TECHNISCHE UNIVERSITÄT WIEN
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Active Three - Phase Rectifier System Using a Flying Converter Cell

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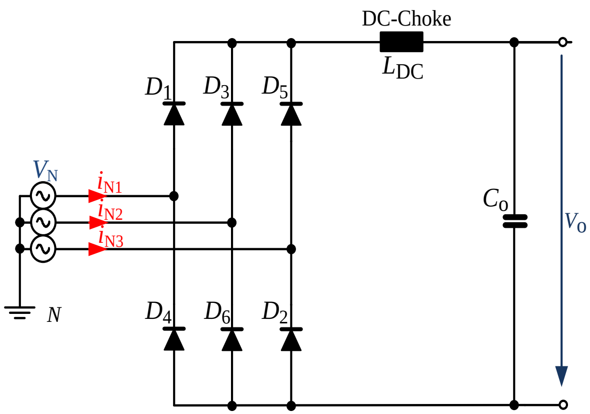
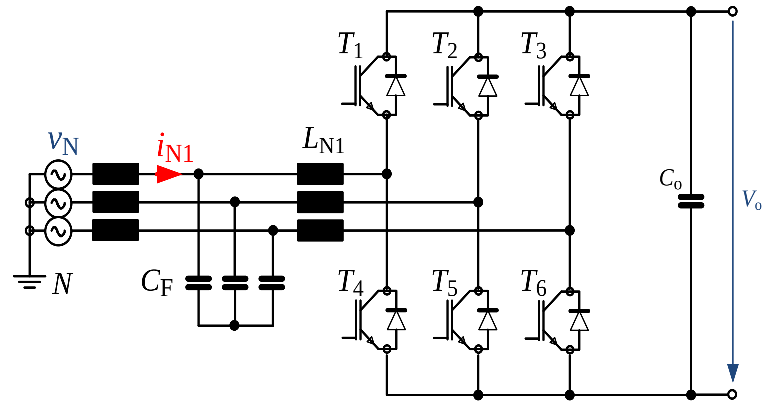
Rectifier Circuits

Passive Rectifier Circuit



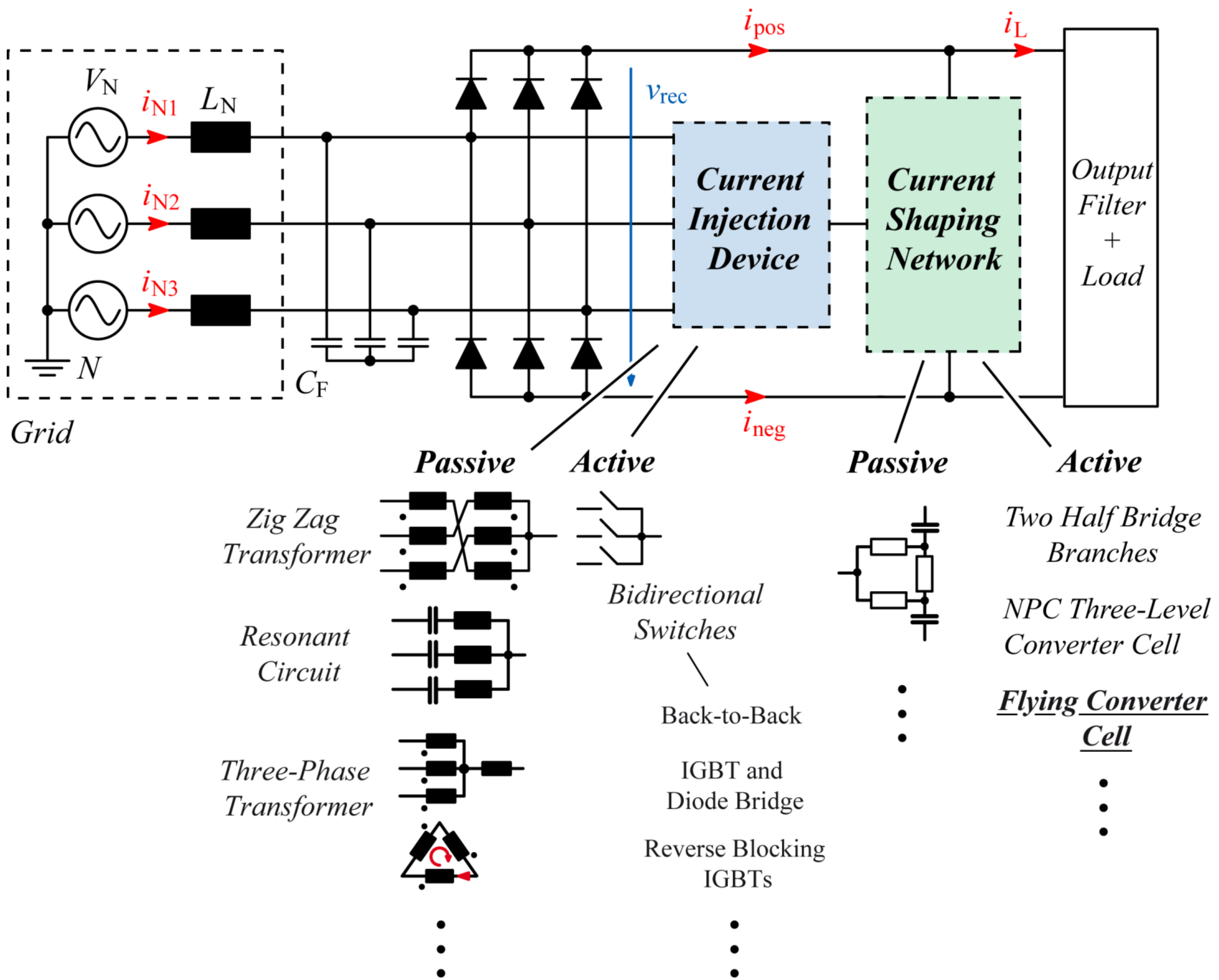
- Widely used in Industry
- Simple and Robust
- High Efficiency
- Poor Input Current Quality THD_i=48%
- Power Factor of 0.9…0.95
- No Active Output Voltage Control

Active 2-Level Rectifier Circuit

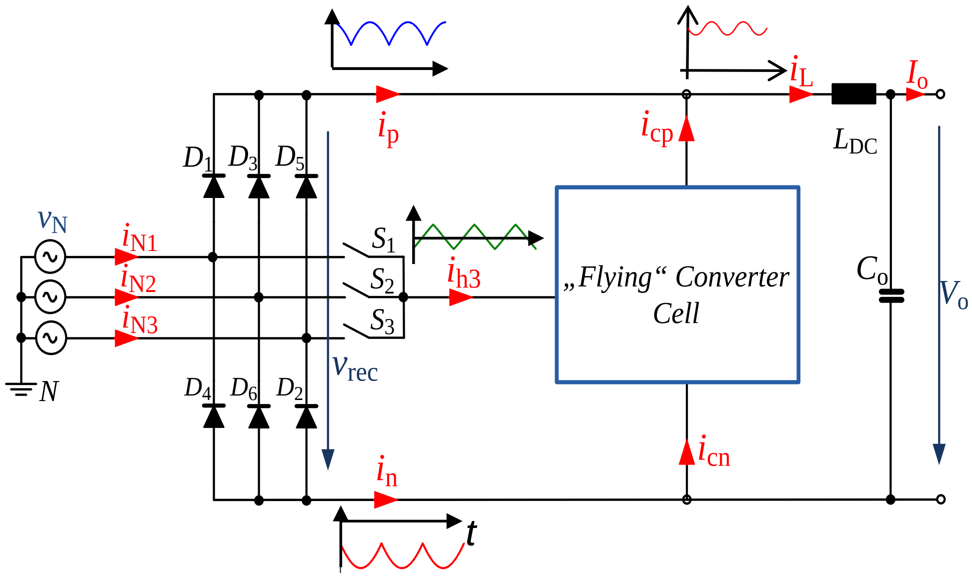


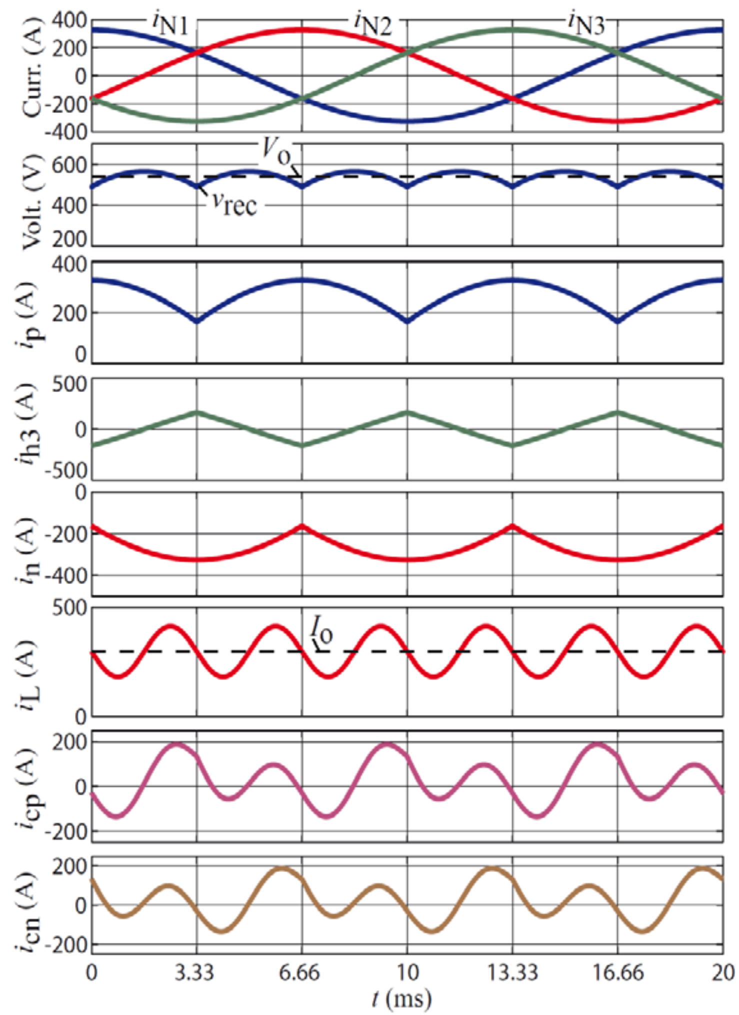
- Industry Standard
- Input Current Quality THD_i < 5%
- High Power Factor
- Controlled Output Voltage
- Active Switches have to Process full Output Power → **Reduced Efficiency**
- **Existing Passive Rectifier Bridges cannot be Extended to the Active 2-Level Rectifier Topology.**

Third Harmonic Injection



“Flying” Converter Cell – Basic Concept





- **Extension of Existing Diode Bridge by Inserting a “Flying” Converter Cell**

  Injects Current into :
  - **One Phase of the Diode-Bridge (i_{h3}).**
  - **Positive / negative Bus-Bar (i_{cp}, i_{cn}).**

- **No Active Control of Output Voltage.**

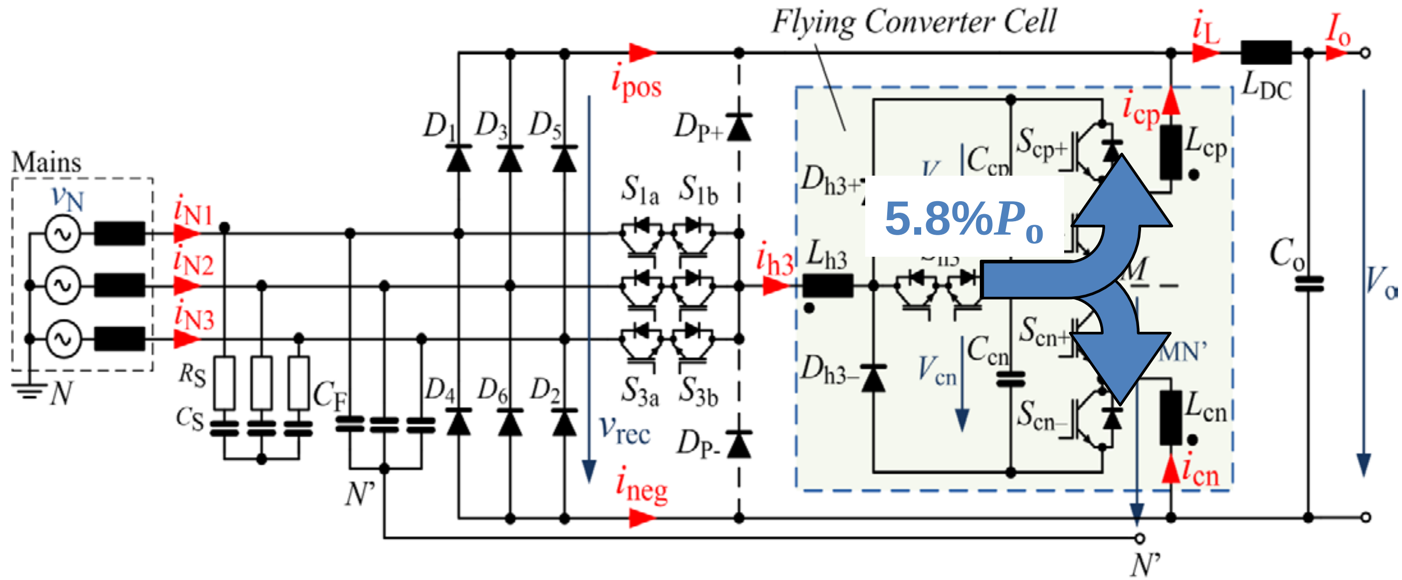
  – Output Voltage is Defined by Mains.

- **Constant Output Voltage:**

  – Output Capacitor C_o can be Considerably Large.

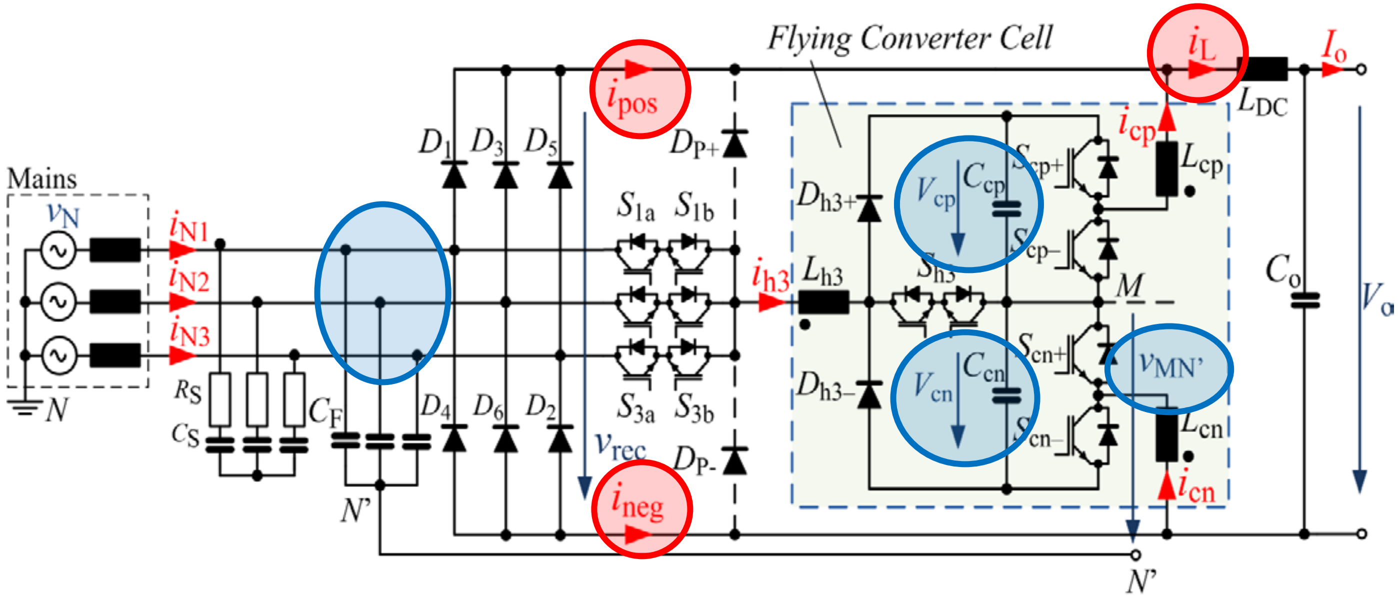
  – No High-Frequency Common Mode Voltage at the DC-Link!

“Flying” Converter Cell – Topology



- **“Flying” Converter Cell: 3 Converter Stages with Common DC-Link:**
  - **FCC DC-Voltage: 2 x 400V at V_{LL}=400V Mains Voltage.**
  - **650V - MOSFETs can be applied.**
  - **FCC Handles only 5.8% P_o, Each Half-Bridge: 16.7% Reactive Power.**
- **Filter Capacitors C_F are Required due to Current Ripple.**
- **Bidirectional Switches $S_{ia,b}$ for Current Injection into Single Phase.**
- **Diodes D_{p+}, D_{p-} Prevent Bidirectional Switches from Damage in Case of Commutation Error.**

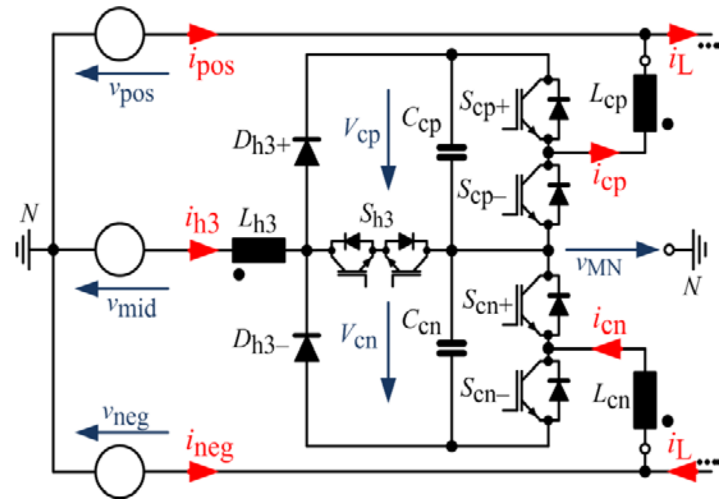
Control of the Converter



- **Required Controllers:**
  - **Current Controller to Achieve Sinusoidal Input Currents.**
  - **Control of Total FCC DC-Voltage.**
  - **Balancing of FCC DC-Voltages.**
- **Required Measurement Signals:**
  - **Currents:** i_{pos}, i_{neg}, i_L
  - **Voltages:** $v_{N1}\ldots v_{N3}$, $v_{MN'}$, V_{cp}, V_{cn}, v_{rec}

Model for Current Controller

Model of Converter



$\varphi_N \in [0 \ldots \frac{\pi}{6}]\ (i_{N1}(\varphi_N) > 0;\ i_{N2}(\varphi_N), i_{N3}(\varphi_N) < 0)$

- **Average mode current control.**
- **System equations:**

$$\delta_{cp} v_{cp} + v_{MN,avg} - v_{pos} = L \frac{di_{cp}}{dt}$$

$$(1 - \delta_{h3})(-v_{cn}) + v_{MN,avg} - v_{mid} = -L \frac{di_{h3}}{dt}$$

$$(1 - \delta_{cn})(-v_{cn}) + v_{MN,avg} - v_{neg} = -L \frac{di_{cn}}{dt}$$

- **Idea is to control i_{pos} and i_{neg}**
- **i_L is disturbance input.**
- **Current i_{h3} is defined by:** $i_{cp} = i_{cn} + i_{h3}$
- **Using** $i_{pos} = i_L - i_{cp}$ **and Applying Laplace Transformation:**

$$sLi_{pos} = sLi_L - \delta_{cp} V_c - V_{MN,avg} + v_{pos}$$

- **Feed-Forward Signal:**

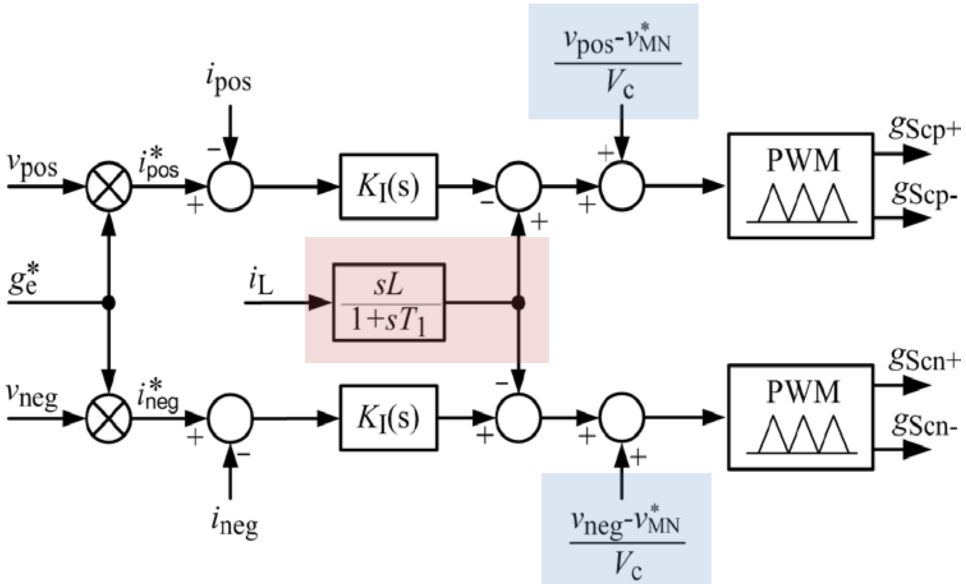
$$\delta_{cp} = \tilde{\delta}_{cp} + \frac{v_{pos} - V_{MN,avg}}{V_c} + s\frac{Li_L}{V_c}$$

- **Simple Model:**

$$G_I(s) = \frac{i_{pos}(s)}{\tilde{\delta}_{cp}(s)} = -\frac{V_c}{sL}$$

Structure of Current Controller

- **Structure of Current Controller:**



$$\delta_{cp} = \tilde{\delta}_{cp} + \frac{v_{pos} - V_{MN,avg}}{V_c} + s\frac{Li_L}{V_c}$$

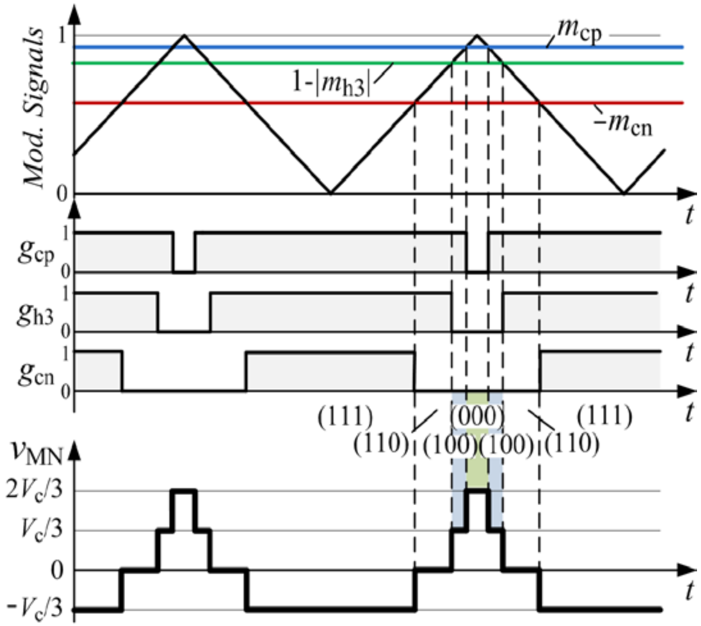
- **Generation of Reference Currents using equivalent Conductance:**

$$g^*_e = \frac{P_{in}}{V^2_{N1,rms} + V^2_{N2,rms} + V^2_{N3,rms}}$$

- **Measurement of Power Transferred to Load:**
  - **At the Input:** $p(t) = v_{N1}(t)i_{N1}(t) + v_{N2}(t)i_{N2}(t) + v_{N3}(t)i_{N3}(t)$
  - **After Rectifier Diodes:** $p(t) = v_{rec}(t)i_L(t)$

Modulation

Carrier Signals in Phase

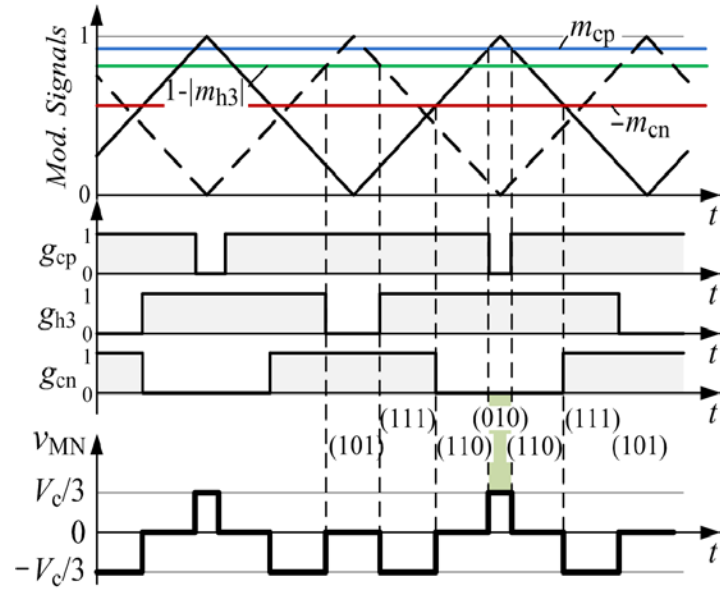


- **Higher FCC Mid-Point Voltage.**
- **Reduced Current Ripple:**

$$\Delta i_{c\frac{p}{n},\mathrm{pkpk}} = \frac{V_c M^2}{4 f_s L}$$

$$\Delta i_{h3,\mathrm{pkpk}} = \frac{V_c \frac{M}{2}\left(1-\frac{M}{2}\right)}{f_s L}$$

Carrier Signals 180° out of Phase



- **Reduced FCC Mid-Point Voltage.**
- **Increased Current Ripple:**

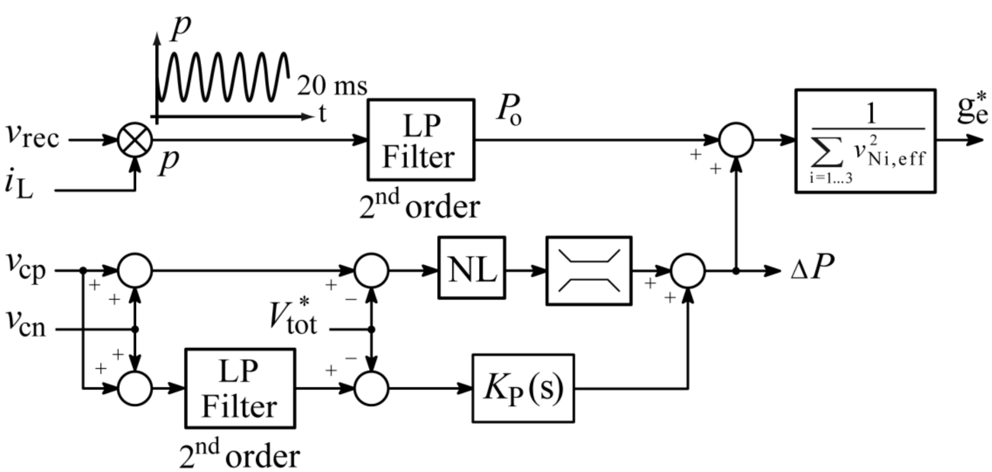
$$\Delta i_{c\frac{p}{n},\mathrm{pkpk}} = \frac{V_c\left(M\frac{\sqrt{3}}{2}-\frac{1}{3}\right)\left(1-M\frac{\sqrt{3}}{2}\right)}{f_s L_c}$$

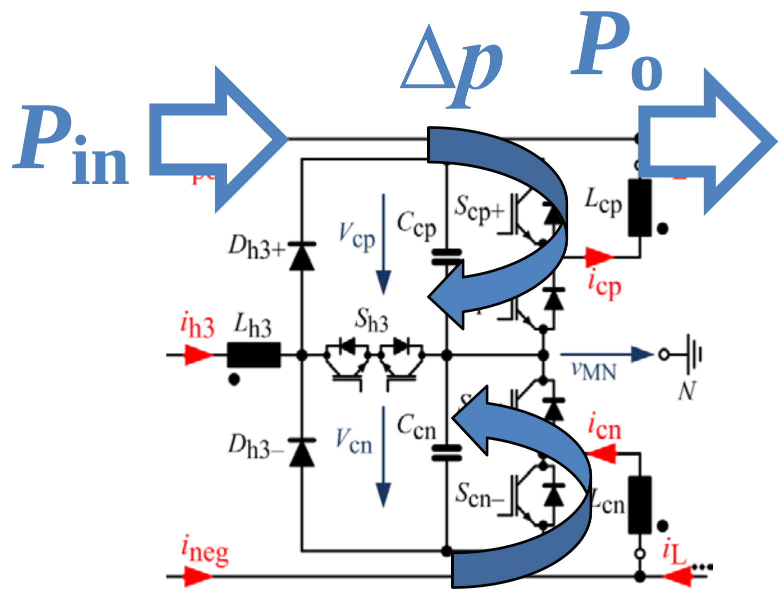
$$\Delta i_{h3,\mathrm{pkpk}} = \frac{V_c\frac{1}{3}\left(1-M\frac{\sqrt{3}}{2}\right)}{f_s L_c}$$

1 : 1.5!

Control of FCC DC-Voltage

- **Control of Total FCC DC-Voltage by Voltage Controller:**
  - **Without Disturbing Mains Current.**
- **Balancing of FCC DC-Voltages by Dedicated Controller.**

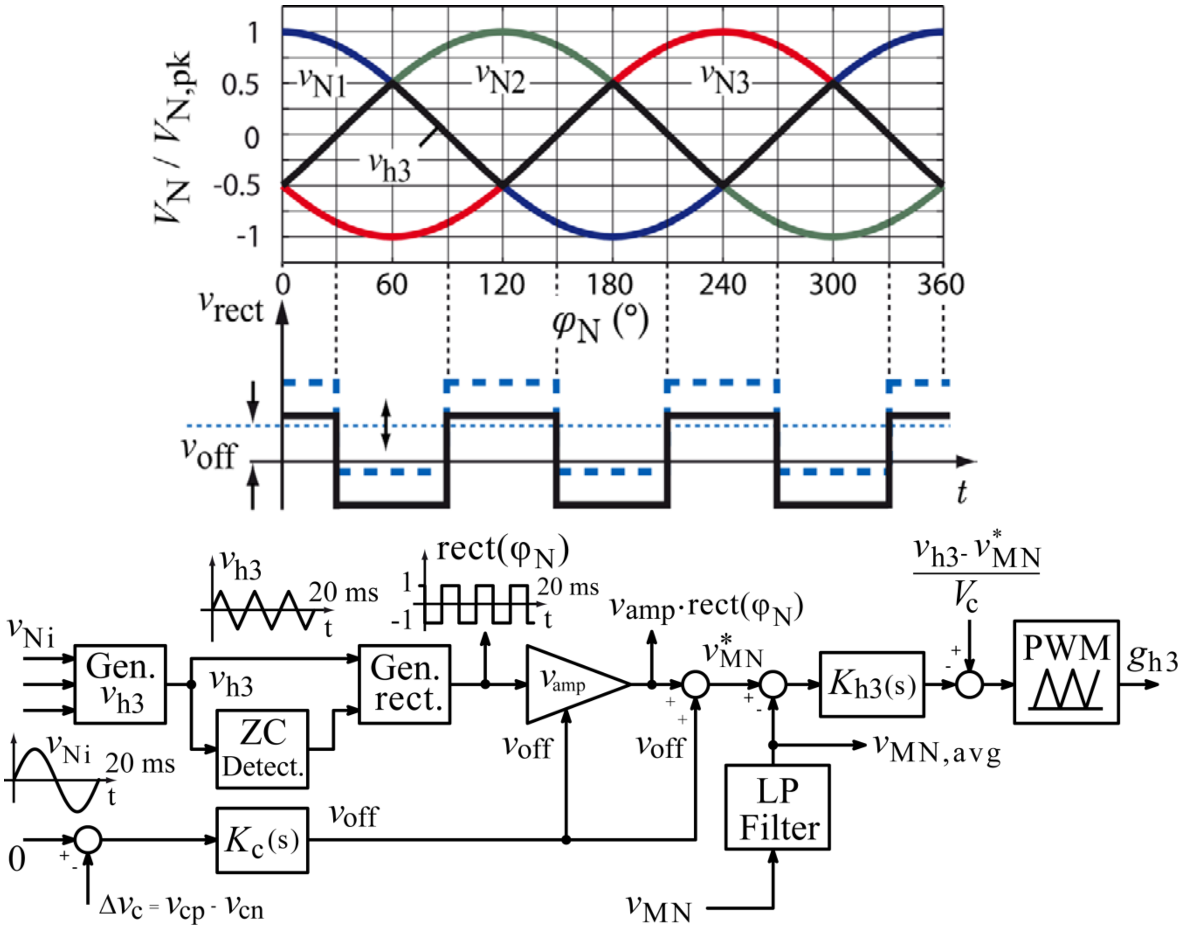




- **Control by Increasing/Reducing the Input Power:**
  - **Remaining Power is Transferred into FCC Capacitors.**

Balancing of DC-Voltages

- **Different Mid-Point Voltages v_{MN} Show Different Currents in V_{cp} and V_{cn}.**
- **Mid-Point Voltage Variations are Used for Balancing.**
- **Without Disturbing Input Currents.**

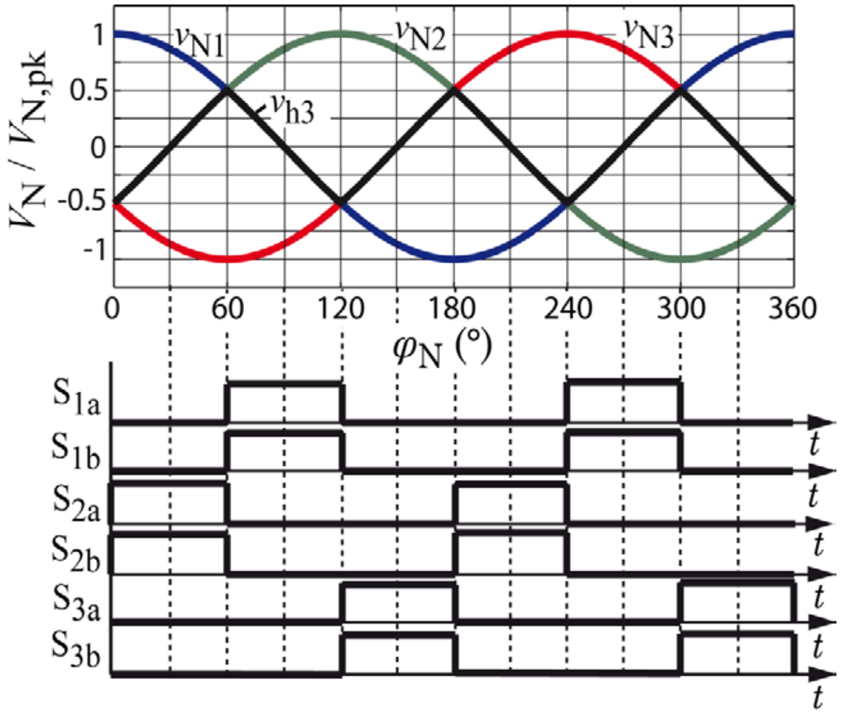


- **Rectangular Shaped Mid-point Voltage Variations.**
- **Capacitors are Charged / Discharged Depending on the Offset v_{off}.**
- **Three-Level Bridge-Leg Controls the Midpoint-Voltage.**

Bidirectional Switches for Current Injection

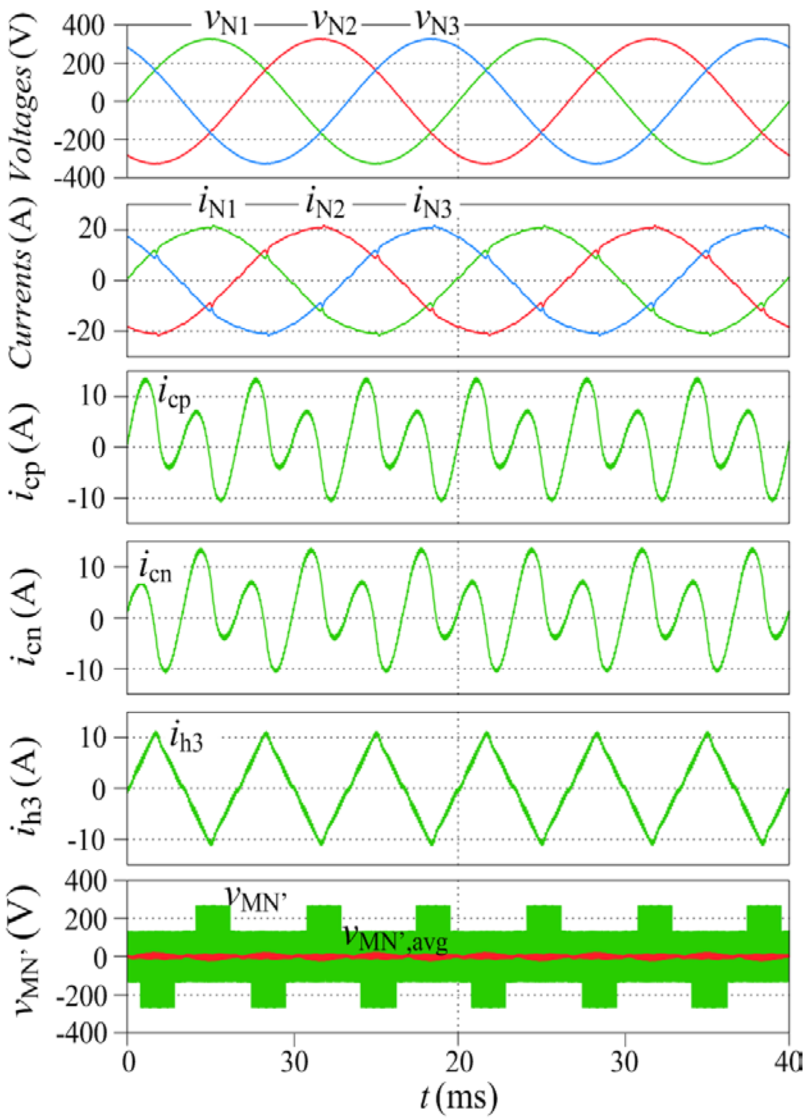
- **Back-to-back Connected IGBTs are Used.**
  - **Using 1200V IGBTs-**
- **Switches are Turned on only Twice a Period:**
  - **Can be Optimized for Low Conduction Losses.**
- **Four Step Commutation Sequence is Required.**

Switching Scheme



- **Switching Instants are Essential for High Input Current Quality.**
- **Analog Comparators in Combination with a CPLD.**
- **Complex Multi-Device Commutation:**
  - **Rectifier Diodes**
  - **Bidirectional Switches**
  - **Filter Capacitors**

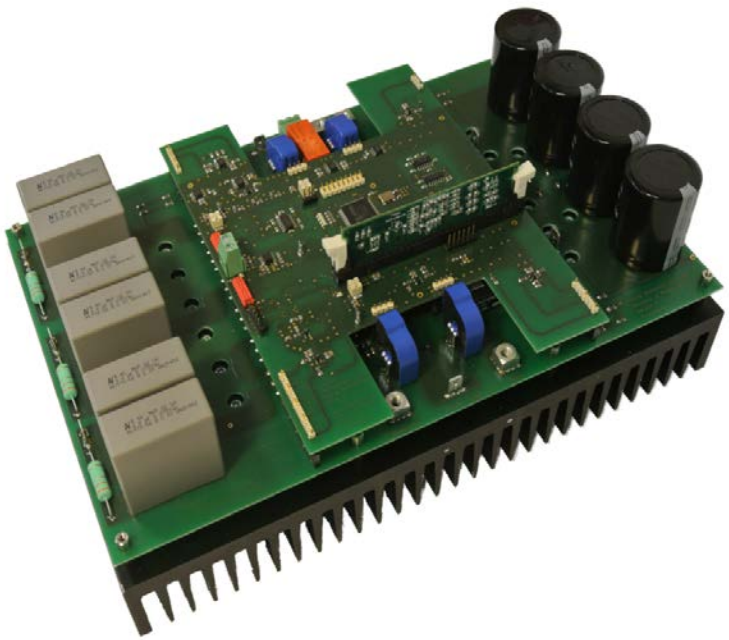
Simulation Results

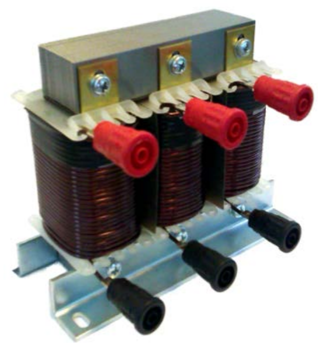


- **System Parameters:**
  V_{LL}=400 V, f_N=50 Hz, P_o=10 kW, $I_{N,rms}$=14.5 A, f_S=10 kHz, L_{h3}=L_{cp}=L_{cn}=3 mH

- **Average Midpoint Voltage is Controlled to Zero.**

Constructed Laboratory Prototype





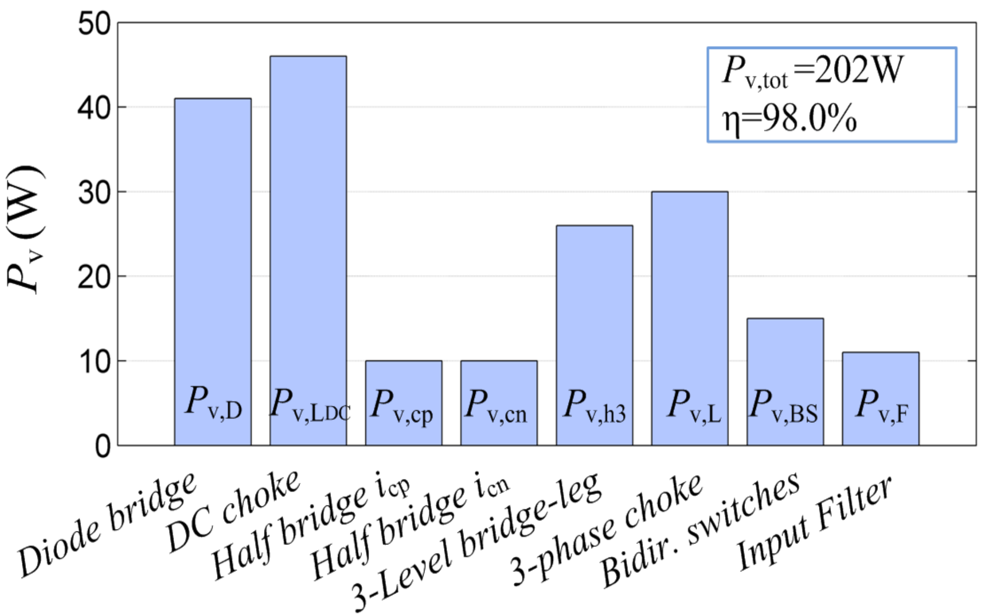
Specifications:

V_{LL}	400 V_{rms}
f_N	50/60 Hz
f_s	10 kHz
V_{cp}, V_{cn}	2 x 400 V_{DC}
P_o	10 kW
L_{cp}, L_{cn}, L_{h3}	2.6 mH

FCC: 300 mm x 200 mm X 97 mm

- **Scaled Demonstrator for Higher Power Ratings (e.g. 200 kW).**
  - **Rather Small Switching Frequency of 10 kHz is Chosen.**
  - **Small Switching Frequency is a Challenge for Controllers.**
- **Coupled Three-Phase Choke is Used.**
- **Prototype is not Optimized (Efficiency, Power Density, etc.)**

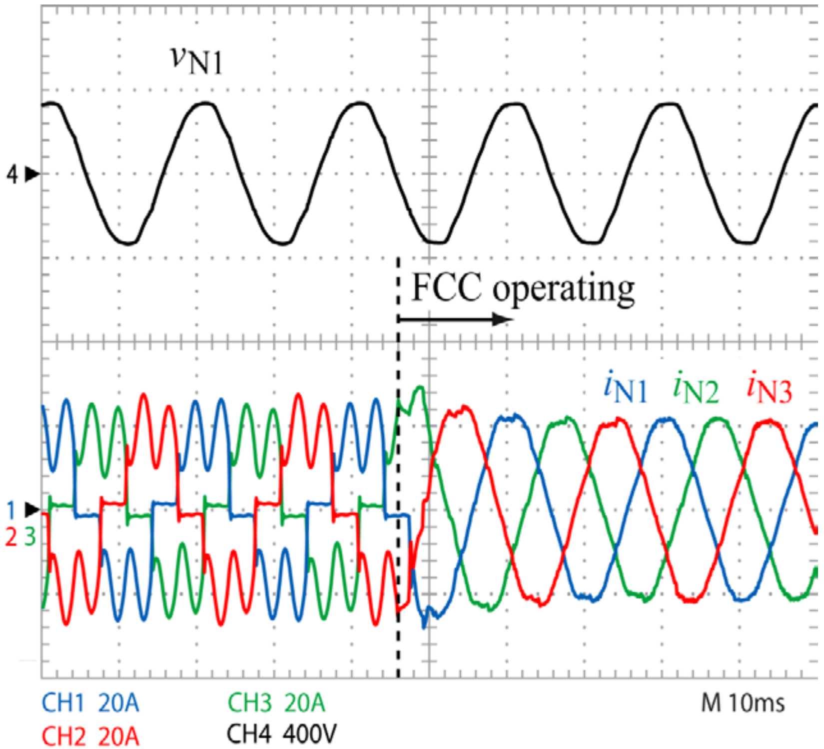
Calculated System Losses



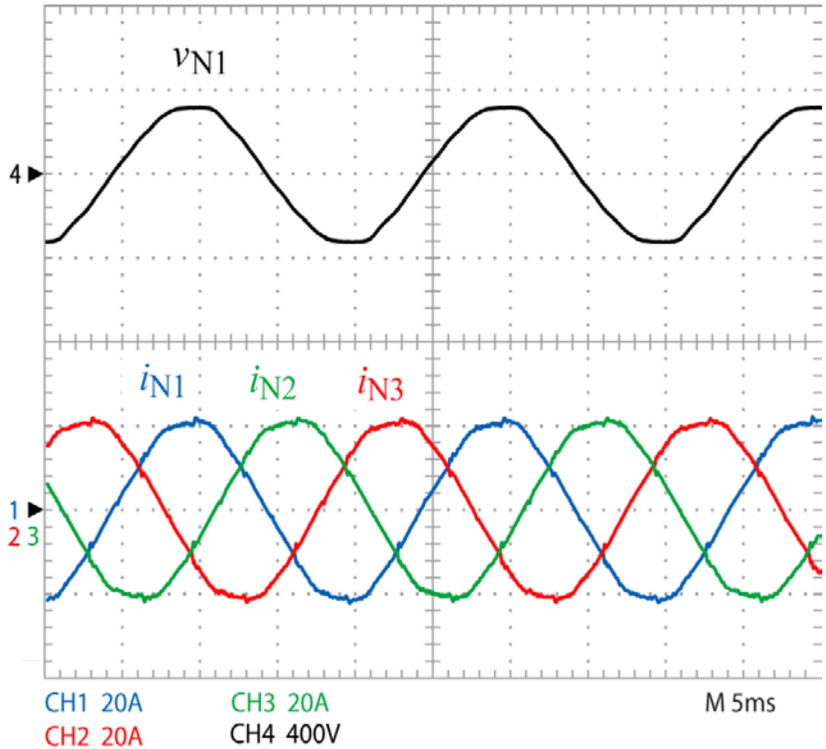
- **Losses are Dominated by Diode-Bridge and DC-choke (Handle 95% of P_o).**
- **FCC Losses are Mainly at 3-Level Bridge-Leg and 3-Phase Choke:**
  - **Primarily Switching Losses, Reduction by Application of SiC Diodes.**
  - **Reduction of Choke-Losses by Better Material in 3-Phase Choke.**

Experimental Results I

Transition
Diode Mode → to Active Current Shaping



Continuous Operation

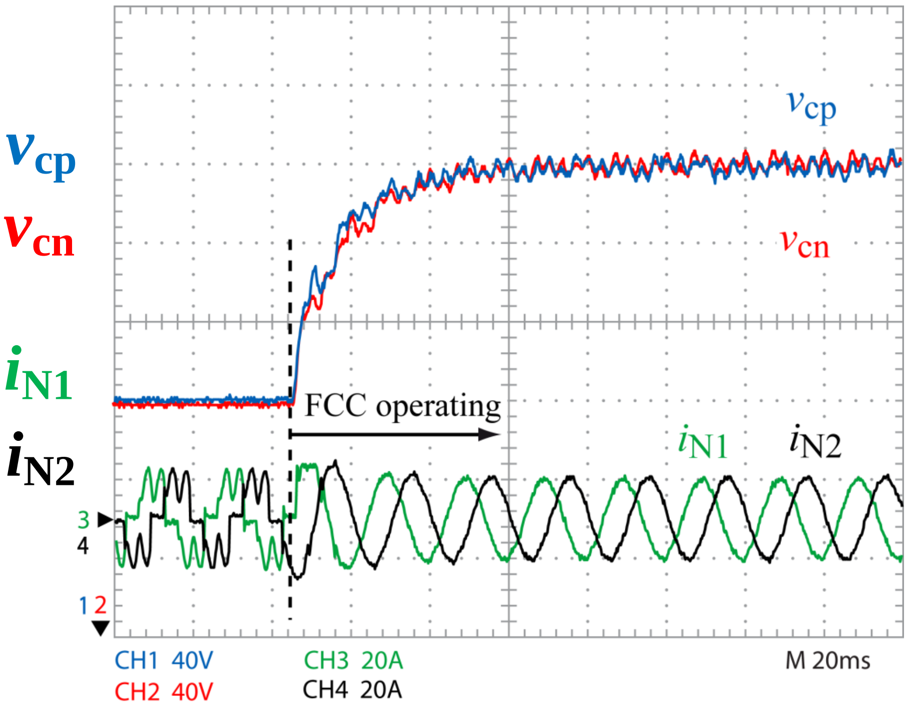


P_o=10kW, THD$_i$=2.3%, λ=0.998

No Nameable Distortions in Current Shapes.

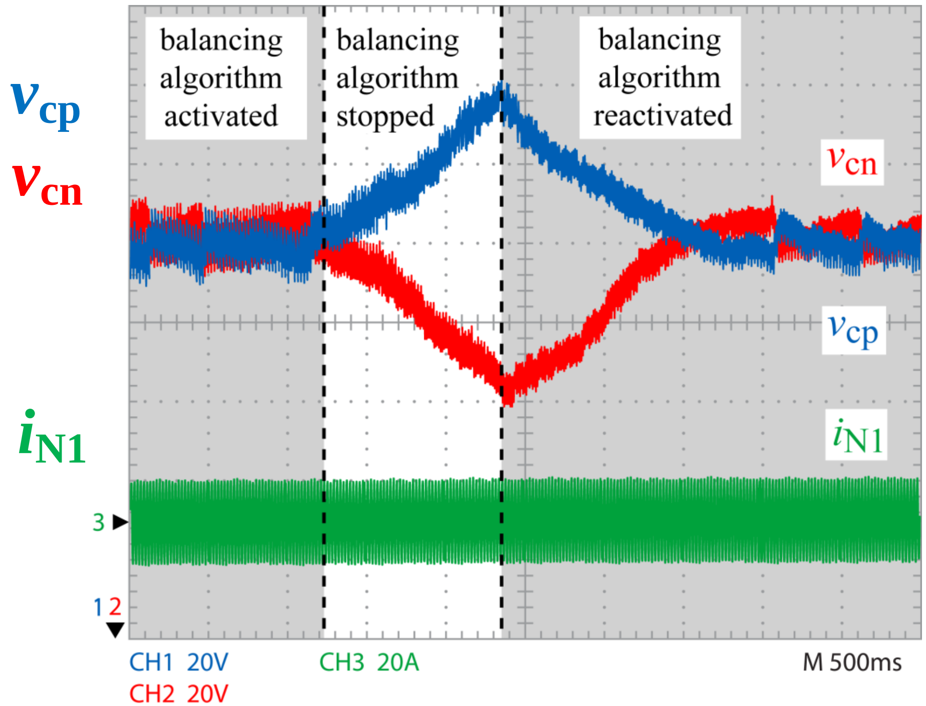
Experimental Results II

Startup of Operation



P_o=10kW, V_{LL}=400V, f_N=50Hz

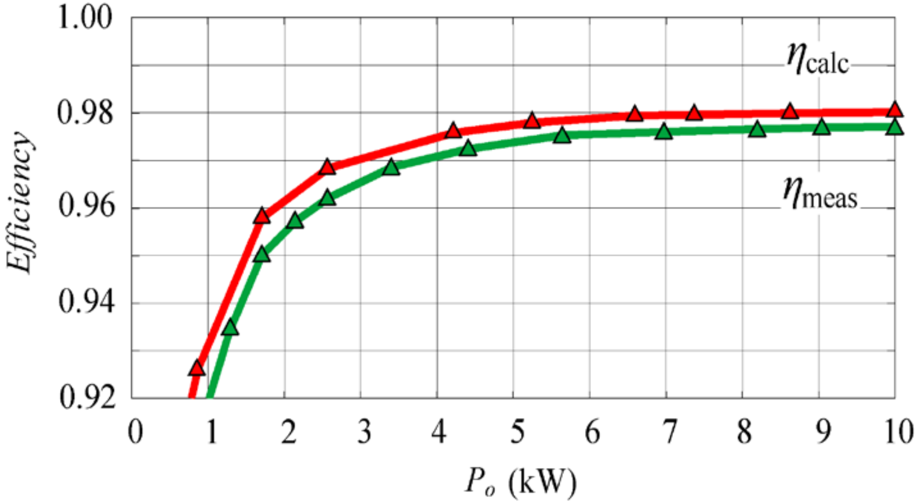
Balancing



P_o=10kW, V_{LL}=400V, f_N=50Hz

Experimental Results III

Measured Efficiency:

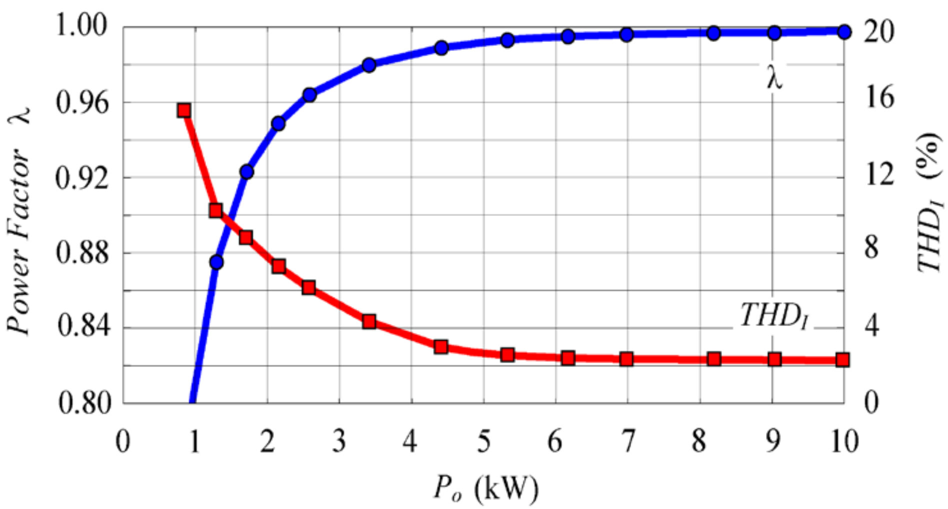


η_{meas} = 97.5%

Measured Efficiency is Slightly Smaller:

– **Higher Losses in 3-Phase Choke.**

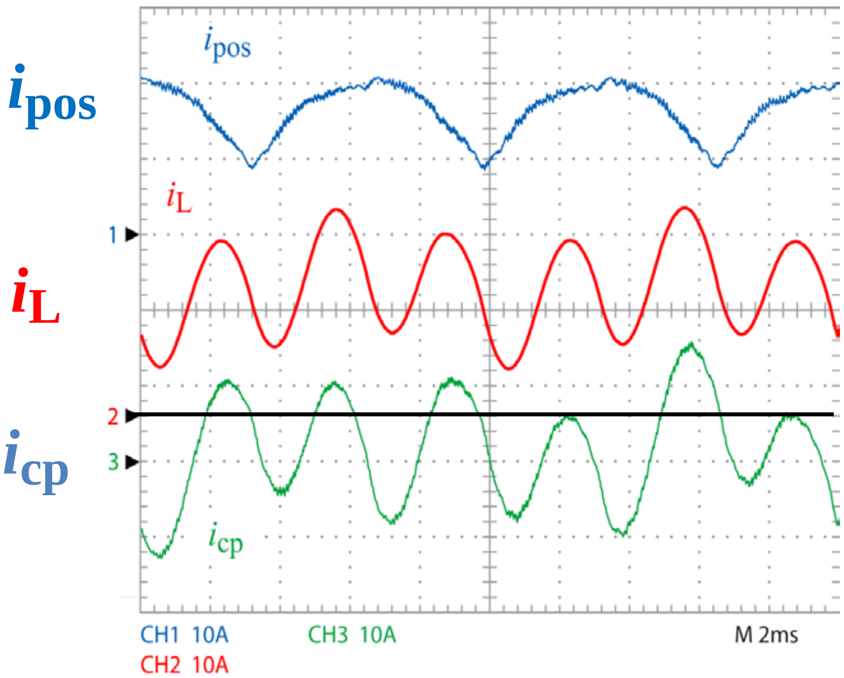
Measured Power Factor / Input Current Quality:



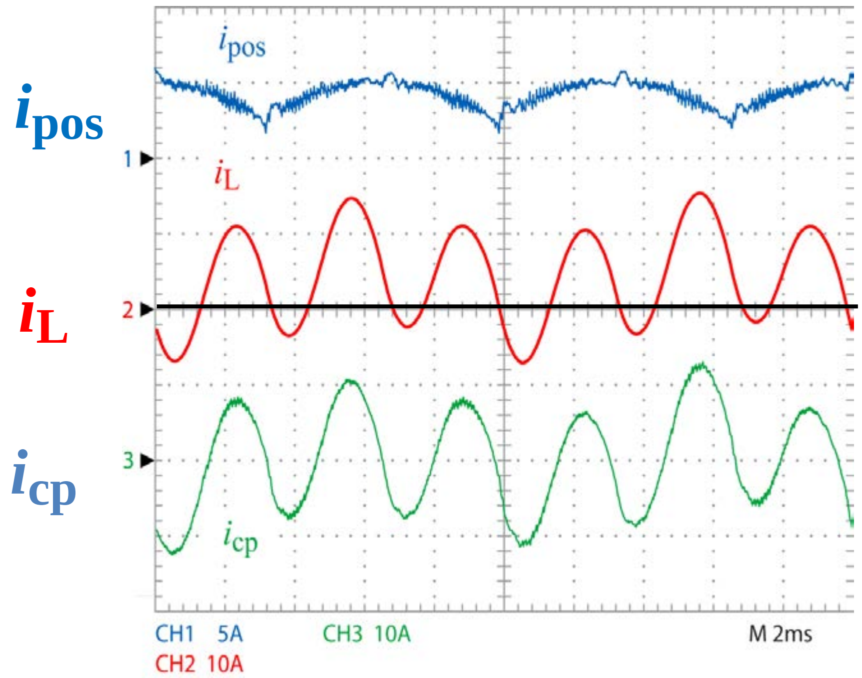
- **Very Good Input Current Quality:**
  - **Also at Partial Load.**

Experimental Results, Partial Load

Operating at P_0 = 10 kW



Operating at P_0 = 2.6 kW



- **DC-choke Current gets Slightly Negative at Light-Load Condition.**
- **Results in a Circulating Current; Reduces Efficiency at Light Load.**
- **FCC can be Turned OFF at Light Load Condition.**

Conclusion

- **Operating Principle of "Flying" Converter Cell is Verified:**
  - **Allows Extension of Existing Diode Bridge to Low Harmonic Input Stage**
  - **Under Retention of the DC-Choke and the Large Output Capacitor.**
  - **Applications Where Controlled DC-Link Voltage is not Required.**
- **Good System Performance:**
  - **Processes Only a Small Amount of Output Power → Efficiency of 97.5%.**
  - **No Intrinsic Input Current Distortion → Very Good THDi also at Light Load.**
- **Suitable Control of Rectifier System is proposed**
  - **Three controllers are required.**
  - **Implemented in a DSP and Small CPLD.**
- **No High-Frequency Common Mode Voltage at the DC-Link.**

Thank you!

Questions?