High frequency three-phase PFC solutions for high power charging stations

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Power Conversion Unit

System Research and Applications

April 26th, 2021

Agenda

1. Introduction
2. Charging Stations
3. Power Factor Correction
4. Semiconductor Technologies
5. Bidirectional PFC: 3LTT converter
6. Conclusions

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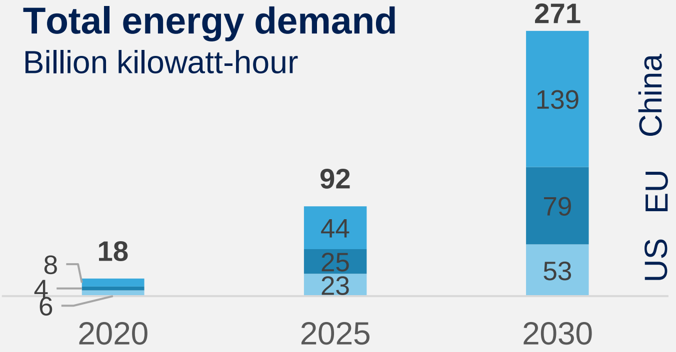
Introduction

- Charging stations are the companion of Car Electrification
- Their intensive installation will impact on the Grid infrastructure and management
- The presentation deals with a building block of a DC Charging station, the Active Front End, which is the interface of the Charging Station with the grid
- Power Quality performance, efficiency and size with reference to cost are the main parameters to be considered
- Several power converters topologies for high power are available but not able to fullfil all the requirements
- Silicon Carbide introduction in the market is changing the game, making possible a revival of simple three phase power converters

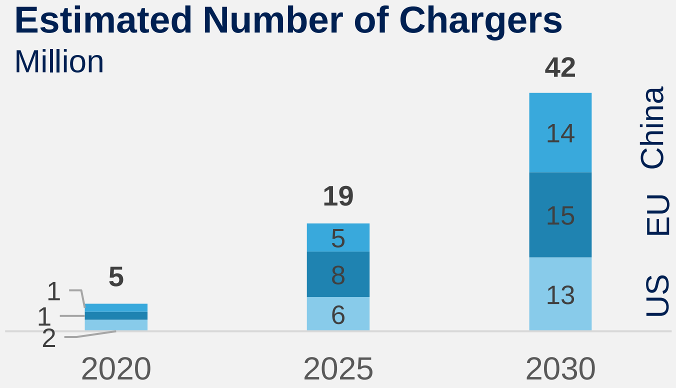
Charging Stations: an energy driven application

50B$ WW investment for **280BkW per hour by 2030**



280 **B kWh**

Estimated charging energy demand for electric vehicle

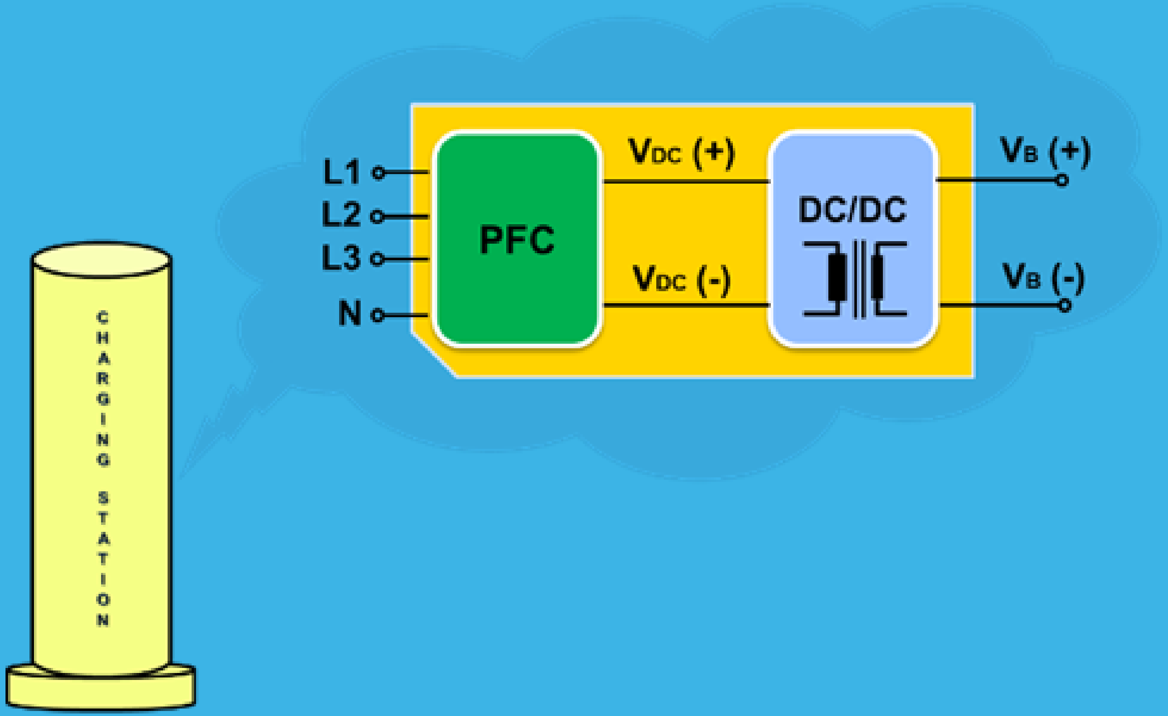


50 **B$**

2030 Investment plan to meet the target

Source: McKinsey

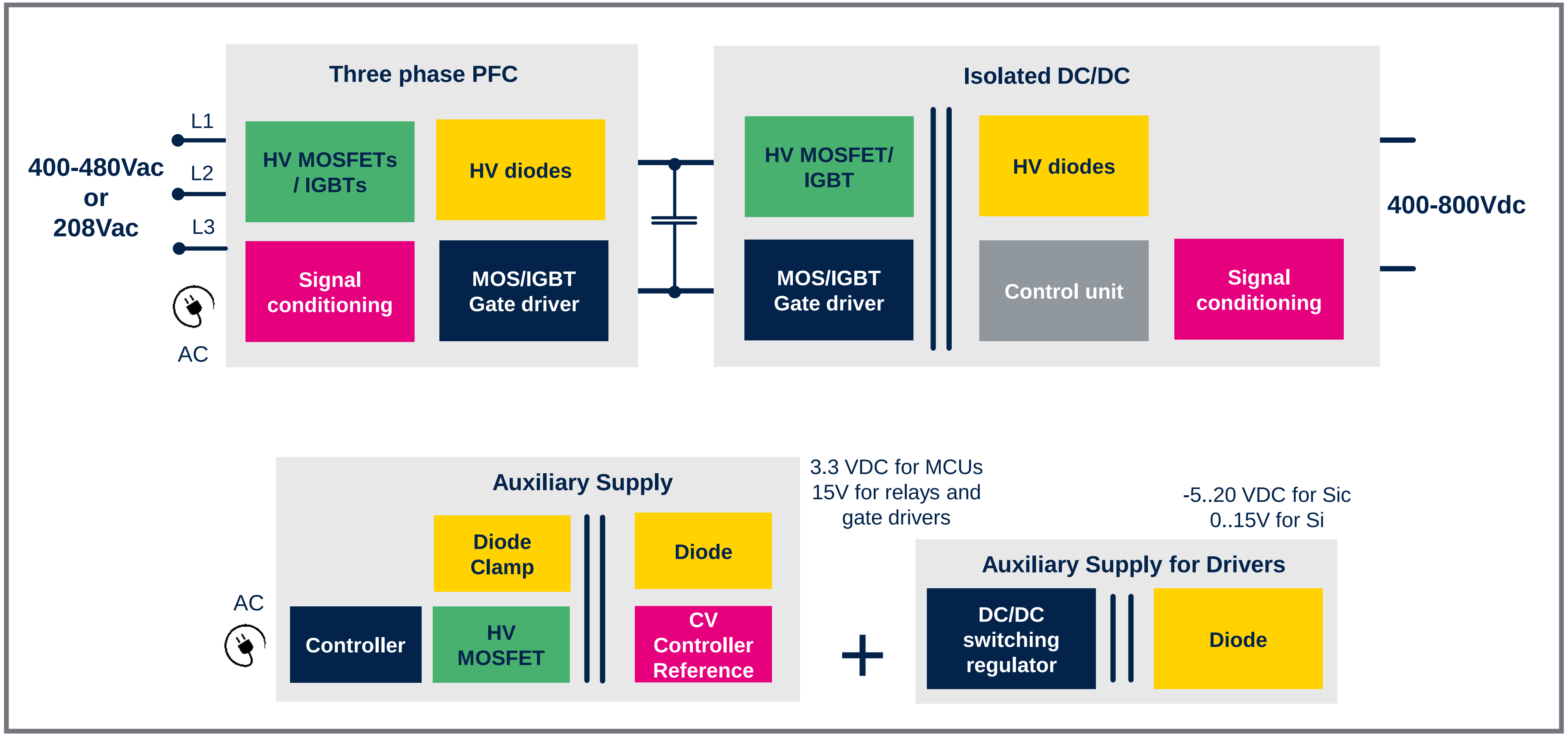
Charging Stations



Charging station

DC Fast Charger

Single 20…50kW block



Power Factor Correction

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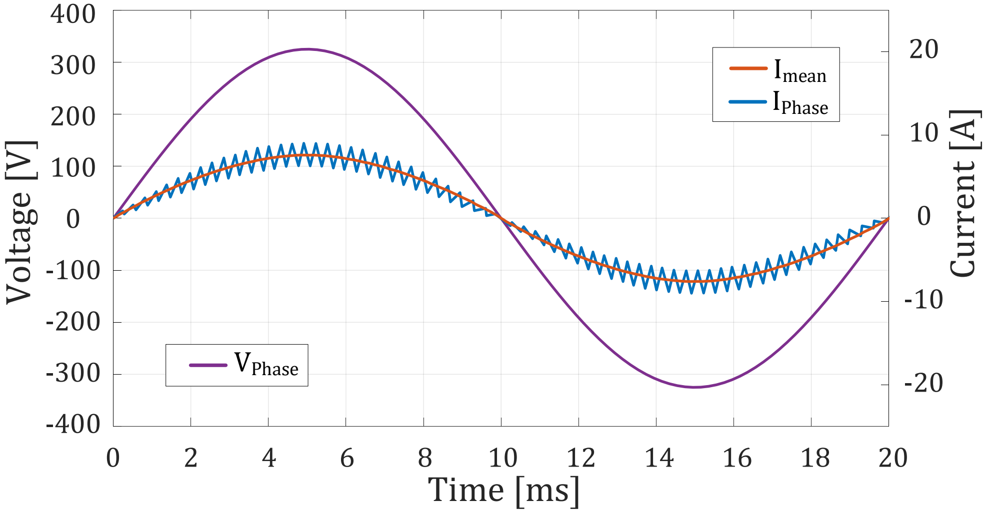
Power Factor Correction

- The Front End converter has to control the current drawn from the grid, ideally showing a pure resistive behaviour. As a result, the input current has to be in phase with the grid voltage in order to take only active power, P.
- Power Quality aspects are considered in terms of apparent power, S, and harmonc distorsion.
- Power Factor, **PF**, and Total Harmonic Distorsion, **THD**, are a metric for the performance of the Front End converter.
- International standards apply for specific product segment, e.g. EN6100-3-2.



Power Factor

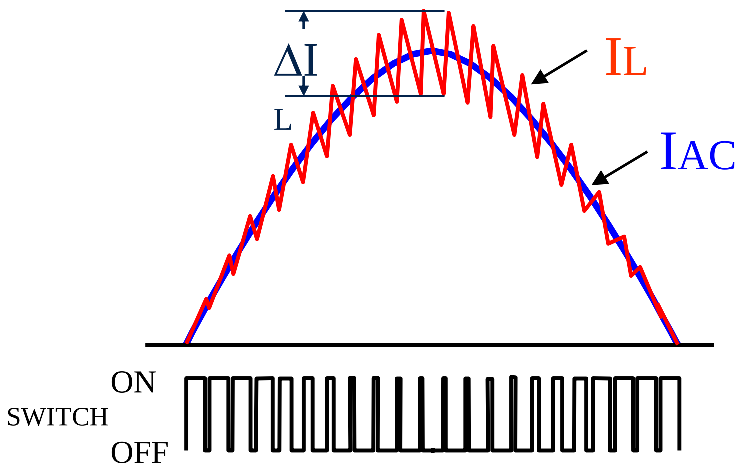
$$PF = \frac{P}{S}$$

Total Harmonic Distorsion

$$THD_i = \frac{\sqrt{\sum_{n\neq1} {I_{n,rms}}^2}}{I_{1,rms}}$$

$$PF = \frac{\cos\varphi}{\sqrt{1 + {THD_i}^2}}$$

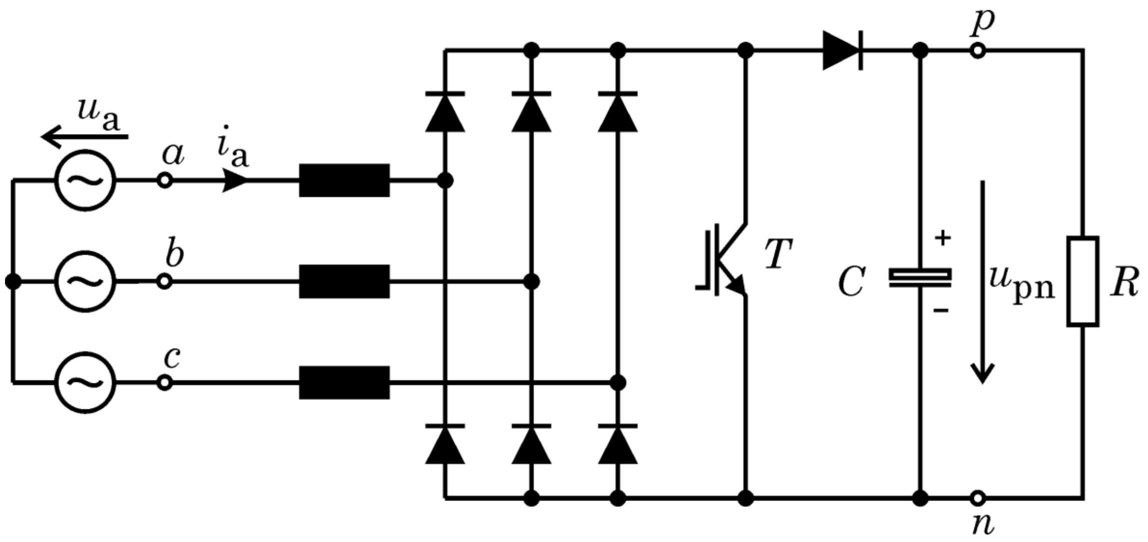
"FF-CCM" type

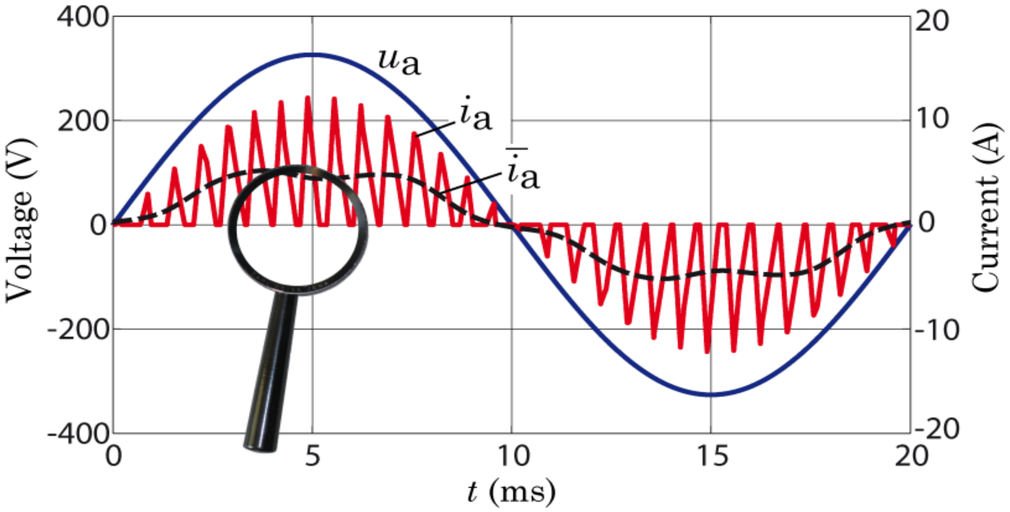


Three-Phase Active PFC

From scientific literature*

- Several topologies are available for active PFC in 3 phase power systems applications.
- The simplest solutions is represented by the boost converter in DCM:





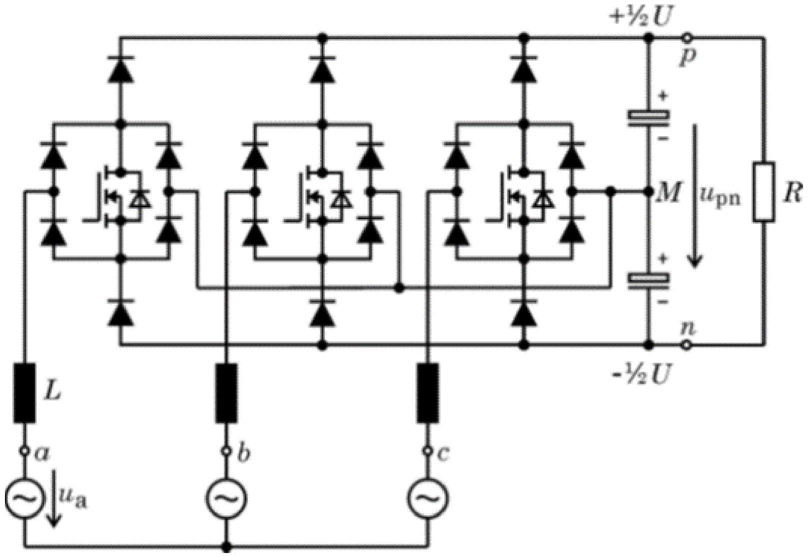
- Cons: high inductance value, high peak current value, high THD.

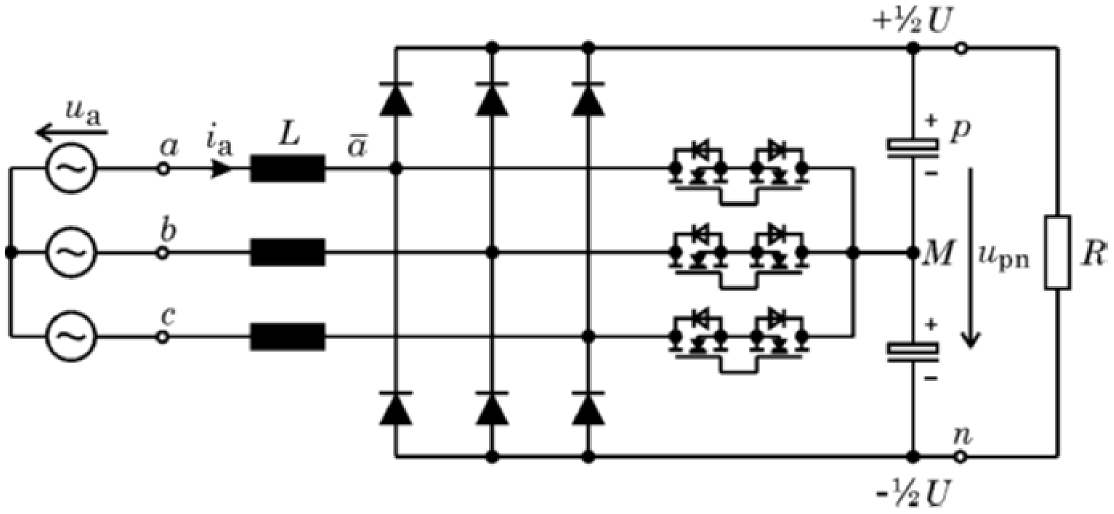
*The Essence of Three-Phase PFC Rectifier Systems – J.W. Kolar and T. Friedli – IEEE TPE Vol. 28 No. 1 Jan 2013

Three-phase active PFC – Vienna rectifier

from literature*

- Going through the Phase Modular Systems (Delta & Y converters), the winning topology is the «Vienna rectifier», in several minor variants, taking advantage of multi-level approach: low input current ripple, lower voltage stress on switches and output capacitors ($V_o/2$).



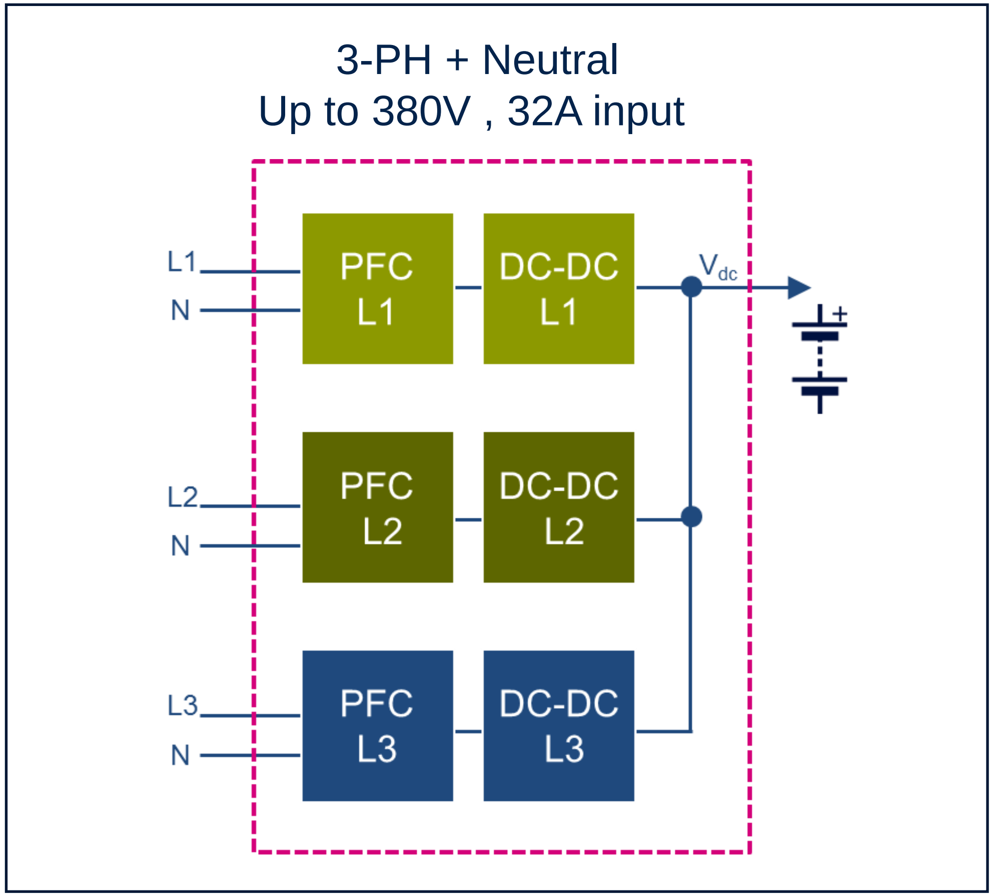


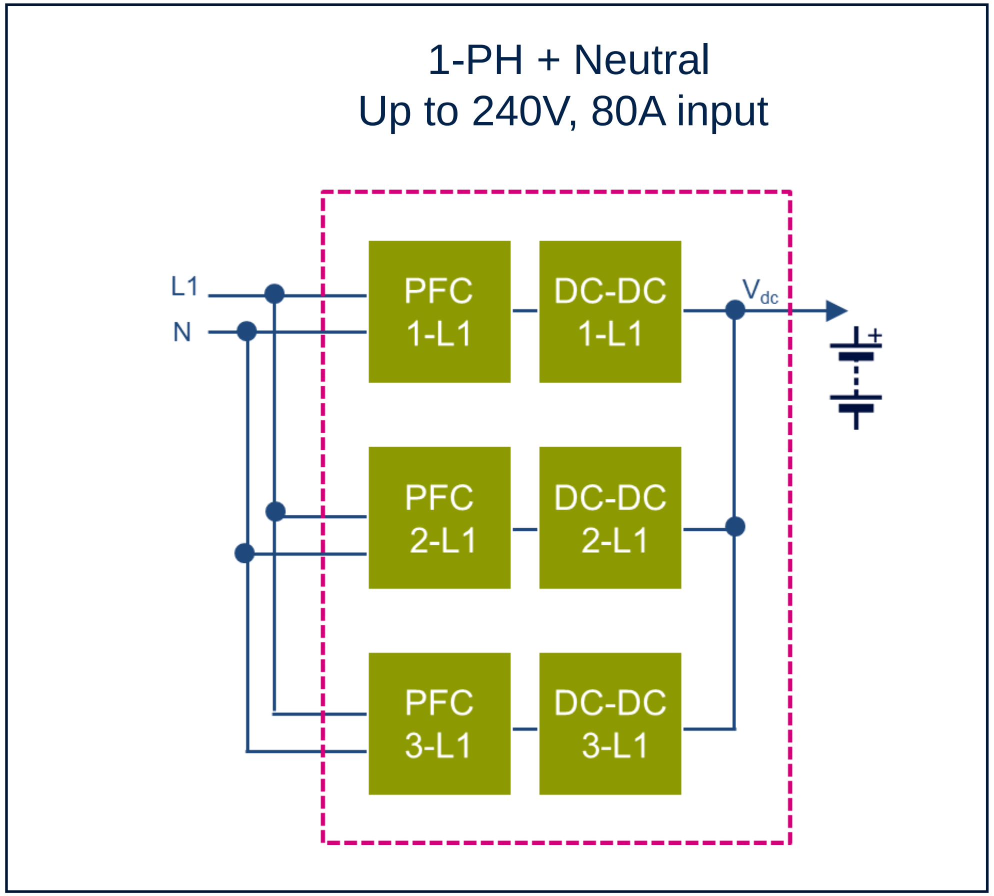
- Cons: complex switching pattern, high side driving, output capacitors voltage balancing.

*The Essence of Three-Phase PFC Rectifier Systems – J.W. Kolar and T. Friedli – IEEE TPE Vol. 28 No. 1 Jan 2013

Single phase modules in 3-phase connection

A modular approach with 3 single phase modules is sometimes considered for power level up to 22kW, allowing single phase operation for domestic charging.


3-PH + Neutral
Up to 380V , 32A input


1-PH + Neutral
Up to 240V, 80A input

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Semiconductor Technologies

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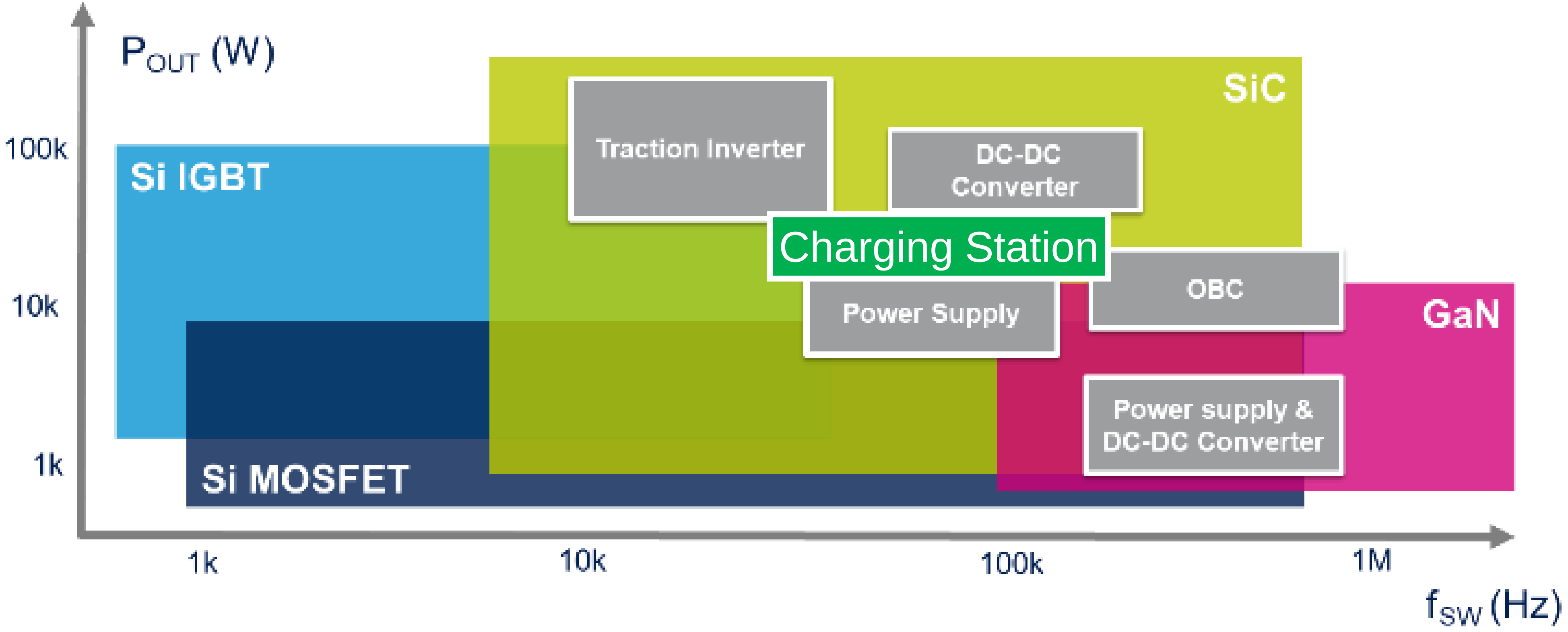
Semiconductor Technologies



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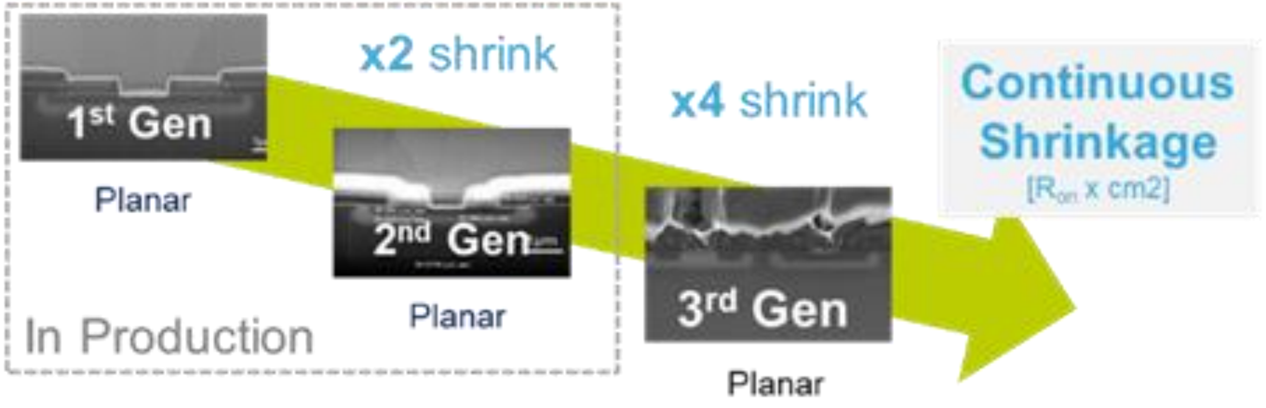
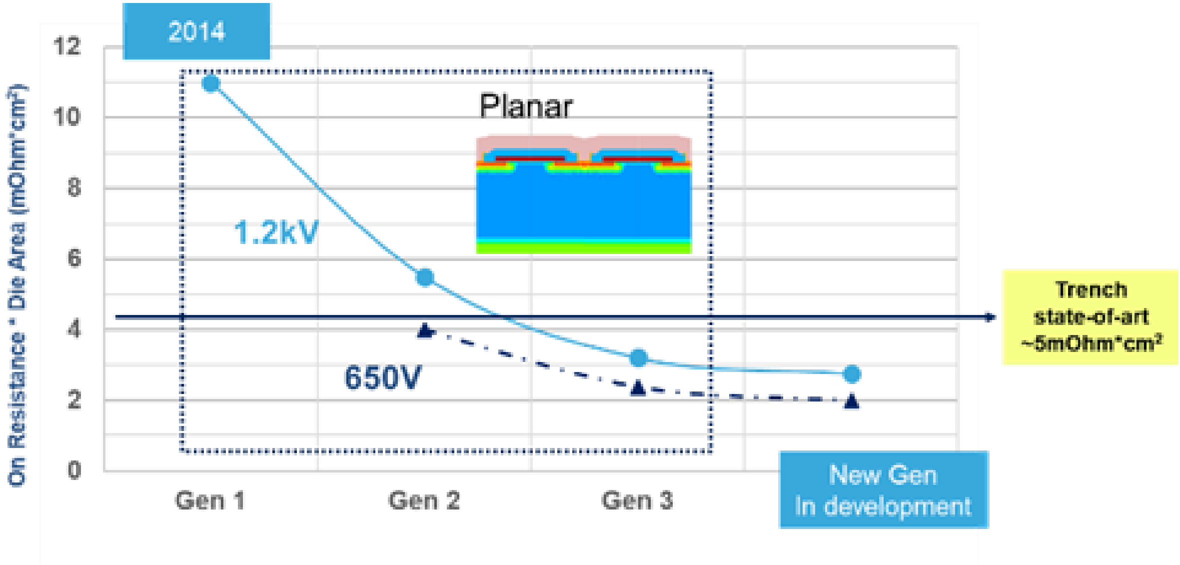
Semiconductor Technologies

SiC MOSFETs

Front-end Evolution



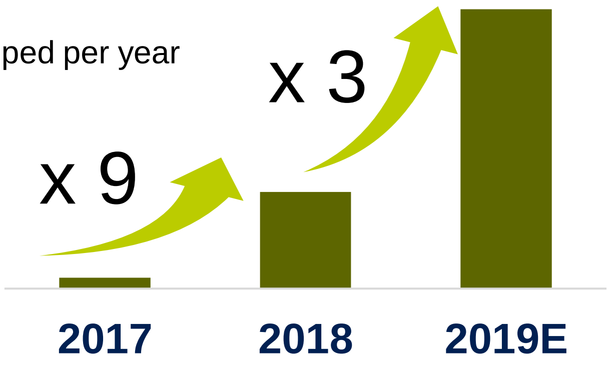


SiC adoption faster than expected

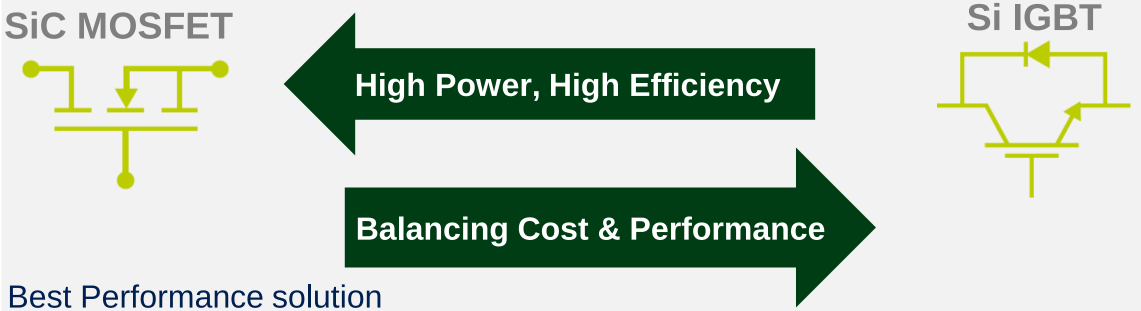
SiC

From 650 V to 1700 V

Units shipped per year



Solutions Tailored to Market Needs



Best Performance solution **up to 1700 V**

Best cost solution **up to 650 V**

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SiC benefits and advantages

SiC Technology Benefits
SiC vs Conventional Silicon IGBT

Higher Performance & Voltage Operation

- Extremely low power losses
- High efficiency at low current
- Intrinsic SiC body diode (4 quadrant operation)

Higher Operating Frequency

- Lower switching losses
- Excellent diode switching performance

Higher Operating Temperature

- Operating up to 200°C junction

SiC Advantages

Electrification – Faster and more efficient charging

Efficiency gain in average	Switching losses	Chip size	Total loss	Switching frequency
From ~2% (high load) to ~10% (low load)	~7x lower	~5x smaller	~50% lower	~ 5 ..10 times higher

Lower System Cost

~7x reduced form factor

~80% cooling system down sizing

~Simpler Sub-systems: smaller passives, no external freewheeling diode…

Relevance of Package Technology

- **The package technology is fundamental for high frequency operations.**

  - **Electrical aspects parasitics related:**
    - Internal connections (layout and wire bonding);
    - Board layout.

  - **Thermal aspects**
    - Operating temperature (max operating junction temperature)
    - Heat dissipation capability;
    - Heat sink mounting.

  - **EMI aspects**
    - Noise and disturbance;
    - Conducted and radiated emissions.

Three-phase PFC Topologies

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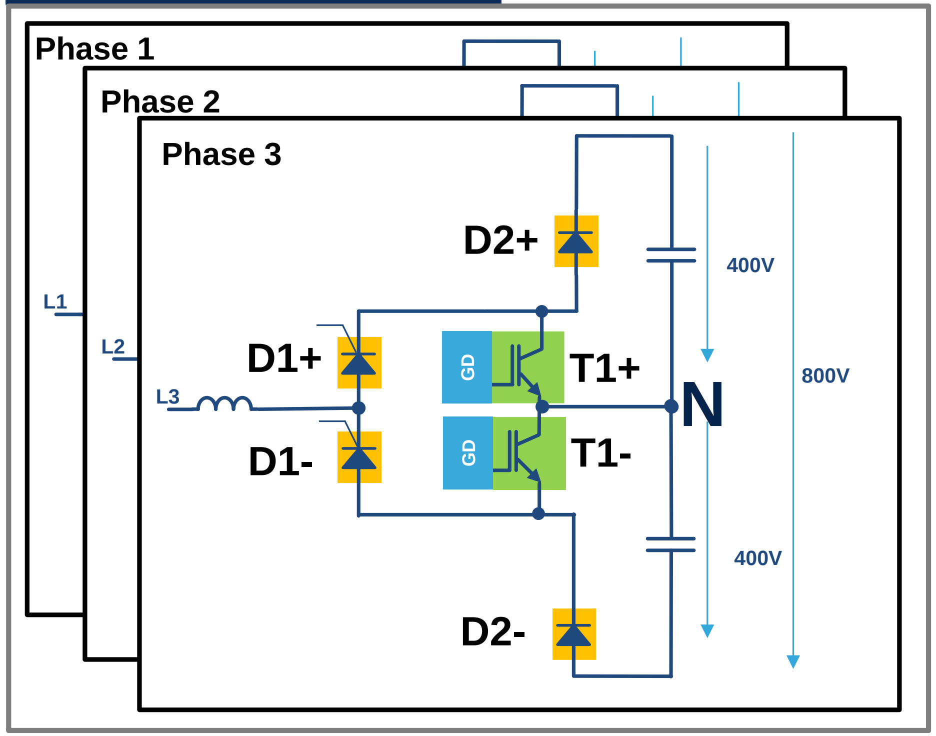
Three-phase PFC converter

Topology comparison

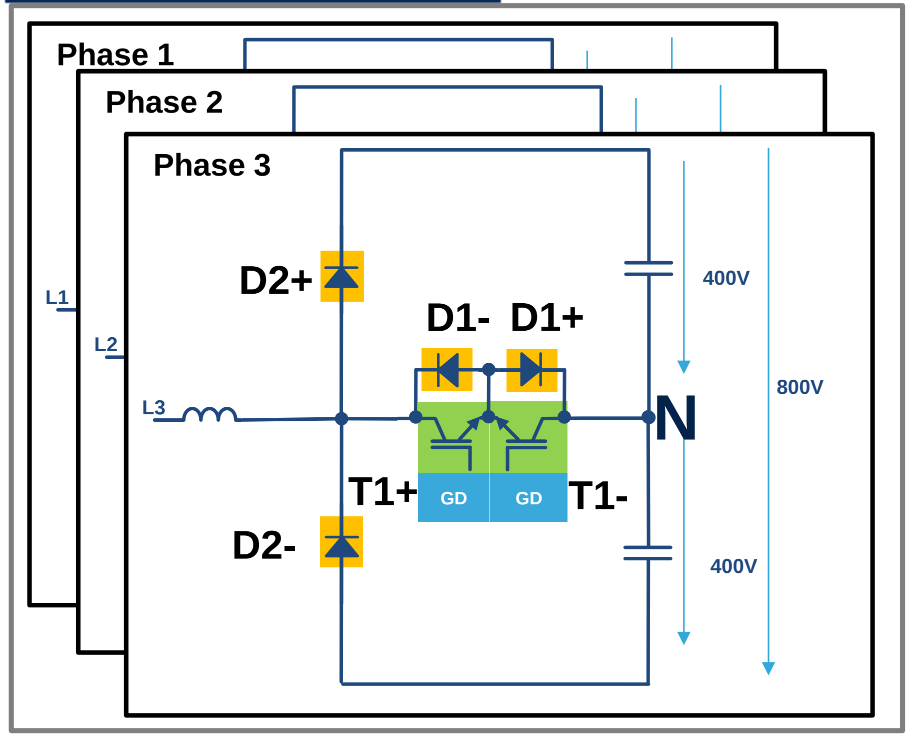
Vienna rectifier Type 1



+ All 650V rated devices!
→ lower cost

- 2 devices in the main current path (D1&D2)
→ lower efficiency

Vienna rectifier Type 2



+ 1 devices in the main current path (D2)
→ Higher efficiency

- Need 1200V diodes (D2), typically SiC.
→ Higher cost

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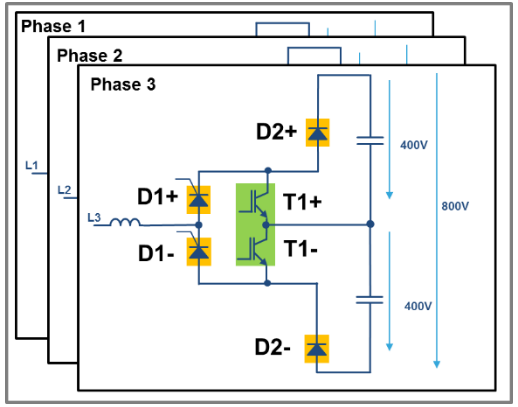
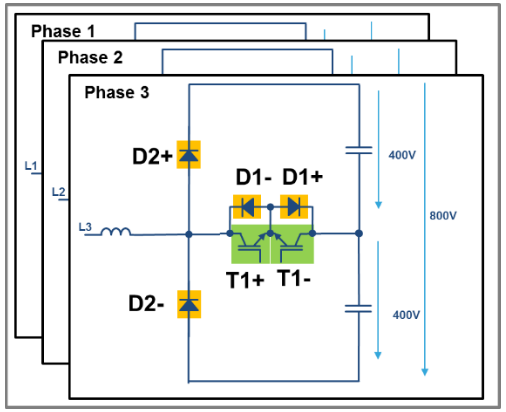
Topology comparison

Efficiency comparison @ P_{out}=30 kW

Vienna rectifier Type 1



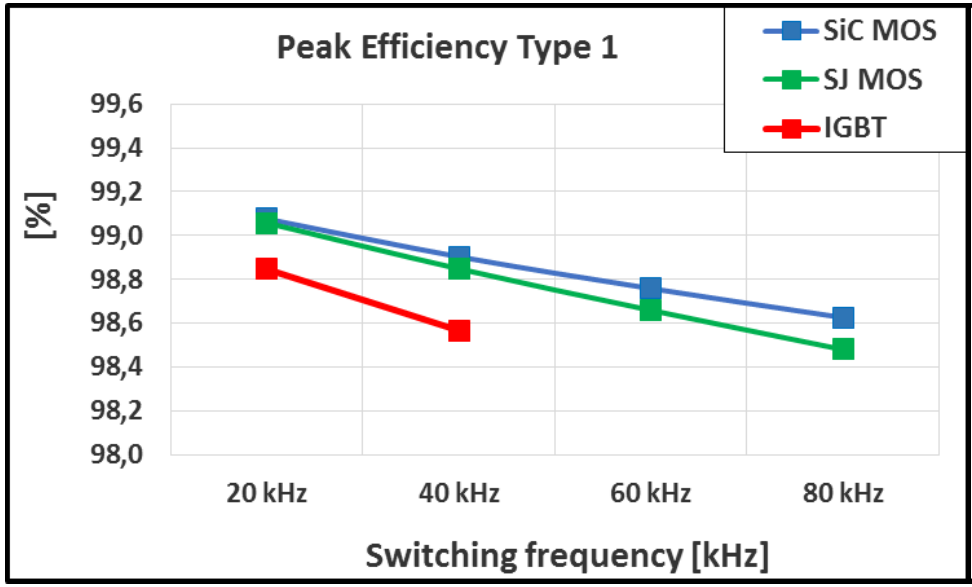
Vienna rectifier Type 2

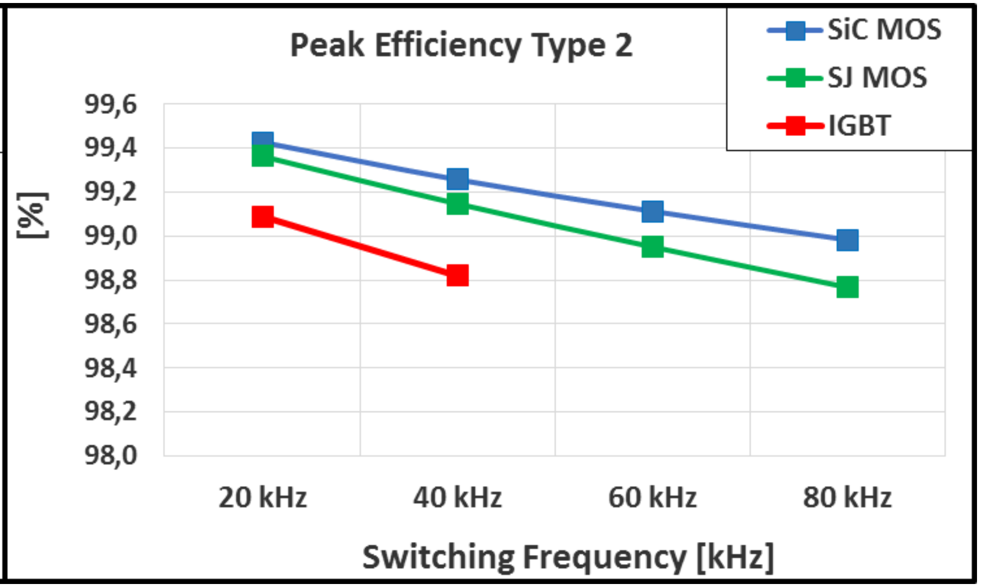


A → Eff. of IGBT: -0.3% than SJ/SiC MOS

B → Eff. of Type 1: -0.3% than Type 2

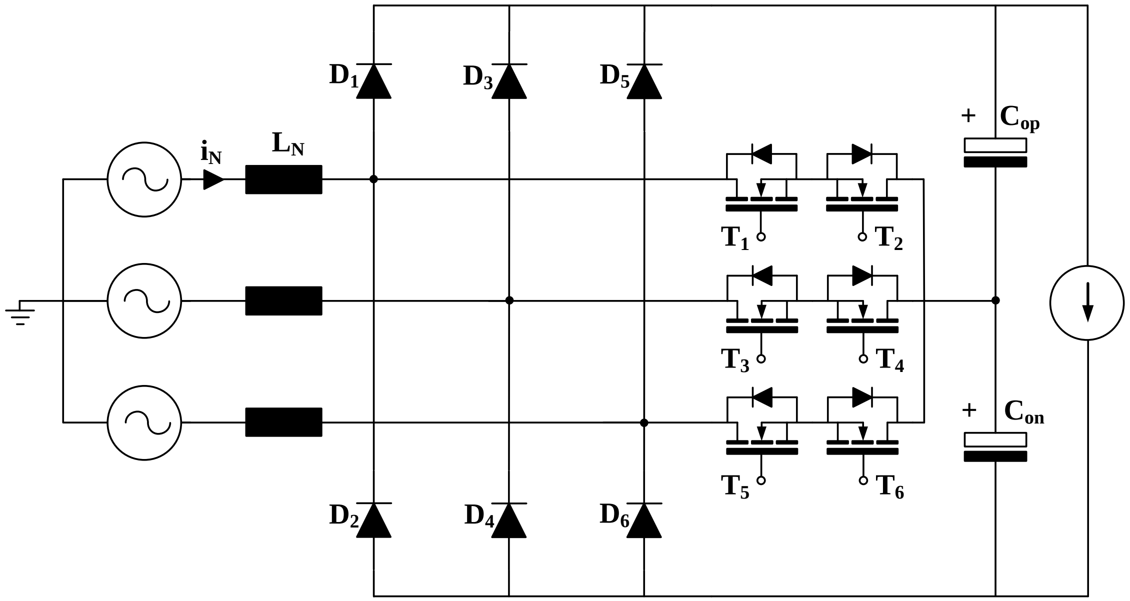
C → >50 kHz: SiC +0.1%..0.2% than SJ MOS



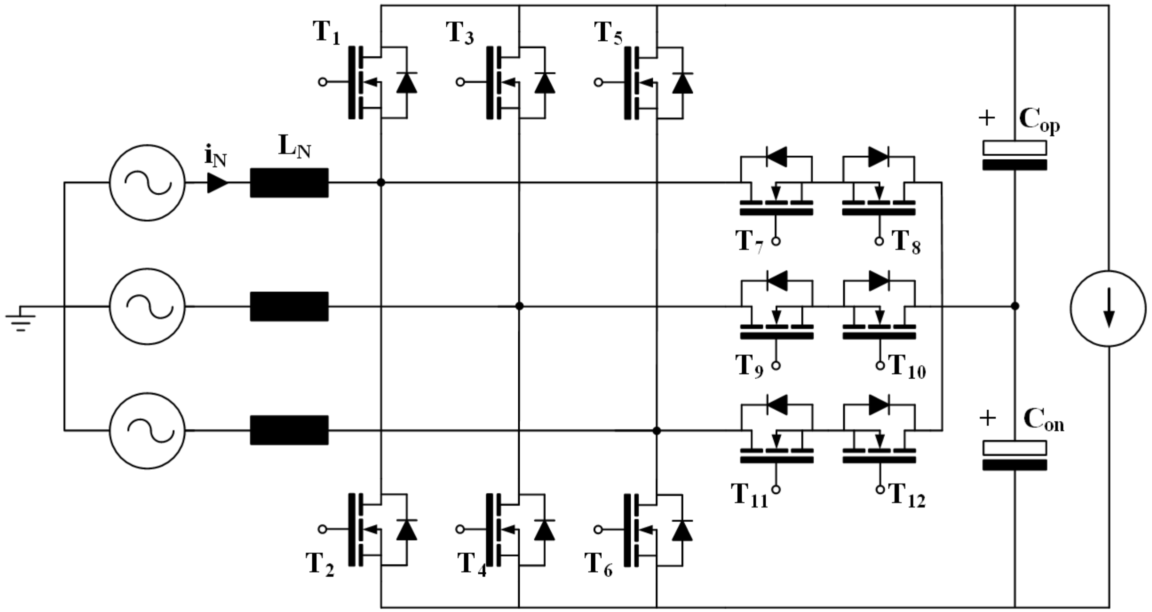


Simulated efficiency @ T_j = 125°C, considering <u>only semiconductor losses</u>.

SiC Enabled Topologies



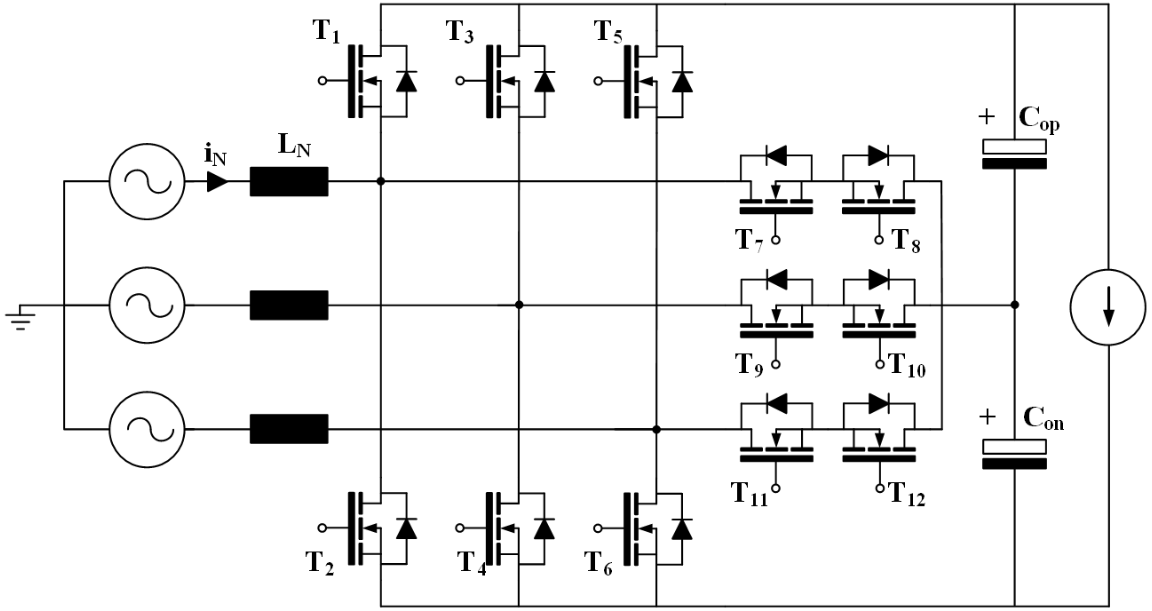
Vienna Rectifier – Type 2



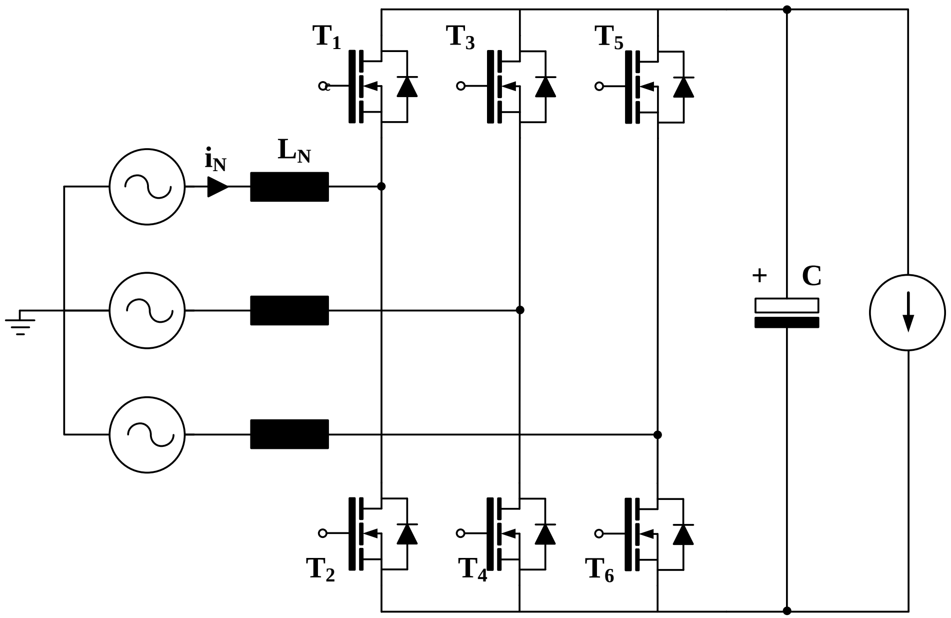
Bidirectional Vienna Rectifier – 3LTT

SiC Enabled Topologies

Bidirectional converters



3LTT Converter



Full Bridge Boost Converter

Bidirectional PFC Topology

Modulation related converter

Specifications

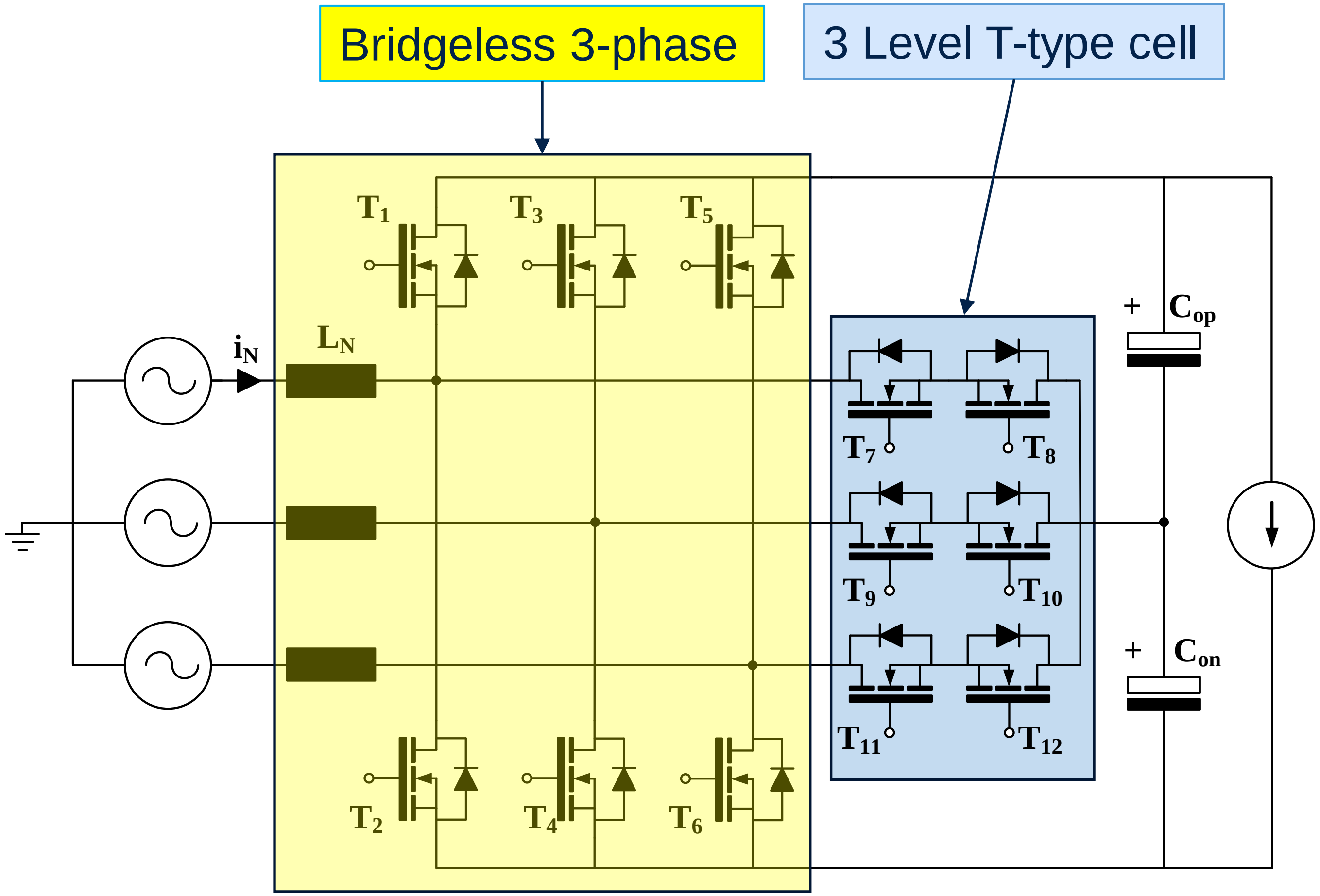
V_{in}	400 Vac
V_{out}	800 Vdc
P_{0ut_max}	13 kW
F_s	70 kHz
I_{ripple}	2.5A
V_{out_ripple}	10 Vpp

$$L_N = \frac{V_O}{f_s * \Delta_{iL}} \frac{\sqrt{3}}{4} M \left(1 - M\frac{\sqrt{3}}{2}\right) = 0.475mH$$

$$\Delta_{iL} = 2.5A \qquad M = \frac{\widehat{U_N}}{\widehat{V_O}/_2} = 0.815$$

$$I_{Lrms} = \frac{P_{DC}}{3V_{rms}} = 17{,}4\ A_{rms}$$

$$\widehat{I_L} = \sqrt{2}\, I_{Lrms} = 24{,}6A$$



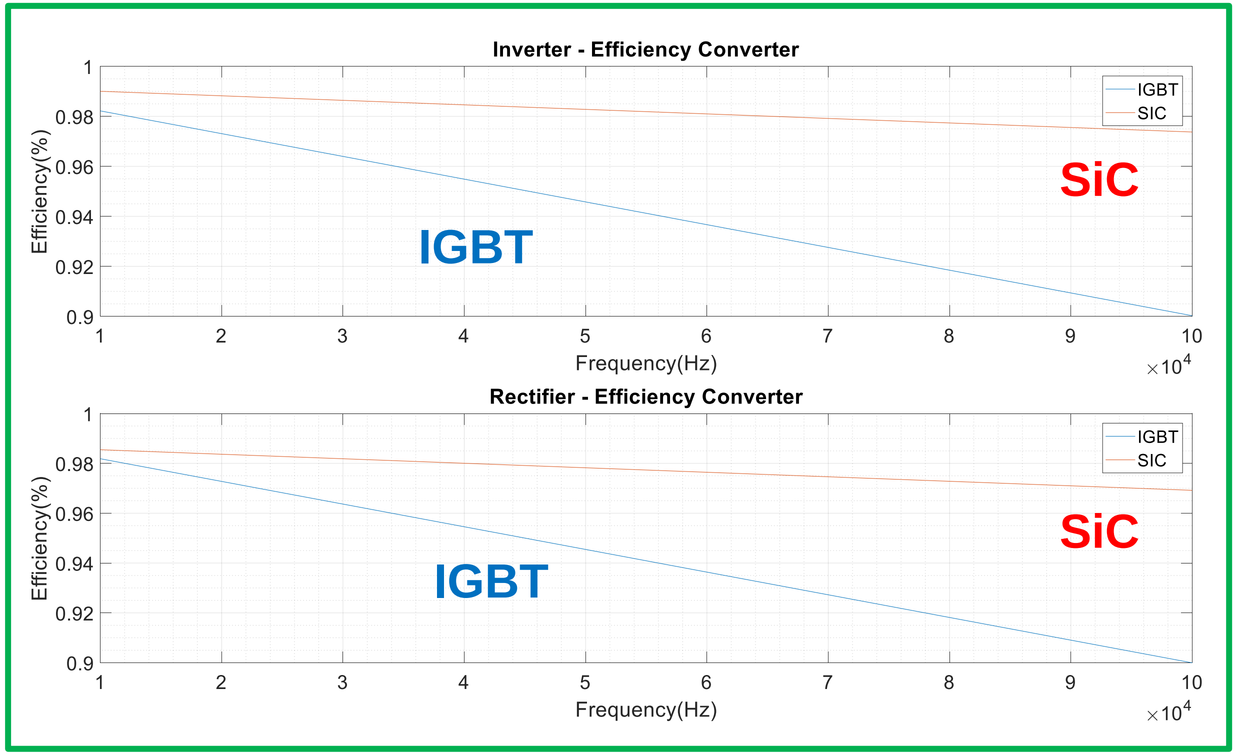
Bridgeless 3-phase

3 Level T-type cell

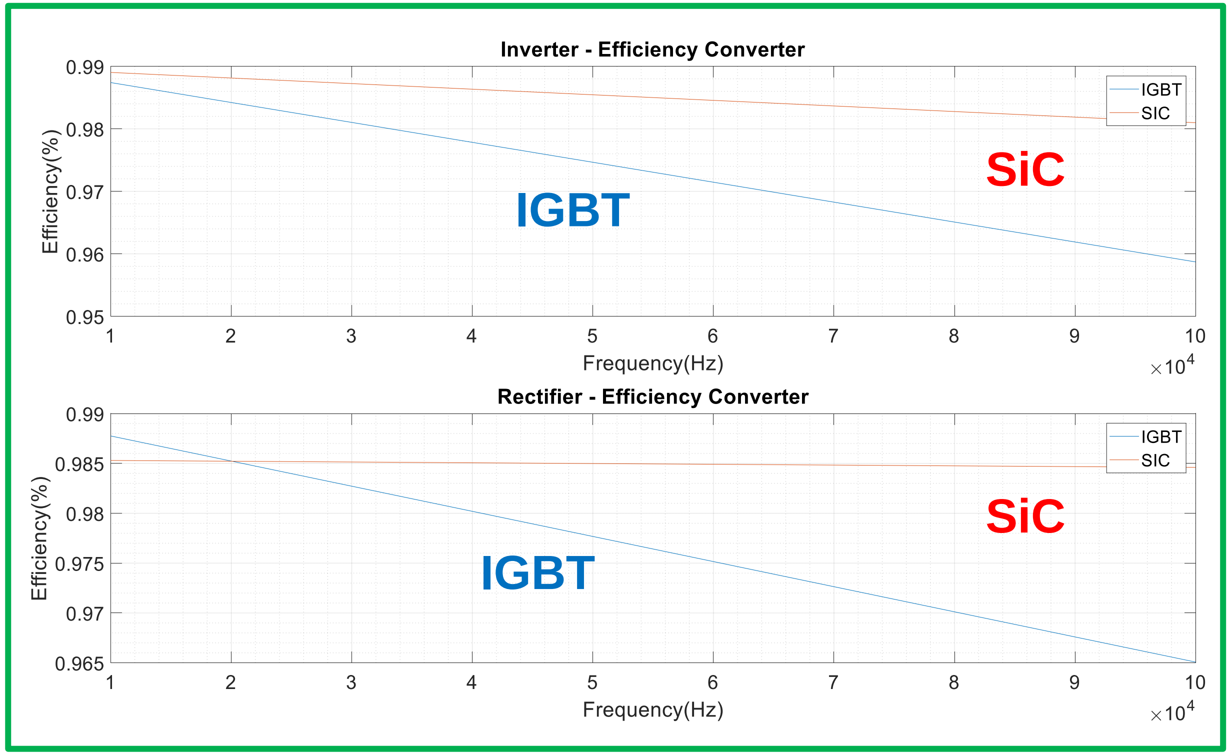
SiC Enabled Topologies

Efficiency comparison

Semiconductor efficiency, f_s=10...100kHz



2L converter



3LTT converter

SiC Enabled Topologies
3L Vs 2L comparison

Pros

- Losses distributed over more components
- Higher efficiency at high switching frequency
- Lower inductor volume (35%)

Cons

- More components
- Higher complexity
- Output voltage balancing
- Expected higher cost

	2LC	3LTTC
PWM (complementary)	3	6 or (3 compl+3 single)
Gate Driver	6	12 o 9
Isolated DC/DC	6	12 o 9

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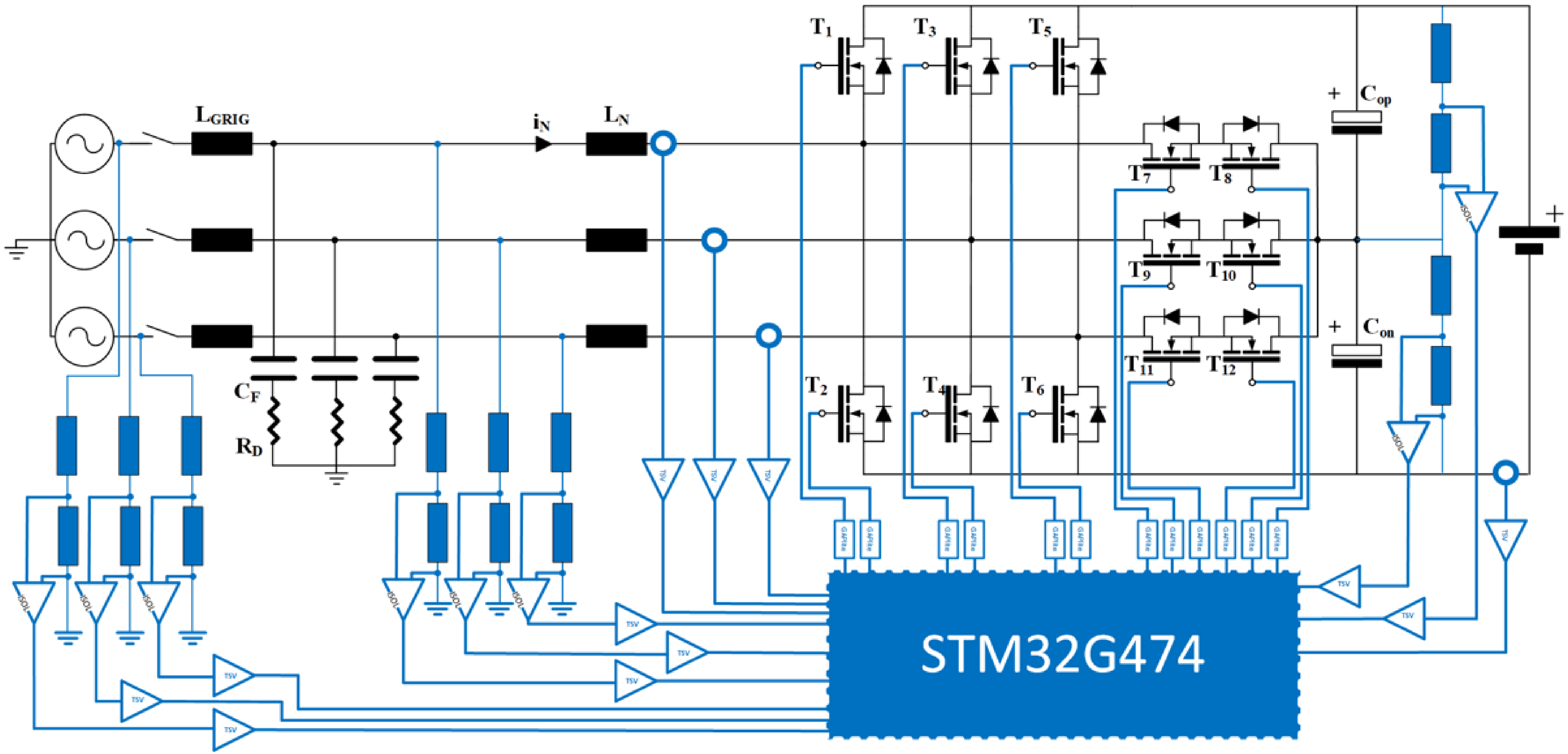
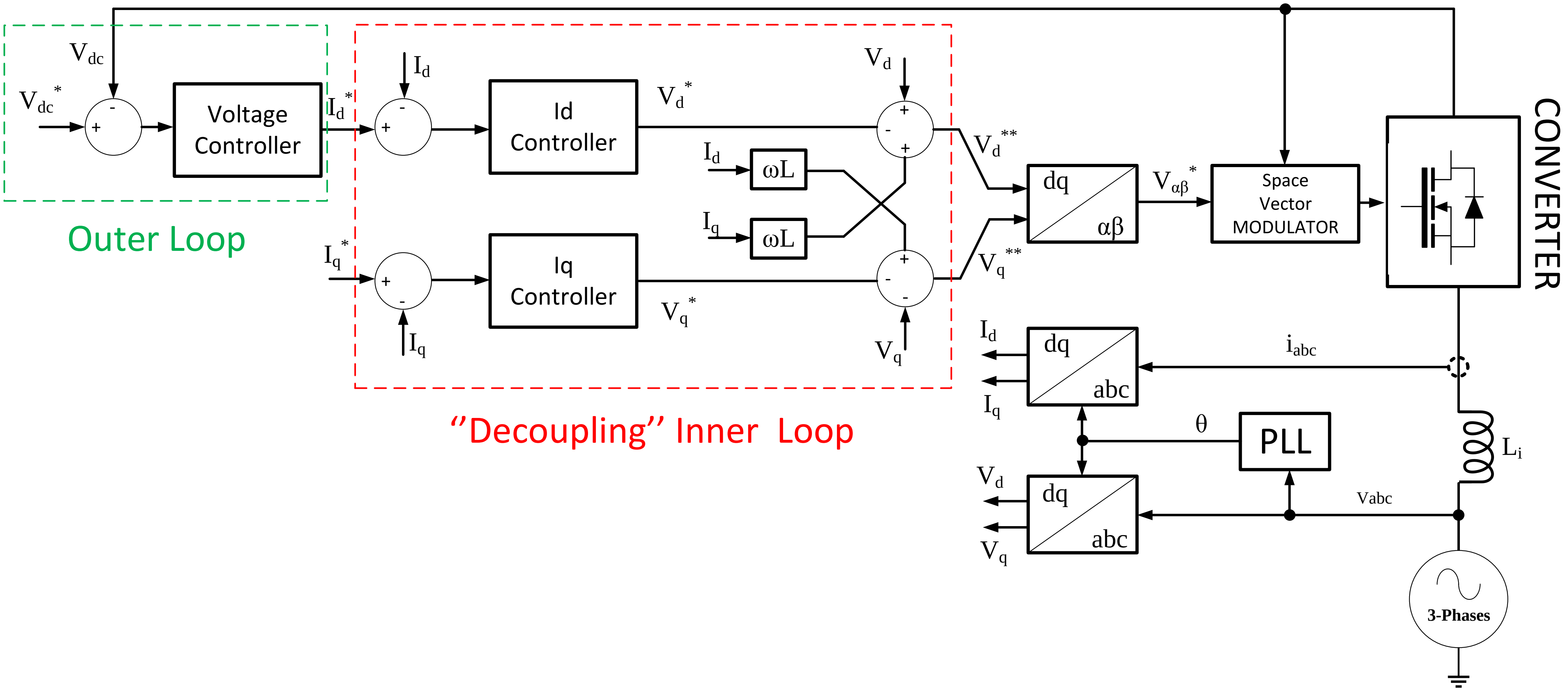
SiC Enabled Topologies

3LTT with Digital control



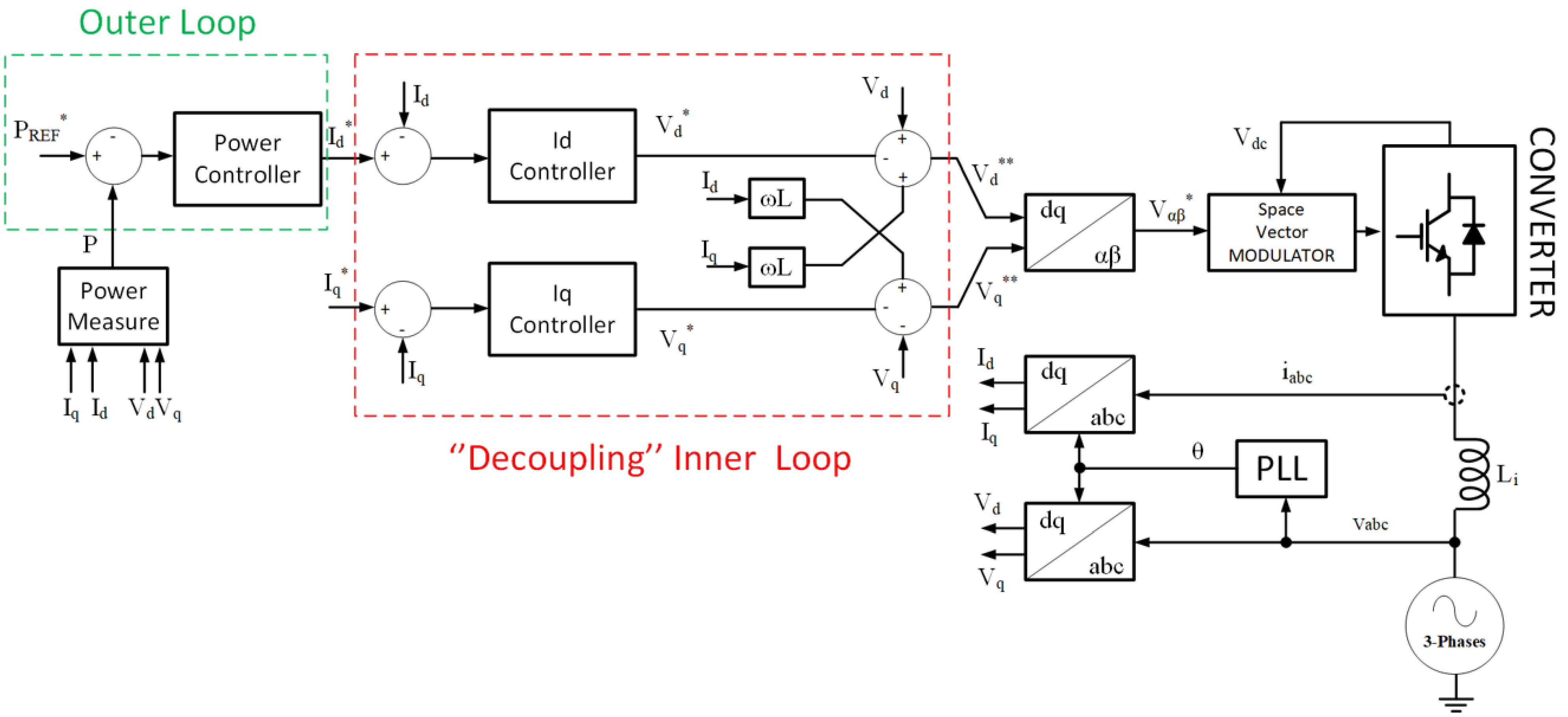
Bidirectional PFC Topology

From grid to battery - Control Strategy AC/DC



Bidirectional PFC – From battery to grid

Control Strategy DC/AC

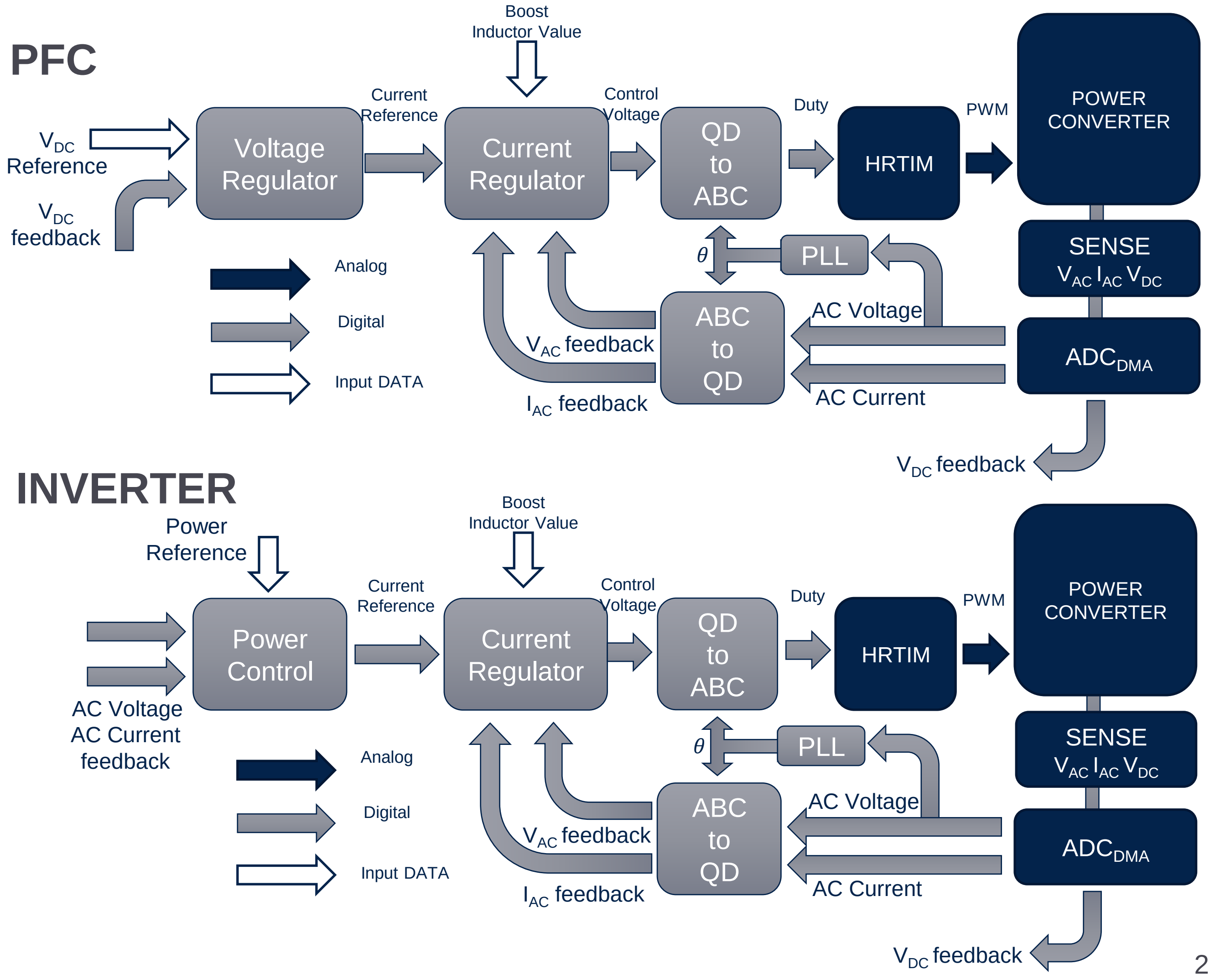


Bidirectional PFC - Control Strategy

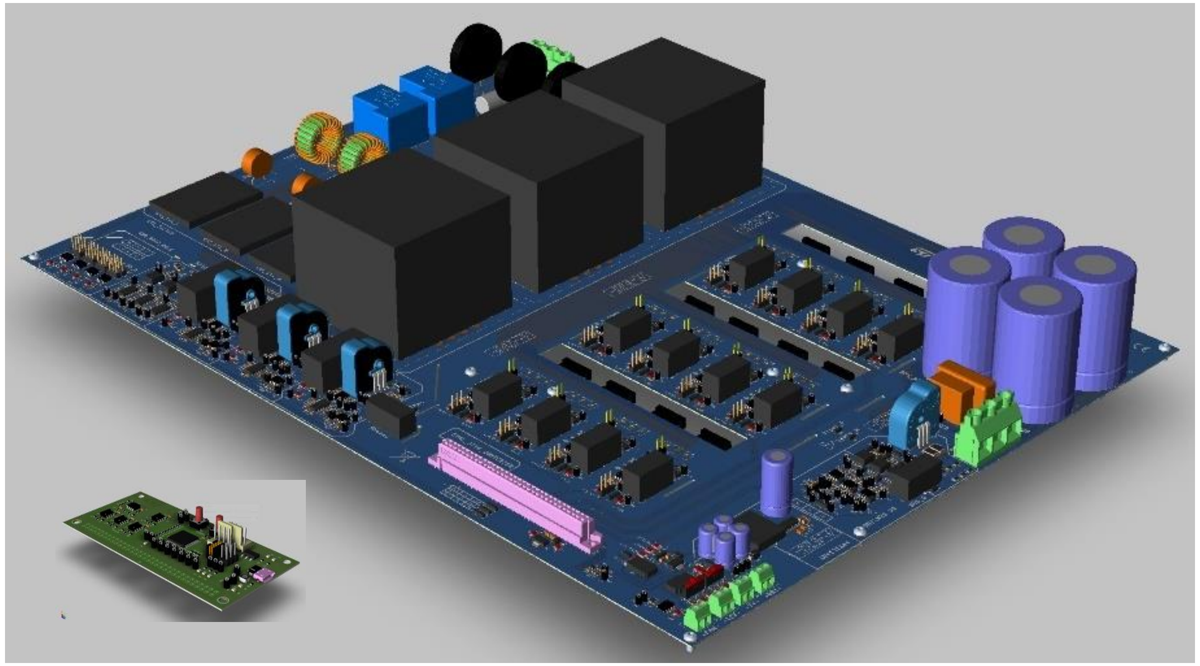
PFC	INVERTER
Sensing	Sensing
Current&Voltage Clarke Park	Current&Voltage Clarke Park
Phase Estimation	Phase Estimation
Voltage Regulator	Power Control
Decoupling Current Regulator	Decoupling Current Regulator
Voltage Inverse Clarke Park	Voltage Inverse Clarke Park
Duty Modulator	Duty Modulator

CONTROLLER FLOW

CONTROLLER FLOW



12kW 3L T-Type Converter PFC



Main specs

- Pout = 12kW @ Vin = 380Vac & Vout =800V
- PF > 0.98 @ 20% load (target)
- THD < 5% @ 20% load (target)
- η>97% @ 20% load (target)
- CCM decoupling current control loop
- Active & Reactive power control
- Grid Connection capability
- Switching frequency = 70kHz
- I_ripple = 2.5A
- VDC_ripple = 10Vpp

Key products

- **STM32G474** (32 bit Microcontroller)
- **SCTW40N120G2V** (70mΩ 1200V SiC MOSFET)
- **SCTW35N65G2V** (55mΩ 650V SiC MOSFET)
- **STGAP2S** (Galvanic Isolated Gate Driver)
- **VIPer26K** (High Voltage Converter)
- **Wurth Power inductor 750344313**

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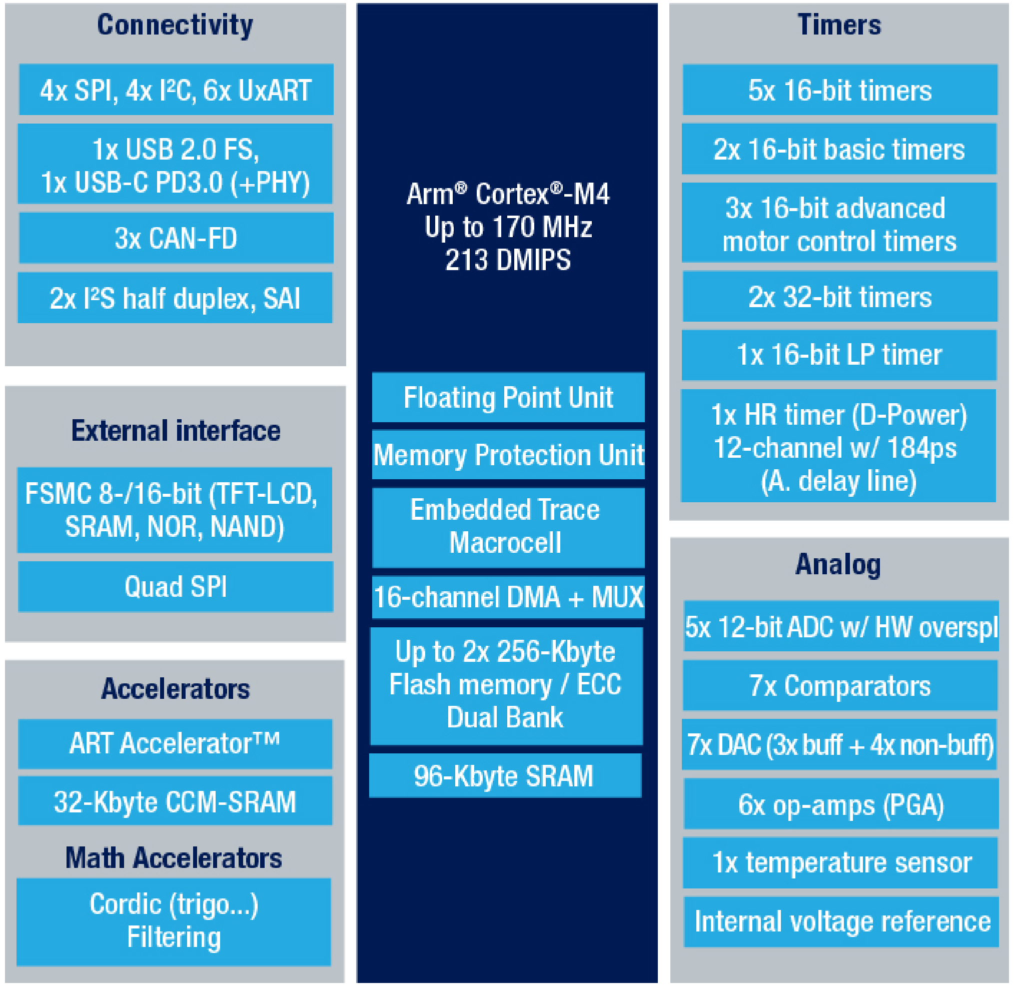
MCU for High Frequency Operations

STM32G4

STM32 G4



Connectivity
- 4x SPI, 4x I²C, 6x UxART
- 1x USB 2.0 FS, 1x USB-C PD3.0 (+PHY)
- 3x CAN-FD
- 2x I²S half duplex, SAI

External interface
- FSMC 8-/16-bit (TFT-LCD, SRAM, NOR, NAND)
- Quad SPI

Accelerators
- ART Accelerator™
- 32-Kbyte CCM-SRAM

Math Accelerators
- Cordic (trigo...) Filtering

Arm® Cortex®-M4
Up to 170 MHz
213 DMIPS

- Floating Point Unit
- Memory Protection Unit
- Embedded Trace Macrocell
- 16-channel DMA + MUX
- Up to 2x 256-Kbyte Flash memory / ECC Dual Bank
- 96-Kbyte SRAM

Timers
- 5x 16-bit timers
- 2x 16-bit basic timers
- 3x 16-bit advanced motor control timers
- 2x 32-bit timers
- 1x 16-bit LP timer
- 1x HR timer (D-Power) 12-channel w/ 184ps (A. delay line)

Analog
- 5x 12-bit ADC w/ HW overspl
- 7x Comparators
- 7x DAC (3x buff + 4x non-buff)
- 6x op-amps (PGA)
- 1x temperature sensor
- Internal voltage reference

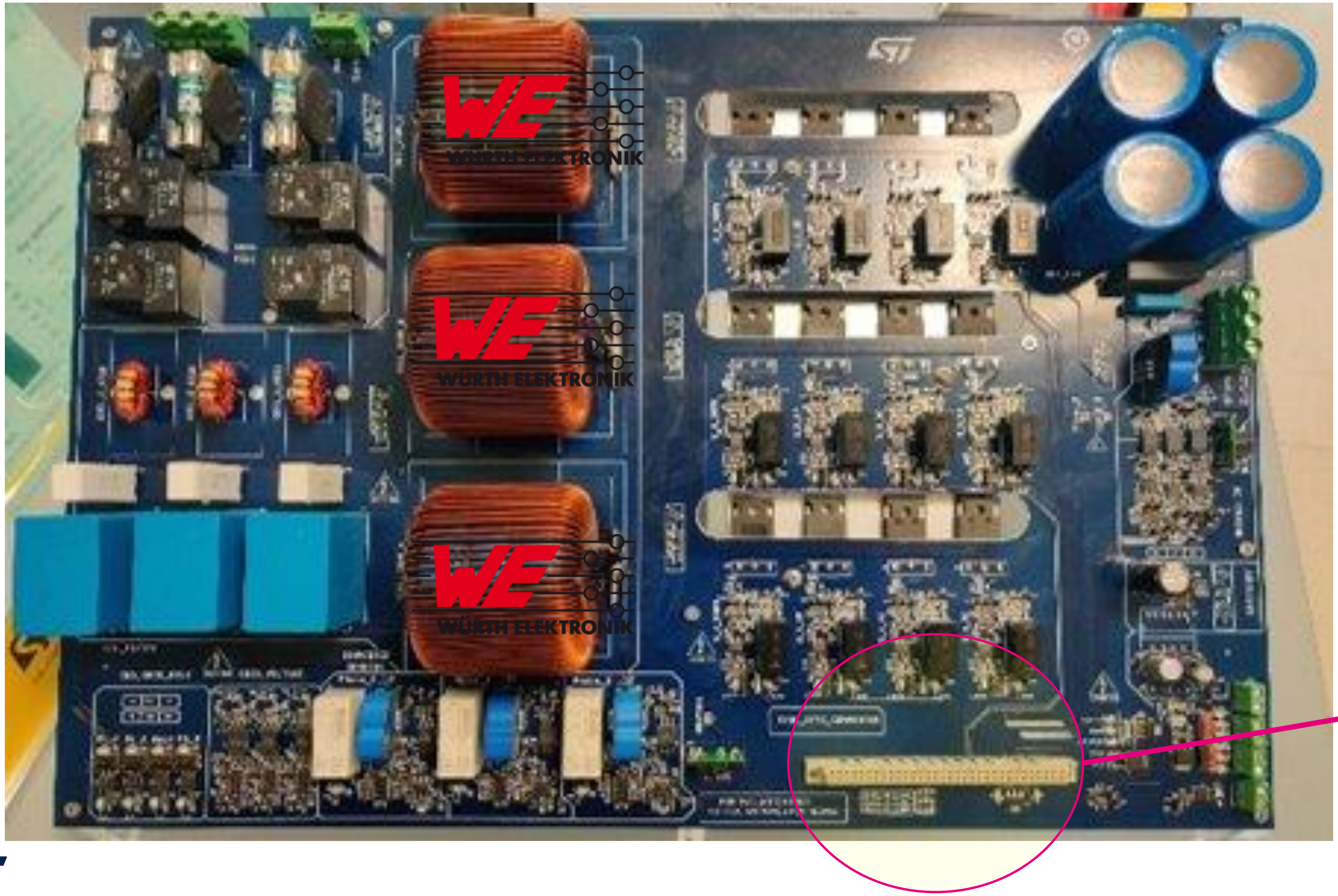
High Resolution Timer

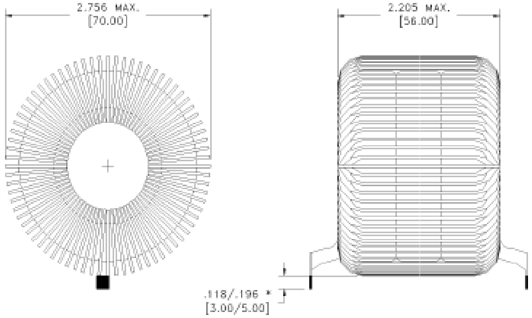
Cordic

3L T-Type Bidirectional PFC

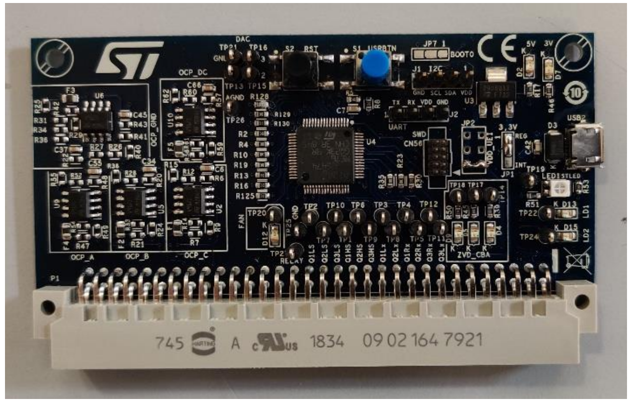
Converter Prototype

15kW Power board





WÜRTH ELEKTRONIK



Control board

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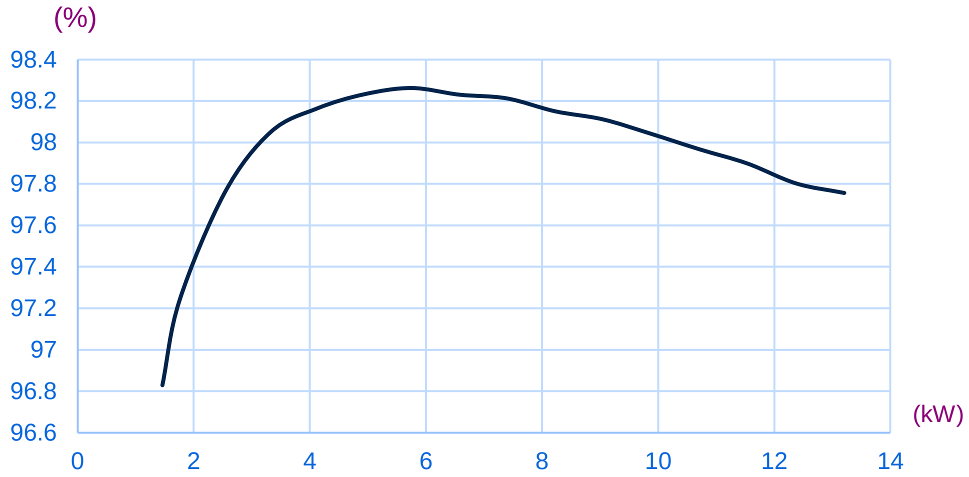
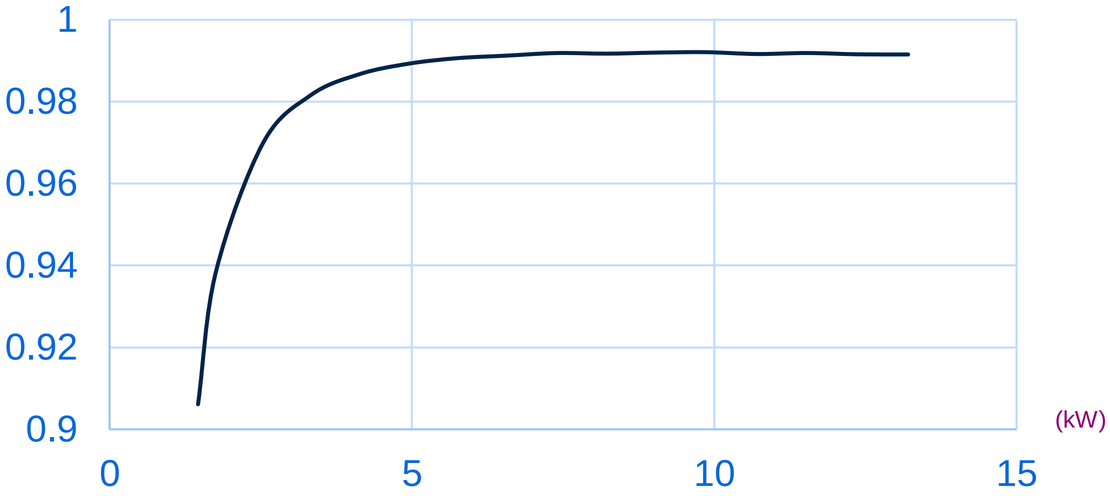
3L T-Type Bidirectional PFC

Main Experimental Results

Efficiency vs Output Power



PF vs Output Power

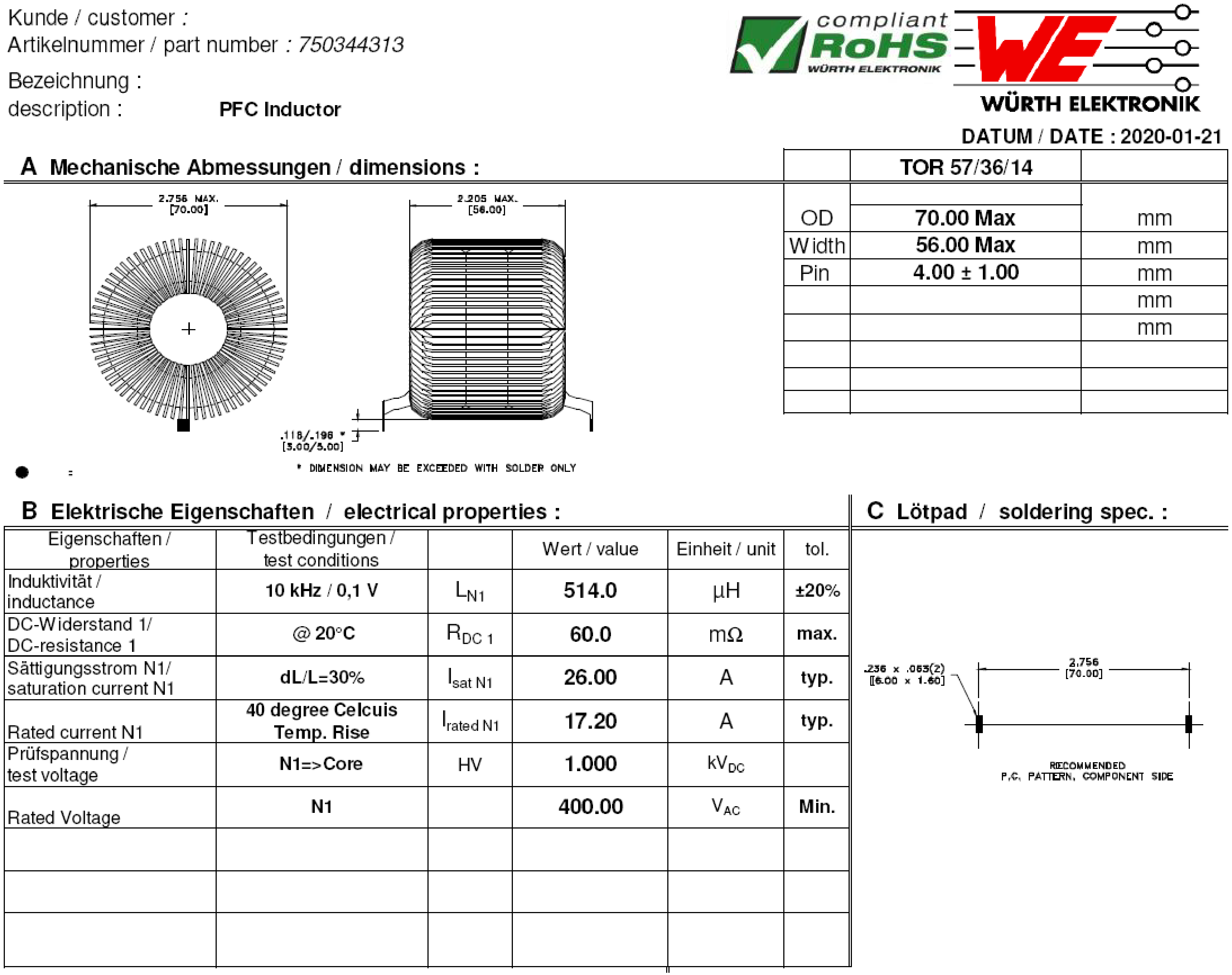


$V_{IN—LN}$ = 230Vac – V_{OUT} = 800V

PFC inductor requirements

- **Low thermal resistance**
- **Low parasitic capacitance**
- **Offline working voltage**
- **Low leakage / low radiated magnetic field**
- **Compact design and easy to mount**
- **High efficiency for high current @ high frequency designs**
- **Typical topology Boost CCM**

CUSTOM SOLUTIONS



Kunde / customer :
Artikelnummer / part number : *750344313*

Bezeichnung :
description : **PFC Inductor**

compliant RoHS WÜRTH ELEKTRONIK

WÜRTH ELEKTRONIK

DATUM / DATE : 2020-01-21

A Mechanische Abmessungen / dimensions :

2.756 MAX.
[70.00]

2.205 MAX.
[56.00]

.118/.196 *
[3.00/5.00]

● =

* DIMENSION MAY BE EXCEEDED WITH SOLDER ONLY

	TOR 57/36/14	
OD	**70.00 Max**	mm
Width	**56.00 Max**	mm
Pin	**4.00 ± 1.00**	mm
		mm
		mm

B Elektrische Eigenschaften / electrical properties :

Eigenschaften / properties	Testbedingungen / test conditions		Wert / value	Einheit / unit	tol.
Induktivität / inductance	**10 kHz / 0,1 V**	L_{N1}	**514.0**	µH	**±20%**
DC-Widerstand 1/ DC-resistance 1	**@ 20°C**	$R_{DC\ 1}$	**60.0**	mΩ	**max.**
Sättigungsstrom N1/ saturation current N1	**dL/L=30%**	$I_{sat\ N1}$	**26.00**	A	**typ.**
Rated current N1	**40 degree Celcuis Temp. Rise**	$I_{rated\ N1}$	**17.20**	A	**typ.**
Prüfspannung / test voltage	**N1=>Core**	HV	**1.000**	kV_{DC}	
Rated Voltage	**N1**		**400.00**	V_{AC}	**Min.**

C Lötpad / soldering spec. :

.236 x .063(2)
[6.00 x 1.60]

2.756
[70.00]

RECOMMENDED
P.C. PATTERN, COMPONENT SIDE

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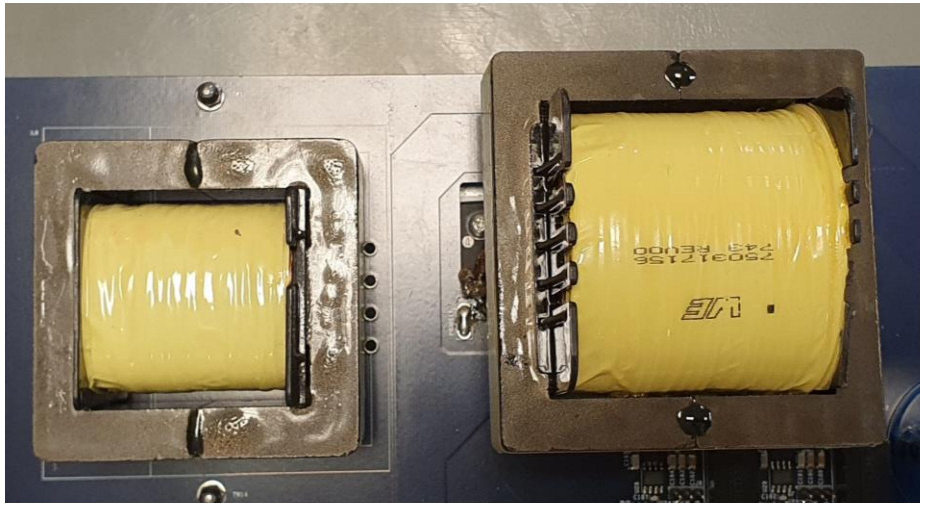
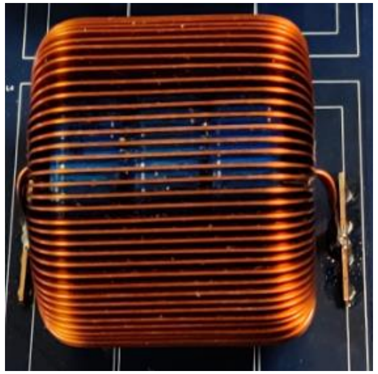
Relative Cost Factor

Package (WE Part Number)	**Relative Cost Factor**
EE65 (750316915)	**1**
EE80 (750317156)	**3.85**
Tor (750344310)	**0.72**





Conclusions

- **Charging stations** are an emerging application in the Industrial market driven by Car Electrification;
- The demand of **DC charger** with output power up to 50kW is increasing at fast pace;
- **Bidirectional** functionality is becoming a requested feature due to Smart Grid implementation of V2G architecture for Grid regulation and storage;
- The **Front End converter** represents the connection with the Grid and has to manage it with high efficiency and smart operations at reasonable cost;
- The introduction of **Silicon Carbide** in Power MOSFET technology has disrupted the efficiency paradigm of high frequency operations;
- Well-known power converter topologies have been rivitalized by **SiC MOSFETs** despite of Si IGBT lower cost thanks to superior performance in terms of efficiency, size and overall cost.

Thank you

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