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Revolutionizing high-power AI server PSU: ORv3 5.5kW AI Server Power Platform

Interleaved TTP PFC - the advantages of hybrid TCM/CCM control over pure TCM Three phase LLC converter

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December 12, 2025

Agenda

1 Background

2 Introduction of mixed TCM/CCM

3 Implementation in interleaved TTP PFC

4 Implementation Three phase LLC

5 Experimental test waveform

6 Summary

Trends in AI server PSUs

- Increased power demand
- Efficiency and energy consumption management
- Increased power density
- Advanced control strategies
- Modularity and scalability
- Enhanced cooling and thermal management
- Redundancy and reliability

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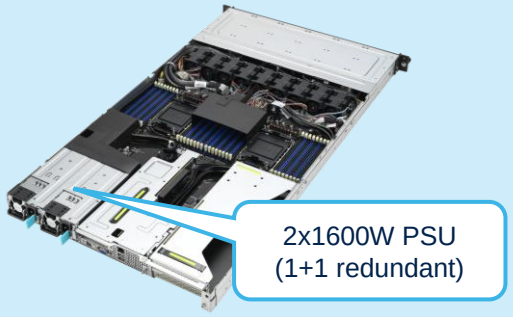
Power requirements in AI servers

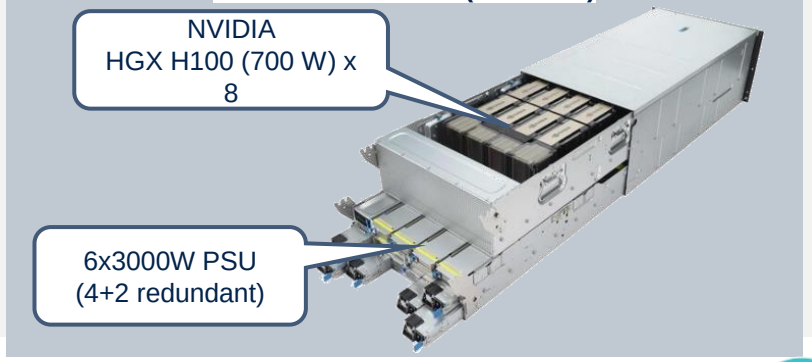
To support GPUs, AI servers require 3~10 times higher power than traditional servers

The GPU, which supports 48 V, has changed the output of the PSU from 12 V to 48/54 V and has become the mainstream in the market.

ASUS: RS700-E11-RS12U (Server)

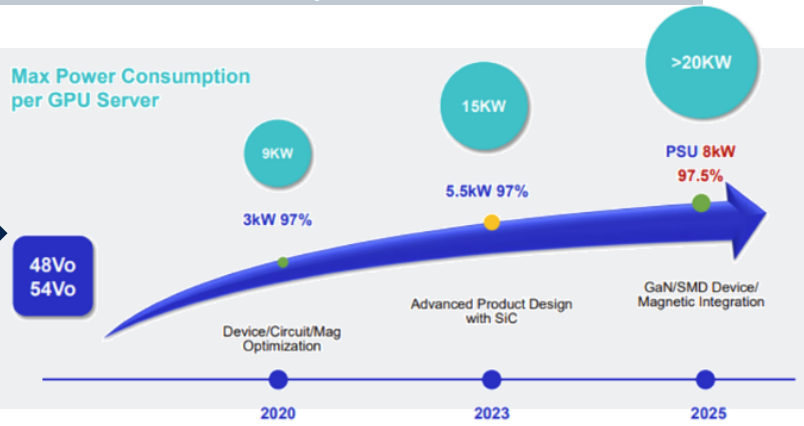


ASUS: ESC-N8-E11 (AI server)



Lite-on advocate single PSU power levels to rise to 5.5~8 kW in 2025 due to AI server applications. GaN and SiC devices are the best solutions to boost efficiency.

	2019	2020	2021	2022	2023	2024
Intel		Purley 800W		Whitley 1200–1600W		Eagle Stream 1600–2000W
AMD		Rome 800W		Milan 1200–1600W	Genoa 1600–2000W	Turin 2000W–3200W



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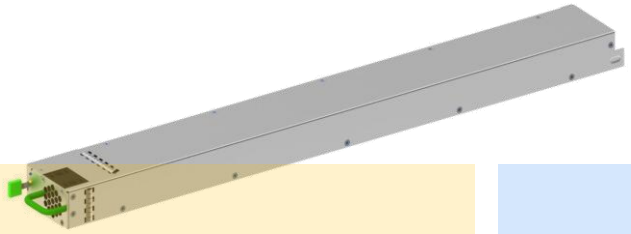
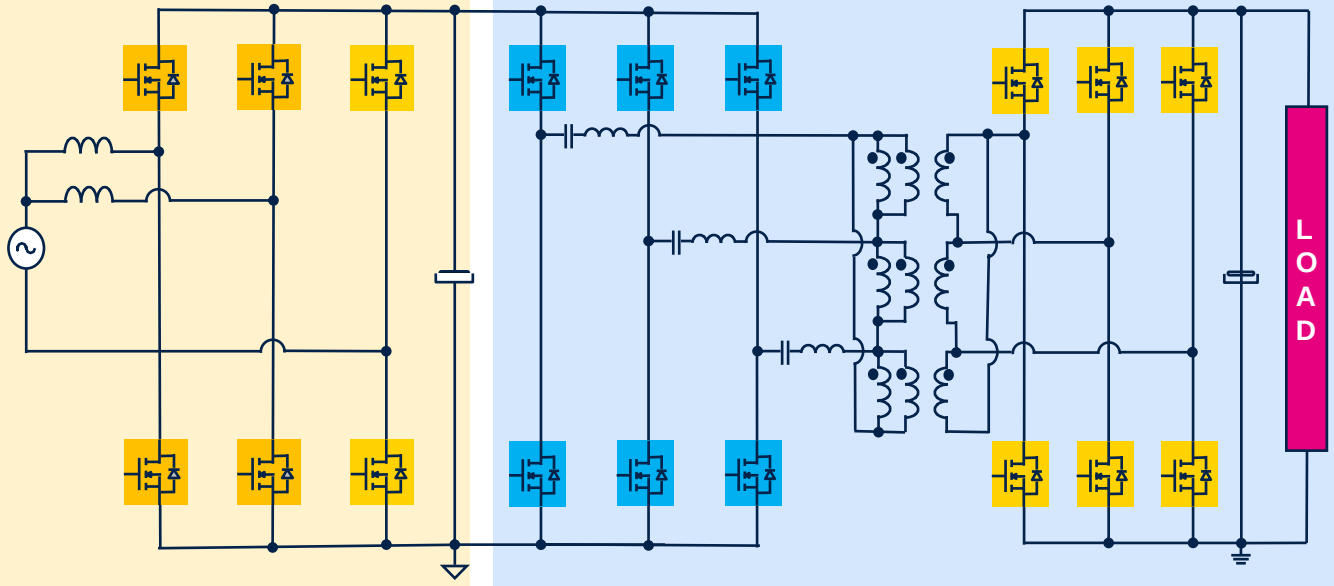
Proposed topology for 5.5 kW AI server power





Interleaved mixed mode
Totem pole PFC
η>99.2%

3-phase LLC
η>99.0%

Key specifications:

- Fully digital AC-DC power supply
- Input AC voltage: 180-305 VAC
- Input AC frequency: 47-63 Hz
- DC output voltage: 48-50 Vdc
- Peak efficiency:
  - 97.5% @ 230, 240, 277 Vac with 30-100% load
  - 96.5% @ 208 Vac with 30-100% load

  Min efficiency:
  - 96.5% @ 230, 240, 277 Vac with 30-100% load
  - 95.5% @ 208 Vac with 30-100% load
- Power Factor >0.98 @ 100% load
- iTHD < 5% @ 100% load
- Outline dimension: 73.5 x 640 x 40 mm
- Power density up to 50 W/inch³
- Peak inrush current <30 A

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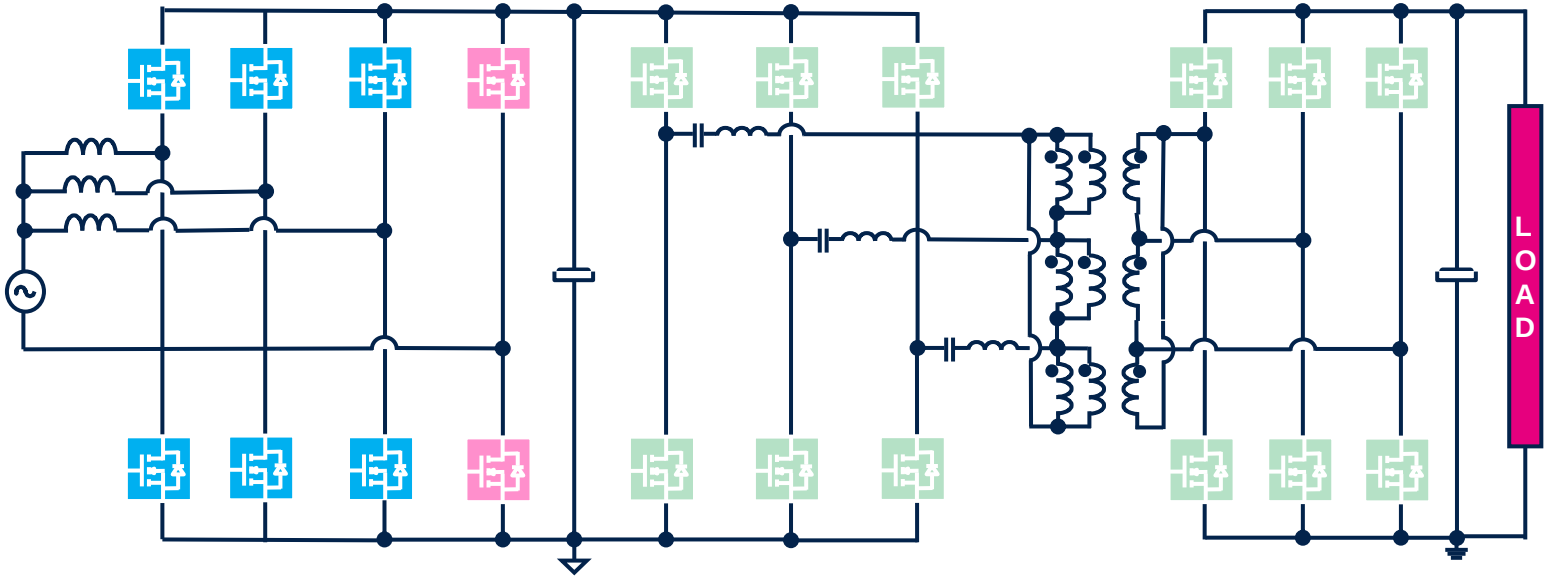
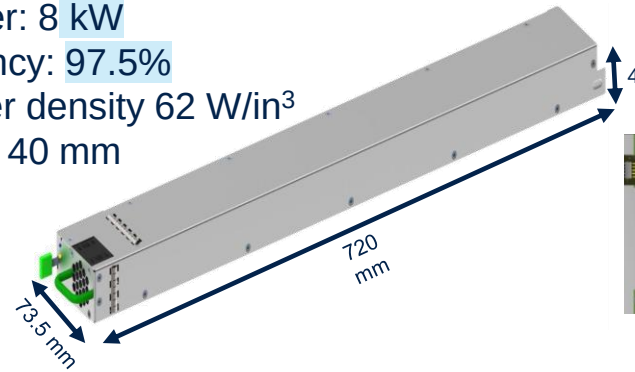
Proposal of topologies for 5.5~12 kW AI server power

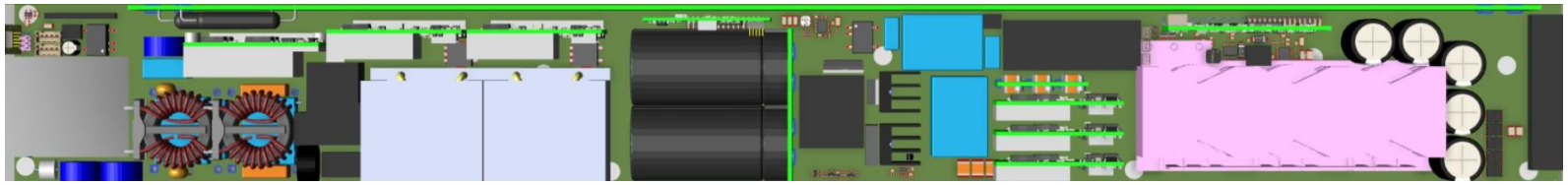
PFC	ST P/N	Vds max (V)	$R_{DS(on)}$(mΩ)	Package
Fast leg	SCT040TO65G3 SCT027TO65G3	650	55 (Max)	TOLL
Slow leg	Si MOS	650	Expected <15mΩ, lower is better	TOLL
Driver for SiC FET	STGAP2SICS	1200	-	SO-8
Driver for Si FET	STGAP2S	1200	-	SO-8

DC-DC	ST P/N	Vds max (V)	$R_{DS(on)}$ (mΩ)	Package
Si FET	STO60N045DM9 SCT040TO65G3 SCT027TO65G3	600 650 650	65 (Max) 40 (Max) 27 (Max)	TOLL
Driver for Si FET	STGAP2HS STGAP2SICS		-	SO-8W SO-8
Si FET	Si MOS	80 V	Expected <1.5mΩ, lower is better	PF5*6 or PF8*8



- Output power: 8 kW
- Peak efficiency: 97.5%
- Higher power density 62 W/in^3
- 73.5 x 720 x 40 mm

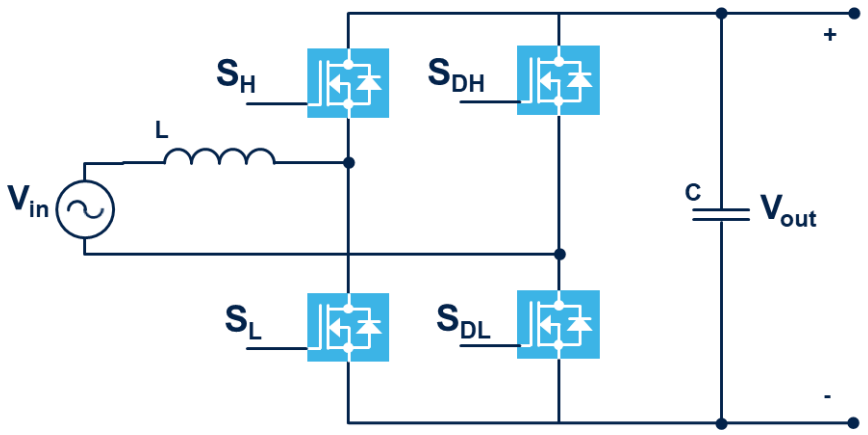




Introduction of Mixed TCM/CCM

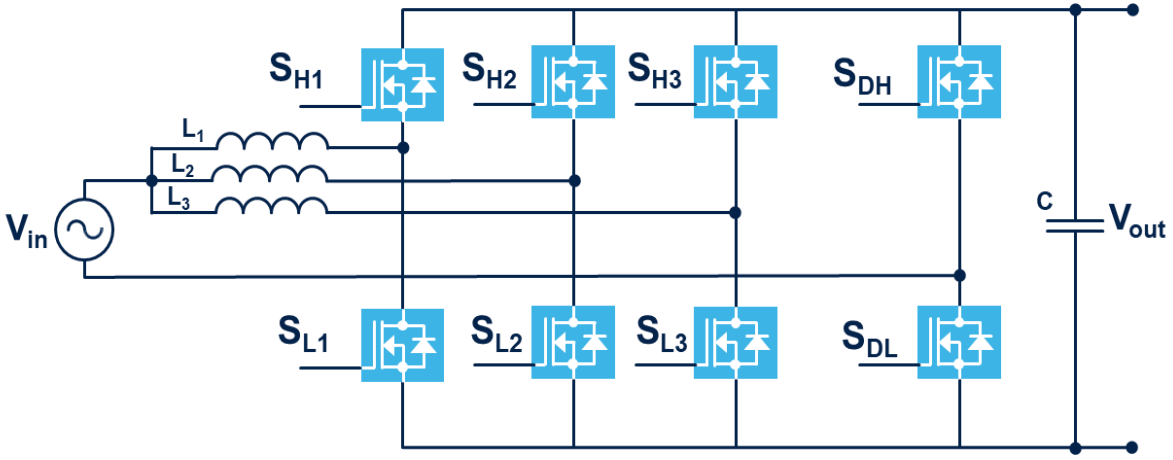
Totem pole PFC architecture

Totem pole bridgeless PFC boost rectifier
Single channel configuration



Main features
- Boosted efficiency thanks to the bridgeless configuration and synchronous rectification
- Minimum number of components
- Require WBG transistors in CCM

Totem pole bridgeless PFC boost rectifier
Three-channel interleaved configuration



Interleaving (and phase shedding) main advantages
- Flat efficiency curve
- Light-load efficiency improvement
- EMI filter and inductor volume reduction
- Lower output capacitor RMS current
- Better thermal management

Control strategy in PFC

4 types control strategies

- CCM: current continuous mode
- DCM: discontinuous current mode
- CRM: critical conduction mode
- TCM: triangle current mode

Characteristic	Triangular current mode (TCM)	Continuous current mode (CCM)
Switching frequency	Variable frequency	Fixed frequency
Current waveform	Triangular	Continuous
Switching losses	Low	High
Electromagnetic Interference (EMI)	Low	High
Control complexity	High	Low
Applicable power Range	Light load	High power
Current Ripple	High	Low
Suitable applications	Light load, high efficiency	High power, high stability

Advantages of mixed TCM/CCM

Optimized efficiency:

The hybrid strategy can switch between TCM and CCM based on load conditions, optimizing efficiency across a wide range of operating points.

TCM is more efficient at light loads due to reduced switching losses, while CCM is more efficient at higher loads due to lower conduction losses.

Reduced ripple current:

Interleaving two phases helps in significantly reducing the input and output current ripple.

The hybrid approach can further optimize ripple reduction by dynamically adjusting the operating mode.

Enhanced thermal management:

Distributing the load between two phases and switching between TCM and CCM can lead to better thermal performance and more balanced heat dissipation.

Improved transient response:

The ability to switch between TCM and CCM allows the system to quickly adapt to changes in load, providing a better transient response.

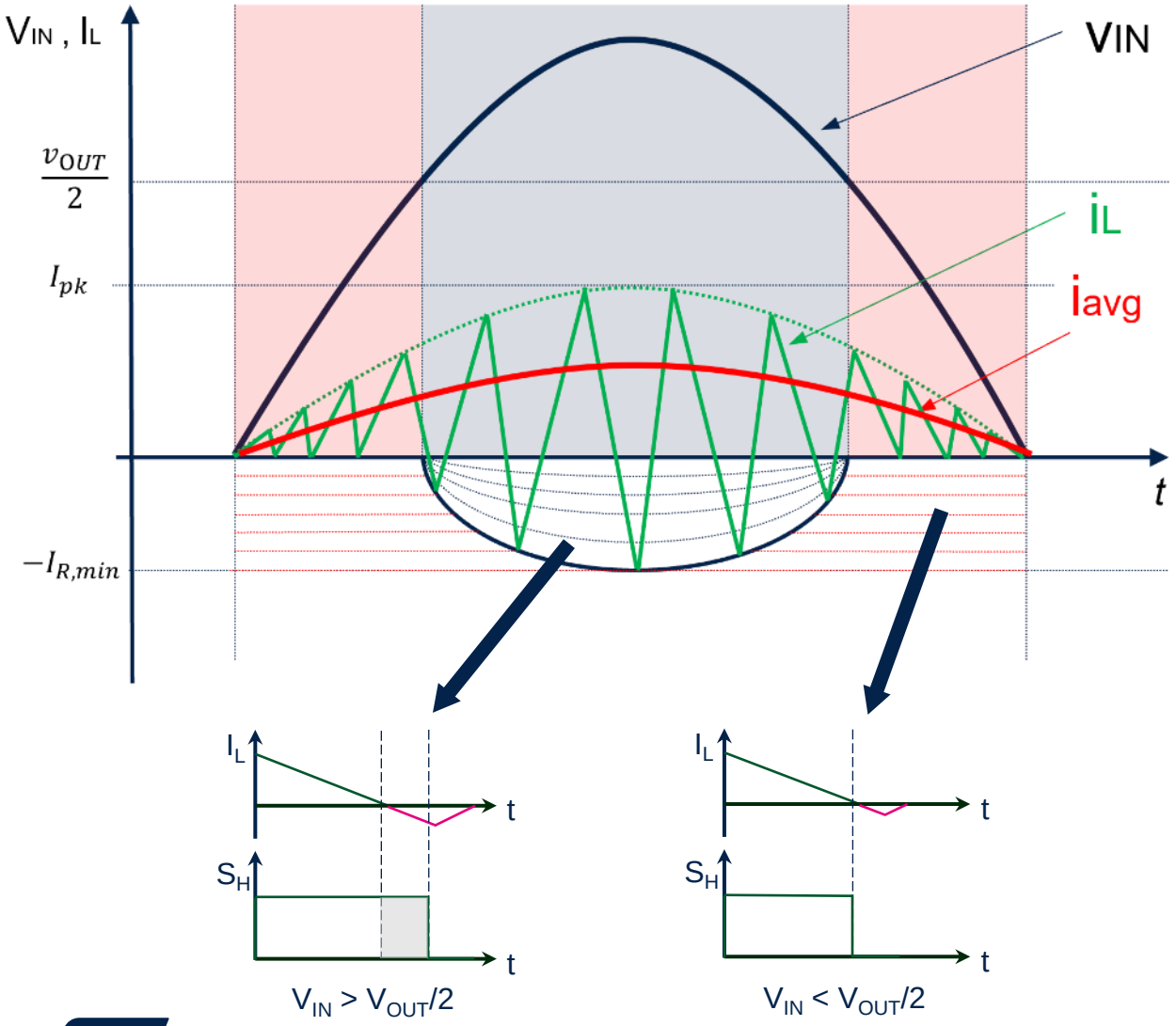
Flexibility and reliability:

The hybrid control strategy offers flexibility in design and application, making it suitable for various operating conditions.

It can enhance the reliability of the PFC circuit by reducing stress on components and improving thermal management.

Implementation in interleaved TTP PFC

Hysteresis current control



Advantages

- No need compensation ramp in all operative modes (CCM, TM, or resonant mode).
- Very fast response: cycle by cycle control
- Flexibility on changing the working mode (from CCM to TM or from TM to resonant)

Disadvantages

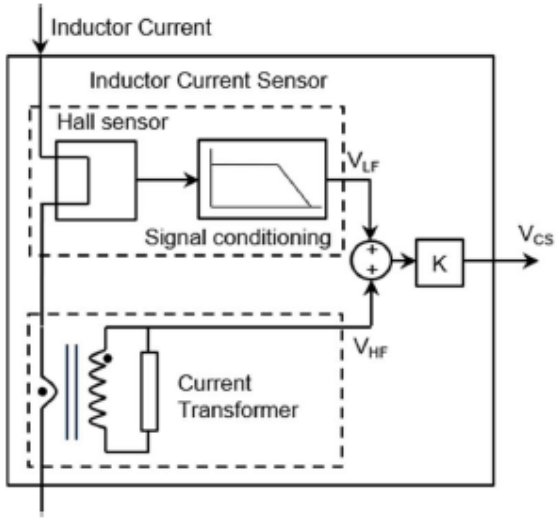
- Variable switching frequency
- High switching frequency near zero-crossing or very close hysteresis thresholds

C. Marxgut, F. Krismer, D. Bortis and J. W. Kolar, "Ultraflat interleaved triangular current mode (TCM) single-phase PFC rectifier," *IEEE Trans. Power Electronics*, vol. 29, no. 2, pp. 873-882, Feb. 2014.

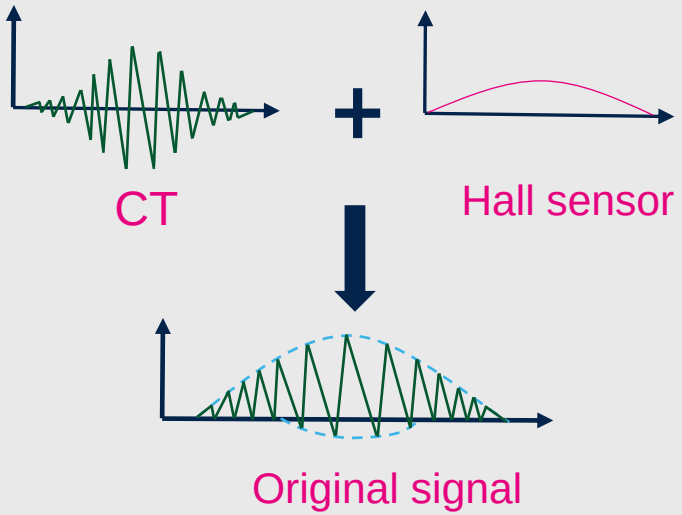
Inductor current sense

Hysteresis current control

- Challenge:
  - Inductor current sensing
- Current sensor requirement:
  - Isolation
  - Bidirectionality
  - Low loss
  - Fast response/OCP protection.
  - High bandwidth
- Solution:
  - Compound sensor (Hall sensor + current transformer)
  - High bandwidth Hall sensor (1.5 MHz sensor under evaluation)



- **CT:** High bandwidth for AC component
- **Hall:** Low bandwidth, for average component

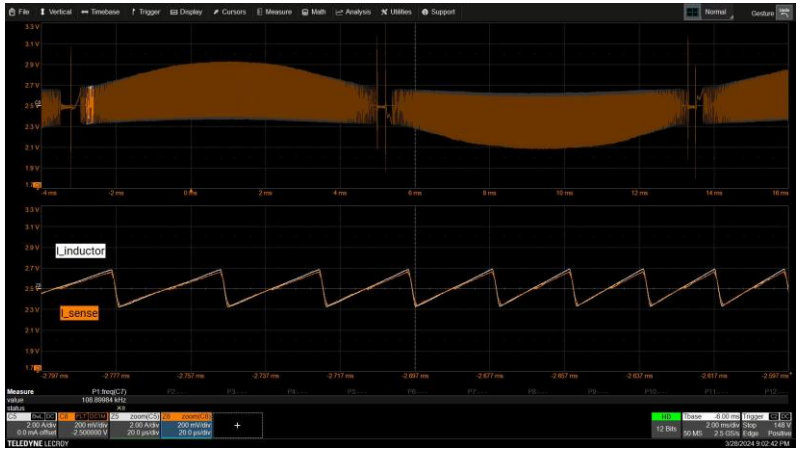


Waveform – near zero

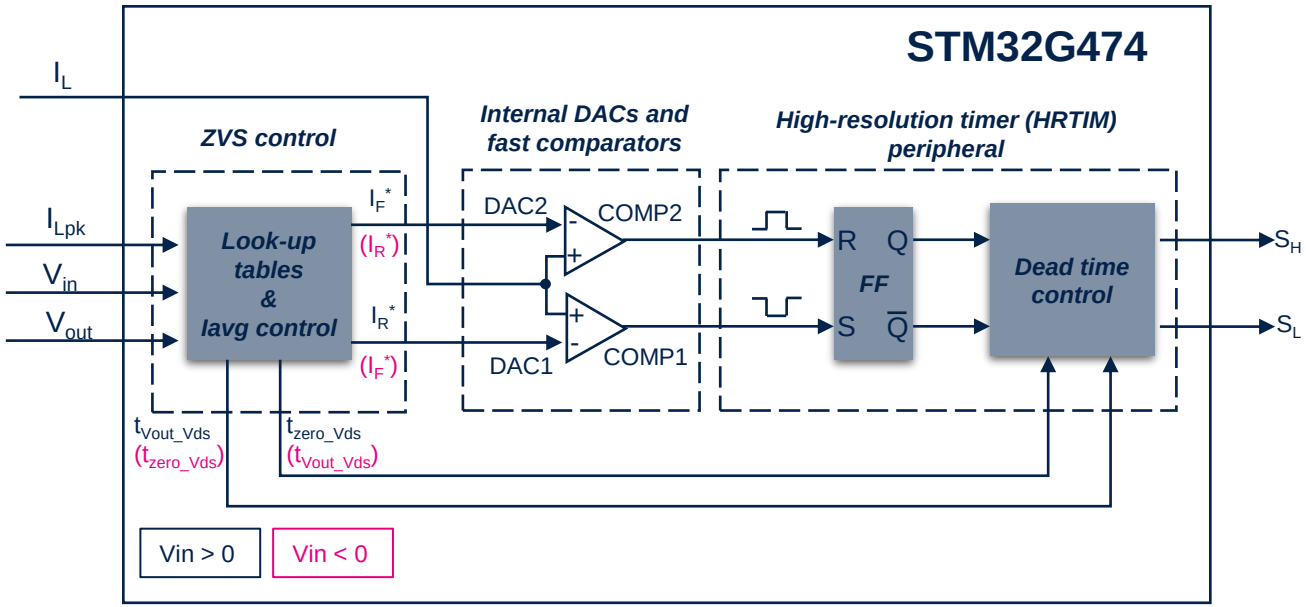
The sensed signal to the MCU matches exactly with the real inductor current

Inductor current vs sensed signal to MCU

Actual waveform from the board
inductor current vs. sensed signal to MCU



ZVS with hysteresis current control: Implementation with STM32G474

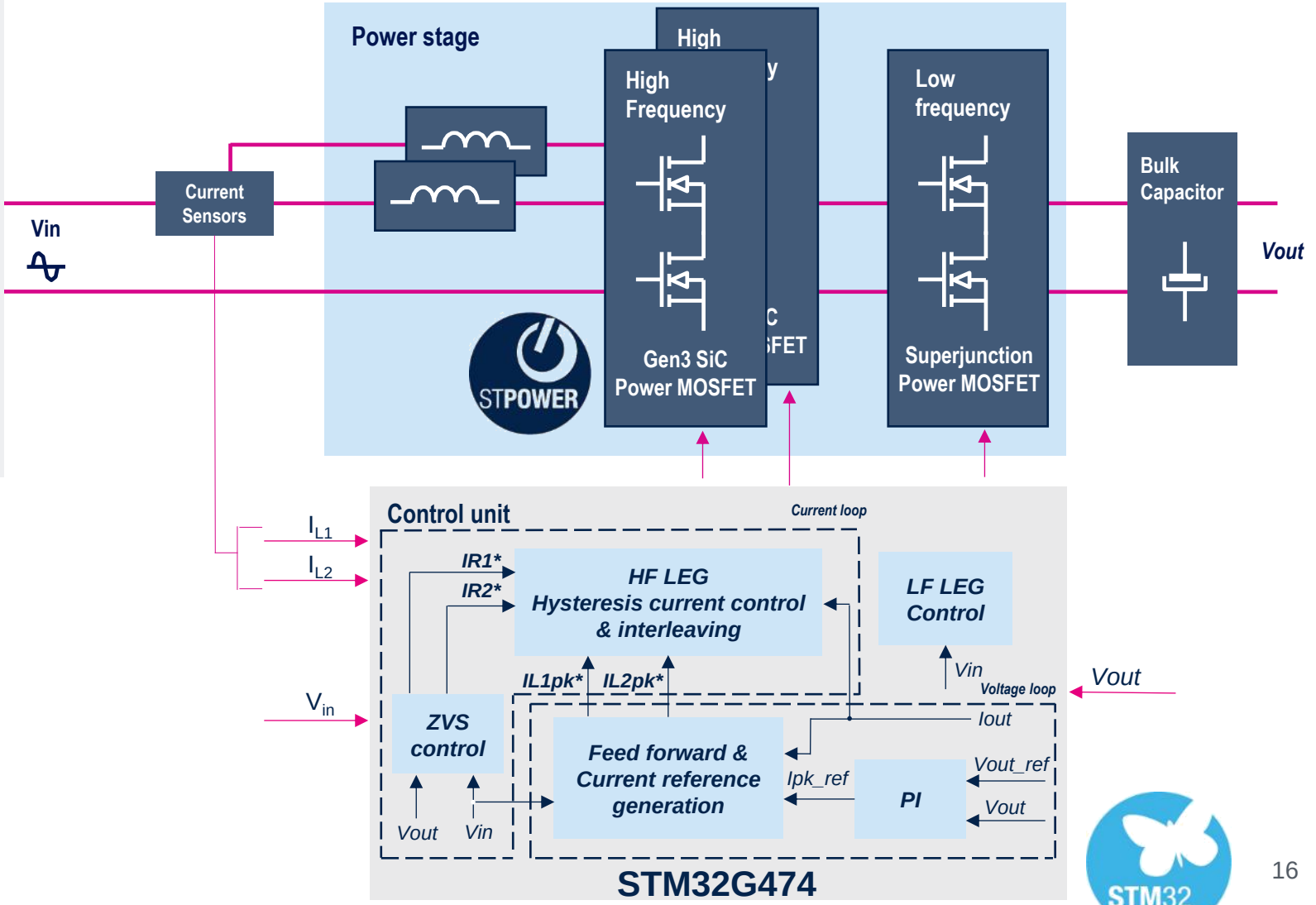


ZVS	Look-up tables for current threshold and dead-time selection
Hysteresis control	Implemented with internal DACs and fast comparators
HRTIM	High-resolution timer (HRTIM) used to provide the driving signals to the high-frequency leg S_H,S_L

Hysteresis current control

Control loop:

- The outer voltage loop for output voltage regulation runs at 1 kHz.
- The inner current loop for inductor currents control runs at 40 kHz.
- Input and output feedforward control to prevent output voltage fluctuations.



Implementation Three-phase LLC

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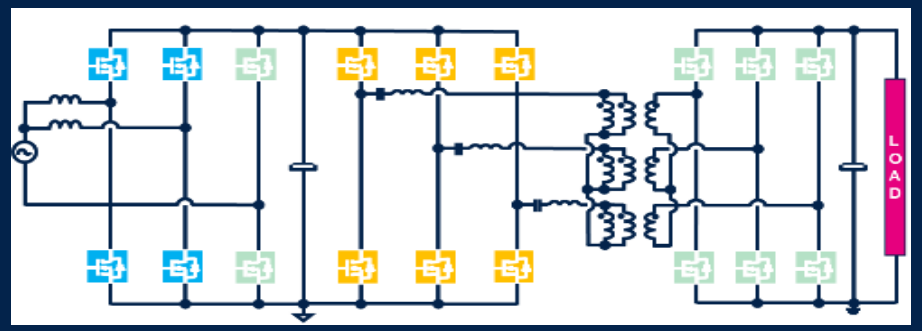
ST PECC ORv3 5.5kW AI Server PSU

Interleaved Totem Pole PFC + 3-phase LLC (PE.SP_0015.24)



Key features:

- ORv3 5.5kW PSU Physical Dimensions
- ORv3 5.5kW Electrical Specification
- Mainstream Power Density = 50W/inch3
- Cutting-Edge Topologies
- Augment ST BOM

Key products

PFC:

- SCT040TO65G3 x4 (SiC FET)
- STGAP2SICS x4 (SiC FET driver)
- STO60N030M9 x4 (Si FET)
- STGAP2SM x2 (Si FET Driver)
- STM32G4 x1 (32-bit MCU)
- STPM32 (Metering solution)

LLC:

- STO60N045DM9 x6 (Si FET)
- SCT040TO65G3 x6 (SiC FET)
- SCT027TO65G3 x6 (SiC FET)
- STGAP2HSMTR x6 (Si FET Driver)
  STGAP2SICS x6 (SiC FET driver)
- STL180N8F8 x 36 (Si FET)
- STM32G4 x1 (32-bit MCU)

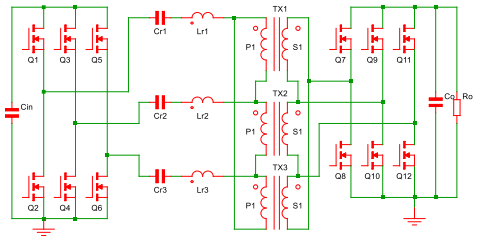
Key benefits

- Peak efficiency > 97.5% (Including fan power loss)
- ORv3 compatible

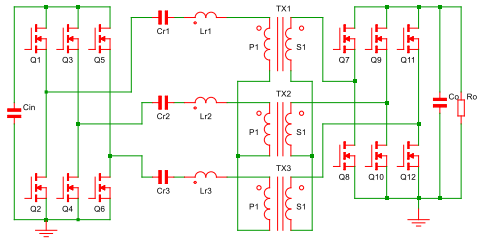
Aux power:

- VIPERGAN65D x1

Comparison between Delta and Wye connection



Delta-Delta



Wye-Wye

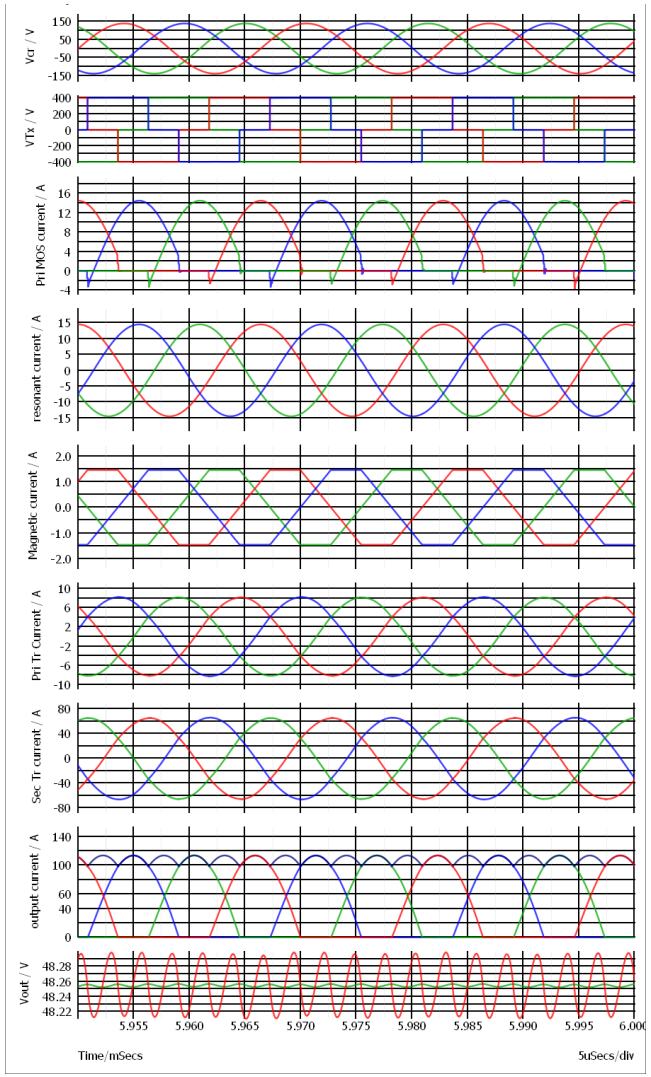
- Simulation Parameters

Input voltage	400V
Switching frequency	61kHz
Dead time	250ns
Load	445mΩ
Magnetic inductance Lm	750uH for delta 250uH for Wye
Resonant inductance Lr	25uH
Resonant capacitance Cr	272nF
Turns ratio	24:3

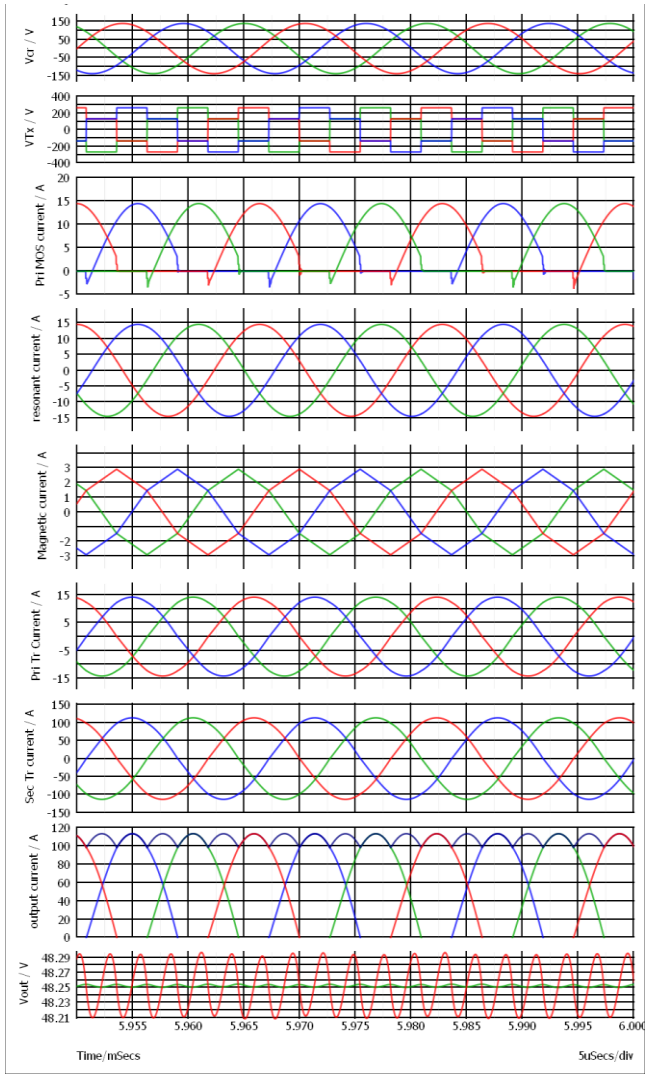
[Conclusion]

- Same current stress of pri MOS and SR MOS
- Same voltage stress of resonant capacitor
- Current stress of transformer for wye connection is $\sqrt{3}$ times of Delta connection
- Voltage stress of transformer for wye connection is 1/ $\sqrt{3}$ times of Delta connection

Delta-Delta

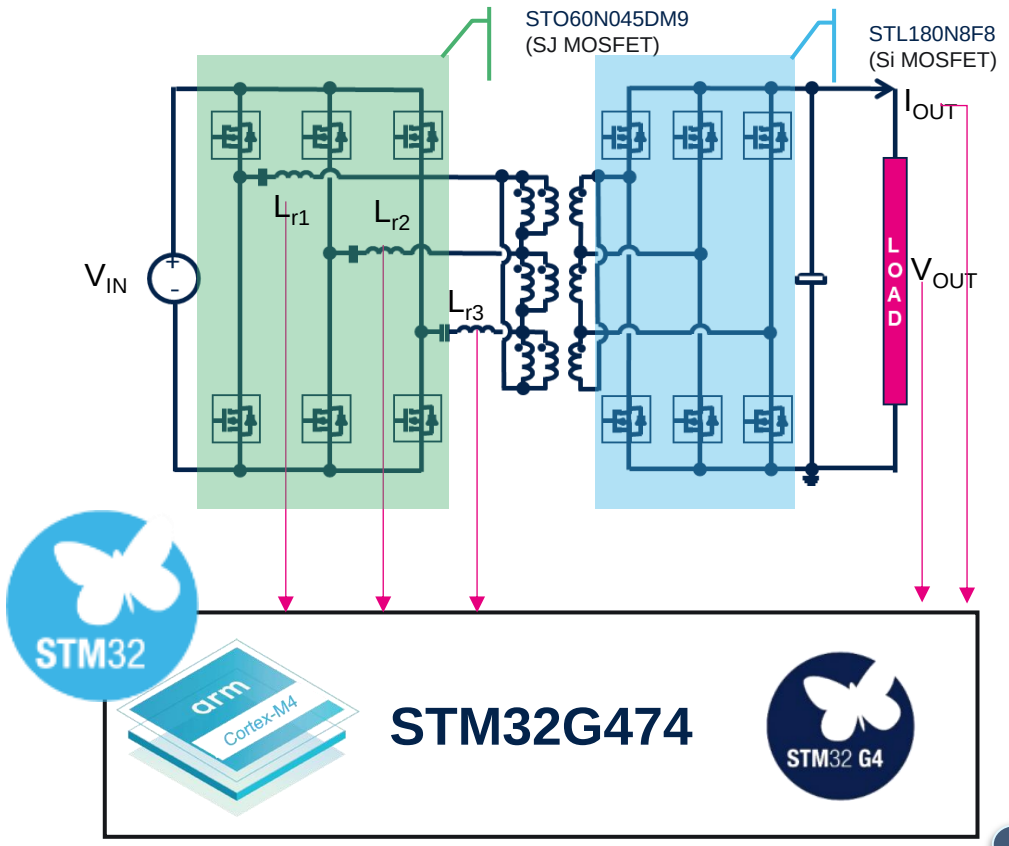


Wye-Wye



MCU requirement
5.5 kW three-phase LLC

3-ph interleaved resonant LLC converter with synchronous rectification



CPU (Cotex-M4)

40kHz(?) execution for control loop (Voltage loop/ HOTC)

8kHz (?) execution for current sharing control between different PSUs

PWM timer (HRTIM)(12 channel)

High flexibility for managing primary PWM (6 channel) and secondary SR PWM (6 channel)

Comparator & DAC (≥5)

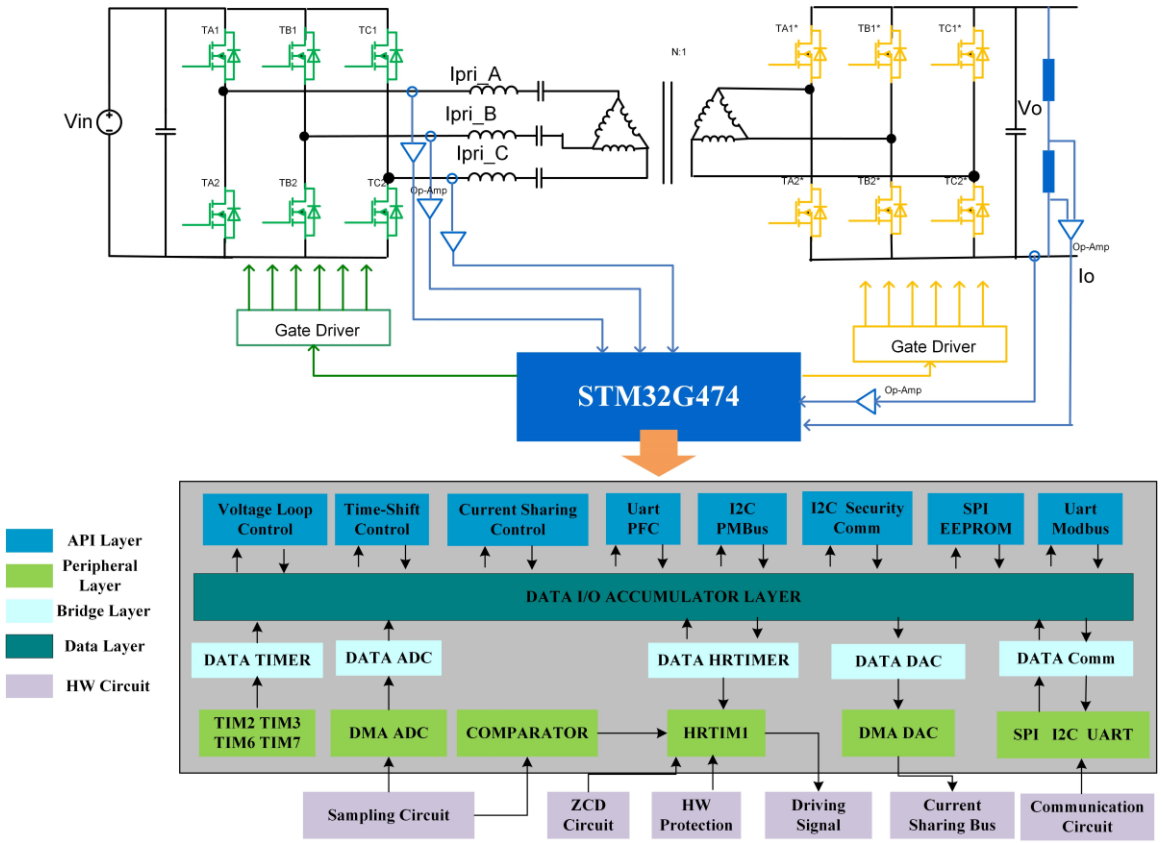
Resonant current cycle by cycle control *3

Output OVP, OCP

ADC (≥2 module, ≥9 channel)

Signal sensing for primary resonant current *3, output voltage, output current, average current, oring circuit voltage and temperature *2

LLC Functional diagram



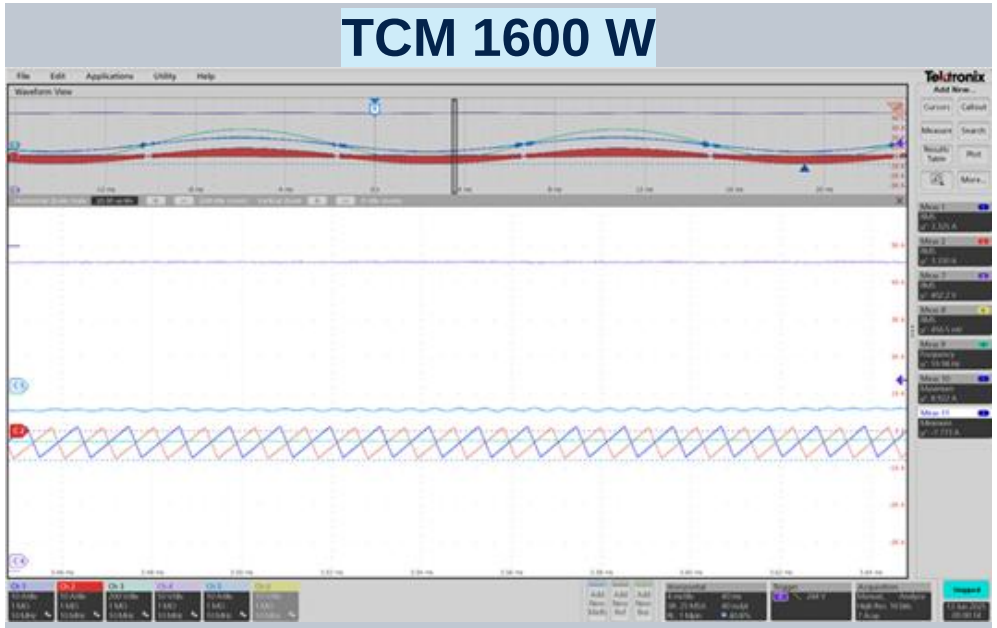
Key features based on digital control

- Soft start control
- Voltage loop control
- Current mode control
- SR control for higher efficiency
- Current sharing control between PSUs
- Resonant current cycle by cycle control
- Software protection
- Hardware protection
- Communications

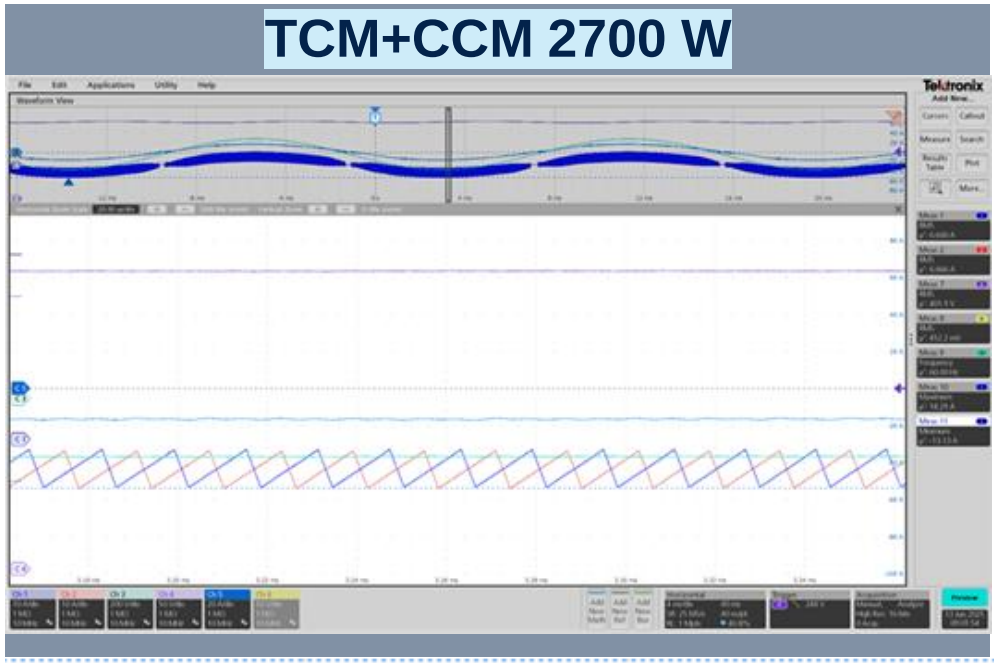
Experimental test waveform

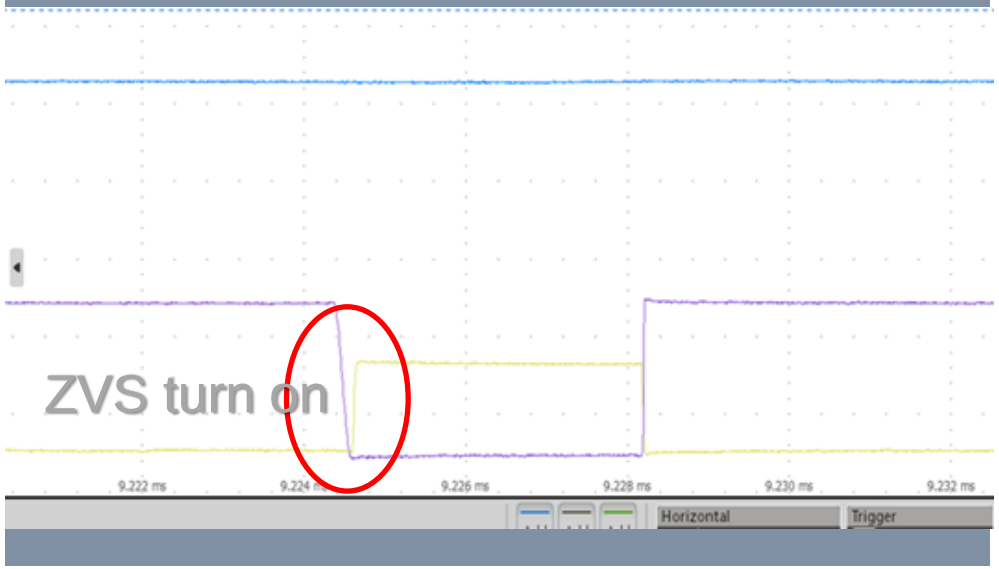
TCM test results

TCM 1600 W



TCM+CCM 2700 W





Key benefits

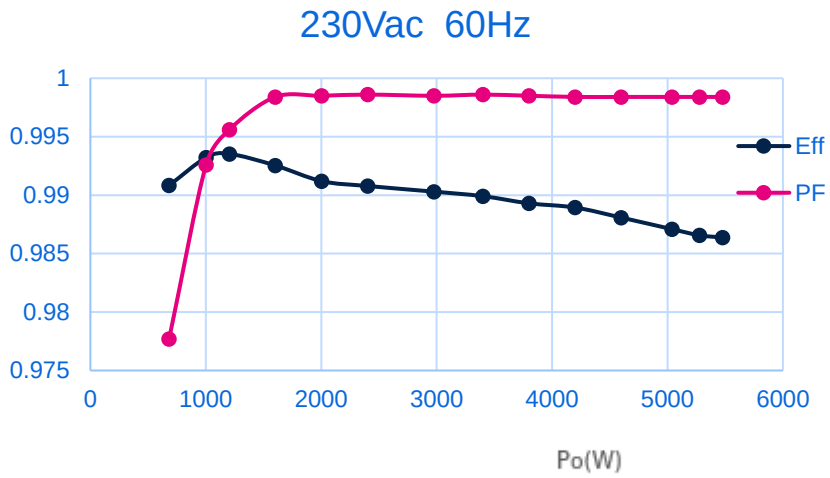
Mixed mode control (TCM/CCM)

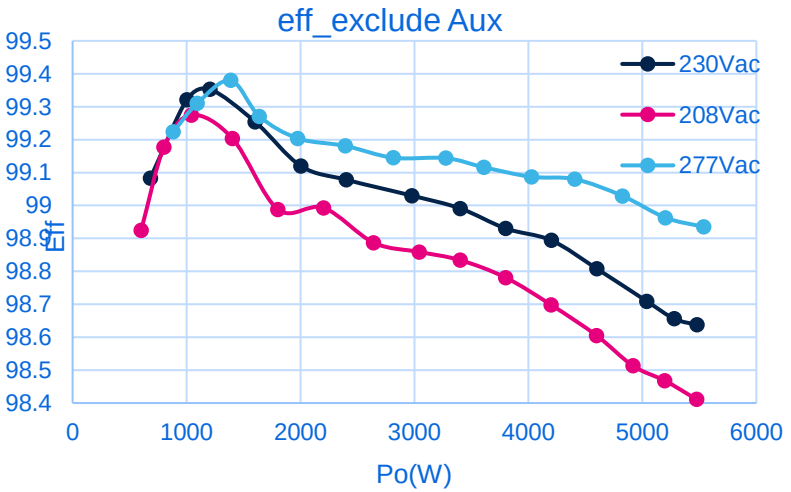
- When the load is below half load, the TCM is operated and ZVS is achieved, effectively improving the efficiency.
- When the load is higher than half load, it operates in CCM and effectively reduces the inductor current ripple, thereby reducing conduction loss.

TCM or CCM

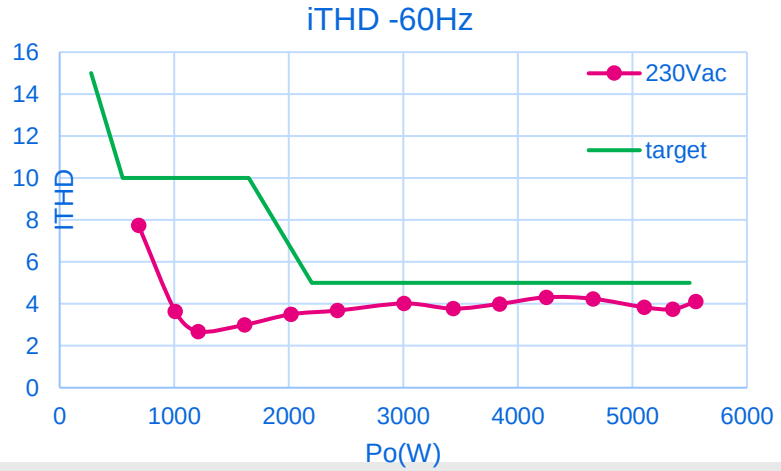
- Use the same hardware. And change software to operate in TCM or CCM.
- Output power below 2.7 kW can be operated with TCM control.
- Output power above 2.7 kW can be operated in CCM or mixed mode control.

ORV3 specifications efficiency





iTHD meet oRV3 specifications



- iTHD meets oRV3 specifications (green target line). We tested iTHD at full load on our PFC board, also under the green line. The iTHD meets spec at full load 5.5 kW (<5%@5.5 kW).

- Meet ORV3 PFC efficiency specifications.
- Peak: 99% @ 230 Vac, 240 Vac, 277 Vac with 50% load
- Min： 98.5% @ 230 Vac, 240 Vac, 277 Vac with 100% load
- Power Factor > 0.98 @ 100% load

Final eval results

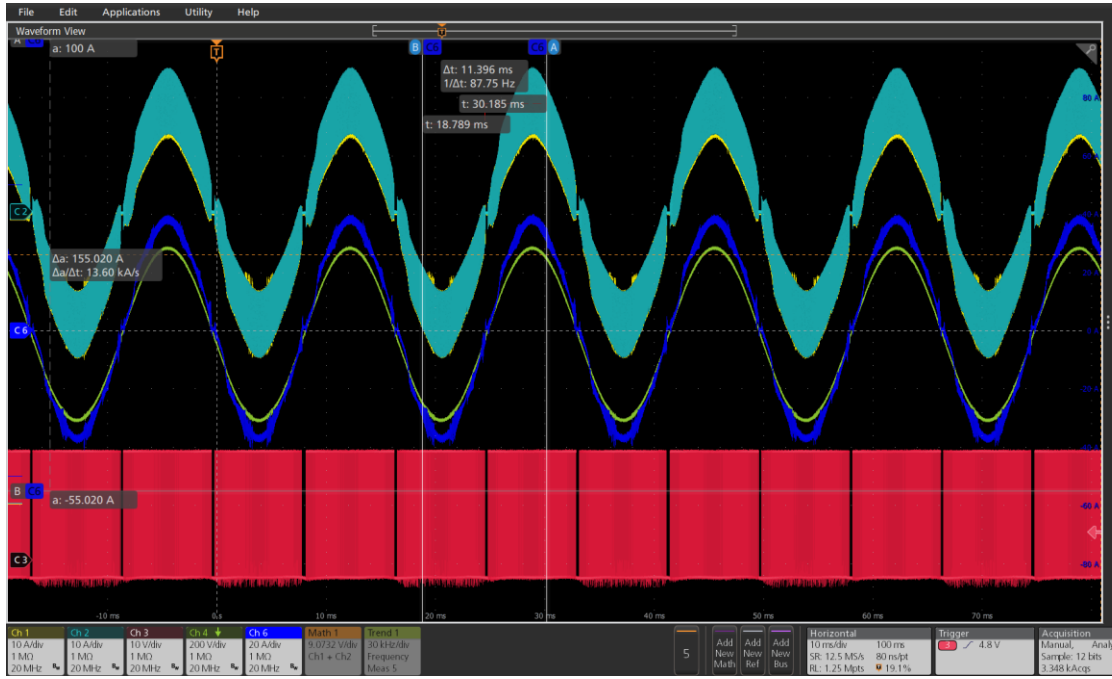
Metering function accuracy

load%	Power meter data					Metering board report data					accuray				
	Urms [V]	Irms [A]	P [W]	PF	iTHD	Urms [V]	Irms [A]	P [W]	PF	iTHD	Urms	Irms	P	PF*	iTHD*
5%	229.68	2.0542	292.6	0.6201	5.76	229.6	2.06	299.09	0.633	36.14	-0.03%	0.28%	2.22%	0.0129	30.38
10%	229.55	2.9078	587.3	0.8798	5.399	229.6	2.89	592.36	0.894	16.38	0.02%	-0.61%	0.86%	0.0142	10.981
15%	229.49	3.7492	849.2	0.987	4.787	229.4	3.72	849.7	0.9946	3.78	-0.04%	-0.78%	0.06%	0.0076	-1.007
30%	229.26	7.238	1655.4	0.9976	3.411	229.1	7.23	1656.36	0.9995	2.92	-0.07%	-0.11%	0.06%	0.0019	-0.491
40%	229.13	9.718	2222.4	0.9981	4.114	229	9.72	2222.82	0.9992	3.91	-0.06%	0.02%	0.02%	0.0011	-0.204
50%	228.97	12.199	2788.4	0.9983	3.894	228.8	12.2	2788.92	0.9992	3.88	-0.07%	0.01%	0.02%	0.0009	-0.014
60%	228.85	14.684	3354.5	0.9983	4.623	228.6	14.68	3354.19	0.999	4.15	-0.11%	-0.03%	-0.01%	0.0007	-0.473
70%	228.74	16.991	3880.3	0.9984	4.113	228.6	16.99	3879.07	0.9991	3.95	-0.06%	-0.01%	-0.03%	0.0007	-0.163
80%	228.64	19.497	4450.5	0.9983	4.337	228.4	19.48	4444.46	0.9991	3.97	-0.10%	-0.09%	-0.14%	0.0008	-0.367
90%	228.54	22.008	5021	0.9983	3.86	228.3	21.98	5013.11	0.9991	3.66	-0.11%	-0.13%	-0.16%	0.0008	-0.2
100%	228.45	24.389	5554	0.9969	4.612	228.2	24.35	5545.62	0.998	4.69	-0.11%	-0.16%	-0.15%	0.0011	0.078

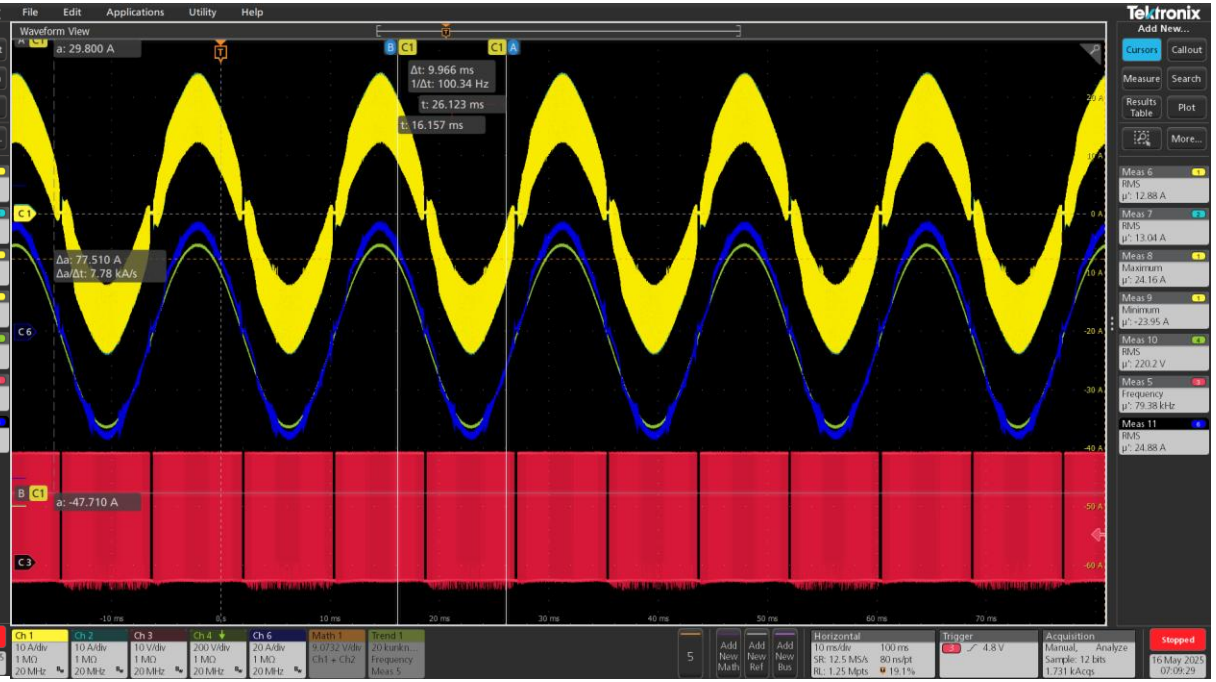
The prelim test result looks good and meets the ORV3-48V-5.5kW-PSU-Spec-Rev 0.4.

Parameter	Load	Accuracy
AC input power	<10%	±25W
	10-20%	± 5%
	20-100%	±3%
AC input current	<15%	±0.5A
	15 -30%	±2%
	30-100%	±1%
AC input current THD (Error difference not %)	<10%	±10
	10-30%	±2
	30-100%	±1.5
Power factor (Error difference not %)	<10%	±0.1
	10-30%	±0.05
	30-100%	±0.01
AC input voltage	0-100%	±1%

Summary



CH1,IL1. CH2, IL2. CH3, HF PWM. CH4, input voltage. CH6, input current at full load 5.5 kW at input voltage 208 V



CH1,IL1. CH2, IL2. CH3, HF PWM. CH4, input voltage. CH6, input current at full load 5.5 kW at input voltage 220 V

1. Input AC 208~277 Vac and the load is from 10 to 100%. The efficiency can reach 99.12% at 10% load and over 98.41% at 100% load.
2. PF higher than 0.967.
3. iTHD meets spec at full load 5.5 kW (<5%@5.5 kW).

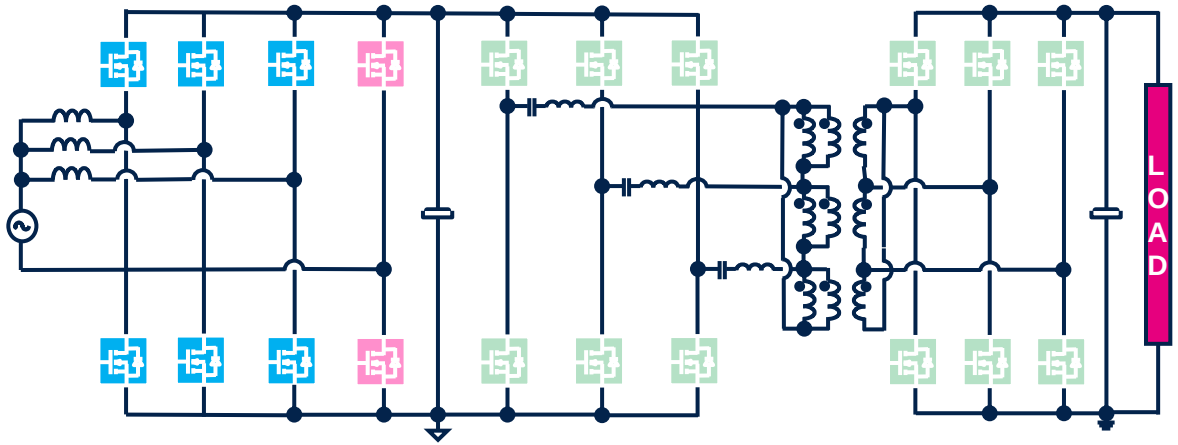
Power & Energy Competence Center

5.5 KW AI server power PFC & LLC solution PE.SP_00016.24

Development Status

2023				2024				2025			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Schedule

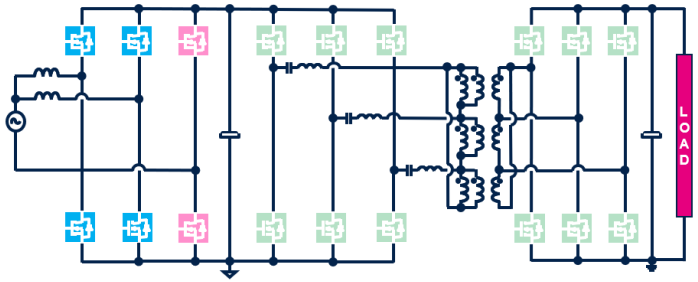


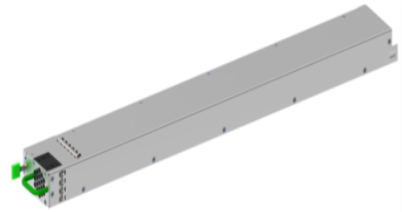
Solution Topology

Key Features:

- Fully Digital AC-DC Power Supply
- Input AC Voltage: 180VAC up to 305 VAC
- Input AC Frequency: 47Hz to 63Hz
- DC output voltage: 50 VDC
- Peak Efficiency: 97.5% @ 230VAC
- Power Factor > 0.98 @ 100% load
- iTHD < 5% @ 100% load
- Outline Dimension: 73.5mm*640mm*40mm
- Power Density up to 50W/inch^3
- Peak inrush current < 30A

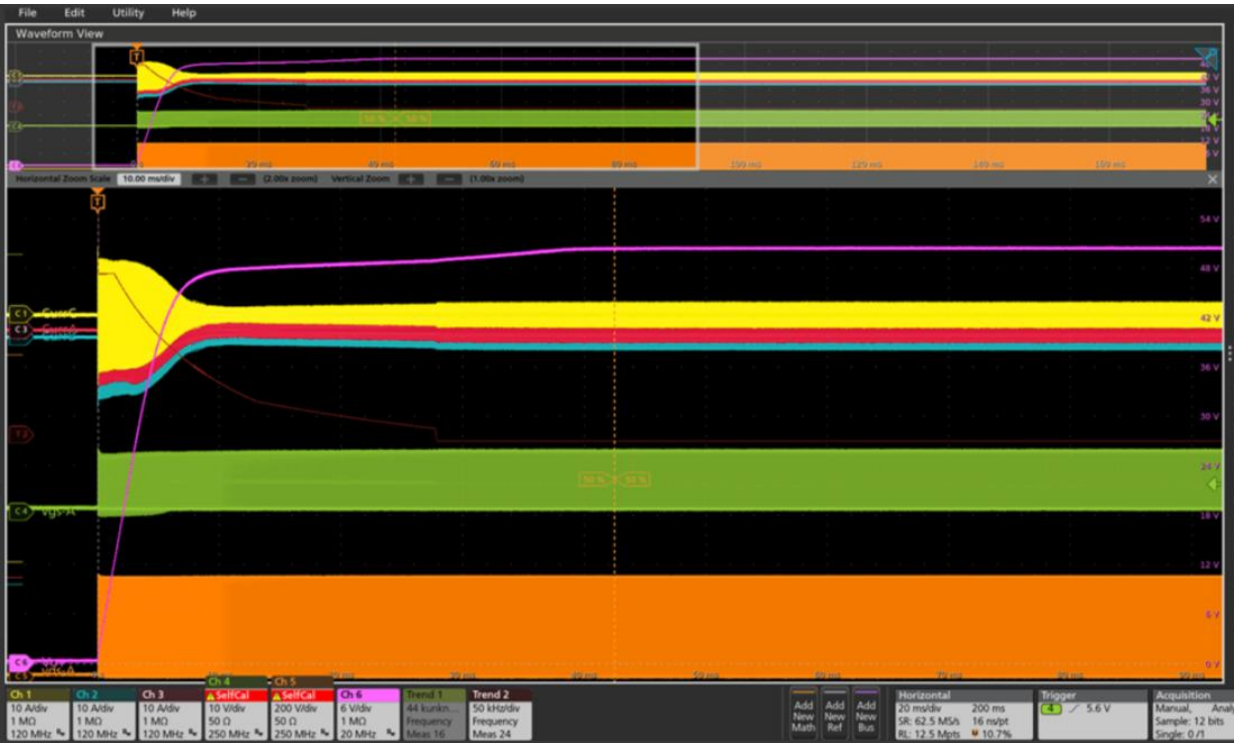
Key products	PFC:	LLC:
	• SCT040TO65G3 x4 (SiC FET) • STGAP2SICS x4 (SiC FET driver) • STO60N030M9 x4 (Si FET) • STGAP2SM x2 (Si FET Driver) • STM32G4 x1 (32-bit MCU) • STPM32 (Metering solution) • VIPERGAN65D (Aux power)	• STO60N045DM9 x6 (Si FET) • SCT040TO65G3 x6 (SiC FET) • SCT027TO65G3 x6 (SiC FET) • STGAP2H x6 (Si FET Driver) • STGAP2SM x6 (Si FET Driver) • STL180N8F8 x 36 (Si FET) • STM32G4 x1 (32-bit MCU)



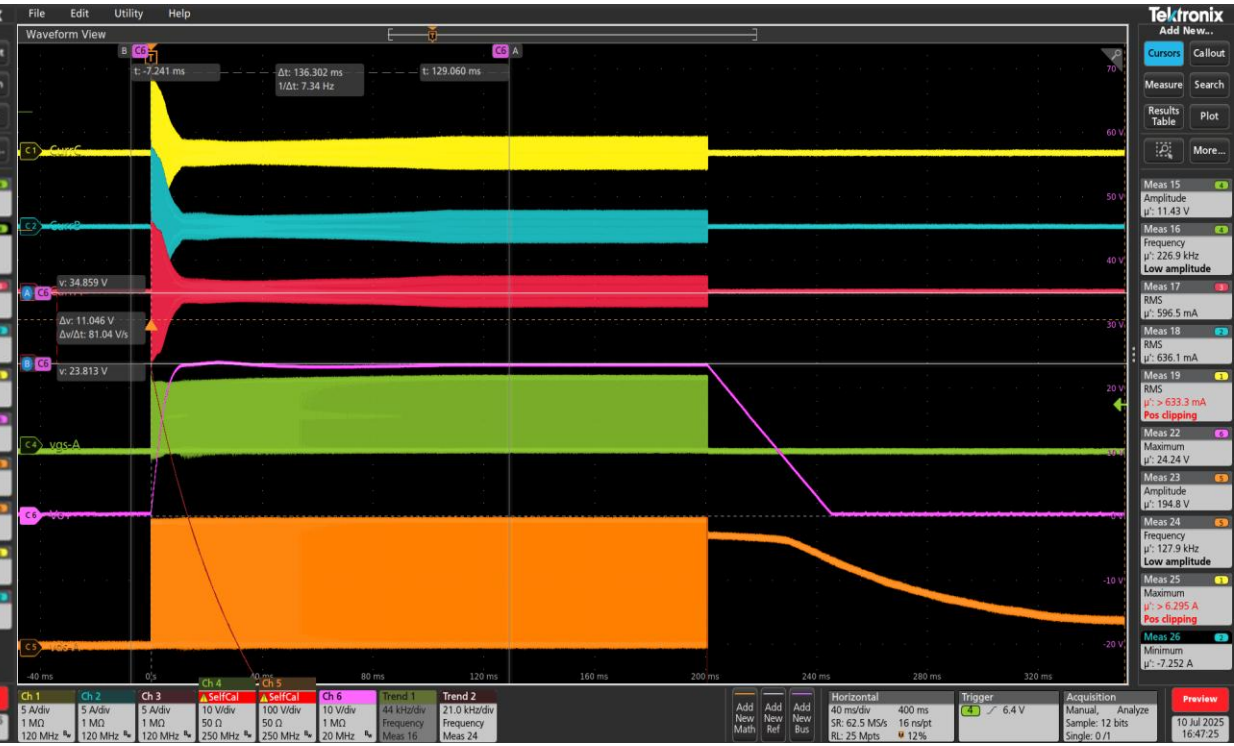


Close loop PFC+ three phase LLC testing

From 250 to 55 kHz



From 250 to 55 kHz



Close loop PFC+ three phase LLC testing

Fig1: Three phase LLC Operation action interval mode

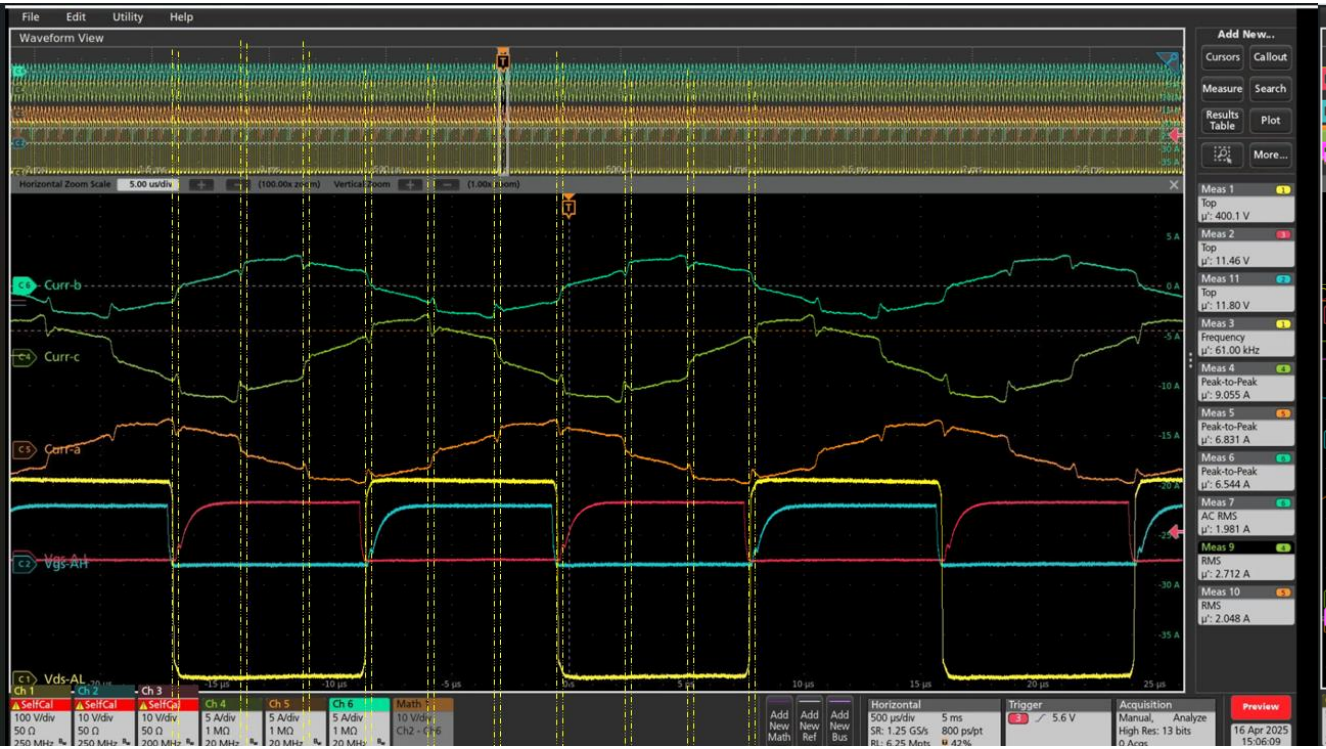
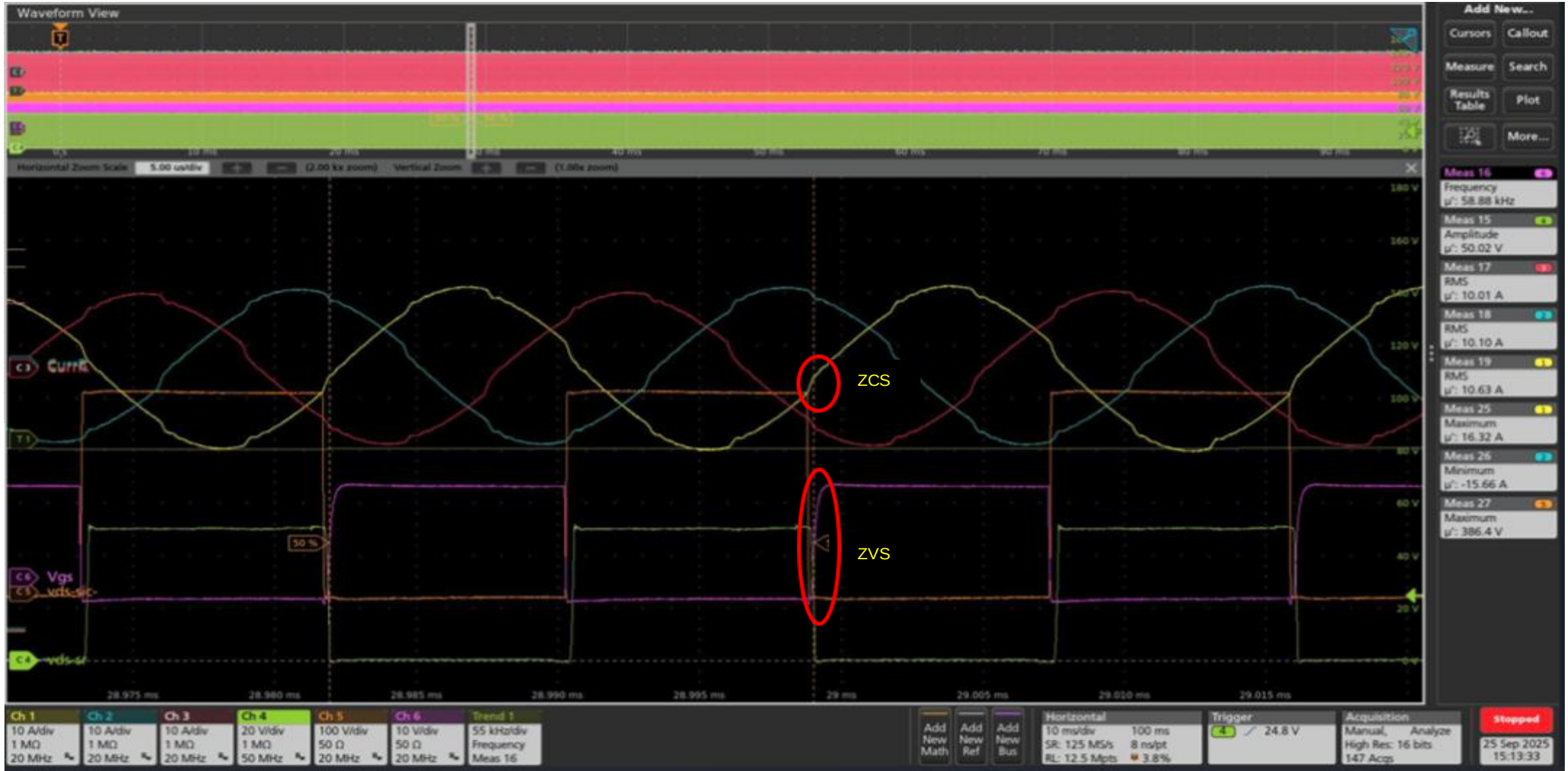


Fig2: Three phase LLC ZVS mode

The three-phase LLC operation shown in Figures 1 and 2 demonstrates the consistency between theory and practice. Therefore, ZVS and ZCS can be achieved at a 10% load, reducing switching losses and conduction losses while improving overall efficiency.

Optimizing transformers testing



5.5 kW AI Server PSU Implementation for ORv3 & MCRPS Applications

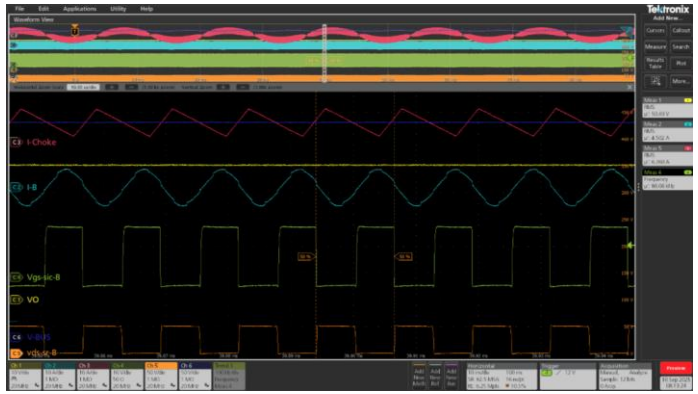
High-Efficiency Front-End Power Supply with Advanced Control

Key features

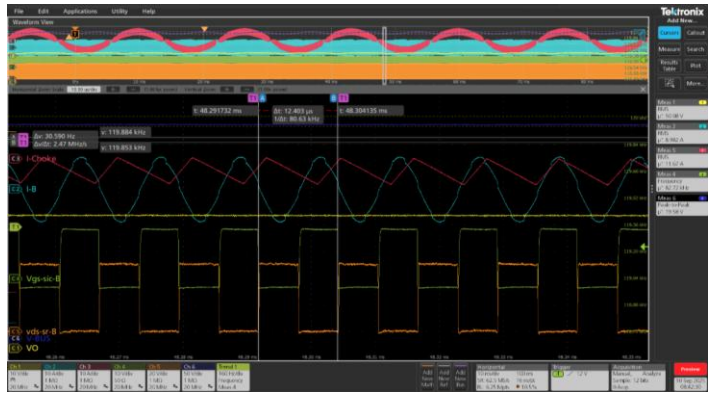
- Integration of SiC FET driver and MCU-based control
- Interleaved Mixed Mode Totem Pole PFC for ripple reduction
- Continuous Conduction Mode (CCM) reduces inductor ripple and conduction loss
- Three-phase LLC with Delta-to-Delta connection minimizes transformer losses
- Achieves Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) for efficiency

Performance highlights

- Output power:
  - 2.5 kW @ 50A, Efficiency: 97.76%
  - 5 kW @ 100A, Efficiency: 96.78%
- Power factor (PF) > 0.987
- Total harmonic distortion (iTHD) < 5%



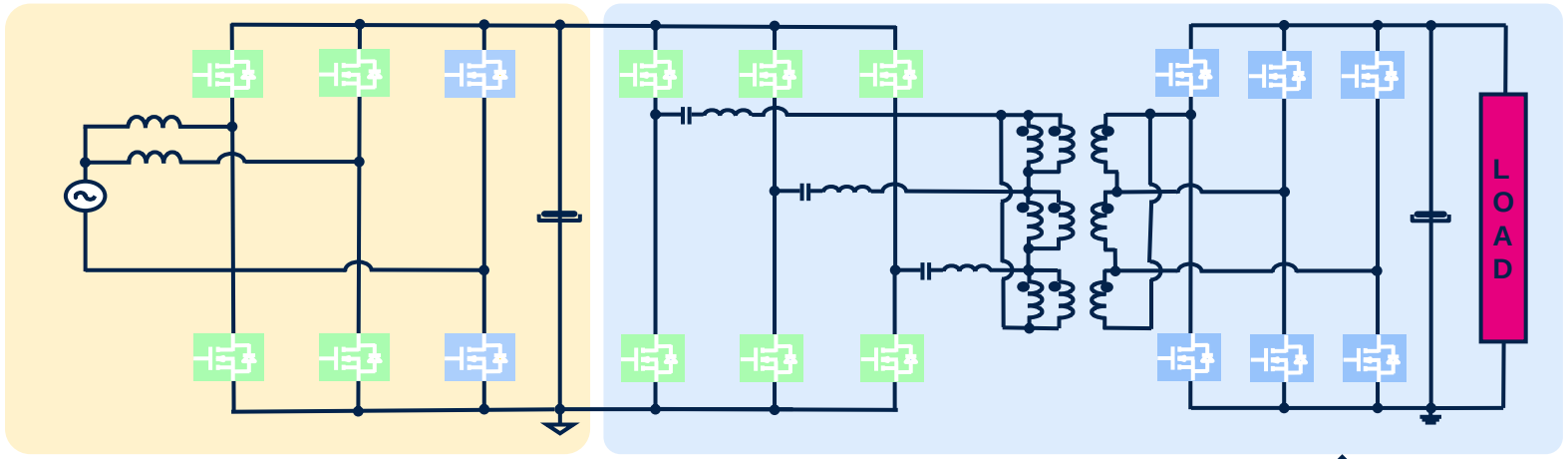
Output current 50 A, at output power 2.5 kW



Output current 100 A, at output power 5 kW

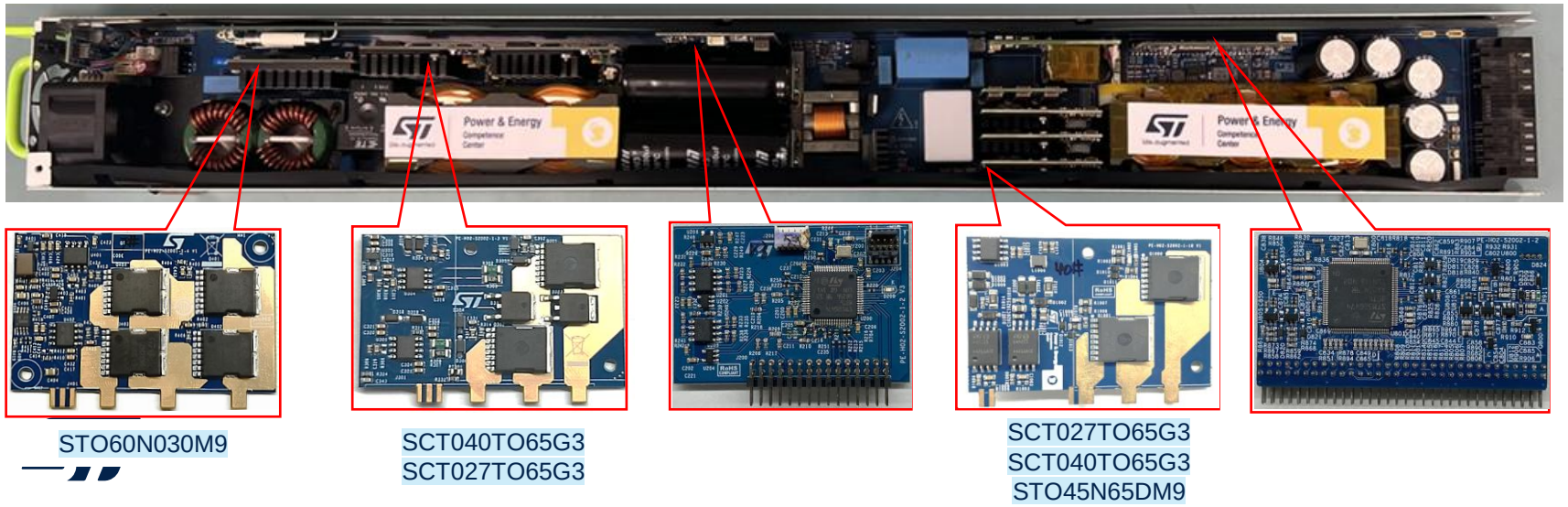
ORv3 5.5kW AI Server PSU

Interleaved Totem Pole PFC + 3-phase LLC



Interleaved Totem Pole PFC

3-phase Interleaved HB



STO60N030M9

SCT040TO65G3
SCT027TO65G3

SCT027TO65G3
SCT040TO65G3
STO45N65DM9

Key specifications:

- Fully digital AC-DC power supply
- Input AC voltage: 180-305 VAC
- Input AC frequency: 47-63 Hz
- DC output voltage: 48-50 Vdc
- Peak efficiency:
  - 97.5% @ 230, 240, 277 Vac with 30-100% load
  - 96.5% @ 208 Vac with 30-100% load

  Min efficiency:
  - 96.5% @ 230, 240, 277 Vac with 30-100% load
  - 95.5% @ 208 Vac with 30-100% load
- Power Factor >0.98 @ 100% load
- iTHD < 5% @ 100% load
- Outline dimension: 73.5 x 640 x 40 mm
- Power density up to 50 W/inch^3
- Peak inrush current <30 A

Key benefits and test results

Benefits

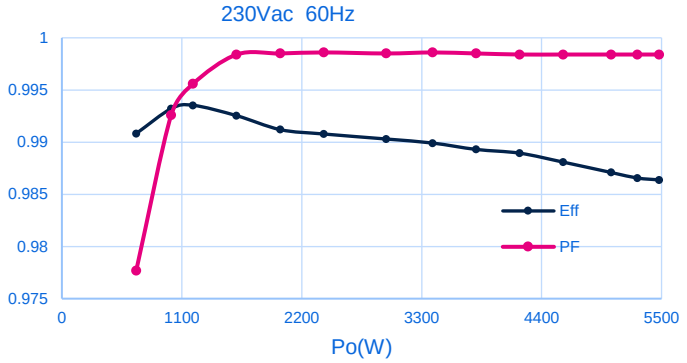
- Mixed mode control can improve efficiency under both light and heavy loads conditions.
- By using hysteric current control, TCM or CCM operation can be achieved on the same hardware with slight software modifications.

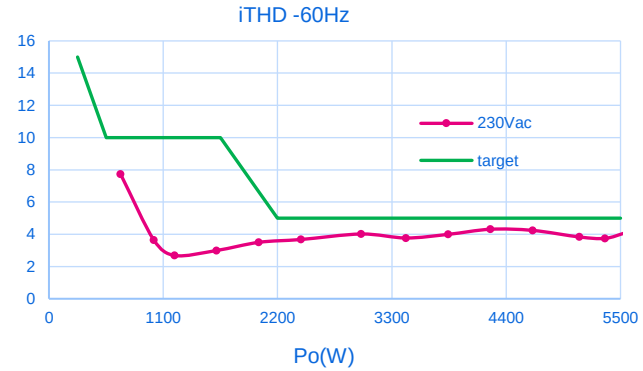
- Two-channel interleaved TTP PFC can easily extend to 3-channel for higher power application.
- Magnetic integration can help reduce the size and power loss which can improve power density and efficiency.

- iTHD performance is enhanced by a novel harmonic injection control strategy and meets ORV3 Specifications.

- The three-phase interleaved LLC can significantly reduce current ripple and facilitate current balancing. Combined with specialized magnetic component design, it can also reduce the size of inductors and transformers.

PFC test results



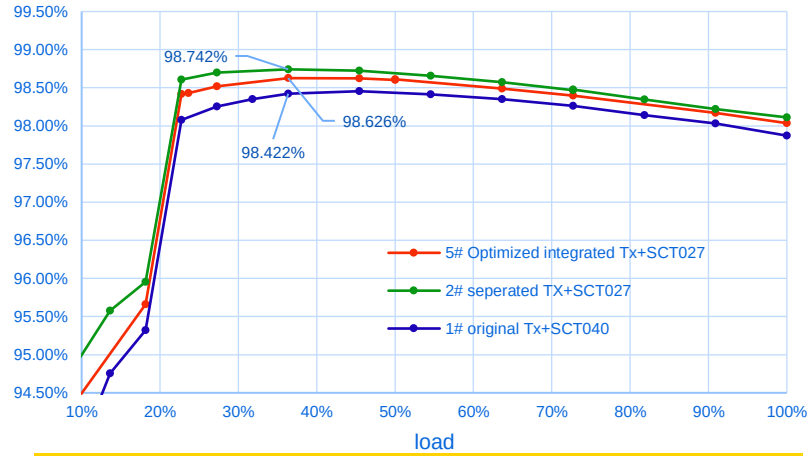


3.8 Efficiency

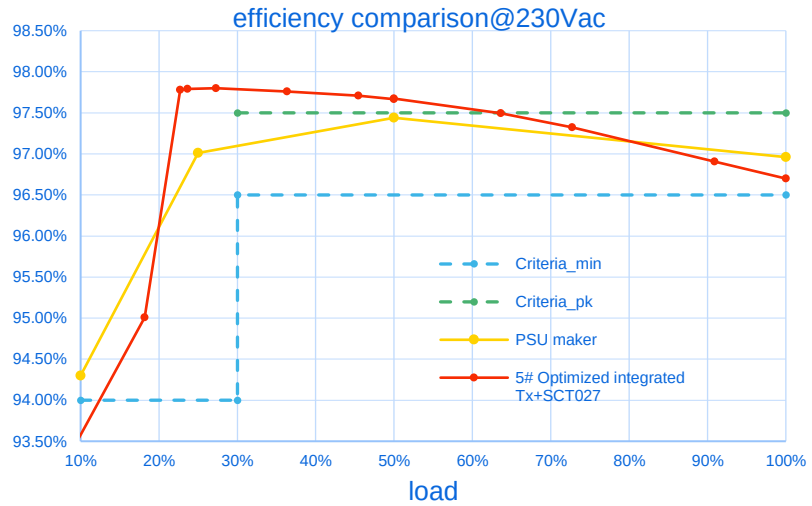
The efficiency of the rectifiers when measured at an AC input voltage of 208V~277V and with the cooling fans connected (with input and output voltage measured at corresponding connectors, at 25 C ambient and after 30 minutes running at full load) shall meet the requirements outlined in Table below.

Load Range (%)	Peak Efficiency (%)	Min Efficiency (%)
30% to 100% of full load	> 97.5% @230, 240, 277V > 96.5% @208V	> 96.5% @230, 240, 277V > 95.5% @208V
10% to 30% of full load	-	94% @208V~277V

LLC Efficiency



Total solution



Summary

- Higher power level PSU is new trend for AI server driven by AI technology
- Interleaved TTP PFC is the most popular topology for high power AI server PSU.
- Hybrid TCM/CCM control strategy offers a comprehensive approach, combining the strengths of both modes to achieve higher efficiency, performance, and reliability in high-power AI server PSUs.
- DC/DC use three phase LLC for Delta to Delta connection . We can reduce primary and secondary side transformer conduction loss. It can also achieve three-phase current sharing and ZVS and ZCS conditions, reducing switching losses and conduction losses while improving overall efficiency.
- Our theoretical analysis is verified by analysis and implementation.
- Close loop PFC+LLC testing can support output power 5.5kW. Output 2.75kW eff 97.76%. At output power 5.5kW the eff 96.78%. PF can also be satisfied above 0.987. iTHD under 5%.
- ST provides design kits tailored for high-power AI server PSUs, includes:
  - 1) Solutions for 5.5 kW to 12kW AI server PSU
  - 2) Comprehensive product portfolio to support various design needs

Our technology starts with You