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Novel Isolated 99+% Efficiency 3- Φ PFC Rectifier Concepts

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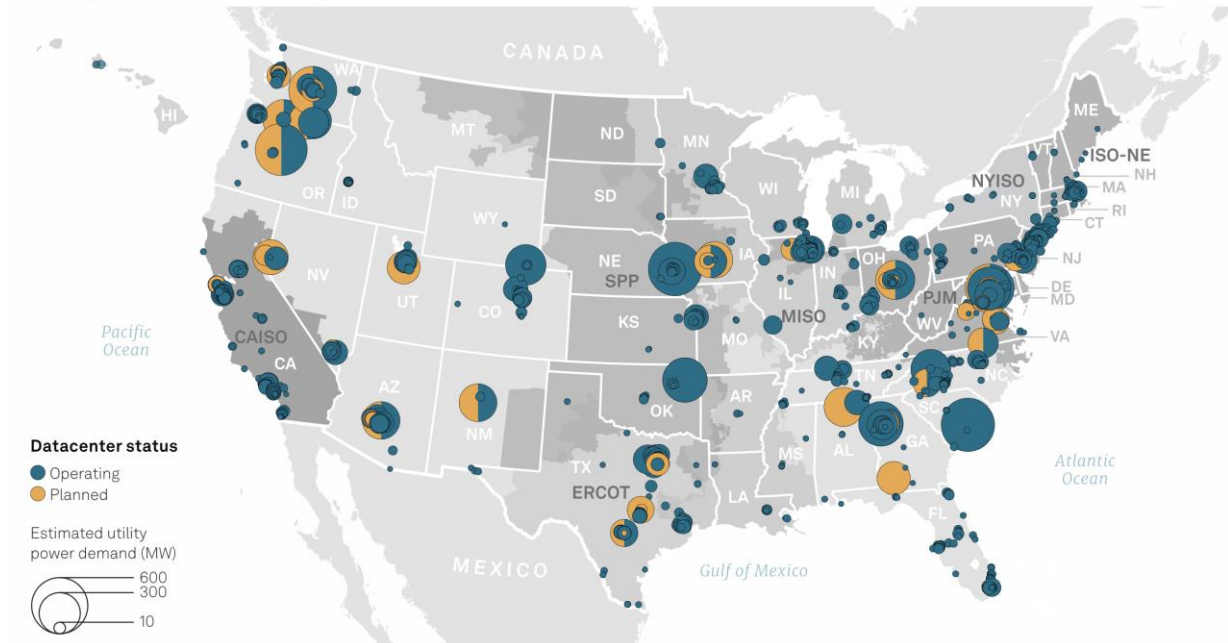
Outline

- ▶ *Introduction*
- ▶ *Quasi-Single-Stage Isol. IAF PFC Rectifier*
- ▶ *Single-Stage Isol. IAF PFC Rectifier*
- ▶ *Single-Stage Isol. Full-Matrix-Type PFC Rectifier*
- ▶ *Outlook*

Future Gigawatt-Scale Datacenters

- **“Explosion” of AI — « Hyperscale » Datacenters Evolving into « Exascale »**
- **Gigawatt Power Levels Despite High Power Usage Effectiveness (PUE)**

AI is expected to drive more power demand from datacenters

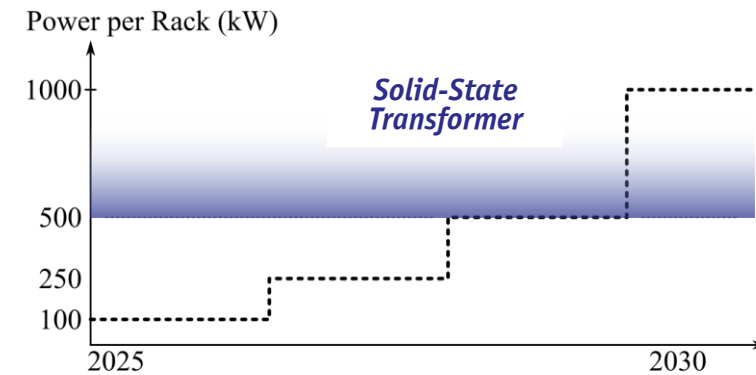
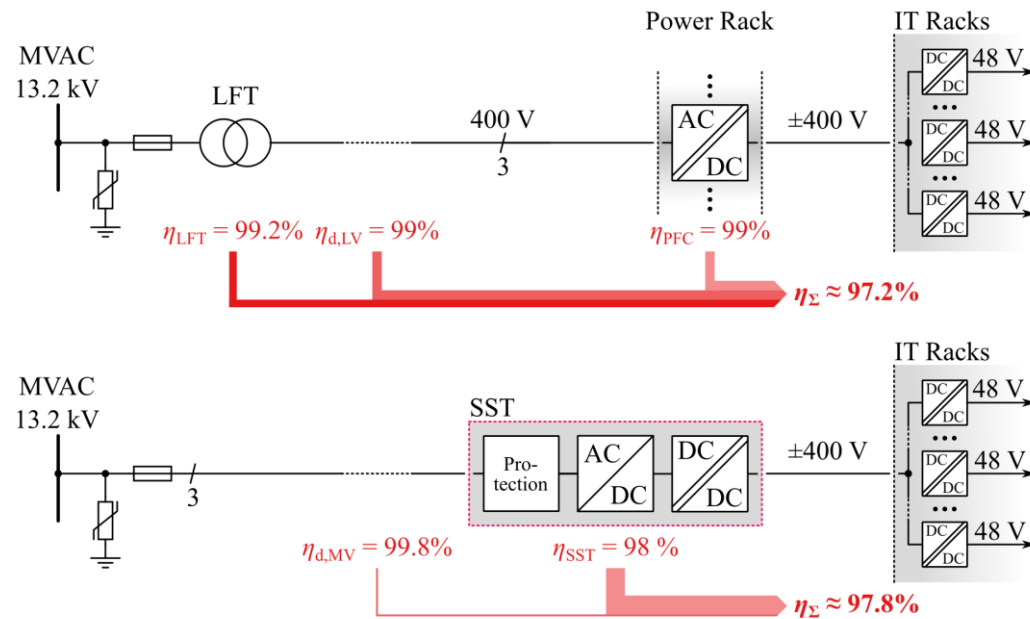


Sources: S&P Global Market Intelligence; 451 Research; S&P Global Commodity Insights

- **Plans for 2.5 ... 6 Gigawatt Campuses Co-Located w/ Nuclear Power Plants —** 
- **Collaboration w/ Utilities — Datacenters as Responsive Loads for Balancing Solar & Wind Power**

Future $\pm 400V_{DC}$ Power Delivery Architecture

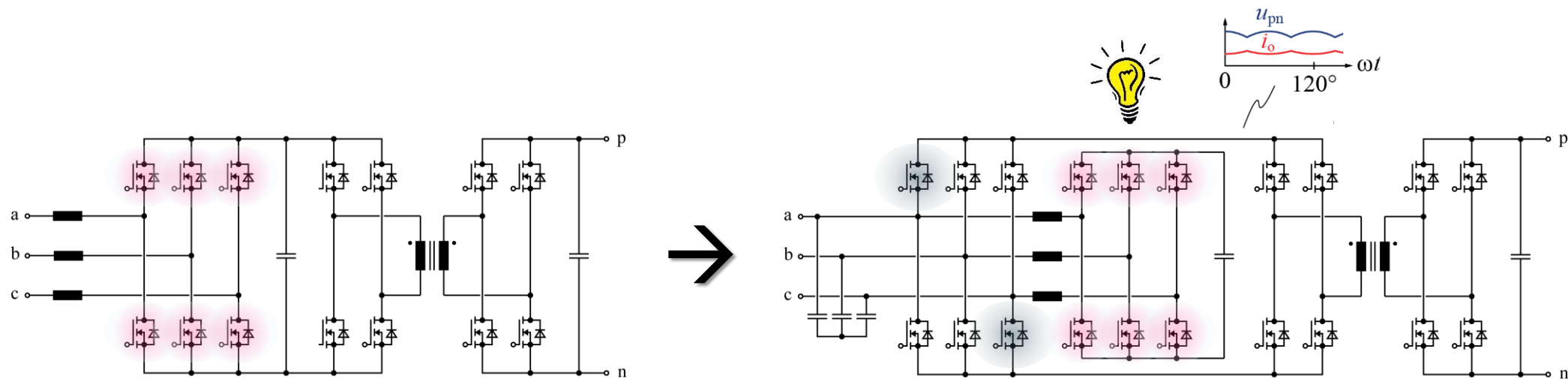
- **Near Term** — $400V_{AC}$ or $480V_{AC}$ or $600V_{AC}$ Distribution & AC/DC Power Racks incl. Battery Buffer Units
- **Mid Term** — Medium-Voltage AC Distribution & AC/DC Solid-State Transformers (SSTs) Replacing Power Racks



- **IT Rack Power Levels Expected to Reach 1MW by 2030**
- **Medium-Voltage AC Supplied SST Largely Eliminates Distribution Losses / $\eta_d = 98,9\%$ of $400V_{AC}$ System**

3- Φ Quasi-Single-Stage Isolated AC/DC Power Conversion

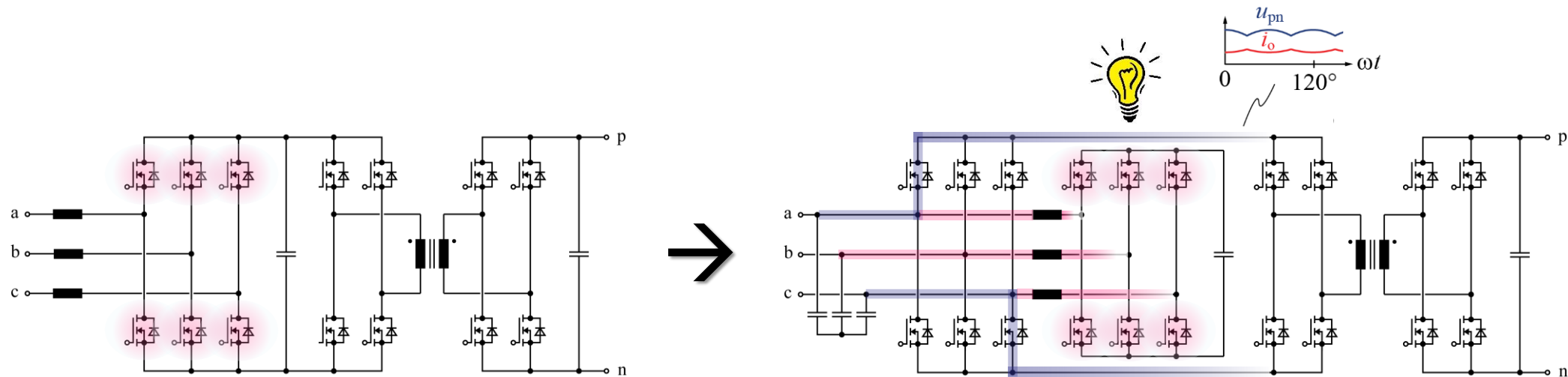
- *Conventional Two-Stage Isolated AC/DC Conversion — 3- Φ Boost-Type PFC Rectifier & DC/DC-Stage*
- *Quasi-Single-Stage Approach — Synchronous 3- Φ Diode Rectifier & Explicit Parallel-Connected Active Filter*



- *DC/DC-Stage Supplied w/ Uncontrolled Six-Pulse-Shaped DC-Voltage*
- *Mains Freq. Switching of Synchron. 3- Φ Diode Rectifier — Large Chip Areas / Very Low Conduction Losses*

3- Φ Quasi-Single-Stage Isolated AC/DC Power Conversion

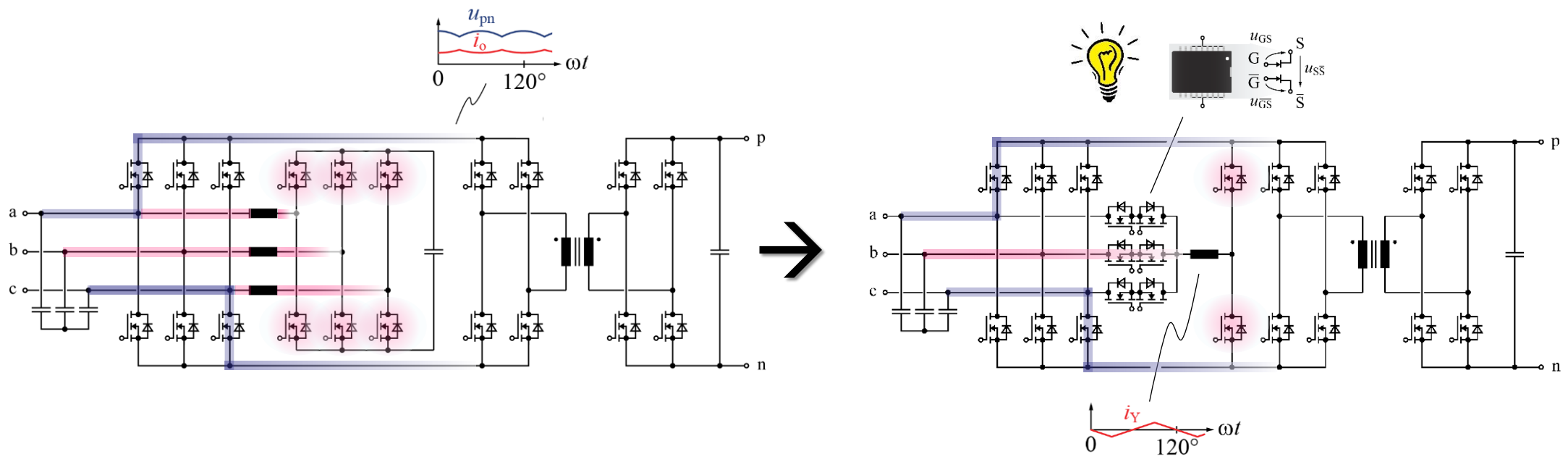
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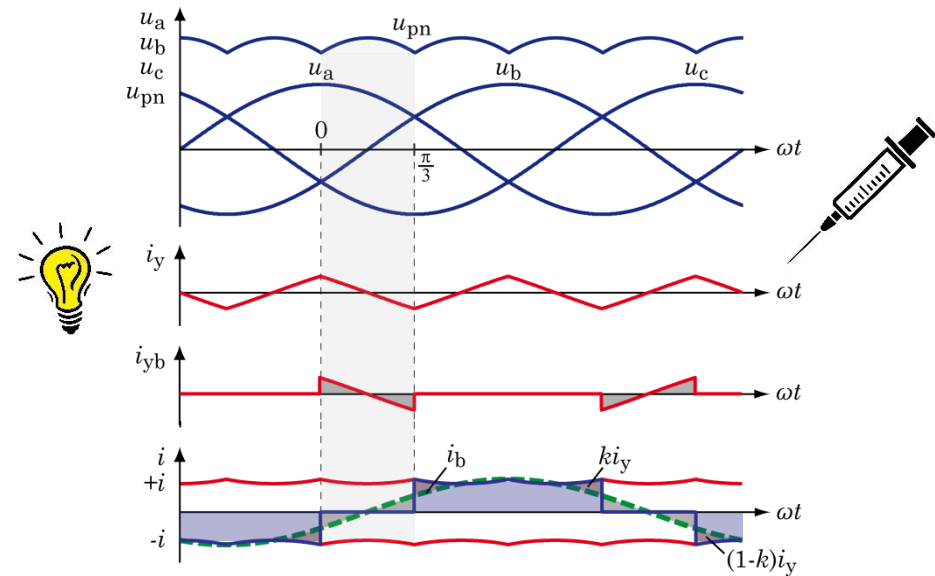
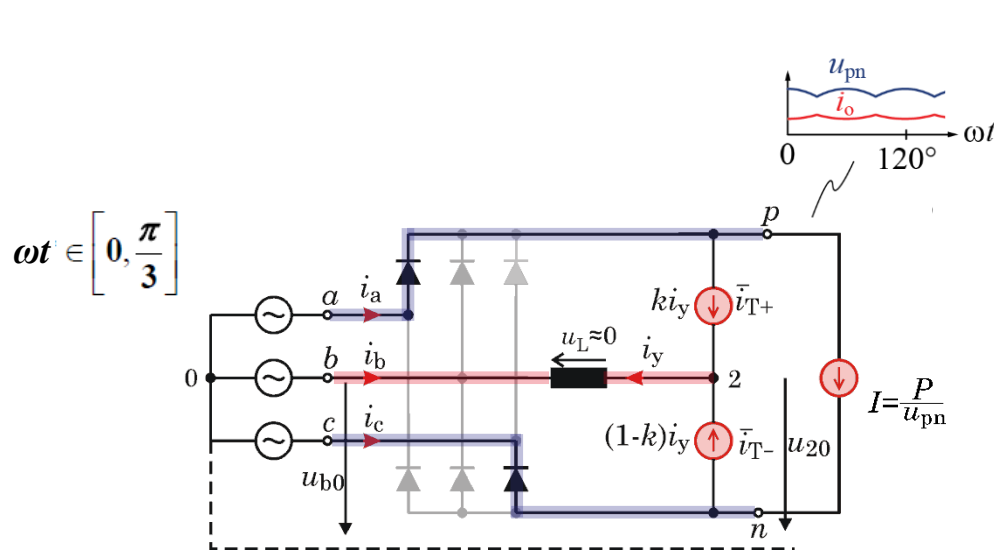
- Synchronous 3- Φ Diode Rectifier Front-End & Explicit Parallel-Connected Active Filter
- 3- Φ Diode Rectifier & Low-Complexity Integrated Active Filter (IAF)



- IAF Employs Single HF Sw. Bridge-Leg / Single Inductor / Phase Selector Switches (Monolithic Bidir. GaN Devices)
- Mains Freq. Switching of Synchr. 3- Φ Diode Rectifier — Large Chip Areas / Very Low Conduction Losses

3-Φ IAF Front-End Operating Behavior

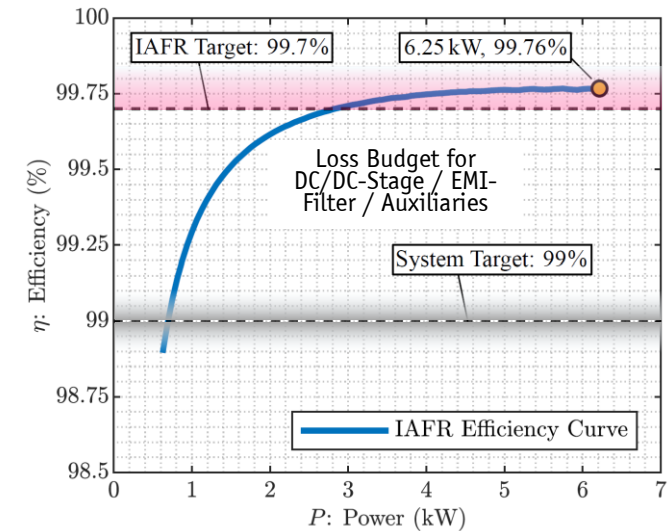
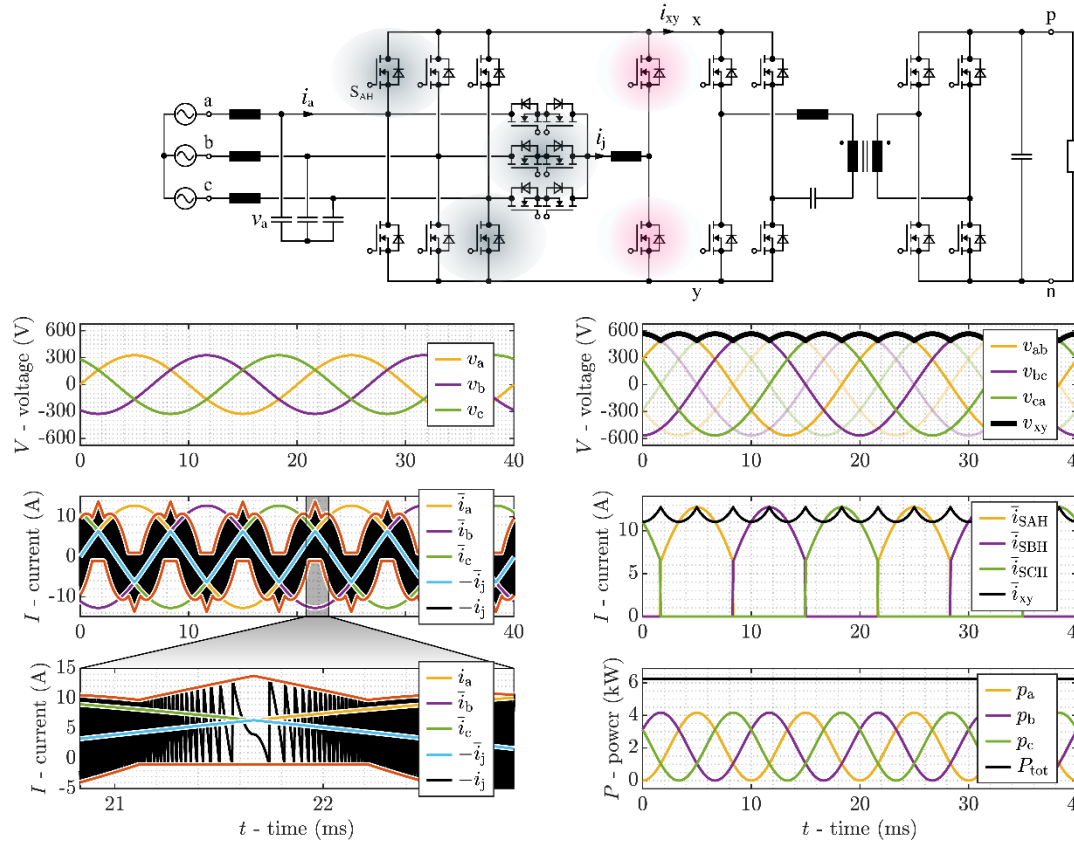
- 3-Φ Diode Rectifier Front-End Generates "DC" Output Voltage w/ $6 \times f_{\text{mains}}$ Pulsation
- Low-Amplitude 3rd Harmonic Current Inj. for Sinusoidal Mains Current Shaping



- Sinusoidal Mains Phase Currents @ Const. Power Load
- Low Switching Transistor T_+ and T_- Current Stress / Low Switching Losses

3- Φ IAF Rectifier @ Symmetric Mains

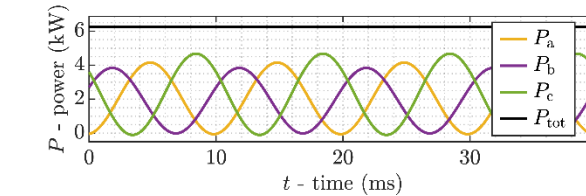
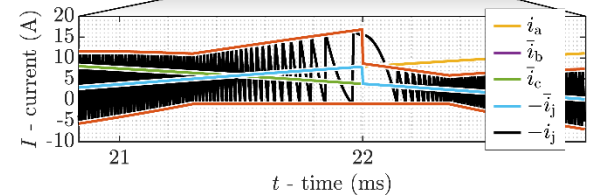
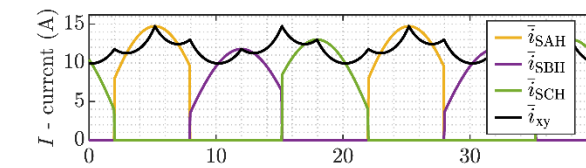
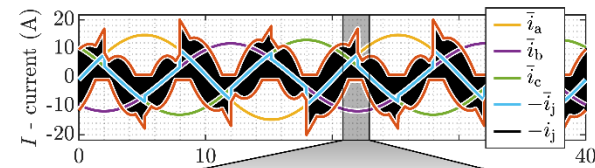
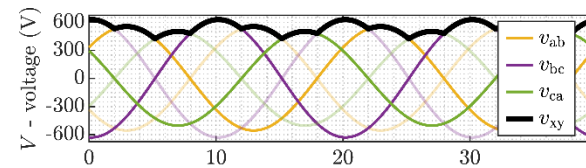
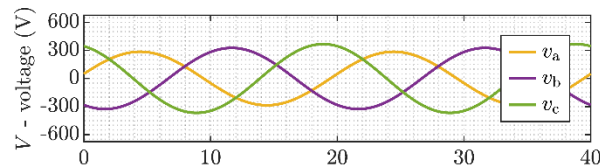
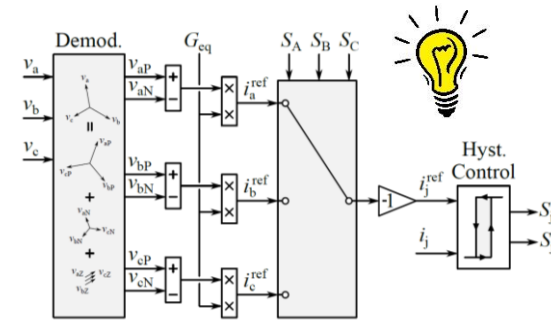
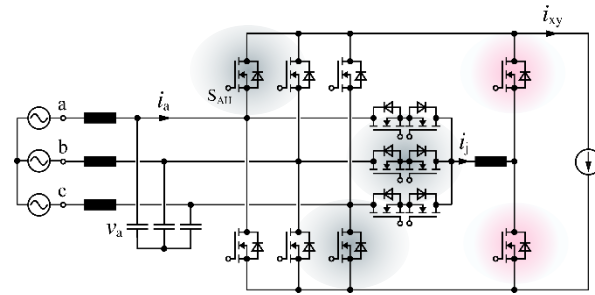
- Simulation of 6.25kW Rated Power @ 3- Φ 400V_{AC} Input $\pm 10\%$ & 400V_{DC} Output
- Loss Budget of 0.3% Assigned to IAF Rectifier Stage | 0.5% DC/DC-Stage | 0.2% EMI Filter & Auxiliaries



- ZVS / TCM Largely Eliminates Sw. Losses of IAF Bridge-Leg
- Series Resonant Operation of DC/DC-Stage @ 99.5% Efficiency & 15kW/dm³ Power Density

3- Φ IAF Rectifier @ Unbalanced Mains

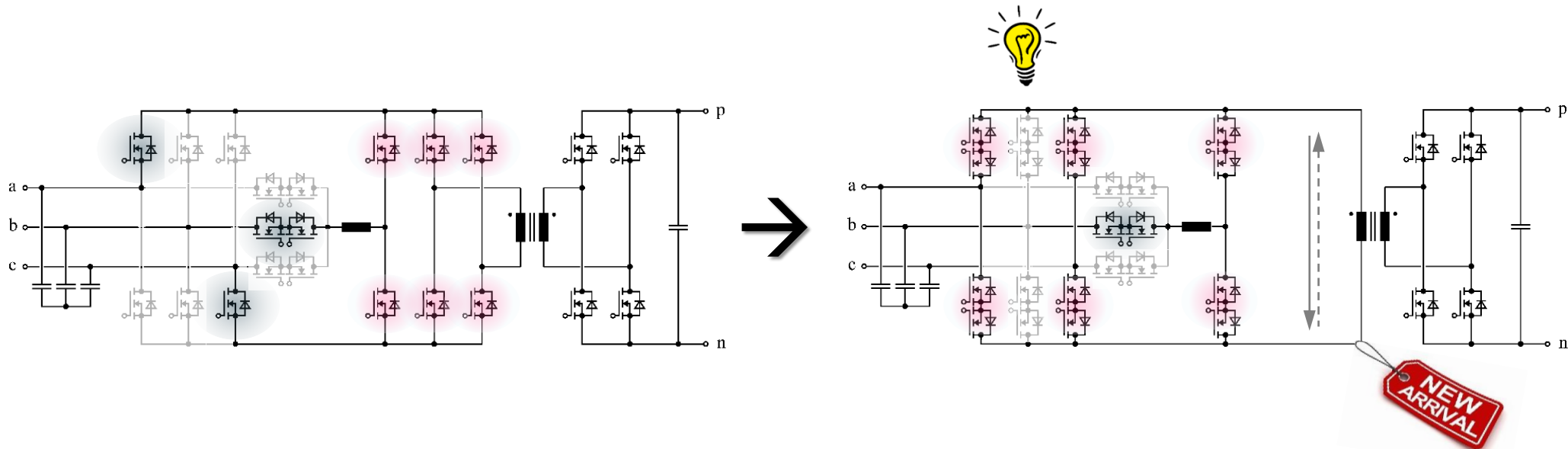
- **Input Current Control Based on Instantaneous 3- Φ Power Theory**
- **Slight Phase-Shift of Mains Phase Voltages and Phase Currents**



- **Instantaneously Const. (!) Power Supplied to DC Output @ Sinusoidal (!) Mains Currents**

3- Φ Single-Stage Isolated IAF AC/DC Power Conversion

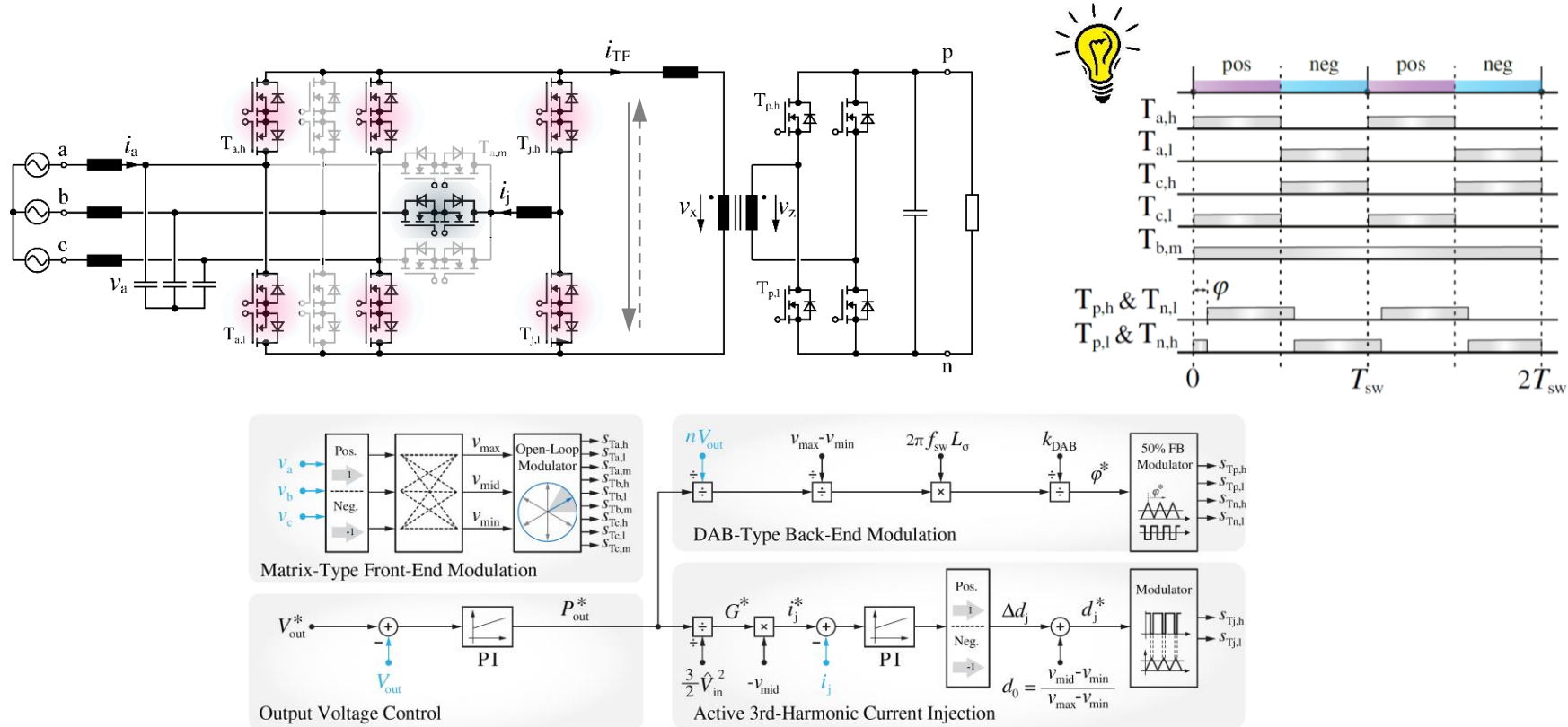
- Rectifier Function of Front-End Modified to Matrix-Type HF AC Voltage Generation
- Elimination of DC/DC-Stage Primary-Side Full-Bridge



- Power Transistors of 3- Φ Rectifier Front-End & IAF Injection Bridge-Leg Replaced by AC-Switches
- High Utilization of the DC/DC-Stage Transformer Maintained – Rectangular HF Voltage Operation

3-Φ IAF Matrix-Type Rectifier Modulation & Control

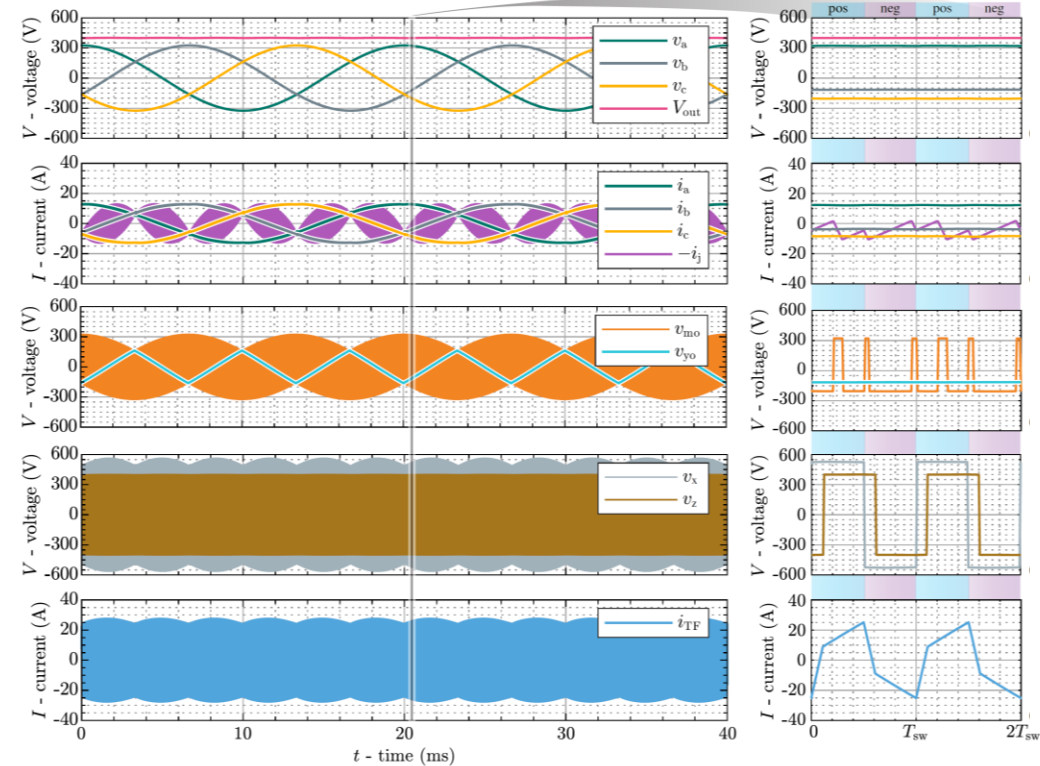
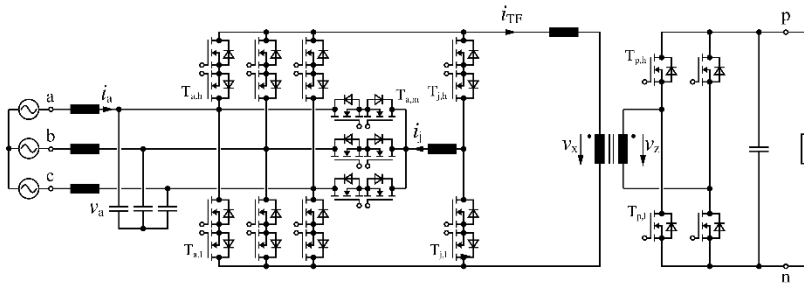
Rectifier Function of Front-End Modified to Matrix-Type HF AC Voltage Generation



- **Inversion of IAF Inj. Bridge-Leg Control Signal Dependent on Transformer Voltage Polarity**

3- Φ IAF Matrix-Type "Toronto" Rectifier Operation

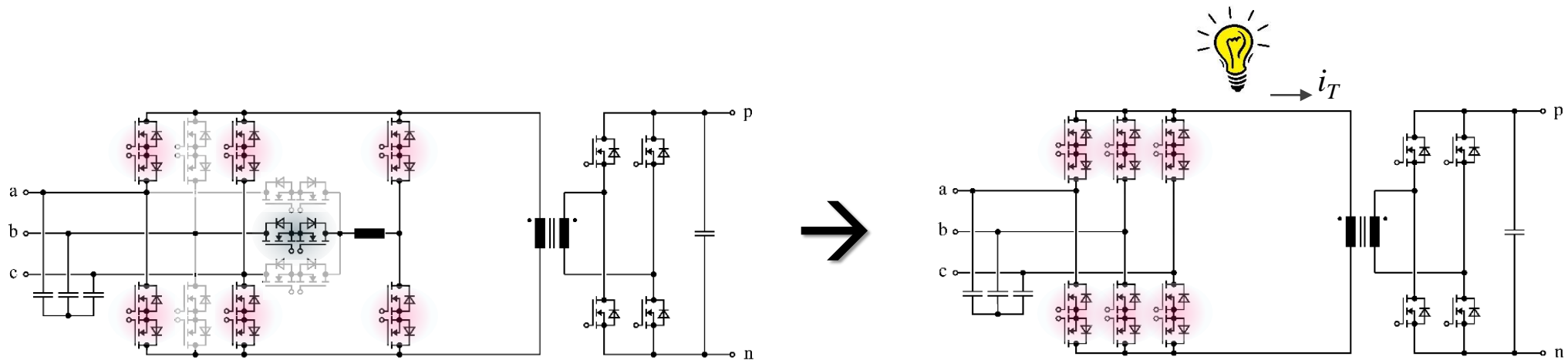
■ Simulation of 6.25kW Rated Power System @ 3- Φ 400V_{AC} Input & 400V_{DC} Output



- ZVS / TCM Largely Eliminates Sw. Losses of IAF Inj. Bridge-Leg
- High-Efficiency ZVS DAB Operation of Isolation Stage — Very High Overall Efficiency

3- Φ Single-Stage Isolated Matrix-Type AC/DC Conversion

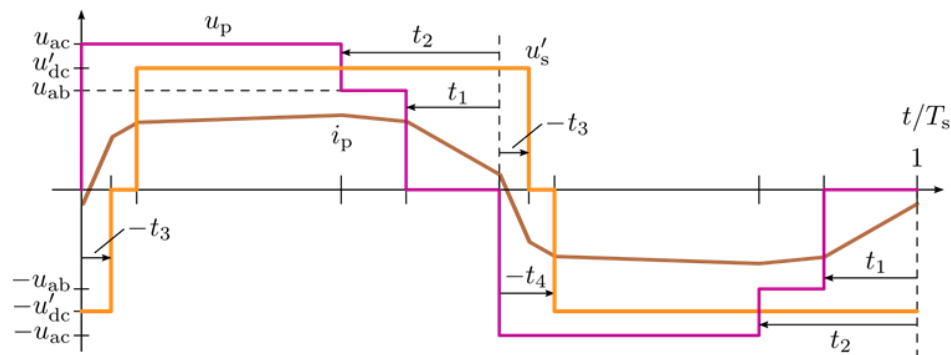
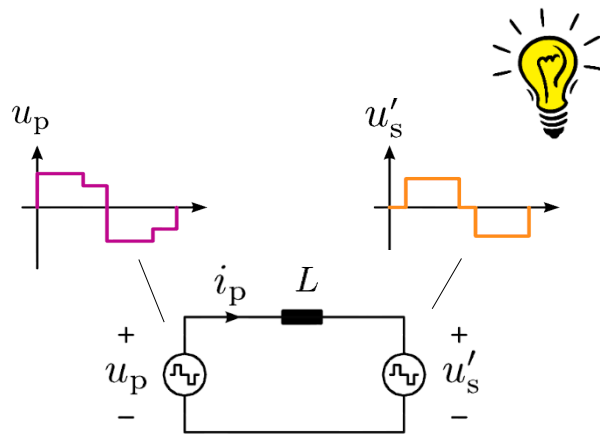
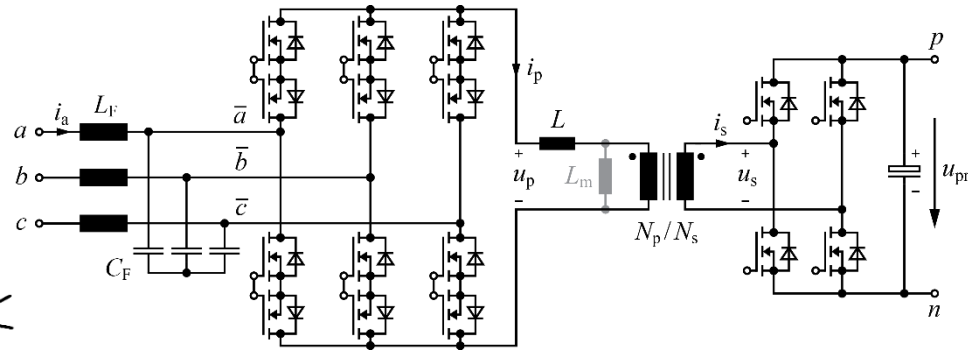
- *Integration of Active Filter & HF Transformer Voltage Generation*
- *Sinus. AC Curr. Shaping & HF Transf. Voltage Gen. Fully Assigned to 3- Φ /1- Φ Matrix-Type Front-End*



- *Operation Analogous to Dual-Active-Bridge DC/DC Converter*
- *Sinusoidal Input Currents | HF AC Transformer Voltage | Min. Transf. RMS Curr. @ ZVS of All Power Transistors*

3- Φ Matrix-Type AC/DC Converter Demonstrator 1/2

- **Based on Dual Active Bridge (DAB) Concept**
- **Opt. Modulation ($t_1 \dots t_4$) for Min. Transformer RMS Current & ZVS or ZCS**
- **Allows Buck-Boost Operation**



● **Equivalent Circuit**

● **Transformer Voltages / Currents**

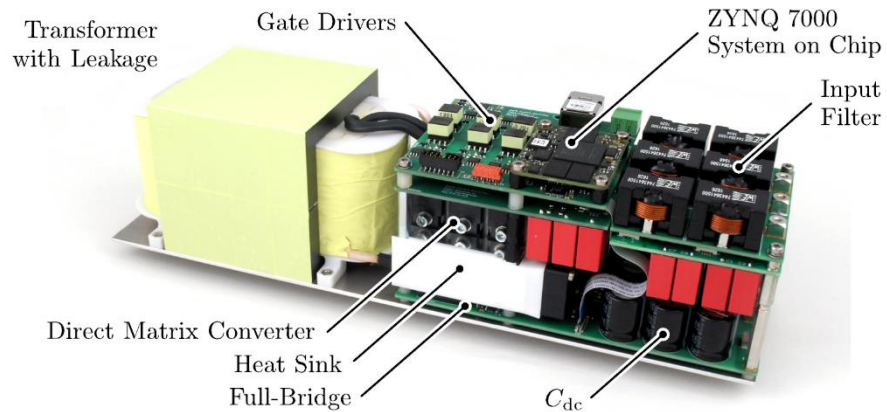
3- Φ Matrix-Type AC/DC Converter Demonstrator 2/2

- Efficiency $\eta = 98.9\%$ @ 60% Rated Load (ZVS)
- Mains Current $THD_I \approx 4\%$ @ Rated Load
- Power Density $\rho \approx 4 \text{ kW/dm}^3$

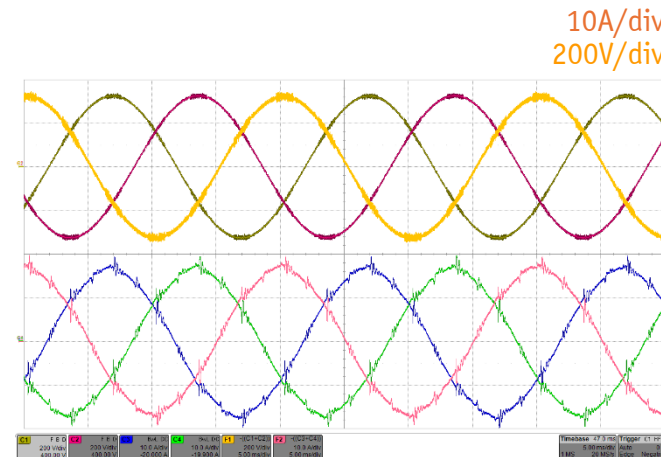
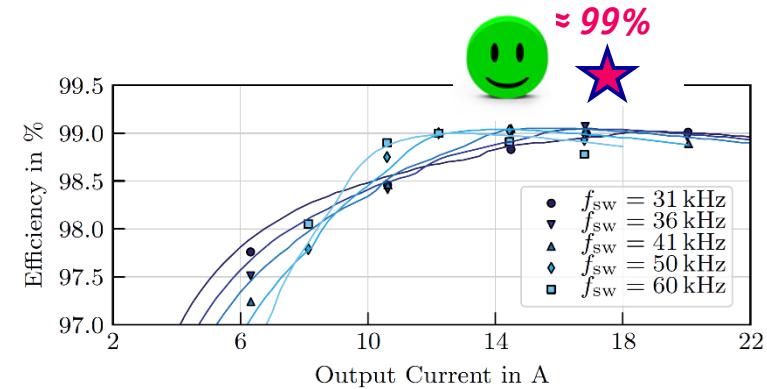
$$P_o = 8 \text{ kW}$$

$$U_N = 400 \text{ V}_{AC} \rightarrow U_o = 400 \text{ V}_{DC}$$

$$f_s = 36 \text{ kHz}$$

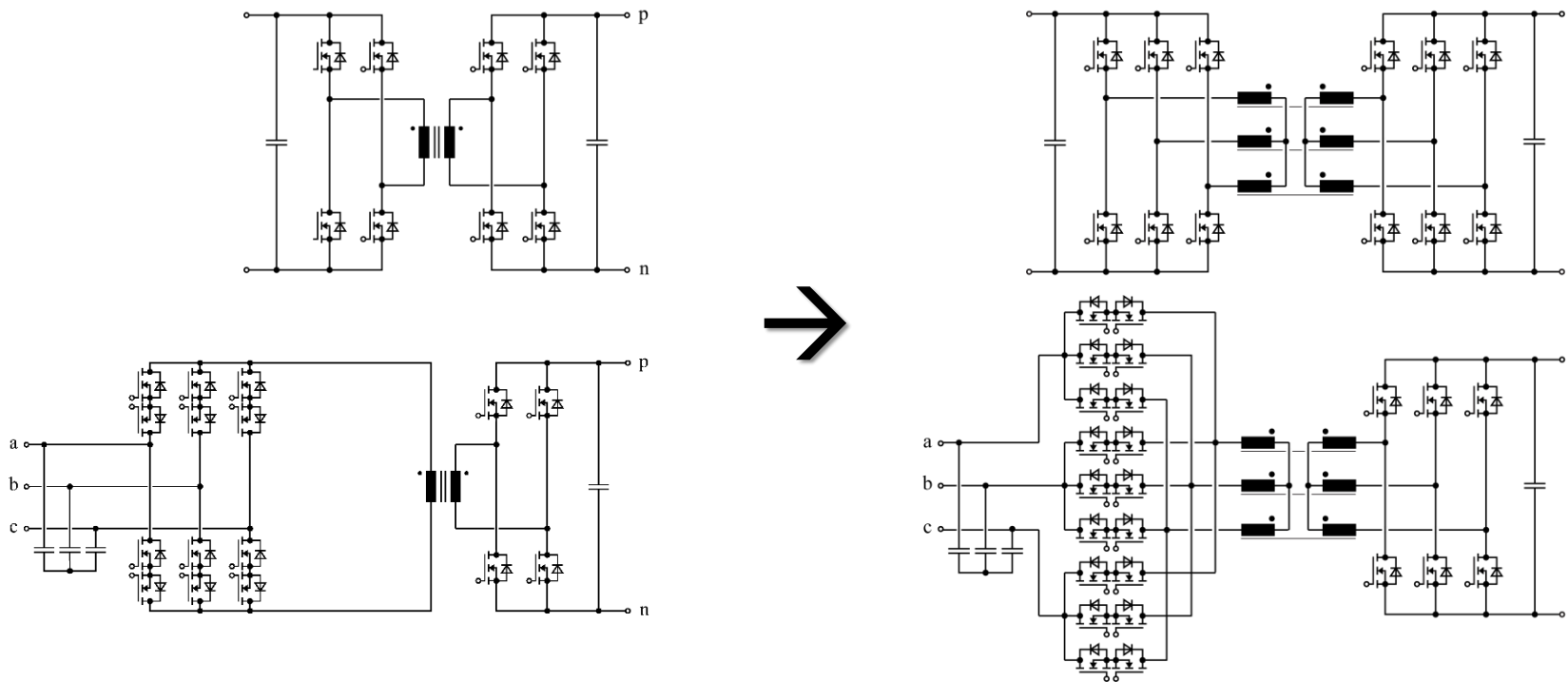


- 900V / 10m Ω SiC Power MOSFETs
- Opt. Modulation Based on 3D Look-Up Table



Outlook — Extension to High Power 1/2

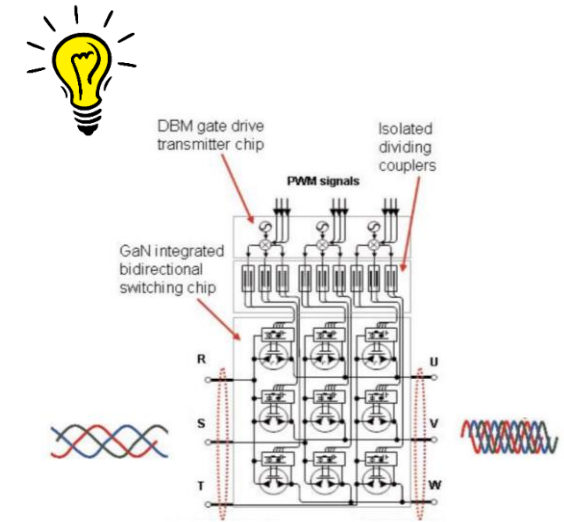
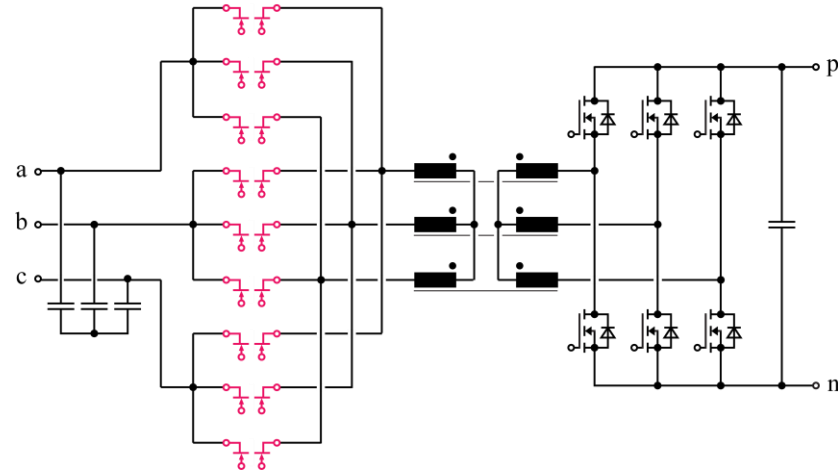
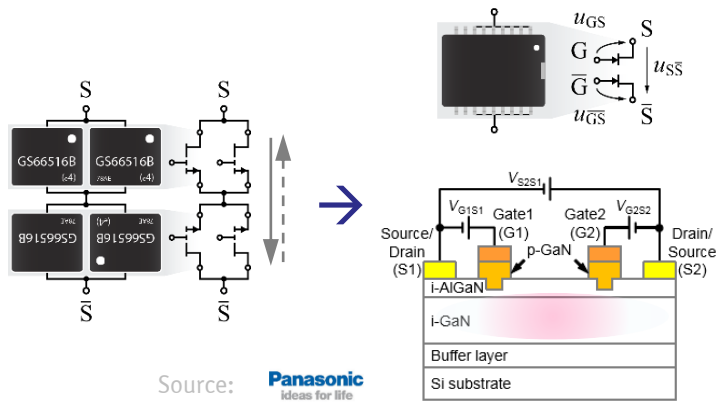
- 3- Φ Matrix-Type AC/DC Converter w/ *Three-Phase Transformer* — “i3X-Rectifier”
- Advantageous for Future *20...50kW AC/DC Power Supply Modules*



- *Application of Future 1200V Monolithic Bidirectional GaN Power Transistors (MBDSs)*

Outlook — Extension to High Power 2/2

- 3- Φ Matrix-Type AC/DC Converter w/ Three-Phase Transformer — *i3X-Rectifier*
- Advantageous for Future **20...50kW** AC/DC Power Supply Modules

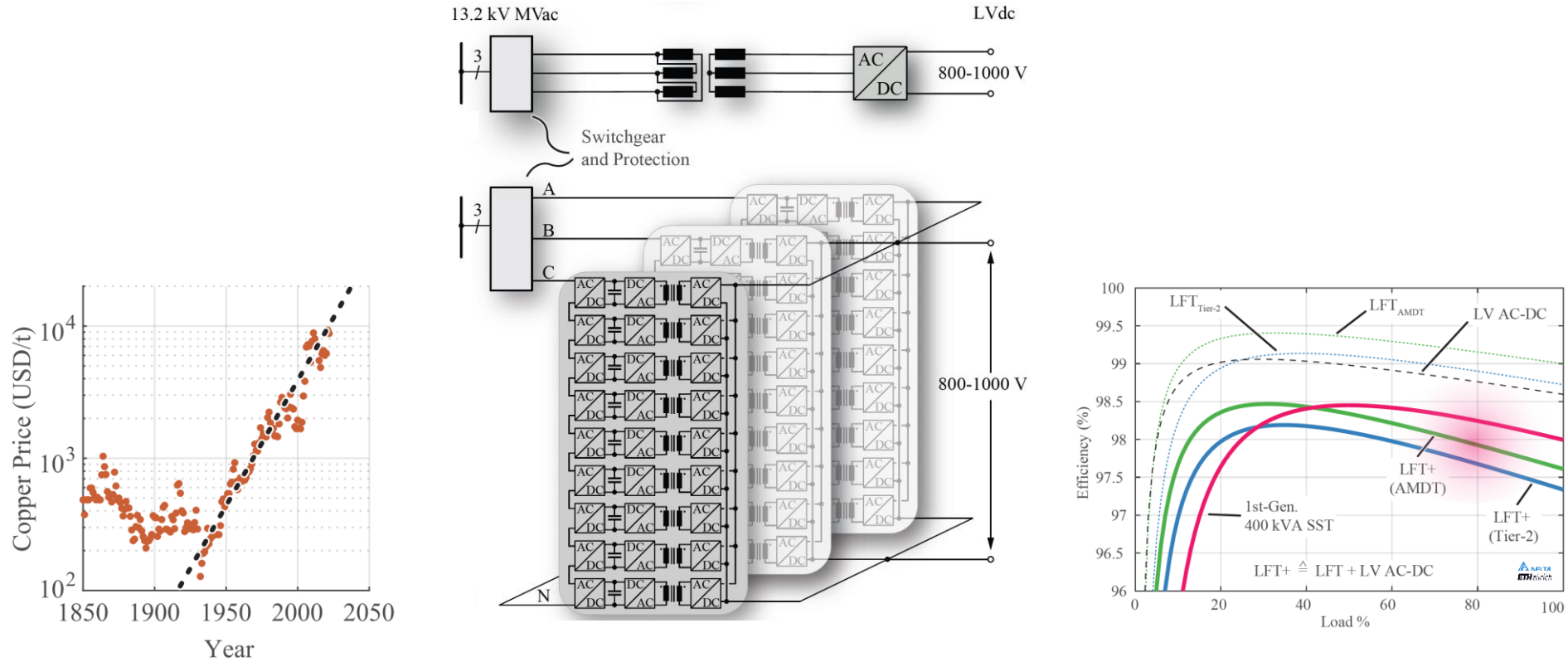


- Use of MBDS GaN Power Transistors — *Eliminates Factor of 4 Chip Area Penalty (!)*
- Lateral GaN Device Technology — *Facilitates Monolithic Integr. of Matrix-Type Switching Stage & Gate Drives*



3- Φ AC/DC Solid-State Transformer (SST) 1/2

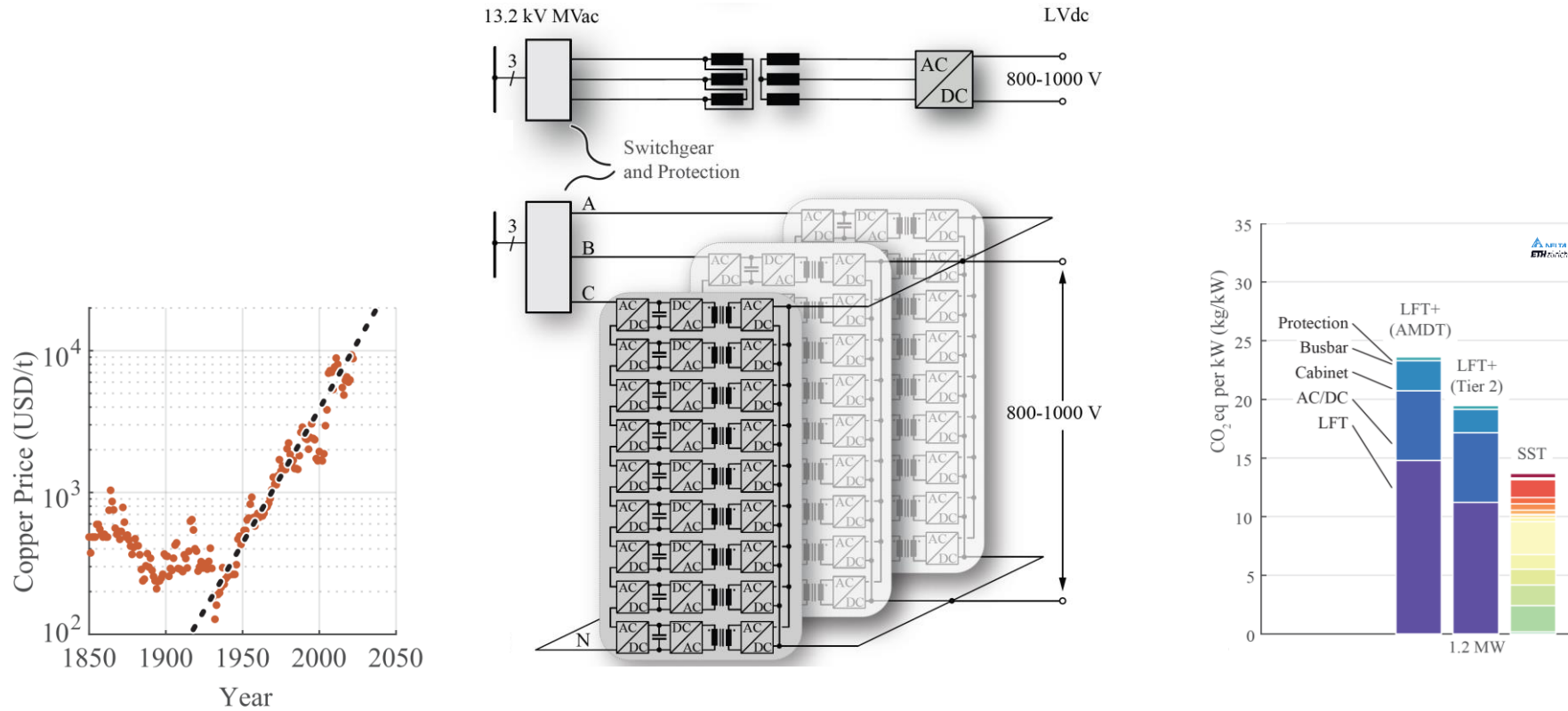
- **1.2MW Gen.2 Fully-Modular SST w/ HF-Isolation Stages**
- **Lower Raw Material Effort / Lower Impact of Increasing Raw Material Costs**



- **Evaluation Against Dry-Type 50/60Hz-Transformer-Based MVAC-LVDC Interface w/ Comparable Efficiency**

3- Φ AC/DC Solid-State Transformer (SST) 2/2

- **1.2MW Gen.2 Fully-Modular SST w/ HF-Isolation Stages**
- **Lower Raw Material Effort / Lower Impact of Increasing Raw Material Costs**



- **Significantly Lower SST Carbon Footprint [kg CO_{2,eq}/kW] Compared to 50/60Hz-Transformer-Based Solution**

Thank You!



If you Think All This is “Too Much Down to Earth” or “Not Cool Enough”, Watch →

