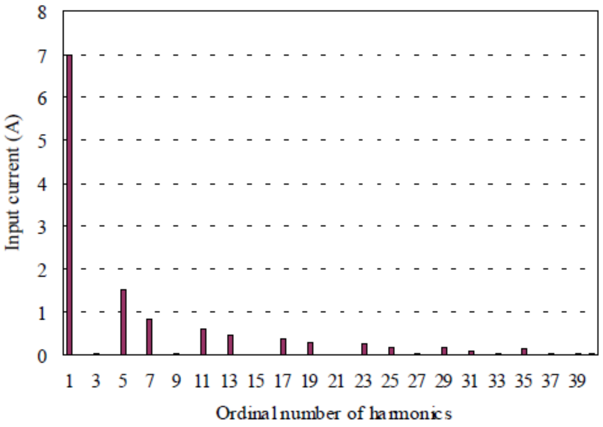
- Current Control could Theoretically Emulate Infinite Inductance Value but Damping (Parallel Ohmic Component) has to be Provided for Preventing Oscillations

▶ Diode Bridge and DC-Side Electronic Inductor (EI)

■ Experimental Results

U_{LL} = 3 x 400 V
P_o = 5 kW
f_s = 70 kHz
C = 4 x 330 µF /100 V

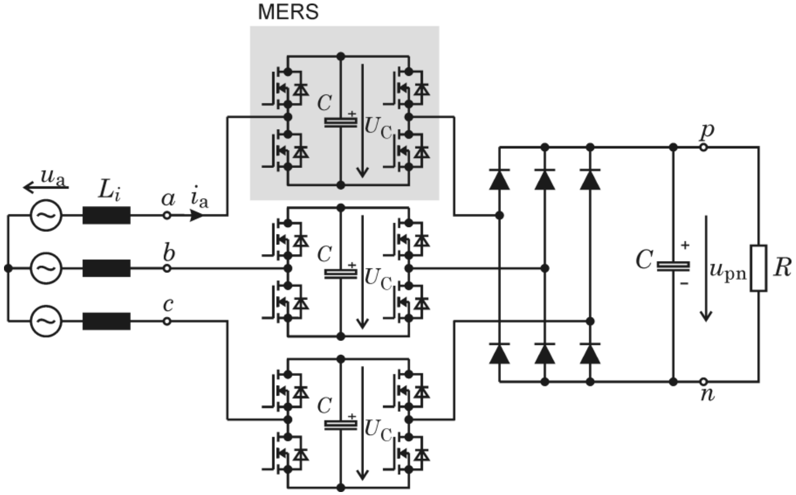


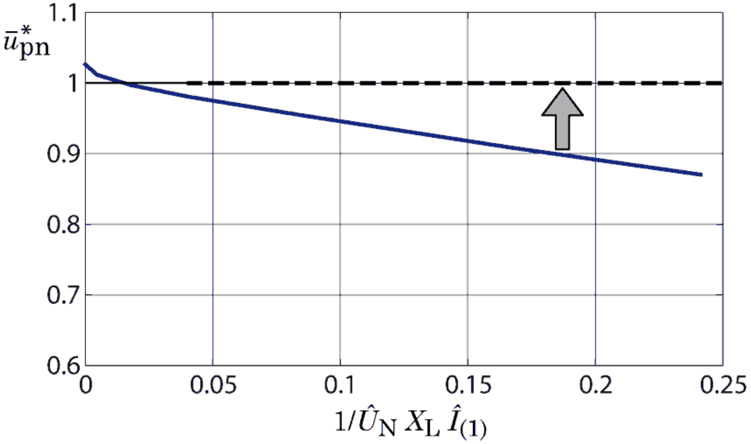


η = 98.3 %
λ = 0.955
THD = 28.4 %

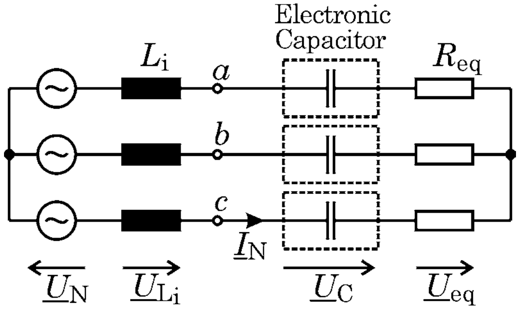
Diode Bridge and DC-Side EI or Electronic Capacitor

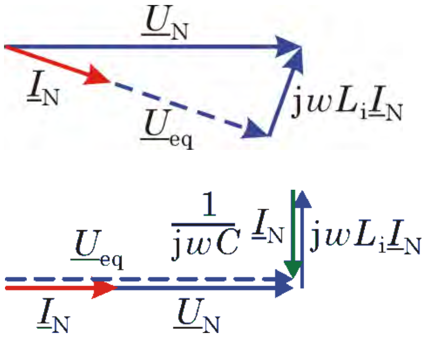
MERS Concept (Magnetic Energy Recovery Switch)



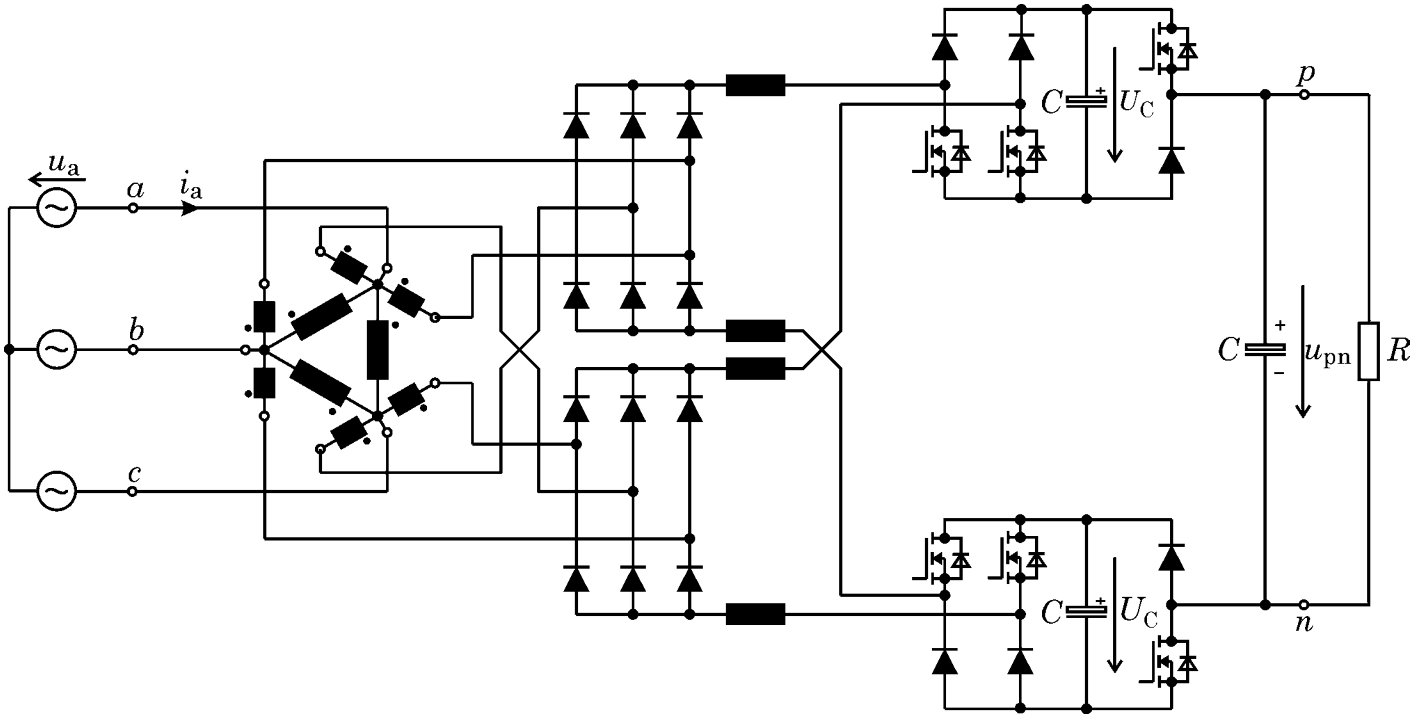


Fundamental Frequency Equivalent Circuit



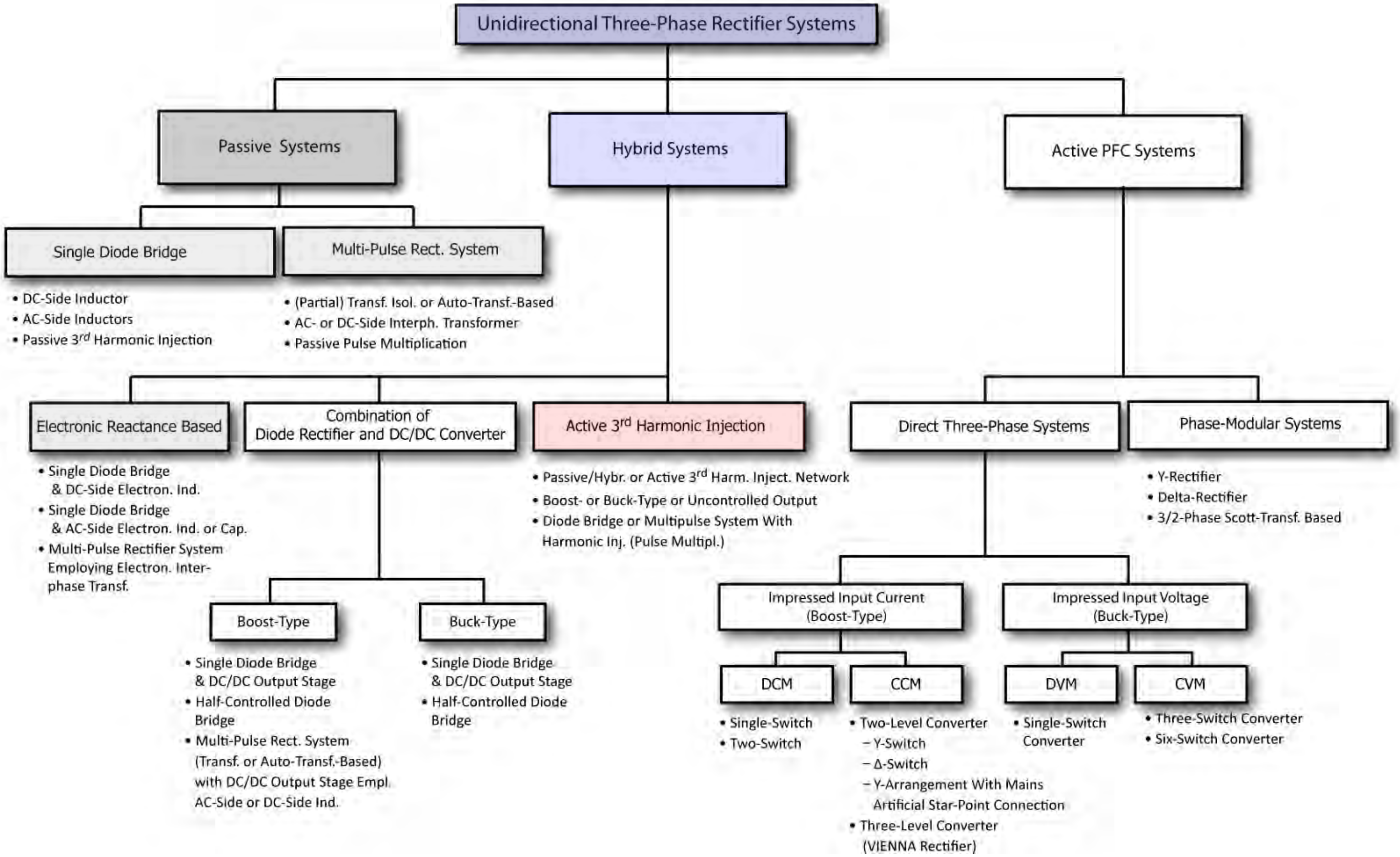


► 12-Pulse Rectifier Employing Electr. Interphase Transformer (EIT)



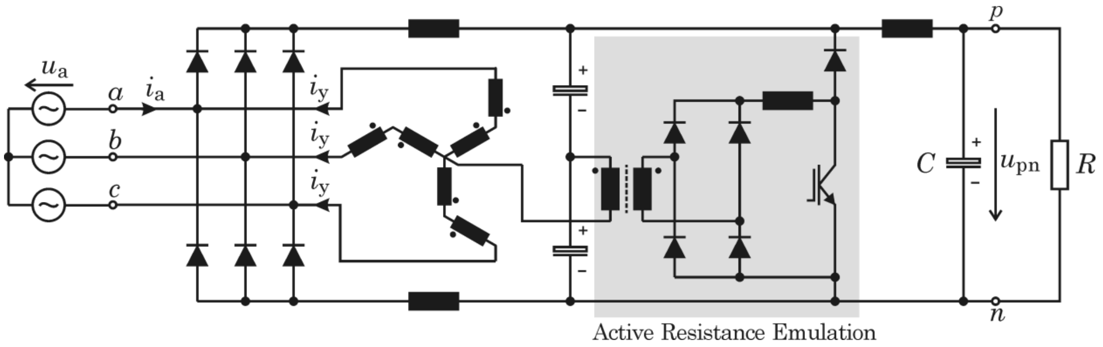
- **Switching Frequency DC-Side Inductors**
- **Proper Control of the EIT Allows to Achieve *Purely Sinusoidal* Mains Current !**

► Classification of Unidirectional Rectifier Systems

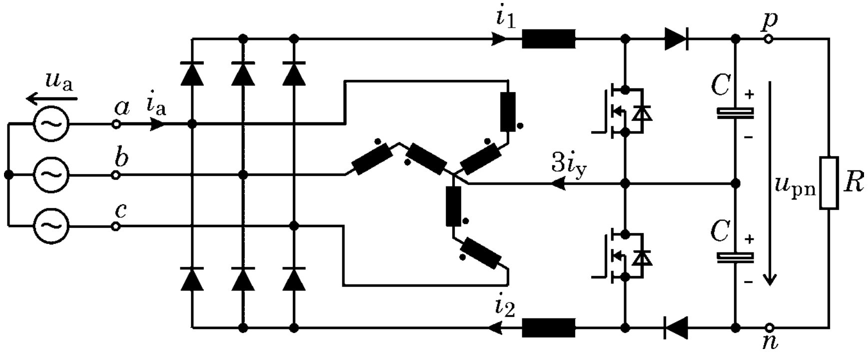


- Unidirectional Three-Phase Rectifier Systems
  - Passive Systems
    - Single Diode Bridge
      - DC-Side Inductor
      - AC-Side Inductors
      - Passive 3rd Harmonic Injection
    - Multi-Pulse Rect. System
      - (Partial) Transf. Isol. or Auto-Transf.-Based
      - AC- or DC-Side Interph. Transformer
      - Passive Pulse Multiplication
  - Hybrid Systems
    - Electronic Reactance Based
      - Single Diode Bridge & DC-Side Electron. Ind.
      - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
      - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
    - Combination of Diode Rectifier and DC/DC Converter
      - Boost-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
        - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
      - Buck-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
    - Active 3rd Harmonic Injection
      - Passive/Hybr. or Active 3rd Harm. Inject. Network
      - Boost- or Buck-Type or Uncontrolled Output
      - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
  - Active PFC Systems
    - Direct Three-Phase Systems
      - Impressed Input Current (Boost-Type)
        - DCM
          - Single-Switch
          - Two-Switch
        - CCM
          - Two-Level Converter
            - Y-Switch
            - Δ-Switch
            - Y-Arrangement With Mains Artificial Star-Point Connection
          - Three-Level Converter (VIENNA Rectifier)
      - Impressed Input Voltage (Buck-Type)
        - DVM
          - Single-Switch Converter
        - CVM
          - Three-Switch Converter
          - Six-Switch Converter
    - Phase-Modular Systems
      - Y-Rectifier
      - Delta-Rectifier
      - 3/2-Phase Scott-Transf. Based

▶ Active 3rd Harmonic Injection into All Phases



- *No Output Voltage Control*
- **Mains Current Close to Sinusoidal Shape**



e.g.: $i_1 = I + 3/2\, i_y$
$i_2 = I - 3/2\, i_y$

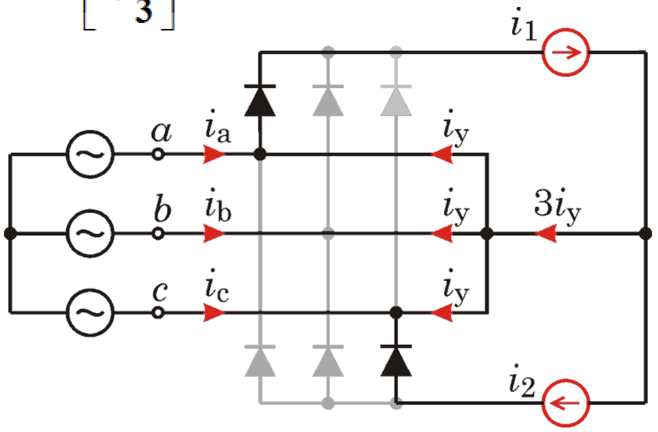
CCL: $3i_y = i_1 - i_2$

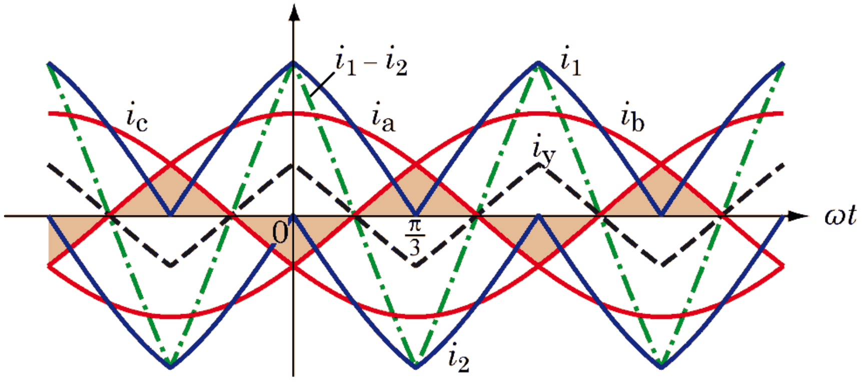
Minnesota Rectifier

- **Controlled Output Voltage**
- **Purely Sinusoidal Shape of Mains Current**

▶ Active 3rd Harmonic Injection into All Phases

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





$$i_a = \hat{I}\cos(\omega t)$$

$$i_b = \hat{I}\cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$i_c = \hat{I}\cos\left(\omega t + \frac{2\pi}{3}\right)$$

$$i_y = -i_b$$

$$i_1 = i_a + i_y$$

$$i_2 = -(i_c + i_y)$$

$$i_a + i_b + i_c = 0$$

$$\boxed{i_1 - i_2} = i_a + i_y + i_c + i_y =$$

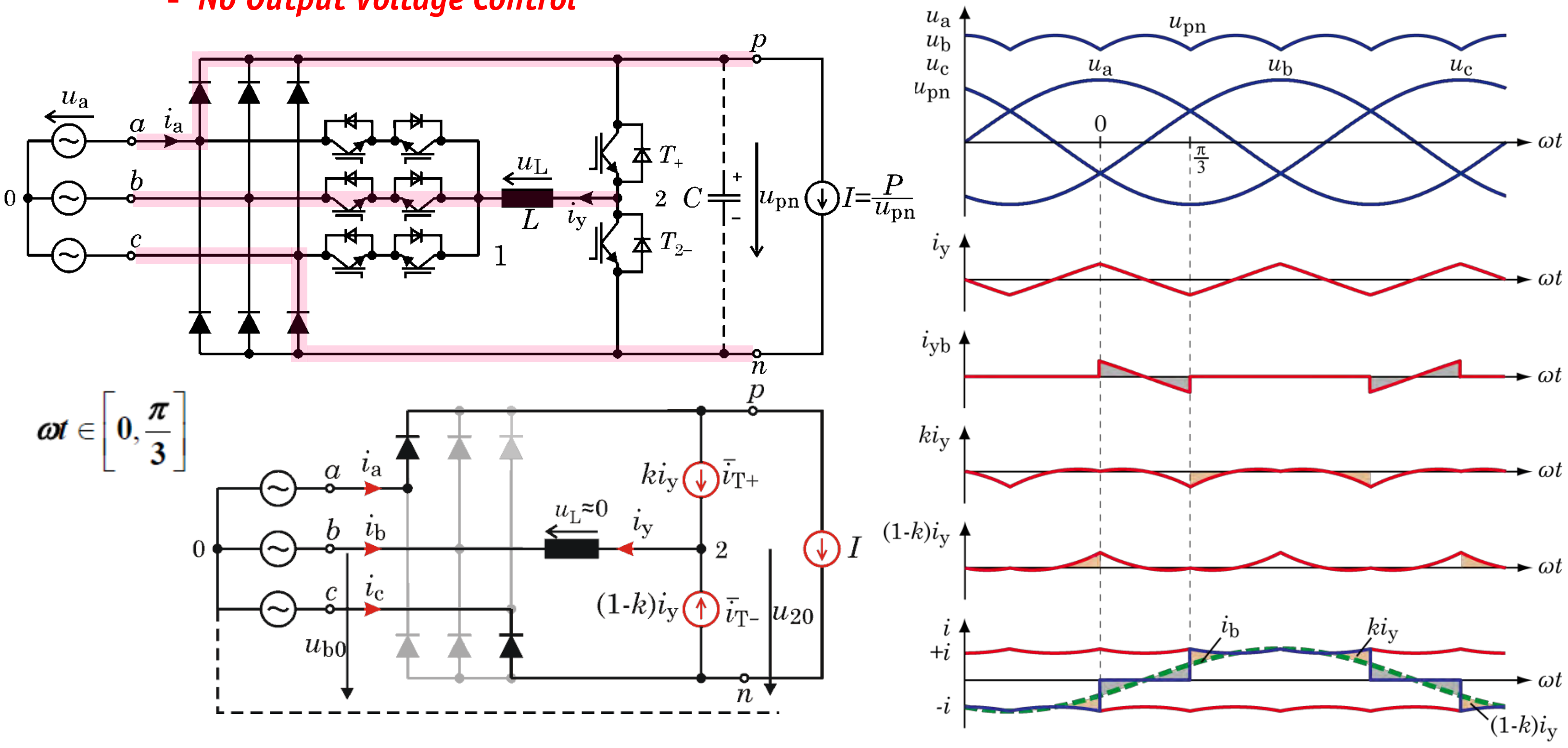
$$= -i_b + 2i_y \boxed{= 3i_y}$$

✓

- **Current Control Implemention with Boost-Type DC/DC Converter (*Minnesota Rectifier*) or with Buck-Type Topology**

▶ Active 3rd Harmonic Inj. Only into One Phase (I)

- \+ Purely Sinusoidal Mains Current (Only for Const. Power Load)
- \+ Low Current Stress on Active Semicond. / High Efficiency
- \+ Low Complexity
- \- *No Output Voltage Control*



- *T_+, T_-* Could be Replaced by Passive Network

■ Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$

$$i_a = G \cdot u_{a0}$$

$$i_b = G \cdot u_{b0}$$

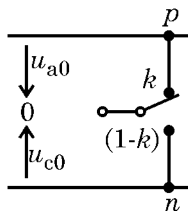
$$i_c = G \cdot u_{c0}$$

- **Current to be Inj. Into Phase *b*:** $i_y = -i_b$
- **Local Avg. Ind. Voltage / Bridge Leg (T_+, T_-) Output Voltage:** $\bar{u}_L \approx 0$ and/or $\bar{u}_{20} = u_{b0}$
- **Bridge Leg Voltage Formation:**

$$\bar{u}_{20} = u_{b0} = k \cdot u_{a0} + (1-k)u_{c0}$$

$$u_{b0} = k \cdot u_{ac} + u_{c0}$$

$$k = \frac{u_{bc}}{u_{ac}}$$



- **Bridge Leg Current Formation:**

$$\bar{i}_{T_+} = k \cdot i_y = -k \cdot G \cdot u_{b0} = -G \cdot u_{b0}\frac{u_{bc}}{u_{ac}}$$

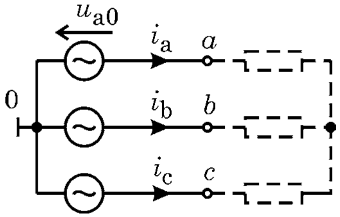
- **Constant Power Load Current:**

$$i = \frac{P}{u_{ac}} = \frac{u_{ac} \cdot i_a + u_{bc} \cdot i_b}{u_{ac}}$$

$$= G\frac{u_a \cdot u_{ac} + u_b \cdot u_{bc}}{u_{ac}} = G\left(u_{a0} + u_{b0}\frac{u_{bc}}{u_{ac}}\right)$$

Condition:

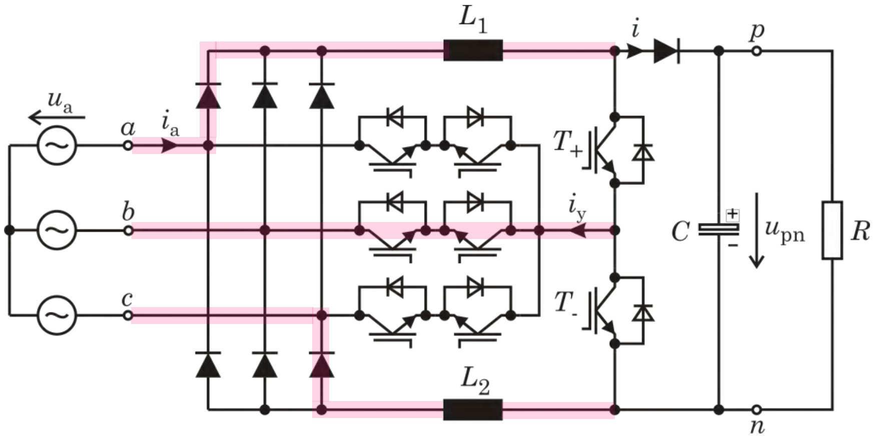
$$i_a + i_b + i_c = 0$$



■ Sinusoidal Mains Current: $i + \bar{i}_{T_+} = G \cdot u_{a0} = i_a$ ✓

► Active 3rd Harmonic Inj. Only into One Phase (II)

■ Boost-Type Topology



- \+ Controlled Output Voltage
- \+ Purely Sinusoidal Mains Current

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

■ Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$ (1)

- 4 Different Switching States:

T_+ on, T_- off } k_1

T_+ off, T_- on
T_+ off, T_- off } k_2

T_+ on, T_- on } $k_3 = (1 - k_1 - k_2)$

3 Different States Regarding the Current Paths with Relative On-Times k_1 , k_2 , and k_3

■ Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$ (2)

$i_a^* = G \cdot u_{a0}$

$i_b^* = G \cdot u_{b0}$

$i_c^* = G \cdot u_{c0}$

- **Current to be Injected into *b*:** $i_y^* = -i_b^*$
- **Inductor Voltages:** $\bar{u}_{L,1}^* \approx 0 \qquad \bar{u}_{L,2}^* \approx 0$
- **Bridge Leg (*T*₊, *T*₋): Voltage Form.:**

$$k_1 u_{ab} + k_2\left(u_{ab} - U_{pn}\right) + \left(1 - k_1 - k_2\right) u_{ab} \overset{!}{=} 0$$

$$k_2 = \frac{u_{ab}}{U_{pn}}$$

$$k_1\left(u_{bc} - U_{pn}\right) + k_2 u_{bc} + \left(1 - k_1 - k_2\right) u_{bc} \overset{!}{=} 0$$

$$k_1 = \frac{u_{bc}}{U_{pn}}$$

- **Constant Power, Load Current:**

$$\bar{i} = \frac{P}{U_{pn}} = \frac{u_{ab} i_a - u_{bc} i_c}{U_{pn}} = -k_1 i_c + k_2 i_a$$

- **Current Formation in *T*₊:**

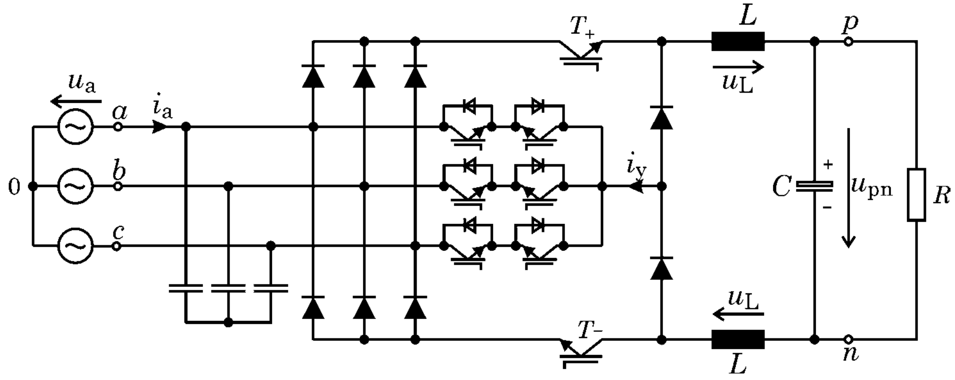
$$\bar{i}_{T+} = k_1 i_y^* + \left(1 - k_1 - k_2\right) i_a^*$$

Condition: $i_a^* + i_b^* + i_c^* = 0$

■ Sinusoidal Mains Current: $\bar{i}_{T+} + \bar{i}^* = i_a^*$ ✓

▶ Active 3rd Harmonic Inj. Only into One Phase (III)

■ Buck-Type Topology

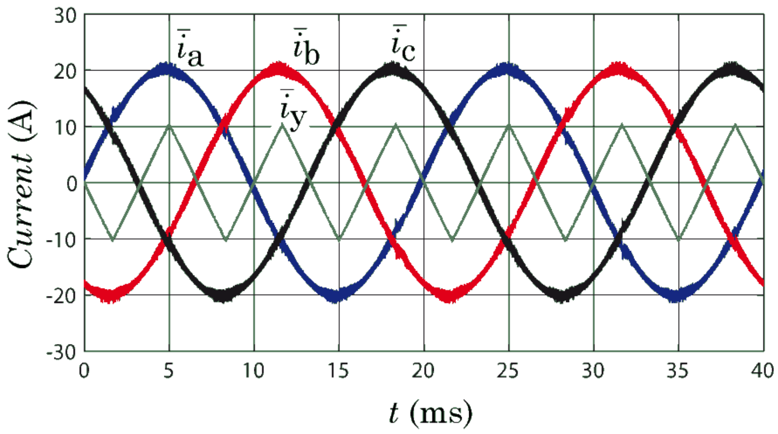


+ Controlled Output Voltage
+ Purely Sinusoidal Mains Current

+ 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)

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



- Patent Pending
- Switches Distributing the Injected Current could be Replaced by Passive Network

■ Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$

- Current to be Inj. into Phase *b*: $i_y = -i_b$

Duty Cycles: $T_+ \ \} \ k_1$
$T_- \ \} \ k_2$

- Current Formation:

$$k_1 I = i_a \qquad k_2 I = -i_c$$

$$i_y = -(1-k_1)I + (1-k_2)I = -i_b$$ ✓

$$\boxed{i_a + i_b + i_c = 0}$$

$$i_a = G \cdot u_{a0}$$
$$i_b = G \cdot u_{b0}$$
$$i_c = G \cdot u_{c0}$$

- Local Avg. Ind. Voltage : $\bar{u}_L \approx 0$

- Voltage Formation:

$$k_1 u_a + (1-k_1)u_b - (k_2 u_c + (1-k_2)u_b) = u_{pn}$$

$$k_1 u_{ab} - k_2 u_{cb} = u_{pn}$$

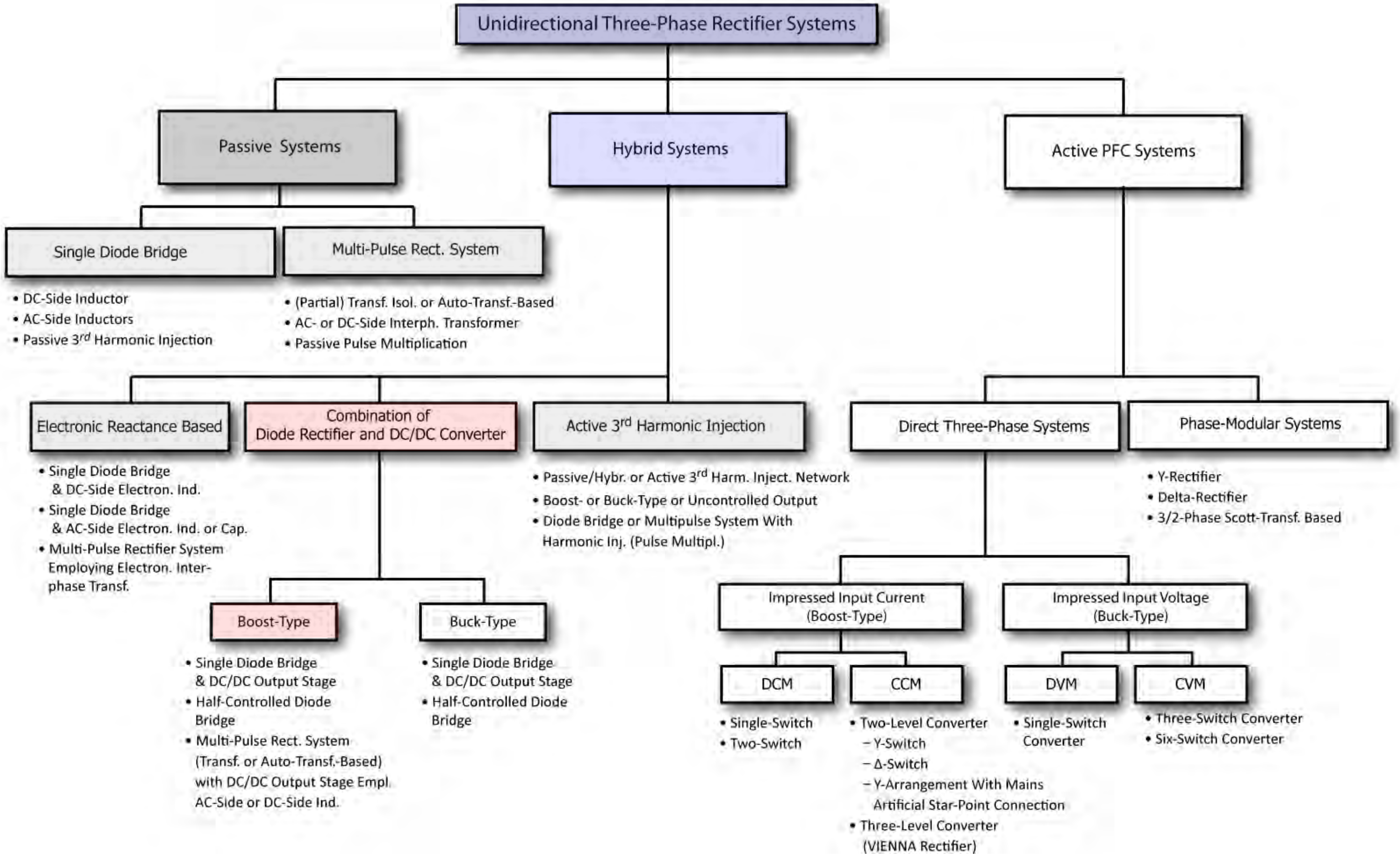
$$i_a u_{ab} + i_c u_{cb} = u_{pn} I$$

$$k_1 I = i_a$$
$$k_2 I = -i_c$$

$\boxed{i_a u_{ab} + i_c u_{cb} = P}$ **= const.** ✓

I **= const.** → u_{pn} **= const.**

► Classification of Unidirectional Rectifier Systems

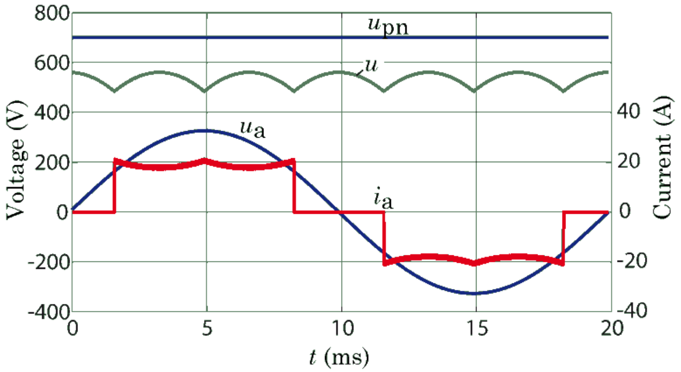


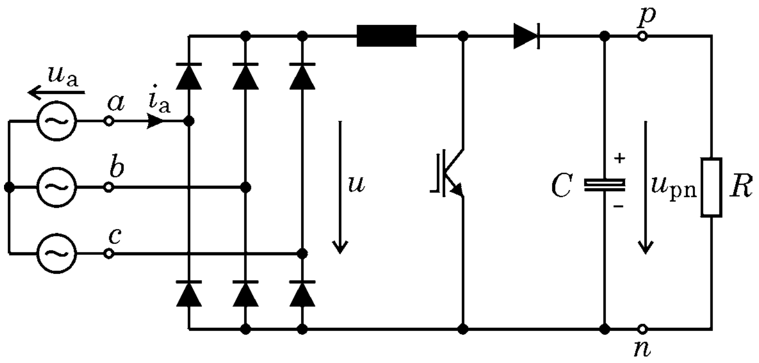
Unidirectional Three-Phase Rectifier Systems

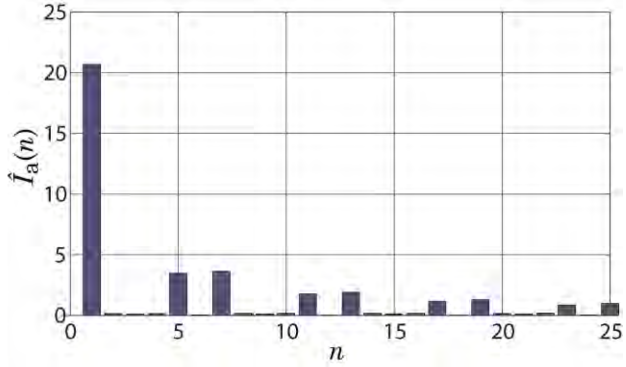
- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3rd Harmonic Injection
  - Multi-Pulse Rect. System
    - (Partial) Transf. Isol. or Auto-Transf.-Based
    - AC- or DC-Side Interph. Transformer
    - Passive Pulse Multiplication
- Hybrid Systems
  - Electronic Reactance Based
    - Single Diode Bridge & DC-Side Electron. Ind.
    - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
    - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
  - Combination of Diode Rectifier and DC/DC Converter
    - Boost-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
      - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
    - Buck-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
  - Active 3rd Harmonic Injection
    - Passive/Hybr. or Active 3rd Harm. Inject. Network
    - Boost- or Buck-Type or Uncontrolled Output
    - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
- Active PFC Systems
  - Direct Three-Phase Systems
    - Impressed Input Current (Boost-Type)
      - DCM
        - Single-Switch
        - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - Δ-Switch
          - Y-Arrangement With Mains Artificial Star-Point Connection
        - Three-Level Converter (VIENNA Rectifier)
    - Impressed Input Voltage (Buck-Type)
      - DVM
        - Single-Switch Converter
      - CVM
        - Three-Switch Converter
        - Six-Switch Converter
  - Phase-Modular Systems
    - Y-Rectifier
    - Delta-Rectifier
    - 3/2-Phase Scott-Transf. Based

▶ Diode Bridge Combined with DC/DC Boost Converter

U_{LL} = 3 x 400 V (f_N = 50 Hz)
P_{out} = 10 kW
λ = 0.952
THD= 32 %

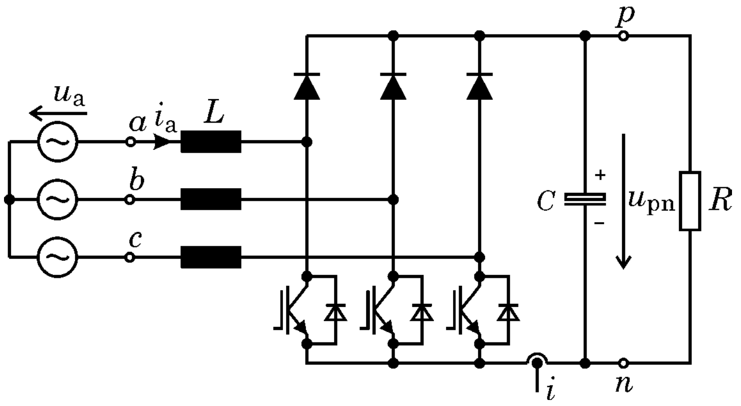






- Other Diode Bridge Output Current Impressing DC/DC Converter Topologies (e.g. SEPIC, Cuk) result in Same Mains Current Shape

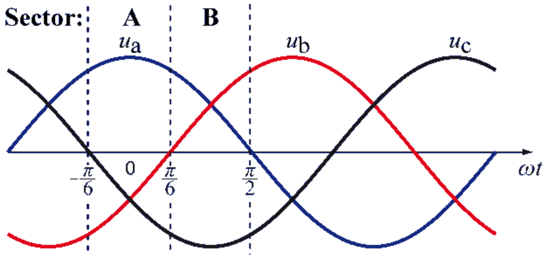
▶ Half-Controlled Rectifier Bridge Boost Converter



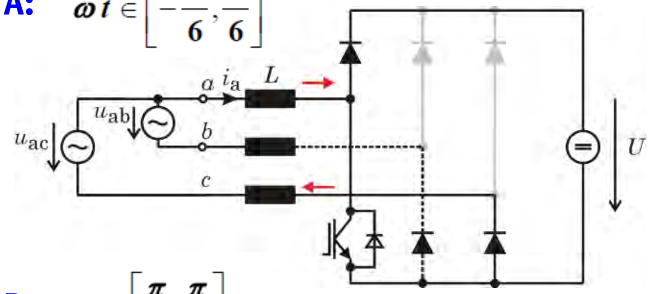
- Sinusoidal Current Control Only in Sectors with 2 Positive Phase Voltages, e.g. in Sector B
- In other Sectors, Only One Phase Current could be Shaped, e.g. in Sector A

\+ Controlled Output Voltage ($U > \sqrt{6}\,\hat{U}$)
\+ Low Complexity (e.g. Single Curr. Sensor)
\+ Low Conduction Losses

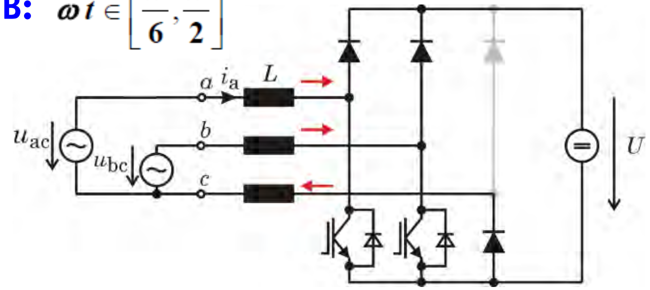
– Block Shaped Mains Current



Sector A: $\omega t \in \left[-\frac{\pi}{6}, \frac{\pi}{6}\right]$



Sector B: $\omega t \in \left[\frac{\pi}{6}, \frac{\pi}{2}\right]$



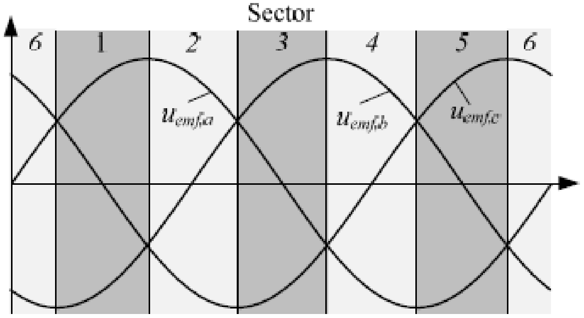
▶ Half-Controlled Rectifier Bridge Boost-Type Converter

■ Current Control Concepts

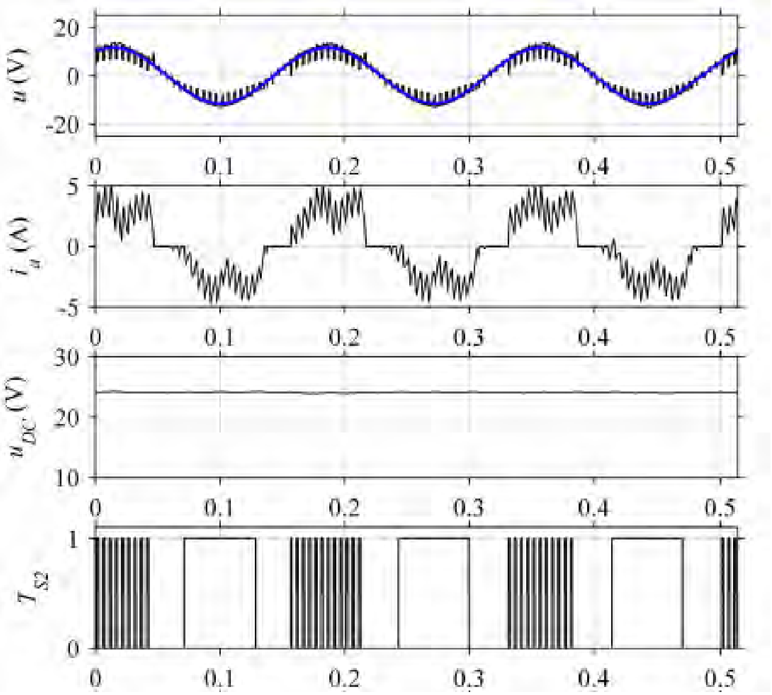
Option 1: All Switches Simultaneously Controlled with Same Duty-Cycle (Synchr. Modulation)

Option 2: Only Phase with most Positive Voltage is Modulated, Switch of Phase with most Neg. Voltage is Cont. Turned on for Lowering Conduction Losses in Case of Switch Implementation with MOSFETs. Middle Phase Switch is OFF; Results in Block Shaped Mains Current

Control Acc. to Option 2

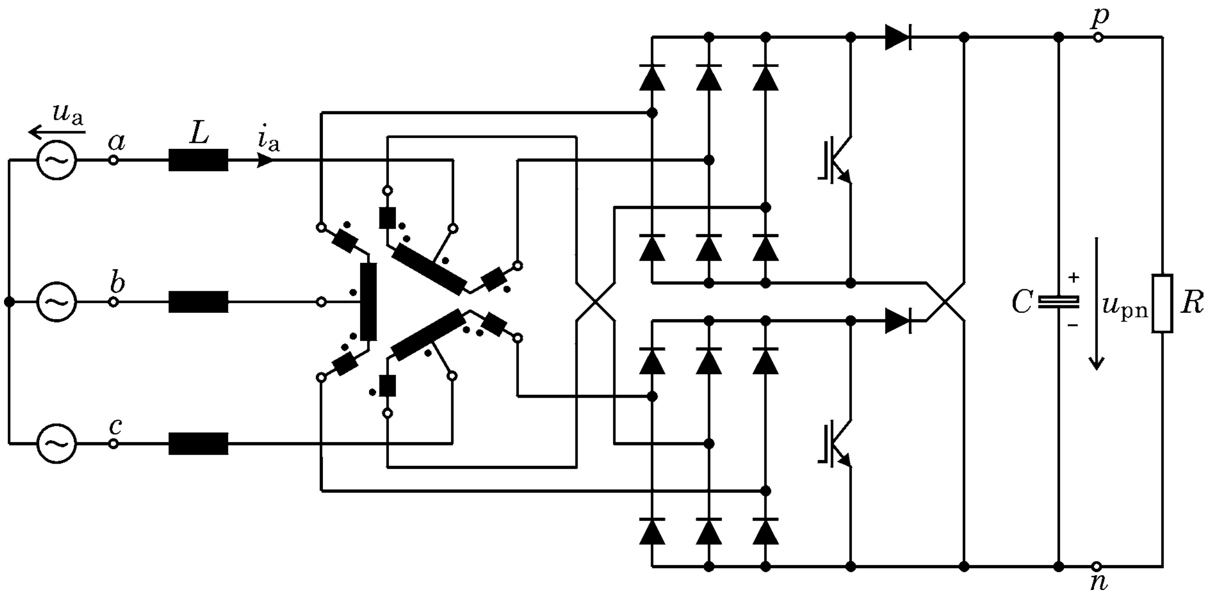


MOSFET S_2	PWM	PWM	off	on	on	off
MOSFET S_4	on	off	PWM	PWM	off	on
MOSFET S_6	off	on	on	off	PWM	PWM



▶ Boost-Type Auto-Transf.-Based 12-Pulse Hybrid Rectifier

■ Impressed Diode Bridge Output Voltages



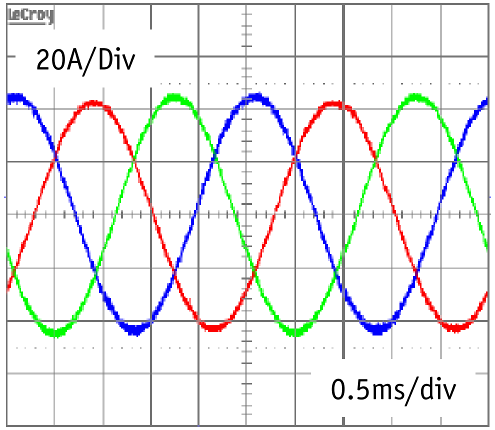
- + **Output Voltage Controlled**
- + **Sinusoidal Mains Current Shaping Possible**

- - **Active Converter Stage Processes Full Output Power**
- - **Low Frequency Magnetics Employed**

▶ Boost-Type Auto-Transf.-Based 12-Pulse Hybrid Rectifier

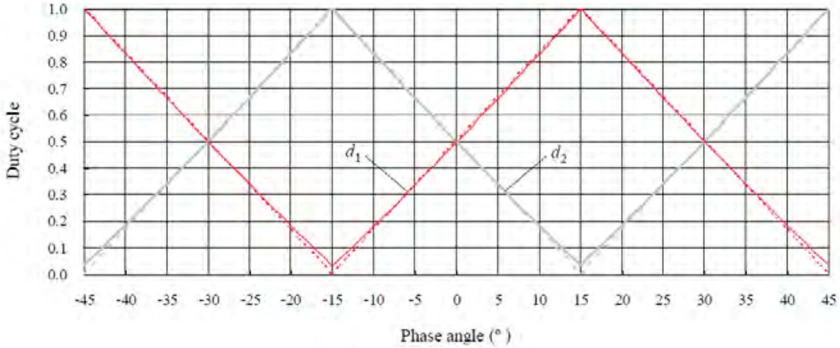
■ Experimental Results (Impressed Diode Bridge Output Voltages)

U_{LL} = 3 x 115 V (400 Hz)
P_o = 10 kW
U_o = 520 V
f_s = 60 kHz
THD_i = 3.1%



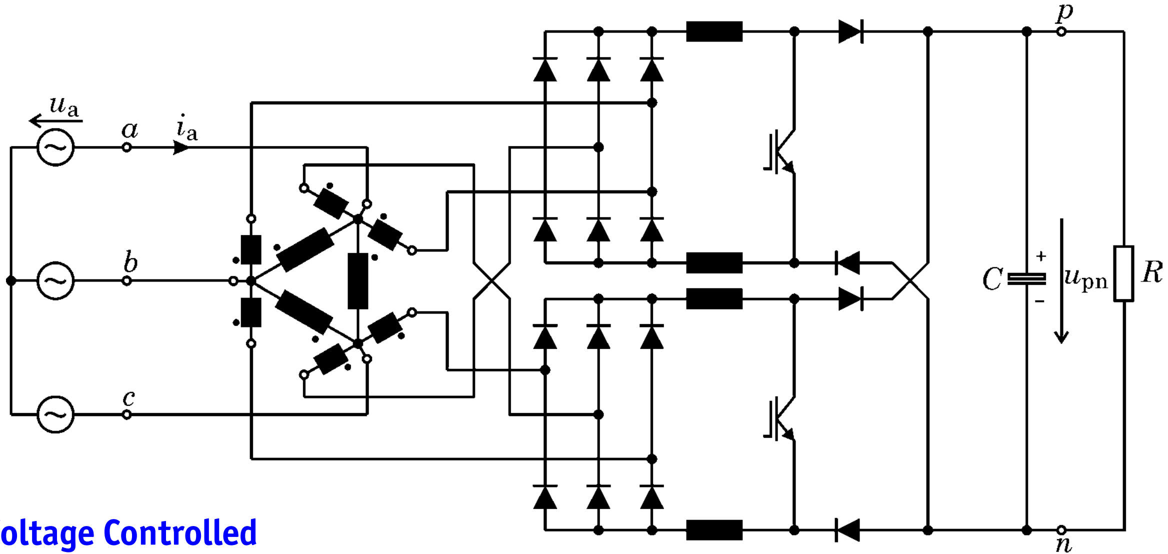
Input Currents

Duty Cycle Variation



▶ Boost-Type Auto-Transf.-Based 12-Pulse Hybrid Rectifier

■ Impressed Diode Bridge Output Currents

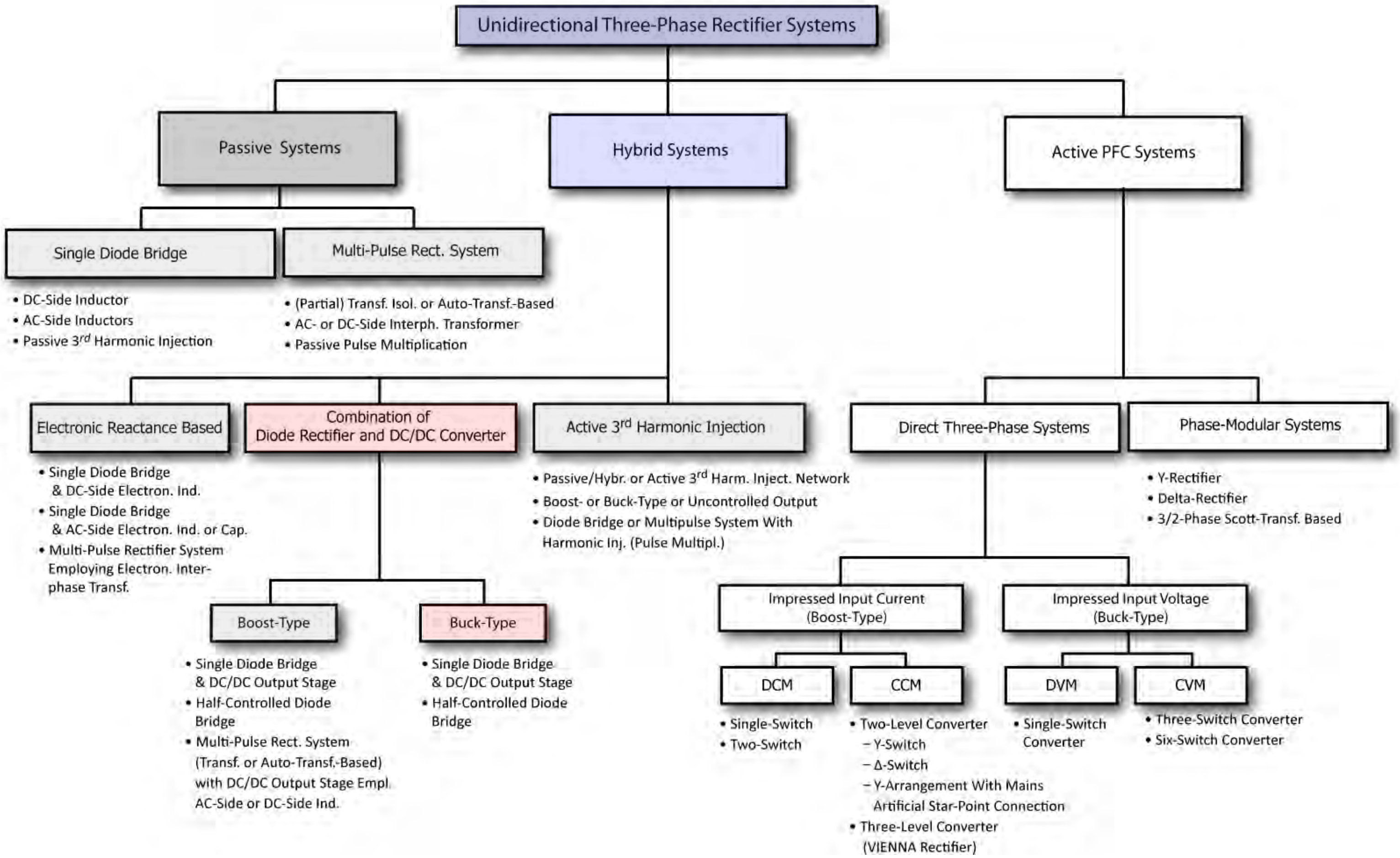


+ Output Voltage Controlled
+ Sinusoidal Mains Current Shaping Possible

- Active Converter Stage Processes Full Output Power
- Low Frequency Magnetics Employed

▶ Wide Varity of Further Topologies for Pulse Multiplication (e.g. 12p → 36p) which Process Only Part of Output Power but don´t Provide Output Voltage Control

► Classification of Unidirectional Rectifier Systems



Unidirectional Three-Phase Rectifier Systems

Passive Systems

Single Diode Bridge

- DC-Side Inductor
- AC-Side Inductors
- Passive 3rd Harmonic Injection

Multi-Pulse Rect. System

- (Partial) Transf. Isol. or Auto-Transf.-Based
- AC- or DC-Side Interph. Transformer
- Passive Pulse Multiplication

Hybrid Systems

Electronic Reactance Based

- Single Diode Bridge & DC-Side Electron. Ind.
- Single Diode Bridge & AC-Side Electron. Ind. or Cap.
- Multi-Pulse Rectifier System Employing Electron. Interphase Transf.

Combination of Diode Rectifier and DC/DC Converter

Boost-Type

- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge
- Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.

Buck-Type

- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge

Active 3rd Harmonic Injection

- Passive/Hybr. or Active 3rd Harm. Inject. Network
- Boost- or Buck-Type or Uncontrolled Output
- Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)

Active PFC Systems

Direct Three-Phase Systems

Impressed Input Current (Boost-Type)

DCM

- Single-Switch
- Two-Switch

CCM

- Two-Level Converter
  - Y-Switch
  - Δ-Switch
  - Y-Arrangement With Mains Artificial Star-Point Connection
- Three-Level Converter (VIENNA Rectifier)

Impressed Input Voltage (Buck-Type)

DVM

- Single-Switch Converter

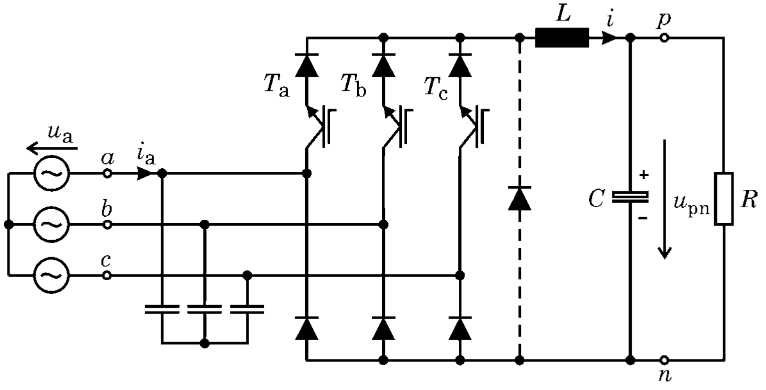
CVM

- Three-Switch Converter
- Six-Switch Converter

Phase-Modular Systems

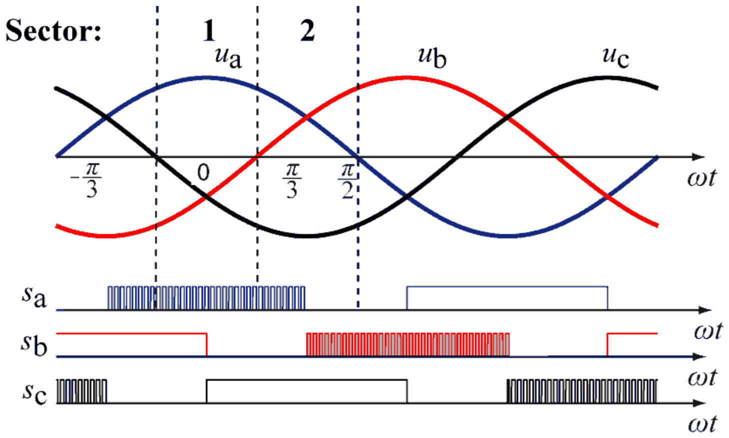
- Y-Rectifier
- Delta-Rectifier
- 3/2-Phase Scott-Transf. Based

▶ Half-Controlled Rectifier Bridge Buck-Type Converter



- \+ Controlled Output Voltage
- \+ Low Complexity
- \+ Low Conduction Losses

- − Block Shaped Mains Current

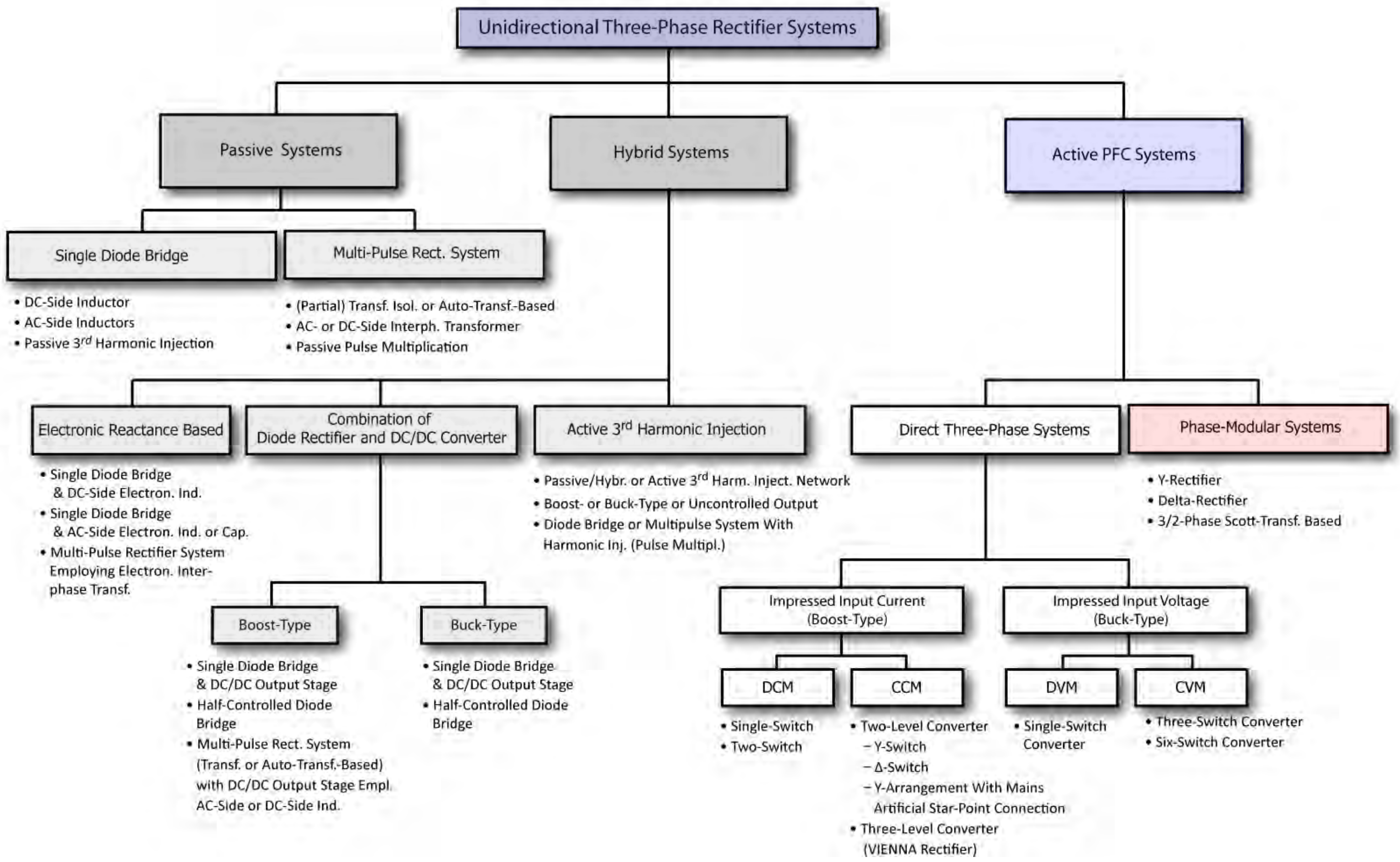


- Topology Limits Input Current Shaping to Intervals with Positive Phase Voltage

  Sector 1: Only i_a could be Controlled
  Sector 2: i_a and i_b could be Controlled

- Low Complexity Control: Only Current of Phase with most Positive Voltage Controlled; Switch of Phase with most Neg. Voltage Turned On Cont. for Providing a Free-Wheeling Path

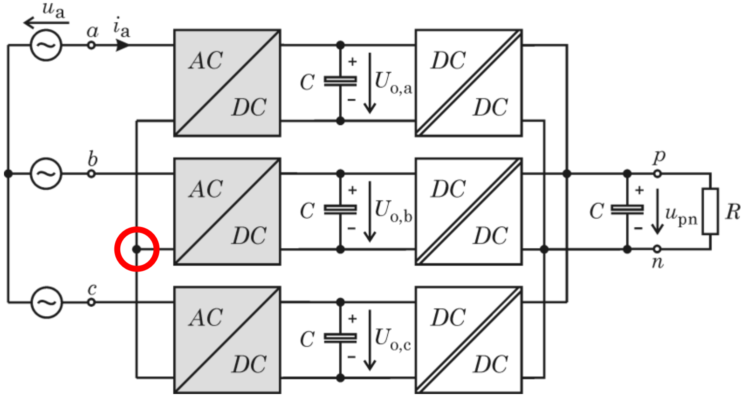
► Classification of Unidirectional Rectifier Systems



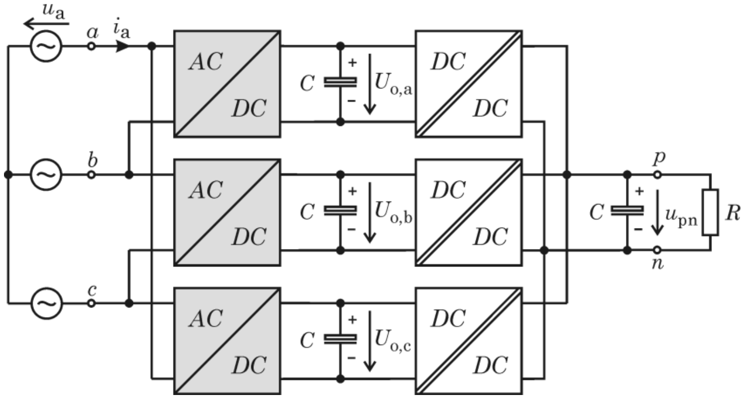
- Unidirectional Three-Phase Rectifier Systems
  - Passive Systems
    - Single Diode Bridge
      - DC-Side Inductor
      - AC-Side Inductors
      - Passive 3^{rd} Harmonic Injection
    - Multi-Pulse Rect. System
      - (Partial) Transf. Isol. or Auto-Transf.-Based
      - AC- or DC-Side Interph. Transformer
      - Passive Pulse Multiplication
  - Hybrid Systems
    - Electronic Reactance Based
      - Single Diode Bridge & DC-Side Electron. Ind.
      - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
      - Multi-Pulse Rectifier System Employing Electron. Interphase Transf.
    - Combination of Diode Rectifier and DC/DC Converter
      - Boost-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
        - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
      - Buck-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
    - Active 3^{rd} Harmonic Injection
      - Passive/Hybr. or Active 3^{rd} Harm. Inject. Network
      - Boost- or Buck-Type or Uncontrolled Output
      - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
  - Active PFC Systems
    - Direct Three-Phase Systems
      - Impressed Input Current (Boost-Type)
        - DCM
          - Single-Switch
          - Two-Switch
        - CCM
          - Two-Level Converter
            - Y-Switch
            - Δ-Switch
            - Y-Arrangement With Mains Artificial Star-Point Connection
          - Three-Level Converter (VIENNA Rectifier)
      - Impressed Input Voltage (Buck-Type)
        - DVM
          - Single-Switch Converter
        - CVM
          - Three-Switch Converter
          - Six-Switch Converter
    - Phase-Modular Systems
      - Y-Rectifier
      - Delta-Rectifier
      - 3/2-Phase Scott-Transf. Based

▶ Phase-Modular Rectifier Topologies

- **Y-Rectifier**

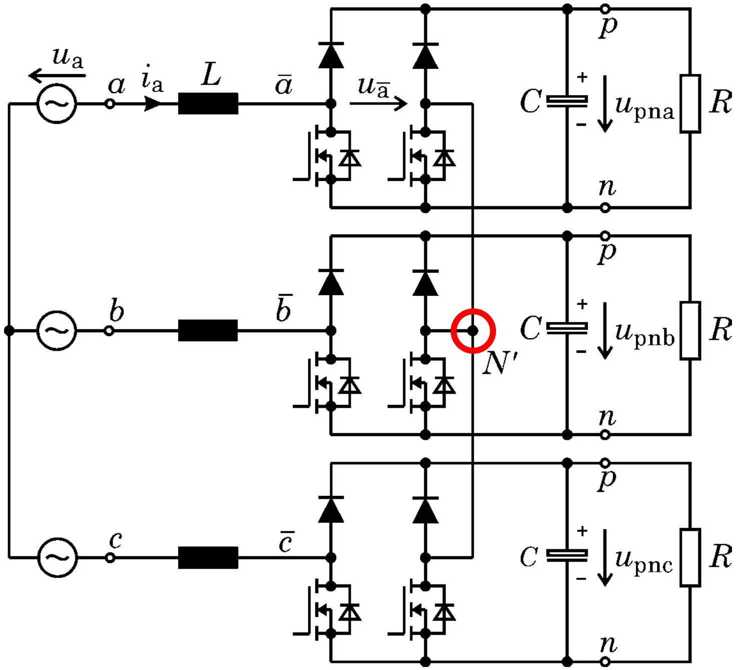


- **Δ-Rectifier**

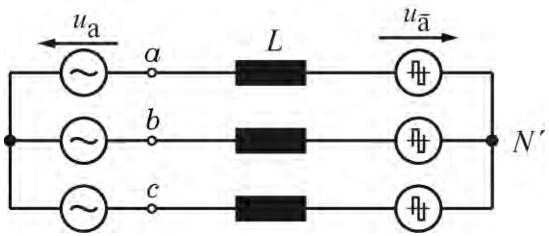


- **Individual DC Output Voltages of the Phase Units**
- **Isolated DC/DC Converter Stages Required for Forming Single DC Output**

▶ Y-Rectifier



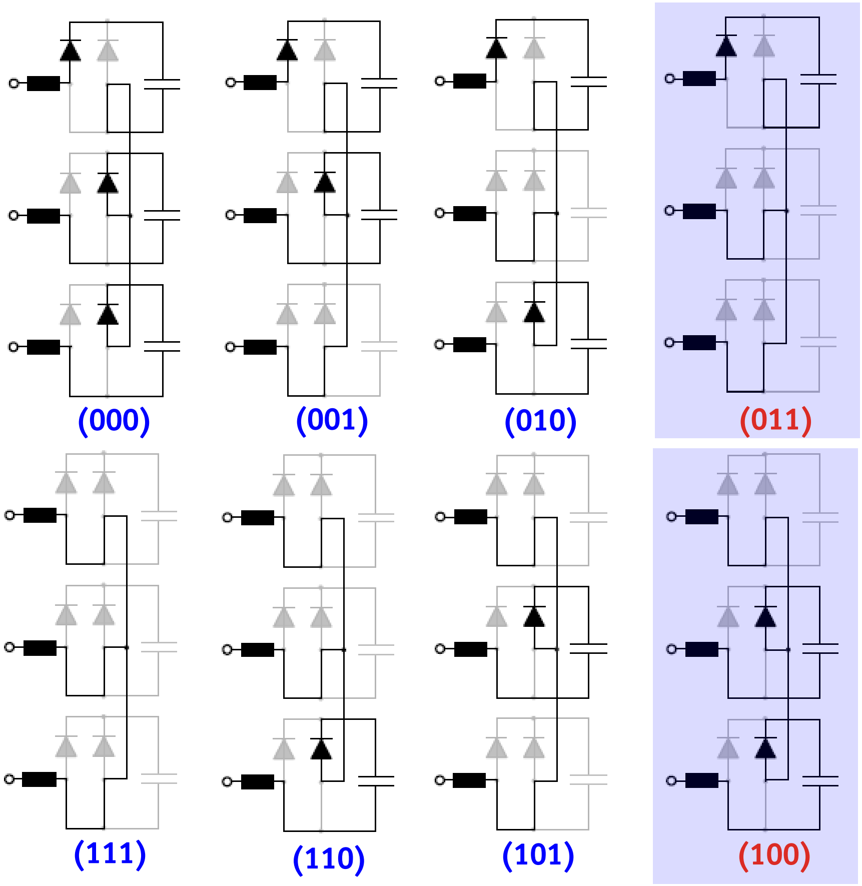
AC-Side Equivalent Circuit



- **Basic AC-Side Behavior Analogous to Direct Three-Phase Three-Level Rectifier Systems**

▶ Y-Rectifier

■ Cond. States for $i_a>0$, $i_b<0$, $i_c<0$ in Dep. on Transistor Switching States ($S_a\ S_b\ S_c$)



(000) (001) (010) (011)

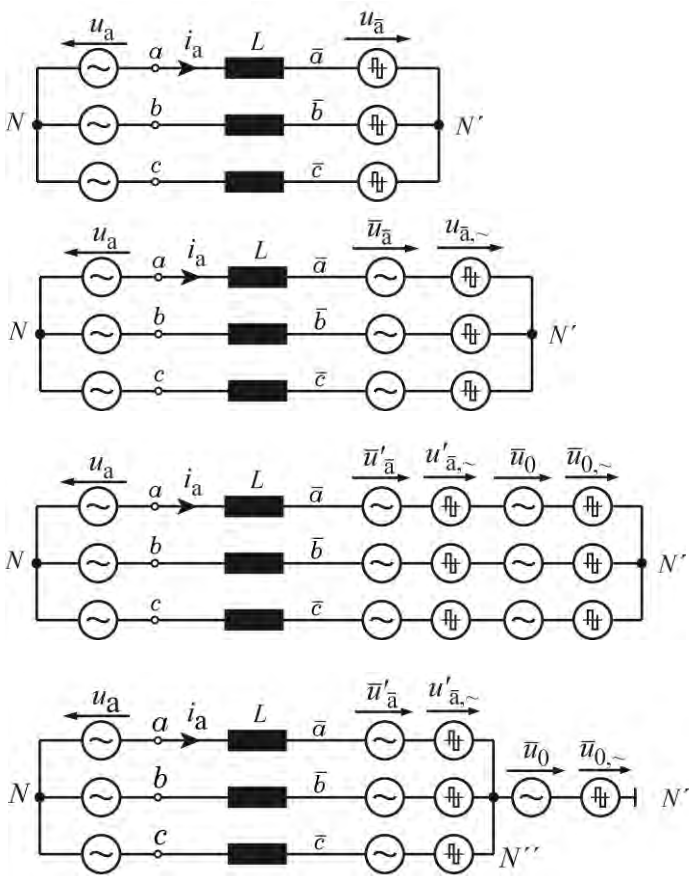
(111) (110) (101) (100)

Switching States (011) and (100)

- Redundant Concerning Formation of $u_{\bar{a}\bar{b}}$, $u_{\bar{b}\bar{c}}$, $u_{\bar{c}\bar{a}}$
- Inverse Concerning Charging of C_a and C_c (and C_b)

▶ Y-Rectifier

■ Equivalent Circuit and Voltage Formation



$$u_{\bar a} = \bar u_{\bar a} + u_{\bar a,\sim}$$
$$u_{\bar b} = \bar u_{\bar b} + u_{\bar b,\sim}$$
$$u_{\bar c} = \bar u_{\bar c} + u_{\bar c,\sim}$$

$$u_{\bar a} = u'_{\bar a} + u_0 \qquad u'_{\bar a} + u'_{\bar b} + u'_{\bar c} \overset{!}{=} 0$$
$$u_{\bar b} = u'_{\bar b} + u_0$$
$$u_{\bar c} = u'_{\bar c} + u_0$$

⇨ $$u_0 = \frac{1}{3}\left(u_{\bar a} + u_{\bar b} + u_{\bar c}\right)$$

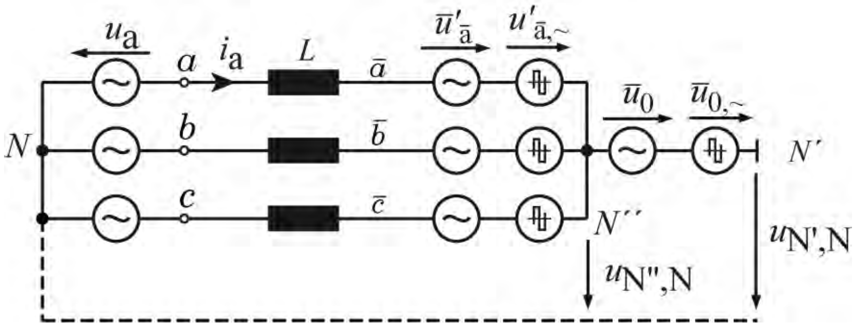
⇨ $$\bar u_{\bar a} = \bar u'_{\bar a} + \bar u_0$$
$$u_{\bar a,\sim} = u'_{\bar a,\sim} + u_{0,\sim}$$

(shown at the Example of Phase a)

▶ Y-Rectifier

■ Equivalent Circuit and Voltage Formation

$u_a + u_b + u_c = 0$



$$u_a = L\frac{di_a}{dt} + \bar{u}'_{\bar{a}} + u'_{\bar{a},\sim} + u_{N'',N}$$

$$u_b = L\frac{di_b}{dt} + \bar{u}'_{\bar{b}} + u'_{\bar{b},\sim} + u_{N'',N}$$

$$u_c = L\frac{di_c}{dt} + \bar{u}'_{\bar{c}} + u'_{\bar{c},\sim} + u_{N'',N}$$

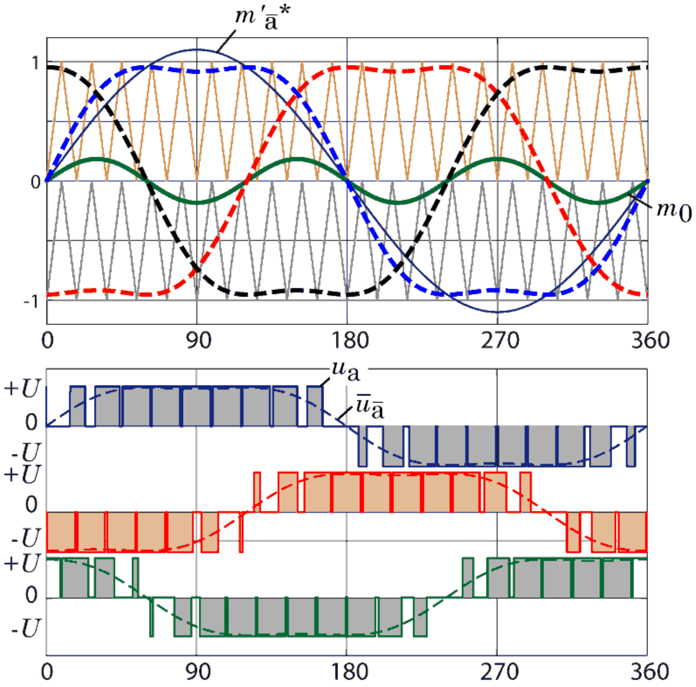
$$0 = 0 + 0 + 0 + 3u_{N'',N}$$

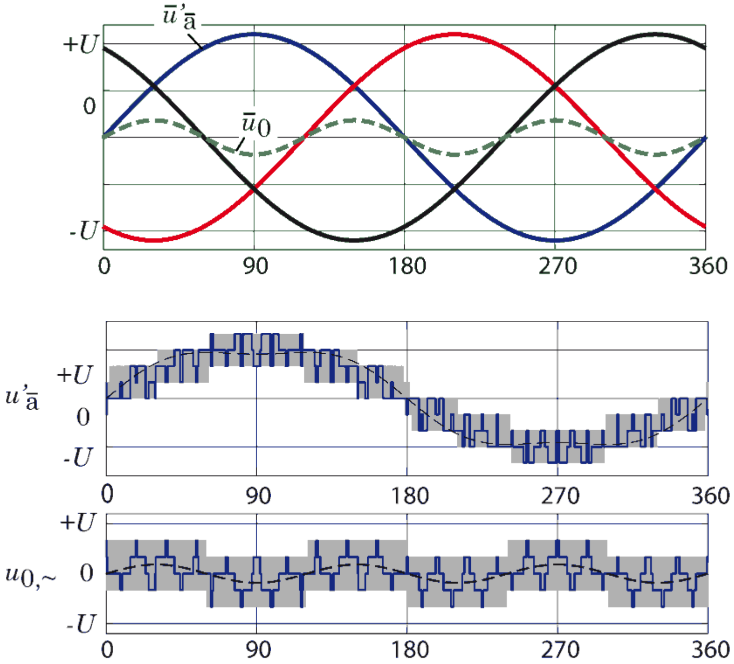
$$\Rightarrow \boxed{u_{N'',N} = 0}$$

- Voltage of the Star Point *N′* Defined by u_0 (CM-Voltage)

▶ Y-Rectifier

■ Modulation and Voltage Formation





$$m'_{\bar{a}} = \frac{\bar{u}'_{\bar{a}}}{U}$$

$$m_0 = \frac{\bar{u}_0}{U}$$

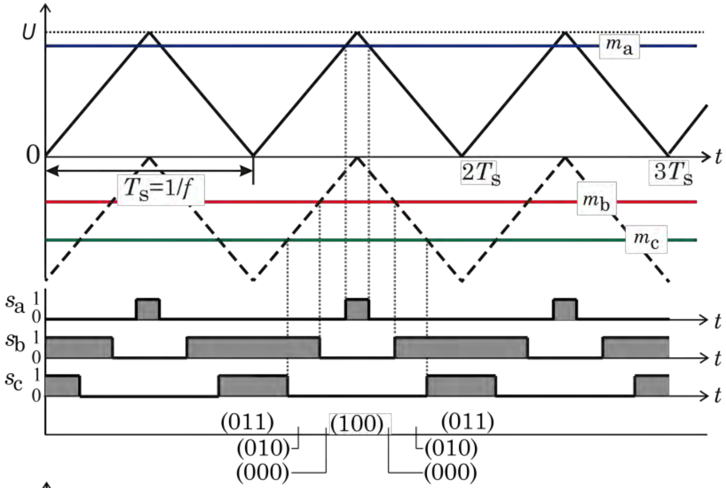
$$u_{0,\sim} = u_{NN',\sim}$$

- Addition of m_0 Increases Modulation Range from $\hat{U}_a = U$ to $\hat{U}_a = 2/\sqrt{3}U$
- Potential of Star Point N' Changes with LF ($\bar{u}_0$) and Switching Frequency ($u_{0,\sim}$)

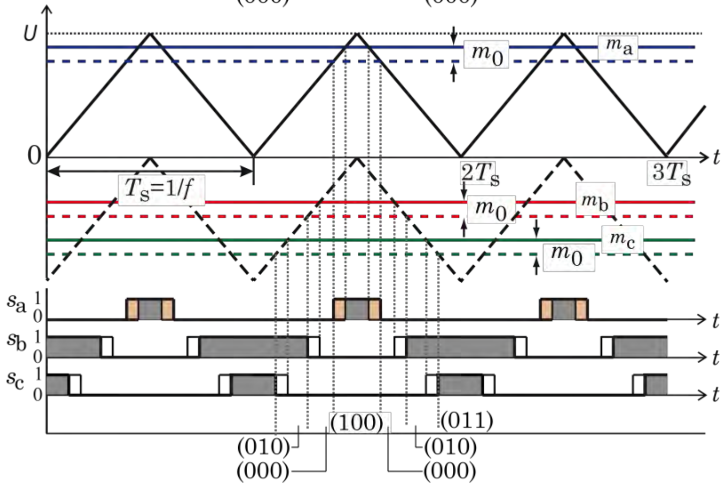
▶ Y-Rectifier

- **Balancing of Phase-Module DC-Output Voltages by DC Component of u_0 ($\overline{m}_0$)**

$\overline{m}_0 = 0$



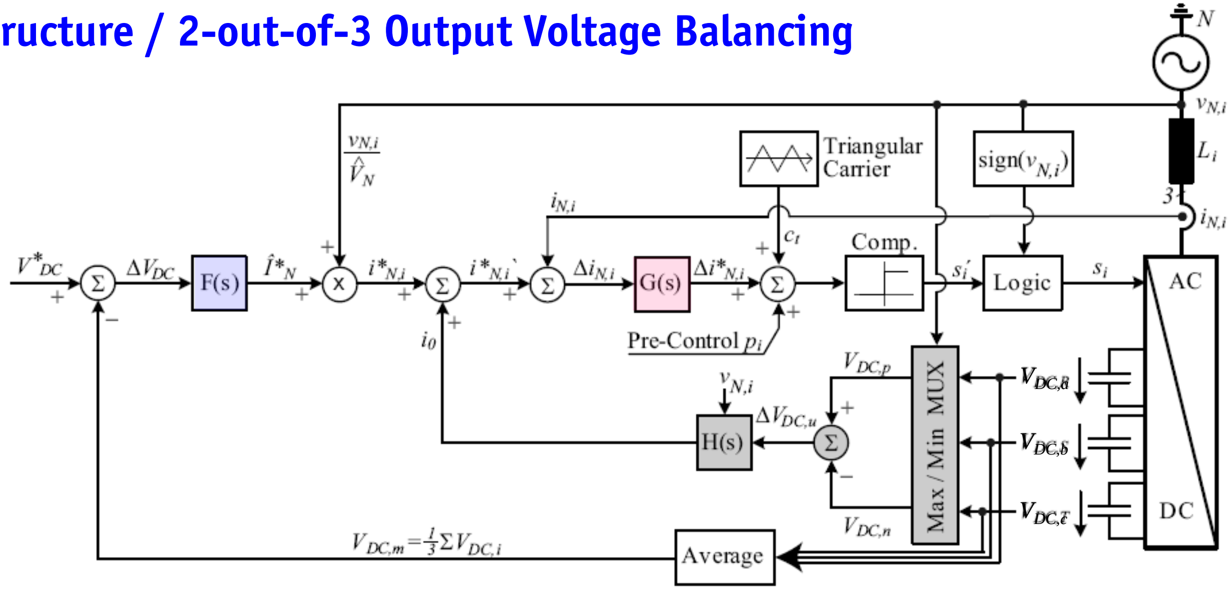
$\overline{m}_0 \neq 0$



- **$\overline{m}_0$ Only Changes the On-Time of Redundant Switching Stages, e.g. (100) and (011)**
- **No Influence on the AC-Side Current Formation– Allows Balancing of the Module Output Voltages Independent of Input Current Shaping**

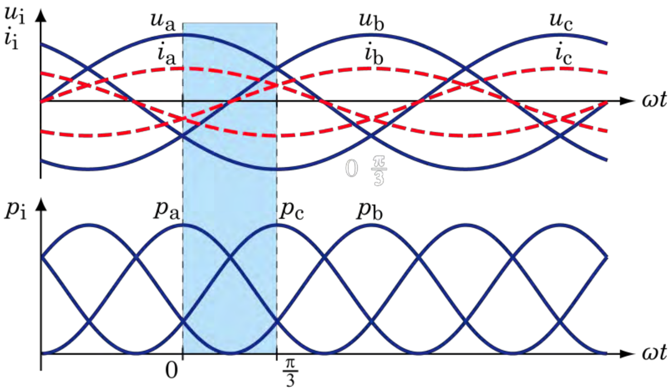
▶ Y-Rectifier

■ Control Structure / 2-out-of-3 Output Voltage Balancing



E.g.: $\omega t \in \left[0, \frac{\pi}{3}\right]$ $\max(u_a, u_b, u_c) = u_a$

$\min(u_a, u_b, u_c) = u_c$



- **Output Voltage Balancing Considers Only Output Cap. Voltage of Phase with Max. Voltage (e.g. Phase *a*) and Phase with Min. Voltage (e.q. Phase *b*).**

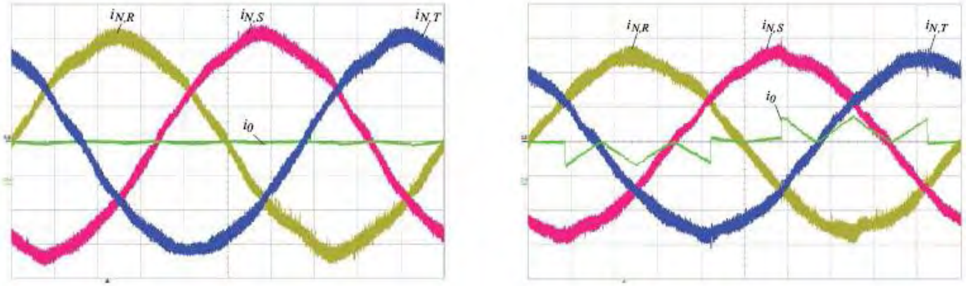
▶ Y-Rectifier

■ Experimental Verification of Output Voltage Balancing

- **Symm. Loading** $P_a = P_b = P_c = 1000$ W
- **Asymm. Loadng** $P_a = 730$ W, $P_b = P_c = 1000$ W

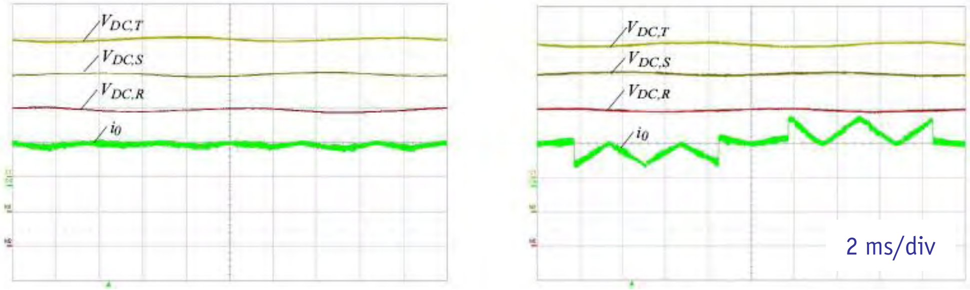
$U_N = 3 \times 230$ V (50 Hz)
$P_o = 3 \times 1$ kW
$U_o = 400$ V
$f_s = 58$ kHz
$L = 2.8$ mH (on AC-side)
$C = 660$ µF

Symm. Loading Asymm. Loading

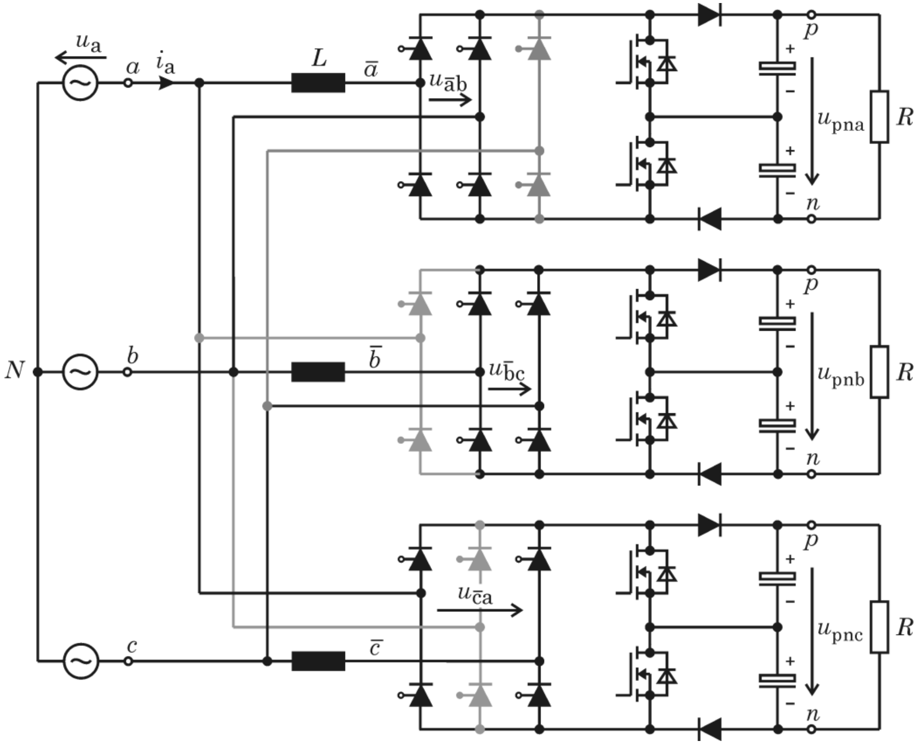


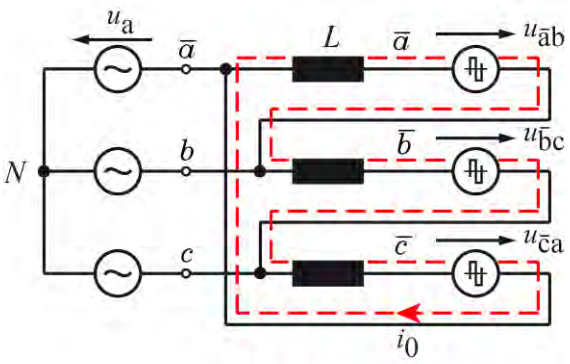
Input Phase Currents, Control Signal i_0, Output Voltages

$i_{N,i}$: 1 A/div
$V_{DC,i}$: 100 V/div



► Δ-Rectifier

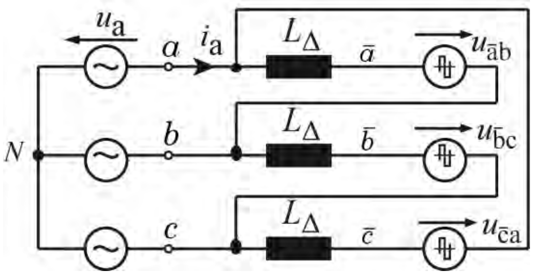




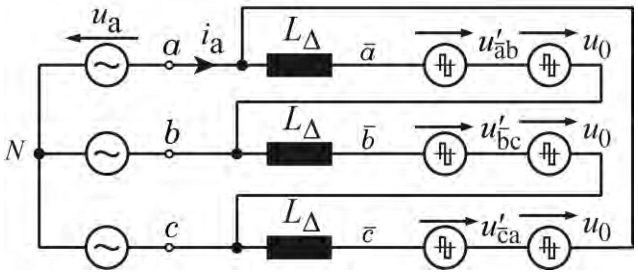
- **Connection of Each Module to All Phases / Rated Power also Available for Phase Loss !**

▶ Δ-Rectifier

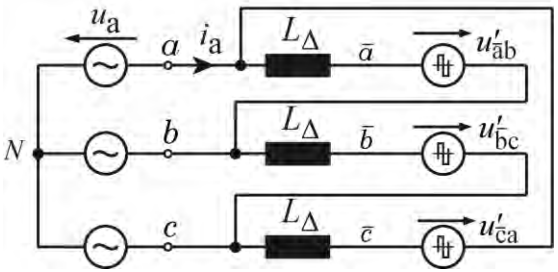
■ Derivation of Equivalent Circuit / Circulating Current Component i_0



$$u_{\bar{a}b} = u'_{\bar{a}b} + u_0$$
$$u_{\bar{b}c} = u'_{\bar{b}c} + u_0$$
$$u_{\bar{c}a} = u'_{\bar{c}a} + u_0$$



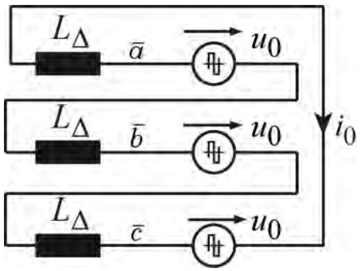
Def.: $u'_{\bar{a}b} + u'_{\bar{b}c} + u'_{\bar{c}a} = 0$



- Mains Phase Current Formed by $u'_{\bar{a}b}$, $u'_{\bar{b}c}$, $u'_{\bar{c}a}$
  and u_a, u_b, u_c
- Circulating Current i_0 Formed by u_0

$$u_0 = \frac{1}{3}\left(u_{\bar{a}b} + u_{\bar{b}c} + u_{\bar{c}a}\right)$$

- u_0 and/or i_0, which does not Appear in i_a, i_b and i_c, can be Maximized by Proper Synchron. of Module PWM Carrier Signals; Accordingly, Switching Frequency Components of $u'_{\bar{a}b}$, $u'_{\bar{b}c}$ and $u'_{\bar{c}a}$ are Minimized



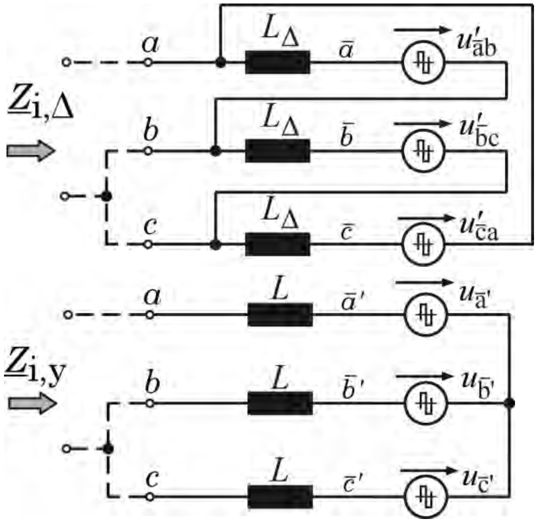
▶ Δ-Rectifier

■ Y-Equivalent Circuit Describing Mains Current Formation

- **Equiv. Conc. No-Load Voltage at Terminals *a*, *b*, *c* (No Circ. Current i_0, i.e. No Voltage Drop across L_Δ**

$$u_{ab} = u'_{\overline{a}b} = u_{\overline{a}'} - u_{\overline{b}'}$$

$$u_{bc} = u_{\overline{b}c} = u_{\overline{b}'} - u_{\overline{c}'}$$



- **Equiv. Y-Voltage Syst. should not Contain Zero Sequ. Comp.**

$$u_{\overline{a}'} + u_{\overline{b}'} + u_{\overline{c}'} \overset{!}{=} 0 \quad \Longrightarrow \quad u'_{\overline{b}c} = u_{\overline{b}'} - (-u_{\overline{a}'} - u_{\overline{b}'})$$

$$u'_{\overline{b}c} = 2u_{\overline{b}'} + u_{\overline{a}'}$$

$$u_{\overline{a}'} = \frac{1}{3}(u'_{\overline{a}b} - \overline{u}'_{\overline{c}a})$$

$$u_{\overline{b}'} = \frac{1}{3}(u'_{\overline{b}c} - u'_{\overline{a}b})$$

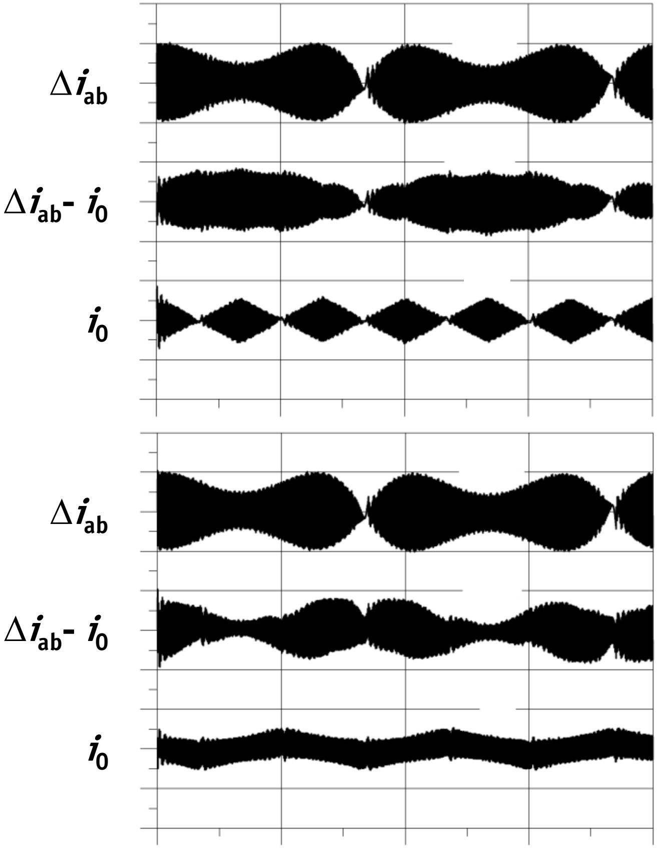
$$u_{\overline{c}}' = \frac{1}{3}(u'_{\overline{c}a} - u'_{\overline{b}c})$$

- **Equiv. Concerning Input Impedance between any Terminals**

$$\underline{Z}_{i,\Delta} = \underline{Z}_{i,y} \quad \Longrightarrow \quad L_\Delta // L_\Delta = \frac{1}{2}L_\Delta = L_Y + L_Y // L_Y = \frac{3}{2}L_Y \qquad \boxed{L_Y = \frac{1}{3}L_\Delta}$$

▶ Δ-Rectifier

■ Circulating Current Max. / Minimization of Mains Current Ripple



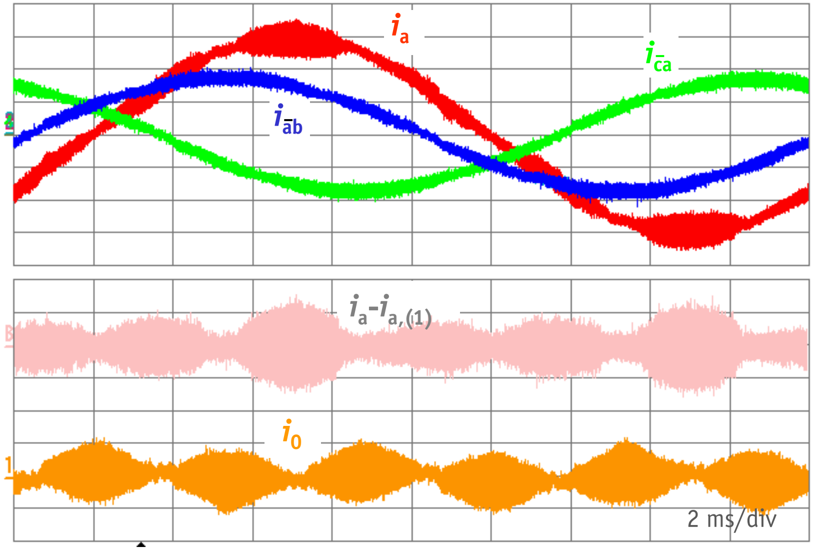
U_{LL} = 3 x 480 V (50 Hz)
P_o = 5 kW
U_o = 800 V
f_s = 25 kHz
L = 2.1 mH (on AC-Side)

- For Proper Phase Shift of Module PWM Carrier Signals a Share of the Line-to-Line Current Ripple can be Confined into the Delta Connection.

▶ Δ-Rectifier

■ Experimental Results

U_{LL} = 3 x 480 V (50 Hz)
P_o = 5 kW
U_o = 800 V
f_s = 25 kHz
L = 2.1 mH (on AC-Side)

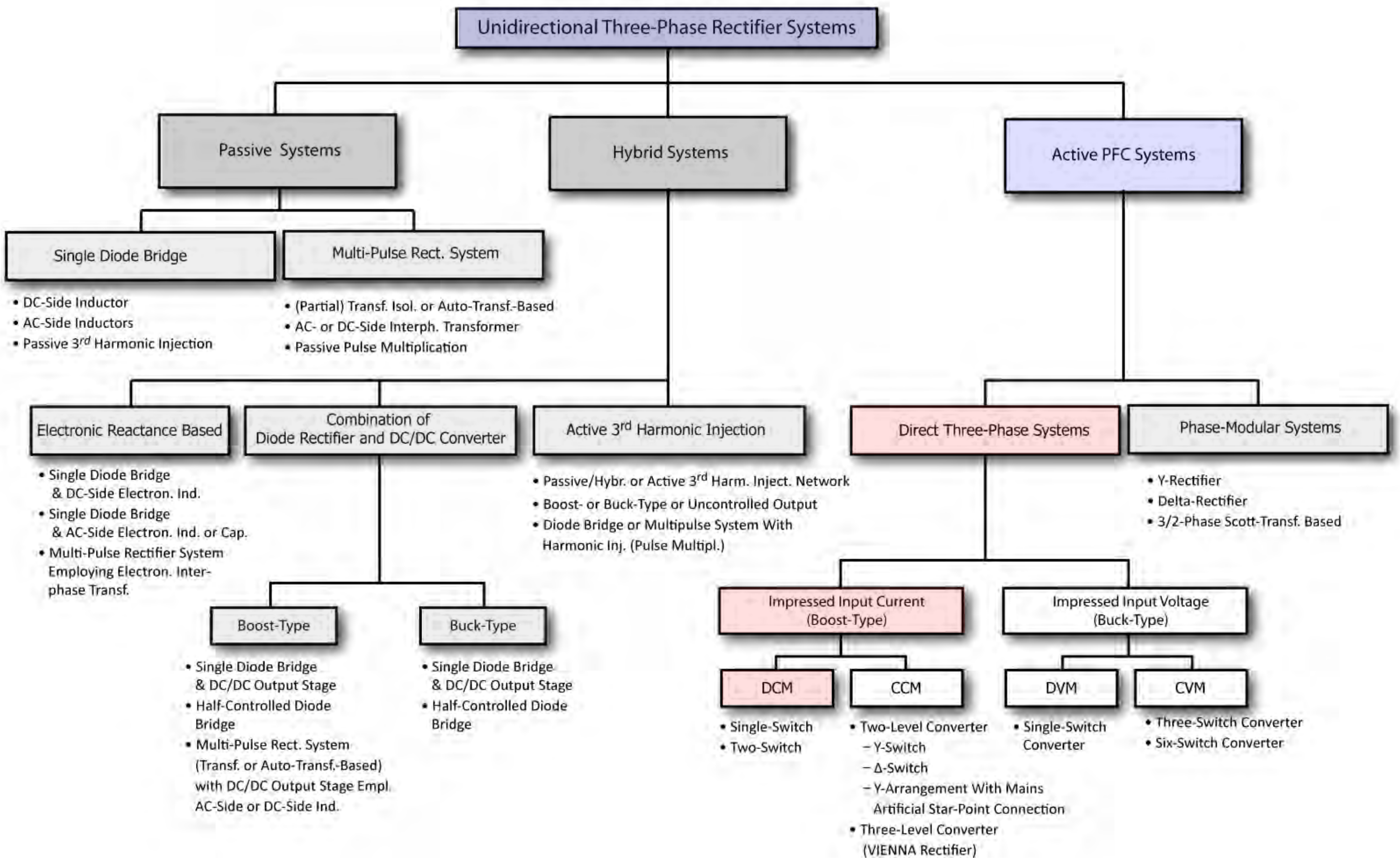


i_a, $i_{\bar{a}b}$, $i_{\bar{c}a}$: 5 A/div; i_a-$i_{a,(1)}$, i_0: 2 A/div

- Formation of Input Phase Current $i_a = i_{\bar{a}b} - i_{\bar{c}a}$
- Circulating Zero Sequence Current i_0

Coffee Break !

▶ Classification of Unidirectional Rectifier Systems



Unidirectional Three-Phase Rectifier Systems

Passive Systems

Single Diode Bridge
- DC-Side Inductor
- AC-Side Inductors
- Passive 3rd Harmonic Injection

Multi-Pulse Rect. System
- (Partial) Transf. Isol. or Auto-Transf.-Based
- AC- or DC-Side Interph. Transformer
- Passive Pulse Multiplication

Hybrid Systems

Electronic Reactance Based
- Single Diode Bridge & DC-Side Electron. Ind.
- Single Diode Bridge & AC-Side Electron. Ind. or Cap.
- Multi-Pulse Rectifier System Employing Electron. Interphase Transf.

Combination of Diode Rectifier and DC/DC Converter

Boost-Type
- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge
- Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.

Buck-Type
- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge

Active 3rd Harmonic Injection
- Passive/Hybr. or Active 3rd Harm. Inject. Network
- Boost- or Buck-Type or Uncontrolled Output
- Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)

Active PFC Systems

Direct Three-Phase Systems

Impressed Input Current (Boost-Type)

DCM
- Single-Switch
- Two-Switch

CCM
- Two-Level Converter
  - Y-Switch
  - Δ-Switch
  - Y-Arrangement With Mains Artificial Star-Point Connection
- Three-Level Converter (VIENNA Rectifier)

Impressed Input Voltage (Buck-Type)

DVM
- Single-Switch Converter

CVM
- Three-Switch Converter
- Six-Switch Converter

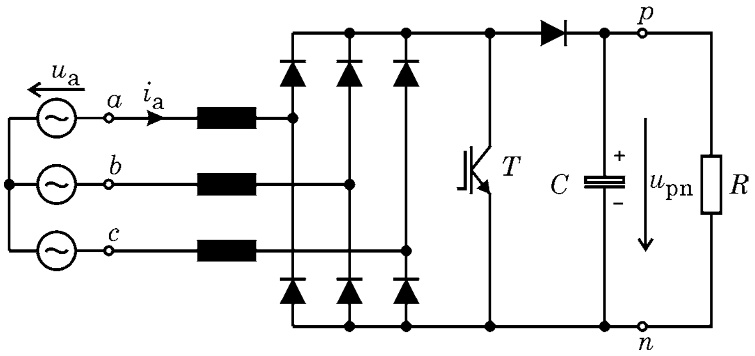
Phase-Modular Systems
- Y-Rectifier
- Delta-Rectifier
- 3/2-Phase Scott-Transf. Based

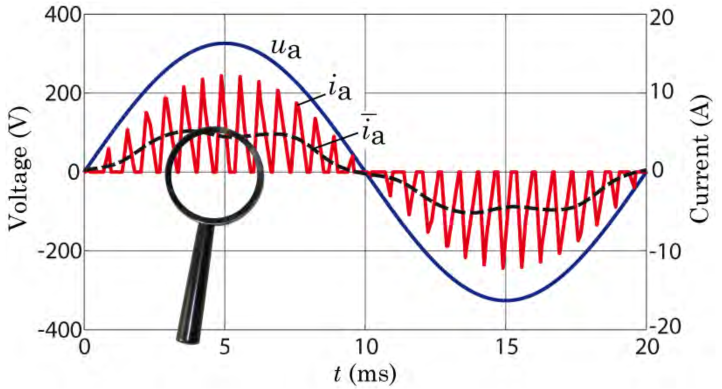
▶ Single-Switch + Boost-Type DCM Converter Topology

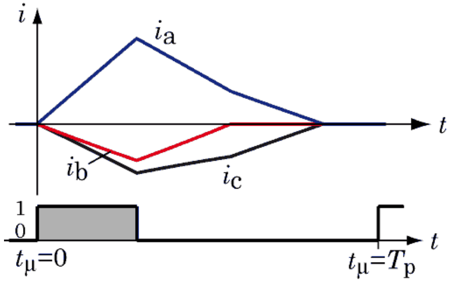
\+ Low Complexity / Single Switch
\+ No PWM, Constant Duty Cycle Operation
\+ No Current Measurement

− High Peak Current Stress
− Low Frequ. Distortion of Mains Currents / Dep. on $U_{pn}/\hat{U}$
− High EMI Filtering Effort

U_{LL} = 3 x 400 V (50Hz)
P_o = 2.5 kW
U_o = 800 V
THD_i = 13.7 %

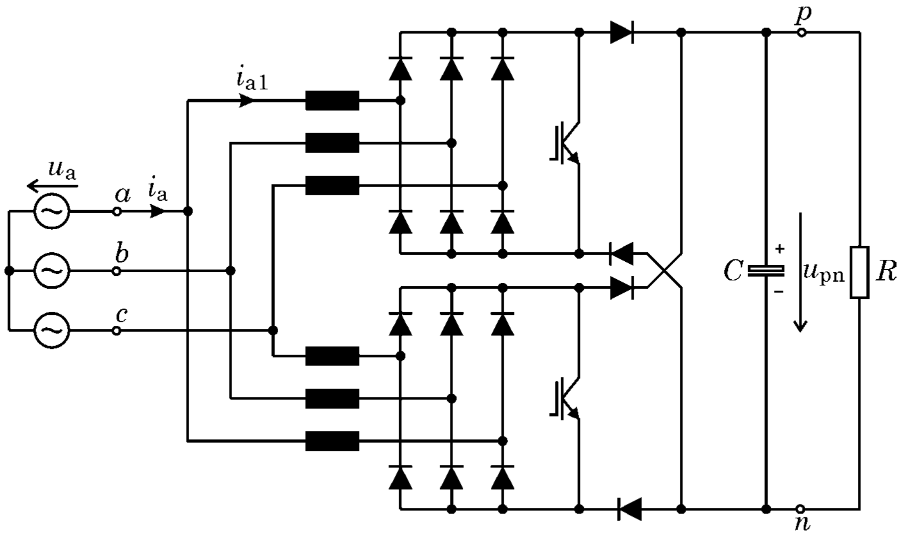


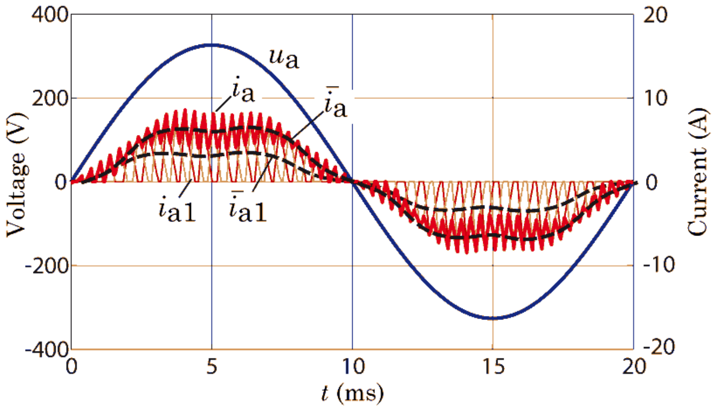




- Improvement of Mains Current Shape by 6th Harmonic Duty Cycle Modulation or Boundary Mode Operation
- Reduction of EMI Filtering Effort by Interleaving

► Two Interleaved Single-Switch Boost-Type DCM Converter Stages

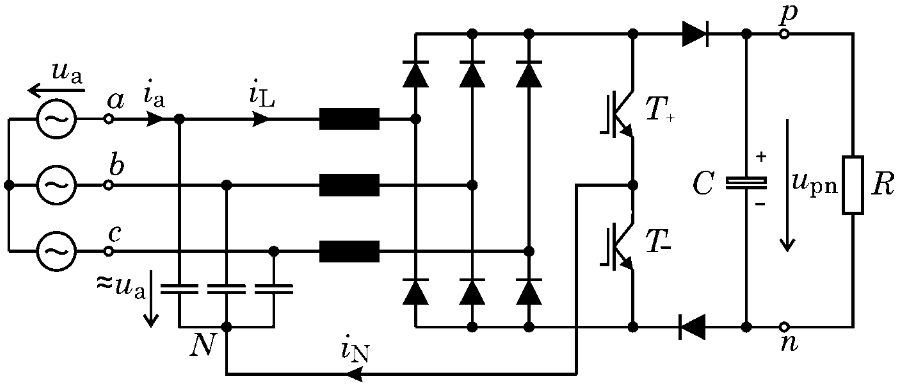




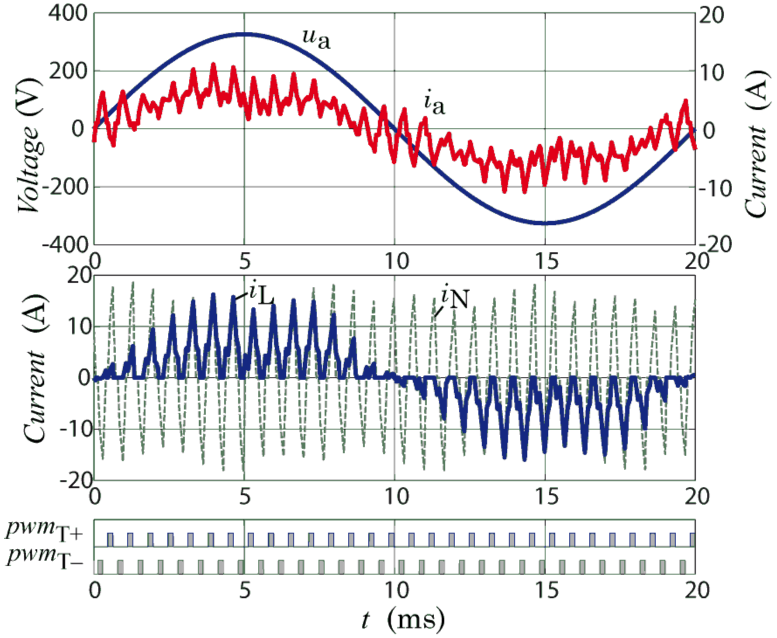
- + Interleaving Reduces Switching Frequency Input Current Ripple
- + For Low Power Only One Unit Could be Operated – Higher Efficiency

- – Low Frequency Mains Current Distortion Still Remaining
- – Relatively High Implementation Effort

▶ Two-Switch Boost-Type DCM Converter Topology



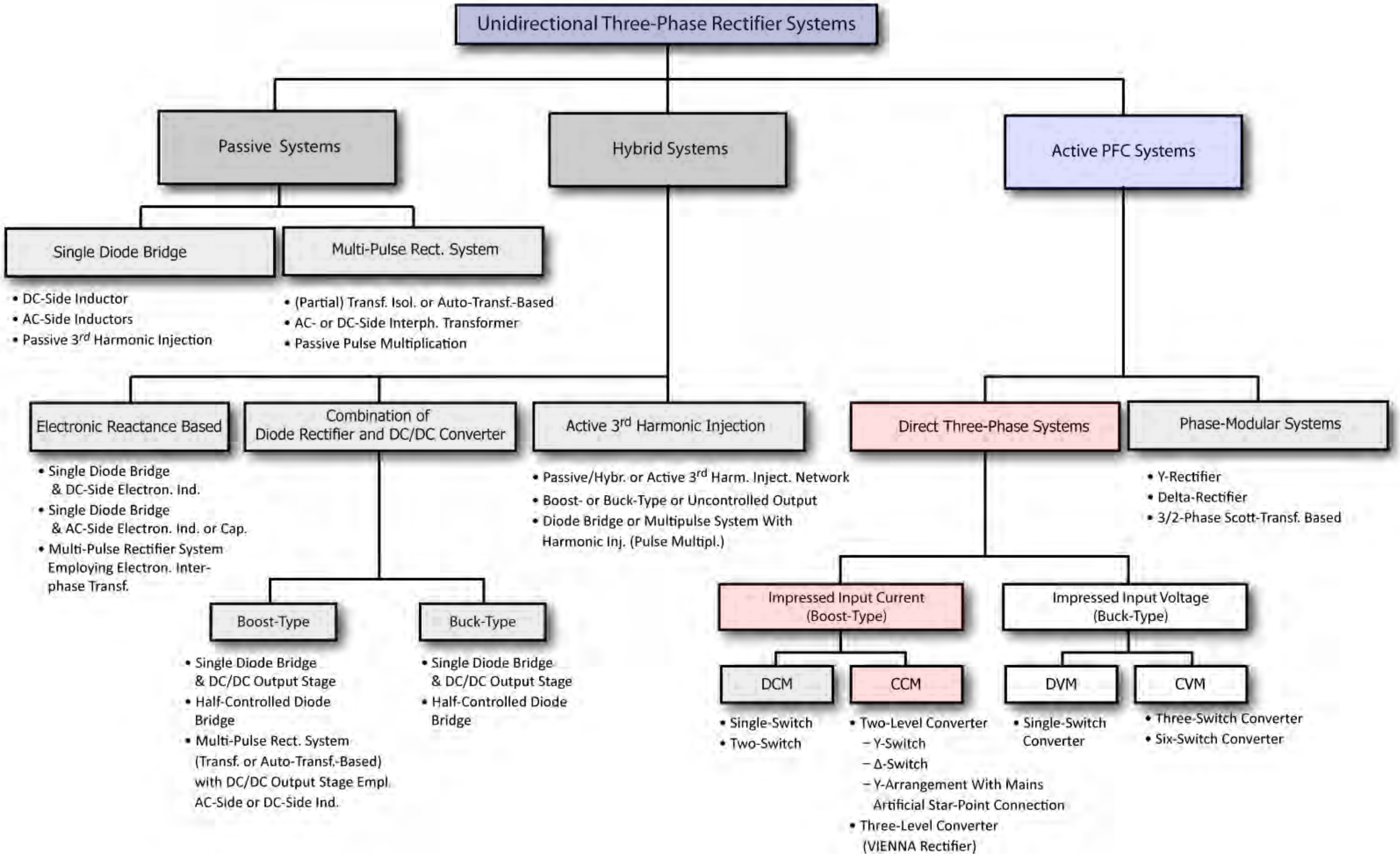
U_{LL} = 3 x 400 V
P_o = 2.5 kW
U_o = 700 V
THD_i = 9 %



- \+ Slightly Lower THD_I for same $U_{pn}/\hat{U}_N$ Component as Single-Switch DCM Converter
- – Large Switching Frequency CM Output Voltage Comp.
- – High Input Capacitor Current Stress

- ● Artificial Capacitive Neutral Point N
- ● Decoupling of the Phases
- ● Pros and Cons. as for Single-Switch Converter
- ● T_+ and T_- Could also be Gated Simultaneously

▶ Classification of Unidirectional Rectifier Systems

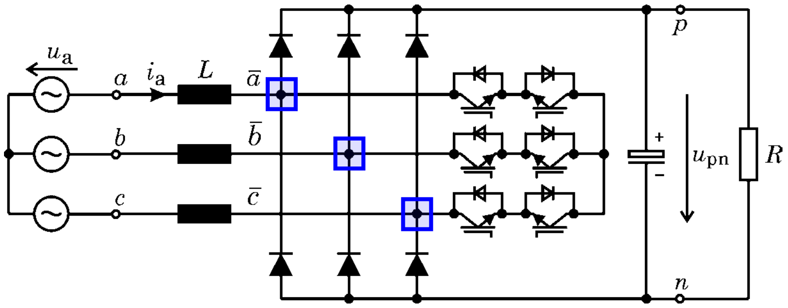


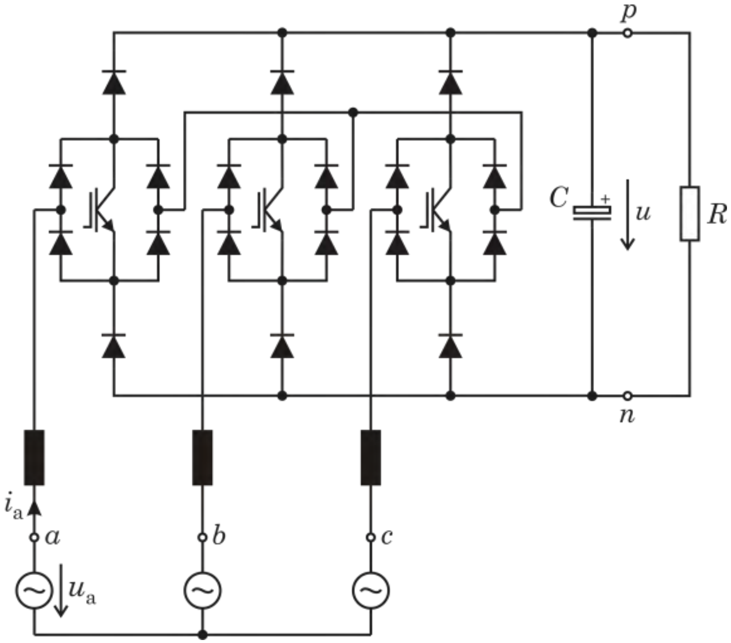
- Unidirectional Three-Phase Rectifier Systems
  - Passive Systems
    - Single Diode Bridge
      - DC-Side Inductor
      - AC-Side Inductors
      - Passive 3rd Harmonic Injection
    - Multi-Pulse Rect. System
      - (Partial) Transf. Isol. or Auto-Transf.-Based
      - AC- or DC-Side Interph. Transformer
      - Passive Pulse Multiplication
  - Hybrid Systems
    - Electronic Reactance Based
      - Single Diode Bridge & DC-Side Electron. Ind.
      - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
      - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
    - Combination of Diode Rectifier and DC/DC Converter
      - Boost-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
        - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
      - Buck-Type
        - Single Diode Bridge & DC/DC Output Stage
        - Half-Controlled Diode Bridge
    - Active 3rd Harmonic Injection
      - Passive/Hybr. or Active 3rd Harm. Inject. Network
      - Boost- or Buck-Type or Uncontrolled Output
      - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
  - Active PFC Systems
    - Direct Three-Phase Systems
      - Impressed Input Current (Boost-Type)
        - DCM
          - Single-Switch
          - Two-Switch
        - CCM
          - Two-Level Converter
            - Y-Switch
            - Δ-Switch
            - Y-Arrangement With Mains Artificial Star-Point Connection
          - Three-Level Converter (VIENNA Rectifier)
      - Impressed Input Voltage (Buck-Type)
        - DVM
          - Single-Switch Converter
        - CVM
          - Three-Switch Converter
          - Six-Switch Converter
    - Phase-Modular Systems
      - Y-Rectifier
      - Delta-Rectifier
      - 3/2-Phase Scott-Transf. Based

Two-Level CCM Boost-Type PFC Rectifier Systems

- *Y-Switch Rectifier*
- *Δ-Switch Rectifier*

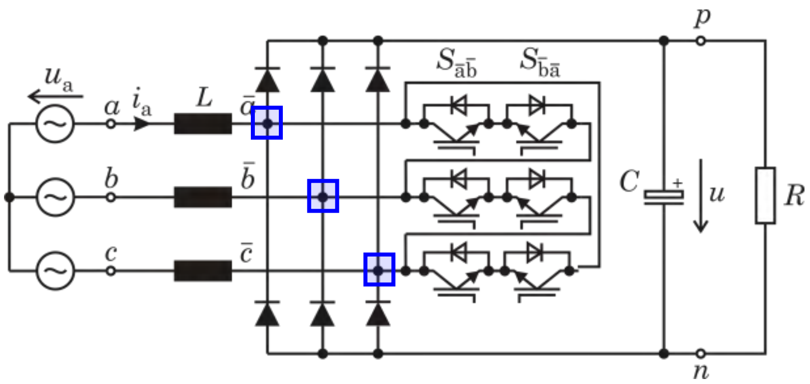
► Y-Switch Rectifier

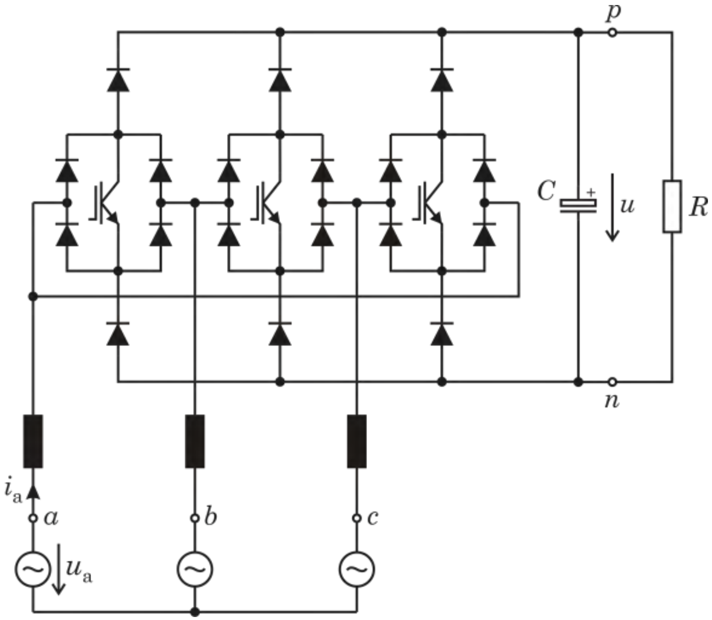




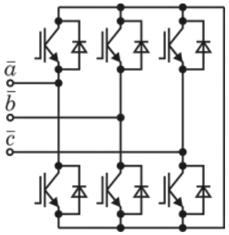
- **Proper Control of Power Transistors Allows Formation of PWM Voltages at $\overline{a}$, $\overline{b}$, $\overline{c}$ and/or Impression of Sinusoidal Mains Current**

▶ Δ-Switch Rectifier





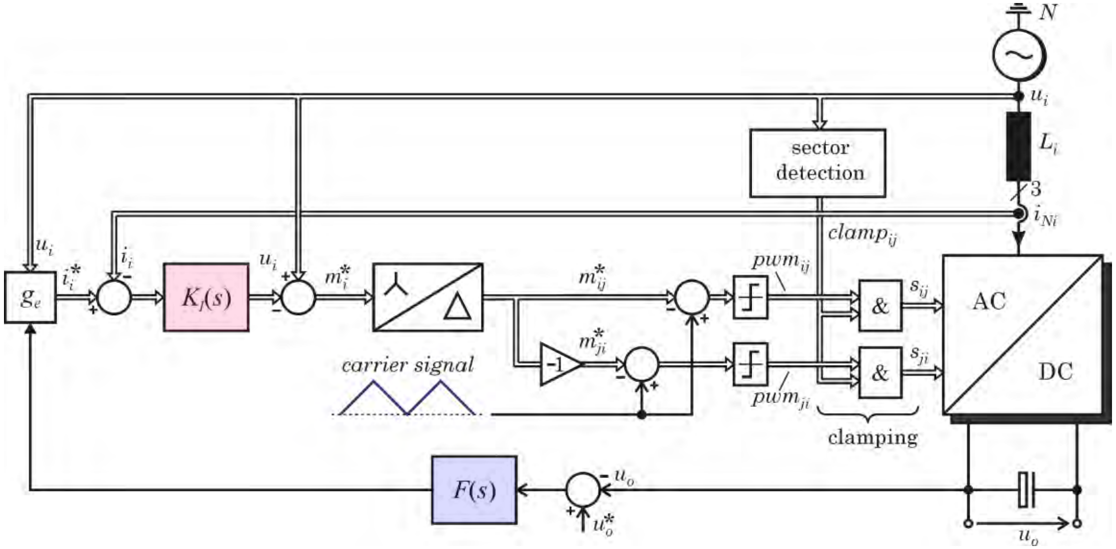
- **Δ-Switch Rectifier Features Lower Conduction Losses Compared to Y-Switch System**
- **Active Switch Could be Implemented with Six-Switch Power Module**

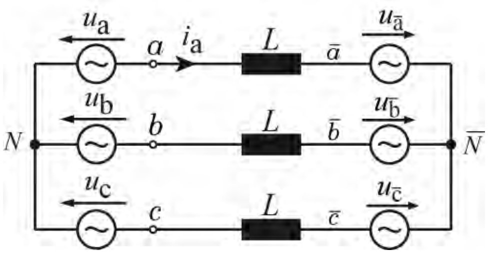


► Δ-Switch Rectifier

■ Equivalent Circuit / Mains Current Control

- Reference Voltages, i.e. the Output of the Phase Current Controllers Need to be Transformed into Δ-Quantities





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

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

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

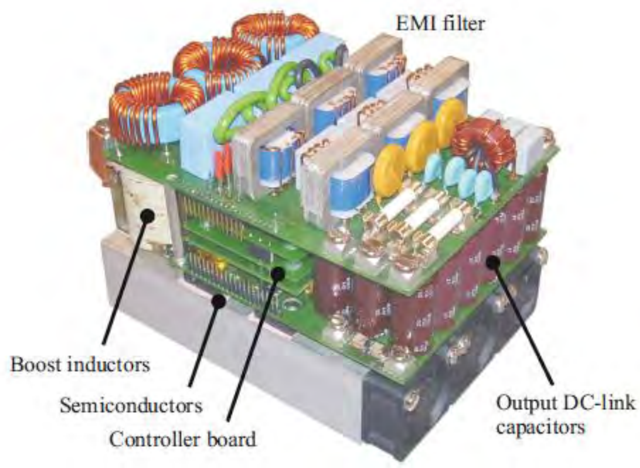
- Mains Currents Controlled in Phase with Mains Voltages u_a, u_b, u_c
- Voltage Formation at a, b, c is Determined by Switching State of $S_{\bar{a}\bar{b}\bar{a}}$, $S_{\bar{b}\bar{c}\bar{b}}$, $S_{\bar{c}\bar{a}\bar{c}}$ and AND Input Current Direction/Magnitude
- Always Only Switches Corresponding to Highest and Lowest Line-to-Line Voltage are Pulsed
- Switch of Middle Phase Turned Off Continuously

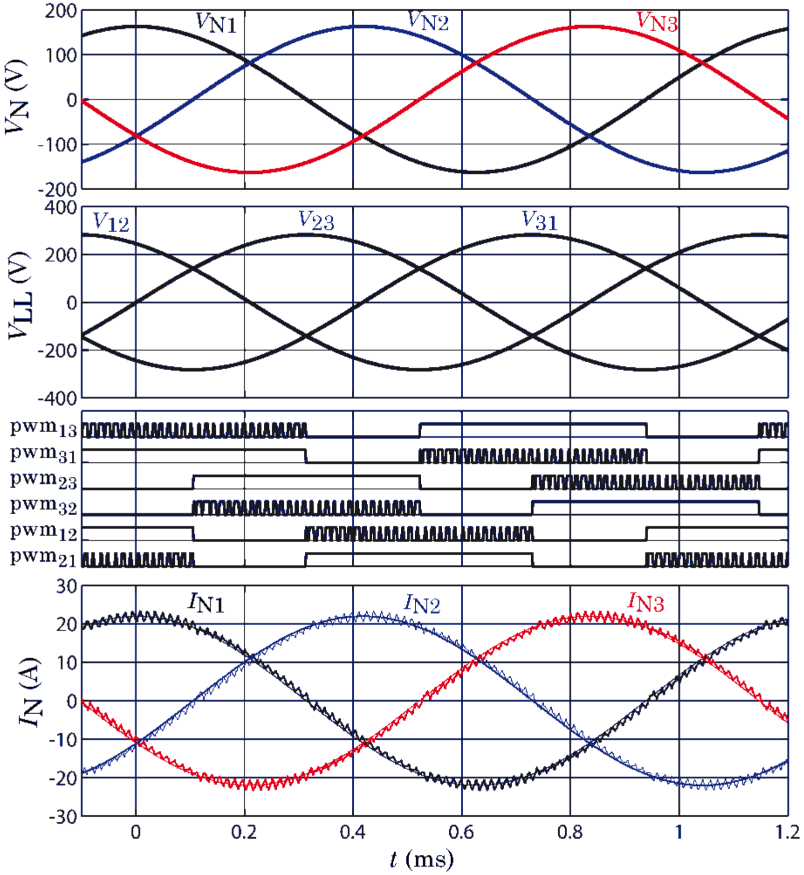
▶ Δ-Switch Rectifier

■ Modulation

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

Power Density: 2.35 kW/dm^3



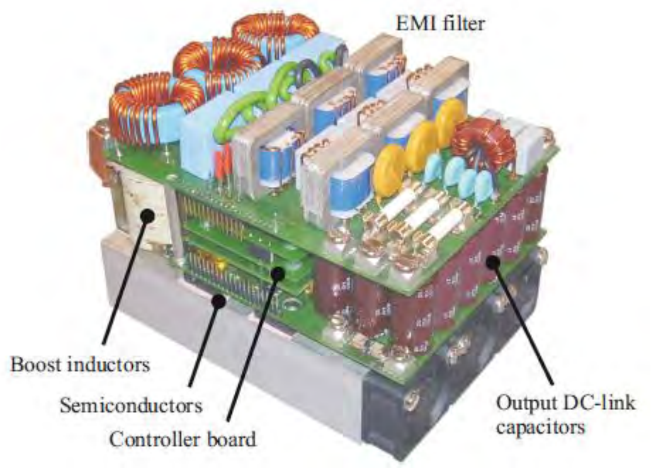


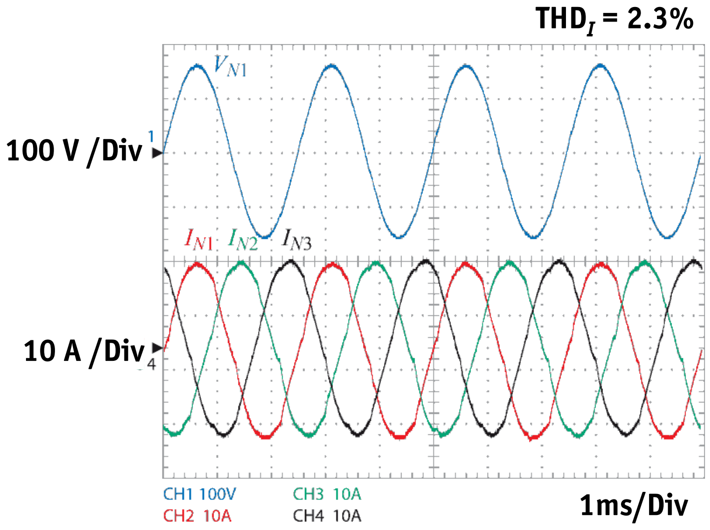
▶ Δ-Switch Rectifier

■ Experimental Analysis

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

Power Density: 2.35 kW/dm^3

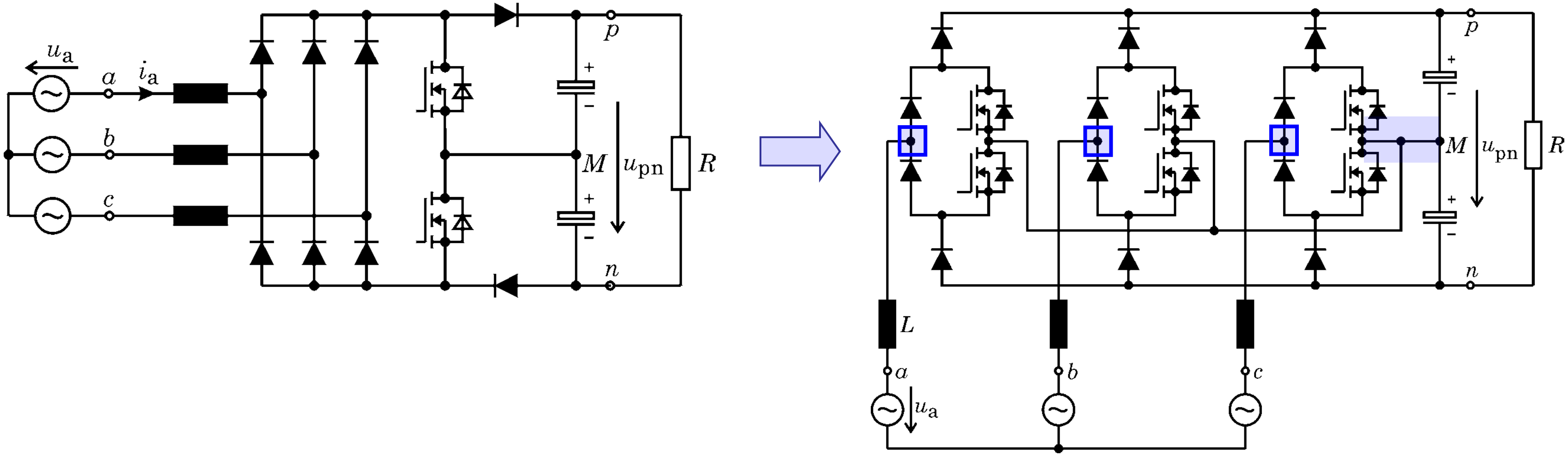




Three-Level Boost-Type CCM PFC Rectifier System

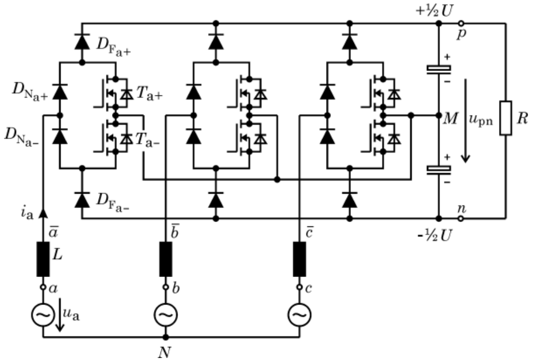
- *Derivation of Circuit Topologies*

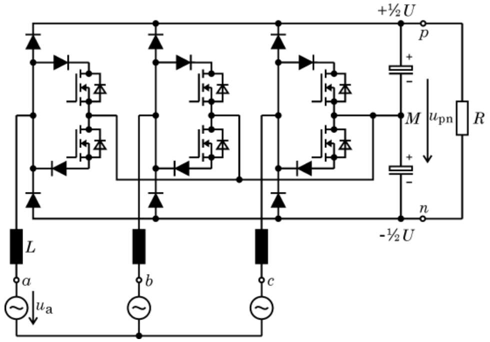
▶ Derivation of Three-Level Rectifier Topologies (1)

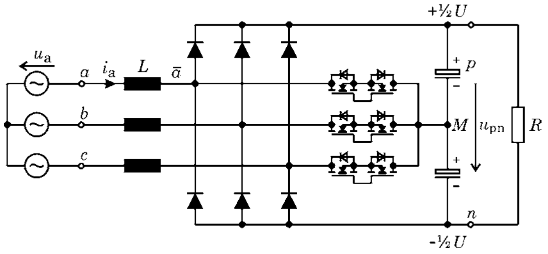


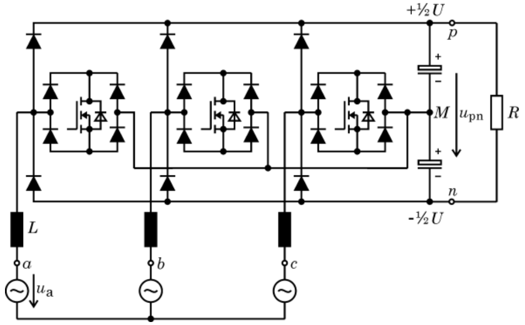
- **Sinusoidal Mains Current Shaping Requires Independent Controllability of the Voltage Formation of the Phases**

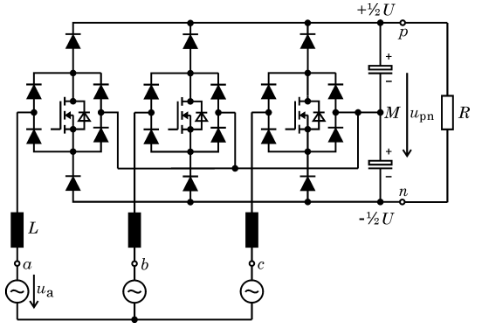
▶ Derivation of Three-Level Rectifier Topologies (2)

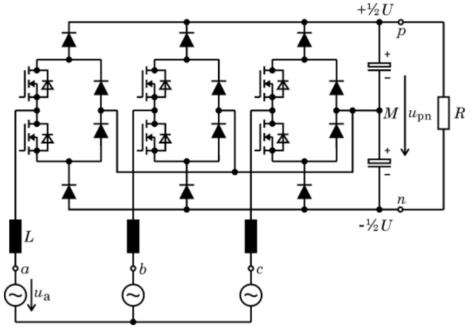












- **Three-Level Characteristics**

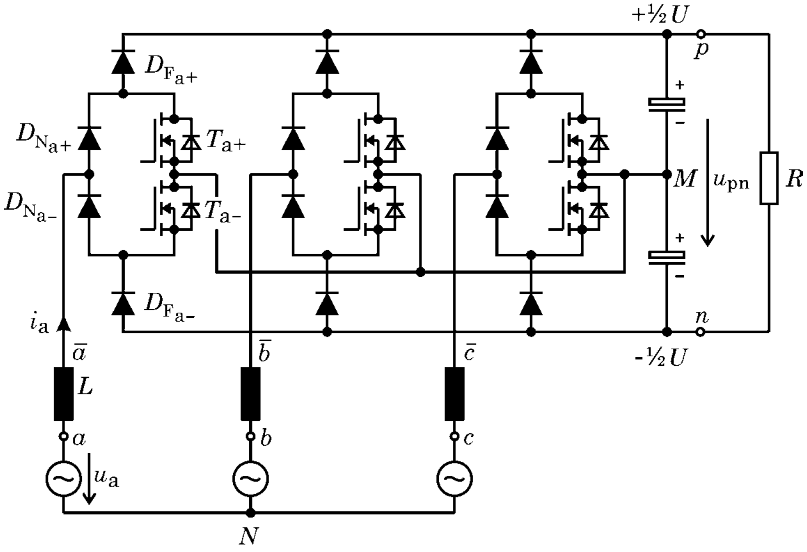
+ Low Input Inductance Requ.
+ Low Switching Losses,
+ Low EMI

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

Three-Level PFC Rectifier Analysis

- *Input Voltage Formation*
- *Modulation / Sinusoidal Input Current Shaping*
- *Output Center Point Formation*
- *Control*
- *Design Considerations*
- *EMI Filtering*
- *Digital Control*
- *Experimental Analysis*

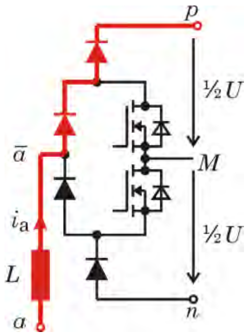
▶ Input Voltage Formation



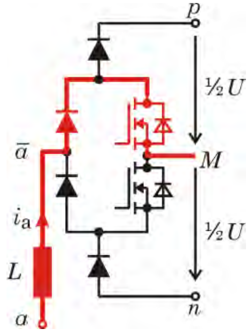
- **Voltage Formation**

$$u_{\bar{a}M} = (1 - s_a)\,\mathrm{sign}(i_a)\frac{U}{2}$$

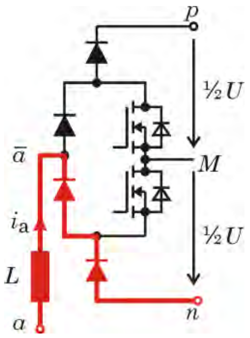
**is Determined by Phase Switching State
AND Direction of Phase Current**



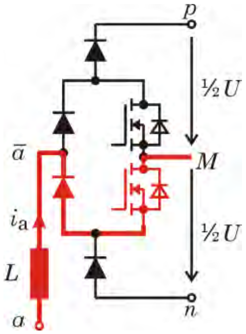
s_a = 0
T_{a+}, T_{a-}: OFF
$u_{\bar{a}M}$ = +½U



s_a = 1
T_{a+}, T_{a-}: ON
$u_{\bar{a}M}$ = 0



s_a = 0
T_{a+}, T_{a-}: OFF
$u_{\bar{a}M}$ = -½U



s_a = 1
T_{a+}, T_{a-}: ON
$u_{\bar{a}M}$ = 0

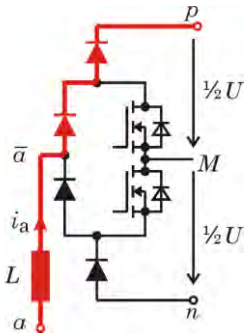
▶ Semiconductor Blocking Voltage Stress

■ Blocking Voltage Definition

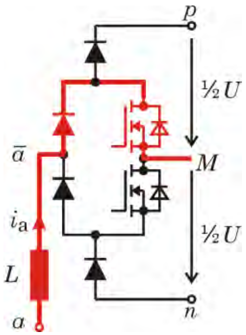
- D_{F+}: Limited to U_+ via Parasitic Diode of T_{a+}

- D_{N+}: Not Dir. Def. by Circuit Structure
- D_{N-}: Not Dir. Def. by Circuit Structure

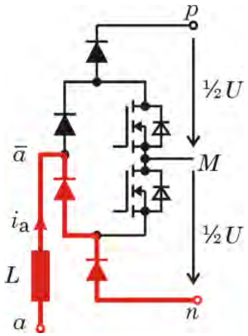
- D_{F-}: Limited to U_- via Paras. Diode of T_{a-}
- T_{a+}: Limited to U_+ via D_{F+}
- T_{a-}: Limited to U_- via D_{F-}



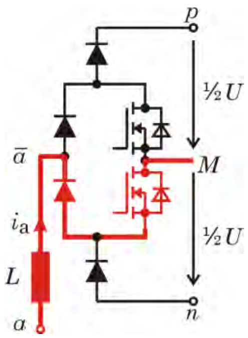
s_a = 0
T_{a+}, T_{a-}: OFF
$u_{\bar{a}M}$ = +½U



s_a = 1
T_{a+}, T_{a-}: ON
$u_{\bar{a}M}$ = 0

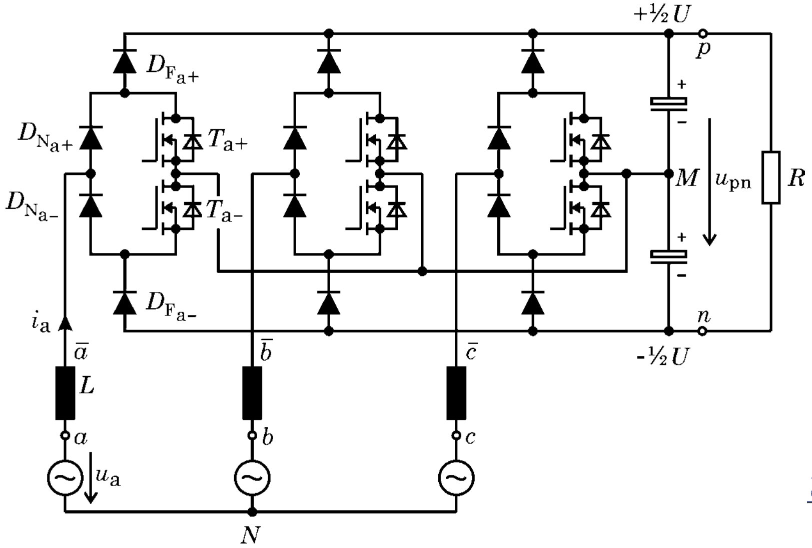


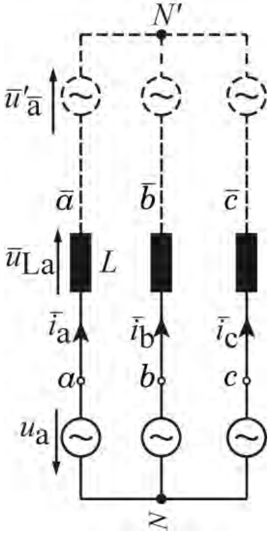
s_a = 0
T_{a+}, T_{a-}: OFF
$u_{\bar{a}M}$ = -½U



s_a = 1
T_{a+}, T_{a-}: ON
$u_{\bar{a}M}$ = 0

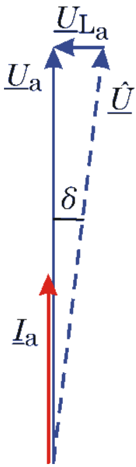
▶ Impression of Input Current Fund. (Ohmic Fund. Mains Behavior)

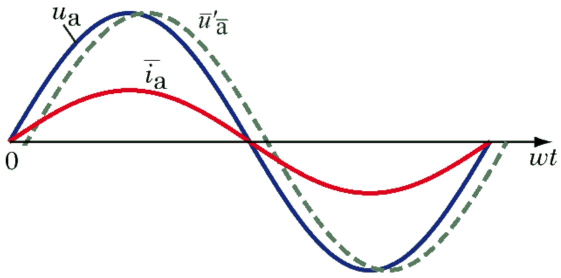




δ = 0,1°… 0,3° (50/60 Hz)
δ = 1°… 3° (360 Hz … 800 Hz)

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





▶ PWM / Formation of $\bar{u}_a$, $\bar{u}_b$, $\bar{u}_c$ / AC-Side Equiv. Circuit (1)

- **Def. of Modulation Index:**

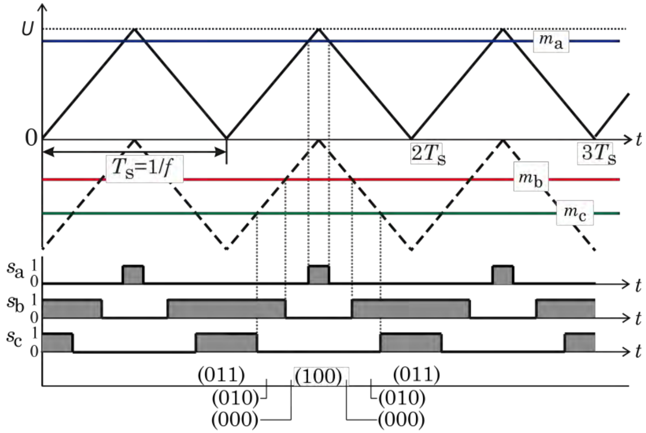
$$M = \frac{\hat{U}_{\bar{a}}}{\frac{1}{2}U} \qquad \left(0 \ldots \frac{2}{\sqrt{3}}\right)$$

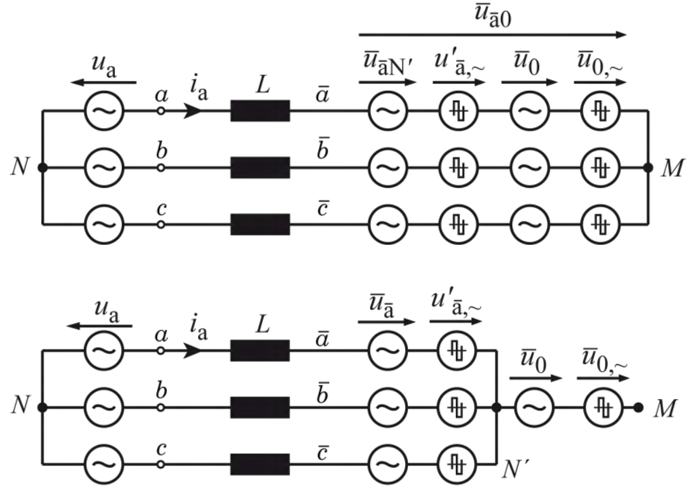
- **Zero-Sequence Signal to Achieve Ext. Mod. Range**

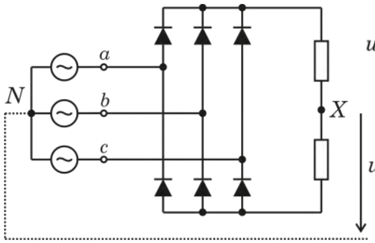
$$u_{\bar{a}0} = u'_{\bar{a}} + u_0$$
$$u_{\bar{b}0} = u'_{\bar{b}} + u_0$$
$$u_{\bar{c}0} = u'_{\bar{c}} + u_0$$

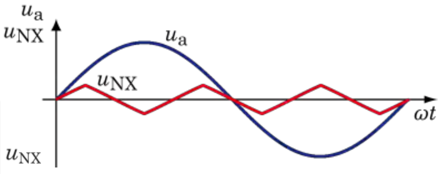
$$u'_{\bar{a}} + u'_{\bar{b}} + u'_{\bar{c}} = 0$$
$$u_0 = \frac{1}{3}\left(u_{\bar{a}0} + u_{\bar{b}0} + u_{\bar{c}0}\right)$$

- **Generation of u_0, *i.e.* 3rd Harmonic Signal**









► PWM / Formation of $\bar{u}_a$, $\bar{u}_b$, $\bar{u}_c$ / AC-Side Equiv. Circuit (2)

$\bar{u}'_a, \bar{u}'_b, \bar{u}'_c$	Impression of Mains Current Fundamental in Combination with u_a, u_b, u_c
$\bar{u}'_{a\sim}, \bar{u}'_{b\sim}, \bar{u}'_{c\sim}$	Causing the Switching Frequ. Ripple of the Mains Currents and/or DM Filtering Requirement
$\bar{u}_0$	Low Frequency Zero Sequence Component for Extending the Modulation Range from $M = 0 \ldots 1$ (Sinusoidal Modulation) to $M = 0 \ldots \frac{2}{\sqrt{3}}$
$u_{0\sim}$	Switching Frequency CM Voltage Fluctuation of the Output → Resulting in CM Current and/or CM Filtering Requirement

$$u'_{\bar{a}} = u_{\bar{a}N'} = \bar{u}'_{\bar{a}} + u_{\bar{a}\sim}$$

$$u'_{\bar{b}} = u_{\bar{b}N'} = \bar{u}'_{\bar{b}} + u_{\bar{b}\sim}$$

$$u'_{\bar{c}} = u_{\bar{c}N'} = \bar{u}'_{\bar{c}} + u_{\bar{c}\sim}$$

Note: $u_{NN'} = 0$

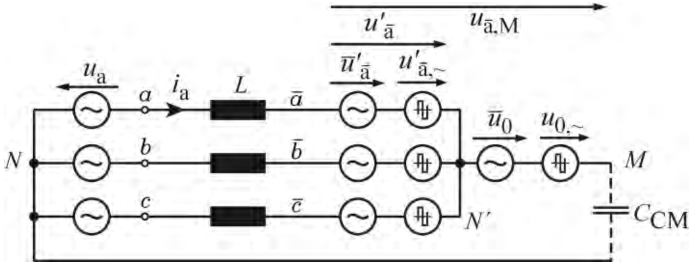
$$u_{\bar{a}0} = u'_{\bar{a}} + u_0$$

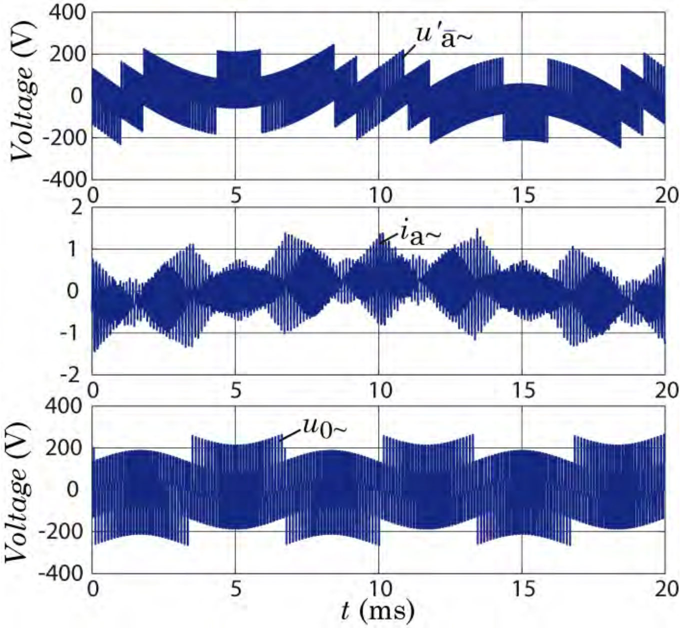
$$u_{\bar{b}0} = u'_{\bar{b}} + u_0$$

$$u_{\bar{c}0} = u'_{\bar{c}} + u_0$$

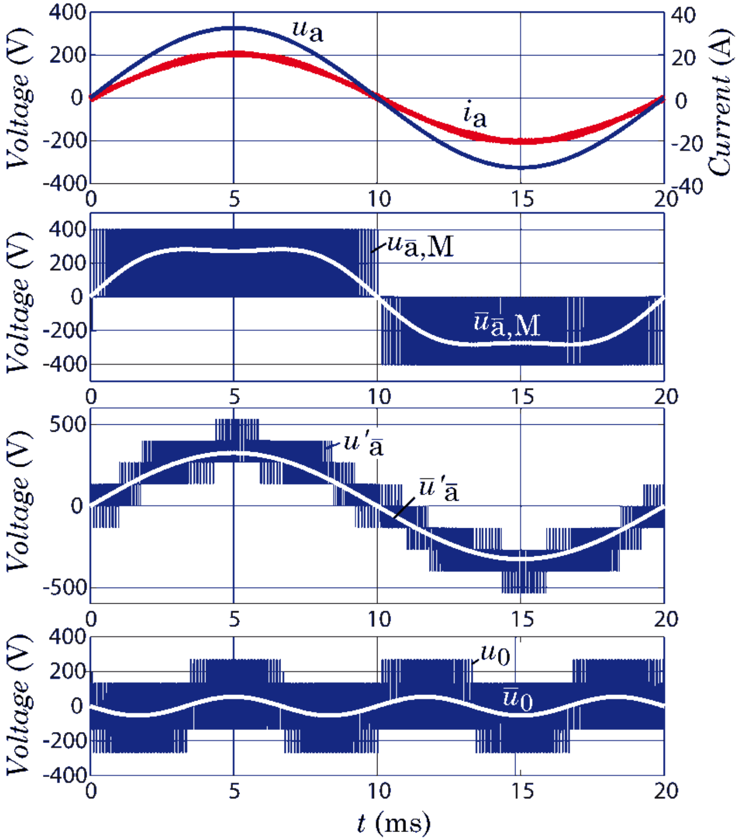
$$u_0 = \bar{u}_0 + u_{0\sim}$$

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





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



► Local Average Value of Center Point Current

- **Derivation of Low-Frequency Component $\bar{i}_M$ of Center Point Current Assuming a 3rd Harmonic Component of u_0 as Employed for Increasing the Modulation Range)**

Assumption: $i_a > 0, i_b < 0, i_c < 0$

$$m_a = m'_a + m_0 = M_1 \cdot \cos(\omega t) + M_3 \cdot \cos(3\omega t)$$

$$m_b = m'_b + m_0 = M_1 \cdot \cos\left(\omega t - \frac{2\pi}{3}\right) + M_3 \cdot \cos(3\omega t)$$

$$m_c = m'_c + m_0 = M_1 \cdot \cos\left(\omega t + \frac{2\pi}{3}\right) + M_3 \cdot \cos(3\omega t)$$

$$M_1 = \frac{\hat{U}}{\frac{1}{2}U} \qquad M_3 = \frac{\hat{U}_0}{\frac{1}{2}U}$$

$\alpha_a = 1 - m_a$ (relative on-time of T_{a+})

$\alpha_b = 1 - m_b$ (relative on-time of T_{b+})

$\alpha_c = 1 - m_c$ (relative on-time of T_{c+})

$$\bar{i}_M = \alpha_a \cdot i_a + \alpha_b \cdot i_b + \alpha_c \cdot i_c$$
$$= (1 - m_a) \cdot i_a + (1 - m_b) \cdot i_b + (1 - m_c) \cdot i_c$$

RMS of $\bar{i}_M$ minimal for $\frac{M_3}{M_1} \approx \frac{1}{4}$

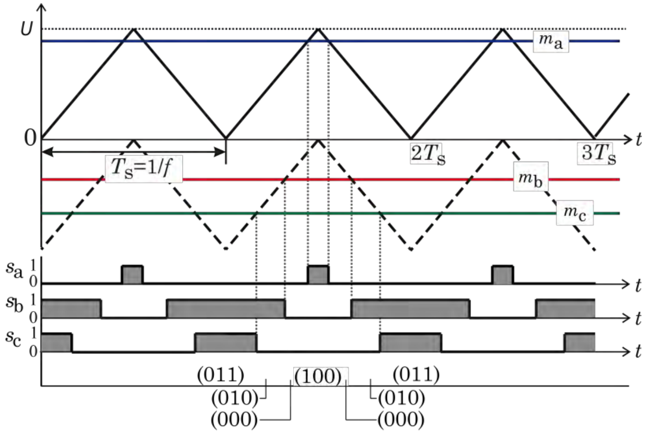
- m_0, i.e. PWM incl. 3rd Harm., Reduces $\bar{i}_M$ and Extends the Modulation Range

▶ Cond. States within a Pulse Period / Center Point Current Formation

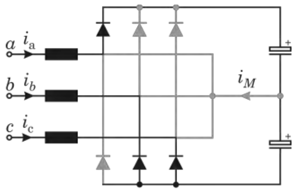
- **Consider e.g.** $i_a > 0, i_b < 0, i_c < 0$

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

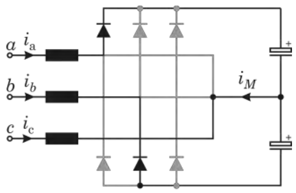
- **Control of i_M by Changing the Partitioning of Total On-Times of (100) and (011)**



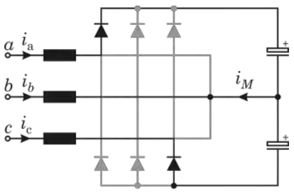
- **Corresponding Switching States and Resulting Currents Paths**



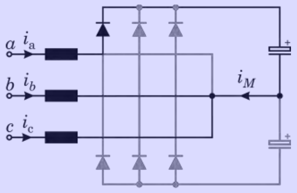
(000), $i_M = 0$



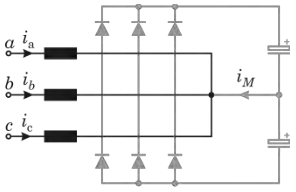
(001), $i_M = i_a$



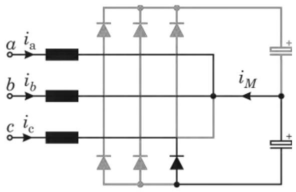
(010), $i_M = -i_b$



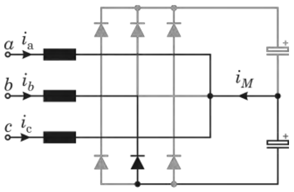
(011), $i_M = i_a$



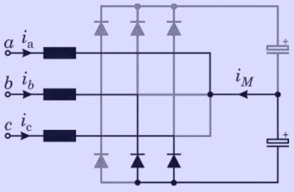
(111), $i_M = 0$



(110), $i_M = i_c$



(101), $i_M = i_b$

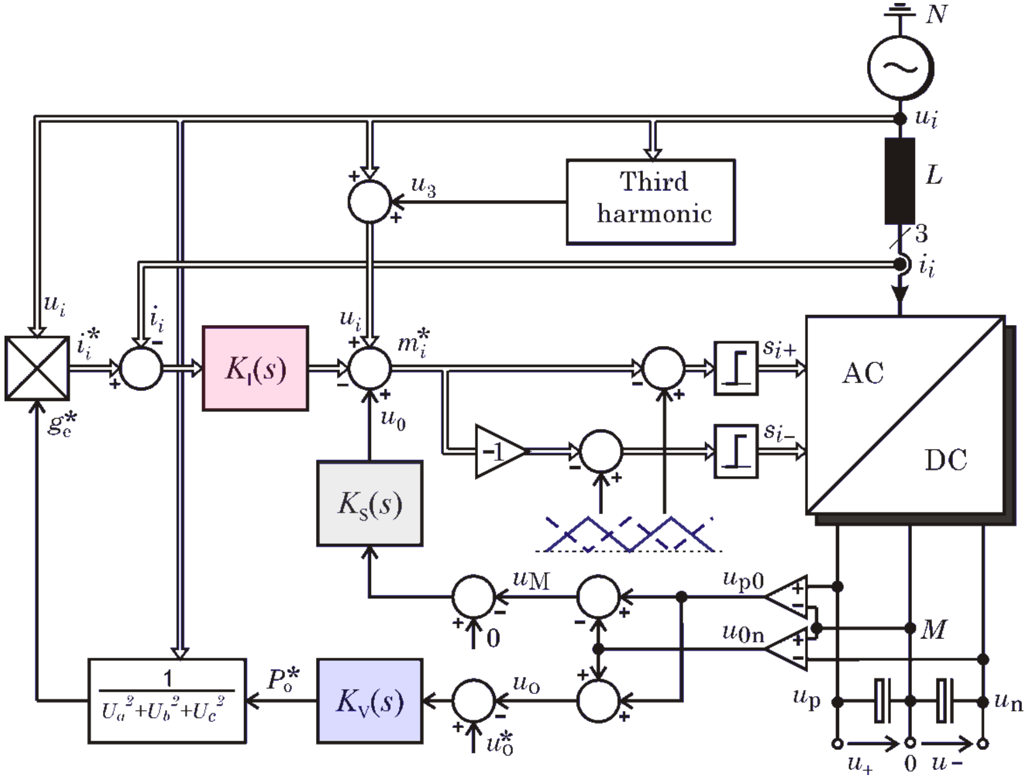


(100), $i_M = -i_a$

System Control

- *Control Structure*
- *Balancing of the Partial Output Voltages*

▶ Control Structure

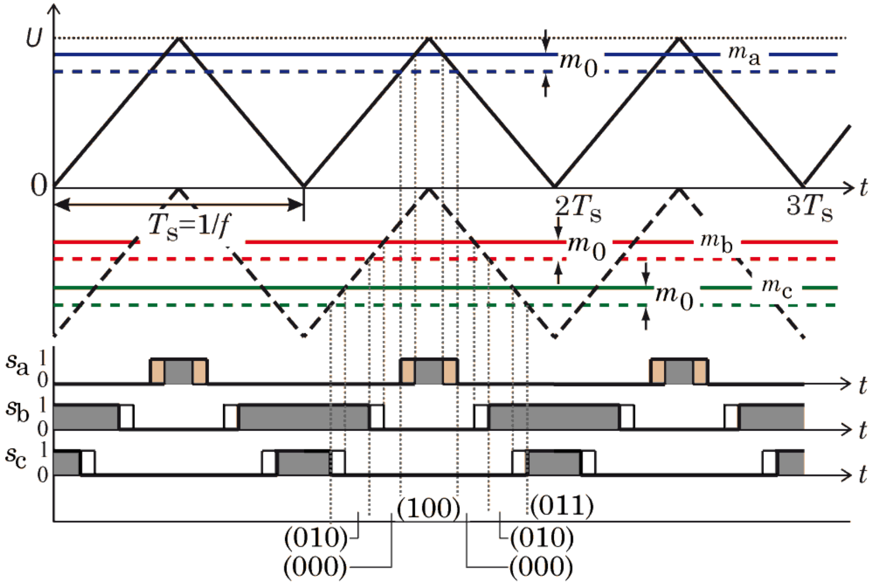


- Output Voltage Control
- Mains Phase Current Control
- Control of Output Center Point Potential (Balancing of U_+, U_-)

- Control of i_a, i_b, i_c Relies on $u_{\overline{a}}$, $u_{\overline{b}}$, $u_{\overline{c}}$
- Control of u_M Relies on $\overline{u}_0$ (DC Component)
- No Cross Coupling of both Control Loops

▶ Control of Potential u_M of Output Voltage Center Point

- **Assumption:** $i_a > 0$, $i_b < 0$, $i_c < 0$



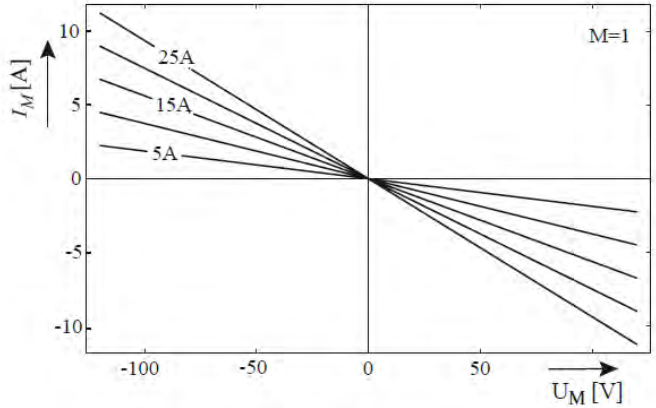
- Control via DC Component of u_0, i.e. by Adding m_0 to the Phase Modulation Signals i.e. by Inversely Changing the Rel. On-Times of (100) and (011), $\delta_{(100)}$ and $\delta_{(011)}$, without taking Influence on the Total On-Time $\delta_{(100)} + \delta_{(011)}$.

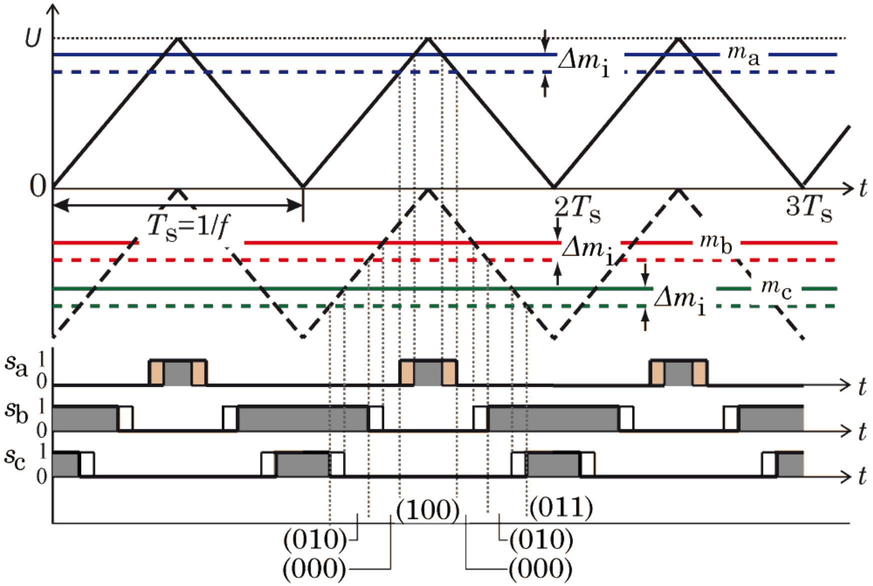
▶ Control of Output Voltage Center Point Potential u_M

- **Assumption:**

$$U_+ = \frac{1}{2}U + \Delta U$$

$$U_- = \frac{1}{2}U - \Delta U$$

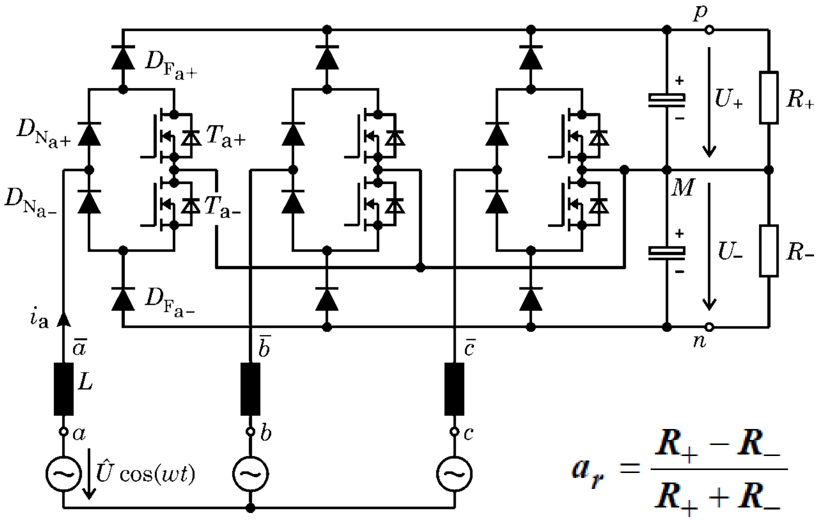




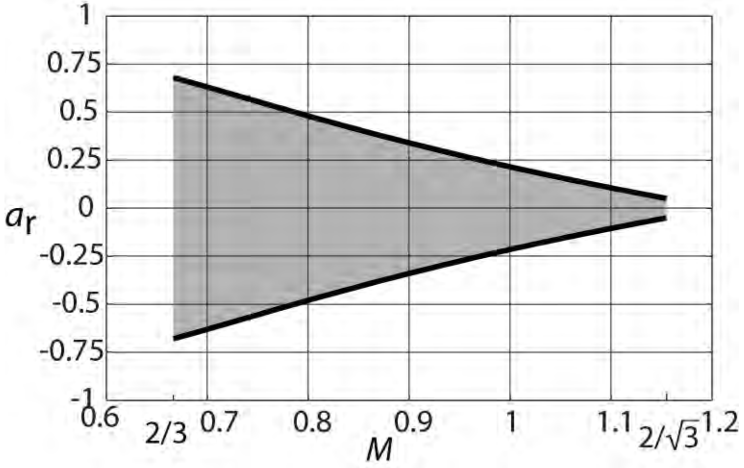
- Output Voltage Unbalance Results in Increasing On-Time of T_{a+} and Decreasing Off-Times of T_{b-} and T_{c-} so that the Voltages $\overline{u}'_{a}$, $\overline{u}'_{b}$, $\overline{u}'_{c}$ are Formed as in the Symmetric Case ($\Delta U = 0$) and/or the Mains Phase Currents Remain at Sinusoidal Shape

- Resulting $\overline{i}_M$ Reduces ΔU, i.e. Self Stability Guaranteed ✓

▶ Admissible Unbalance of Loading of U_+ and U_-



$$a_r = \frac{R_+ - R_-}{R_+ + R_-}$$



- System Tolerates Load Unbalance Dependent on the Voltage Transfer Ratio $(U_+ + U_-)/\hat{U}$ and/or the Value of The Modulation Index M

Design Guidelines

- *Current Stress on the Components*
- *Transistor Selection*
- *Output Pre-Charging at Start-up*

▶ Current Stress on Power Semiconductors

■ 6-Switch Circuit Topology

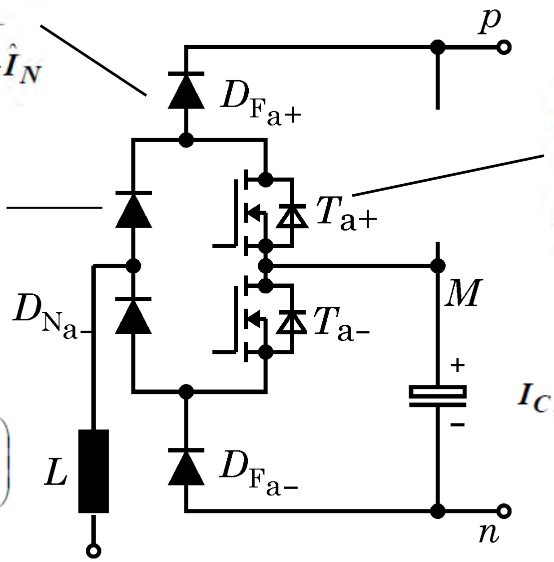
$$I_{DF,avg} = \frac{M}{4}\hat{I}_N$$

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

$$I_{DN,avg} = \frac{1}{\pi}\hat{I}_N$$

$$I_{DN,rms} = \frac{1}{2}\hat{I}_N$$

$$\Delta i_{L,pp,\max} = \frac{U}{f_s L_N}\frac{\sqrt{3}}{4}M\left(1 - M\frac{\sqrt{3}}{2}\right)$$



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

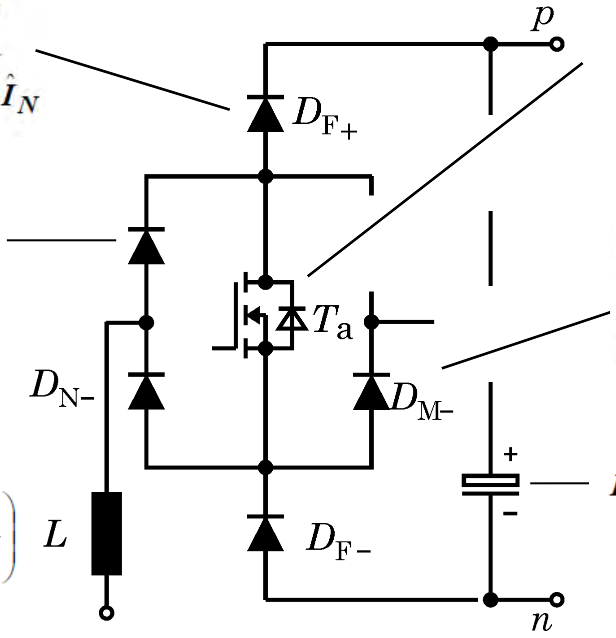
$$I_{T,rms} = \sqrt{\frac{1}{4} - \frac{2M}{3\pi}}\hat{I}_N$$

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

- Output Voltage > $\sqrt{3}\,\hat{U}_{max}$ (typ. 1.2 $\sqrt{3}\,\hat{U}_{max}$); $\hat{U}_{max}$: Ampl. of Max. Mains Phase Voltage
- Required Blocking Capability of All Semiconductors: ½ U

▶ Current Stress on Power Semiconductors

■ 3-Switch Circuit Topology



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

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

$$I_{DN,avg} = \frac{1}{\pi}\hat{I}_N$$

$$I_{DN,rms} = \frac{1}{2}\hat{I}_N$$

$$\Delta i_{L,pp,\max} = \frac{U}{f_s L_N}\frac{\sqrt{3}}{4}M\left(1 - M\frac{\sqrt{3}}{2}\right)$$

$$I_{T,avg} = \left(\frac{2}{\pi} - \frac{M}{2}\right)\hat{I}_N$$

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

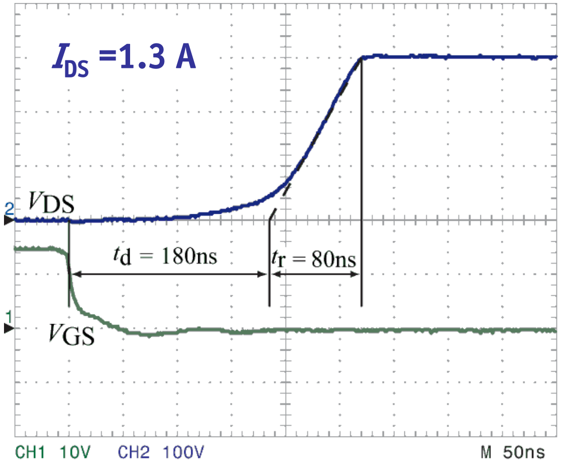
$$I_{DM,avg} = \left(\frac{1}{\pi} - \frac{M}{4}\right)\hat{I}_N$$

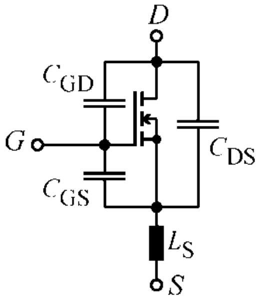
$$I_{DM,rms} = \sqrt{\left(\frac{1}{4} - \frac{2M}{3\pi}\right)}\hat{I}_N$$

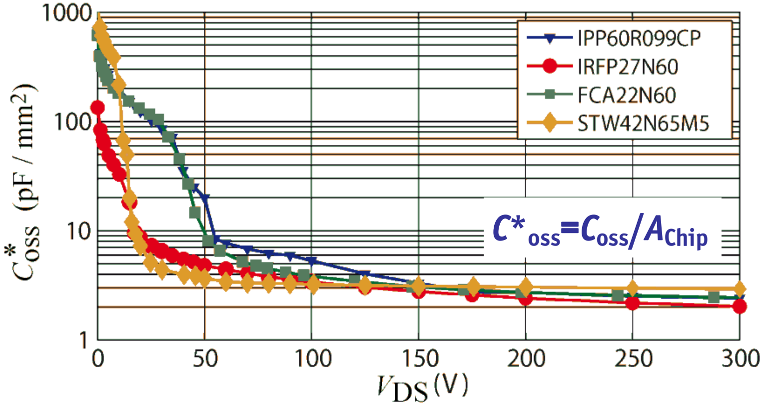
$$I_{C,rms} = \sqrt{\frac{5\sqrt{3}M}{4\pi} - \frac{9M^2}{16}}\hat{I}_N$$

- Output Voltage > √3 $\hat{U}_{max}$ (typ. 1.2 √3 $\hat{U}_{max}$); $\hat{U}_{max}$: Ampl. of Max. Mains Phase Voltage
- Required Blocking Capability of All Semiconductors: ½ U

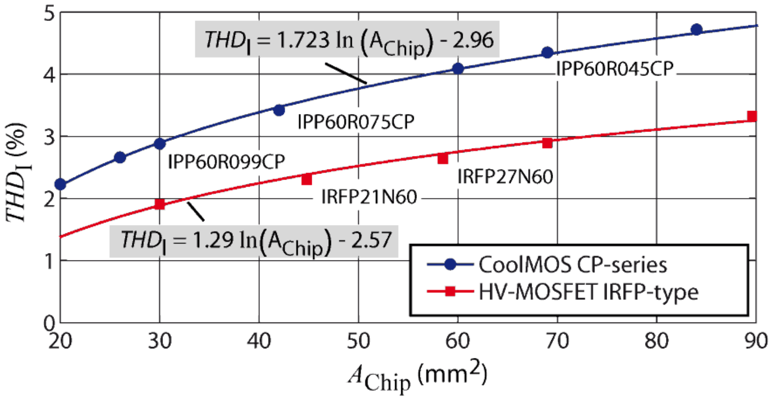
▶ Nonlin. C_{oss} of Superjunct. MOSFETs Causes Input Curr. Distortion







U_{LL} = 3 x 400 V (50 Hz), f_s = 1 MHz, P_o = 10 kW



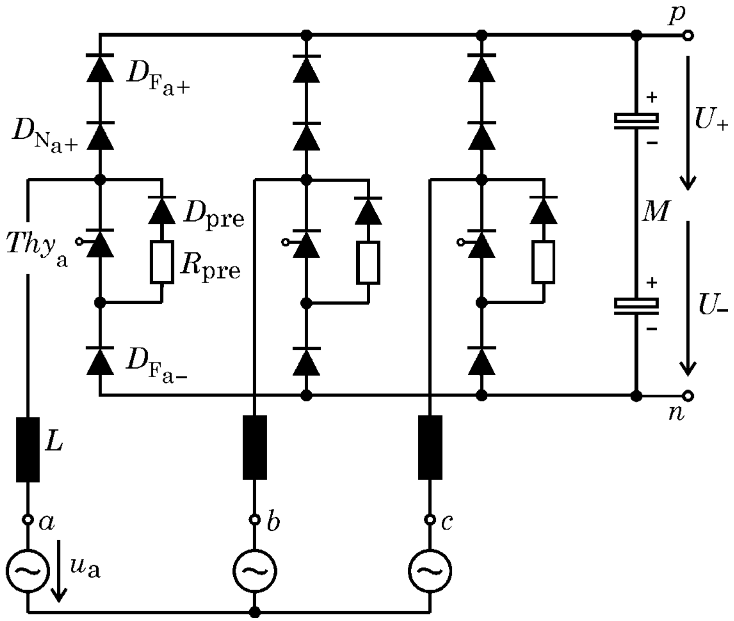
- **Nonlinear Output Capacitance C_{oss} of MOSFET (CoolMOS) has to be Charged at Turn-off**

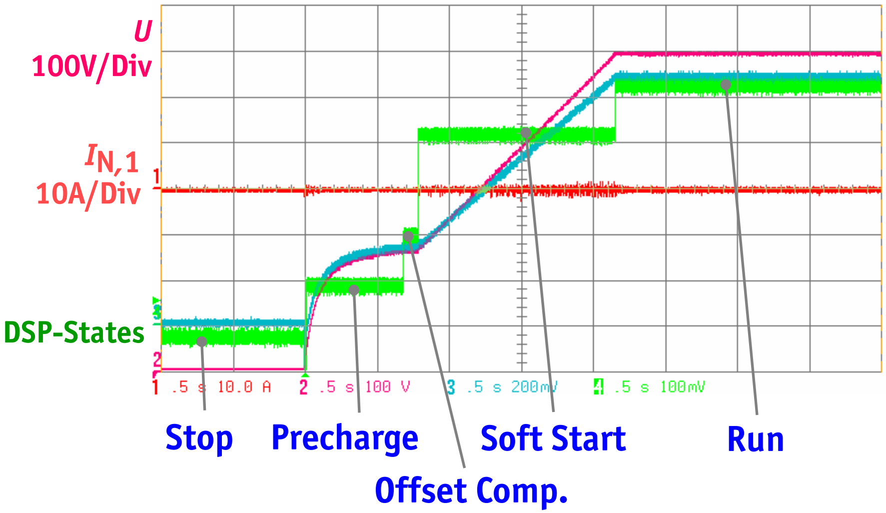
- **Large Turn-Off Delay for Low Currents (e.g. Delay of CoolMOS IPP60R099 (@ IDS = 1.3 A): 11% of Switching Cycle @ fs = 500 kHz**

- **Results in PWM Volt. and/or Input Curr. Distortion**

▶ Pre-Charging of Output Capacitors / Start-Up Sequence

- Lower Mains Diode D_{N-} is Replaced by Thyristor
- Inrush Current is Limited by R_{pre}
- Switches are not Gated During Start-Up
- Start-up Sequence is Required





EMI Filtering

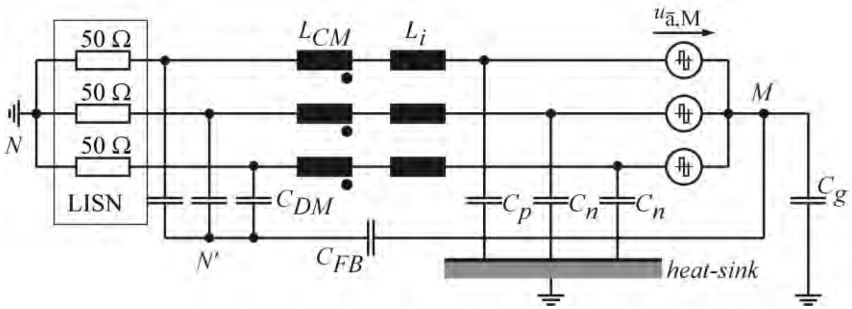
- *DM Filtering*
- *CM Filtering*

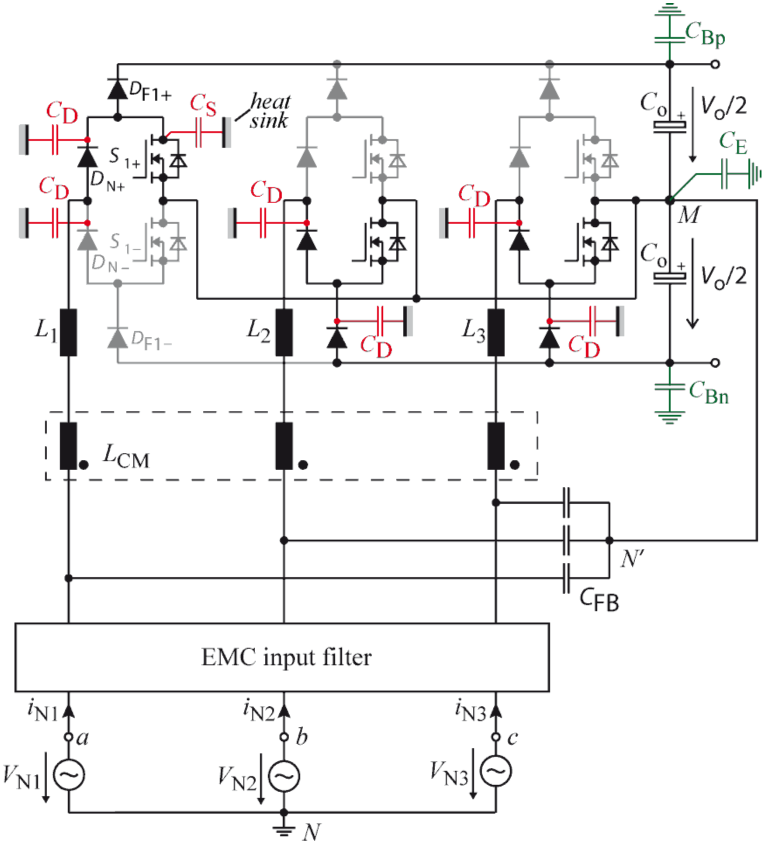
▶ EMI Filtering Concept

- **DM and CM Filter Stages**
- **Connection of Output Voltage Midpoint *M* to Artificial Mains Star-Point *N′***

→ No High-Frequency CM-Voltage at *M*
→ Capacitance of C_{FB} Not Limited by Safety Standards

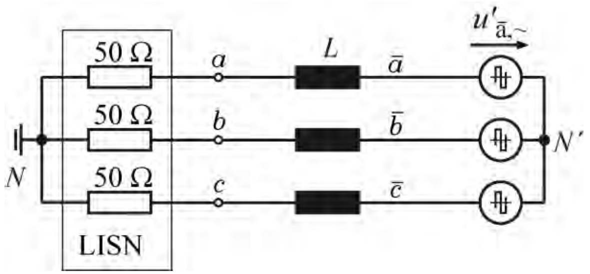
- **Parasitic Capacitances have to be Considered for CM-Filter Design**



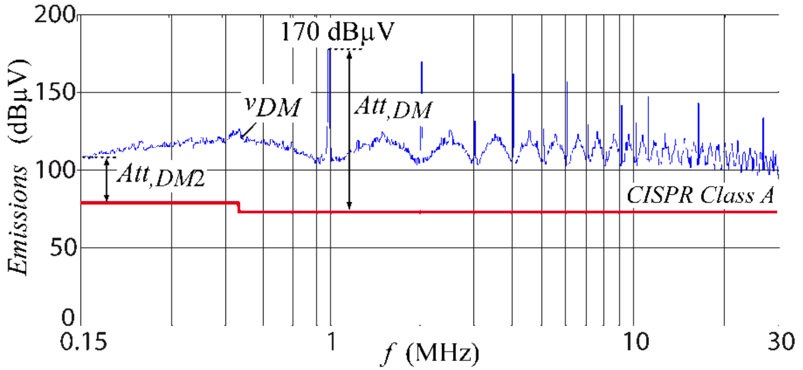


▶ DM Filter Design

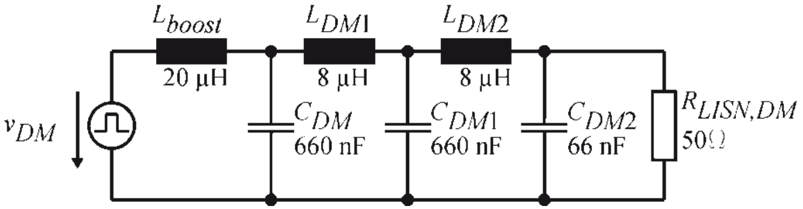
- **DM Equivalent Circuit**



- **Required DM Attenuation, e.g. for fs = 1 MHz (VR1000)**

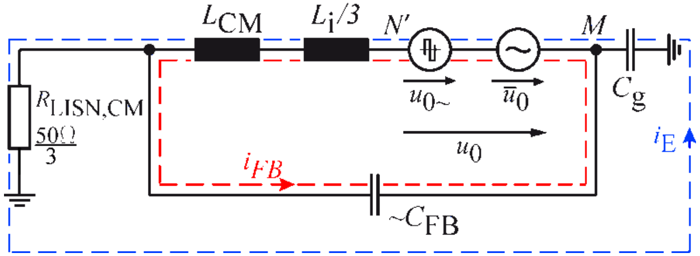


- **DM Filter Structure**

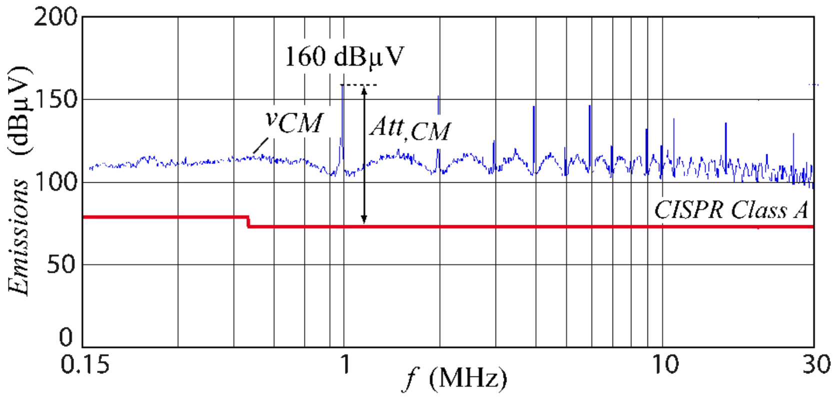


▶ CM Filter Design

- **CM Equivalent Circuit**



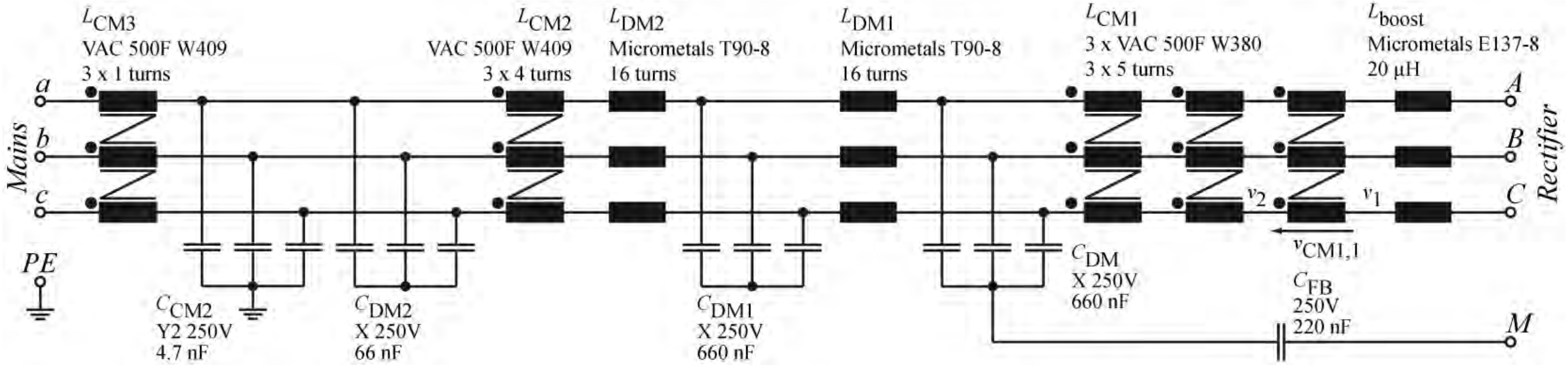
C_{FB} = 220 nF



- **Required CM Attenuation**

▶ EMI Filter Structure for VR1000 Rectifier System

- 3 Stage DM Filter
- 2 Filter Stages for CM Filter

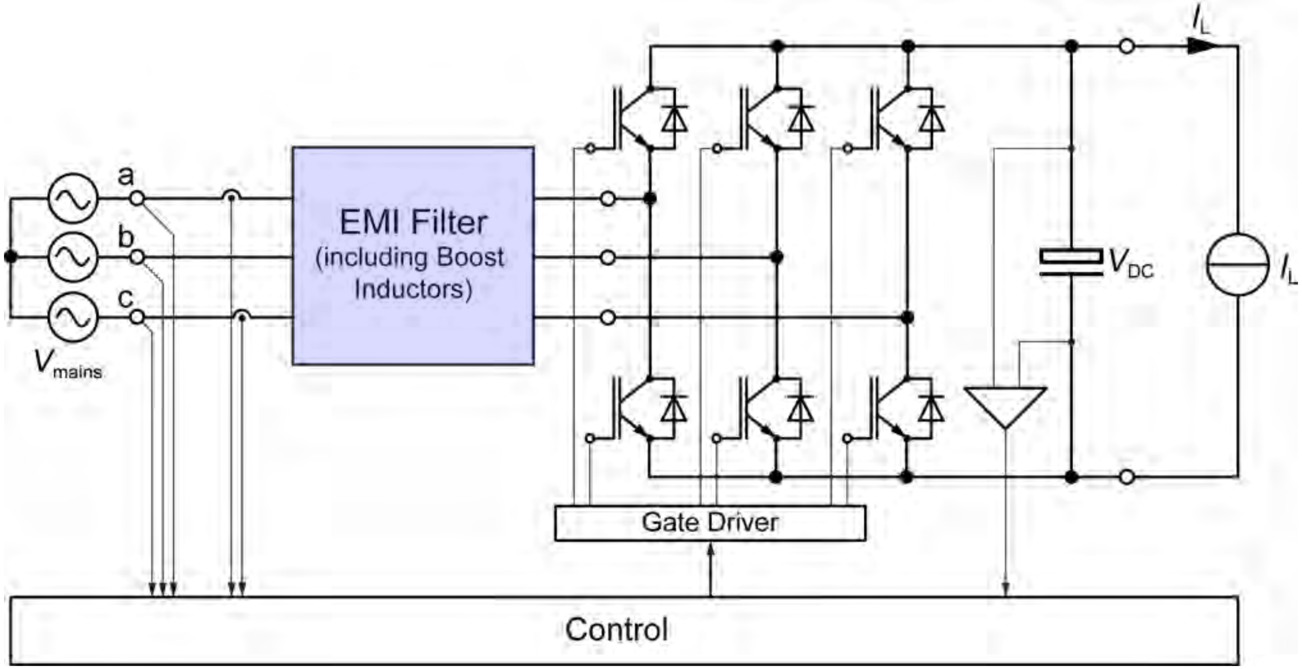


- 3 x CM Inductors in Series to Implement Proposed Filter Concept
- Additional CM Filter Stage Required Due to Parasitic Capacitances

EMI Filter Design

- *Analytical Approximation*
- *Volume / Efficiency Optimization*

Considered System

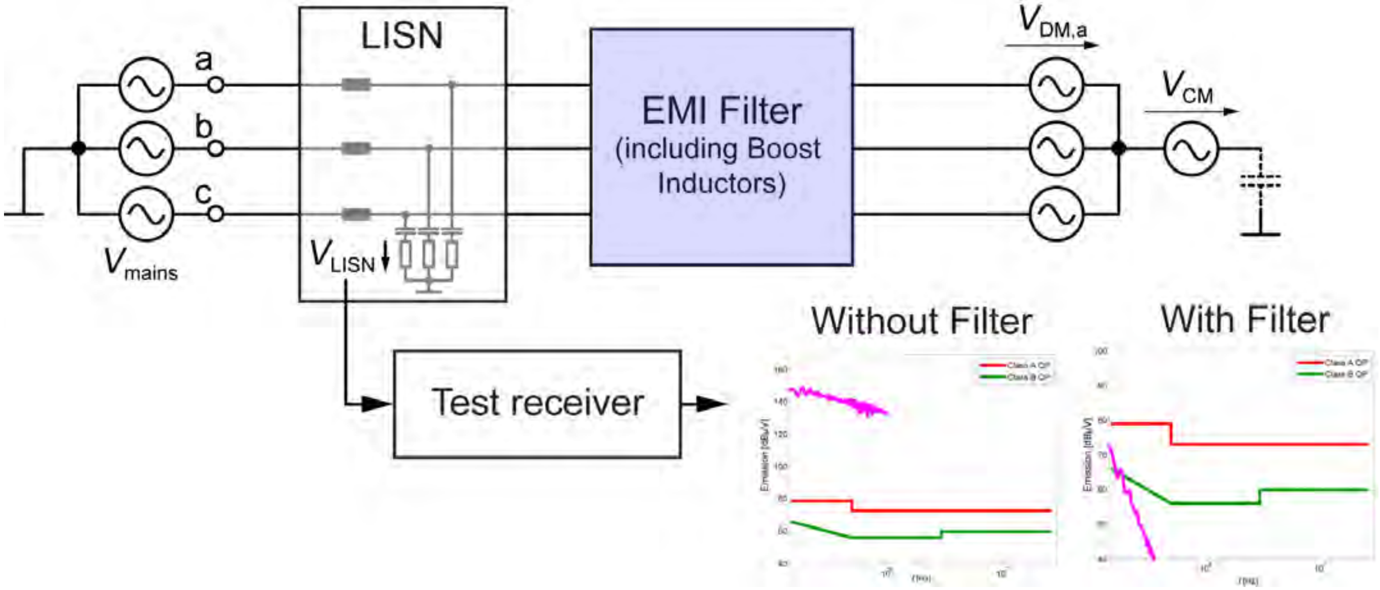


Goal → Meet Conducted EMI Standards (e.g. CISPR 11, Class A or Class B)

Tasks

1) Find Needed Filter Attenuation
2) Design Filter Accordingly

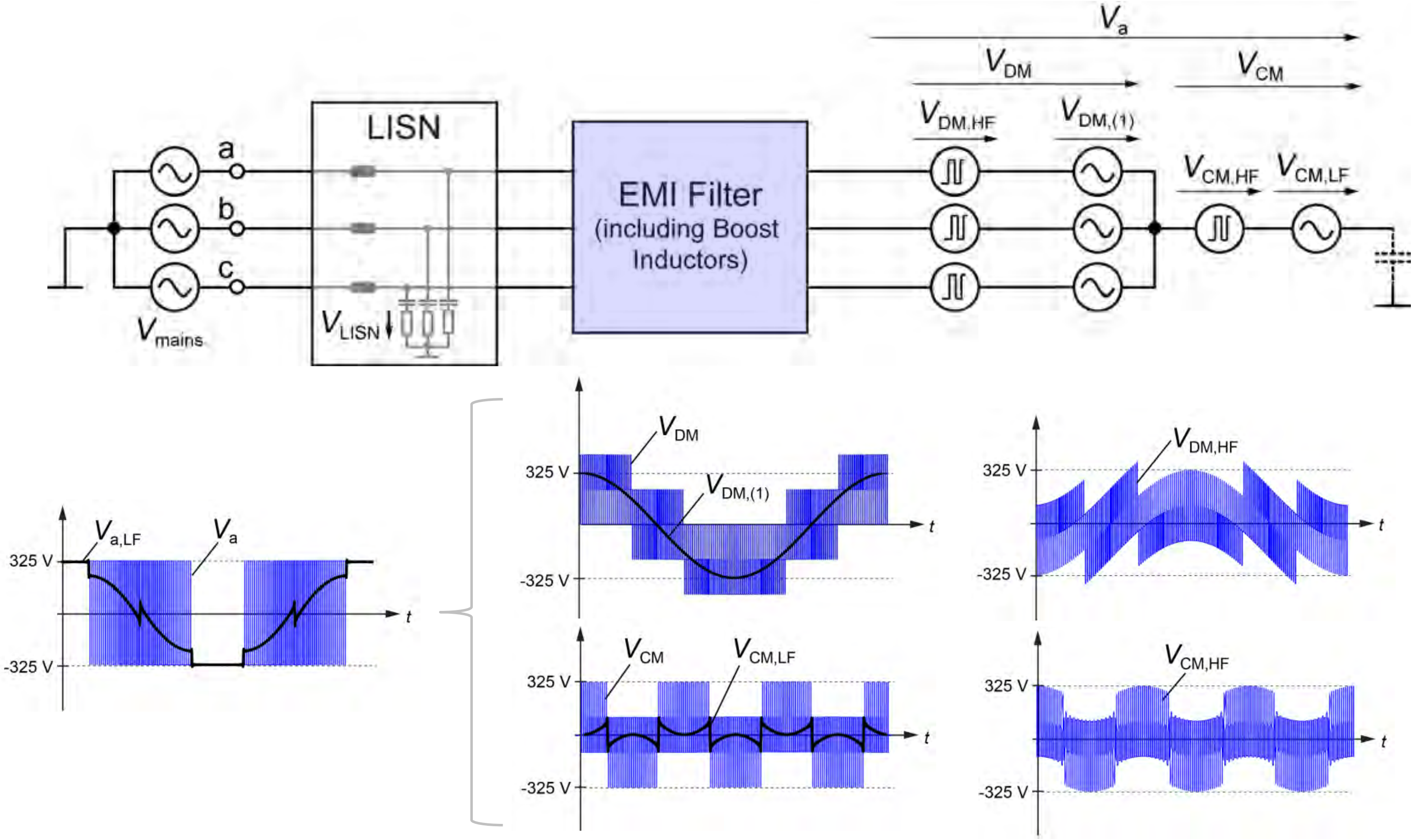
Calculate Required Filter Attenuation



DM Attenuation → Determine Filter Attenuation such that Test Receiver Output is Below EMI Limits at all Frequencies

Challenges
→ Determine Spectrum of VDM and VCM
→ Computationally Intensive Test Receiver Modeling

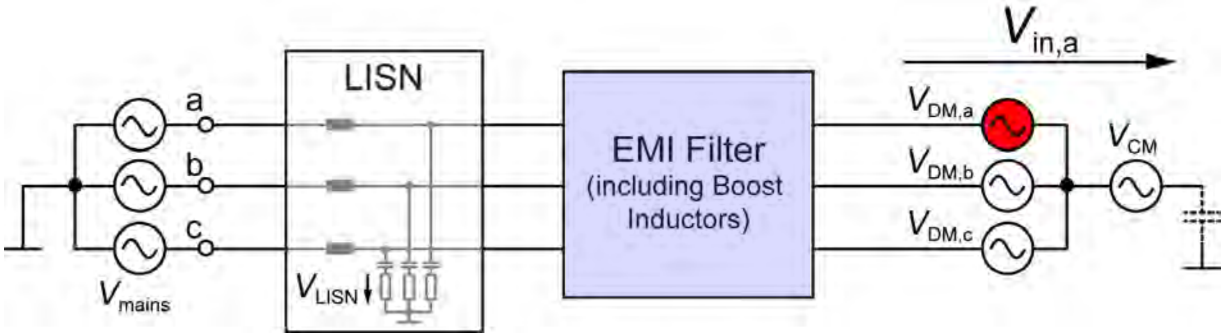
CM and DM Voltage Formation / Time Behavior

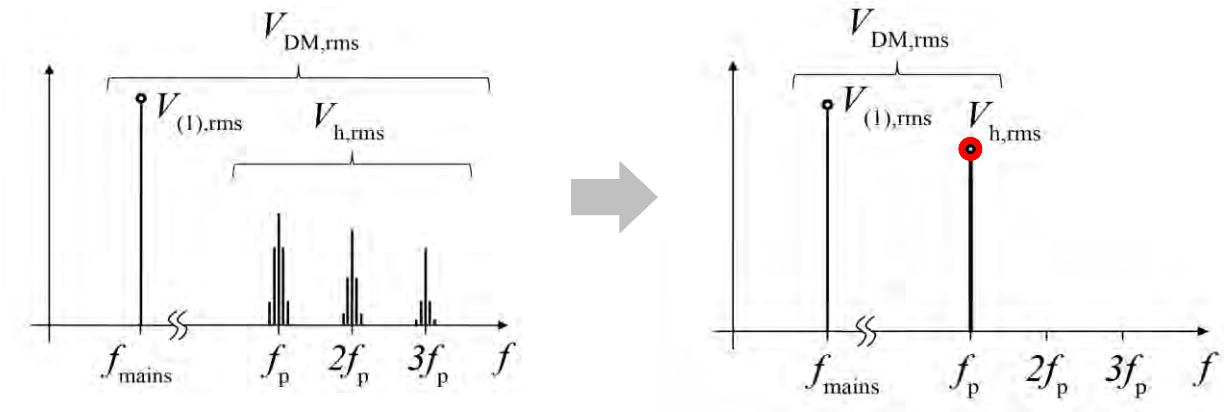


- Voltage V_a splitted into LF and High Frequency Components

Simplified Calculation of Required Filter Attenuation

- Shown for DM Attenuation

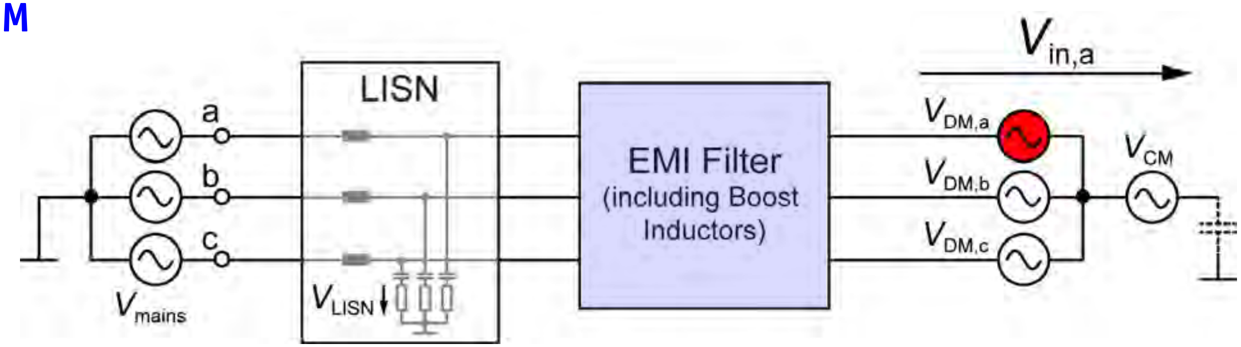




→ Model of Test Receiver is Omitted
→ Harmonic Power Concentrated only @ Switching Frequency
→ VDM,rms can be Calculated in Time Domain

Simplified Calculation of Required Filter Attenuation

- ▶ **Shown for DM Attenuation**

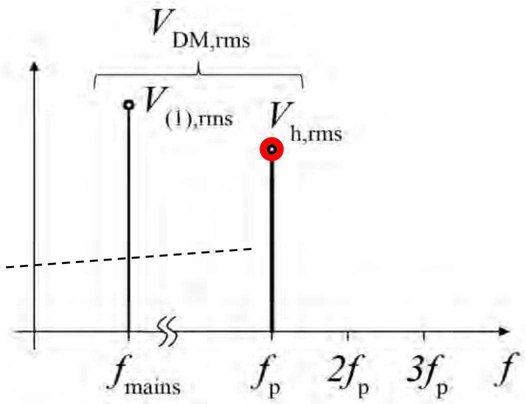


For Space Vector Modulation:

$$V_{CM,rms}^2 = \frac{1}{12}\frac{V_{DC}^2(3\pi - 4\sqrt{3}M)}{\pi}$$

$$V_{DM,h,rms} = \sqrt{V_{in,rms}^2 - V_{(1),rms}^2 - V_{CM,rms}^2}$$

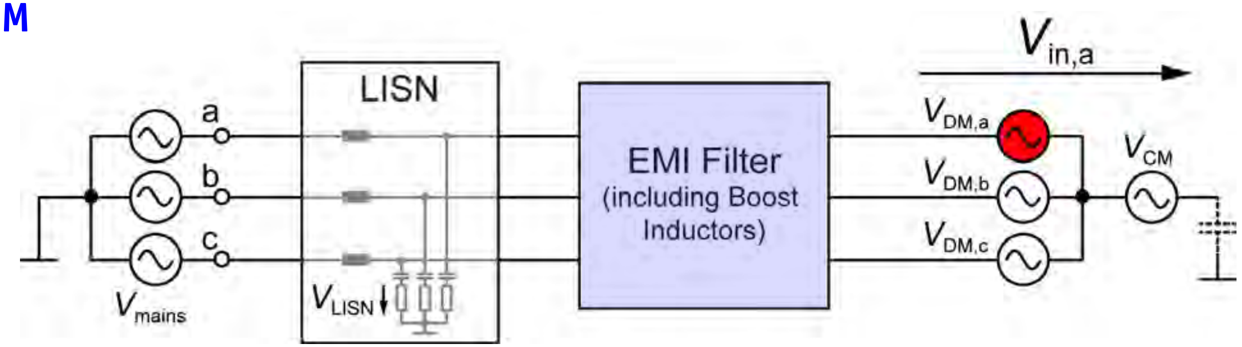
$$= \sqrt{\frac{1}{24}\frac{V_{DC}^2 M(8\sqrt{3} - 3M\pi)}{\pi}}$$

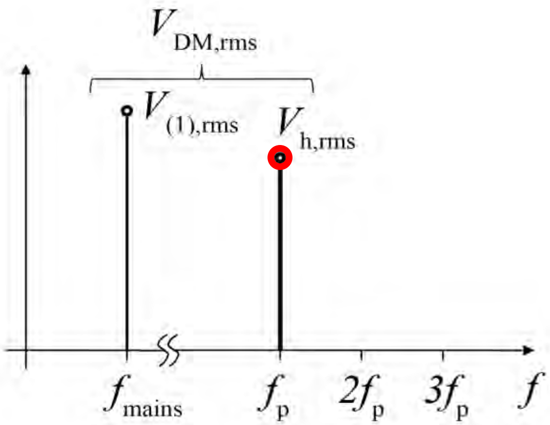


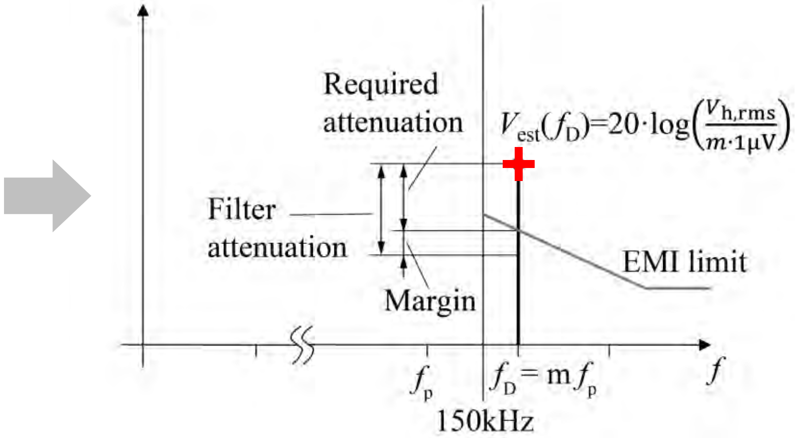
→ **Model of Test Receiver is Omitted**
→ **Harmonic Power Concentrated only @ Switching Frequency f_P**
→ **$V_{DM,rms}$ can be Calculated in Time Domain**

Simplified Calculation of Required Filter Attenuation

- **Shown for DM Attenuation**



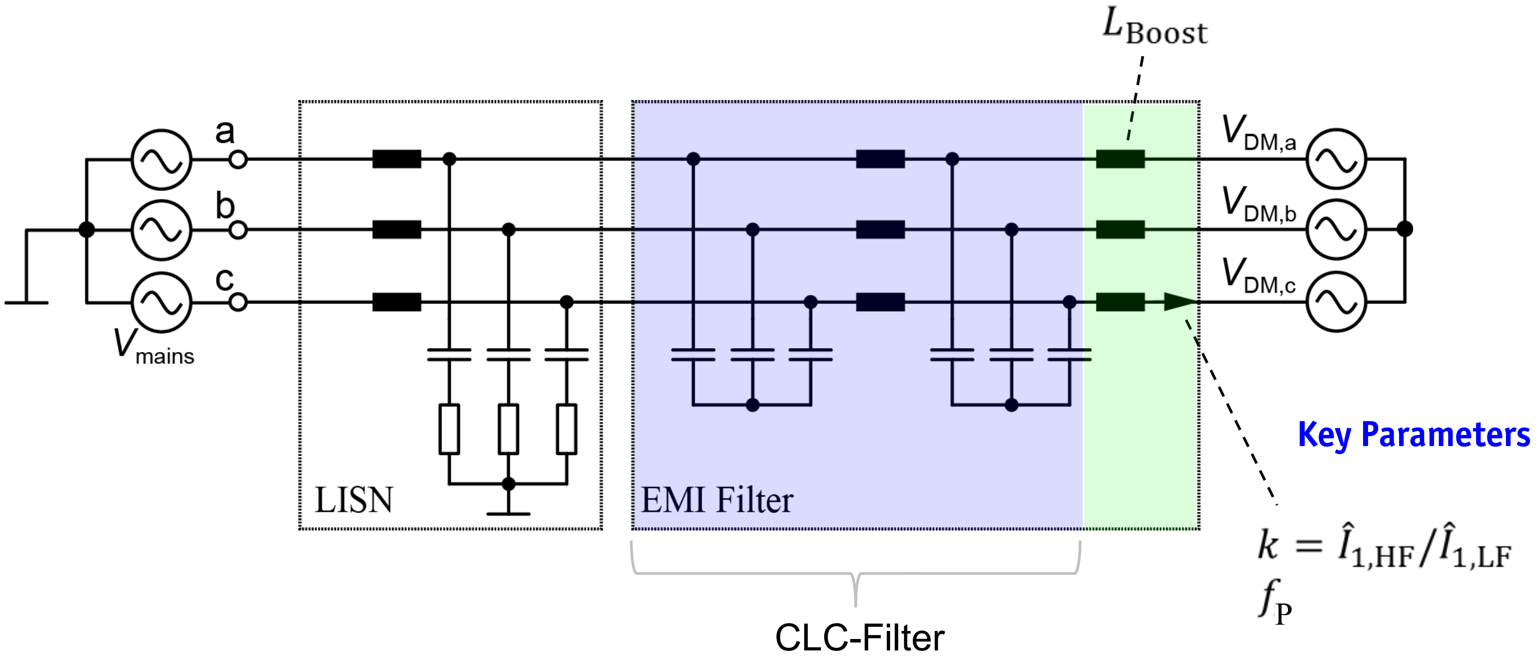




$$A_{filter}(f_D)[\mathrm{dB\mu V}] = V_{est}(f_D)[\mathrm{dB\mu V}] - \mathrm{Limit}(f_D)[\mathrm{dB\mu V}] + \mathrm{Margin}(f_D)[\mathrm{dB\mu V}]$$

EMI Filter Optimization

- **Shown for DM Filter**



Key Parameters

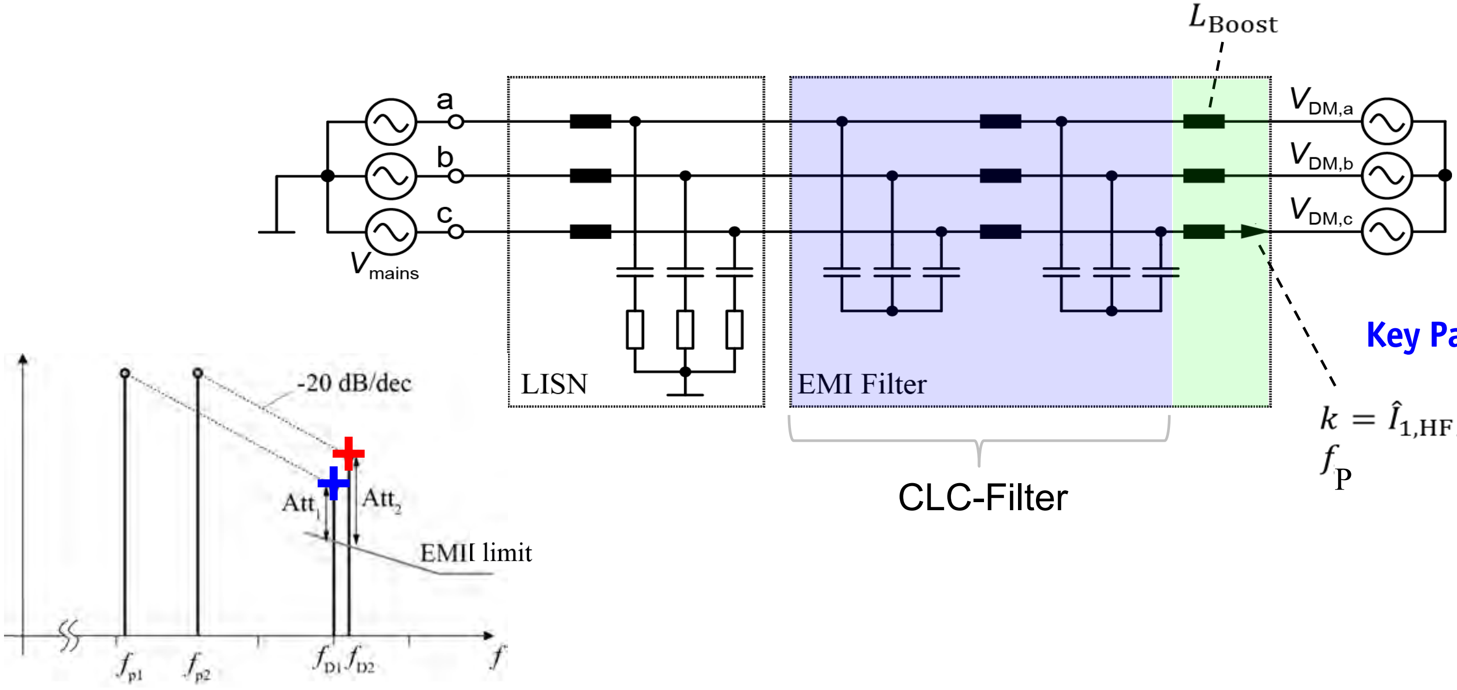
$k = \hat{I}_{1,\text{HF}} / \hat{I}_{1,\text{LF}}$
f_{P}

- **Optimal Selection of Current Ripple Ratio k (f_{P} = const.)**

→ **High Ripple Current in L_{Boost} (→ high k) requires Large CLC-filter; in Return the L_{boost} is Small**
→ **Small Ripple Current in L_{Boost} (→ small k) requires Large L_{boost}; in Return the CLC-filter is Small**

EMI Filter Optimization

- **Shown for DM Filter**



Key Parameters

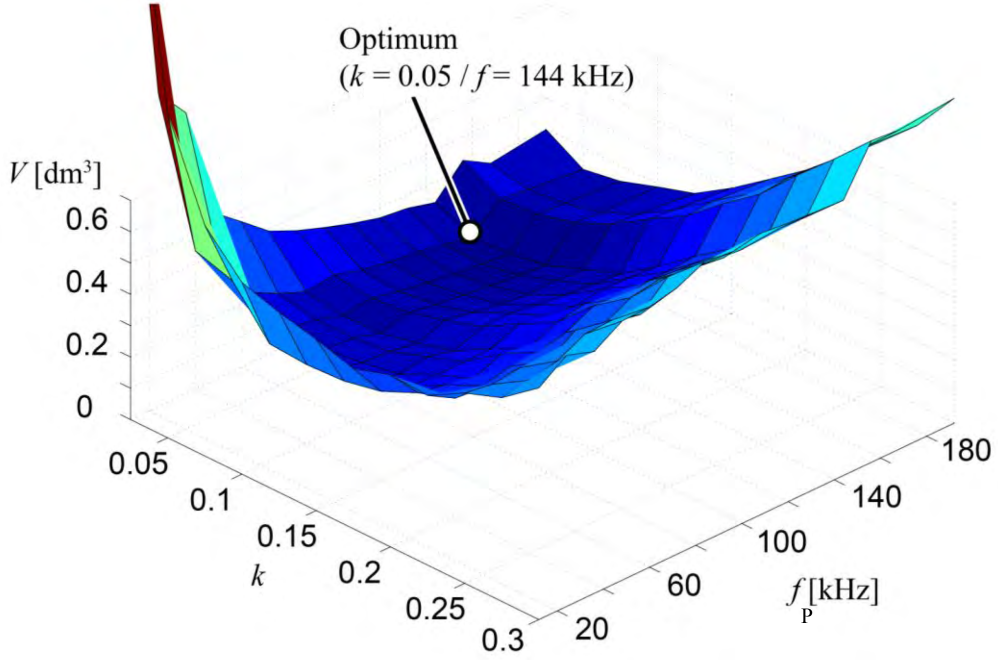
$k = \hat{I}_{1,\mathrm{HF}} / \hat{I}_{1,\mathrm{LF}}$

f_{P}

- **Optimal Selection of Switching Frequency f_{P} ($k = const.$)**

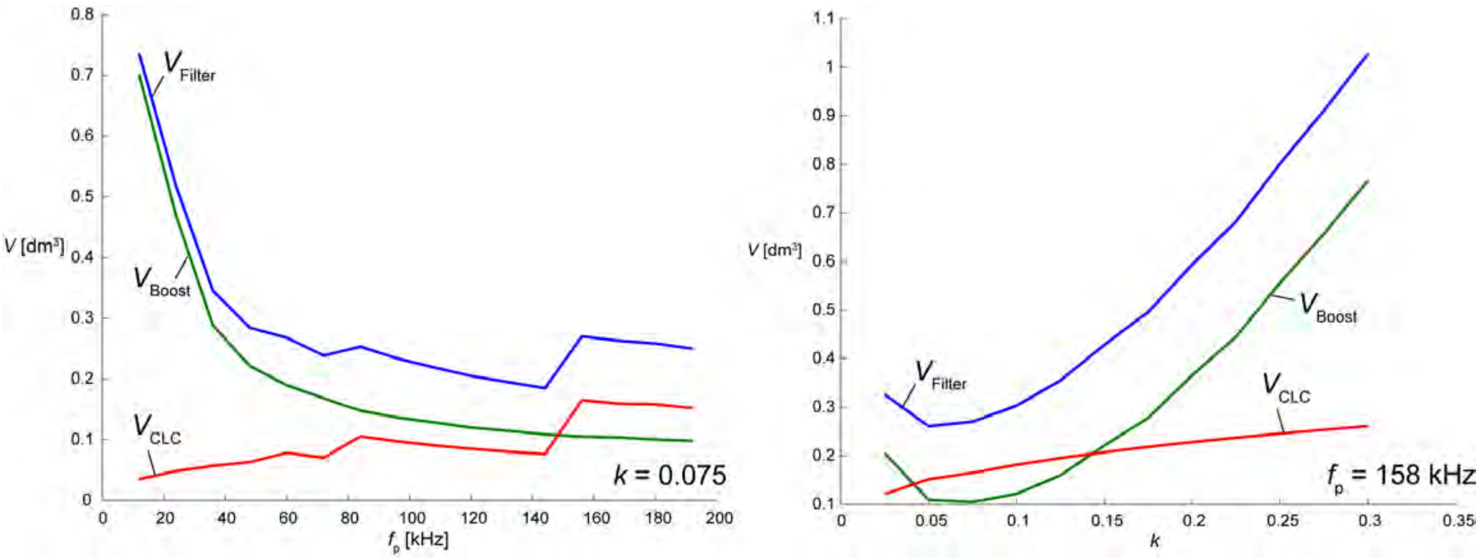
→ High Switching Frequency requires Large CLC-filter; in Return the L_{boost} is Small
→ Low Switching Frequency requires Large L_{boost}; in Return the CLC-filter is Small

EMI Filter Optimization



- **Optimization Result for DM Filter of a Single-Phase Boost-Type PFC Rectifier**

EMI Filter Optimization



- ► Optimization Result for DM Filter of a Single-Phase Boost-Type PFC Rectifier

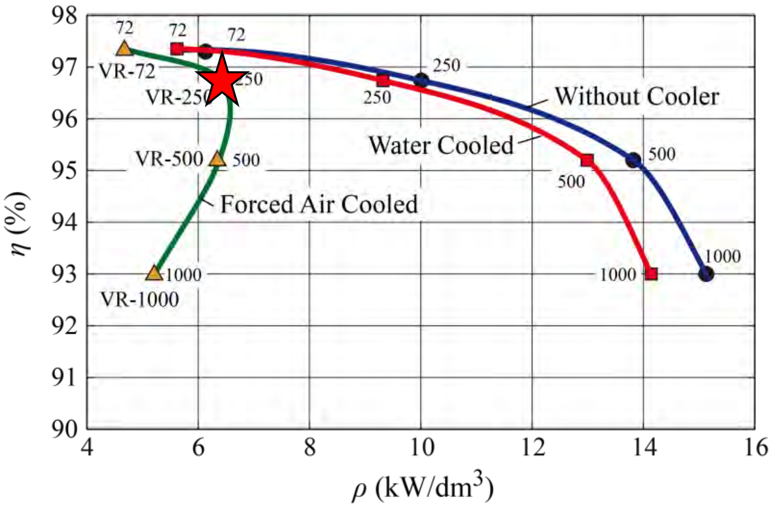
Experimental Analysis

- *Power Density / Efficiency Pareto Limit*
- *Experimental Analysis – VR250*

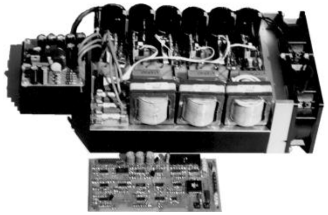
▶ Experimental Analysis

■ Generation 1 – 4 of VIENNA Rectifier Systems

- Switching Frequency of f_S = 250 kHz Offers Good Compromise Concerning Power Density / Weight per Unit Power, Efficiency and Input Current Quality THD_i



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

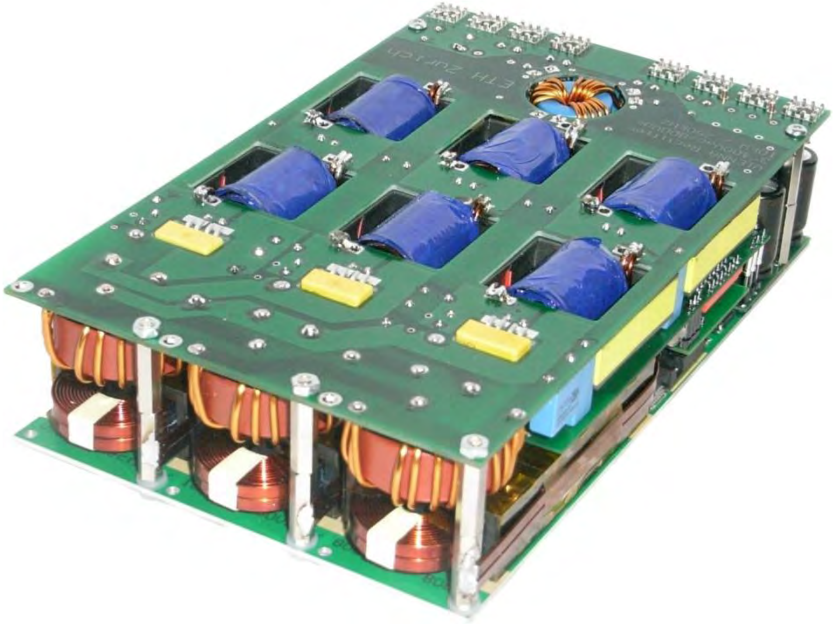
▶ Demonstrator – VR250 (1)

- 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

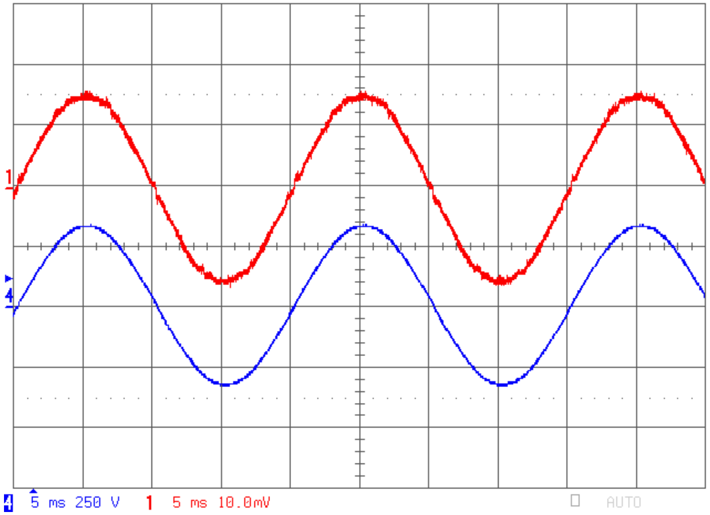
η = 96.8 %
THD_i = 1.6 % @ 800 Hz
10 kW/dm3
3.3 kg (≈3 kW/kg)

Dimensions: 195 x 120 x 42.7 mm^3

▶ Mains Behavior @ f_N = 50 Hz

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

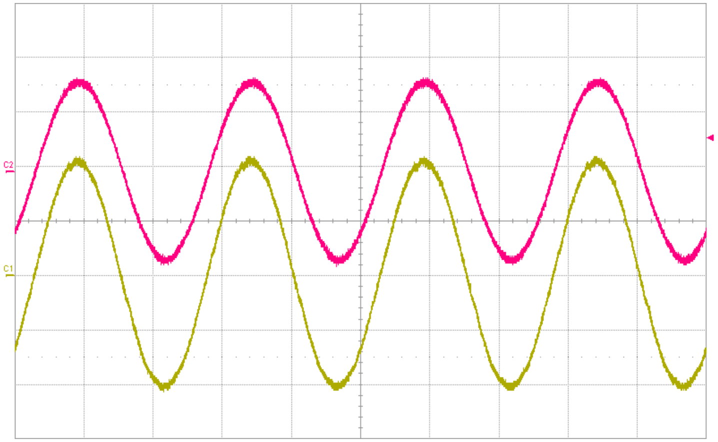
P_0 = 4kW
U_N = 230V
f_N = 50Hz
U_0 = 800V
THD_i = 1.1%



▶ Mains Behavior @ f_N = 400Hz / 800Hz

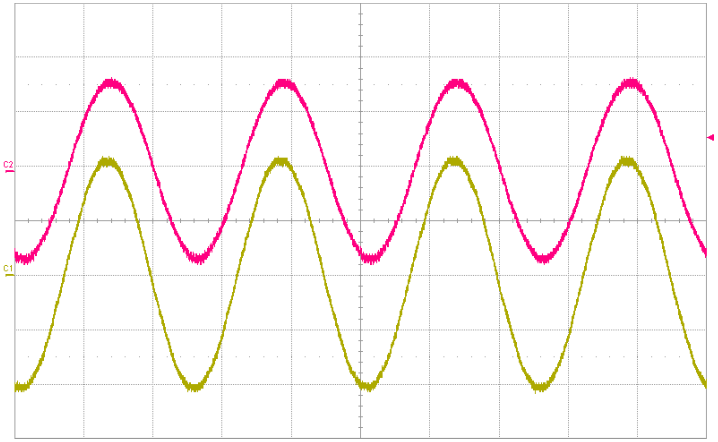
P_0 = 10kW
U_N = 230V
f_N = 400Hz
U_0 = 800V
THD_i = 1.4%

10A/Div
200V/Div
1ms/Div



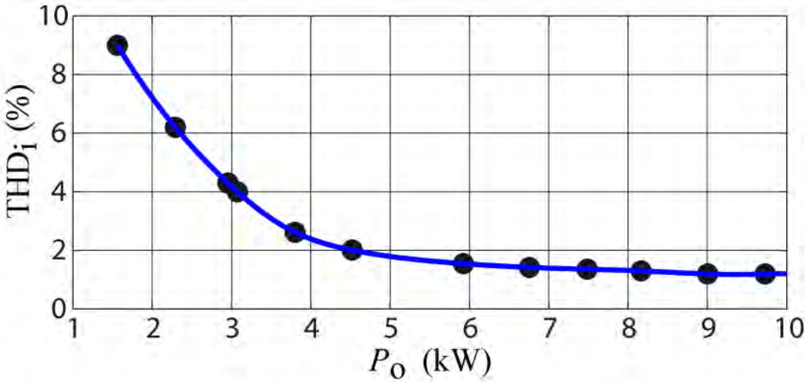
P_0 = 10kW
U_N = 230V
f_N = 800Hz
U_0 = 800V
THD_i = 1.6%

10A/Div
200V/Div
0.5ms/Div

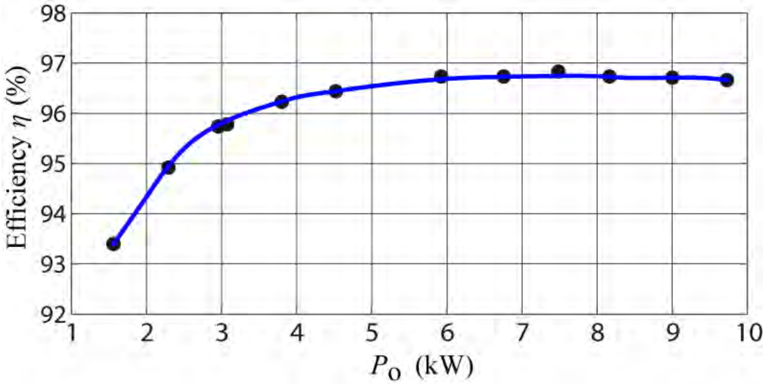


▶ Demonstrator Performance (VR250)

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

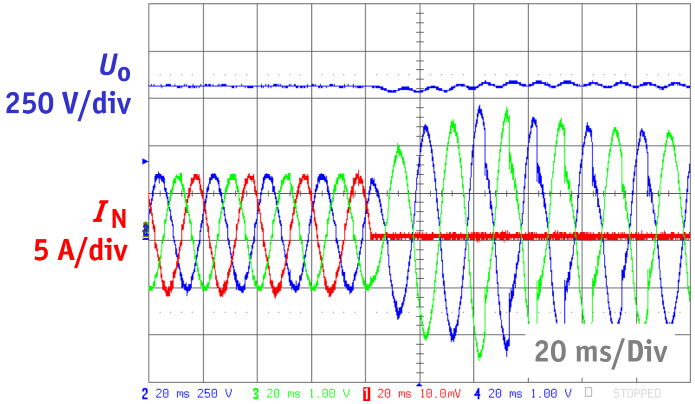


- **Efficiency @ f_N = 800 Hz**

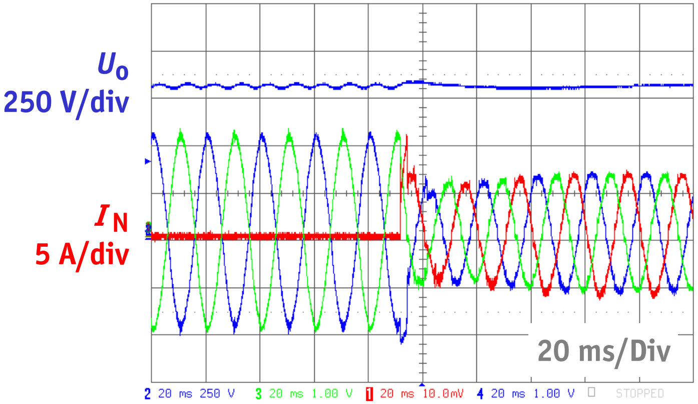


▶ Demonstrator (VR250) Control Behavior

- **Mains Phase Loss**

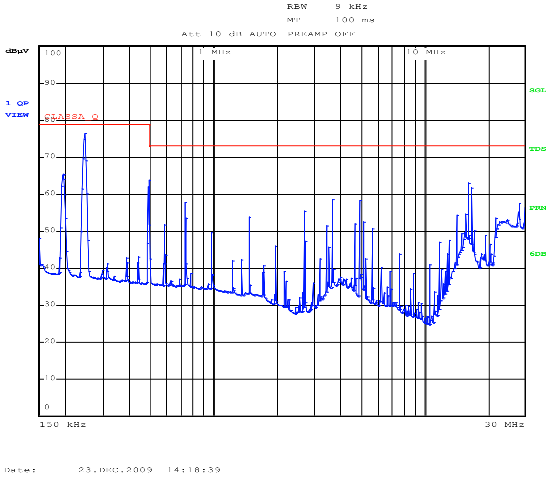


- **Mains Phase Return**

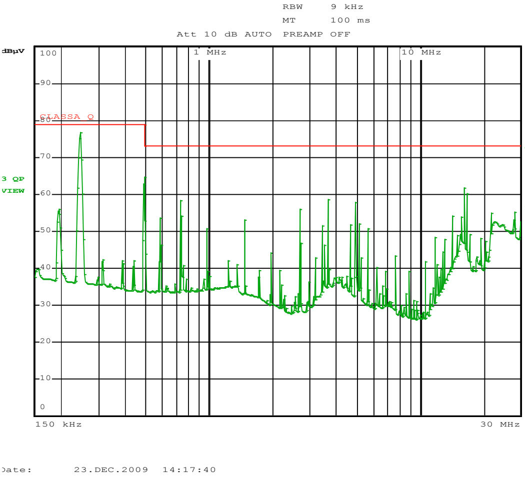


▶ Demonstrator (VR250) EMI Analysis

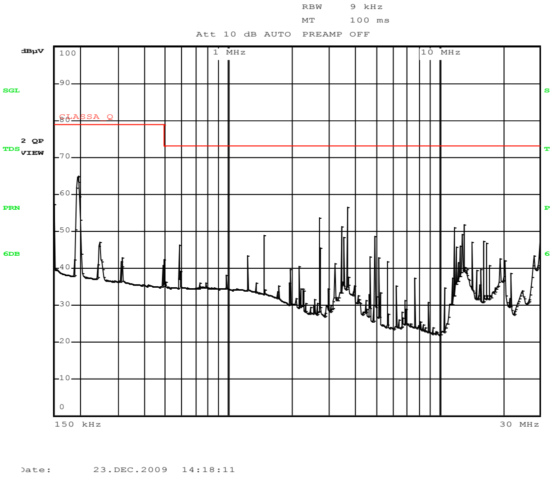
- **Total Emissions**



- **DM Emissions**



- **CM Emissions**

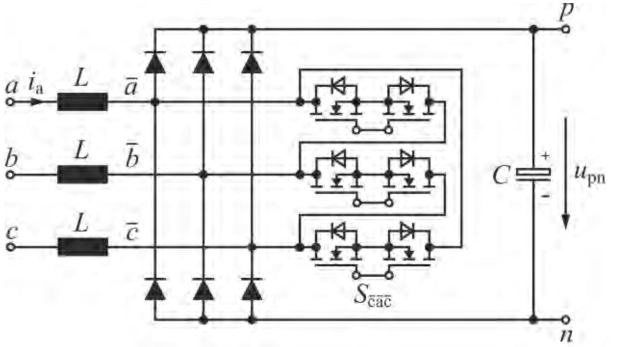


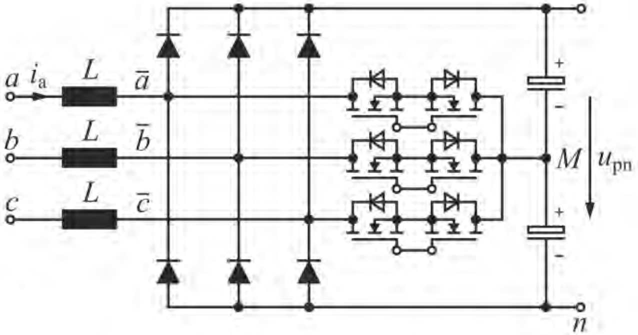
Evaluation of Boost-Type Systems

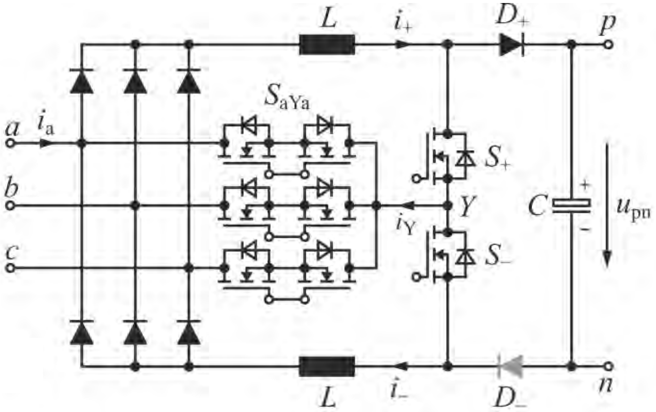
3^{rd} Harmonic Inj. Rectifier
Δ-Switch Rectifier
Vienna-Rectifier
Six-Switch Rectifier

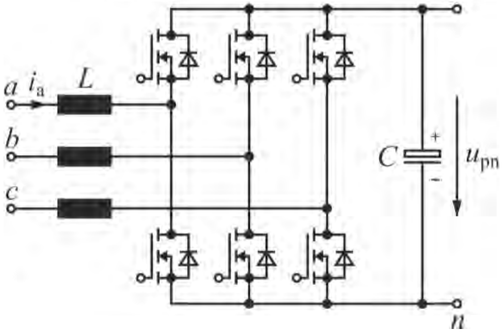
Boost-Type PFC Rectifiers

- 3rd Harmonic Inj. Type
- Diode Bridge Conduction Modulation



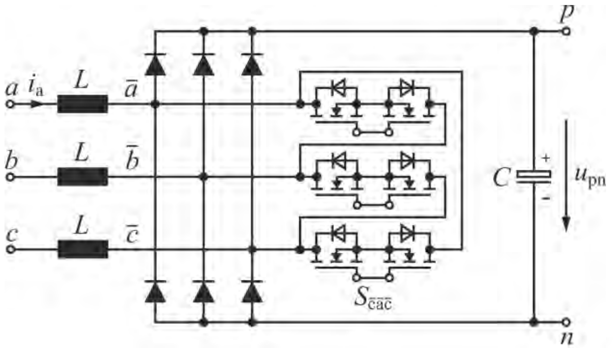


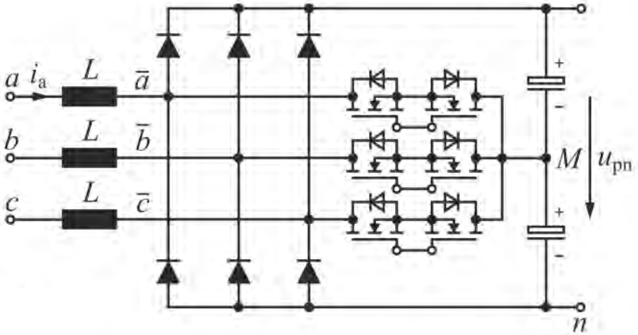


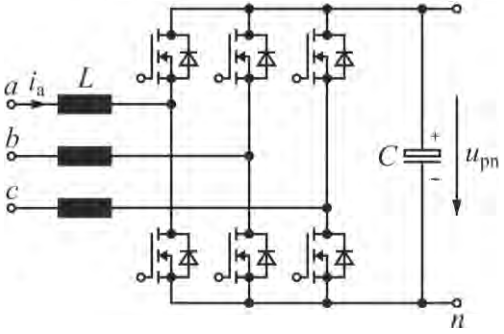


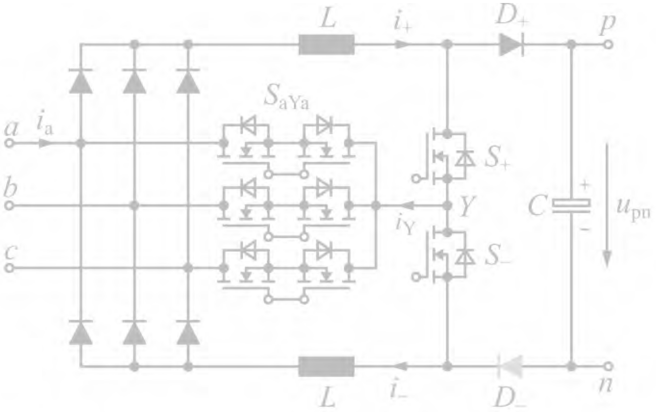
Boost-Type PFC Rectifiers

- 3rd Harmonic Inj. Type
  → **Limited Operating Range**



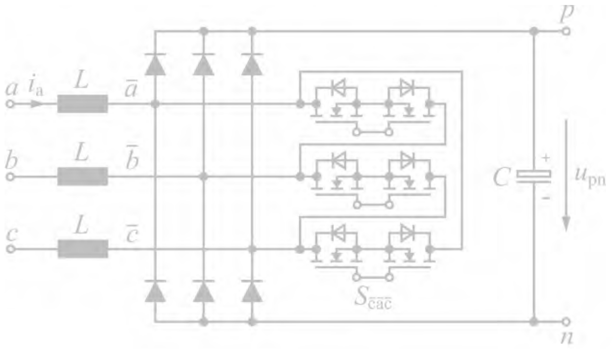


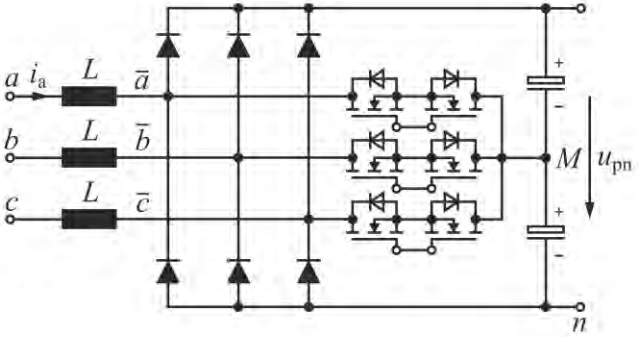


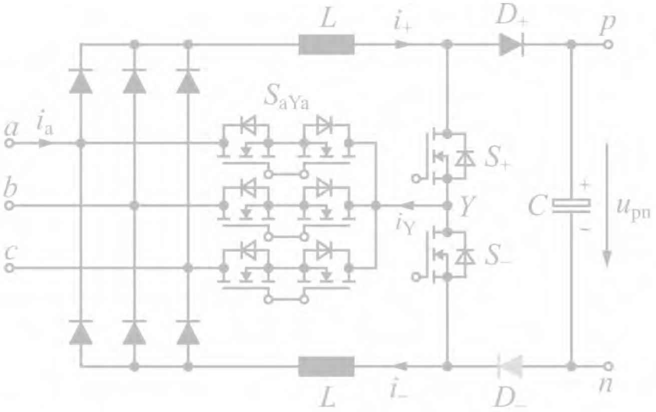


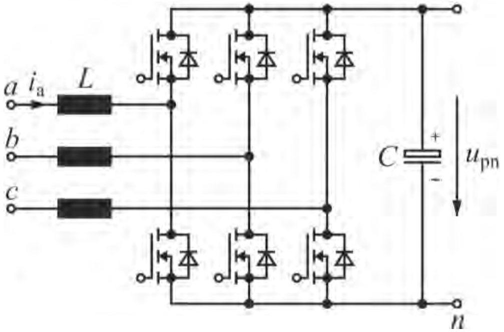
Boost-Type PFC Rectifiers

- Δ-Switch Rectifier
  → System Complexity

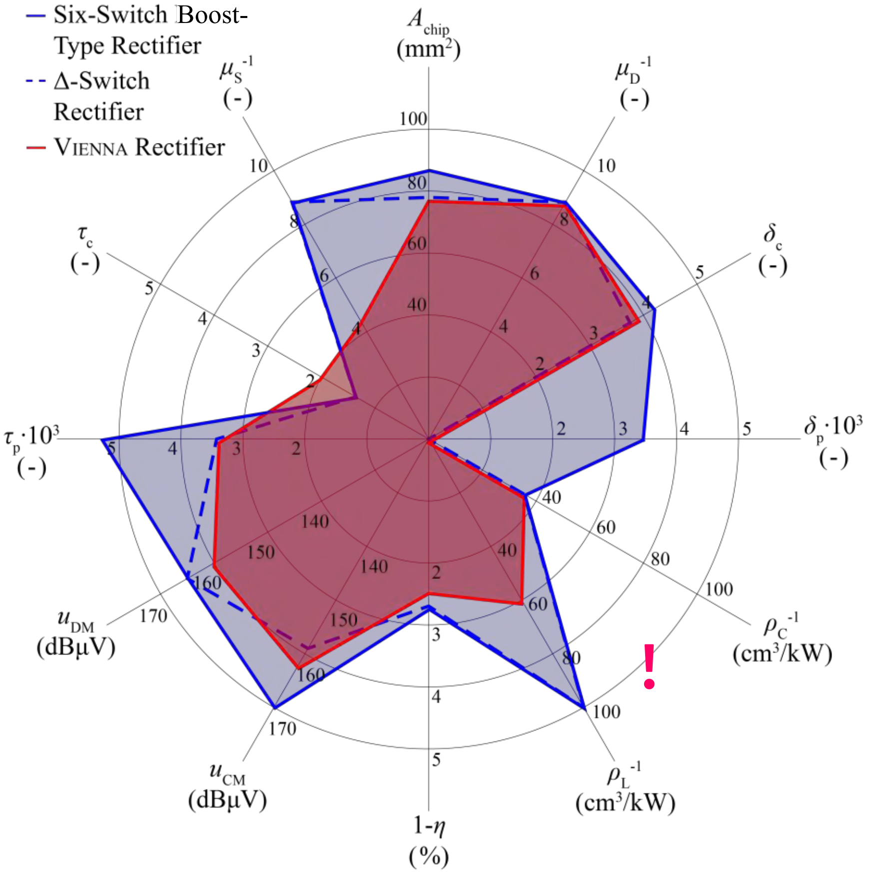


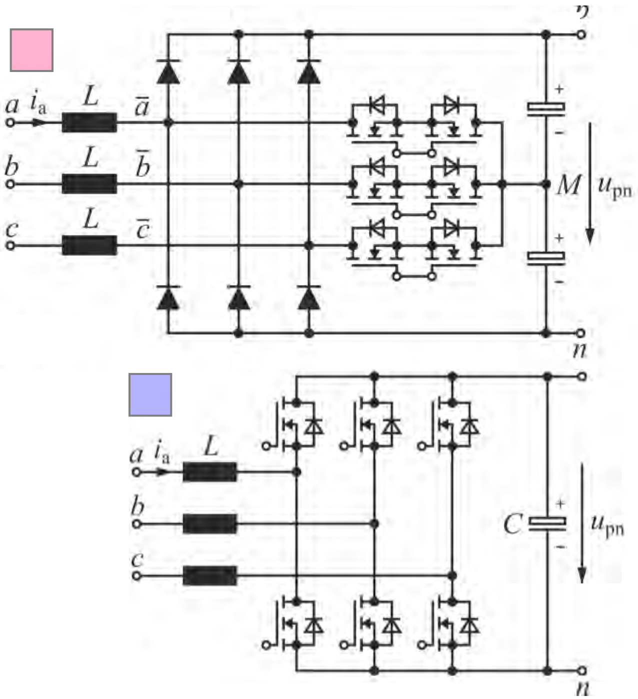




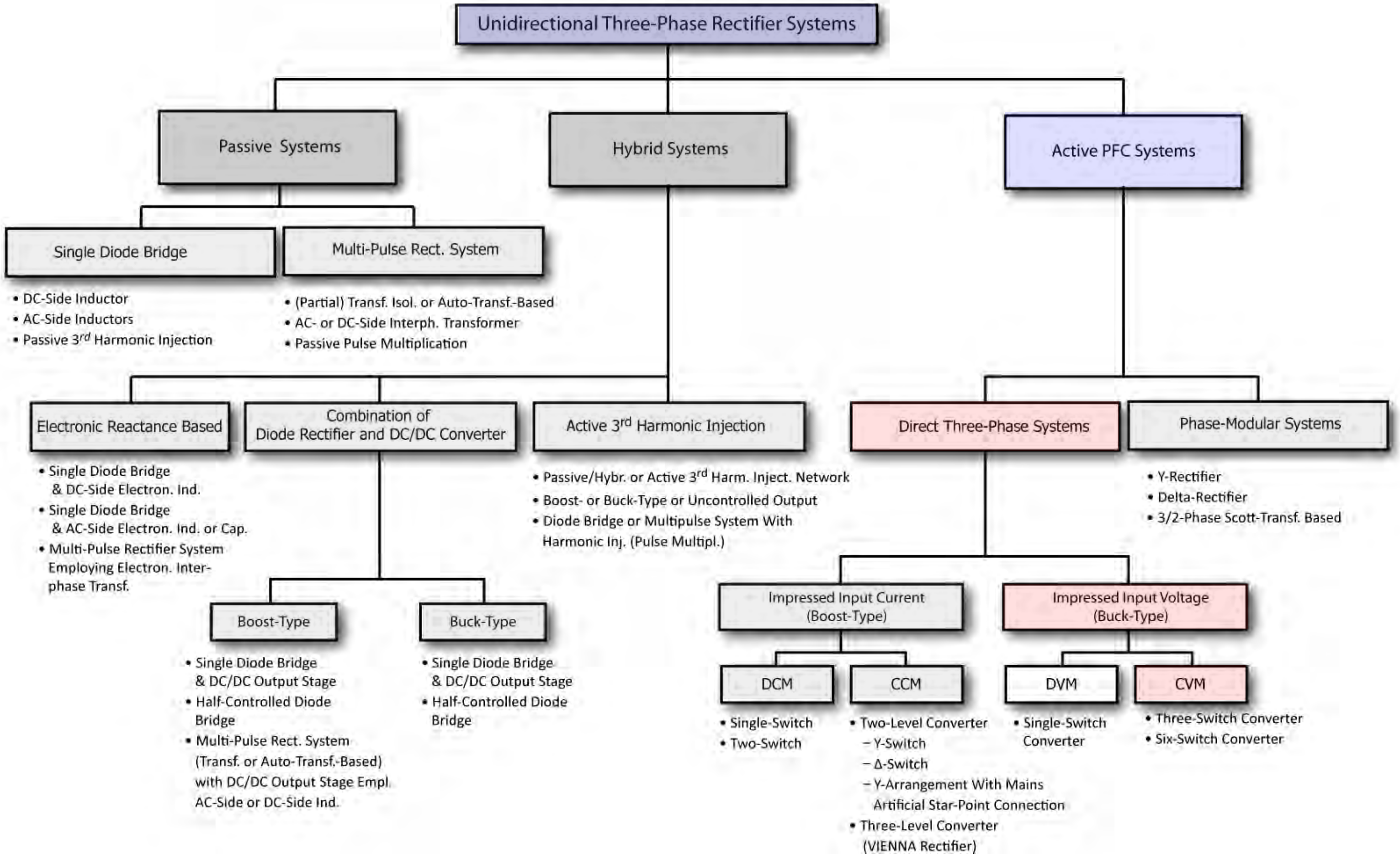


Vienna Rectifier vs. Six-Switch Rectifier





▶ Classification of Unidirectional Rectifier Systems



Unidirectional Three-Phase Rectifier Systems

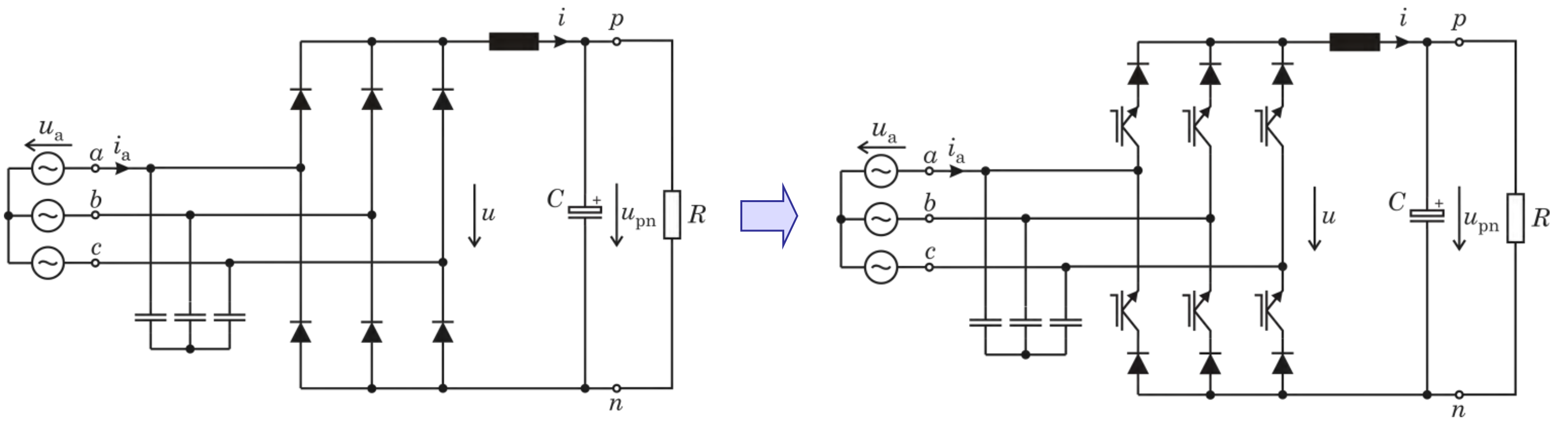
- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3rd Harmonic Injection
  - Multi-Pulse Rect. System
    - (Partial) Transf. Isol. or Auto-Transf.-Based
    - AC- or DC-Side Interph. Transformer
    - Passive Pulse Multiplication
- Hybrid Systems
  - Electronic Reactance Based
    - Single Diode Bridge & DC-Side Electron. Ind.
    - Single Diode Bridge & AC-Side Electron. Ind. or Cap.
    - Multi-Pulse Rectifier System Employing Electron. Inter-phase Transf.
  - Combination of Diode Rectifier and DC/DC Converter
    - Boost-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
      - Multi-Pulse Rect. System (Transf. or Auto-Transf.-Based) with DC/DC Output Stage Empl. AC-Side or DC-Side Ind.
    - Buck-Type
      - Single Diode Bridge & DC/DC Output Stage
      - Half-Controlled Diode Bridge
  - Active 3rd Harmonic Injection
    - Passive/Hybr. or Active 3rd Harm. Inject. Network
    - Boost- or Buck-Type or Uncontrolled Output
    - Diode Bridge or Multipulse System With Harmonic Inj. (Pulse Multipl.)
- Active PFC Systems
  - Direct Three-Phase Systems
    - Impressed Input Current (Boost-Type)
      - DCM
        - Single-Switch
        - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - Δ-Switch
          - Y-Arrangement With Mains Artificial Star-Point Connection
        - Three-Level Converter (VIENNA Rectifier)
    - Impressed Input Voltage (Buck-Type)
      - DVM
        - Single-Switch Converter
      - CVM
        - Three-Switch Converter
        - Six-Switch Converter
  - Phase-Modular Systems
    - Y-Rectifier
    - Delta-Rectifier
    - 3/2-Phase Scott-Transf. Based

Buck-Type CVM PFC Rectifier System

- *Derivation of Circuit Topologies*

▶ Derivation of the Circuit Topology (1)

■ Insertion of Switches in Series to the Diodes

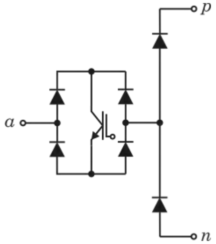


- \+ DC Current Distribution to Phases *a*, *b*, *c* can be Controlled
- \+ Control of Output Voltage $0 \le u \le \frac{3}{2}\hat{U}$

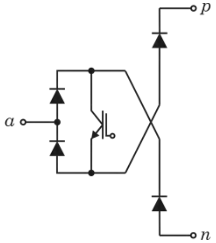
- – Pulsating Input Currents / EMI Filtering Requ.
- – Relatively High Conduction Losses

▶ Derivation of the Circuit Topology (2)

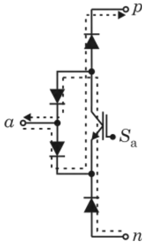
(1)

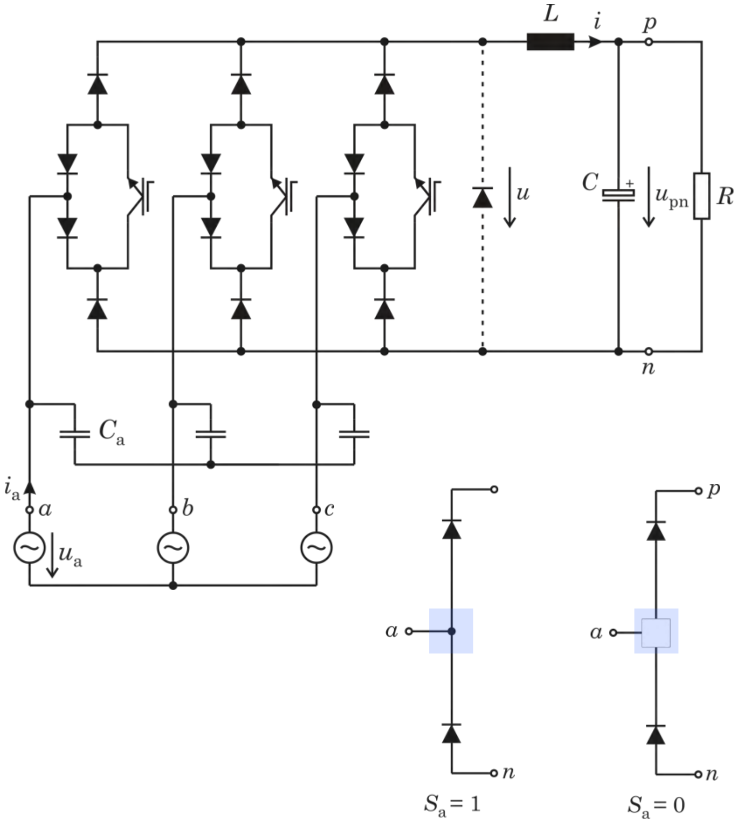


(2)



(3)



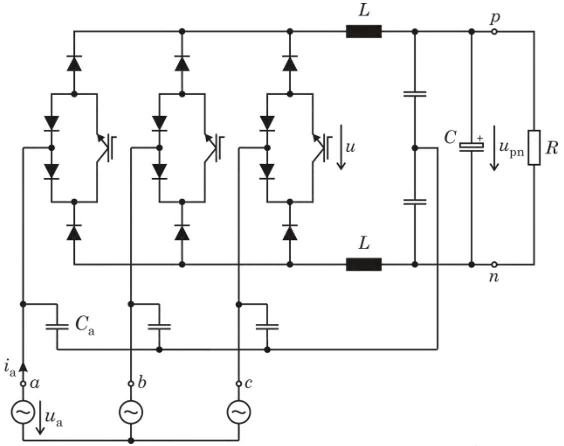


- **Insertion of 4Q-Switches on the AC-Side in Order to Enable Control of the DC Current Distribution to Phases *a*, *b*, *c***

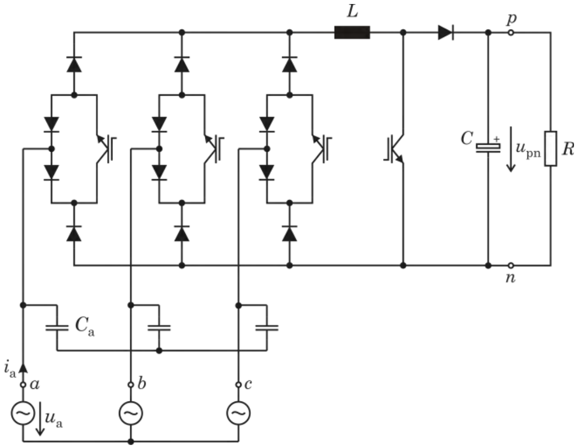
▶ Derivation of the Circuit Topology (3)

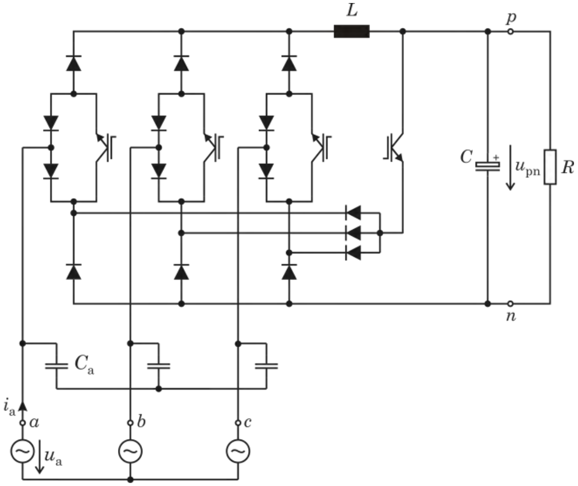
■ Circuit Extensions

- **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**





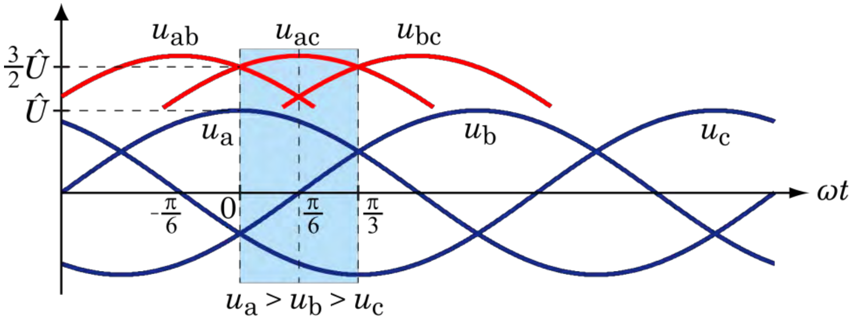
■ Circuit Extensions Shown for 3-Switch Topology, but is also Applicable to 6-Switch Topology

Buck-Type PFC Rectifier Analysis

- *Modulation*
- *Input Current Formation*
- *Output Voltage Formation*
- *Experimental Analysis*

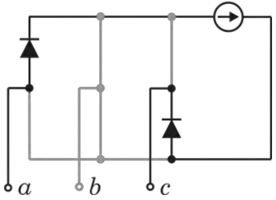
▶ Modulation Scheme

- Consider 60°-Wide Segment of the Mains Period; Suitable Switching States Denominated by (s_a, s_b, s_c)

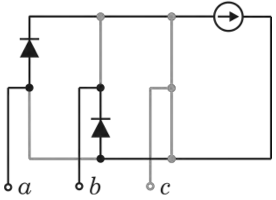


- Clamping to Phase with Highest Absolute Voltage Value, i.e.
  - Phase *a* for $\omega t \in \left(-\frac{\pi}{6}, +\frac{\pi}{6}\right)$,
  - Phase *c* for $\omega t \in \left(+\frac{\pi}{6}, +\frac{\pi}{2}\right)$ etc.
  - Assumption: $\omega t \in \left(0, +\frac{\pi}{6}\right)$

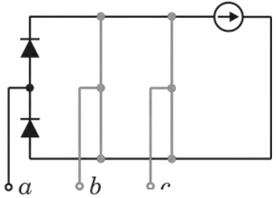
(111)



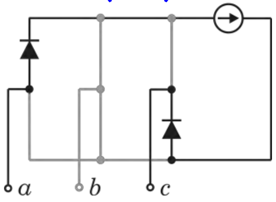
(110)



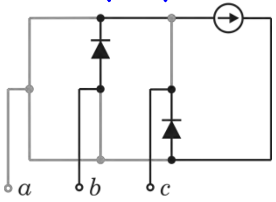
(100)



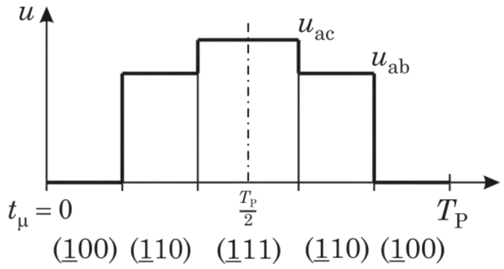
(101)



(011)



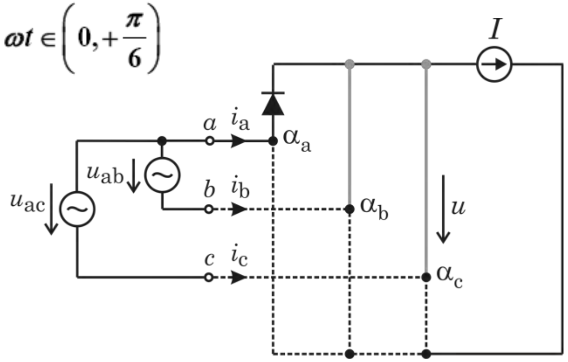
also: (010)
(011)

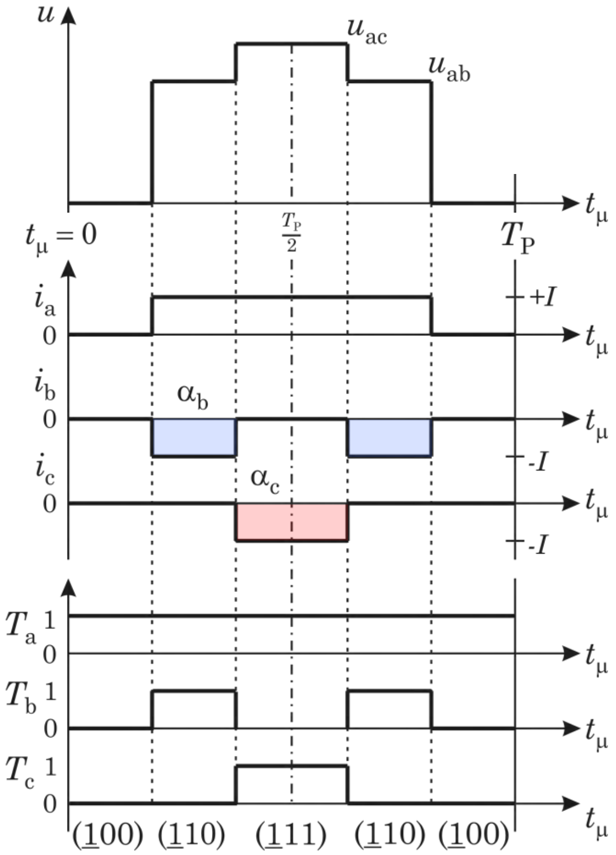


- Clamping and "Staircase-Shaped" Link Voltage in Order to Minimize the Switching Losses

► Input Current and Output Voltage Formation (1)

- Assumption: $\omega t \in \left(0, +\frac{\pi}{6}\right)$





- Ohmic Mains Behavior:

$$i_a = G^* u_a = (\alpha_b + \alpha_c) \cdot I$$

$$i_b = G^* u_b = -\alpha_b \cdot I$$

$$i_c = G^* u_c = -\alpha_c \cdot I$$

- Example:

$$\alpha_b + \alpha_c = \frac{G^* u_a}{I} = \frac{G^* \hat{U}}{I} \cdot \cos(\omega t) = M \cdot \cos(\omega t)$$

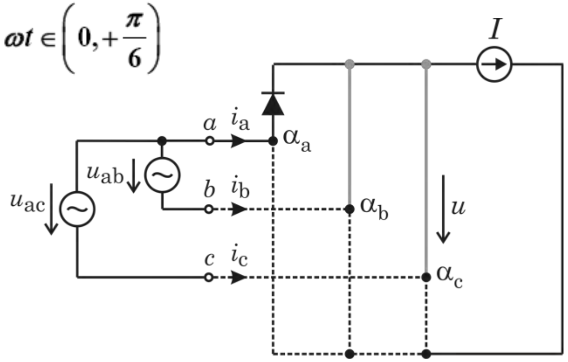
$$\alpha_b = -\frac{G^* u_b}{I} = M \cdot \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$M \in (0 \ldots 1), I \geq \hat{I}^*$

$$\alpha_c = -\frac{G^* u_c}{I} = M \cdot \cos\left(\omega t + \frac{2\pi}{3}\right)$$

► Input Current and Output Voltage Formation (2)

- Assumption: $\omega t \in \left(0, +\frac{\pi}{6}\right)$



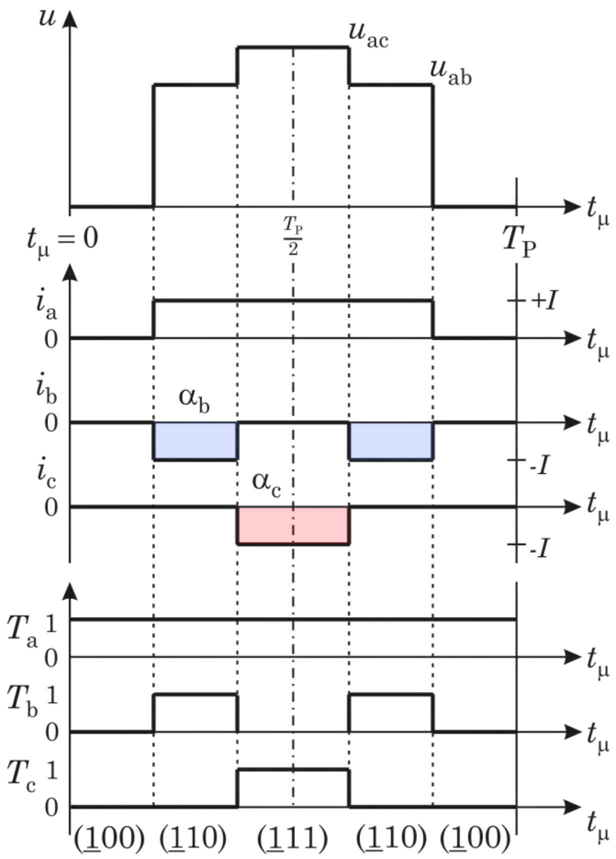
- Output Voltage Formation:

$$\bar{u} = u_{ab}\cdot\alpha_b + u_{ac}\cdot\alpha_c$$

$$P_{link} = P_{input}$$

$$\bar{u}\cdot I = \frac{3}{2}\cdot\hat{U}\cdot\hat{I}^*$$

$$\bar{u} = \frac{3}{2}\cdot\hat{U}\cdot\frac{\hat{I}^*}{I} = \frac{3}{2}\cdot\hat{U}\cdot M$$



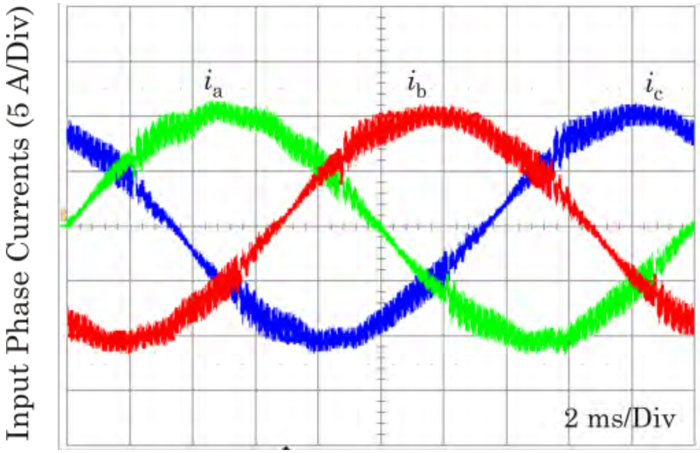
- **Output Voltage is Formed by Segments of the Input Line-to-Line Voltages**
- **Output Voltage Shows Const. Local Average Value**

▶ 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)

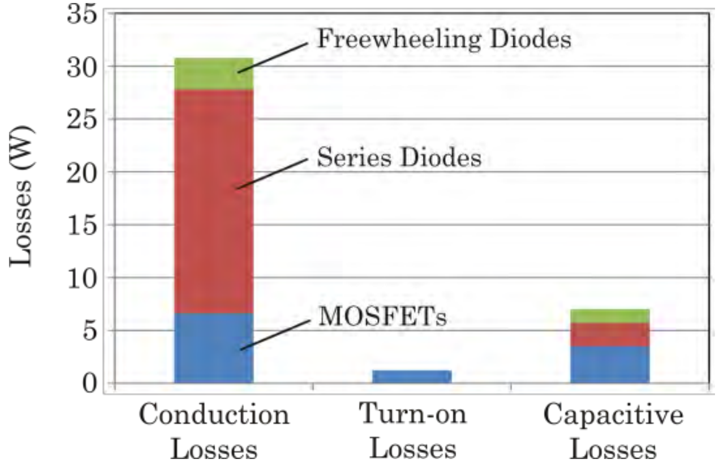


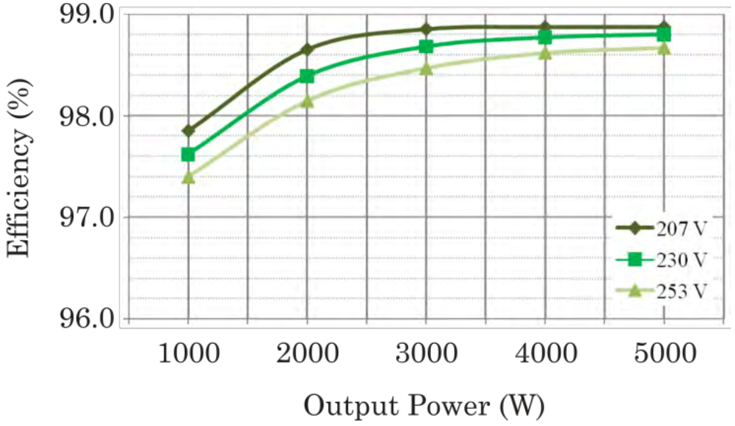
▶ Experimental Results

■ 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)

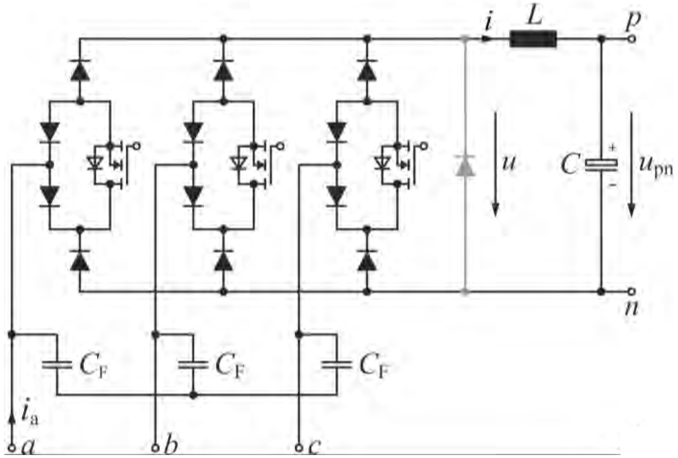


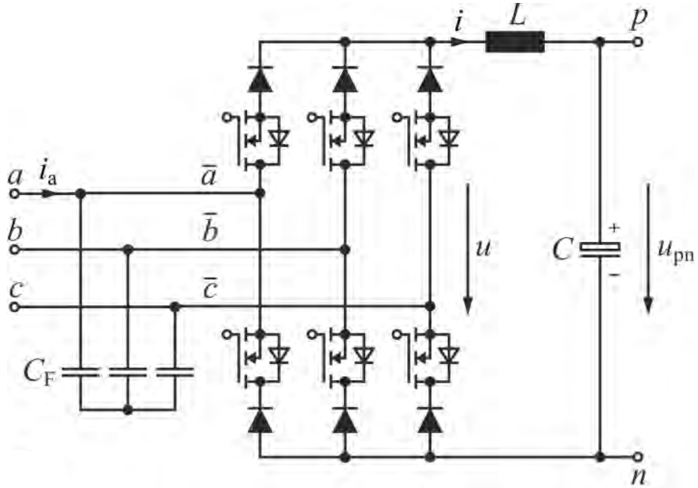


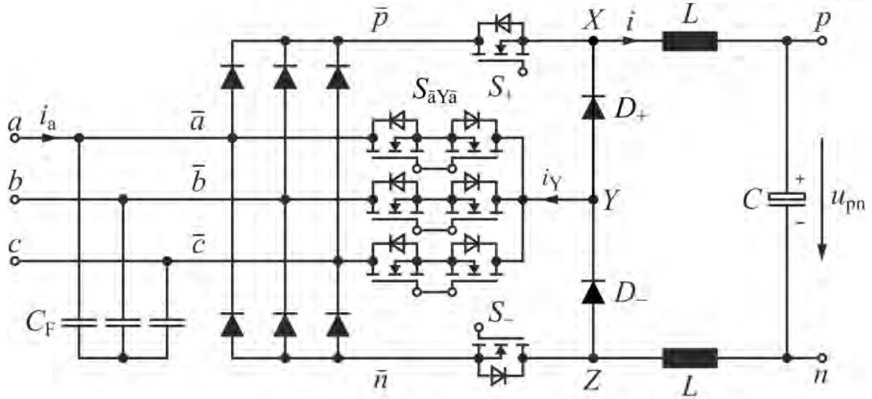
Comparison of Buck-Type Systems

Six-Switch Rectifier
SWISS-Rectifier

Buck-Type PFC Rectifiers

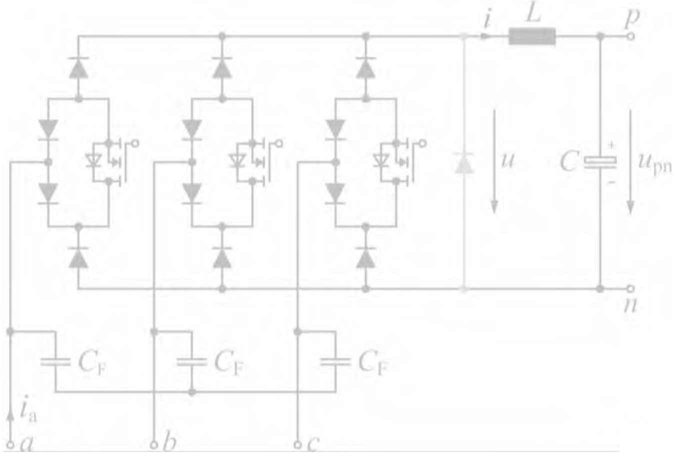


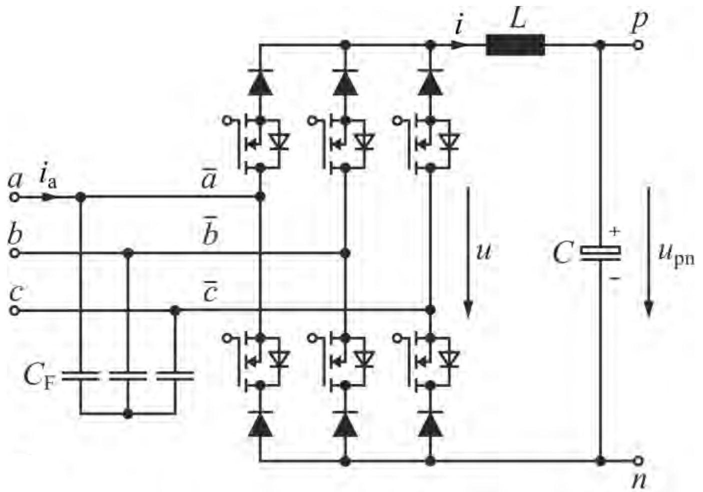


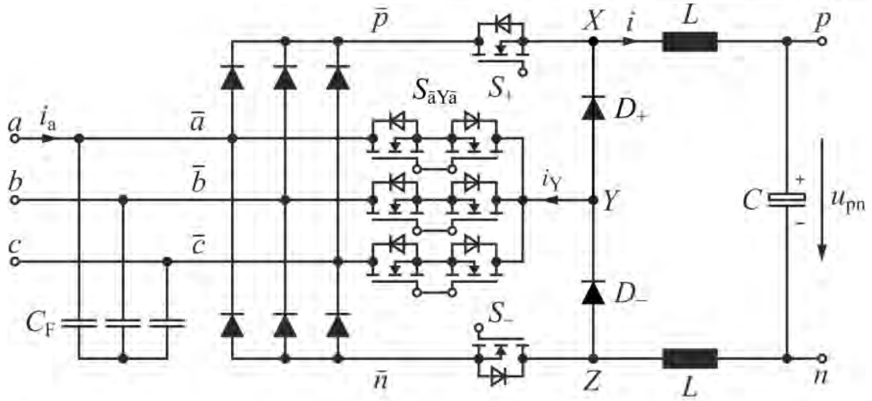


- 3^{rd} Harmonic Inj. Type
- Diode Bridge Cond. Modulation

Buck-Type PFC Rectifiers

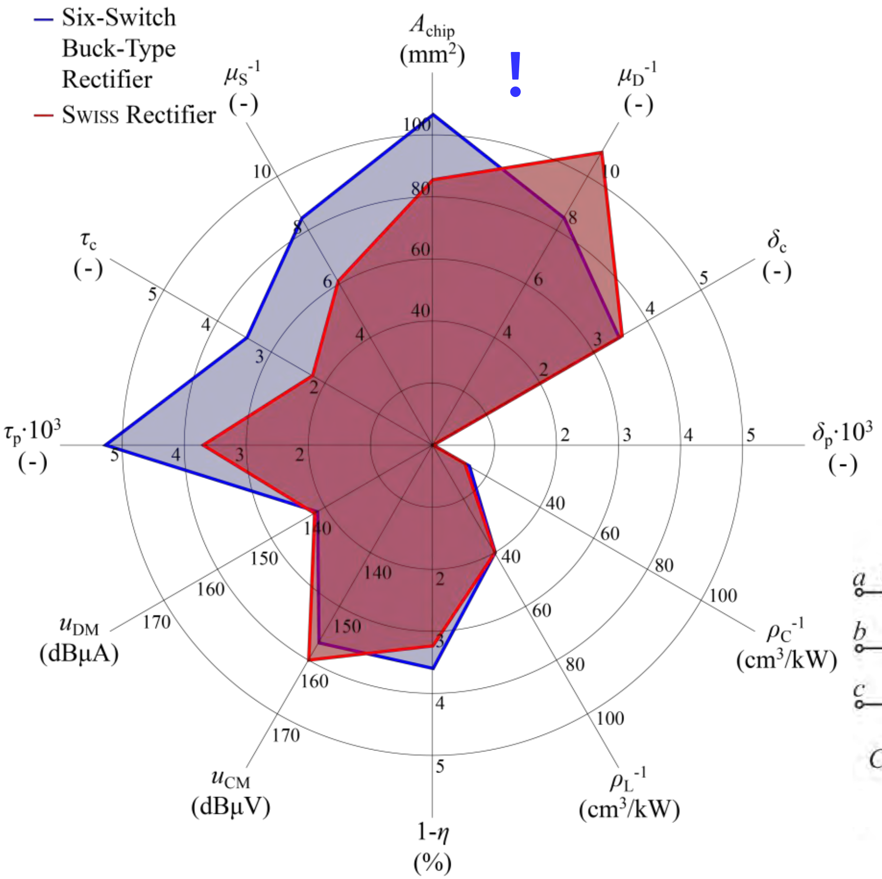


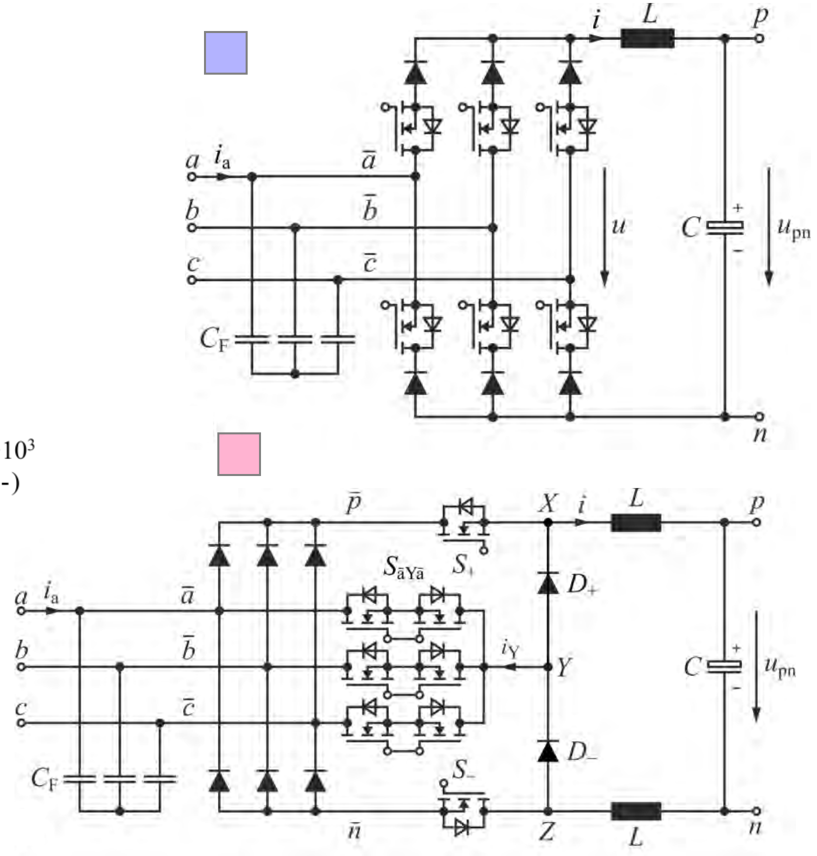




- Three-Switch Rectifier
  → Conduction Losses

SWISS Rectifier vs. Six-Switch Rectifier





Summary of Unidirectional PFC Rectifier Systems

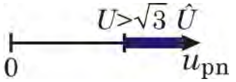
- *Block Shaped Input Current Systems*
- *Sinusoidal Input Current Systems*

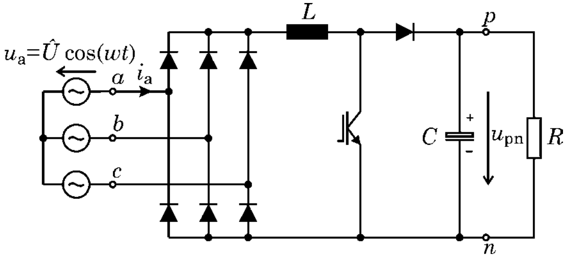
► Block Shaped Input Current Rectifier Systems

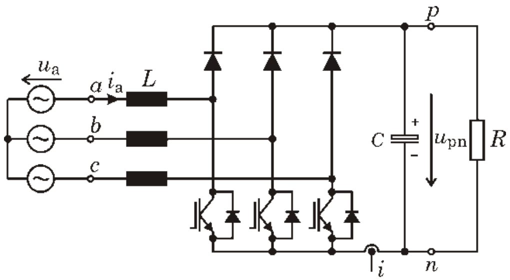
+ Controlled Output Voltage
+ Low Complexity
+ High Semicond. Utilization
+ Total Power Factor $\lambda \approx 0.95$

− $\mathrm{THD}_\mathrm{I} \approx 30\%$

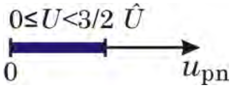
Boost-Type

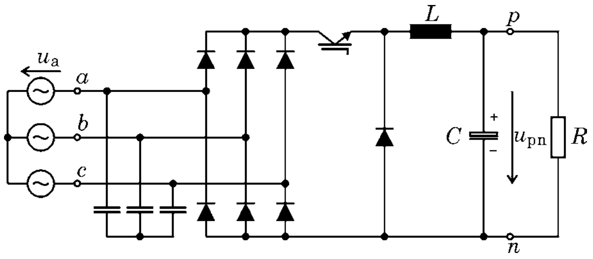


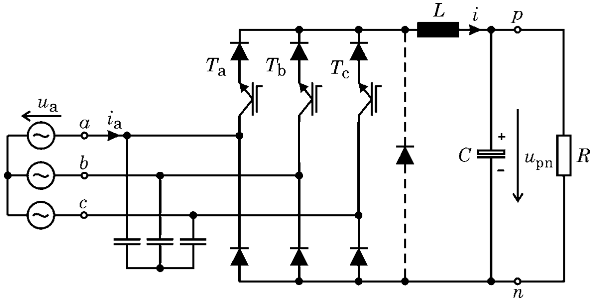




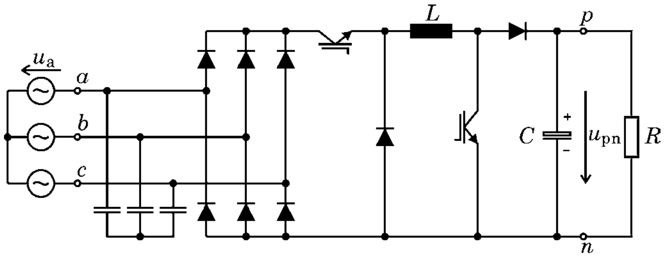
Buck-Type

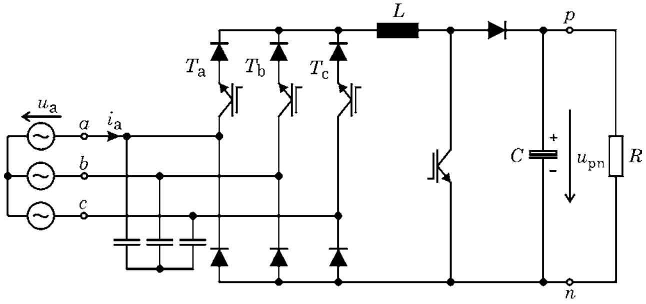






Buck+Boost-Type

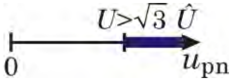


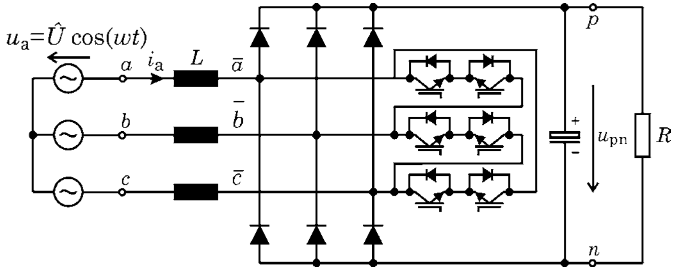


► Sinusoidal Input Current Rectifier Systems (1)

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

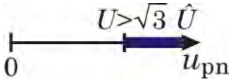
Boost-Type

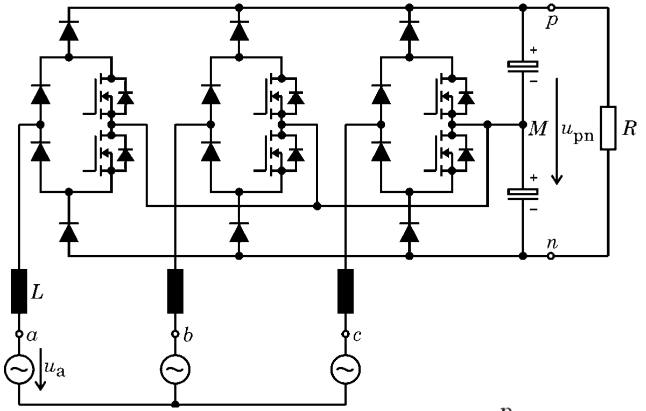




- \+ Controlled Output Voltage
- \+ 3-Level Characteristic
- \+ Tolerates Mains Phase Loss
- \+ Power Semicond. Stressed with Half Output Voltage
- − Higher Control Complexity

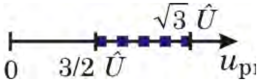
Boost-Type

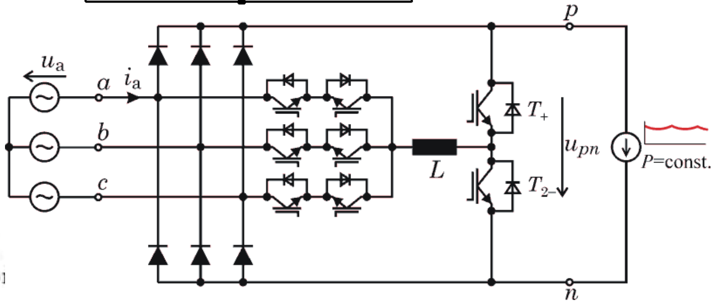




- \+ Low Current Stress on Power Semicond.
- \+ In Principal No DC-Link Cap. Required
- \+ Control Shows Low Complexity
- − Sinusoidal Mains Current Only for Const. Power Load
- − Power Semicond. Stressed with Full Output Voltage
- − Does Not Tolerate Loss of a Mains Phase

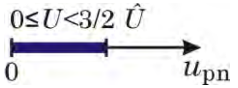
Unregulated Output

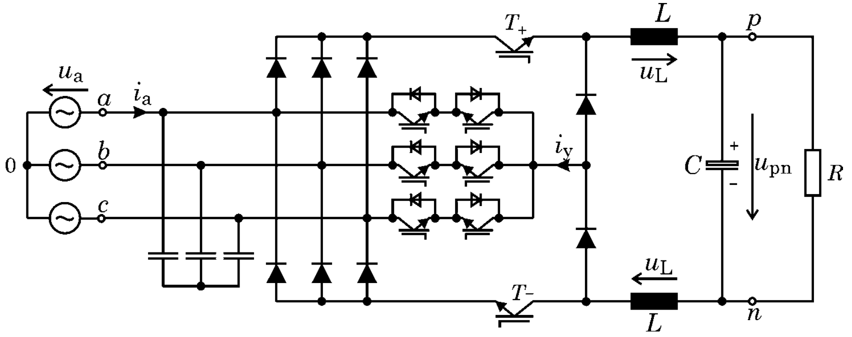




▶ Sinusoidal Input Current Rectifier Systems (2)

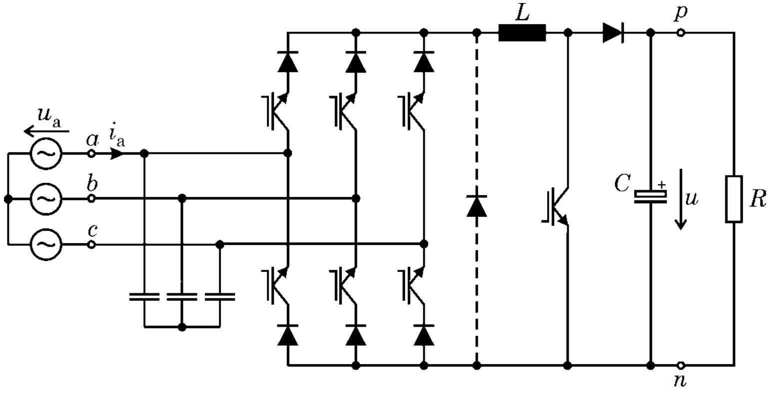
Buck-Type





- \+ 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



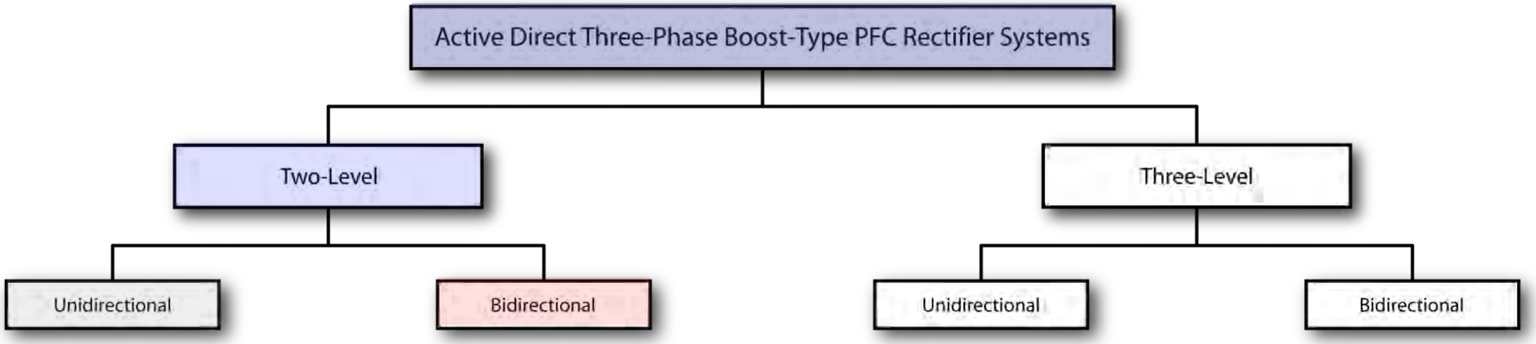
- \+ See Buck-Type Converter
- \+ Wide Output Voltage Range
- \+ Tolerates Mains Phase Loss, i.e. Sinusoidal Mains Current also for 2-Phase Operation
- – See Buck-Type Converter (6-Switch Version of Buck Stage Enables Compensation of AC-Side Filter Cap. Reactive Power)

Bidirectional PFC Rectifier Systems

- *Boost-Type Topologies*
- *Buck-Type Topologies*

Boost-Type Topologies

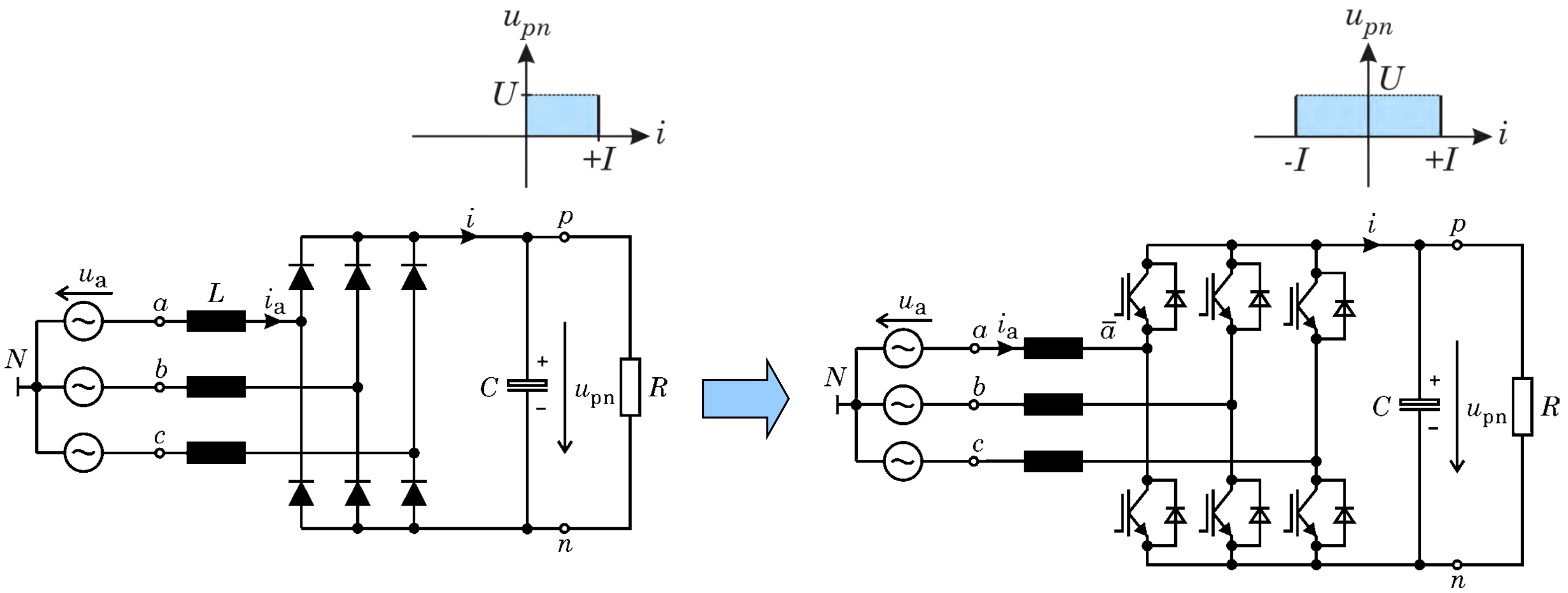
► Classification of Bidirectional Boost-Type Rectifier Systems



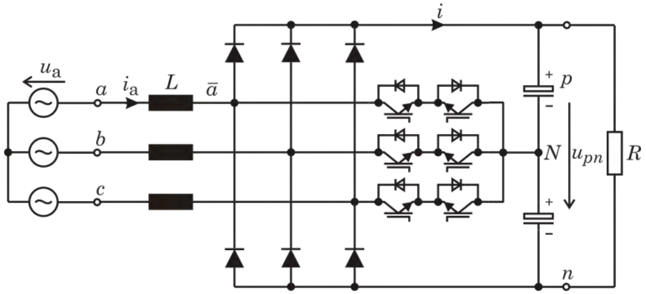
- Active Direct Three-Phase Boost-Type PFC Rectifier Systems
  - Two-Level
    - Unidirectional
    - Bidirectional
      - Six-Switch Converter
      - Z-Source Converter
  - Three-Level
    - Unidirectional
    - Bidirectional
      - Neutral Point Clamped (NPC) Converter
      - Flying Capacitor (FC) Converter
      - T-Type Converter
      - Active NPC (ANPC) Converter
      - Bridge-Leg Inductor (BLI) Converter

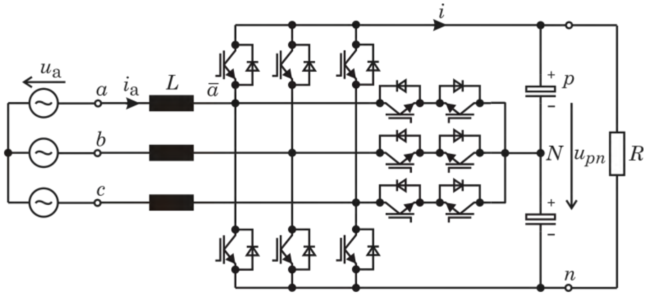
▶ Derivation of Two-Level Boost-Type Topologies

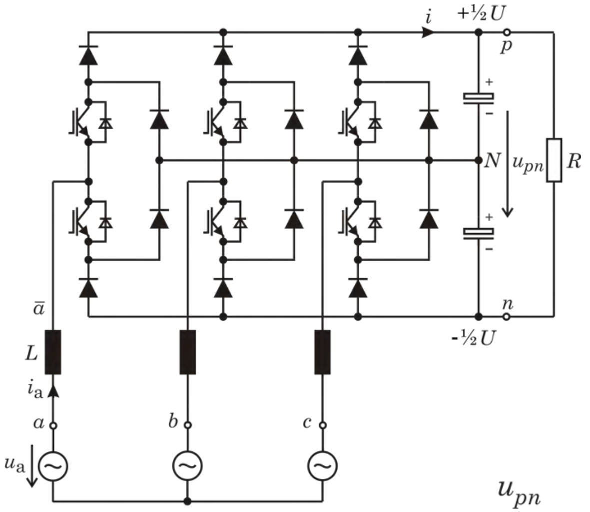
- **Output Operating Range**

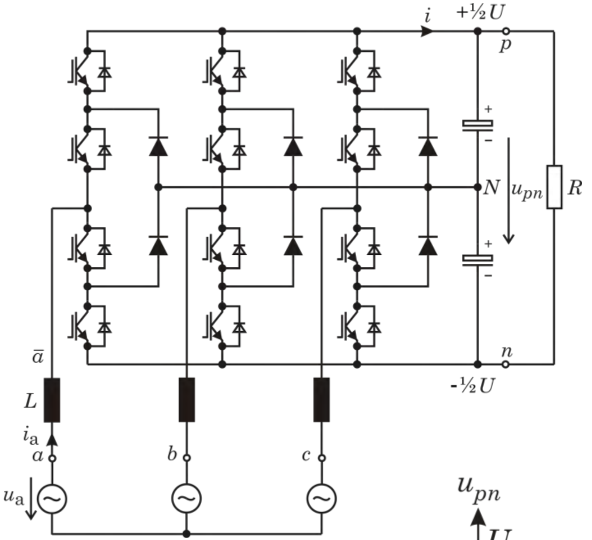


▶ Derivation of Three-Level Boost-Type Topologies

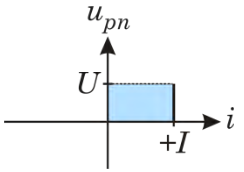


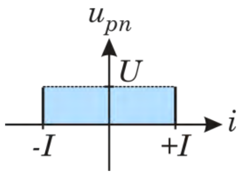




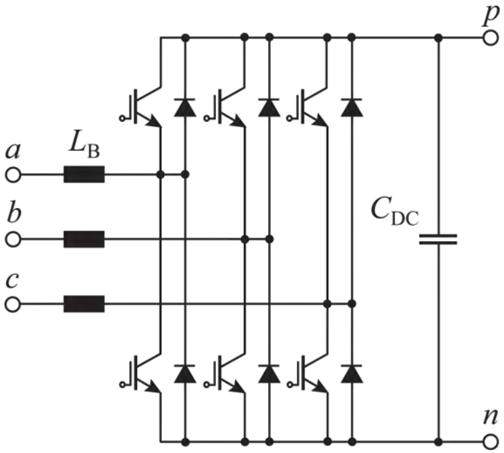


- **Output Operating Range**





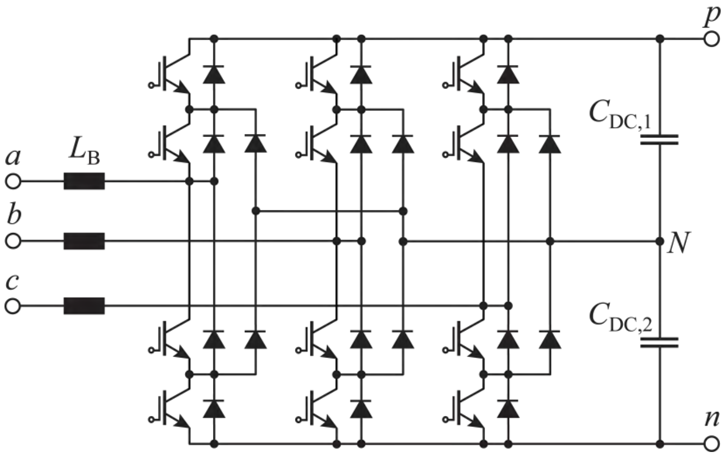
► Comparison of Two-Level/Three-Level NPC Boost-Type Rectifier Systems



- Two-Level Converter Systems

\+ State-of-the-Art Topology for LV Appl.
\+ Simple, Robust, and Well-Known
\+ Power Modules and Auxiliary Components Available from Several Manufacturers

\- Limited Maximum Switching Frequency
\- Large Volume of Input Inductors

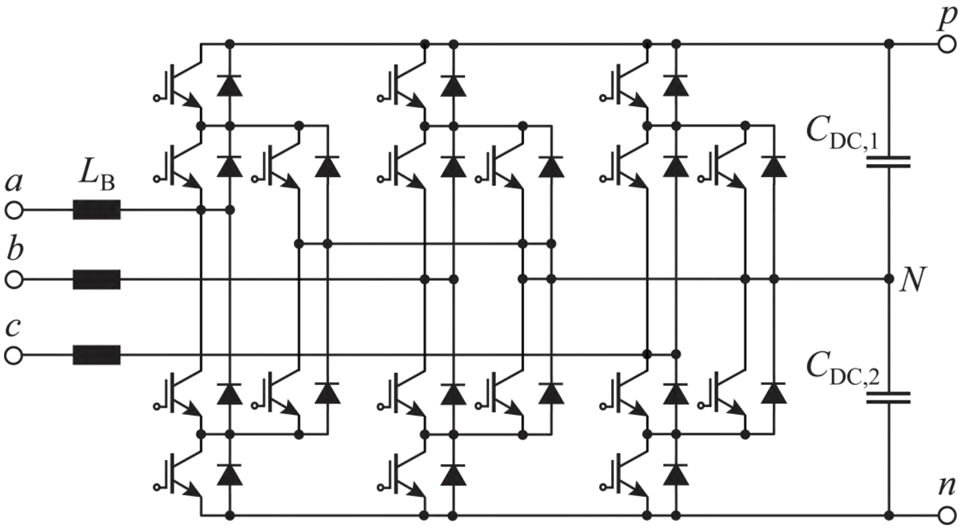


- Two-Level → Three-Level Converter Systems

\+ Reduction of Device Blocking Voltage Stress
\+ Lower Switching Losses
\+ Reduction of Passive Component Volume

\- Higher Conduction Losses
\- Increased Complexity and Implementation Effort

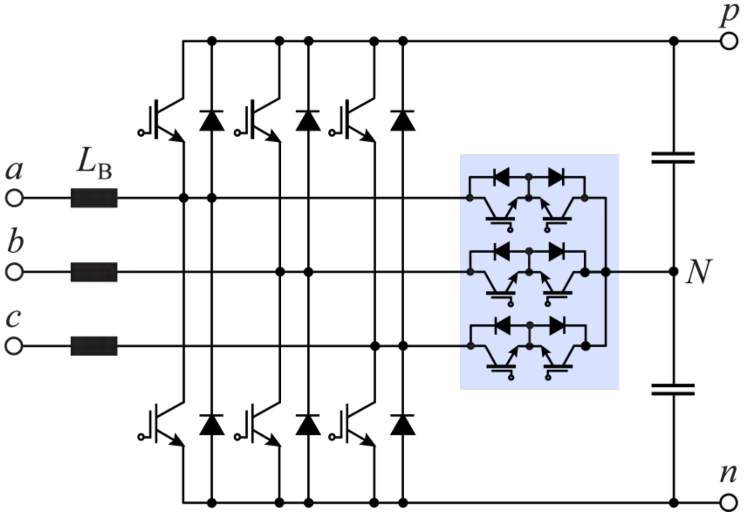
▶ Active Neutral Point Clamped (ANPC) Three-Level Boost-Type System



+ Active Distribution of the Switching Losses Possible
+ Better Utilization of the Installed Switching Power Devices

– Higher Implementation Effort Compared to NPC Topology

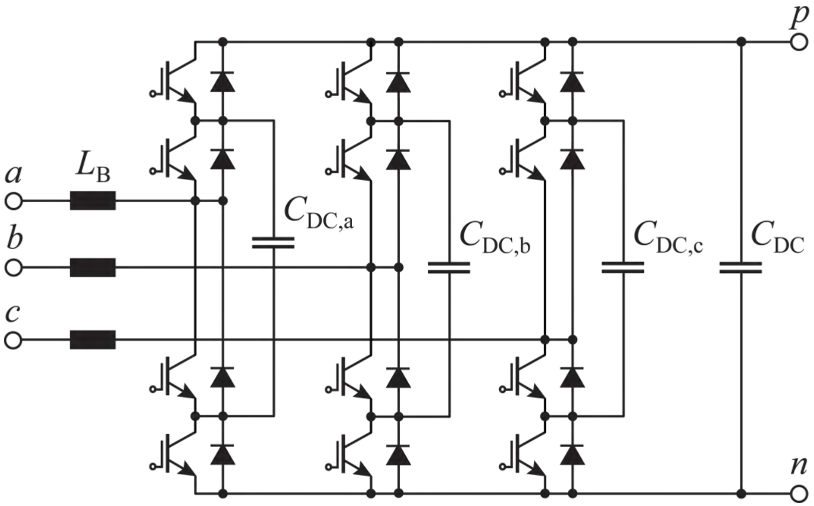
▶ T-Type Three-Level Boost-Type Rectifier System



+ Semiconductor Losses for Low Switching Frequencies Lower than for NPC Topologies
+ Can be Implemented with Standard Six-Pack Module

– Requires Switches for 2 Different Blocking Voltage Levels

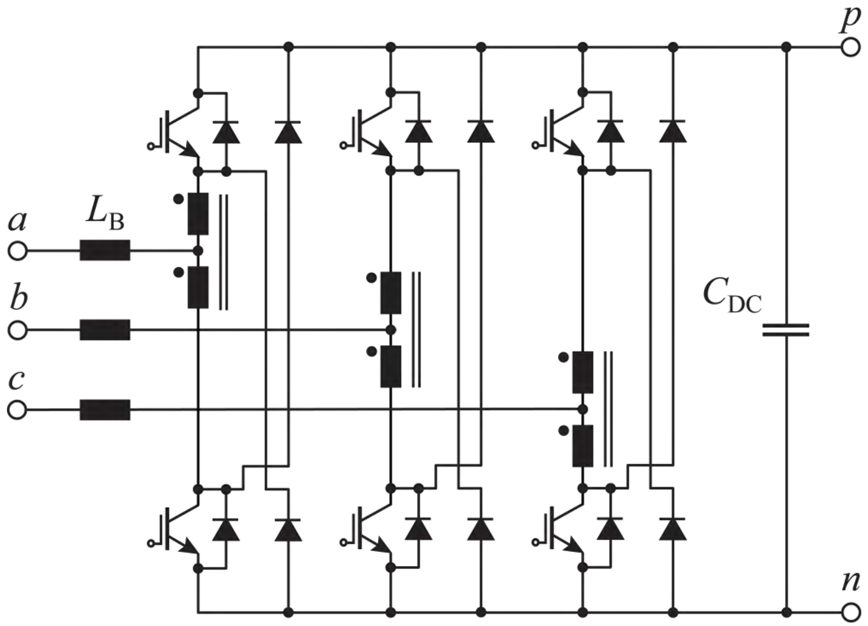
► Three-Level Flying Capacitor (FC) Boost-Type Rectifier System



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

– Volume of Flying Capacitors
– No Standard Industrial Topology

▶ Three-Level Bridge-Leg Inductor (BLI) Boost-Type Rectifier System



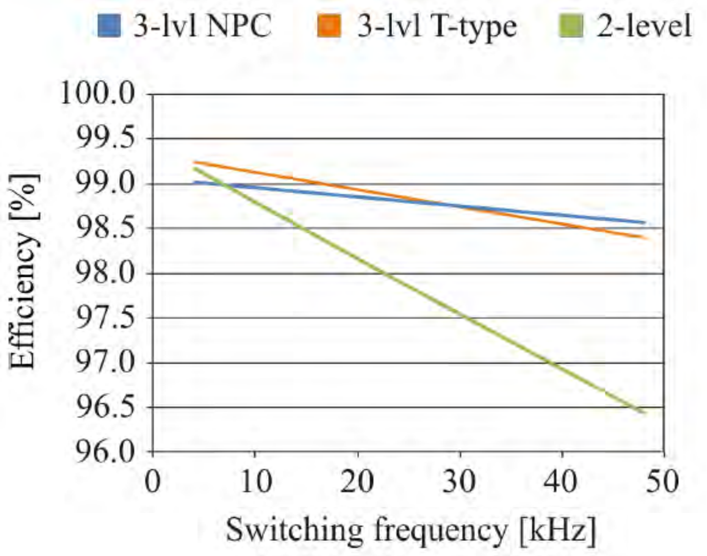
- \+ Lower Number of Components (per Voltage Level)
- \+ For Three-Level Topology only Two Output Terminals

- – Additional Volume due to Coupled Inductors
- – Semiconductor Blocking Voltage Equal to DC Link Voltage

▶ Pros and Cons of Three-Level vs. Two-Level Boost-Type Rectifier Systems

- \+ Losses are Distributed over Many Semicond. Devices; More Even Loading of the Chips → Potential for Chip Area Optimization for Pure Rectifier Operation
- \+ High Efficiency at High Switching Frequency
- \+ Lower Volume of Passive Components

- – More Semiconductors
- – More Gate Drive Units
- – Increased Complexity
- – Capacitor Voltage Balancing Required
- – Increased Cost



- ● Moderate Increase of the Component Count with the T-Type Topology

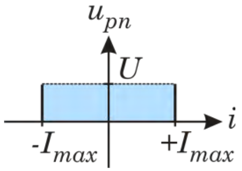
Consideration for 10kVA/400V$_{AC}$ Rectifier Operation; Min. Chip Area, $T_{j,max}$ = 125°C

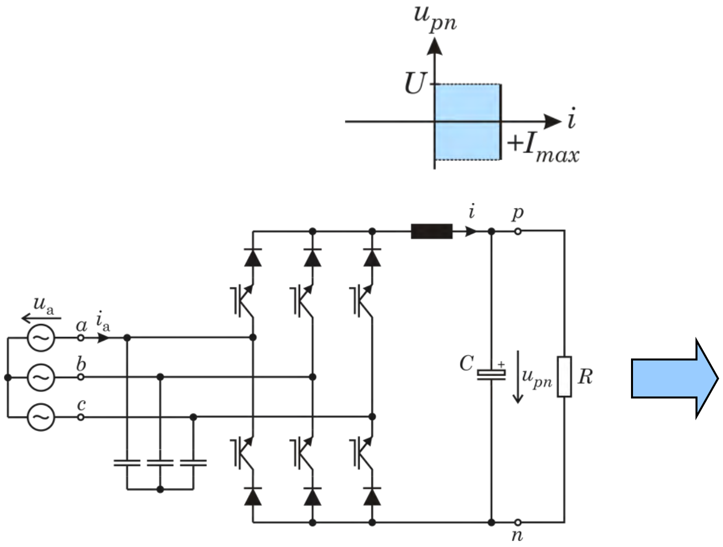
▶ Multi-Level Topologies are Commonly Used for Medium Voltage Applications but Gain Steadily in Importance also for Low-Voltage Renewable Energy Applications

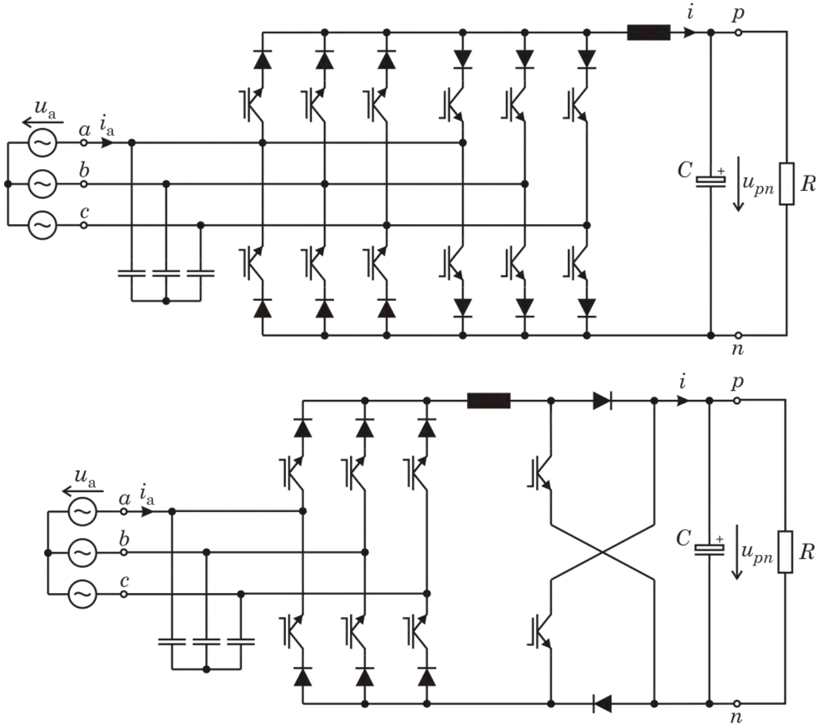
Buck-Type Topologies

▶ Derivation of Unipolar Output Bidirectional Buck-Type Topologies

- **Output Operating Range**

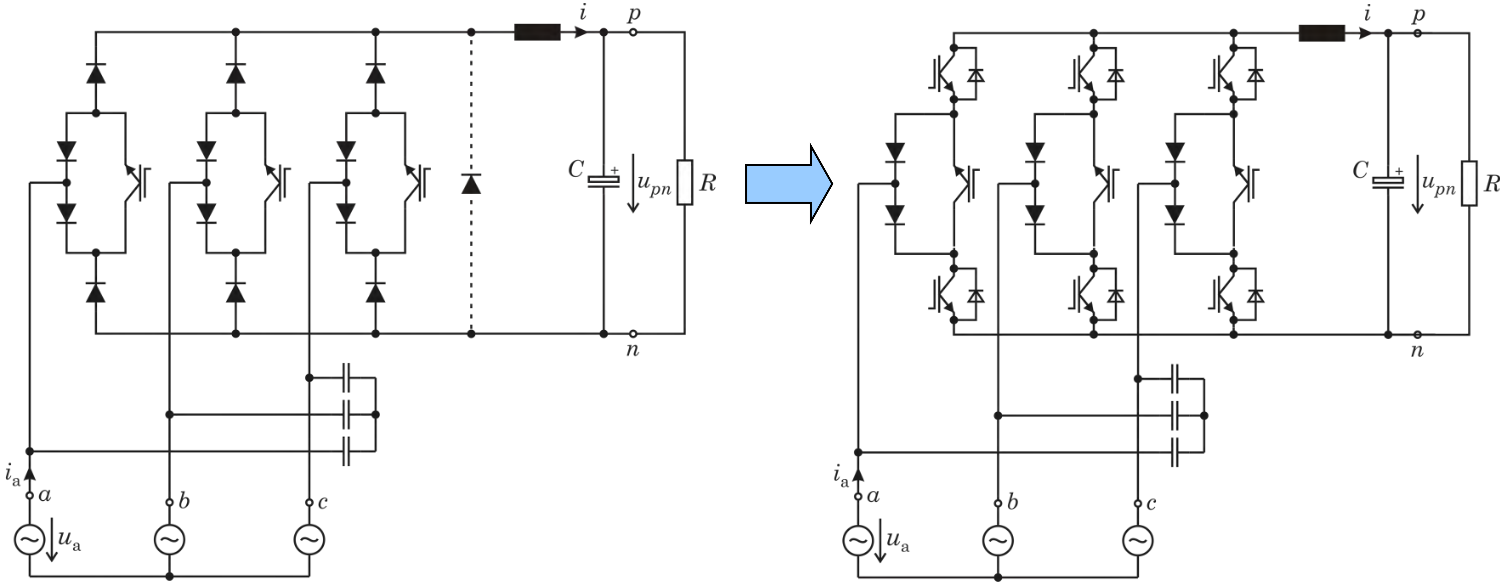




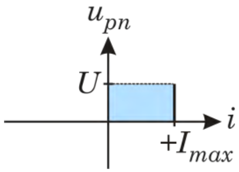


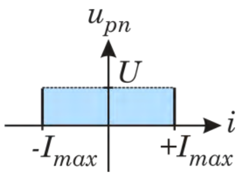
- System also Features Boost-Type Operation

▶ Derivation of Unipolar Output Bidirectional Buck-Type Topologies



- **Output Operating Range**



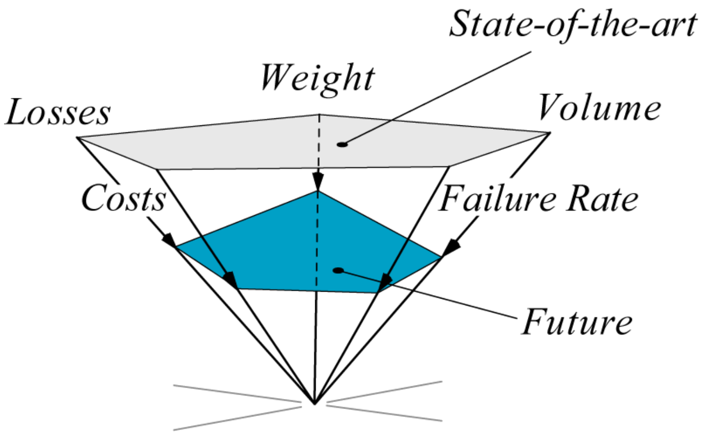


Final Remarks

Performance Trends
Multi-Objective Optimization

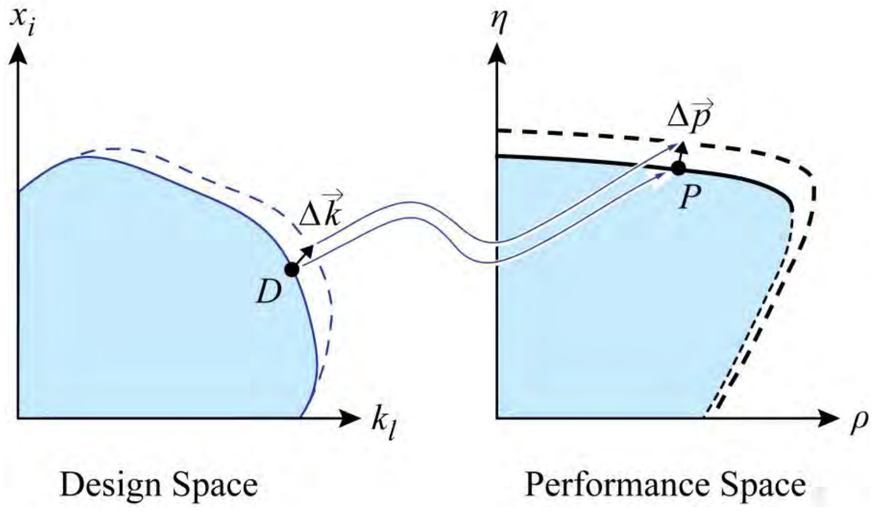
Power Electronics
Performance Trends

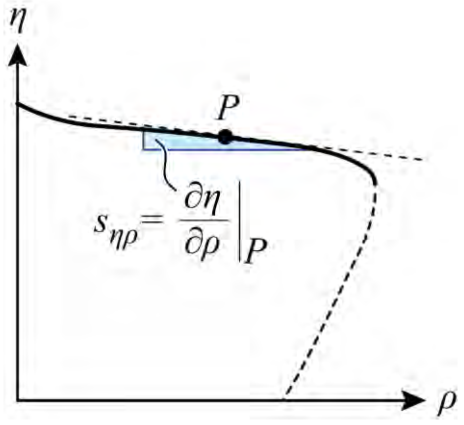
- **Performance Indices**
  - Power Density [kW/dm^3]
  - Power per Unit Weight [kW/kg]
  - Relative Costs [kW/$]
  - Relative Losses [%]
  - Failure Rate [h^{-1}]



Technology Sensitivity Analysis Based on η-ρ-Pareto Front

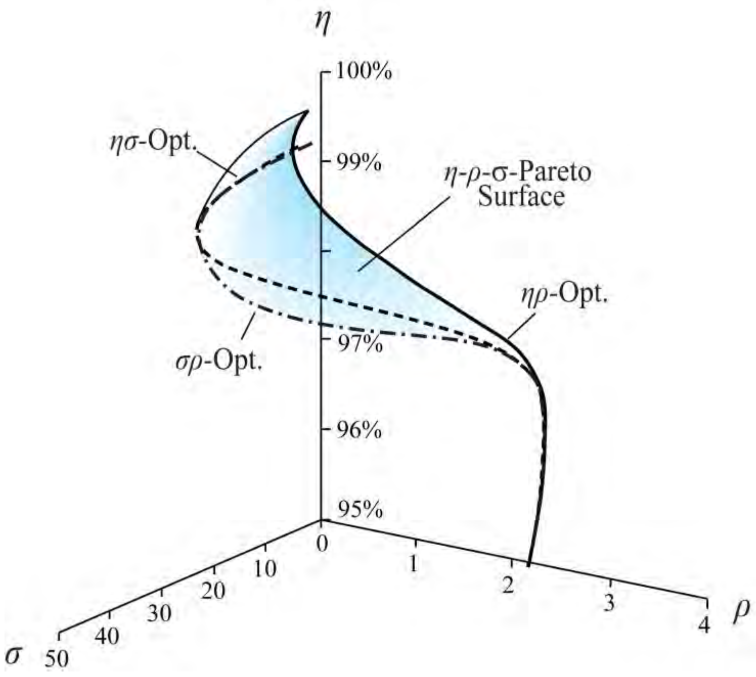
- ▶ **Sensitivity to Technology Advancements**
- ▶ **Trade-off Analysis**

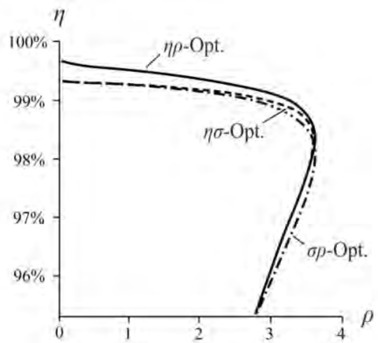


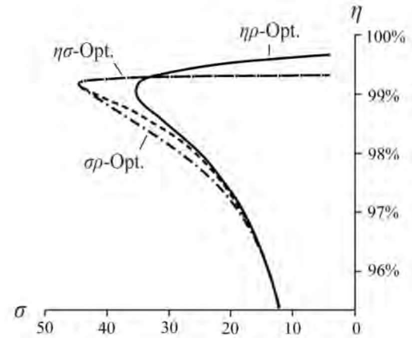


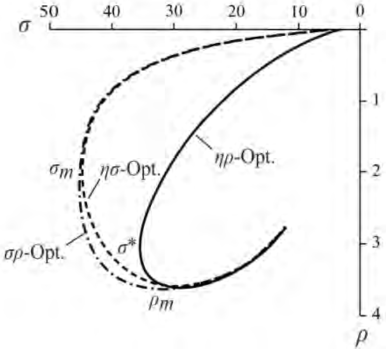
Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

- **σ: kW/$**



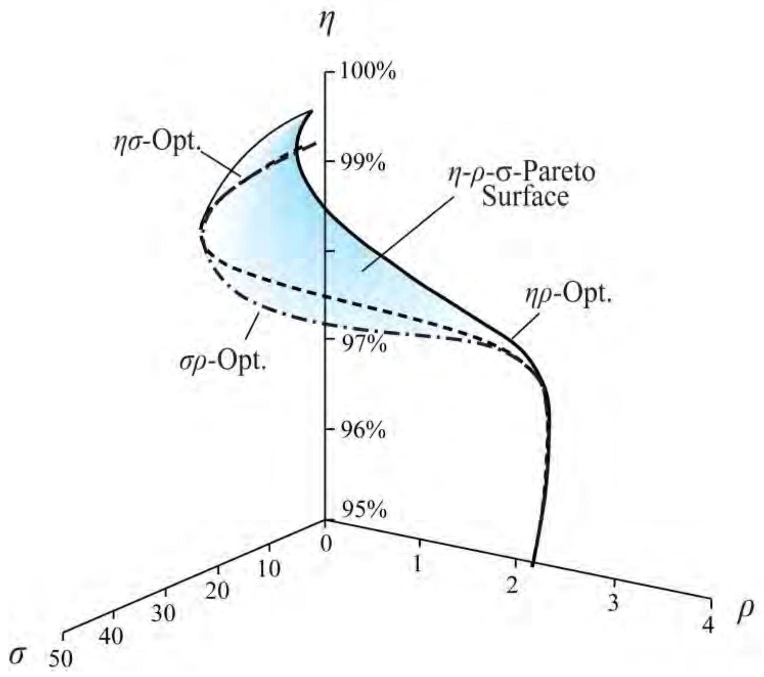


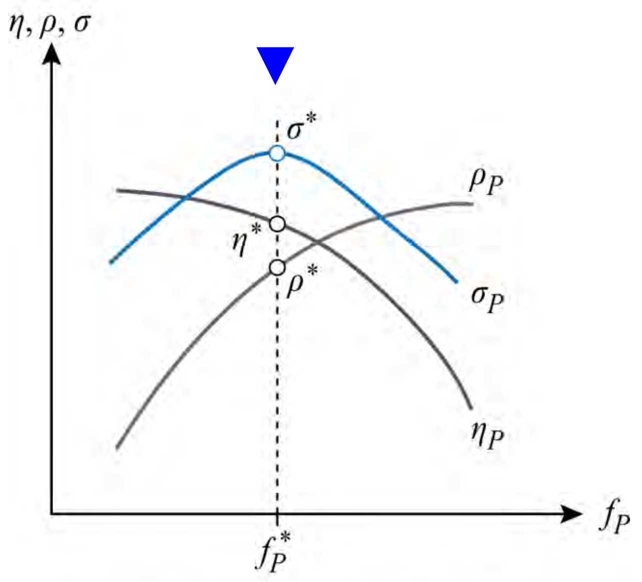




Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

► ´ *Technology Node*´





Technology Node: $(\sigma^*, \eta^*, \rho^*, f_P^*)$

Thank You!

Questions ?

Passive Rectifier Systems

[1.1] **P. Pejovic ,** *"A Novel Low-Harmonic Three-Phase Rectifier,"* IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, vol.49, no.7, pp.955-965, Jul 2002.

[1.2] **P. Pejovic, P. Bozovic, D. Shmilovitz,** *"Low-Harmonic, Three-Phase Rectifier That Applies Current Injection and a Passive Resistance Emulator,"* IEEE Power Electronics Letters , vol.3, no.3, pp. 96- 100, Sept. 2005.

[1.3] **P. Pejovic, Z. Janda,** *"Optimal Current Programming in Three-Phase High-Power-Factor Rectifier Based on Two Boost Converters,"* IEEE Transactions on Power Electronics, vol.13, no.6, pp.1152-1163, Nov 1998.

[1.4] **S. Kim, P. Enjeti, P. Packebush, and I. Pitel,** *"A New Approach to Improve Power Factor and Reduce Harmonics in a Three Phase Diode Rectifier Type Utility Interface,"* Record of the IEEE Industry Applications Society Annual Meeting, Pt. II, pp. 993-1000, 1993.

[1.5] **P. Pejovic Z. Janda,** *"Low Harmonic Three-Phase Rectifiers Applying Current Injection,"* Proc. of the Internat. Conf. on Power Electronics and Motion Control, Prague, 1998.

[1.6] **P. Pejovic and Z. Janda,** *"A Novel Harmonic-Free Three-Phase Diode Bridge Rectifier Applying Current Injection,"* Proc. of the 14th IEEE Appl. Power Electron. Conf. APEC´99, Dallas, USA, March 14-18, Vol. 1, pp. 241-247, 1999.

[1.7] **P. Pejovic, and Z. Janda,** *"An Improved Current Injection Network for Three-Phase High-Power-Factor Rectifiers that Apply Third Harmonic Current Injection,"* Letter to the Editor, IEEE Transactions on Industrial Electronics, Vol. 47, No. 2, pp. 497-499, 2000.

[1.8] **T. Sakkos and V. Sarv,** *"New Unity Power Factor Diode Rectifiers Using Ripple-Power Re-Rectification*," in. Proc. of the 8th Internat. Conf. on Power Electron. and Variable Speed Drives, London, Sept. 18-19, pp. 378-381, 2000.

[1.9] **T. Sakkos, V. Sarv, and J. Soojärv,** *"Optimun Diode-Switched Active Filters for Power Factor Correction of Single- and Three- Phase Diode Recifiers with Capacitive Smoothing,"* in Proc. of the 7th European Conf. on Power Electron. and Appl., Trondheim, Norway, Vol. 2, pp. 870-875, 1997.

Hybrid Rectifier Systems (Electronic Reactance Based)

[2.1] **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 Internat. Conf. on Power Conversion, Nuremberg, June 22-24, pp. 645–651 (1999).

[2.2] **K. Mino, M.L. Heldwein, and J.W. Kolar,** *"Ultra Compact Three-Phase Rectifier With Electronic Smoothing Inductor,"* Proc. of the 20th Annual IEEE Appl. Power Electron. Conf. and Exp. (APEC 2005), Vol.1, pp. 522-528 (2005).

[2.3] **R. Shimada, J.A. Wiik, T. Isobe, T. Takaku, N. Iwamuro, Y. Uchida, M. Molinas, T.M. Undeland,** *"A New AC Current Switch Called MERS with Low On-State Voltage IGBTs (1.54 V) for Renewable Energy and Power Saving Applications,"* Proc. of the 20th Internat. Symp. on Power Semicond. Devices and IC's, (ISPSD '08), pp.4-11, (2008).

[2.4] **T. Takaku, G. Homma, T. Isober, S. Igarashi, Y. Uchida, R. Shimada**, "Improved Wind Power Conversion System Using Magnetic Energy Recovery Switch (MERS)," Proc. of the Industry Appl. Conf. 2005. 40th IAS Annual Meeting, Vol.3, pp. 2007- 2012 (2005).

[2.5] **J.A. Wiik, F.D. Widjaya, T. Isobe, T. Kitahara, R. Shimada,** *"Series Connected Power Flow Control using Magnetic Energy Recovery Switch (MERS),"* Proc. of the Power Conv. Conf. - Nagoya, 2007 (PCC '07), pp.983-990 (2007).

[2.6] **J.A. Wiik, F.D. Wijaya, R. Shimada,** *"Characteristics of the Magnetic Energy Recovery Switch (MERS) as a Series FACTS Controller,“* IEEE Transactions on Power Delivery, vol.24, no.2, pp.828-836, (2009).

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

[2.7] **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 Internat. Conf. on Power Conversion, Nuremberg, June 22-24, pp. 645–651 (1999).

[2.8] **S. Hansen, P.J. Enjeti, J.H. Hahn, and F. Blaabjerg,** *"An Integrated Single-Switch Approach to Improve Harmonic Performance of Standard PWM Adjustable Speed Drives,"* Record of the 34th IEEE Industry Appl. Society Annual Meeting, Phoenix, USA, Oct. 3-7, Vol. 2, pp. 789–795 (1999).

[2.9] **A.M. El-Tamaly, P.N. Enjeti, and H.H. El-Tamaly,** *"An Improved Approach to Reduce Harmonics in the Utility Interface of Wind, Photovoltaic and Fuel Cell Power Systems,"* Proc. of the 15th IEEE Appl. Power Electron. Conf., New Orleans, USA, Feb. 6-10, Vol. 2, pp. 1059–1065 (2000).

[2.11] **Z. Janda and P. Pejovic,** *"A High Power Factor Three-Phase Rectifier based on Adaptive Current Injection Applying Buck Converter,"* Proc. of the 9th Internat. Conf. on Power Electron. and Motion Control, Kosice, Slovak Republic, Sept. 5-7, Vol. 3, pp. 140–144 (2000).

[2.12] **N. Mohan,** *"A Novel Approach to Minimize Line Current Harmonics in Interfacing Renewable Energy Sources with 3-Phase Utility Systems,"* Proc. of the IEEE Appl. Power Electron. Conf., pp. 852–858 (1992).

[2.13] **S. Kim, P. Enjeti, D. Rendusara, and I.J. Pitel,** *"A New Method to Improve THD and Reduce Harmonics Generated by Three-Phase Diode Rectifier Type Utility Interface,"* Record of the 29th IEEE Industry Appl. Society Annual Meeting, Denver, USA, Oct. 2-5, Vol. 2, pp. 1071–1077 (1994).

[2.14] **Y. Nishida, M. Nakaoka, Y. Ohgoe, and A. Maeda,** *"A Simple Three-Phase Boost-Mode PFC Rectifier,"* Record of the 31st IEEE Industry Appl. Aociety Annual Meeting, San Diego, USA, Oct. 6-10, Vol. 2, pp. 1056–1060 (1996).

[2.15] **M. Rastogi, R. Naik, and N. Mohan,** *"Optimization of a Novel DC-Link Current Modulated Interface with 3-Phase Utility Systems to Minimize Line Current Harmonics,"* Proc. of the Power Electron. Specialists Conf., Vol. I, pp. 162–167 (1992).

[2.16] **R. Naik, M. Rastogi, N. Mohan, R. Nilssen, C.P. Henze,** *"A Magnetic Device for Current Injection in a Three-Phase Sinusoidal Current Utility Interface,"* Record of the IEEE Industry Appl. society Annual Meeting, Toronto, Canada, Oct. 2-8, Pt. II, pp. 926–930 (1993).

[2.17] **M. Rastogi, R. Naik, and N. Mohan,** *"A Sinusoidal-Current Rectifier for Industrial and Distribution AC to DC Regulated DC Voltage,"* Internat. Symp. on Electric Power Engin., Stockholm, Sweden, Pt.: Power Electronics, pp. 197–200 (1995).

[2.18] **Y. Nishida,** *"A New Simple Topology for Three-Phase Buck-Mode PFC,"* Proc. of the 11th IEEE Appl. Power Electron. Conf., San Jose, USA, March 3-7, Vol. 2, pp. 531-537 (1996).

[2.19] **H. Kanaan, H.F. Blanchette, K. Al-Haddad, R. Chaffai, and L. Duguay,** "Modeling and Analysis of a Three-Phase Unity Power Factor Current Injection Rectifier using One Loop Control Strategy," Proc. of the 22nd IEEE Internat. Telecom. Energy Conf. Phoenix, USA, Sept. 10-14, pp. 518-525 (2000).

Hybrid Rectifier Systems (Active 3rd Harmonic Injection) (2)

[2.20] J.-I. Itoh, I. Ashida, *"A Novel Three-Phase PFC Rectifier Using a Harmonic Current Injection Method,"* IEEE Transactions on Power Electronics, Vol.23, No.2, pp.715-722, March 2008.

[2.21] H. Yoo, S.-K. Sul, *„A Novel Approach to Reduce Line Harmonic Current for a Three-phase Diode Rectifier-fed Electrolytic Capacitor-less Inverter,“* Proc. of the IEEE Appl. Power Electronics Conf. and Exp. (APEC 2009), pp.1897-1903, 2009.

[2.22] H. Yoo S.-K. Sul, *"A New Circuit Design and Control to Reduce Input Harmonic Current for a Three-Phase AC Machine Drive System Having a very Small DC-link Capacitor,“* Proc. Of the 25th Ann. IEEE Appl. Power Electron. Conf. and Exp. (APEC 2010), pp.611-618, 2010.

[2.23] L.R. Chaar, N. Mohan, and C.P. Henze, *"Sinusoidal Current Rectification in a Very Wide Range Three-Phase AC Input to a Regulated DC Output,"* Proc. of the 30thIndust. Appl. Conf. (IAS '95), 8-12 Oct 1995, Vol.3, pp.2341-2347.

Hybrid Rectifier Systems (Combination of Diode Bridge and DC/DC Converter)

[2.23] A. Pietkiewicz and D. Tollik, *"Three-Phase 7 kW Fan Cooled Telecom Rectifier with Active Power Factor Correction,"* Proc. of the Internat. Telecom. Energy Conf., Paris, Vol. 1, pp. 407- 412 (1993).

[2.24] A. Pietkiewicz and D. Tollik, *"Cost/Performance Considerations for 3-Phase Input Current Shapers,"* Proc. of the 1st Internat. Telecom. Energy Special Conf., Berlin, Germany, April 11-15, pp. 165-170 (1994).

[2.25] N. Bäckman and H. Thorslund, *"A New Light-Weight 100A/48V Three-Phase Rectifier,"* Proc. of the Internat. Telecom. Energy Conference, pp. 92-97 (1991).

[2.26] L.D. Salazar, P.D. Ziogas, and G. Joos, *"On the Optimization of Switching Losses in DC-DC Boost Converters,"* Proc. of the IEEE Applied Power Electron. Conf., pp. 703-708 (1992).

[2.27] W.E. Rippel, *"Optimizing Boost Chopper Charger Design,"* IEEE Appl. Power Electron. Conf., Seminar 4: Electronic Power Factor Correction/Part 2 (1991).

[2.28] J.C. Salmon, *"A Variable Speed Drive Circuit Topology for Feeding a Three-Phase Inverter Bridge with Combined Current and Voltage DC Link,"* Proc. of the 5th European Conf. on Power Electron. and Appl., Brighton, UK, Sept. 13-16, Vol. 5, pp. 139-144 (1993).

[2.29] J.W. Kolar, H. Ertl, und F.C. Zach, *"Realization Considerations for Unidirectional Three-Phase PWM Rectifier Systems with Low Effects on the Mains,"* Proc. of the 6th Internat. Conf. on Power Electron. and Motion Control, Budapest, Oct. 1-3, Vol. 2, pp. 560 - 565 (1990).

[2.30] M.E. Jacobs, R.W. Farrington, G.H. Fasullo, Y. Jiang, R.J. Murphy, V.J. Thottuvelil, and K.J. Timm *"An Improved High-Efficiency Rectifier for Telecom Applications,"* Proc. of the 18th Internat. Telecom. Energy Conf., Oct. 6-10, Boston, USA, pp. 530-535 (1996).

[2.31] J. Salmon, *"PWM Inverter Harmonic Correction Topologies for Three-Phase Diode Rectifiers,"* Proc. of the 8th Intern. Conf. on Power Electron. and Variable Speed Drives, London, Sept. 18-19, pp. 299-304 (2000).

Hybrid Rectifier Systems (Multi-Pulse / Half Controlled Rectifier Systems)

[2.32] S. Masukawa and S. Iida, *"An Improved Three-Phase Diode Rectifier for Reducing AC Line Current Harmonics,"* in Proc. of the European Conf. on Power Electronics and Applications, Trondheim, Norway, Vol. 4, pp. 227–232, 1997.

[2.33] C. Sewan, S.L. Bang, and P.N. Enjeti, *"New 24-Pulse Diode Rectifier System for Utility Interface of High-Power AC Motor Drives,"* IEEE Trans. On Ind. Applications, Vol. 32, No. 2, pp. 531–541, 1997.

[2.34] K. Oguchi, H. Hama, and T. Kubota, *"Line-Side Reactor-Coupled Double Voltage-Fed Converter System with Ripple-Voltage Injection,"* Record of the 29th IEEE Power Electr. Specialists Conf., Fukuoka, Japan, Vol. 1, pp. 753–757, 1998.

[2.35] J. Kikuchi, M.D. Manjrekar, and T.A. Lipo, *"Performance Improvement of Half Controlled Three-Phase PWM Boost Rectifier,"* Proceedings of the 30th IEEE Power Electronics Specialists Conf., Charleston (SC), Vol. 1, pp. 319–324, 1999.

[2.36] C.A. Munoz, I. Barbi, *"A New High-Power-Factor Three-Phase AC-DC Converter: Analysis Design, and Experimentation,"* IEEE Transactions on Power Electronics, Vol. 14, No. 1, pp. 90–97, 1999.

[2.37] K. Oguchi, G. Maeda, N. Hoshi, and T. Kubota, "*Voltage-Phase Shifting Effect of Three-Phase Harmonic Canceling Reactors and Their Applications to Three-Level Diode Rectifiers,"* Record of the 34th IEEE Ind. Appl. Society Annual Meeting, Phoenix (AZ), Vol. 2, pp. 796–803, 1999.

[2.38] G.R. Kamath, B. Runyan, and R. Wood, *"A Compact Auto-Transformer-Based 12-Pulse Rectifier Circuit*," in Proc. of the 27th Annual Conf. of the Ind. Electr. Society, Denver (CO), Vol. 2, pp. 1344–1349, 2001.

[2.39] D.J. Perreault, and V. Caliskan, *"Automotive Power Generation and Control,"* IEEE Transactions on Power Electronics, Vol. 19, No. 3, pp. 618–630, 2004.

[2.40] S. Choi, *"A Three-Phase Unity-Power-Factor Diode Rectifier with Active Input Current Shaping,"* IEEE Transactions on Ind. Electronics, Vol. 52, No. 6, pp. 1711–1714, 2005.

[2.41] F. J. Chivite-Zabalza, *"High Power Factor Rectification for Aerospace Systems,"* Ph.D. Thesis, The Univ. of Manchester, 2006.

Phase Modular Y-Rectifier (1)

[3.1] **D. Gauger,T. Froeschle, L. Illingworth, and E. Rhyne,** “*A Three-Phase Off-Line Switching Power Supply with Unity Power Factor and Low TIF,”* Proceedings of the International Telecommunications Energy Conference, Toronto, Oct. 19-22, pp. 115-121,1986.

[3.2] **R.A. Langley, J.D. van Wyk, J.J. Schoeman,** “*A High Technology Battery Charging System for Railway Signaling Applications,”* Proceedings of the 3rd European Conference on Power Electronics and Applications, Aachen, Germany, Vol. III, pp. 1433- 1434, 1989.

[3.3] **D. Chapman, D. James, and C.J. Tuck,** *“A High Density 48V 200A Rectifier with Power Factor Correction – An Engineering Overview,”* Proceedings of the IEEE International Telecommunications Energy Conference, Paris, France, Vol. 1, pp. 118-125, 1993.

[3.4] **S.Y.R Hui, and H. Chung,** “*Paralleling Power Converters for AC-DC Step-Down Power Conversion with Inherent Power Factor Correction,”* Proceedings of the 7th European Conference on Power Electronics and Applications, Trondheim, Norway, Vol. 1, pp. 1.182-1.187, 1997.

[3.5] **D. S. L. Simonetti, J. Sebastian, and J. Uceda,** *“The Discontinuous Conduction Mode Sepic and Cuk Power Factor Preregulators: Analysis and Design*,” in IEEE Transactions on Industrial Electronics, Vol. 44, No. 5, pp. 630-637, 1997.

[3.6] **S.Y.R Hui, H. Chung, Y.K.E. Ho, and Y.S. Lee,** *“Modular Development of Single-Stage 3-Phase PFC using Single-Phase Step-Down Converters,”* Record of the 29th IEEE Power Electronics Specialists Conference, Fukuoka, Japan, May 17-22, Vol. 1, pp. 776-782, 1998.

[3.7] **M.A. de Rooij, J.A. Ferreira, and J.D. van Wyk,** *“A Three-Phase Soft-Switching Transformer Isolated Unity Power Factor Front End Converter,”* Record of the 29th IEEE Power Electronics Specialists Conference, Fukuoka, Japan, May 17-22, Vol. 1, pp. 798-804, 1998.

[3.8] **M. Karlsson, C. Thoren, and T. Wolpert,** *“A Novel Approach to the Design of Three-Phase AC/DC Power Converters with Unity Power Factor,”* Proceedings of the 21st IEEE International Telecommunications Energy Conference, Copenhagen, Denmark, June 6-9, paper no. 5-1,1999.

[3.9] **M.L. Heldwein, A.F. de Souza, and I. Barbi,** *”A Simple Control Strategy Applied to Three-Phase Rectifier Units for Telecommunication Applications using Single-Phase Rectifier Modules,”* Proceedings of the 30th IEEE Power Electronics Specialists Conference, Charleston (SC), USA, Vol.2, pp. 795-800, 1999.

[3.10] **Y.K.E. Ho, S.Y.R. Hui, and Y.S. Lee,** *“Characterization of Single-Stage 3-Phase Power Factor Correction Circuit Using Modular Single-Phase PWM DC-to-DC Converters,”* Proceedings of the 30th IEEE Power Electronics Specialists Conference, Charleston (SC), USA, Vol.2, pp. 704-708, 1999.

Phase Modular Y-Rectifier (2)

[3.11] Y.K.E. Ho, S.Y.R. Hui, and Y.S. Lee, *"Characterization of Single-Stage Three-Phase Power-Factor-Correction Circuit Using Modular Single-Phase PWM DC-to-DC Converters,"* IEEE Transactions on Power Electronics, Vol. 15, No. 1, pp. 62-71, 2000.

[3.12] R. Greul, U. Drofenik, and J.W. Kolar, *"Analysis and Comparative Evaluation of a Three-Level Unity Power Factor Y-Rectifier"*, in Proc. 25th International Telecommunications Energy Conference INTELEC 2003, pp. 421–428, 2003.

[3.13] J. Biela, U. Drofenik, F. Krenn, J. Miniböck, and J.W. Kolar, *"Novel Three-Phase Y-Rectifier Cyclic 2 Out of 3 DC Output Voltage Balancing"*, in Proc. 29th International Telecommunications Energy Conference INTELEC 2007, pp. 677–685, 2007.

[3.14] R. Greul, S.D. Round, J.W. Kolar, *"Analysis and Control of a Three-Phase Unity Power Factor Y-Rectifier"*, IEEE Trans. Power Electron., vol. 22, no. 5, pp. 1900–1911, Sept. 2007.

Phase Modular Δ-Rectifier

[3.15] M.J. Kocher, and R.L. Steigerwald, *"An AC-to-DC Converter with High Quality Input Waveforms,"* IEEE Transactions on Industry Applications", Vol. IA-19, No. 4, pp. 586-599, 1983.

[3.16] S.A. El-Hammamsy, *"Coupled Inductor Rectification and Cycloconversion,"* Proceedings of the 3rd IEEE Applied Power Electronics Conference, Feb. 1-5, New Orleans, USA, pp. 258-266, 1988.

[3.17] R. Ridley, S. Kern, and B. Fuld, *"Analysis of a Wide Input Range Power Factor Correction Circuit for Three-Phase Applications,"* Proceedings of the IEEE Applied Power Electronics Conference, pp. 299-305, 1993.

[3.18] B. Fuld, S. Kern, and R.A. Ridley, *"Combined Buck and Boost Power Factor Controller for Three-Phase Input,"* Proceedings of the 5th European Conference on Power Electronics and Applications, Brighton, UK, Vol. 7, pp. 144-148, 1993.

[3.19] D. York, E. Filer, and K. Haliburton, "*A Three-Phase Input Power Processing Unit with Unity Power Factor and Regulated DC Output,"* Proceedings of the High Frequency Power Conversion Conference, pp. 349-356, 1994.

[3.20] A.-Ch. Rufer and Ch.-B. Andrianirina, *"A Symmetrical 3 Phase-2 Switch PFC-Power Supply for Variable Output Voltage,"* Proceedings of the 6th European Conference on Power Electronics and Applications, Sevilla, Spain, Sept. 19-21, Vol. 3, pp. 3.254-3.258, 1995.

[3.21] E.S. de Andrade, D.C. Martins, and I. Barbi, *"Isolated Three-Phase Rectifier Unit with High Power Factor"*, Proceedings of the 18th IEEE International Telecommunications Energy Conference, Boston, USA, Oct. 6-10, pp. 536-542, 1996.

[3.22] M. Tognolini, M., and A.-Ch. Rufer, *"A DSP-Based Control for a Symmetrical Three-Phase Two-Switch PFC-Power Supply for Variable Output Voltage,"* Proceedings of the 27th IEEE Power Electronics Specialists Conference, Baveno, Italy, June 23-27, Vol. II, pp. 1588-1594, 1996.

[3.23] R. Ayyanar, et al., *"Single-Stage Power-Factor-Correction Circuit Using Three Isolated Single-Phase SEPIC Converters Operating in CCM,"* Records of 2000 IEEE PESC, 2000.

[3.24] J.W. Kolar, F. Stögerer, Y. Nishida, *"Evaluation of a Delta-Connection of Three Single-Phase Unity Power Factor Rectifier Systems (Δ-Rectifier) in Comparison to a Direct Three-Phase Realization, Part I –Modulation Schemes and Input Current Ripple"*, in Proc. 7th European Power Quality Conference, pp. 101–108, 2001.

[3.25] R. Greul, *"Modulare Dreiphasen-Pulsgleichrichtersysteme"*, Ph.D. Thesis, Eidgenössische Technische Hochschule – ETH Zürich, Switzerland, 2006.

[3.26] R. Greul, S.D. Round, J.W. Kolar, *"The Delta-Rectifier: Analysis, Control and Operation"*, IEEE Trans. Power Electron., vol. 21, no. 6, pp. 1637–1648, Nov. 2006.

Direct Three-Phase Active PFC Converter (Boost-Type DCM Converters)

[4.1] **A. R. Prasad et al.,** *"An Active Power Factor Correction Technique for Three-Phase Diode Rectifiers,"* IEEE Transactions on Power Electronics, Vol. 6, No. 1, pp. 83-92, 1991.

[4.2] **J.W. Kolar et al,** *"Space Vector-Based Analytical Analysis of the Input Current Distortion of a Three-Phase Discontinuous-Mode Boost Rectifier System,"* in IEEE PESC'93 Records, pp. 696-703.

[4.3] **J.W. Kolar, et al.,** *"A Comprehensive Design Approach for a Three-Phase High-Frequency Single-Switch Discontinuous-Mode Boost Power Factor Corrector based on Analyticaly Derived Normalized Converter Component Ratings,"* IEEE Transactions on Industry Applications, Vol. 31, No. 3, 1995, pp. 569-582.

[4.4] **J. Sun, et al.,** *"Harmonic Reduction Techniques for Single-Switch Three-Phase Boost Rectifiers,"* IAS'96, pp. 1225-1232.

[4.5] **Y. Jang and M.M. Jovanovic,** *"A Comparative Study of Single-Switch, Three-Phase, High-Power-Factor Rectifiers,"* Proc. Of the IEEE Appl. Power Electronics Conf. (APEC'98), 1093-1099.

[4.6] **S. Gataric, et al.,** *"Soft-Switched Single-Switch Three-Phase Rectifier with Power Factor Correction,"* in Proceedings of IEEE Appl. Power Electron. Conf. (APEC'94), pp. 738-744.

[4.7] **E. H. Ismail,** *"A low-distortion Three-Phase Multiresonant Boost Rectifier with Zero-Current Switching,"* IEEE Transactions on Power Electronics, Vol. 13, No. 4, pp. 718-726, 1998.

[4.8] **H. Oishi et al.,** *"Sepic-Derived Three-Phase Sinusoidal Rectifier Operating in Discontinuous Current Conduction Mode,"* in IEE Proceedings – Electric Power Applications, Vol. 142, No. 4, pp. 239-245, 1995.

[4.9] **L. Malesani et al.,** "Three-Phase Power Factor Controller with Minimum Output Voltage Distortion," in Proceedings of INTELEC'93, pp. 463-468.

[4.10] **D. M. Xu, C. Yang, J. H. Kong, and Z. Qian,** *"Quasi Soft-Switching Partly Decoupled Three-Phase PFC with Approximate Unity Power Factor,"* In Proc. of the Appl. Power Electron. Conf. (APEC'98), pp. 953-957.

[4.11] **P. Barbosa, F. Canales, J.-C. Crebier, F.C. Lee,** *"Interleaved Three-Phase Boost Rectifiers Operated in the Discontinuous Conduction Mode: Analysis, Design Considerations and Experimentation,"* IEEE Transactions on Power Electronics, Vol.16, No.5, pp.724-734, Sep 2001.

[4.12] **P. Barbosa, F. Canales, F. Lee,** *"Analysis and Evaluation of the Two-switch Three-Level Boost Rectifier,"* Proc. of the 32nd Annual IEEE Power Electronics Specialists Conf. (PESC 2001), Vol. 3, pp.1659-1664, 2001.

Direct Active Three-Phase PFC Rectifier Systems (Two-Level CCM Boost-Type) (1)

[5.1] **J.W. Kolar, H. Ertl, F.C. Zach,** *"Realization Considerations for Unidirectional Three-Phase PWM Rectifier Systems with low Effects on the Mains,"* Proc. of the 6th Int. Conf. on Power Electronics and Motion (PEMC 1990), Budapest.

[5.2] **M. Hartmann, J. Miniboeck, J.W. Kolar,** *"A Three-Phase Delta Switch Rectifier for More Electric Aircraft Applications Employing a Novel PWM Current Control Concept,"* Proc. of 24th Annual IEEE Applied Power Electron. Conf. and Exp. (APEC 2009), 15-19 Feb. 2009, pp.1633-1640.

[5.3] **S.K.T. Miller, J. Sun,** *"Comparative study of three-phase PWM rectifiers for wind energy conversion,"* Proc. of the 21th Annual IEEE Applied 12 Power Electronics Conference and Exposition (APEC '06), 19-23 March 2006, pp.937-943.

[5.4] **J.C. Salmon,** *"Reliable 3-phase PWM Boost Rectifiers Employing a Stacked Dual Boost Converter Subtopology,"* IEEE Transactions on Industry Applications, Vol. 32, No. 3, pp.542-551, 1996.

[5.5] **I. Barbi, J.C. Fagundes, and C.M.T Cruz,** *"A Low Cost High Power Factor Three-Phase Diode Rectifier with Capacitive Load,"* Proc. of the IEEE Appl. Power Electron. Conf., Vol. 2, pp. 745-751 (1994).

[5.6] **W. Koczara, and P. Bialoskorski,** *"Modified Rectifiers with Unity Power Factor," Proc. of the Internat. Conf. on Power Electron. and Motion Control,"* Warsaw, Poland, Sept. 20-22, Vol. 1, pp. 309-314 (1994).

[5.7] **J. Spanicek, and D. Platt,** *"Minimal Circuit for Power System Conditioning,"* Proc. of the Internat. Conf. on Power Electronics and Drive Systems, Singapore, Feb. 21-24, Vol. 1, pp. 543-548 (1995).

[5.8] **F. Lafitte, B. Dakyo, L. Protin, and Koczara, W,** *"Three-Phase Sinusoidal Current Absorption AC-DC Converter for High Power Supply for Telecommunication,"* Proc. of the 17th IEEE Internat. Telecom. Energy Conf., The Hague, The Netherlands, Oct. 29-Nov. 1, pp. 715-720 (1995).

[5.9] **D. Carlton, W.G. Dunford, M. Edmunds,** *"Continuous Conduction Mode Operation of a Three-Phase Power Factor Correction Circuit with Quasi Tridirectional Switches,"* Proc. of the 30th Annual IEEE Power Electronics Specialists Conf. (PESC 99), Aug 1999, vol.1, pp.205-210.

[5.10] **A. Lima, C. Cruz, F. Antunes,** *"A new low cost AC-DC Converter with High Input Power Factor,"* Proc. of the 22nd IEEE Internat. Conf. on Indust. Electron., Control, and Instrumentation (IECON'96), 5-10 Aug 1996, Vol.3, pp.1808-1813.

[5.11] **C. Qiao, K.M. Smedley,** *"A General Three-Phase PFC Controller for Rectifiers with a Parallel-Connected Dual Boost Topology,"* IEEE Transactions on Power Electronics, Vol.17, No.6, Nov 2002, pp. 925-934.

[5.12] **N. Noor, J. Ewanchuk, J.C. Salmon,** *"PWM Current Controllers for a Family of 3-Switch Utility Rectifier Topologies,"* Proc. of the Canadian Conference on Electrical and Computer Engineering (CCECE2007), 22-26 April 2007, pp.1141-1144.

[5.13] **J.C. Salmon,** "Comparative Evaluation of Circuit Topologies for 1-Phase and 3-Phase Boost Rectifiers Operated with a Low Current Distortion," Proc. of Canadian Conference on Electrical and Computer Engineering, Halifax, NS, Canada (1994), 25-28 Sep. 1994, Vol.1, pp. 30-33.

Direct Active Three-Phase PFC Rectifier Systems (Two-Level CCM Boost-Type) (2)

[5.14] **J.C. Salmon,** *"Comparative Evaluation of Circuit Topologies for 1-Phase and 3-Phase Boost Rectifiers Operated with a Low Current Distortion,"* Proc. of Canadian Conference on Electrical and Computer Engineering, Halifax, NS, Canada (1994), 25-28 Sep. 1994, Vol.1, pp. 30-33.

[5.15] **D. Carlton, W.G. Dunford, M. Edmunds,** *"Harmonic Reduction in the 3-Phase 3-Switches Boost-Delta Power Factor Correction Circuit Operating in Discontinuous Conduction mode,"* 20th Internat. Telecom. Energy Conf. (INTELEC 1998), pp.483-490.

[5.16] **Tao Lei, Xiao-Bin Zhang, Yan-Jun Dong, Jing-Hui Zhao, Hui Lin**, *"Study of High Power Factor Rectifiers Based on One Cycle Control in Aircraft Electric Power System,"* 12th Internat. Middle East Power System Conf. (MEPCON 2008), pp.325-329.

[5.17] **C.L. Chen,** *"A new Space-Vector-Modulated Control for a Unidirectional Three-Phase Switch-Mode Rectifier,"* IEEE Transactions on Industrial Electronics, Vol.45, No.2, Apr 1998, pp.256-262.

[5.18] **W. Koczara,** *"Unity Power Factor Three-Phase Rectifier,"* Proc. of the Internat. Power Quality Conf., Munich, pp. 79-88 (1992).

[5.19] **W. Koczara and P. Bialoskorski,** *"Controllability of the Simple Three-Phase Rectifier Operating with Unity Power Factor,"* Proc. of the 5th European Conf. on Power Electron. and Appl., Brighton, UK, Vol. 7, pp. 183-187 (1993).

[5.20] **G. Spiazzi and F. C. Lee,** *"Implementation of Single-Phase Boost Power Factor Correction Circuits in Three-Phase Applications,"* Proc. of the IEEE IECON'94, pp. 250-255 (1994).

[5.20] **B. Singh, B.N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, D.P. Kothari,** *"A review of three-phase improved power quality AC-DC converters,"* Industrial Electronics, IEEE Transactions on , vol.51, no.3, pp. 641- 660, June 2004.

[5.21] **J.W. Kolar, H. Ertl,** *"Status of the techniques of three-phase rectifier systems with low effects on the mains,"* Proc.of the 21st Internat. *Telecom. Energy Conf. (INTELEC '99),* pp.16 pp., Jun 1999.

Direct Active Three-Phase PFC Rectifier Systems (Three-Level CCM Boost-Type) (1)

[6.1] **E.L.M. Mehl and I. Barbi,** *"Design Oriented Analysis of a High Power Factor and Low Cost Three-Phase Rectifier,"* Proc. of the 27th IEEE Power Electron. Specialists Conf., Baveno, Italy, June 23-27, Vol. I, pp. 165-170 (1996).

[6.2] **F. Daniel, R. Chaffai, and K. Al-Haddad,** *"Three-Phase Diode Rectifier with Low Harmonic Distortion to Feed Capacitive Loads,"* Proc. of the 11th IEEE Appl. Power Electron. Conf., San Jose, USA, March 3-7, Vol. 2, pp. 932-938 (1996).

[6.3] **F. Daniel, R. Chaffai, K. Al-Haddad, and R. Parimelalagan,** *"A New Modulation Technique for Reducing the Input Current Harmonics of a Three-Phase Diode Rectifier with Capacitive Load,"* IEEE Transactions on Industry Applications, Vol. 33, No. 5, pp. 1185-1193 (1997).

[6.4] **K. Oguchi, T. Yoshizawa, N. Hoshi, and T. Kubota,** *"Programmed Pulse Width Modulation of Three-Phase Three-Level Diode Rectifiers,"* Proc. of the 9th Internat. Conf. on Power Electron. and Motion Control, Kosice, Slovak Republic, Sept. 5-7, Vol. 3, pp. 102-107 (2000).

[6.5] **Y. Zhao, Y. Li, and T.A. Lipo,** *"Force Commutated Three-Level Boost Type Rectifier,"* Record of the IEEE Industry Appl. Society Annual Meeting, Toronto, Canada, Vol. II, pp. 771-777 (1993).

[6.6] **J.W. Kolar and F.C. Zach,** *"A Novel Three-Phase Three-Switch Three-Level Unity Power Factor PWM Rectifier,"* Proc. of the 28th Internat. Power Conv. Conf., Nürnberg, 28. bis 30. Juni, S. 125 - 138 (1994).

[6.7] **J.W. Kolar and F.C. Zach,** *"A Novel Three-Phase Utility Interface Minimizing Line Current Harmonics of High-Power Telecommunications Rectifier Modules,"* Proc. of the 16th IEEE Internat. Telecom. Energy Conf., Vancouver, Canada, Oct. 30-Nov. 3, pp. 367 - 374 (1994).

[6.8] **J.W. Kolar, U. Drofenik, and F.C. Zach,** *"Space Vector Based Analysis of the Variation and Control of the Neutral Point Potential of Hysteresis Current Controlled Three-Phase/Switch/Level PWM Rectifier Systems,"* Proc. of the Internat. Conf. on Power Electronics and Drive Systems, Singapore, Feb. 21-24, Vol. 1, pp. 22 - 33 (1995).

[6.9] **J.W. Kolar, U. Drofenik, and F.C. Zach,** *"Current Handling Capability of the Neutral Point of a Three-Phase/Switch/Level Boost-Type PWM (VIENNA) Rectifier,"* Proc. of the 28th IEEE Power Electronics Conf., Baveno, Italy, June 24-27, Vol. II, pp. 1329 - 1336 (1996).

[6.10] **J.W. Kolar, U. Drofenik and F.C. Zach,** *"On the Interdependence of AC-Side and DC-Side Optimum Control of Three-Phase Neutral-Point-Clamped (Three-Level) PWM Rectifier Systems,"* Invited Paper, Proceedings of the 7th Internat. Power Electronics and Motion Control Conf., Budapest, Hungary, Sept. 2-4, Vol. 1, pp. 40 - 49 (1996).

[6.11] **J.W. Kolar, H. Sree, U. Drofenik, N. Mohan, and F.C. Zach,** *"A Novel Three-Phase Three-Switch Three-Level High Power Factor SEPIC-Type AC-to-DC Converter,"* Proc. of the 12th IEEE Appl. Power Electron. Conf., Atlanta, Feb. 23-27, Vol. 2, pp. 657 - 665 (1997).

Direct Active Three-Phase PFC Rectifier Systems (Three-Level CCM Boost-Type) (2)

[6.12] U. Drofenik, R. Windauer, J.W. Kolar, E. Masada, and F.C. Zach, *"Analysis and Comparison of Different Input Current Control Schemes for a Three-Phase/Switch/Level Boost-Type (VIENNA) Rectifier,"* Proc. of the 1st Internat. Congress on Energy, Power & Motion Control, Tel Aviv, Israel, May 5-6, pp. 35 - 41 (1997).

[6.13] J.W. Kolar and U. Drofenik, *"A New Switching Loss Reduced Discontinuous PWM Scheme for a Unidirectional Three-Phase/Switch/Level Boost-Type PWM (VIENNA) Rectifier,"* Proc. of the 21st IEEE Internat. Telecom. Energy Conf., Copenhagen, Denmark, June 6-9, Paper No. 29-2 (1999).

[6.14] U. Drofenik, and J.W. Kolar, *"Comparison of Not Synchronized Sawtooth Carrier and Synchronized Triangular Carrier Phase Current Control for the VIENNA Rectifier I,"* Record of the IEEE Internat. Symp. on Industr. Electronics, Bled, Slovenia, June 12-16, Vol. 1, pp. 13 - 19 (1999).

[6.15] U. Drofenik and J.W. Kolar, *"Influence of the Current-Dependency of the Inductance of the Input Inductors of Three-Phase PWM Rectifier Systems on the Modulation Scheme being Optimal Concerning the Mains Current Ripple RMS Value,"* Proc. of the International Power Electronics Conference, Tokyo, April 3-7, Vol. 2, pp. 1017 - 1022 (2000).

[6.16] J.W. Kolar, F. Stögerer, J. Miniböck, and H. Ertl, *"A Novel Concept for Reconstruction of the Input Phase Currents of a Three-Phase/Switch/Level PWM (VIENNA) Rectifier Based on Neutral Point Current Measurement,"* Proc. of the 31st IEEE Power Electronics Specialists Conf., Galway, Ireland, June 18-23, pp. 139 - 146 (2000).

[6.17] J. Miniböck, F. Stögerer and J.W. Kolar, *"A Novel Concept for Mains Voltage Proportional Input Current Shaping of a CCM Three-Phase PWM Rectifier Eliminating Controller Multipliers I. Basic Theoretical Considerations and Experimental Verification,"* Proc. of the 16th Annual IEEE *Appl. Power Electronics Conf. and Exp. (APEC 2001)*, Vol.1, pp.582-586 vol.1, 2001.

[6.18] J. Miniböck, and J.W. Kolar, *"Comparative Theoretical and Experimental Evaluation of Bridge Leg Topologies of a Three-Phase/Switch/Level PWM (VIENNA) Rectifier,"* Proc. of the 32nd Annual Power Electronics Specialists Conference, (PESC. 2001) Vol.3, no., pp.1641-1646 vol. 3, 2001.

[6.19] F. Stogerer, J. Minibock, J.W. Kolar, *"Implementation of a Novel Control Concept for Reliable Operation of a VIENNA Rectifier Under Heavily Unbalanced Mains Voltage Conditions,"* 32nd Annual Power Electronics Specialists Conference, (PESC. 2001), Vol.3, pp.1333-1338, 2001.

[6.20] C. Qiao, and K.M. Smedley, *"Three-Phase Unity-Power-Factor VIENNA Rectifier with Unified Constant Frequency Integration Control,"* Proc. of the IEEE Internat. Power Electronics Congress, Acapulco, Mexico, Oct. 15-19, pp. 125-130 (2000).

[6.21] C. Qiao, and K.M. Smedley, *"A General Three-Phase PFC Controller – Part II. for Rectifiers with Series-Connected Dual-Boost Topology,"* Record of the 34th IEEE Industry Applications Society Annual Meeting, Phoenix, USA, Oct. 3-7, Vol. 4, pp. 2512-2519 (1999).

Direct Active Three-Phase PFC Rectifier Systems (Three-Level CCM Boost-Type) (3)

[6.22] M.L. Heldwein, S.A. Mussa, I. Barbi, *"Three-Phase Multilevel PWM Rectifiers Based on Conventional Bidirectional Converters,"* IEEE Transactions on Power Electronics, Vol.25, No.3, pp.545-549, March 2010.

[6.23] P. Ide, N. Froehleke, and H. Grotstollen, *"Comparison of Selected 3-Phase Switched Mode Rectifiers,"* Proc. of the 19th IEEE Internat. Telecom. Energy Conf., Melbourne, Australia, Oct. 19-23, pp. 630-636 (1997).

[6.24] P. Ide, N. Froehleke, N. and H. Grotstollen, *"Investigation of Low Cost Control Schemes for a Selected 3-Level Switched Mode Rectifier,"* Proc. of the 19th IEEE Internat. Telecom. Energy Conference, Melbourne, Australia, Oct. 19-23, pp. 413-418 (1997).

[6.25] P. Ide, N. Froehleke, H. Grotstollen, W. Korb, and B. Margaritis, *"Analysis of Three-Phase/Three-Level Rectifiers at Low Load and Discontinuous Conduction Mode,"* Proc. of the IEEE Applied Power Electronics Conf., New Orleans, USA, Feb. 6-10, Vol. 1, pp. 197-204 (2000).

[6.26] P. Ide, N. Froehleke, H. Grotstollen, W. Korb, and B. Margaritis, *"Operation of a Three-Phase/Three-Level Rectifier in Wide Range and Single-Phase Applications,"* Proc. of the 25th Annual Conf. of the Industrial Electronics Society (IECON), San Jose, USA, Nov. 29 - Dec. 3, pp. 577-582 (1999).

[6.27] W. Koczara, and P. Bialoskorski, *"Multilevel Boost Rectifiers as a Unity Power Factor Supply for Power Electronics Drive and for Battery Charger,"* Proc. of the IEEE Internat. Symp. on Industrial Electronics, Budapest, Hungary, June 1-3, pp. 477-481 (1993).

[6.28] M.S. Dawande, V.R. Kanetkar, and G.K. Dubey, "Three-Phase Switch Mode Rectifier with Hysteresis Current Control," IEEE Transactions on Power Electronics, Vol. 11, No. 3, pp. 466-471 (1996).

[6.29] M. Milanovic and F. Mihalic, *"Analysis of Switching Power Converter by Using a Switching Matrix Approach,"* Proc. of the 22nd IEEE Internat. Conf. on Industrial Electronics, Control and Instrumentation, Vol. 3, pp. 1770-1775 (1996).

[6.30] J.C. Salmon, "Reliable 3-phase PWM Boost Rectifiers Employing a Series-Connected Dual Boost Converter Sub-Topology," Record of the 29th IEEE Industry Applications Society Annual Meeting, Denver, USA, Oct. 2-6, Vol. II, pp. 781-788 (1994).

[6.31] J.C. Salmon, *"Circuit Topologies for PWM Boost Rectifiers Operated from 1-Phase and 3-Phase AC Supplies and Using Either Single or Split DC Rail Output Voltages,"* Proc. of the 10th IEEE Applied Power Electronics Conference, Dallas, USA, March 5-9, Vol. 1, pp. 473-479 (1995).

[6.32] J.C. Salmon, *"A 3-Phase Buck-Boost Converter for Lowering the Input Current Distortion of a Voltage Source Inverter Drive,"* Record of the 30th IEEE Industry Applications Society Annual Meeting, Orlando, USA, Oct. 2-6, Vol. 3, pp. 2475-2482 (1995

Direct Active Three-Phase PFC Rectifier Systems (Three-Level CCM Boost-Type) (4)

[6.33] **R. Burgos, Rixin Lai, Yunqing Pei, F. Wang, D. Boroyevich, J. Pou**, *"Space Vector Modulator for Vienna-Type Rectifiers Based on the Equivalence Between Two- and Three-Level Converters:A Carrier-Based Implementation,"* IEEE Transactions on Power Electronics, Vol.23, No.4, pp.1888-1898, July 2008.

[6.34] **Rixin Lai, F. Wang, R. Burgos, D. Boroyevich, Dong Jiang, Di Zhang**, *"Average Modeling and Control Design for VIENNA-Type Rectifiers Considering the DC-Link Voltage Balance,"* IEEE Transactions on Power Electronics, Vol.24, No.11, pp.2509-2522, Nov. 2009.

[6.35] **Rixin Lai, et. al,** *"A Systematic Topology Evaluation Methodology for High-Density Three-Phase PWM AC-AC Converters,"* IEEE Transactions on Power Electronics, Vol.23, No.6, pp.2665-2680, Nov. 2008.

[6.36] **P. Ide, F. Schafmeister, N. Frohleke, H. Grotstollen,** *"Enhanced Control Scheme for Three-Phase Three-Level Rectifiers at Partial Load,"* IEEE Transactions on Industrial Electronics, Vol.52, No.3, pp. 719- 726, June 2005.

[6.37] **L. Dalessandro, S.D. Round, U. Drofenik, J.W. Kolar,** *"Discontinuous Space-Vector Modulation for Three-Level PWM Rectifiers,"* IEEE Transactions on Power Electronics, Vol.23, No.2, pp.530-542, March 2008.

[6.38] **L. Dalessandro, S.D. Round, and Kolar, J.W** *"Center-Point Voltage Balancing of Hysteresis Current Controlled Three-Level PWM Rectifiers,"* IEEE Transactions on *Power Electronics*, Vol.23, No.5, pp.2477-2488, Sept. 2008.

[6.39] **S.D. Round, P. Karutz, M.L. Heldwein, J.W. Kolar,** *"Towards a 30 kW/liter, Three-PhaseUnity Power Factor Rectifier,"* Proc. of the 4th Power Conversion Conf.(PCC'07), Nagoya, Japan, April 2 - 5, CD-ROM, ISBN: 1-4244-0844-X, (2007).

[6.40] **J.W. Kolar, U. Drofenik, J. Minibock, H. Ertl,** *"A New Concept for Minimizing High-Frequency Common-Mode EMI of Three-Phase PWM Rectifier Systems Keeping High Utilization of the Output Voltage,"* 15th Annual IEEE Appl. Power Electronics Conf. and Exp., (APEC 2000), Vol.1, no., pp.519-527 vol.1, 2000.

[6.41] **G. Gong, M.L.Heldwein, U. Drofenik, J. Minibock, K. Mino, J.W. Kolar,** *"Comparative Evaluation of Three-Phase High-Power-Factor AC-DC Converter Concepts for Application in Future More Electric Aircraft,"* IEEE Transaction on Industrial Electronics, Vol.52, No.3, pp. 727- 737, June 2005.

[6.42] **M.L. Heldwein, J.W. Kolar,** *"Impact of EMC Filters on the Power Density of Modern Three-Phase PWM Converters,"* IEEE Transactions on Power Electronics, Vol.24, No.6, pp.1577-1588, June 2009.

[6.43] **M.L. Heldwein, S.A. Mussa, and I. Barbi,** *"Three-Phase Milti-Level PWM Rectifiers Based on Conventional Bidirectional Converters,"* IEEE Trans. On Power Electr., Vol. 25, No. 3, pp. 545–549, 2010.

[6.44] **J. Alahuhtala, J. Virtakoivu, T. Viitanen, M. Routimo, H. Tuusa,** *"Space Vector Modulated and Vector Controlled Vienna I Rectifier with Active Filter Function,"* Proc. of the Power Conv. Conf. - Nagoya, (PCC '07), 2-5 April 2007, pp.62-68.

[6.45] **J. Alahuhtala, H. Tuusa,** *"Four-Wire Unidirectional Three-Phase/Level/Switch (VIENNA) Rectifier,"* Proc. of the 32nd Ann. Conf. on IEEE Industrial Electronics (IECON 2006), 6-10 Nov. 2006, pp.2420-2425.

Direct Active Three-Phase PFC Rectifier Systems (Design Considerations)

[6.46] **J.W. Kolar, H. Ertl, and F.C. Zach,** *“Calculation of the Passive and Active Component Stress of Three-Phase PWM Converter Systems with High Pulse Rate,”* Proc. of the 3rd European Conf. on Power Electronics and Applications, Aachen, Germany, Oct. 9-12, Vol. 3, pp. 1303 - 1311 (1989).

[6.47] **J.W. Kolar, H. Ertl, and F.C. Zach,** *“Design and Experimental Investigation of a Three-Phase High Power Density High Efficiency Unity Power Factor PWM (VIENNA) Rectifier Employing a Novel Power Semiconductor Module,”* Proc. of the 11th IEEE Appl. Power Electronics Conf., San Jose, USA, March 3-7, Vol. 2, pp. 514 - 523 (1996).

[6.48] **J.W. Kolar, T.M. Wolbank, and M. Schrödl,** *“Analytical Calculation of the RMS Current Stress on the DC Link Capacitor of Voltage DC Link PWM Converter Systems,”* Proc. of the 9th Internat. Conf. on Electrical Machines and Drives, Canterbury, Sept. 1-3, pp. 81 - 89 (1999).

[6.49] **M. Hartmann, H. Ertl, J.W. Kolar,** *"EMI Filter Design for a 1 MHz, 10 kW Three-Phase/Level PWM Rectifier,"* To be published in the IEEE Transactions on Power Electronics.

[6.50] **M. Hartmann, S.D. Round, H. Ertl, J.W. Kolar,** *"Digital Current Controller for a 1 MHz, 10 kW Three-Phase VIENNA Rectifier,"* IEEE Transactions on Power Electronics, Vol.24, No.11, pp.2496-2508, Nov. 2009.

[6.51] **M. Hartmann, J.W. Kolar,** *"Analysis of the Trade-Off Between Input Current Quality and Efficiency of High Switching Frequency PWM Rectifiers,"* 2010 International Power Electronics Conference (IPEC), pp.534-541, 21-24 June 2010 .

[6.52] **J. Minibock, J.W. Kolar,** *"Wide Input Voltage Range High Power Density High Efficiency 10 kW Three-Phase Three-Level Unity Power Factor PWM Rectifier,"* Proc. of the Power Electron. Spec. Conf. (PESC2002), Vol.4, pp. 1642- 1648, 2002.

[6.53] **P. Karutz, P. S.D. Round, M.L. Heldwein, J.W. Kolar,** *"Ultra Compact Three-phase PWM Rectifier,"* 22nd Annual IEEE Appl. Power Electron. Conf., (APEC 2007), pp.816-822, 2007.

Unidirectional Buck-Type PFC Rectifier Systems

[7.1] **L. Malesani and P. Tenti,** *"Three-Phase AC/DC PWM Converter with Sinusoidal AC Currents and Minimum Filter Requirements"*, IEEE Trans. Ind. Appl., vol. 23, no. 1, pp. 71–77, 1987.

[7.2] **J.W. Kolar and F.C. Zach,** *"A Novel Three-Phase Three Switch Three-Level Unity Power Factor Rectifier"*, in Proc. 28th International Power Conversion Conference, pp. 125–138, 1994.

[7.3] **S. Hiti, V. Vlatkovic, D. Borojevic, and F. C. Lee,** *"A New Control Algorithm for Three-Phase PWM Buck Rectifier with Input Displacement Factor Compensation"*, IEEE Trans. Power Electron., vol. 9, no. 2, pp. 173–180, Mar. 1994.

[7.4] **Y. Jang Y and R.W. Erickson,** *"New Single-Switch Three-Phase High-Power-Factor Rectifiers using Multi-Resonant Zero-Current Switching,"* IEEE Transactions on Power Electronics, Vol. 13, No. 1, pp. 194-201, 1998.

[7.5] **D. F. Wang and S. Yuvarajan,** *"Resonant boost input three-phase power factor corrector,"* APEC'98, pp. 958-962, 1998.

[7.6] **M. Baumann and J.W. Kolar,** *"Comparative Evaluation of Modulation Schemes for a Three-Phase Buck+Boost Power Factor Corrector Concerning the Input Capacitor Voltage Ripple,"* IEEE Power Electronics Specialists Conference, Vancouver, Canada, June 17-22, 2001.

[7.7] **M. Baumann, F. Stögerer, J.W. Kolar, and A. Lindemann,** *"Design of a Novel Multi-Chip Power Module for a Three- Phase Buck+Boost Unity Power Factor Utility Interface Supplying the Variable Voltage DC Link of a Square-Wave Inverter Drive,"* Proceedings of the Applied Power Electronics Conference, Anaheim, March 4-8, 2001.

[7.8] **M. Baumann, U. Drofenik, and J.W. Kolar,** *"New Wide Input Voltage Range Three-phase Unity Power Rectifier Formed by Integration of a Three-Switch Buck-Derived Front-End and a DC/DC Boost Converter Output Stage"*, in Proc. 22th European Power Quality Conference, pp. 461–470, 2001.

[7.9] **T. Nussbaumer, M.L. Heldwein, and J.W. Kolar,** *"Differential Mode EMC Input Filter Design for a Three-Phase Buck-Type Unity Power Factor PWM Rectifier"*, in Proc. 4th International Power Electronics and Motion Control Conference IPEMC 2004, pp. 1521–1526, 2004.

[7.10] **T. Nussbaumer, M. Baumann, and J.W. Kolar,** *"Comprehensive Design of Three-Phase Three-Switch Buck-Type PWM Rectifier"*, IEEE Trans. Power Electron., vol. 22, no. 2, pp. 551–562, Mar. 2007.

[7.11] **T. Callaway, J. Cass, R. Burgos, F. Wang, D. Boroyevich,** *"Three-Phase AC Buck Rectifier using Normally-On SiC JFETs at a 150 kHz Switching Frequency"*, in Proc. 38th IEEE Power Electronics Specialists Conference PESC 2007, pp. 2162–2167, 2007.

[7.12] **A. Stupar, T. Friedli, J. Miniböck, and J.W. Kolar,** *"Towards a 99% Efficient Three-Phase Buck-Type PFC Rectifier for 400 V DC Distribution Systems"*, to be published at APEC 2011.

Bidirectional Boost-Type PFC Rectifier Systems (1)

[8.1] **A. Nabae, I. Takahashi, and H. Akagi,** *"A New Neutral-Point-Clamped PWM Inverter"*, IEEE Trans. Ind. Appl. vol. 17, no. 5, Sept./Oct. 1981.

[8.2] **B. Fuld,** *"Aufwandsarmer Thyristor-Dreistufen-Wechselrichter mit geringen Verlusten"*, in etzArchiv, vol. 11, pp. 261–264, VDE Verlag, Berlin, Germany, 1989.

[8.3] **J.S. Lai and F.Z. Peng,** *"Multilevel converters – A New Breed of Power Converters,"* IEEE Trans. Ind. Appl., vol. 32, pp. 509–517, May/June 1996.

[8.4] **S. Fukuda and Y. Matsumoto,** *"Optimal Regulator Based Control of NPC Boost Rectifiers for Unity Power Factor and Reduced Neutral Point Potential Variations"*, in Proc. Annual Meeting of the IEEE Industry Application Society IAS 1997, pp. 1455–1462, 1997.

[8.5] **B. Kaku, I. Miyashita, and S. Sone,** *"Switching Loss Minimized Space Vector PWM Method for IGBT Three-Level Inverter"*, IEE Proc. of Electric Power Applications, vol. 144, pp. 182–190, May 1997.

[8.6] **N. Celanovic and D. Boroyevich,** *"A Comprehensive Study of Neutral-Point Voltage Balancing Problem in Three-Level Neutral-Point Clamped Voltage Source PWM Inverters"*, IEEE Trans. Power Electron., vol. 15, pp. 242–249, Mar. 2000.

[8.7] **T. Brückner and S. Bernet,** *"Loss Balancing in Three-Level Voltage Source Inverters Applying Active NPC Switches"*, in Proc. 21st IEEE Power Electronics Specialists Conference, PESC 2001, pp. 1135–1140, 2001.

[8.8] **J. Pou, D. Boroyevich, and R. Pindado,** *"New Feedforward Space-Vector PWM Method to Obtain Balanced AC Output Voltages in a Three-Level Neutral-Point-Clamped Converter"*, IEEE Trans. on Ind. Electron., vol. 49, no. 5, pp. 102–1034, Oct. 2002.

[8.9] **P. Barbosa, P. Steimer, J. Steinke, M. Winkelnkemper, and N. Celanovic,** *"Active-Neutral-Point-Clamped (ANPC) Multilevel Converter Technology"*, in Proc. European Power Electronics and Applications Conference EPE 2005, pp. 1-10, 2005.

[8.10] **R. Teichmann and S. Bernet,** *"A Comparison of Three-Level Converters versus Two-Level Converters for Low-Voltage Drives, Traction and Utility Applications"*, IEEE Trans. Ind. Appl., vol. 41, pp. 855–865, May/June 2005.

Bidirectional Boost-Type PFC Rectifier Systems (2)

[8.11] **B.P. McGrath, T. Meynard, G. Gateau, D.G. Holmes,** *"Optimal Modulation of Flying Capacitor and Stacked Multicell Converters Using a State Machine Decoder"*, IEEE Trans. Power Electron., vol. 22, no. 2, p. 508–516, Mar. 2007.

[8.12] **J. Ewanchuk, J. Salmon, and A.M. Knight,** *"Performance of a High-Speed Motor Drive System Using a Novel Multilevel Inverter Topology"*, IEEE Trans. Ind. Appl., vol. 45, no. 5, pp. 1706–1714, Sept/Oct. 2009.

[8.13] **M. Schweizer, T. Friedli, and J.W. Kolar,** *"Comparison and Implementation of a 3-level NPC Voltage Link Back-to-Back Converter with SiC and Si Diodes"*, in Proc. of 25th IEEE Applied Power Electronics Conf. and Exposition APEC 2010, pp. 1527–1530, 2010.

[8.14] **M. Schweizer, I. Lizama, T. Friedli, and J.W. Kolar,** *"Comparison of the Chip Area Usage of 2-Level and 3-Level Voltage Source Converter Topologies"*, in Proc. 36th IEEE Industrial Electronics Conference IECON 2010, pp. 391–396, 2010.

Bidirectional Buck- and Buck-Boost Type PFC Rectifier Systems

[8.15] T. Kataoka, K. Mizumachi, and S. Miyairi, "*A Pulsewidth Controlled AC-to DC Converter to Improve Power Factor and Waveform of AC Line Current*", IEEE Trans. Ind. Appl., vol. 15, pp. 670–675, Nov./Dec. 1979.
[8.16] M. Hombu, S. Ueda, and A. Ueda, *"A Current Source GTO Inverter with Sinusoidal Inputs and Outputs,"* Record of the IEEE Industry Applications Society Annual Meeting, pp. 1033–1039, 1985.
[8.17] H. Inaba, S. Shima, A. Ueda, T. Ando, T. Kurosawa, and Y. Sakai, *"A New Speed Control System for DC Motors using GTO Converter and Its Applications to Elevators"*, IEEE Trans. Ind. Appl., vol. IA-21, pp. 391–397, Mar./Apr. 1985.
[8.18] G. Ledwich, "*Current Source Inverter Modulation,"* IEEE Transactions on Power Electronics, Vol. 6, No. 4, pp. 618–623, 1991.
[8.19] D. Ciscato, L. Malesani, L. Rossetto, P. Tenti, G. L. Basile, M. Pasti, and F. Voelker, *"PWM Rectifier with Low DC Voltage Ripple for Magnet Supply"*, IEEE Trans. Ind. Appl., vol. 28, pp. 414–420, Mar./Apr. 1992.
[8.20] G. Joos and J. Espinoza, *"PWM Control Techniques in Current Source Rectifiers*", in Proc. IEEE Industrial Electronics Conference IECON 1993, pp. 1210–1214, 1993.
[8.21] R. Zargari and G. Joos, *"A Current-Controlled Current Source Type Unity Power Factor PWM Rectifier"*, in Proc. 4th Annual Meeting of the IEEE Industry Application Society IAS 1993, pp. 793–799, 1993.
[8.22] T.C. Green, M.H. Taha, N.A. Rahim, and B.W. Williams, *"Three-Phase Step-Down Reversible AC-DC Power Converter"*, IEEE Trans. Power Electron., vol. 12, pp. 319–324, Mar. 1997.

About the Instructors

Johann W. Kolar (F´ 10) received his M.Sc. and Ph.D. degree (summa cum laude / promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria. Since 1984 he has been working as an independent international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drives. He has proposed numerous novel converter topologies and modulation/control concepts, e.g., the VIENNA Rectifier, the Swiss Rectifier, and the three-phase AC-AC Sparse Matrix Converter. Dr. Kolar has published over 450 scientific papers in international journals and conference proceedings and has filed more than 85 patents. He was appointed Professor and Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich on Feb. 1, 2001.

The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, e.g. for data centers, More-Electric-Aircraft and distributed renewable energy systems, and on Solid-State Transformers for Smart Microgrid Systems. Further main research areas are the realization of ultra-compact and ultra-efficient converter modules employing latest power semiconductor technology (SiC and GaN), micro power electronics and/or Power Supplies on Chip, multi-domain/scale modeling/simulation and multi-objective optimization, physical model-based lifetime prediction, pulsed power, and ultra-high speed and bearingless motors. He has been appointed an IEEE Distinguished Lecturer by the IEEE Power Electronics Society in 2011.

He received the Best Transactions Paper Award of the IEEE Industrial Electronics Society in 2005, the Best Paper Award of the ICPE in 2007, the 1st Prize Paper Award of the IEEE IAS IPCC in 2008, the IEEE IECON Best Paper Award of the IES PETC in 2009, the IEEE PELS Transaction Prize Paper Award 2009, the Best Paper Award of the IEEE/ASME Transactions on Mechatronics 2010, the IEEE PELS Transactions Prize Paper Award 2010, the Best Paper 1st Prize Award at the IEEE ECCE Asia 2011, and the 1st Place IEEE IAS Society Prize Paper Award 2011 and the IEEE IAS EMC Paper Award 2012. Furthermore, he received the ETH Zurich Golden Owl Award 2011 for Excellence in Teaching. He also received an Erskine Fellowship from the University of Canterbury, New Zealand, in 2003.

He initiated and/or is the founder/co-founder of 4 spin-off companies targeting ultra-high speed drives, multi-domain/level simulation, ultra-compact/efficient converter systems and pulsed power/electronic energy processing. In 2006, the European Power Supplies Manufacturers Association (EPSMA) awarded the Power Electronics Systems Laboratory of ETH Zurich as the leading academic research institution in Power Electronics in Europe.

Dr. Kolar is a Fellow of the IEEE and a Member of the IEEJ and of International Steering Committees and Technical Program Committees of numerous international conferences in the field (e.g. Director of the Power Quality Branch of the International Conference on Power Conversion and Intelligent Motion). He is the founding Chairman of the IEEE PELS Austria and Switzerland Chapter and Chairman of the Education Chapter of the EPE Association. From 1997 through 2000 he has been serving as an Associate Editor of the IEEE Transactions on Industrial Electronics and since 2001 as an Associate Editor of the IEEE Transactions on Power Electronics. Since 2002 he also is an Associate Editor of the Journal of Power Electronics of the Korean Institute of Power Electronics and a member of the Editorial Advisory Board of the IEEJ Transactions on Electrical and Electronic Engineering.

About the Instructors (Cont'd)

Jonas Mühlethaler (M´09) received his M.Sc. in 2008 and the Ph.D. degree in 2012, both in electrical engineering and both from the Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland. During his master studies, he focused on power electronics and electrical machines. In his M.Sc. thesis, which he wrote at ABB Corporate Research in Sweden, he worked on compensating torque pulsation in Permanent Magnet Motors. In 2008 he joined the Power Electronic Systems Laboratory (PES), ETHZ, to work towards his Ph.D. degree. During the Ph.D. studies, which he finished in 2012, he worked on modeling and multi-objective optimization of inductive power components. Currently, he is working as a Postdoctoral Fellow at PES. Dr. Mühlethaler is the author of 13 conference and Transactions papers and a Member of the IEEE.