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
  - Active 3rd Harmonic Injection
    - Passive/Hybrid 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)
      - DVM
        - Single-Switch Converter
    - Impressed Input Voltage (Buck-Type)
      - 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

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.)

Electronic Reactance Based
- Single Diode Bridge & DC-Side Electron. Ind.
- Multi-Pulse Rectifier System Employing Electron. Interphase Tran.

Combination of Diode Rectifier and DC/DC Converter
- 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.

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

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

Impressed Input Current (Boost-Type)
- Single-Switch
- Two-Switch
- Y-Switch
- Δ-Switch
- Y-Arrangement With Mains
- Artificial Star-Point Connection
- Three-Level Converter (VIENNA Rectifier)

Impressed Input Voltage (Buck-Type)
- Single-Switch Converter
- Three-Switch Converter
- Six-Switch Converter

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

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

Phase-Modular Systems
- DCM
- CCM
- DVM
- CVM
Diode Bridge Rectifier with Capacitive Smoothing

\[ U_{LL} = 3 \times 400 \text{ V} \]
\[ f_N = 50 \text{ Hz} \]
\[ P_{out} = 2.5 \text{ kW } (R=125 \text{ } \Omega) \]
\[ C = 1 \text{ mF}; 40 \mu F \]
\[ X_c/R = 0.025; 0.636 \]
Diode Bridge Rectifier / DC-Side Inductor and Output Capacitor

\[ U_{LL} = 3 \times 400 \text{ V} \]
\[ f_N = 50 \text{ Hz} \]
\[ P_{out} = 2.5 \text{ kW} \ (R=125 \ \Omega) \]
\[ C = 1 \text{ mF} \]
\[ L = 5 \text{ mH}; 20 \text{ mH} \]

\[ \bar{u}^*_{pn} = \frac{\bar{u}_{pn}}{\pi \hat{U}_{N,LL}} \]
Diode Bridge Rectifier / AC-Side Inductor and Output Capacitor

\[ U_{LL} = 3 \times 400 \, V \]

\[ f_N = 50 \, Hz \]

\[ P_{out} = 2.5 \, kW \quad (R=125 \, \Omega) \]

\[ R = 1 \, mF \]

\[ L = 2 \, mH; \ 20 \, mH \]
Passive 3rd Harmonic Injection

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

\[ 3i_y = \frac{u_{1} + u_{2}}{2} \]

\[ R \approx \frac{1}{I} \]
● **Passive 3rd Harmonic Injection**

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

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

Direct Three-Phase Systems

Phase-Modular 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

Active PFC Systems

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
- Multi-Pulse Rect. System
  - DC-Side Inductor
  - AC-Side Inductors
  - Passive 3rd Harmonic Injection

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

Active PFC Systems

Electronic Reactance Based
- Single Diode Bridge & DC-Side Electron. Ind.
- Single Diode Bridge & AC-Side Electron. Ind. or Cap.

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

Direct Three-Phase Systems

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

Impressed Input Current (Boost-Type)
- DCM
- 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
- CVM
- Single-Switch Converter
- Three-Switch Converter
- Six-Switch Converter
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

\[ U_{LL} = 3 \times 400 \text{ V} \]
\[ P_o = 5 \text{ kW} \]
\[ f_S = 70 \text{ kHz} \]
\[ C = 4 \times 330 \mu \text{F}/100 \text{ V} \]

\[ \eta = 98.3 \% \]
\[ \lambda = 0.955 \]
\[ \text{THD} = 28.4 \% \]
Diode Bridge and DC-Side EI or Electronic Capacitor

- **MERS Concept (Magnetic Energy Recovery Switch)**

![Fundamental Frequency Equivalent Circuit](image)
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
- Active PFC Systems

Electronic Reactance Based

- Single Diode Bridge & DC-Side Electron. Ind.
- Single Diode Bridge & AC-Side Electron. Ind. or Cap.

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.)

Direct Three-Phase Systems

- Impressed Input Current (Boost-Type)
  - DCM
  - Single-Switch
  - Two-Switch
  - Y-Switch
  - Δ-Switch
  - Y-Arrangement With Mains
  - Artificial Star-Point Connection
  - Three-Level Converter (VIENNIA Rectifier)
- CCM
  - Two-Level Converter

Phase-Modular Systems

- Impressed Input Voltage (Buck-Type)
  - DVM
  - Single-Switch Converter
  - Three-Switch Converter
  - Six-Switch Converter
- CVM
  - 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

\[ i_1 = I + \frac{3}{2} i_y \]
\[ i_2 = I - \frac{3}{2} i_y \]

CCL: \[ 3i_y = i_1 - i_2 \]

Minnesota Rectifier

- Controlled Output Voltage
- Purely Sinusoidal Shape of Mains Current
Active 3\textsuperscript{rd} Harmonic Injection into All Phases

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

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

\[ i_a = \hat{I} \cos(\omega t) \]
\[ i_b = \hat{I} \cos\left(\omega t - \frac{2\pi}{3}\right) \]
\[ i_c = \hat{I} \cos\left(\omega t + \frac{2\pi}{3}\right) \]

\[ i_y = -i_b \]
\[ i_1 = i_a + i_y \]
\[ i_2 = -(i_c + i_y) \]
\[ i_a + i_b + i_c = 0 \]
\[ i_1 - i_2 = i_a + i_y + i_c + i_y = -i_b + 2i_y = 3i_y \]
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

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

- $T_+ , T_- \text{ Could be Replaced by Passive Network}$
Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$

- Current to be Inj. Into Phase $b$:
  \[ i_y = -i_b \]

- Local Avg. Ind. Voltage / Bridge Leg $(T_+, T_-)$ Output Voltage:
  \[ \bar{u}_L \approx 0 \quad \text{and/or} \quad \bar{u}_{20} = u_{b0} \]

- 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:
  \[ i = \frac{P}{u_{ac}} = \frac{u_{ac} \cdot i_a + u_{bc} \cdot i_b}{u_{ac}} \]
  \[ = G \frac{u_a \cdot u_{ac} + u_b \cdot u_{bc}}{u_{ac}} = G \left( u_{a0} + u_{b0} \frac{u_{bc}}{u_{ac}} \right) \]

- Sinusoidal Mains Current:
  \[ i + \bar{i}_{T_+} = G \cdot u_{a0} = i_a \]
Active 3\textsuperscript{rd} 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 $\omega t = \left[ 0, \frac{\pi}{3} \right] (1)$

4 Different Switching States:
- $T_+ \text{ on, } T_- \text{ off}$ \quad $k_1$
- $T_+ \text{ off, } T_- \text{ on}$ \quad $k_2$
- $T_+ \text{ off, } T_- \text{ off}$
- $T_+ \text{ on, } T_- \text{ on}$ \quad $k_3 = (1 - k_1 - k_2)$

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 $\omega \in \left[0, \frac{\pi}{3}\right]$ (2)

- Current to be Injected into $b$: $i_Y^* = -i_b^*$

- Inductor Voltages:
  $\bar{u}_{L,1}^* \approx 0$
  $\bar{u}_{L,2}^* \approx 0$

- Bridge Leg ($T_+, T$): Voltage Form.:
  $k_1 u_{ab} + k_2 \left( u_{ab} - U_{pn} \right) + (1 - k_1 - k_2) u_{ab} = 0$
  $k_2 = \frac{u_{ab}}{U_{pn}}$
  $k_1 \left( u_{bc} - U_{pn} \right) + k_2 u_{bc} + (1 - k_1 - k_2) u_{bc} = 0$
  $k_1 = \frac{u_{bc}}{U_{pn}}$

- Constant Power, Load Current:
  $i = \frac{P}{U_{pn}} = \frac{u_{ab} i_a - u_{bc} i_c}{U_{pn}} = -k_1 i_c + k_2 i_a$

- Current Formation in $T_+$:
  $\bar{i}_{T+} = k_1 i_Y^* + (1 - k_1 - k_2) i_a^*$

Sinusoidal Mains Current:

$\bar{i}_{T+} + i_a^* = i_a^*$
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)

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

\[ U_{N,LL} = 400V_{\text{rms}} \]
\[ U_{pn} = 400V_{\text{DC}} \]
\[ P=10kW \]
Proof of Sinusoidal Mains Current Shape for $\omega t \in \left[0, \frac{\pi}{3}\right]$

- Current to be Inj. into Phase $b$:
  \[ i_y = -i_b \]

- Current Formation:
  \[
  k_1 I = i_a \\
  k_2 I = -i_c \\
  i_y = -(1 - k_1)I + (1 - k_2)I = -i_b
  \]

\[
  i_a + i_b + i_c = 0
  \]

Duty Cycles:
\[
T_+ \rightarrow k_1 \\
T_- \rightarrow k_2
\]

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

- Voltage Formation:
  \[
  k_1 u_a + (1 - k_1)u_b - (k_2 u_c + (1 - k_2)u_b) = u_{pn}
  \]

\[
  k_1 u_{ab} - k_2 u_{cb} = u_{pn}
  \]

\[
  i_a u_{ab} + i_c u_{cb} = u_{pn} I
  \]

\[
  i_a u_{ab} + i_c u_{cb} = P = \text{const.} \\
  I = \text{const.} \rightarrow u_{pn} = \text{const.}
  \]
Classification of Unidirectional Rectifier Systems

Unidirectional Three-Phase Rectifier Systems

 Passive Systems
 - Single Diode Bridge
 - Multi-Pulse Rect. System

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

 Active PFC Systems

 Electronic Reactance Based
 - Single Diode Bridge
 - DC-Side Electron. Ind.
 - Single Diode Bridge
 - AC-Side Electron. Ind. or Cap.

 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.

 Active 3rd Harmonic Injection
 - Buck-Type
 - Single Diode Bridge
 - DC/DC Output Stage
 - Half-Controlled Diode Bridge

 Direct Three-Phase Systems

 Impressed Input Current (Boost-Type)
 - DCM
 - Single-Switch
 - Two-Switch
 - Y-Switch
 - Δ-Switch
 - Y-Arrangement With Mains
 - Artificial Star-Point Connection
 - Three-Level Converter (VIENNA Rectifier)

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

 Phase-Modular Systems

 Direct Three-Phase Systems
 - DVM
 - Single-Switch Converter
 - Six-Switch Converter

 Active PFC Systems
 - Y-Rectifier
 - Delta-Rectifier
 - 3/2-Phase Scott-Transf. Based
Diode Bridge Combined with DC/DC Boost Converter

\[ U_{LL} = 3 \times 400 \text{ V} \ (f_N = 50 \text{ Hz}) \]
\[ P_{\text{out}} = 10 \text{ kW} \]
\[ \lambda = 0.952 \]
\[ \text{THD} = 32\% \]

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 \((U > \sqrt{6} \bar{U})\)
+ Low Complexity (e.g. Single Curr. Sensor)
+ Low Conduction Losses

- Block Shaped Mains Current
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
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)

\[ U_{LL} = 3 \times 115 \text{ V (400 Hz)} \]
\[ P_o = 10 \text{ kW} \]
\[ U_o = 520 \text{ V} \]
\[ f_s = 60 \text{ kHz} \]
\[ \text{THD}_i = 3.1\% \]
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 Variety 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

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

Active PFC Systems
- Electronic Reactance Based
- Combination of Diode Rectifier and DC/DC Converter
- Active 3rd Harmonic Injection
- Passive/Hyr. or Active 3rd Harm. Inject. Network
- Boost- or Buck-Type or Uncontrolled Output
- Diode Bridge or Multipulse System with Harmonic Inj. (Pulse Multipl.)

Direct Three-Phase Systems
- 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
- Combination of Diode Rectifier and DC/DC Converter

Phase-Modular Systems
- Impressed Input Current (Boost-Type)
- DC/DC
- Single-Switch
- Two-Level Converter
- Y-Switch
- Δ-Switch
- Y-Arrangement With Mains
- Three-Level Converter (VIENNA Rectifier)

- Impressed Input Voltage (Buck-Type)
- CCM
- DCM
- Three-Level Converter
- CVM
- Single-Switch Converter
- Six-Switch Converter

- 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
  - **Hybrid Systems**
    - Multi-Pulse Rect. System
      - (Partial) Transf. Isol. or Auto-Transf.-Based
      - AC- or DC-Side Interph. Transformer
      - Passive Pulse Multiplication
  - **Active PFC Systems**
    - Direct Three-Phase Systems
    - Phase-Modular Systems
      - Impressed Input Current (Boost-Type)
        - DCM
          - Single-Switch
          - Two-Switch
      - CCM
        - Two-Level Converter
          - Y-Switch
          - ∆-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

- **Electronic Reactance Based**
  - Single Diode Bridge
    - DC-Side Electron. Ind.
    - Single Diode Bridge
      - & AC-Side Electron. Ind. or Cap.
  - 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.)

- **Impressed Input Current (Boost-Type)**
  - DCM
    - Single-Switch
    - Two-Switch
  - CCM
    - Two-Level Converter
      - Y-Switch
      - ∆-Switch
      - Y-Arrangement With Mains
      - Artificial Star-Point Connection
      - Three-Level Converter (VIENNA Rectifier)
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

- 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 ($S_a S_b S_c$)

Switching States (011) and (100)

- Redundant Concerning Formation of $u_{ab}$, $u_{bc}$, $u_{ca}$
- Inverse Concerning Charging of $C_a$ and $C_c$ (and $C_b$)
Y-Rectifier

- Equivalent Circuit and Voltage Formation

\[ u_{\bar{a}} = u_{\bar{a}}' + u_{0} \]  
\[ u_{\bar{b}} = u_{b}' + u_0 \]  
\[ u_{\bar{c}} = u_{c}' + u_0 \]

\[ u_{\bar{a}} + u_{\bar{b}} + u_{\bar{c}} = 0 \]

\[ u_0 = \frac{1}{3} (u_{\bar{a}} + u_{\bar{b}} + u_{\bar{c}}) \]

\[ \bar{u}_{\bar{a}} = u_{\bar{a}}' + u_0 \]
\[ u_{\bar{a}}',\sim = u_{\bar{a}}',\sim + u_0,\sim \]

(shown at the Example of Phase a)
Y-Rectifier

- Equivalent Circuit and Voltage Formation

\[ u_a + u_b + u_c = 0 \]

\[ u_a = L \frac{di_a}{dt} + \bar{u}_{a} + \bar{u}_{a} + u_{N',N} \]
\[ u_b = L \frac{di_b}{dt} + \bar{u}_{b} + \bar{u}_{b} + u_{N',N} \]
\[ u_c = L \frac{di_c}{dt} + \bar{u}_{c} + \bar{u}_{c} + u_{N',N} \]

\[ 0 = 0 + 0 + 0 + 3u_{N',N} \]

\[ u_{N',N} = 0 \]

- Voltage of the Star Point \( N' \) Defined by \( u_0 \) (CM-Voltage)
Y-Rectifier

Modulation and Voltage Formation

- 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 (\( u_{0,~} \))
Y-Rectifier

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

- $\bar{m}_0 = 0$

- $\bar{m}_0 \neq 0$

- $\bar{m}_0$ 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.g. Phase \( b \)).

![Diagram of Y-Rectifier and Control Structure](image)
Y-Rectifier

**Experimental Verification of Output Voltage Balancing**

- **Symm. Loading**  \( P_a = P_b = P_c = 1000 \text{ W} \)
- **Asymm. Loading**  \( P_a = 730 \text{ W}, P_b = P_c = 1000 \text{ W} \)

\[
\begin{align*}
U_N &= 3 \times 230 \text{ V (50 Hz)} \\
P_o &= 3 \times 1 \text{ kW} \\
U_o &= 400 \text{ V} \\
f_s &= 58 \text{ kHz} \\
L &= 2.8 \text{ mH (on AC-side)} \\
C &= 660 \mu\text{F}
\end{align*}
\]

Input Phase Currents, Control Signal \( i_0 \), Output Voltages

- **Symm. Loading**
- **Asymm. Loading**

\( i_{N,i}; 1 \text{ A/div} \)
\( V_{DC,i}; 100 \text{ V/div} \)

2 ms/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 \(i_0\)**

\[
\begin{align*}
\sum_{a}^{} u_a & \rightarrow \alpha \rightarrow L_\Delta \rightarrow \bar{a} \rightarrow u_{\bar{a}b} \\
\sum_{b}^{} u_b & \rightarrow \bar{b} \rightarrow L_\Delta \rightarrow u_{\bar{b}c} \\
\sum_{c}^{} u_c & \rightarrow \bar{c} \rightarrow L_\Delta \rightarrow u_{\bar{c}a}
\end{align*}
\]

\[
\begin{align*}
u_{\bar{a}b} &= u_{\bar{a}b}^\prime + u_0 \\
u_{\bar{b}c} &= u_{\bar{b}c}^\prime + u_0 \\
u_{\bar{c}a} &= u_{\bar{c}a}^\prime + u_0
\end{align*}
\]

**Def.:** \(u_{\bar{a}b}^\prime + u_{\bar{b}c}^\prime + u_{\bar{c}a}^\prime = 0\)

- Mains Phase Current Formed by \(u_a, u_b, u_c\) and \(u_{\bar{a}b}^\prime, u_{\bar{b}c}^\prime, u_{\bar{c}a}^\prime\)
- Circulating Current \(i_0\) Formed by \(u_0\)

\[
u_0 = \frac{1}{3}(u_{\bar{a}b} + u_{\bar{b}c} + u_{\bar{c}a})
\]

- \(u_0\) 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 \(u_{\bar{a}b}^\prime, u_{\bar{b}c}^\prime\) and \(u_{\bar{c}a}^\prime\) are minimized
\[ u_{ab} = u_{\Delta ab} = u_{\Delta a} - u_{\Delta b}, \]
\[ u_{bc} = u_{\Delta bc} = u_{\Delta b} - u_{\Delta c}. \]

- Equiv. Y-Voltage Syst. should not Contain Zero Sequ. Comp.
  \[ u_{\Delta a} = \frac{1}{3}(u_{\Delta ab} + u_{\Delta ca}) \]
  \[ u_{\Delta b} = \frac{1}{3}(u_{\Delta bc} + u_{\Delta ab}) \]
  \[ u_{\Delta c} = \frac{1}{3}(u_{\Delta ca} + u_{\Delta bc}) \]

- Equiv. Concerning Input Impedance between any Terminals
  \[ Z_{i,\Delta} = Z_{i,Y} \rightarrow L_{\Delta} \parallel L_{\Delta} = \frac{1}{2} L_{\Delta} = L_Y + L_Y \parallel L_Y = \frac{3}{2} L_Y \]
  \[ L_Y = \frac{1}{3} L_{\Delta} \]
**Δ-Rectifier**

- **Circulating Current Max. / Minimization of Mains Current Ripple**

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

- 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**

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

- Formation of Input Phase Current \[ i_a = i_{\overline{ab}} - i_{ca} \]

- 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

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

Active PFC Systems
- Active 3rd Harmonic Injection
- Direct Three-Phase Systems
- Impressed Input Current (Boost-Type)
  - Single-Switch
  - Two-Level Converter
  - Y-Switch
  - Δ-Switch
  - Y-Arrangement With Mains
  - Artificial Star-Point Connection
  - Three-Level Converter (VIENNA Rectifier)

Electron Reactance Based
- Impressed Input Voltage (Buck-Type)
  - Single-Switch Converter
  - Three-Switch Converter
  - Six-Switch Converter

Combination of
Diode Rectifier and DC/DC Converter
- Buck-Type
- Boost-Type
- Single Diode Bridge & DC/DC Output Stage
- Half-Controlled Diode Bridge
- Multi-Pulse Rectifier System Employing Electron. Interphase Transformer

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 $U_{pn}/\dot{U}$
- High EMI Filtering Effort

**Improvement of Mains Current Shape by 6\textsuperscript{th} Harmonic Duty Cycle Modulation or Boundary Mode Operation**

- Reduction of EMI Filtering Effort by Interleaving

$U_{LL} = 3 \times 400 \text{ V (50Hz)}$

$P_o = 2.5 \text{ kW}$

$U_o = 800 \text{ V}$

$\text{THD}_i = 13.7 \text{ %}$
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

- Slightly Lower \( \text{THDI} \) for same \( U_{\text{pn}}/U_N \) 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

\[ U_{\text{LL}} = 3 \times 400 \, \text{V} \]
\[ P_0 = 2.5 \, \text{kW} \]
\[ U_0 = 700 \, \text{V} \]
\[ \text{THDI} = 9 \% \]
Classification of Unidirectional Rectifier Systems

Unidirectional Three-Phase Rectifier Systems
- Passive Systems
  - Single Diode Bridge
    - DC-Side Inductor
    - AC-Side Inductors
    - Passive 3\textsuperscript{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.
- Active 3\textsuperscript{rd} Harmonic Injection
  - 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
- Direct Three-Phase Systems
  - Impressed Input Current (Boost-Type)
    - DCM
      - Single-Switch
      - Two-Switch
    - CCM
      - Two-Level Converter
      - Y-Switch
      - ∆-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
- Active PFC Systems
  - 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 $\bar{a}$, $\bar{b}$, $\bar{c}$ 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
**△-Switch Rectifier**

- **Equivalent Circuit / Mains Current Control**
  - Reference Voltages, i.e. the Output of the Phase Current Controllers Need to be Transformed into \( \Delta \)-Quantities
  - 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 \( S_{\bar{a}b\bar{a}}, S_{\bar{b}c\bar{b}}, S_{\bar{c}a\bar{c}} \) 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
Modulation

\[ U_{LL} = 115 \text{ V (400Hz)} \]
\[ P_0 = 5 \text{ kW} \]
\[ U_o = 400 \text{ V} \]
\[ f_s = 72 \text{ kHz} \]

Power Density: 2.35 kW/dm\(^3\)
\( U_{LL} = 115 \text{ V (400Hz)} \)
\( P_o = 5 \text{ kW} \)
\( U_o = 400 \text{ V} \)
\( f_s = 72 \text{ kHz} \)

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 Req.
  - 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

\[ u_{\alpha M} = \left(1 - s_\alpha \right) \text{sign}(i_\alpha) \frac{U}{2} \]

is Determined by Phase Switching State AND Direction of Phase Current

\[ s_\alpha = 0 \quad \text{\(T_{a+}, T_{a-}: \text{OFF}\)} \]
\[ u_{\alpha M} = +\frac{1}{2}U \]

\[ s_\alpha = 1 \quad \text{\(T_{a+}, T_{a-}: \text{ON}\)} \]
\[ u_{\alpha M} = 0 \]
Semiconductor Blocking Voltage Stress

**Blocking Voltage Definition**

- \( DF_+ \): Limited to \( U_+ \) via Parasitic Diode of \( T_{a+} \)
- \( DN_+ \): Not Dir. Def. by Circuit Structure
- \( DN_- \): Not Dir. Def. by Circuit Structure
- \( DF_- \): Limited to \( U_- \) via Paras. Diode of \( T_{a-} \)
- \( T_{a+} \): Limited to \( U_+ \) via \( DF_+ \)
- \( T_{a-} \): Limited to \( U_- \) via \( DF_- \)

For \( sa = 0 \):
- \( T_{a+}, T_{a-} \): OFF
  - \( u_{aM} = +\frac{1}{2}U \)

For \( sa = 1 \):
- \( T_{a+}, T_{a-} \): ON
  - \( u_{aM} = 0 \)
Impression of Input Current Fund. (Ohmic Fund. Mains Behavior)

\[
\begin{align*}
\delta &= 0.1^\circ \ldots 0.3^\circ \ (50/60 \text{ Hz}) \\
\delta &= 1^\circ \ldots 3^\circ \quad (360 \text{ Hz} \ldots 800 \text{ Hz})
\end{align*}
\]

- Difference of Mains Voltage (e.g. \(u_a\)) and Mains Frequency Comp. of Voltage Formed at Rectifier Bridge Input (e.g. \(\bar{u}_{\tilde{a}}\)) Impresses Mains Current (e.g. \(i_a\))
PWM / Formation of $\tilde{u}_a, \tilde{u}_b, \tilde{u}_c$ / AC-Side Equiv. Circuit (1)

- Def. of Modulation Index:
  \[ M = \frac{\tilde{U}_a}{\frac{1}{2} U} \left( 0 \ldots \frac{2}{\sqrt{3}} \right) \]

- Zero-Sequence Signal to Achieve Ext. Mod. Range
  \[ u_{\tilde{a}0} = u'_{\tilde{a}} + u_0 \]
  \[ u_{\tilde{b}0} = u'_{\tilde{b}} + u_0 \]
  \[ u_{\tilde{c}0} = u'_{\tilde{c}} + u_0 \]
  \[ u_0 = \frac{1}{3} \left( u_{\tilde{a}0} + u_{\tilde{b}0} + u_{\tilde{c}0} \right) \]

- 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 $u_a, u_b, u_c$

$u_a' = u_{aN'} = \bar{u}_a' + u_{a\sim}$
$u_b' = u_{bN'} = \bar{u}_b' + u_{b\sim}$
$u_c' = u_{cN'} = \bar{u}_c' + u_{c\sim}$

$\bar{u}_a', \bar{u}_b', \bar{u}_c'$
Causing the Switching Frequ. Ripple of the Mains Currents and/or DM Filtering Requirement

Note: $u_{NN'} = 0$

$u_{a0} = u_{a}' + u_0$
$u_{b0} = u_{b}' + u_0$
$u_{c0} = u_{c}' + u_0$

$\bar{u}_0$
Low Frequency Zero Sequence Component for Extending the Modulation Range from $M = 0 \ldots 1$ (Sinusoidal Modulation) to $M = 0 \ldots \frac{2}{\sqrt{3}}$

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

$u_{0\sim}$
Switching Frequency CM Voltage Fluctuation of the Output $\rightarrow$ Resulting in CM Current and/or CM Filtering Requirement
Time Behavior of the Components of Voltages

\[ i_a = \tilde{i}_a + i_{a\sim} \]

\[ u_{a\sim}, u_{b\sim}, u_{c\sim} \]
Local Average Value of Center Point Current

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

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

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

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

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

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

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

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

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

$$\bar{i}_M = \alpha_a \cdot i_a + \alpha_b \cdot i_b + \alpha_c \cdot i_c$$

$$= (1 - m_a) \cdot i_a + (1 - m_b) \cdot i_b + (1 - m_c) \cdot i_c$$

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

- $m_0$, i.e. PWM incl. 3$^{rd}$ 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

\[
\begin{align*}
(000), & \quad i_M = 0 \\
(001), & \quad i_M = i_a \\
(010), & \quad i_M = -i_b \\
(011), & \quad i_M = i_a \\
(111), & \quad i_M = 0 \\
(110), & \quad i_M = i_c \\
(101), & \quad i_M = i_b \\
(100), & \quad i_M = -i_a
\end{align*}
\]
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 $u_a$, $u_b$, $u_c$
- 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 $\delta_{(100)} + \delta_{(011)}$. 

$Ts=1/f$
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 $\bar{u}_a$, $\bar{u}_b$, $\bar{u}_c$ are Formed as in the Symmetric Case ($\Delta U = 0$) and/or the Mains Phase Currents Remain at Sinusoidal Shape.

- Resulting $\bar{i}_M$ Reduces $\Delta U$, i.e. Self Stability Guaranteed.
\[ a_r = \frac{R_+ - R_-}{R_+ + R_-} \]

- 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

\[
I_{DF,\text{avg}} = \frac{M}{4} \hat{I}_N
\]
\[
I_{DF,\text{rms}} = \sqrt{\frac{2M}{3\pi}} \hat{I}_N
\]
\[
I_{DN,\text{avg}} = \frac{1}{\pi} \hat{I}_N
\]
\[
I_{DN,\text{rms}} = \frac{1}{2} \hat{I}_N
\]

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

- Output Voltage $> \sqrt{3} \hat{U}_{\text{max}}$ (typ. 1.2 $\sqrt{3} \hat{U}_{\text{max}}$): $\hat{U}_{\text{max}}$: Ampl. of Max. Mains Phase Voltage
- Required Blocking Capability of All Semiconductors: $\frac{1}{2} U$
Current Stress on Power Semiconductors

3-Switch Circuit Topology

- Output Voltage $> \sqrt{3} \hat{U}_{\text{max}}$ (typ. 1.2 $\sqrt{3} \hat{U}_{\text{max}}$): $\hat{U}_{\text{max}}$: Ampl. of Max. Mains Phase Voltage
- Required Blocking Capability of All Semiconductors: $\frac{1}{2} U$
Nonlin. $C_{oss}$ of Superjunct. MOSFETs Causes Input Curr. Distortion

- 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 @ $f_s = 500$ 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 \( f_s = 1 \text{ MHz} \) (VR1000)

- DM Filter Structure
- **CM Filter Design**

- **CM Equivalent Circuit**

- **Required CM Attenuation**

\[ C_{FB} = 220 \text{ nF} \]
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  \rightarrow  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:

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

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

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

→ 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

\[ A_{\text{filter}}(f_D) [\text{dB} \mu \text{V}] = V_{\text{est}}(f_D) [\text{dB} \mu \text{V}] - \text{Limit}(f_D) [\text{dB} \mu \text{V}] + \text{Margin}(f_D) [\text{dB} \mu \text{V}] \]
**EMI Filter Optimization**

- **Shown for DM Filter**

![Diagram of EMI Filter Optimization](image)

**Key Parameters**

- $L_{\text{Boost}}$
- $V_{\text{DM,a}}$
- $V_{\text{DM,b}}$
- $V_{\text{DM,c}}$

**Optimal Selection of Current Ripple Ratio $k$ ($f_p = \text{const}$)**

- High Ripple Current in $L_{\text{Boost}}$ (→ high $k$) requires Large CLC-filter; in Return the $L_{\text{boost}}$ is Small
- Small Ripple Current in $L_{\text{Boost}}$ (→ small $k$) requires Large $L_{\text{boost}}$; in Return the CLC-filter is Small
EMI Filter Optimization

► Shown for DM Filter

Key Parameters

- $k = \frac{I_{1,\text{HF}}}{I_{1,\text{LF}}}$
- $f_P$

► Optimal Selection of Switching Frequency $f_P$ ($k = \text{const.}$)

→ High Switching Frequency requires Large CLC-filter; in Return the $L_{\text{boost}}$ is Small
→ Low Switching Frequency requires Large $L_{\text{boost}}$; 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
  $\rho = 3$ kW/dm$^3$

- $f_s = 72$ kHz
  $\rho = 4.6$ kW/dm$^3$

- $f_s = 250$ kHz
  $\rho = 10$ kW/dm$^3$
  (164 W/in$^3$)
  Weight = 3.4 kg

- $f_s = 1$ MHz
  $\rho = 14.1$ kW/dm$^3$
  Weight = 1.1 kg
Demonstrator – VR250 (1)

- **Specifications**
  
  \[
  U_{LL} = 3 \times 400 \text{ V} \\
  f_{HN} = 50 \text{ Hz ... 60 Hz or 360 Hz ... 800 Hz} \\
  P_0 = 10 \text{ kW} \\
  U_0 = 2 \times 400 \text{ V} \\
  f_s = 250 \text{ kHz}
  \]

- **Characteristics**
  
  \[
  \eta = 96.8 \% \\
  \text{THD}_i = 1.6 \% @ 800 \text{ Hz} \\
  10 \text{ kW/dm}^3 \\
  3.3 \text{ kg (≈3 kW/kg)}
  \]

Dimensions: 195 x 120 x 42.7 mm³
 ► Demonstrator – VR250 (2)

**Specifications**

- \( U_{LL} = 3 \times 400 \, \text{V} \)
- \( f_n = 50 \, \text{Hz} \ldots 60 \, \text{Hz or} \, 360 \, \text{Hz} \ldots 800 \, \text{Hz} \)
- \( P_o = 10 \, \text{kW} \)
- \( U_o = 2 \times 400 \, \text{V} \)
- \( f_s = 250 \, \text{kHz} \)

**Characteristics**

- \( \eta = 96.8 \% \)
- \( \text{THD}_i = 1.6 \% \, @ \, 800 \, \text{Hz} \)
- \( 10 \, \text{kW/dm}^3 \)
- \( 3.3 \, \text{kg} \, (\approx 3 \, \text{kW/kg}) \)

Dimensions: 195 x 120 x 42.7 mm\(^3\)
Mains Behavior @ $f_N = 50$ Hz

- $P_0 = 4$ kW
- $U_N = 230$ V
- $f_N = 50$ Hz
- $U_0 = 800$ V
- $THD_i = 1.1\%$
Mains Behavior @ $f_N = 400\text{Hz} / 800\text{Hz}$

\[ P_0 = 10\text{kW} \]
\[ U_N = 230\text{V} \]
\[ f_N = 400\text{Hz} \]
\[ U_0 = 800\text{V} \]
\[ \text{THD}_i = 1.4\% \]

\[ P_0 = 10\text{kW} \]
\[ U_N = 230\text{V} \]
\[ f_N = 800\text{Hz} \]
\[ U_0 = 800\text{V} \]
\[ \text{THD}_i = 1.6\% \]
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\textsuperscript{rd} Harmonic Inj. Rectifier
\Delta-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
  - Multi-Pulse Rect. System
  - DC-Side Inductor
  - AC-Side Inductors
  - Passive 3rd Harmonic Injection

- Hybrid Systems
  - 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)
  - Phase-Modular Systems
    - Impressed Input Voltage (Buck-Type)
      - DVM
      - Single-Switch Converter
      - Three-Switch Converter
      - Six-Switch Converter
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 $0 \leq u \leq \frac{3}{2} \hat{U}$

- Pulsating Input Currents / EMI Filtering Req.
- Relatively High Conduction Losses
**Derivation of the Circuit Topology (2)**

- 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 $\bar{U} > \frac{3}{2}\hat{U}$
  
  - 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: \(\omega t \in \left(0, +\frac{\pi}{6}\right)\)

- 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: \( \alpha_b + \alpha_c = \frac{G^* u_a}{I} = \frac{G^* \hat{U}}{I} \cdot \cos(\omega t) = M \cdot \cos(\omega t) \)
  \[ \alpha_b = -\frac{G^* u_b}{I} = M \cdot \cos \left( \omega t - \frac{2\pi}{3} \right) \]
  \[ M \in (0 \ldots 1), \quad I \geq \hat{I}^* \]
  \[ \alpha_c = -\frac{G^* u_c}{I} = M \cdot \cos \left( \omega t + \frac{2\pi}{3} \right) \]
Input Current and Output Voltage Formation (2)

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

- Output Voltage Formation:
  \[ \bar{u} = u_{ab} \cdot \alpha_b + u_{ac} \cdot \alpha_c \]
  \[ P_{\text{link}} = P_{\text{input}} \]
  \[ \bar{u} \cdot I = \frac{3}{2} \cdot \hat{U} \cdot \hat{I}^* \]
  \[ \bar{u} = \frac{3}{2} \cdot \hat{U} \cdot \frac{\hat{I}^*}{I} = \frac{3}{2} \cdot \hat{U} \cdot M \]

- 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

\[ U_{LL} = 3 \times 400 \text{ V (50 Hz)} \]
\[ P_0 = 5 \text{ kW} \]
\[ U_0 = 400 \text{ V} \]
\[ f_s = 18 \text{ kHz} \]
\[ L = 2 \times 0.65 \text{ mH} \]

\[ \eta = 98.8\% \text{ (Calorimetric Measurement)} \]
Experimental Results

Ultra-Efficient Demonstrator System

\[ U_{LL} = 3 \times 400 \text{ V (50 Hz)} \]
\[ P_0 = 5 \text{ kW} \]
\[ U_0 = 400 \text{ V} \]
\[ f_s = 18 \text{ kHz} \]
\[ L = 2 \times 0.65 \text{ mH} \]

\[ \eta = 98.8\% \text{ (Calorimetric Measurement)} \]
Comparison of Buck-Type Systems

Six-Switch Rectifier

SWISS-Rectifier
Buck-Type PFC Rectifiers

- 3rd Harmonic Inj. Type
- Diode Bridge Cond. Modulation
Buck-Type PFC Rectifiers

- Three-Switch Rectifier
  → Conduction Losses
SWISS Rectifier vs. Six-Switch Rectifier

- Six-Switch Buck-Type Rectifier
- Swiss Rectifier

![Graph showing comparison between SWISS Rectifier and Six-Switch Rectifier]
Summary of Unidirectional PFC Rectifier Systems

- Block Shaped Input Current Systems
- Sinusoidal Input Current Systems
Block Shaped Input Current Rectifier Systems

- **Boost-Type**
  - \( U > \sqrt{3} \hat{U} \)
  - \( U_{pn} \)

- **Buck-Type**
  - \( 0 < U < \frac{3}{2} \hat{U} \)
  - \( U_{pn} \)

- **Buck+Boost-Type**
  - \( U \geq 0 \)
  - \( U_{pn} \)

- **Controlled Output Voltage**
- **Low Complexity**
- **High Semicond. Utilization**
- **Total Power Factor** \( \lambda \approx 0.95 \)
- **THD** \( I \approx 30\% \)

\[ u_a = \hat{U} \cos(\omega t) \]
**Sinusoidal Input Current Rectifier Systems (1)**

- **Boost-Type**

  + Controlled Output Voltage
  + 3-Level Characteristic
  + Tolerates Mains Phase Loss
  + Lower Control Complexity
  + Power Semiconductors Stressed with Half Output Voltage

- **Unregulated Output**

  + 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
Sinusoidal Input Current Rectifier Systems (2)

**Buck-Type**

\[ 0 \leq U < 3/2 \bar{U} \]

- 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**

\[ U \geq 0 \]

- 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 $\rightarrow$ 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<sub>AC</sub> 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/dm³]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h⁻¹]
Technology Sensitivity Analysis
Based on $\eta$-$\rho$-Pareto Front

- Sensitivity to Technology Advancements
- Trade-off Analysis

Design Space

Performance Space

$s_{\eta \rho} = \frac{\partial \eta}{\partial \rho} \bigg|_P$
Converter Performance Evaluation Based on $\eta$-$\rho$-$\sigma$-Pareto Surface

$\sigma$: kW/$
Converter Performance Evaluation Based on $\eta$-$\rho$-$\sigma$-Pareto Surface

► 'Technology Node'

Technology Node: $(\sigma^*, \eta^*, \rho^*, f_P^*)$
Thank You!
Questions?
Passive Rectifier Systems


Hybrid Rectifier Systems (Electronic Reactance Based)


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


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


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


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

Phase Modular Y-Rectifier (1)


Phase Modular Y-Rectifier (2)


Phase Modular △-Rectifier


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


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


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


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


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


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


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


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


Unidirectional Buck-Type PFC Rectifier Systems

Bidirectional Boost-Type PFC Rectifier Systems (1)


Bidirectional Boost-Type PFC Rectifier Systems (2)


Bidirectional Buck- and Buck-Boost Type PFC Rectifier Systems

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 PTEC 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.