life.augmented

50 kW Digital DC-AC Inverter Based on SiC ACEPACK and STM32H743

Rain XU

Power & Energy
Competence
Center

Agenda

1 PV Inverter Background

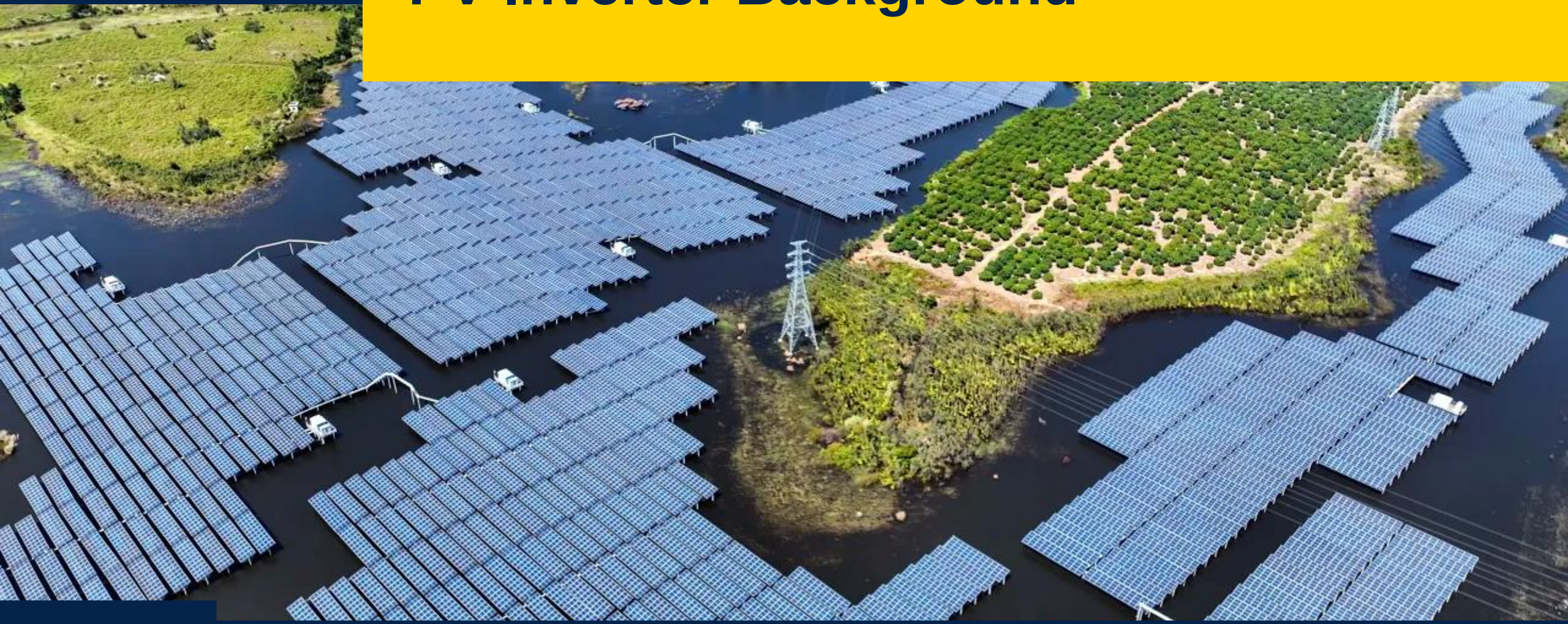
2 ST PV Digital Solution

3 ST PV Board Performance

4 Summary

life.augmented

PV Inverter Background



life.augmented

PV inverters

Residential installations

Typically <5 kW

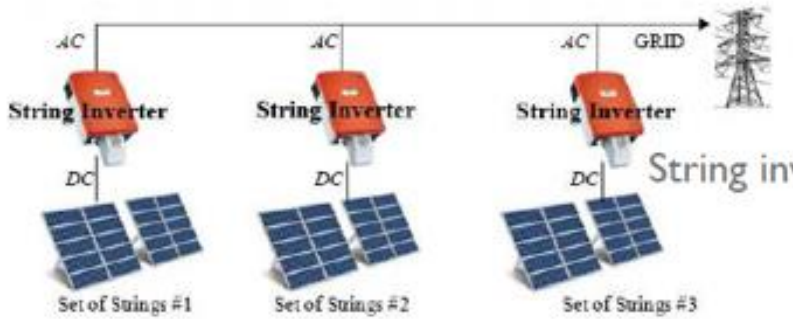
PV inverters

Micro-inverter

Micro-inverters are used for low-power installations up to 300W. The input voltage is generally 48V or 62V.

Commercial and industrial buildings

5 kW-1 MW

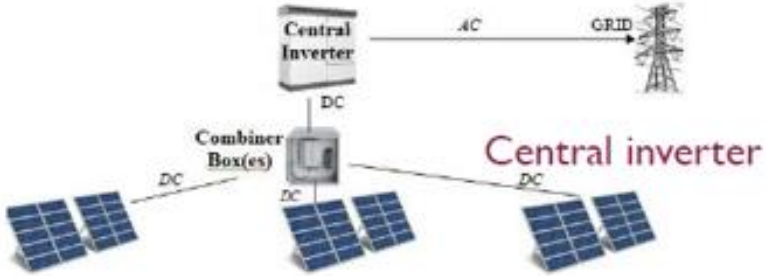


String inverter

Single-phase or three-phase string inverters are used for residential and commercial PV installations up to 120kW.

Ground-mounted power plants

1-100 MW



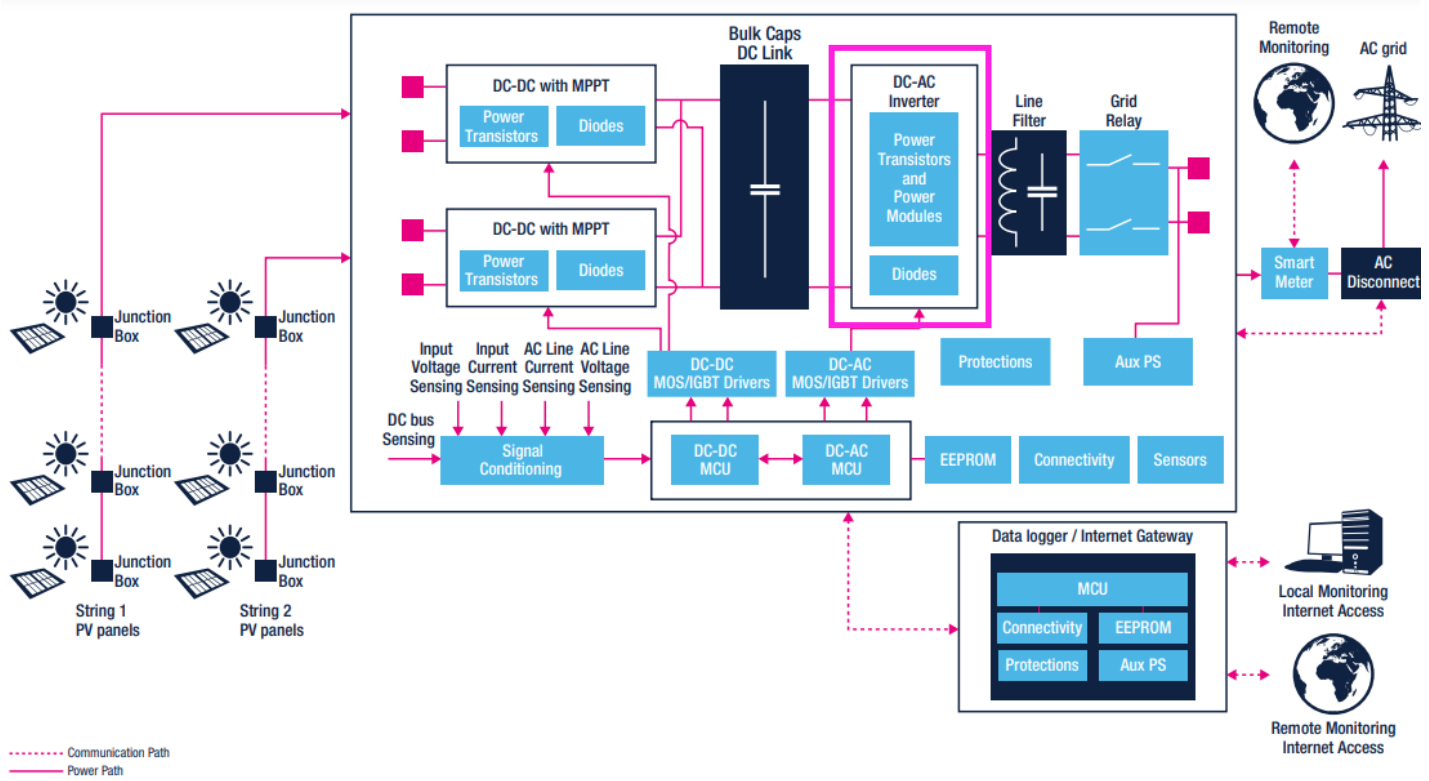
Central inverter

Central PV inverters are used in installations supplying beyond 200kW.

String inverters

Input specs and requirements	
Input voltage	200-1100 Vdc
Normal voltage	600 Vdc
Input current	120 A max@450 V
MPPT voltage	200-1000 Vdc
MPPT number	4

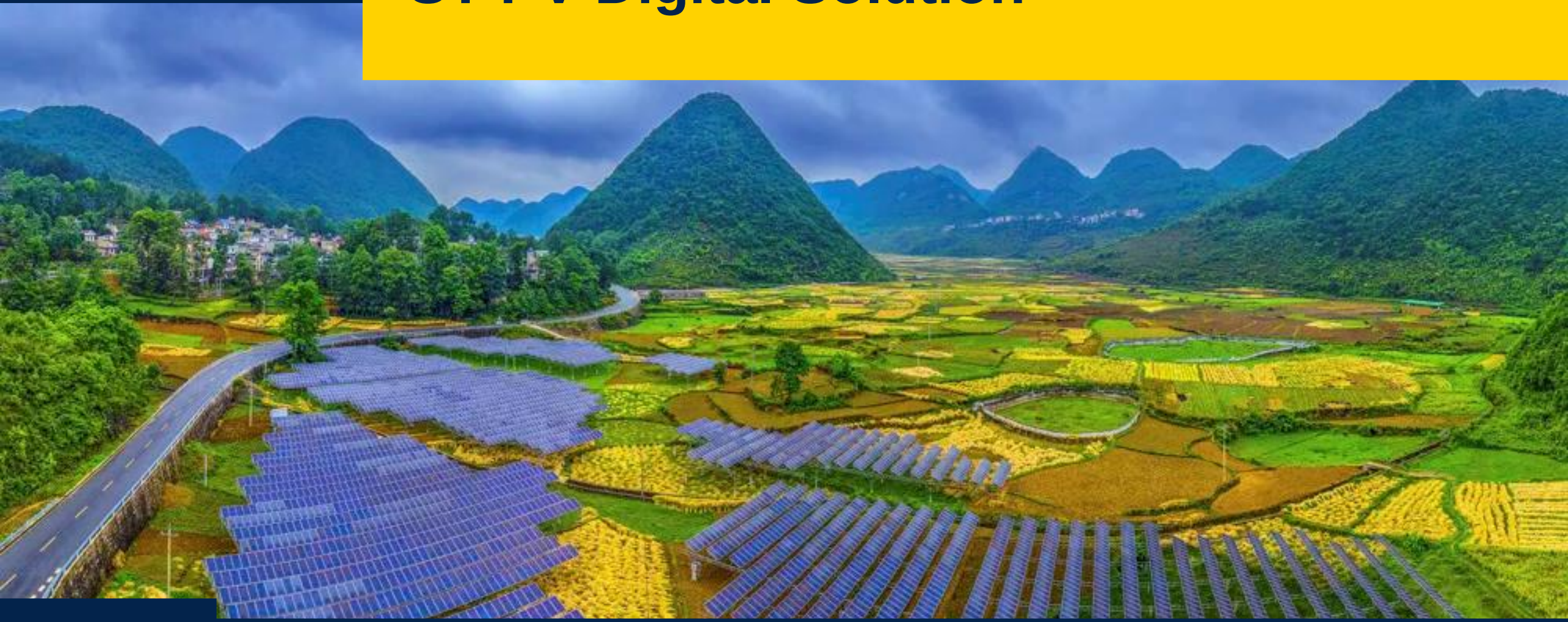
Output specs and requirements	
Output voltage	312~480 V L-L
Frequency	50 Hz / 45~55 Hz
Output power	50 kW normal (55 kW max)
Thd	< 3 %
Power factor	0.8 ~ -0.8
Eff	98.5%



Benefits of SiC

- Extremely low switching losses and ultralow $R_{DS(on)}$
- Good thermal performance
- Easy to drive
- Very fast and robust intrinsic body diode

ST PV Digital Solution

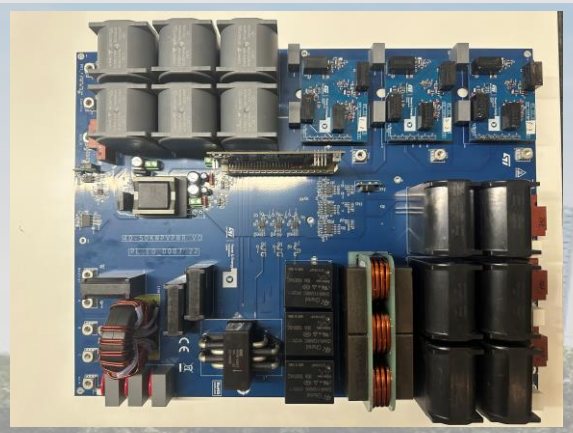


life.augmented

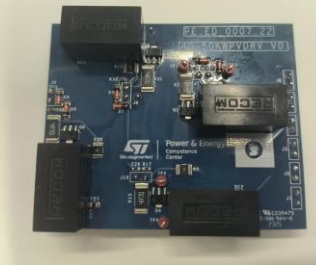
Power & Energy Competence Center

50 kW T-type DC-AC PV Inverter

Solution board available



T type three-level DC-AC with ACEPACK module



Application key features:

- DC input voltage 800 VDC, rated output power 50 kW · switching frequency 40 kHz
- Output AC voltage: Three-phase 380 VAC with 45 Hz up to 55 Hz
- Maximum output current: 84 ARMS
- Peak efficiency 98.89% (800Vdc)
- 0.99 power factor with lower than 3% THD @ full load operation
- STM32H743ZGT6

Key products

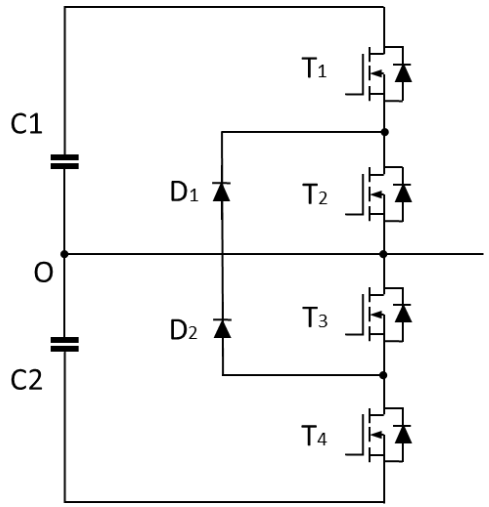
STM32H743ZGT6
A2U8M12W3-FC *3 (9.5mΩ 1200 V & 6mΩ 750 V SiC module)
STGAP2SICSC (galvanic insulated gate driver)
IPC product: L6565, ISOSD61, (L6983i)
Schottky diodes: STPS1150A, STPS2H100A, STPS2L60A
GPA：TSV914IDT, LD29080S33R, STLM20W87F, LD29080DT50R
，

Key benefits

- Higher efficiency achieved based SiC module
- Low output LCL filter cost with 40 kHz frequency
- Higher reliability, low design complexity

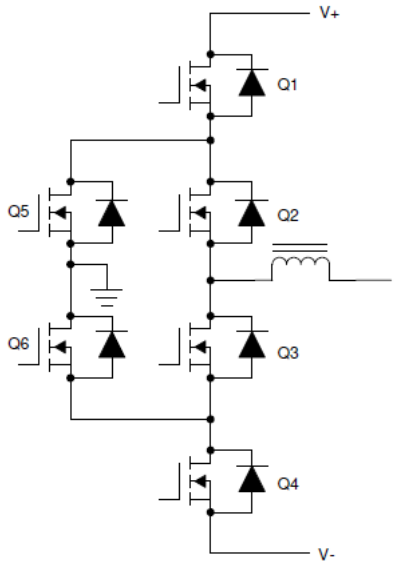
Topology Comparison

INPC



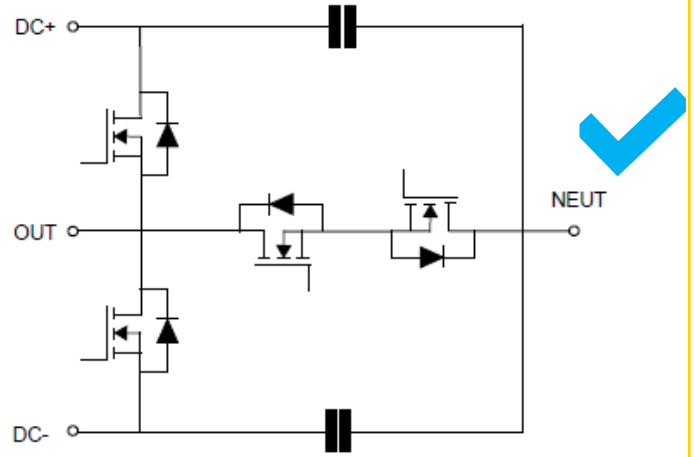
- \+ Suitable for high bus voltage
- \+ 3-level topology
- \- Shoot-through issue
- \- Control complexity: medium-high
- \- Component count: high
- \- 2 devices in the main current path

ANPC



- \+ Suitable for high bus voltage
- \+ Better for thermal
- \+ 3-level topology
- \- Shoot-through issue
- \- Control complexity: high
- \- Component count: high
- \- 2 devices in the main current path

TNPC



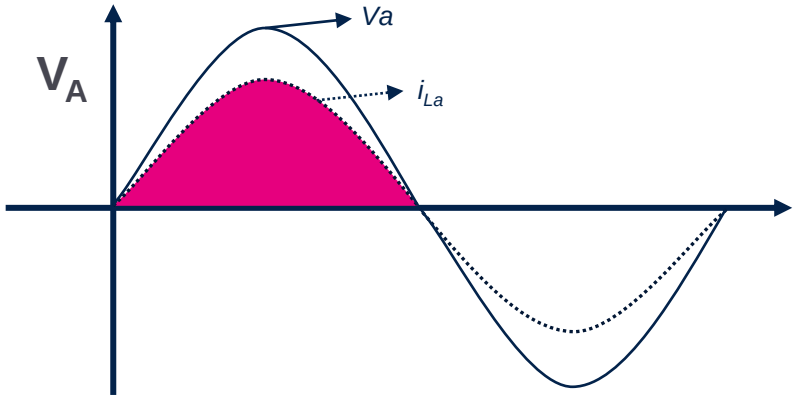
- \+ Component count: low
- \+ 2 device in the main current path
- \+ 3-level topology
- \- Shoot-through issue
- \- Control complexity: medium-high
- \- Suitable for bus voltage ≤ 850 V

T type three level is commonly used as the DC-AC topology in 30-100 kW PV inverters.

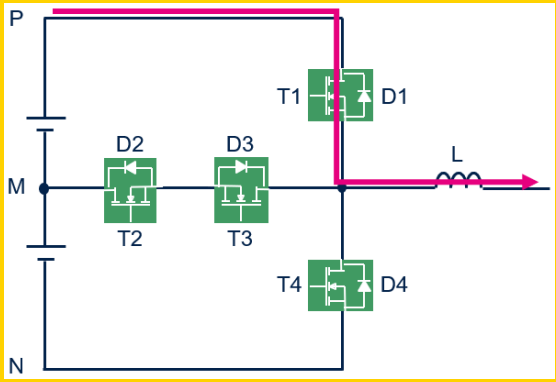
Power & Energy Competence Center

T-type Three Phase Operation SiC MOS

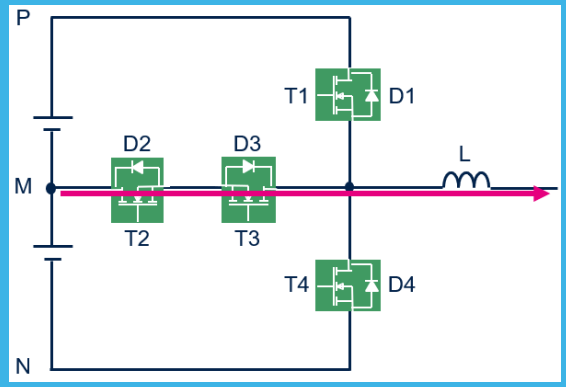
$Va>0, i_{La}>0$



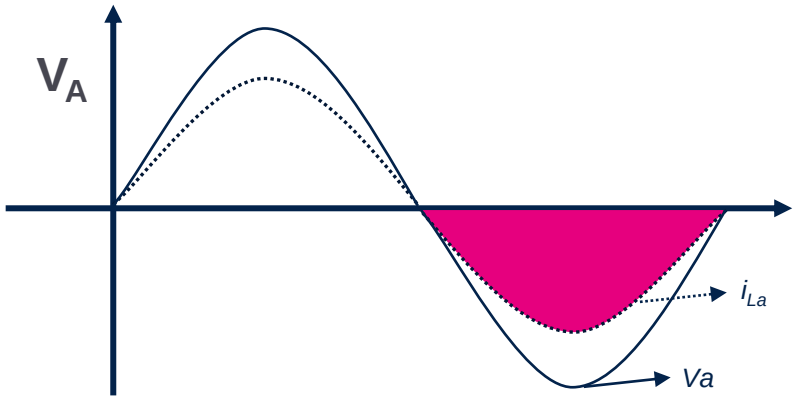
T1 on (=1), energy releasing



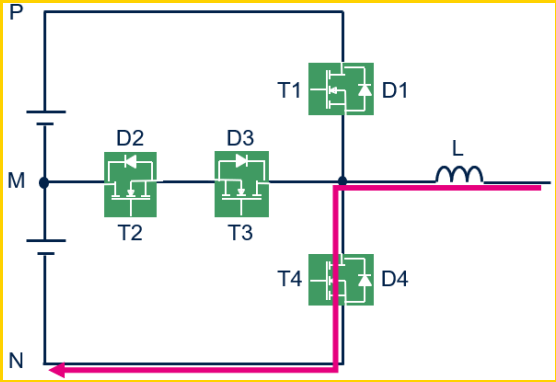
T3 on (=1), energy releasing



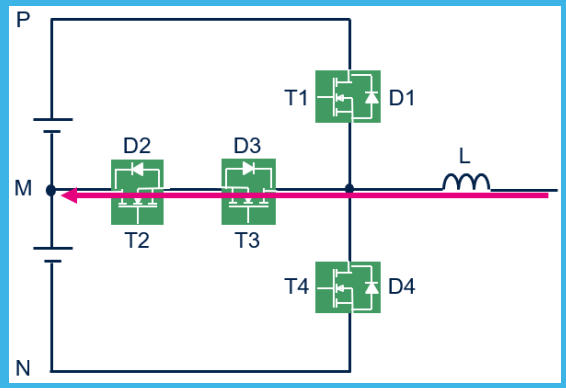
$Va<0, i_{La}<0$



T4 on (=1), energy releasing



T2 on (=1), energy releasing



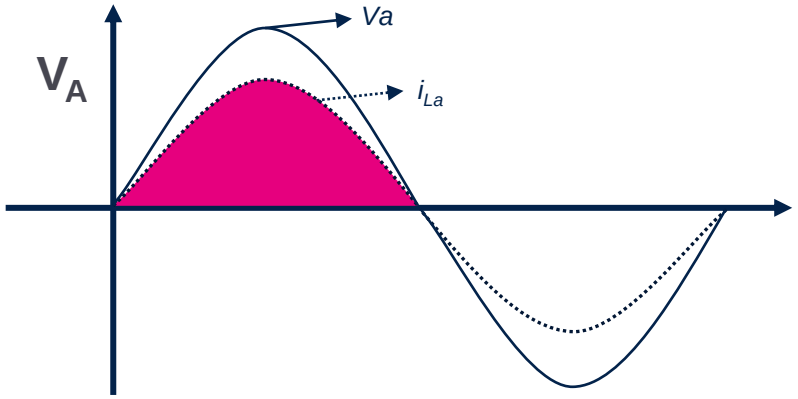
- Current from BUS CAP to inductor through MOS T1 or T4
- Energy from BUS CAP to inductor and output

- Current from output to M-point and inductor through MOS T2 and T3
- Energy from output to M-point and inductor

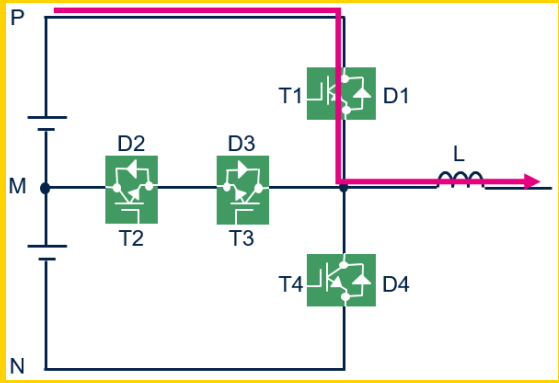
life.augmented

T-type Three Phase Operation Si IGBT

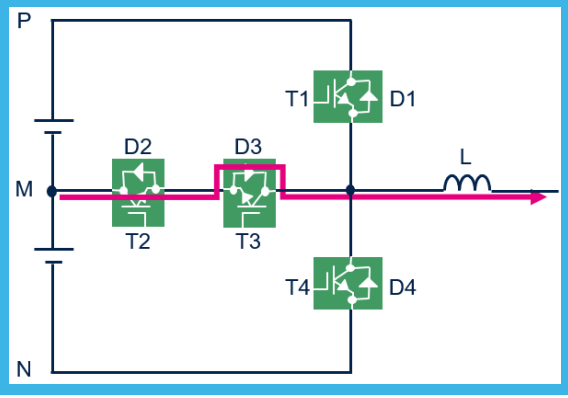
$Va>0, i_{La}>0$



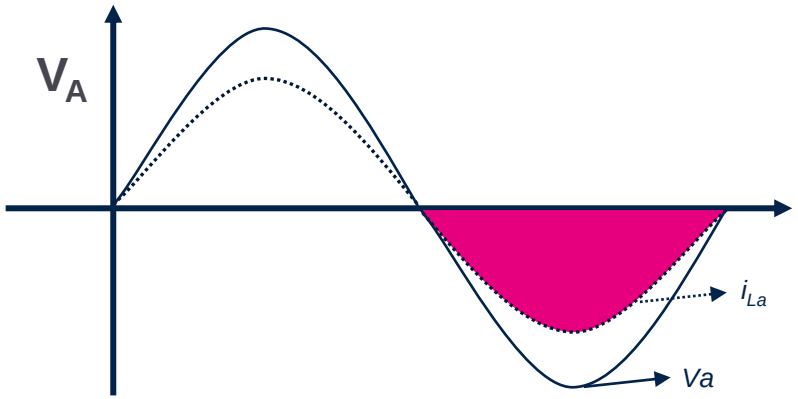
T1 on (=1), energy releasing



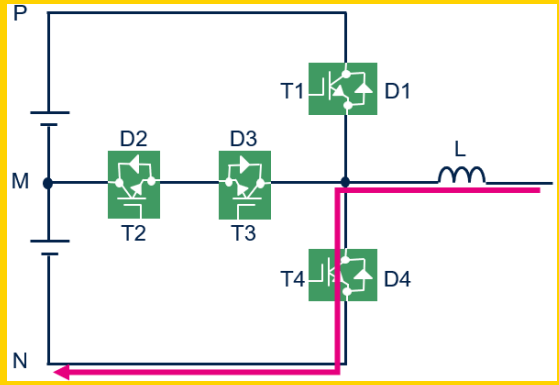
T3 on (=1), energy releasing



$Va<0, i_{La}<0$

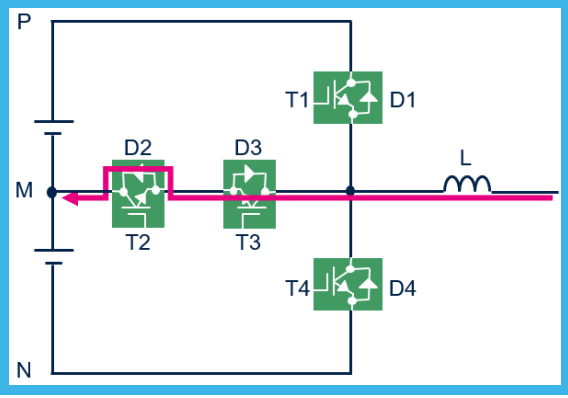


T4 on (=1), energy releasing



- Current from BUS CAP to inductor through MOS T1 or T4
- Energy from BUS CAP to inductor and output

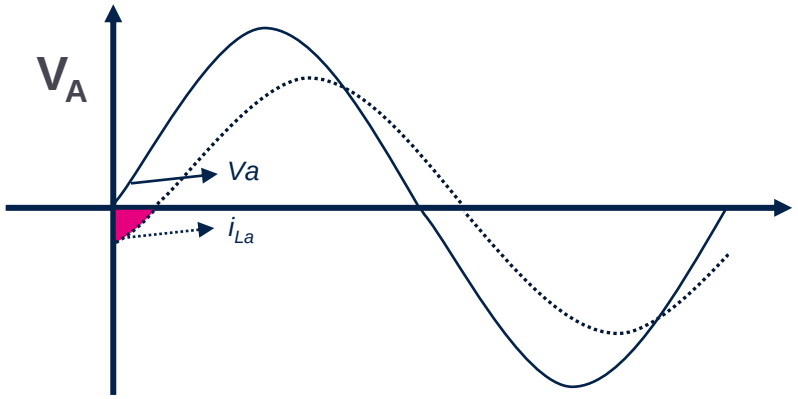
T2 on (=1), energy releasing



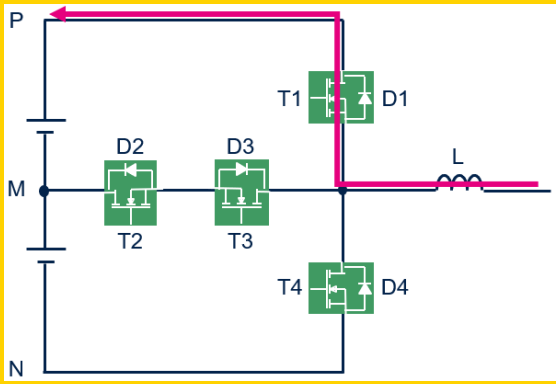
- Current from output to M-point and inductor through MOS T2&Diode D3 or MOS T3&Diode D2
- Energy from output to M-point and inductor

T-type Three Phase Operation SiC MOS

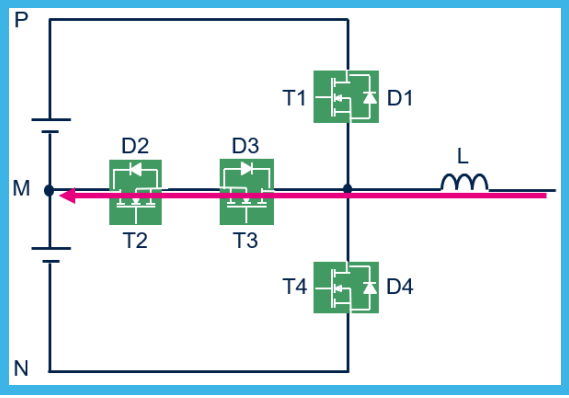
$Va>0, i_{La}<0$



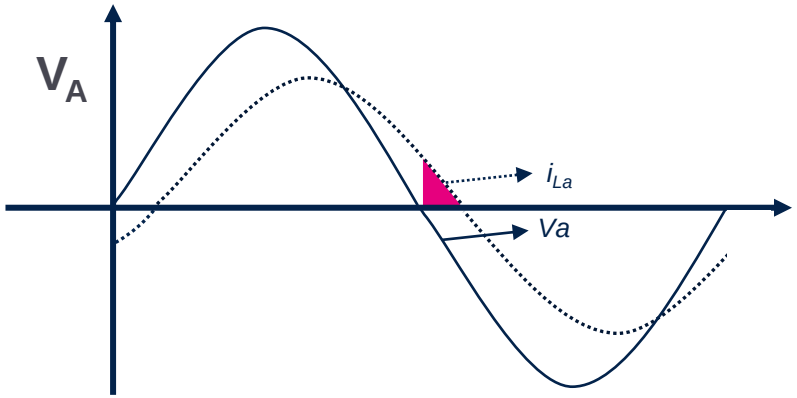
T1 on (=1), energy releasing



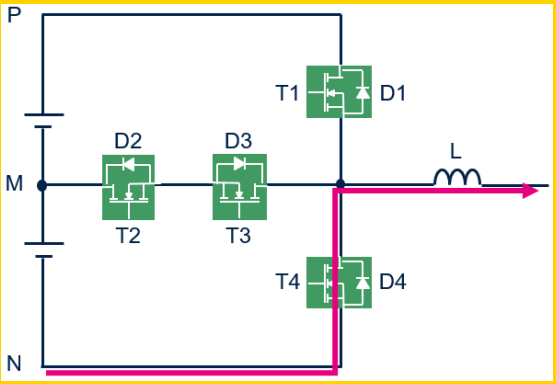
T3 on (=1), energy releasing



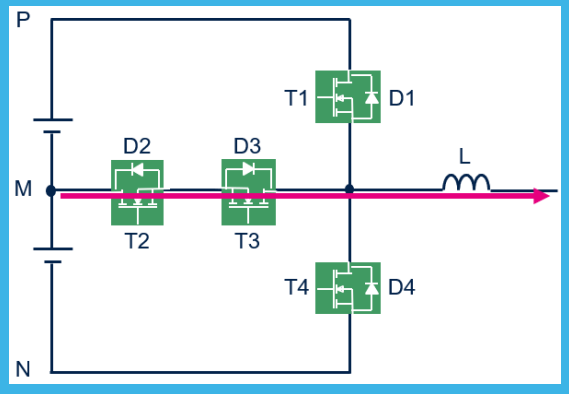
$Va<0, i_{La}>0$



T4 on (=1), energy releasing



T2 on (=1), energy releasing

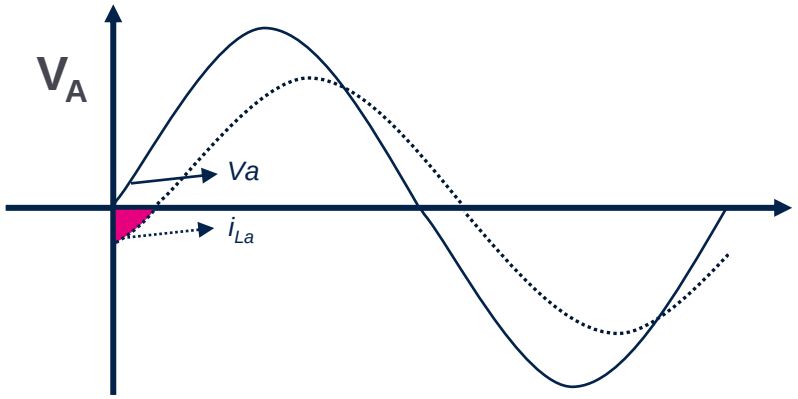


- Current from inductor to BUS CAP through MOS T1 or T4
- Energy from output and inductor to BUS CAP

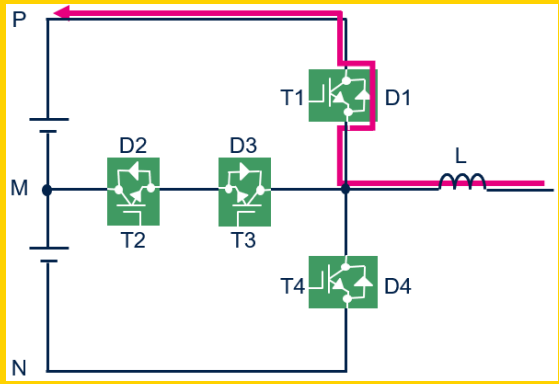
- Current from output to M-point and inductor through MOS T2 and T3
- Energy from output to M-point and inductor

T-type Three Phase Operation Si IGBT

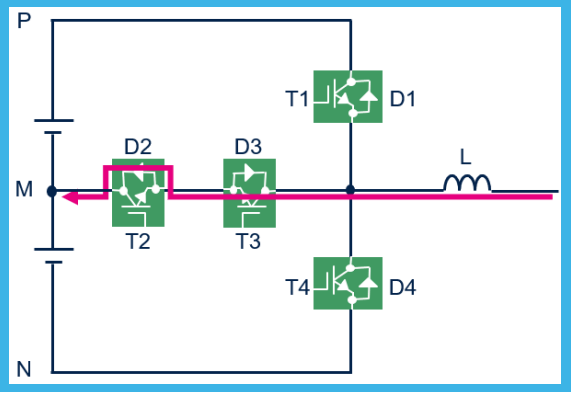
$Va>0, i_{La}<0$



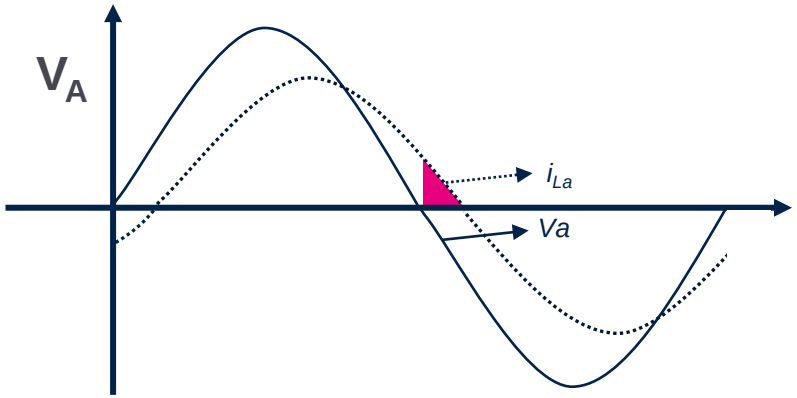
T1 on (=1), energy releasing



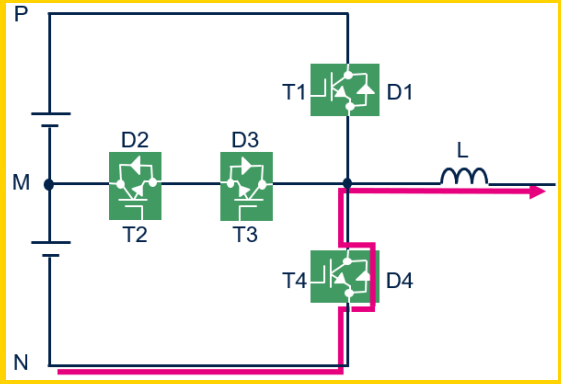
T3 on (=1), energy releasing



$Va<0, i_{La}>0$

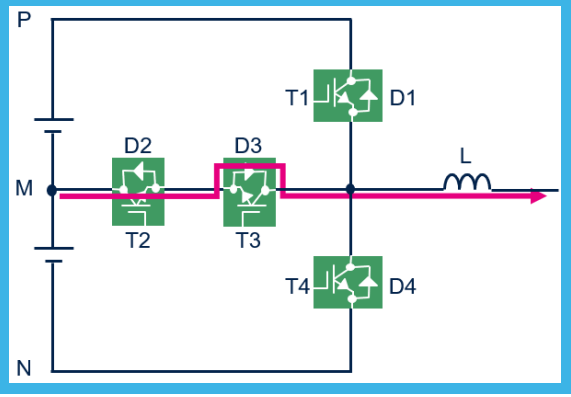


T4 on (=1), energy releasing



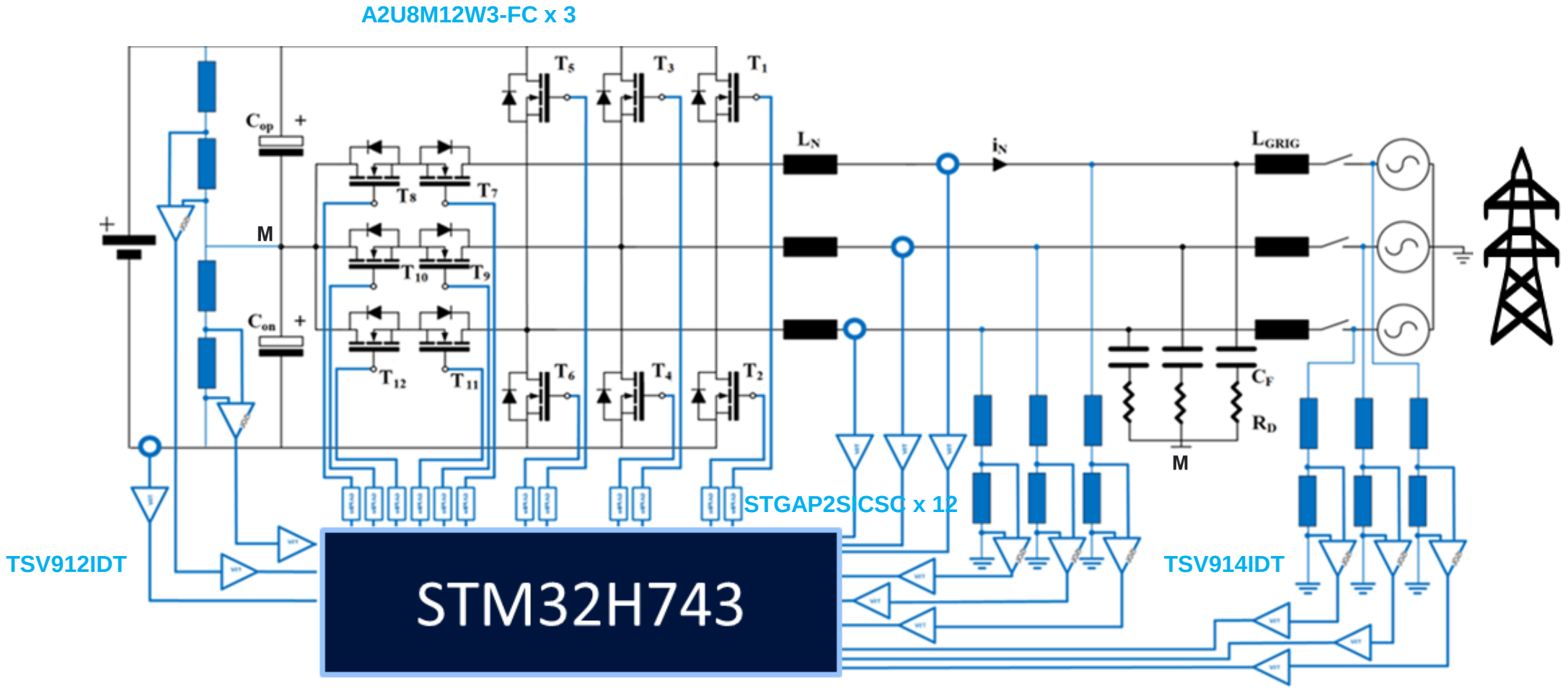
- Current from inductor to BUS CAP through diode D1 or D4
- Energy from output and inductor to BUS CAP

T2 on (=1), energy releasing



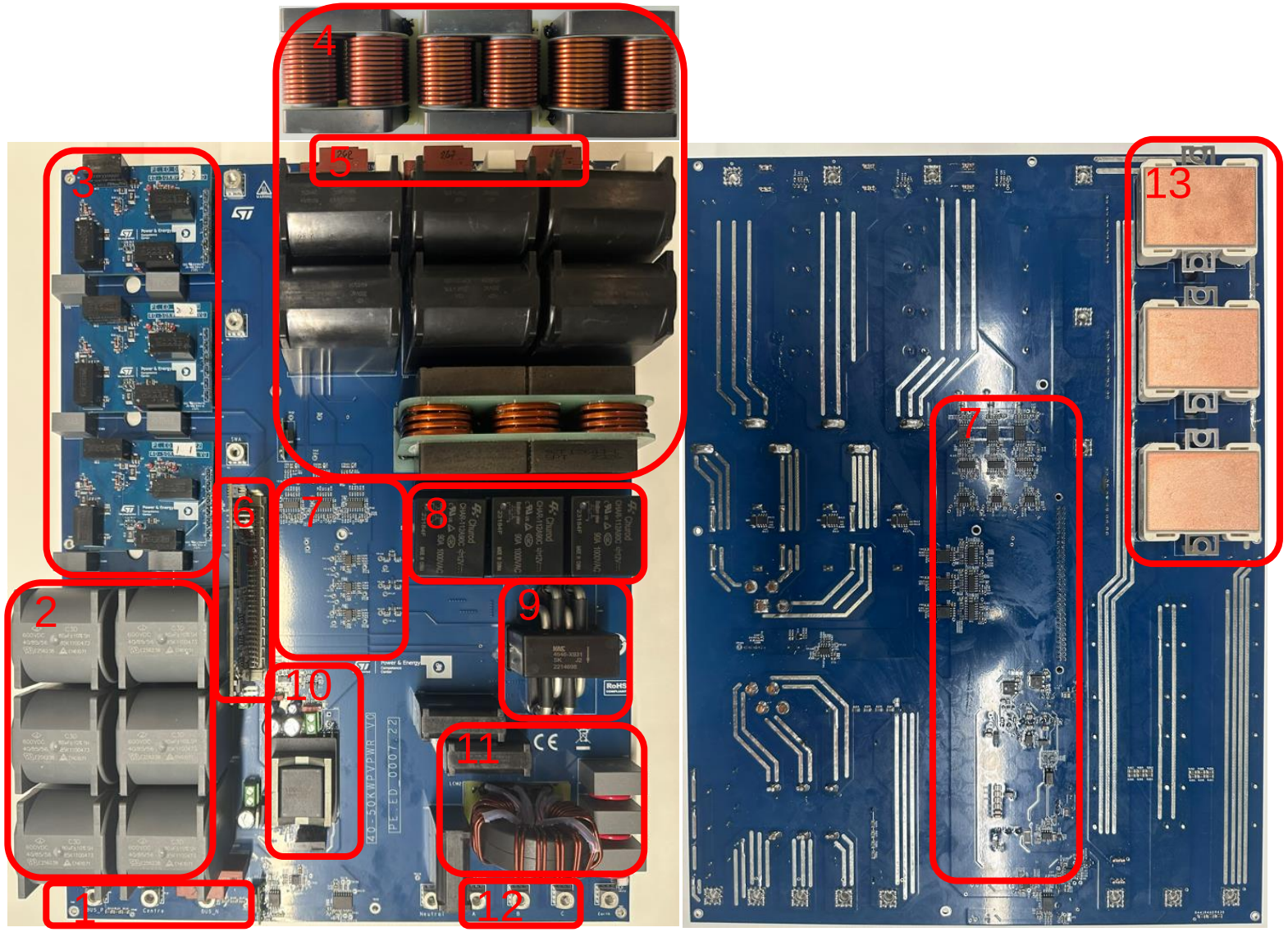
- Current from output to M-point and inductor through MOS T3&Diode D2 or MOS T2&Diode D3
- Energy from output to M-point and inductor

Simplified Block Diagram



Board Assembly Overview

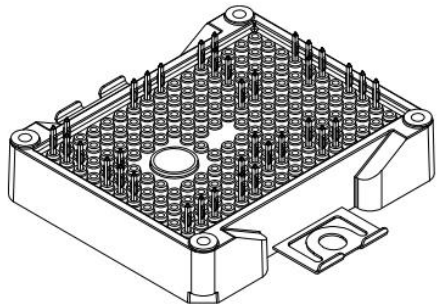
1. DC input connector
2. BUS CAP
3. Driver board
4. LCL filter
5. Inductor current sensor
6. Control board
7. Sensing circuit
8. Relay
9. Residual current sensor
10. Aux power circuit
11. EMI filter
12. AC output connector
13. SiC module



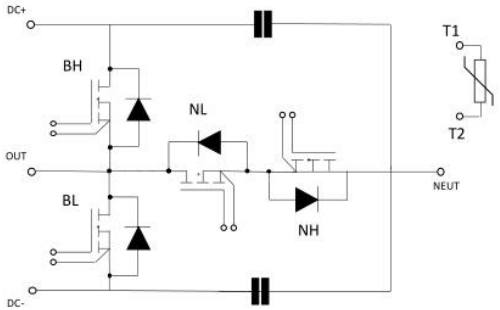
WxLxH: 300 x 400 x 70 mm

SiC Module-A2U8M12W3

ACEPACK 2 power module, 3-level topology based on silicon carbide power MOSFETs: 750 & 1200 V, 100 A



ACEPACK 2



Features

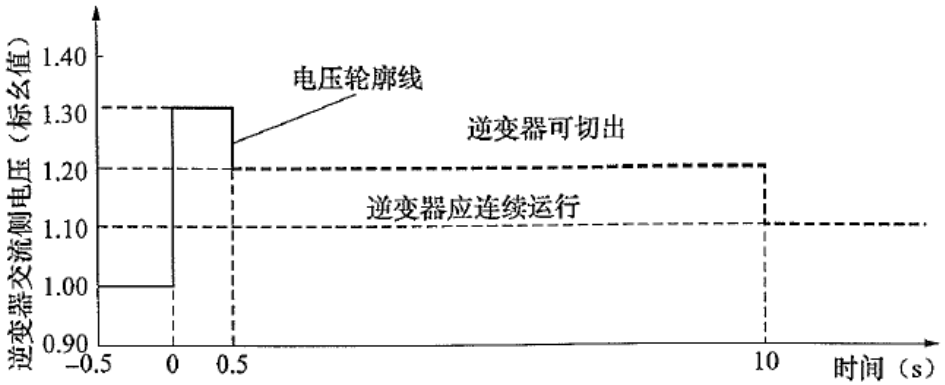
- ACEPACK 2 power module:
  - NH and NL: 750 V, 6 mΩ of typical $R_{DS(on)}$ each switch
  - BH and BL: 1200 V, 9.5 mΩ of typical $R_{DS(on)}$ each switch
  - 2.5 kVrms insulation
  - Integrated NTC temperature sensor
  - DC link capacitors between DC BUS and neutral
  - AIN DBC improved thermal performance
  - Press-fit contact pins

Application

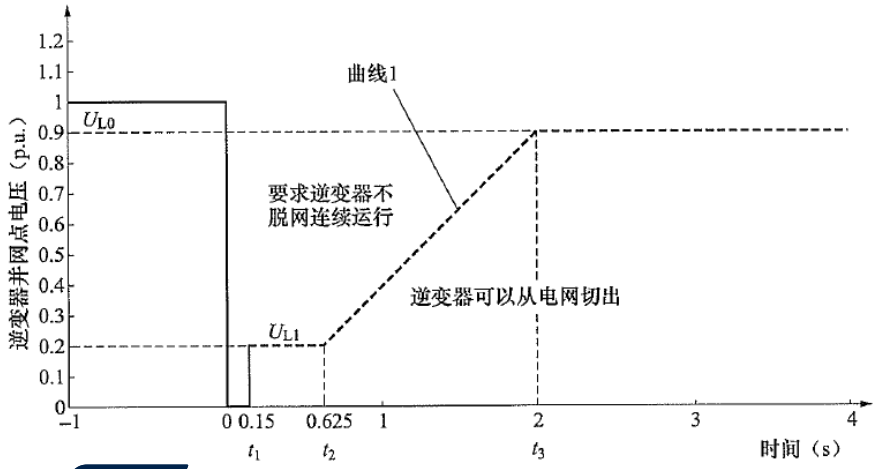
- DC-DC converters

SiC Module-A2U8M12W3

HVRT

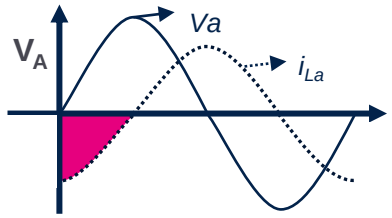


LVRT

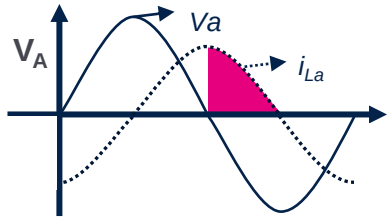


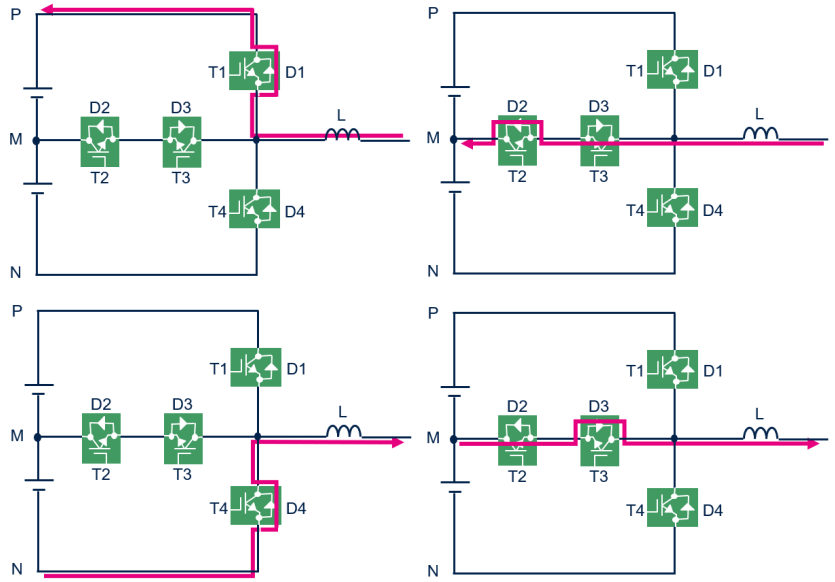
Operation

$Va>0, i_{La}>0$



$Va<0, i_{La}<0$



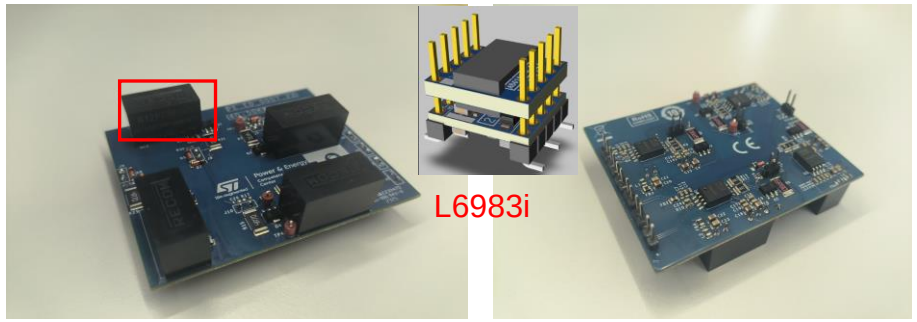


Three-phase symmetrical LVRT or HVRT fault:

$I_{qmax} \leq 1.05 * I_{rated} = 79.8A$

Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_{SD}	Forward on voltage drop	V_{GS} = -5 V, I_{SD} = 100 A	-	5.2	-	V

Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_{SD}	Forward on voltage drop	V_{GS} = -5 V, I_{SD} = 100 A	-	4.15	-	V

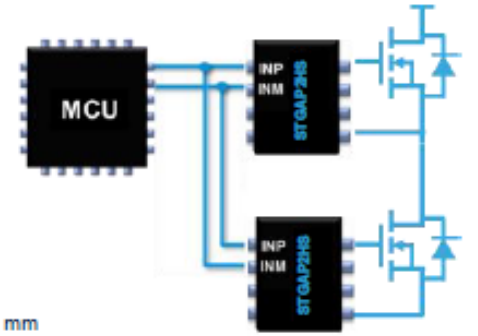


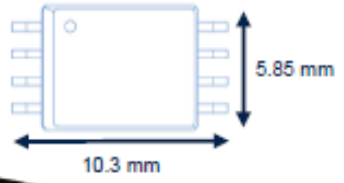
STGAP2 Wide Galvanic Isolation

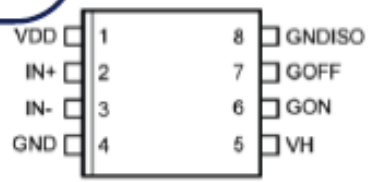
6 kV_{pk} galvanic isolation – 4A single gate drivers

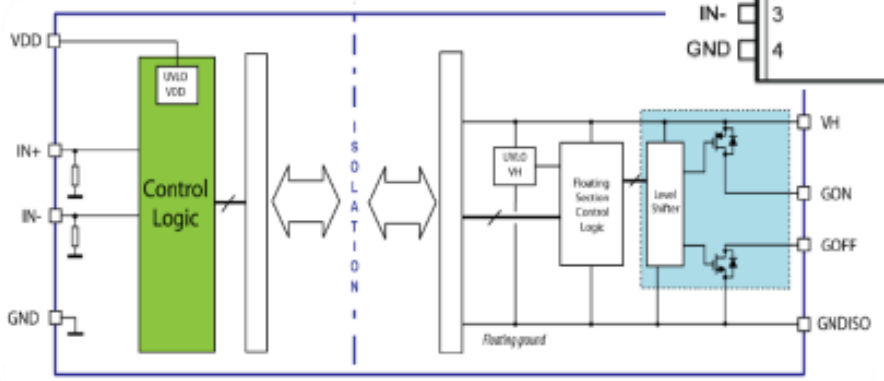
- 3V3 / 5 V logic inputs (logic thresholds 1/3, 2/3 of VDD)
- **Up to 26 V supply voltage**
- **4 A Sink/Source current capability**
- Short propagation delay: 75 ns
- UVLO Function (Si MOS-IGBT & SiC options)
- Stand-by function
- 100 V/ns CMTI
- High voltage rail up to 1200 V
- Thermal shut-down protection

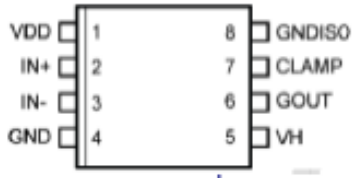
- Active High & Active Low input pins, for HW interlocking
- **STGAP2HSM, STGAP2SICS**: Separated Outputs option for easy gate driving tuning
- **STGAP2SHSCM, STGAP2SICSC**: Miller CLAMP pin option to avoid induced turn-on
- SO-8W Package (Wide Body)

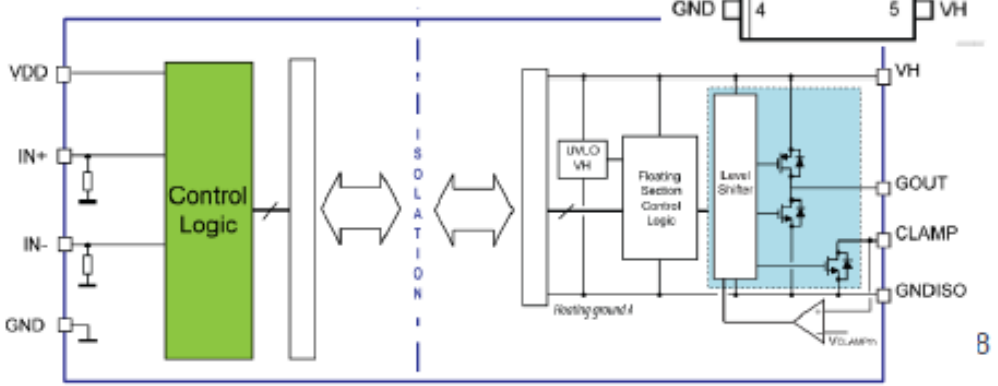










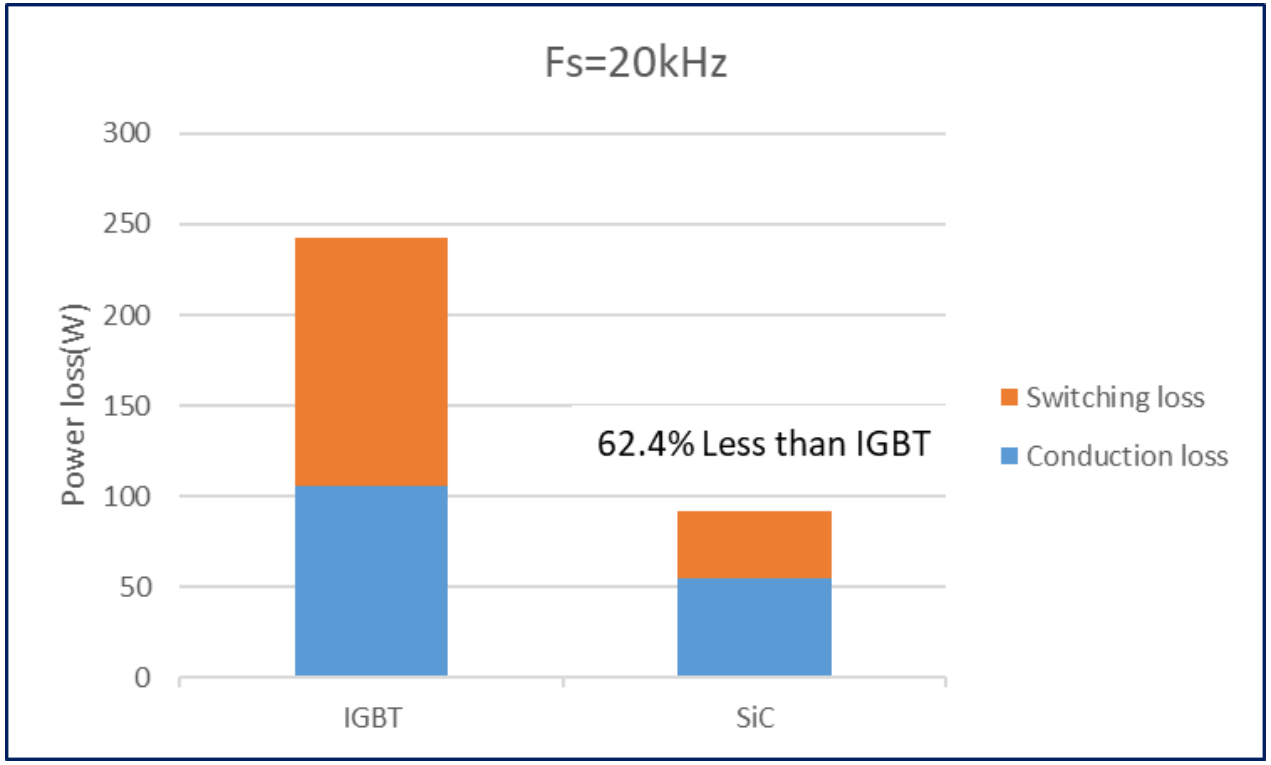


life.augmented

Power Loss Contrast At Full Load

Fsw=40 kHz, Po=50 kW

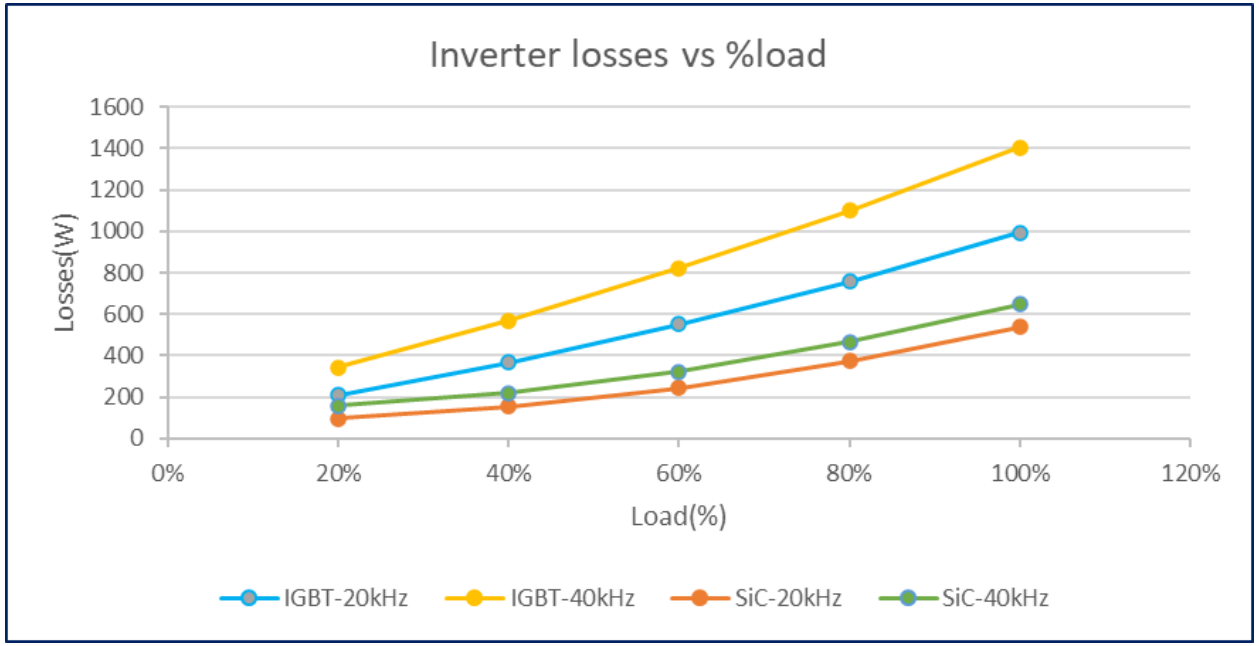
SW type	fs(kHz)	Pconduction(W)				Psw(W)						Eff(%)
		Pcond(T1+T4)	Pcond(T2+T3)	Pcond(D1+D4)	Pcond(D2+D3)	Pon(T1+T4)	Poff(T1+T4)	Pon(T2+T3)	Poff(T2+T3)	Prec(D1+D4)	Prec(D2+D3)	
ST SiC	40	31.015	24.136	0	0	37.226	13.314	0	10.577	0	11.28	98.72%
ST SiC	20	31.015	24.136	0	0	18.613	6.657	0	5.288	0	5.64	98.94%
IGBT	40	47.613	26.693	0	30.854	115.39	119.16	0	0	0	40.9	97.26%
IGBT	20	47.613	26.693	0	30.854	57.7	59.588	0	0	0	20.451	98.05%

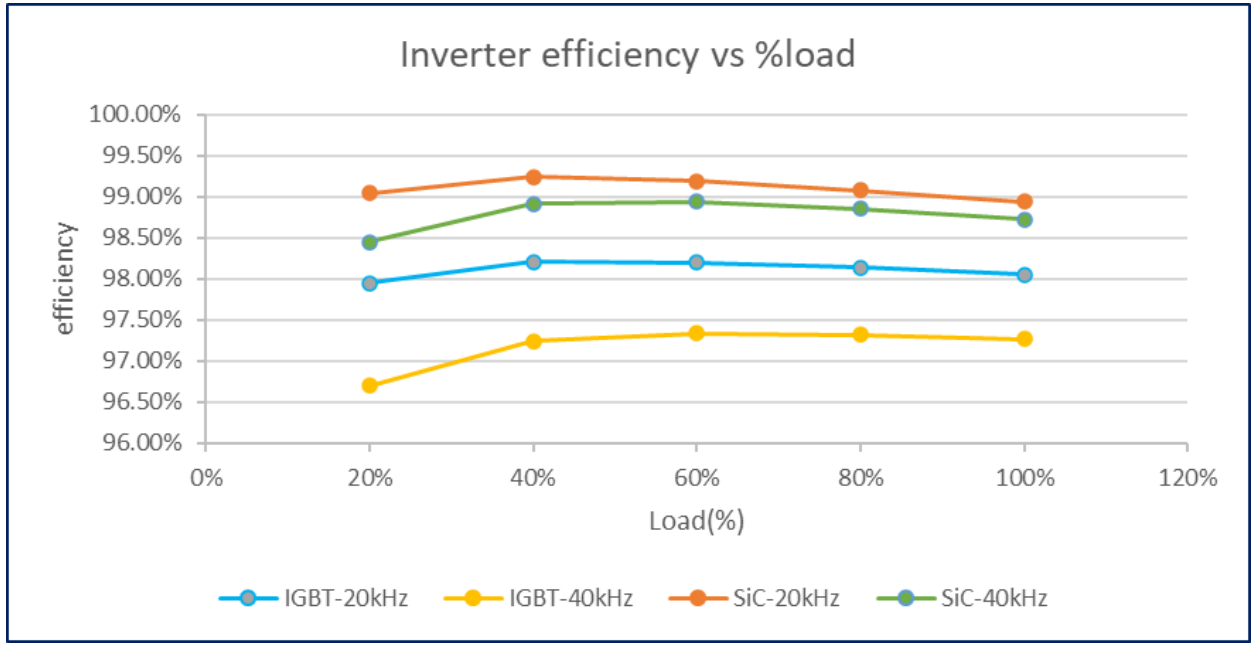


Type	IGBT	SiC	%
Conduction loss	105.1653	55.151	52.44%
Switching loss	137.739	36.198	26.28%

Lower conduction loss → 47.56% less
Lower switching loss → 73.72% less

SiC: Lower Losses, Higher Efficiency





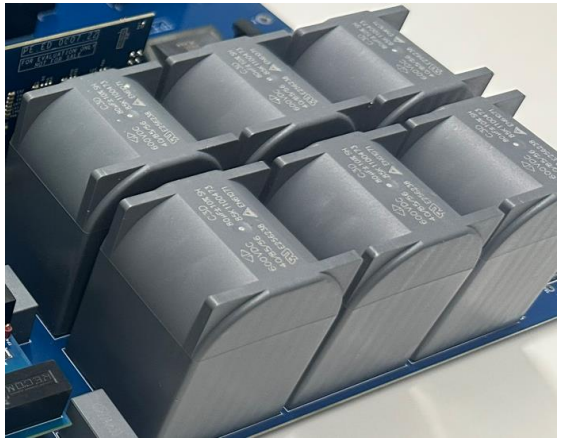
SiC MOSFET module shows lower loss over the whole load range

SiC MOSFET module shows higher efficiency over the whole load range

Lower losses mean smaller cooling system and high efficiency mean better performance

BUS CAP & LCL Filter Optimization

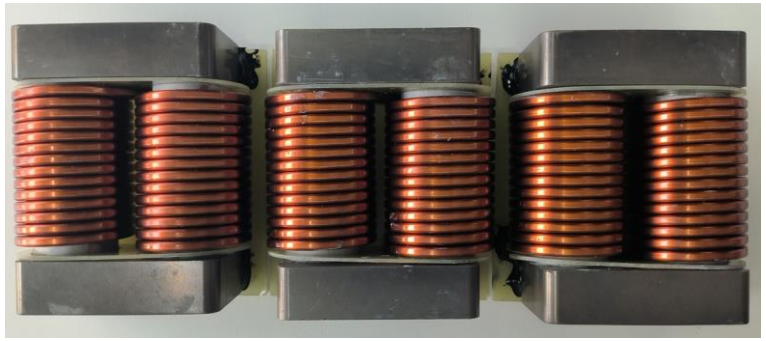
BUS CAP



+ Higher frequency
+ Lower capacitance

120 µF

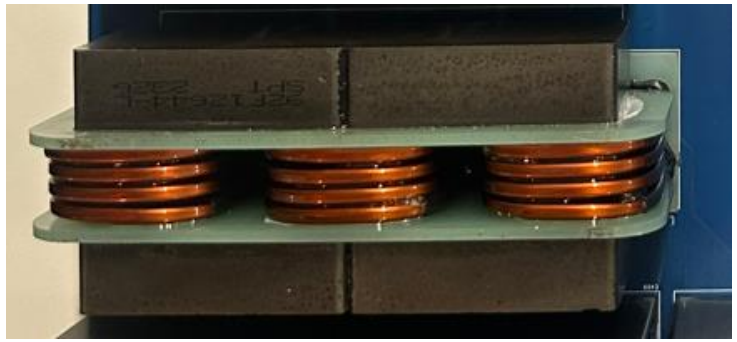
Inverter inductor Lf



+ Higher frequency
+ Lower inductance

80 µH

Grid inductor Lg



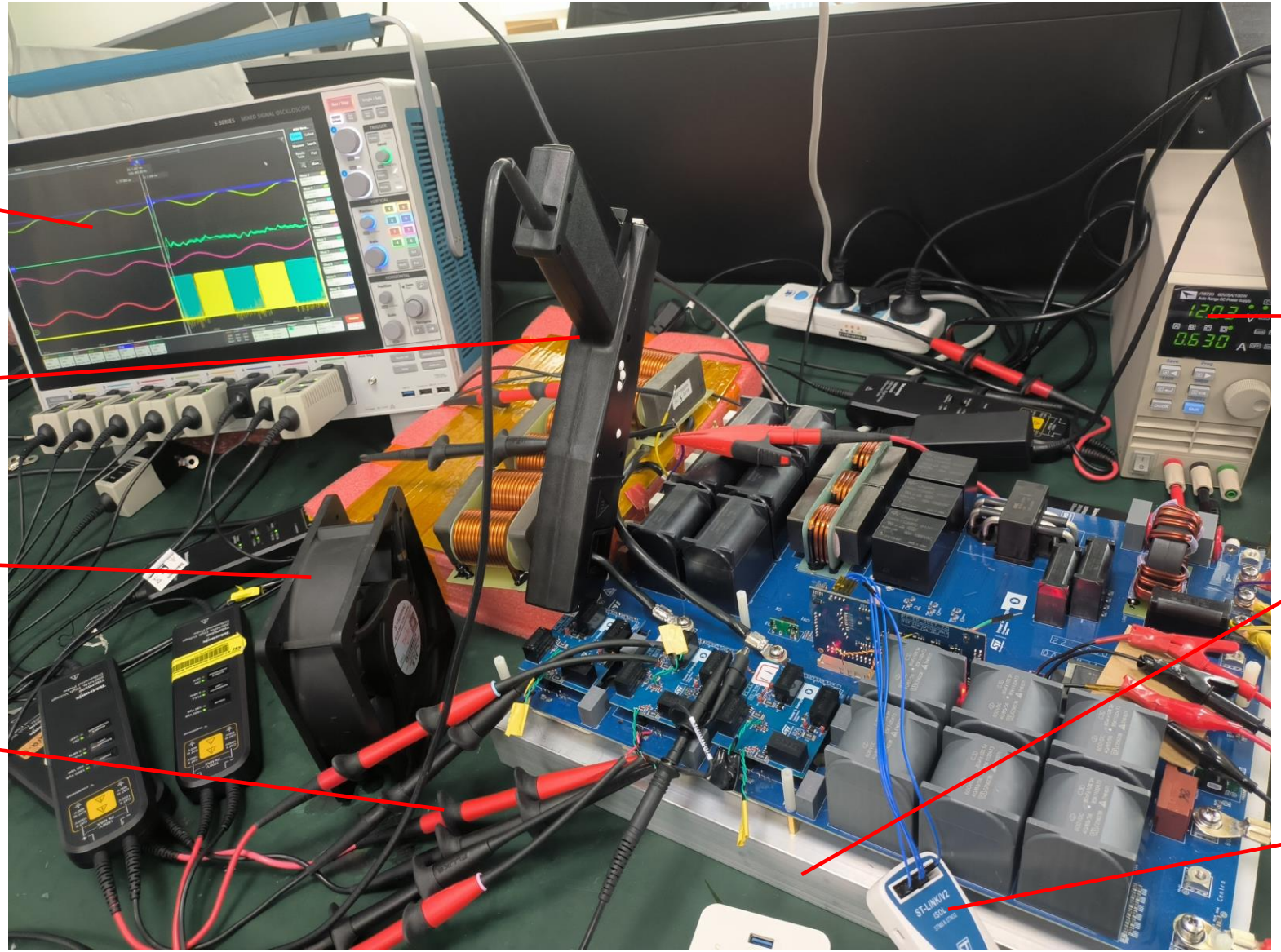
+ Higher frequency
+ Lower inductance

6 µH

ST PV Board Performance

life.augmented

50 kW PV Test Platform

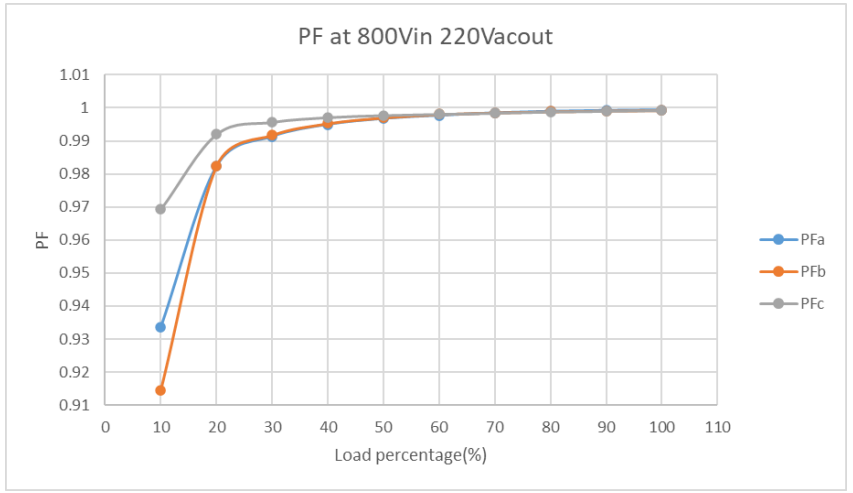


Efficiency, Power Factor & Harmonics

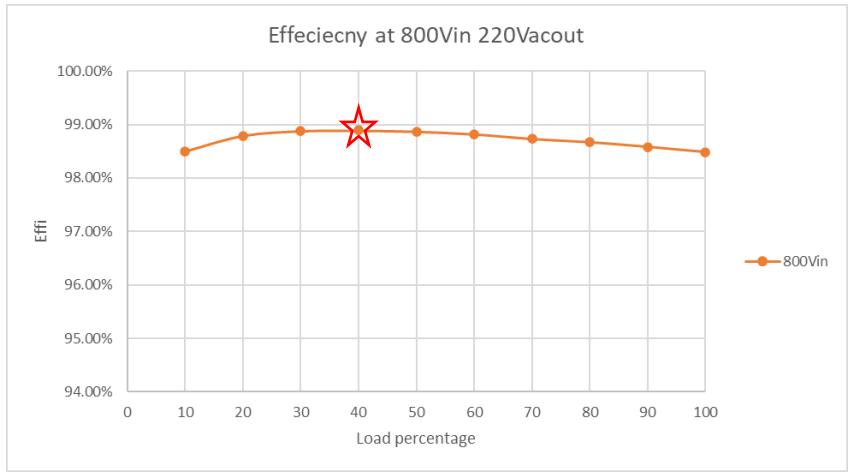
800Vin 220Vacout

Load %	Effe	PF			thd		
		A	B	C	A	B	C
10	98.49%	0.93373	0.91461	0.9693	10.53%	15.63%	10.00%
20	98.79%	0.98242	0.98248	0.99199	5.60%	7.52%	4.61%
30	98.88%	0.99134	0.99176	0.99568	3.96%	5.38%	3.42%
40	98.89%	0.99499	0.9953	0.99711	3.12%	4.22%	3.09%
50	98.87%	0.99678	0.99708	0.99772	2.36%	3.35%	3.06%
60	98.82%	0.99772	0.99806	0.99808	2.27%	2.75%	3.07%
70	98.73%	0.99846	0.99858	0.99844	2.16%	2.56%	2.89%
80	98.67%	0.99893	0.99892	0.9988	2.12%	2.45%	2.77%
90	98.58%	0.9992	0.99915	0.99901	1.95%	2.30%	2.72%
100	98.48%	0.99936	0.99929	0.99922	2.03%	2.10%	2.77%

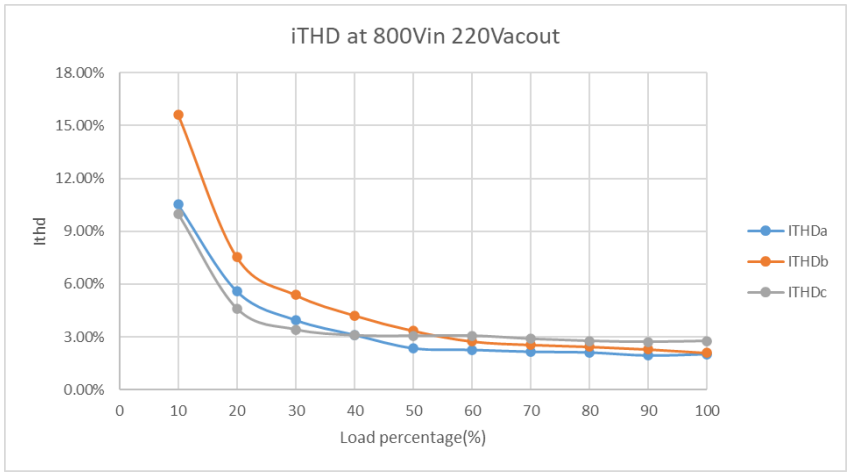
PF at 800Vin 220Vacout



Peak efficiency 98.89% at 800Vin 220Vacout



iTHD < 3% at full load

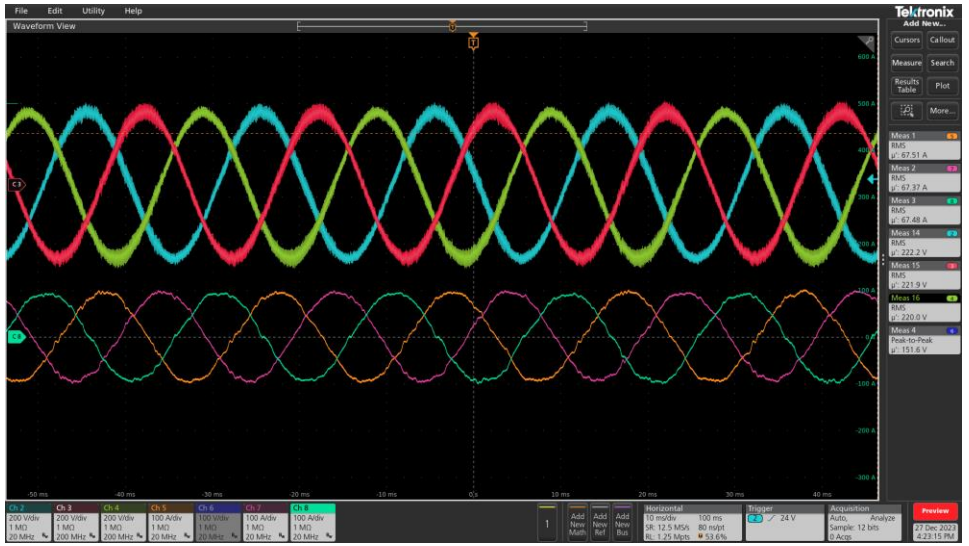


50kW T-type DC/AC PV Inverter PF Range

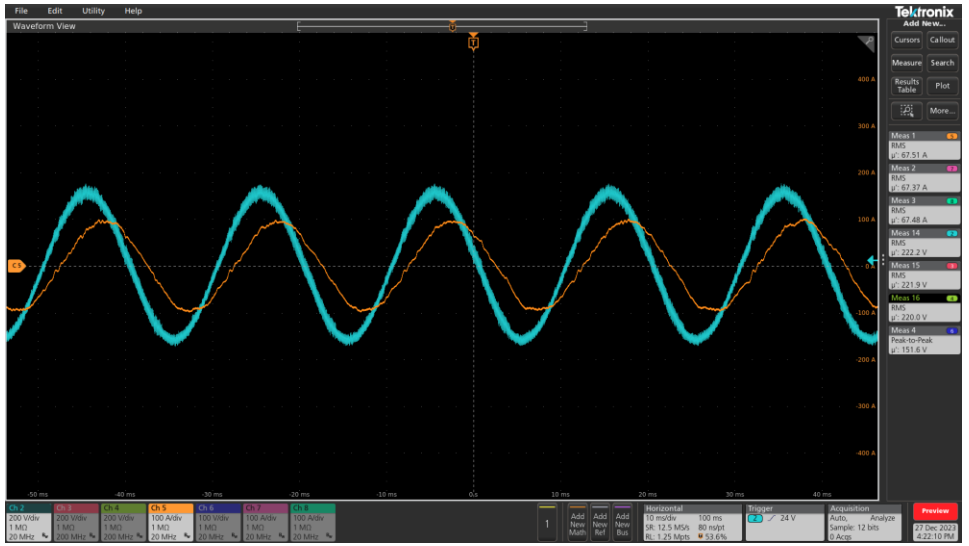
800Vin 220Vacout 50kw

PF=0.8 voltage lead current

VoutA
VoutB
VoutC
IoutA
IoutB
IoutC

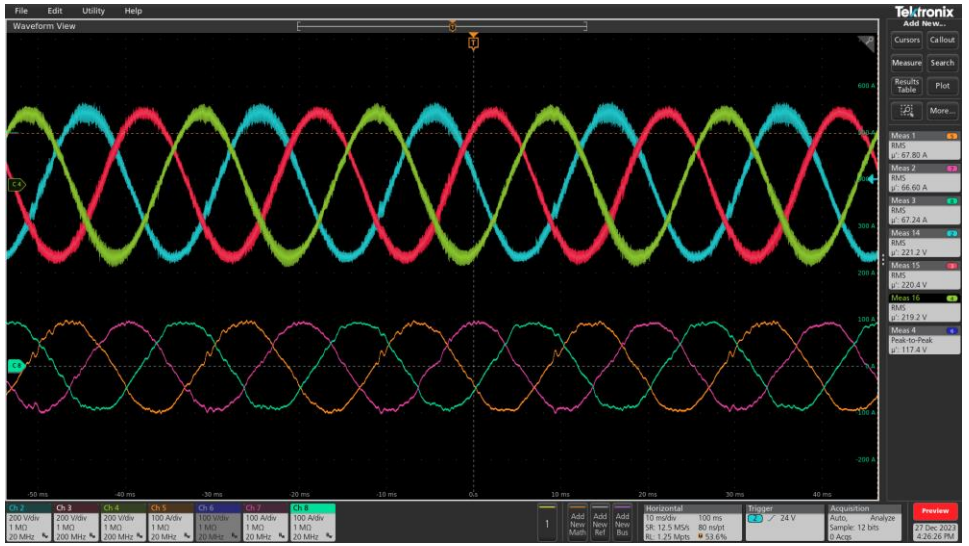


VoutA
IoutA

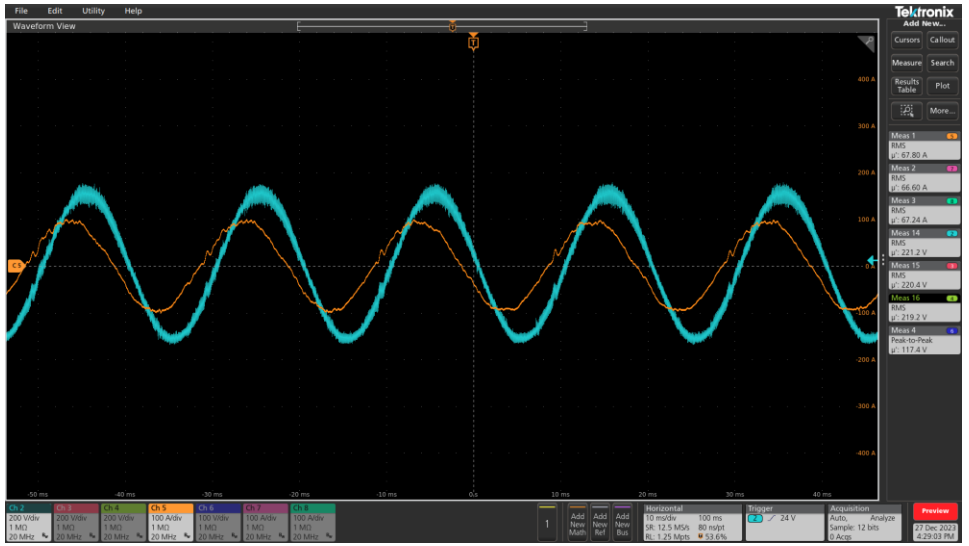


PF=0.8 voltage lag current

VoutA
VoutB
VoutC
IoutA
IoutB
IoutC



VoutA
IoutA



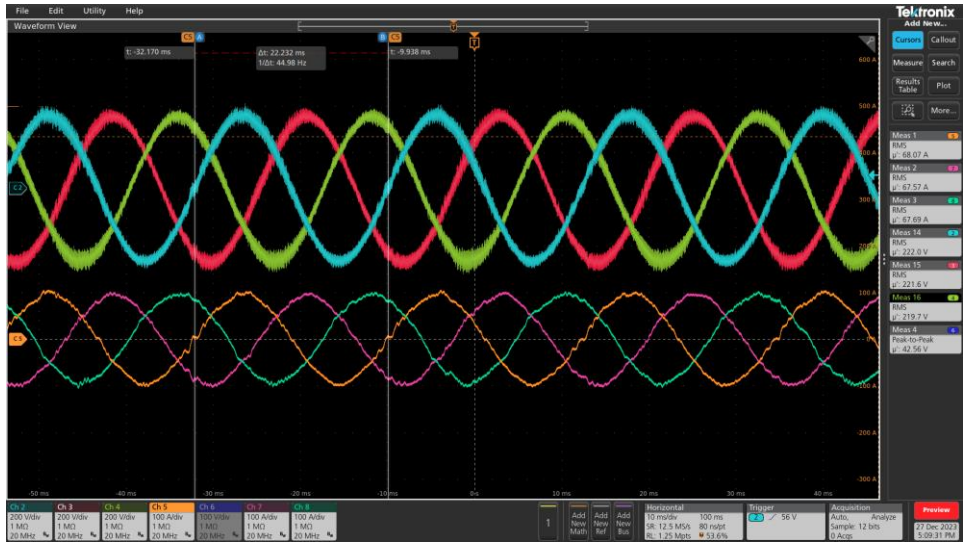
50kW T-type DC/AC PV Inverter Frequency Range

800Vin 220Vacout 50kw

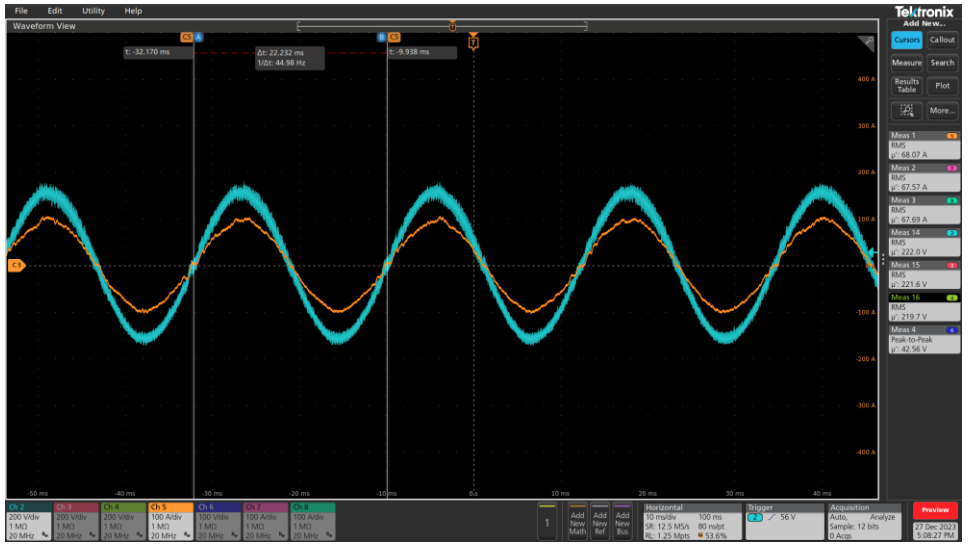
Frequency=45 Hz

VoutA
VoutB
VoutC

IoutA
IoutB
IoutC



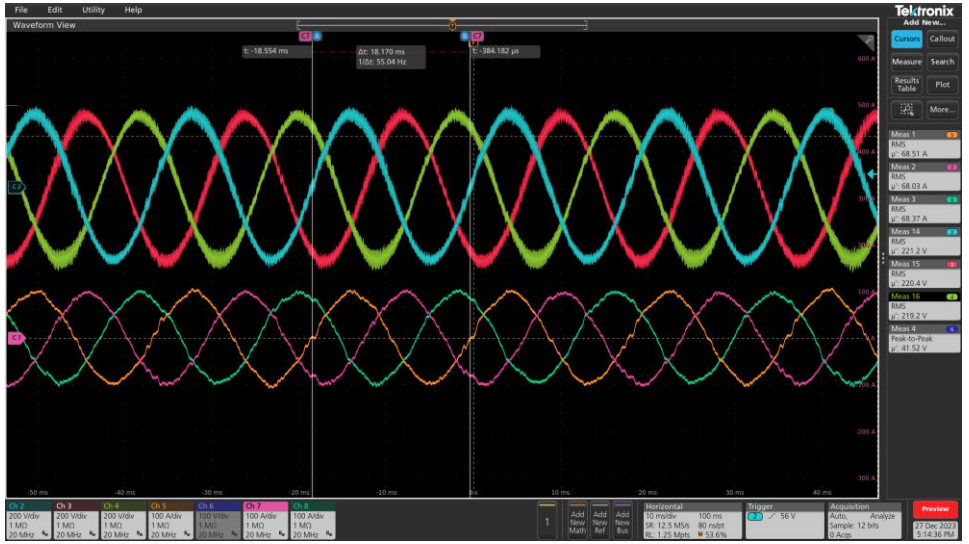
VoutA
IoutA



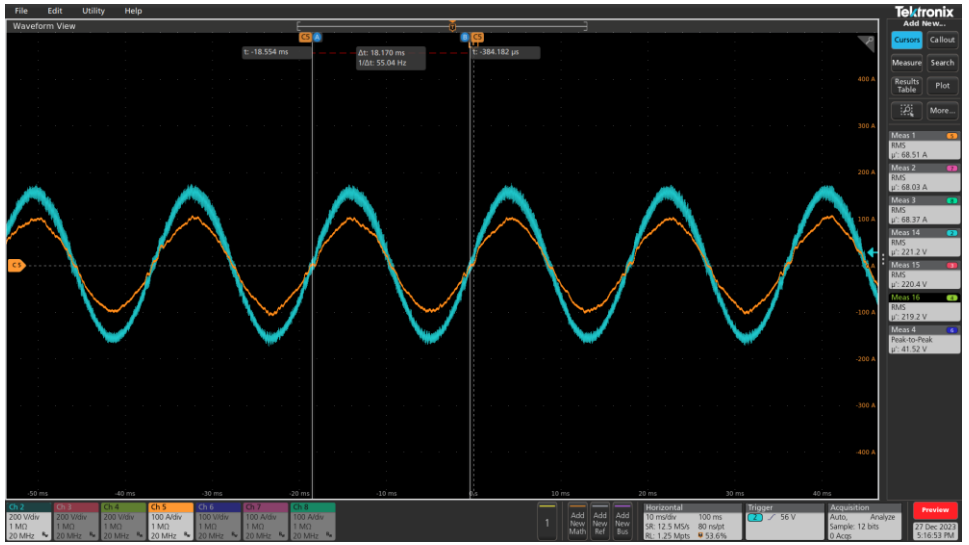
Frequency=55 Hz

VoutA
VoutB
VoutC

IoutA
IoutB
IoutC



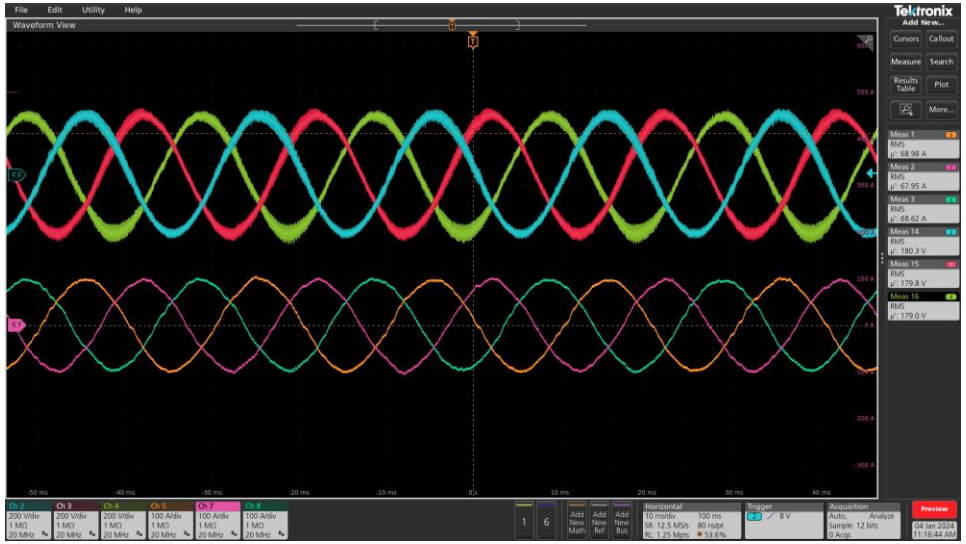
VoutA
IoutA

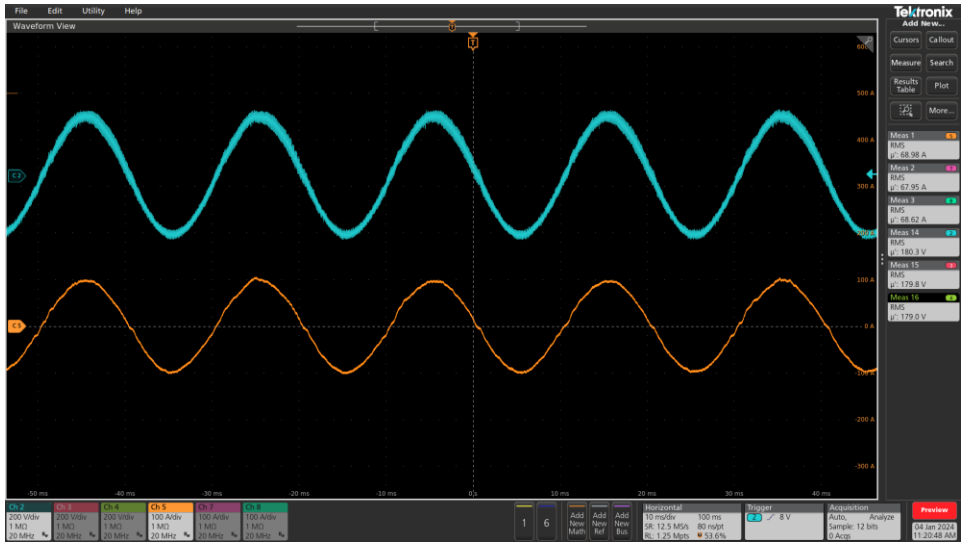


50kW T-type DC/AC PV Inverter Vout Range

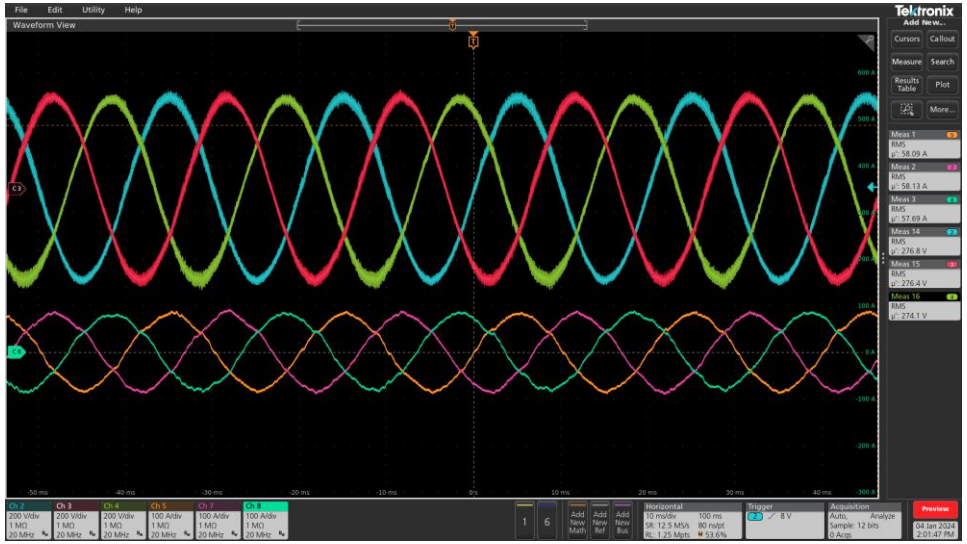
800Vin

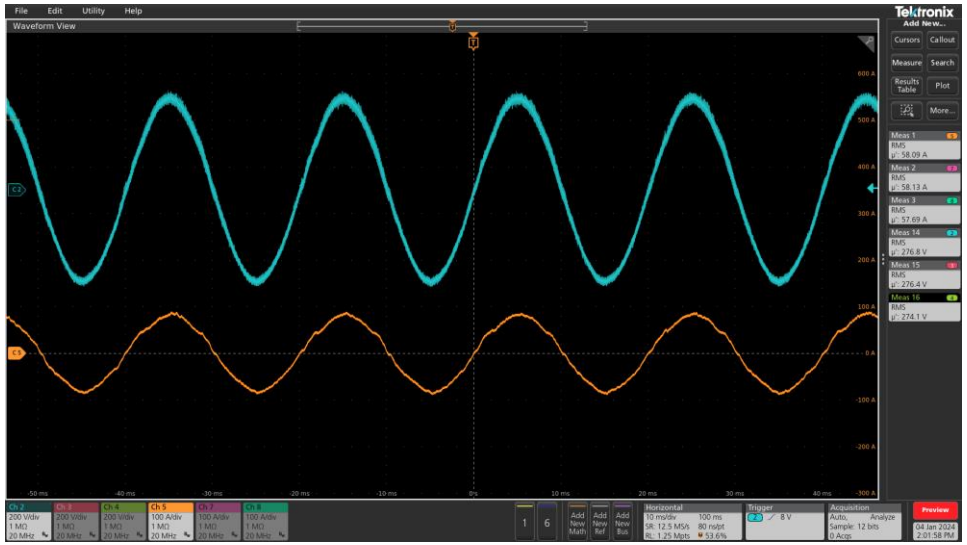
Vout=310 V(L-L)





Vout=476 V(L-L)

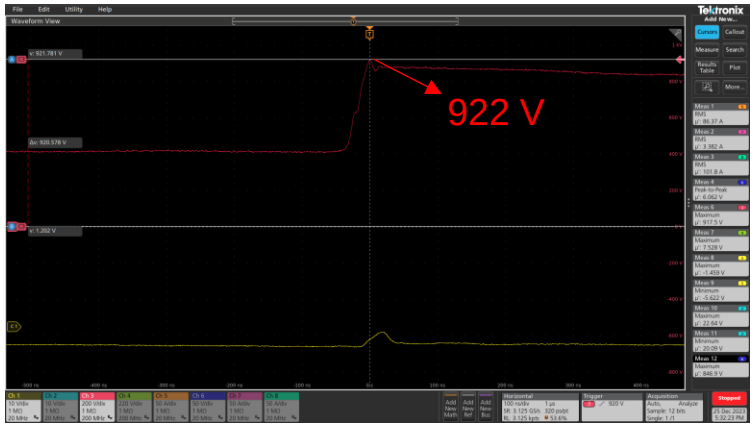




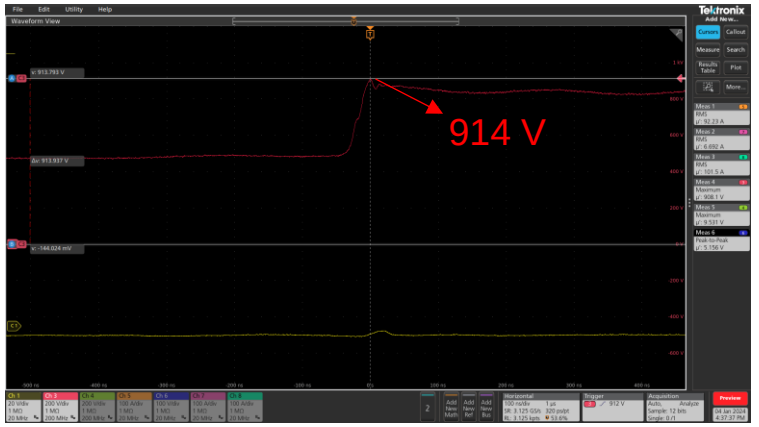
50kW T-type DC/AC PV inverter Vds Spike

850Vin 220Vacout 50kw

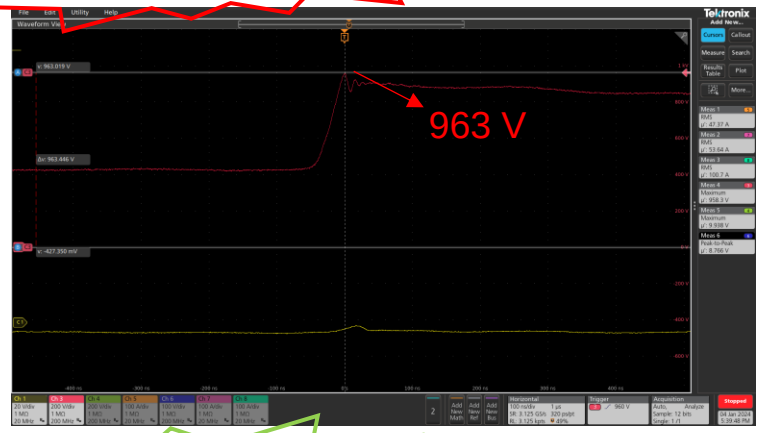
Vertical bridge(PF=1)



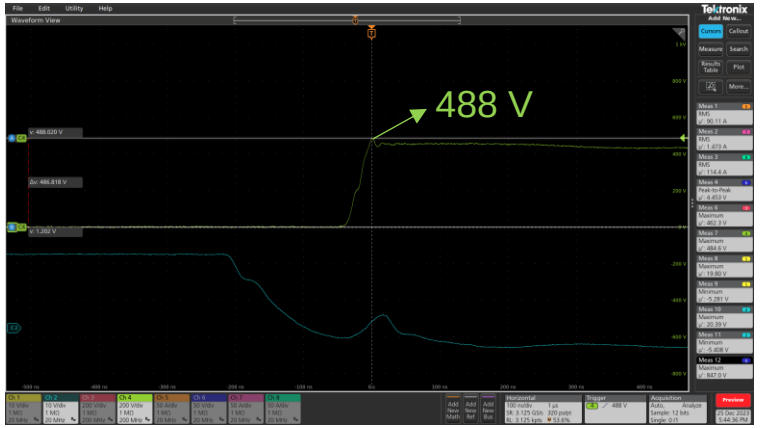
Vertical bridge(PF=0.8 lead)



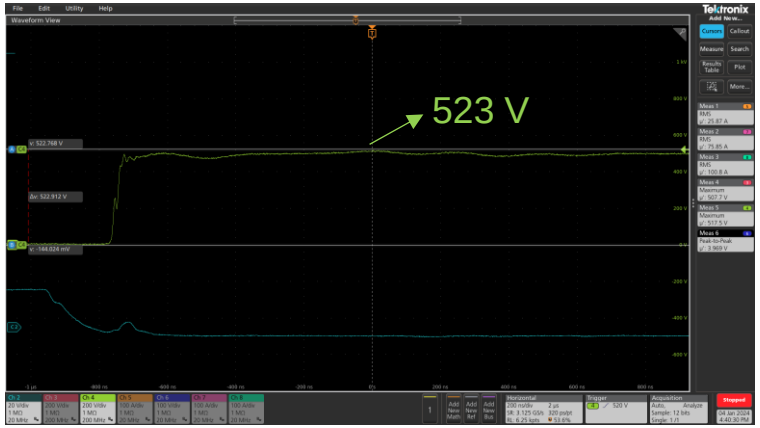
Vertical bridge(PF=0.8 lag)



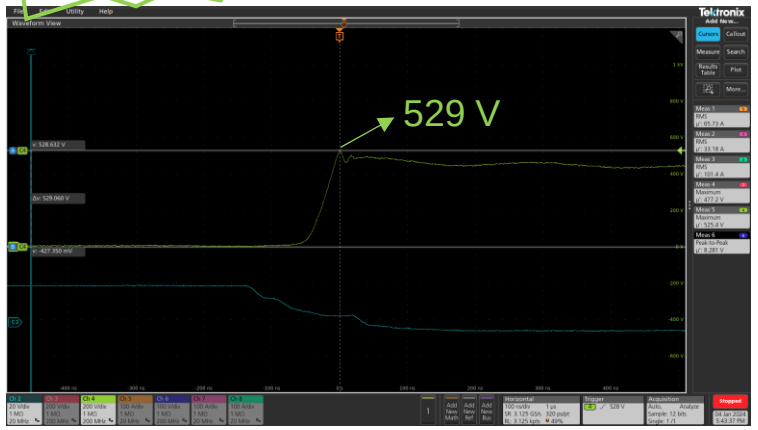
Horizontal bridge(PF=1)



Horizontal bridge(PF=0.8 lead)



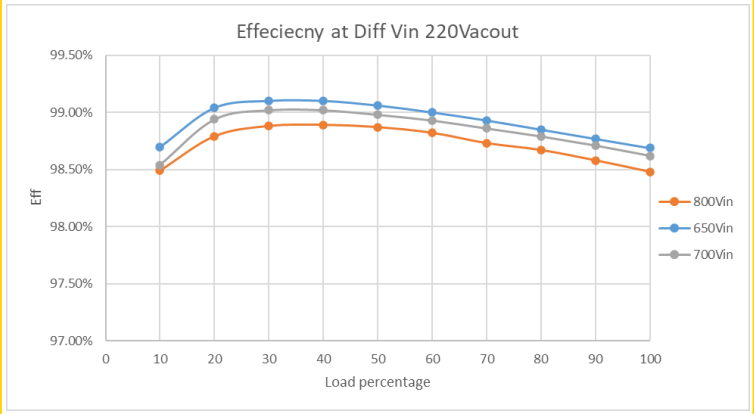
Horizontal bridge(PF=0.8 lag)



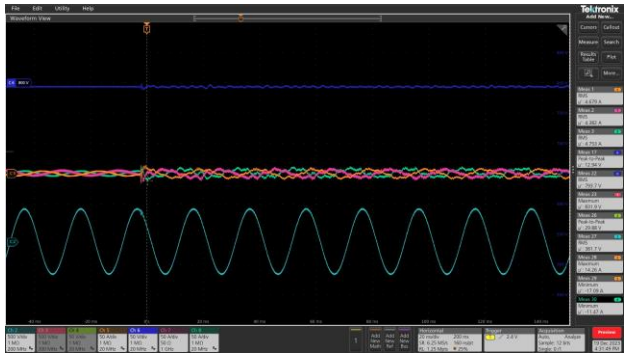
Power & Energy
Competence
Center

Final EVAL Results

Efficiency

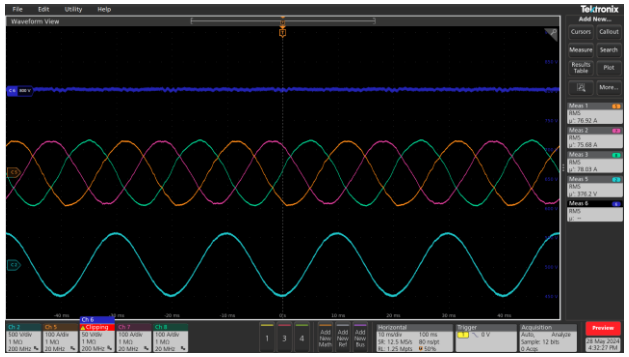


Waveforms



CH5,7,8-ABC output Current；CH6-Input voltage；CH2-Output voltage

Startup

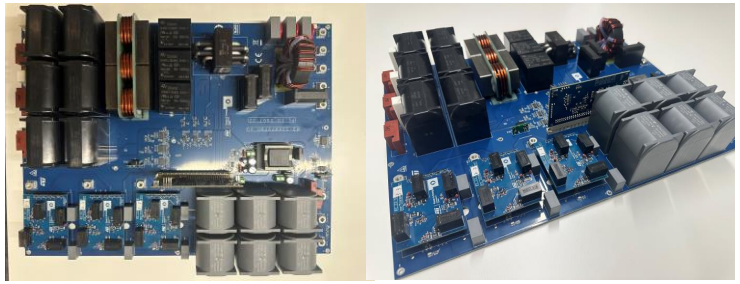


CH5,7,8-ABC output Current；CH6-Input voltage；CH2-Output voltage

800 V 50 kW output

Key performance result

1. 650-850 Vdc input voltage; 310-476 V output voltage; 45-55 Hz output frequency; 50 kW output max power
2. Peak efficiency 99.10%@650 Vdc input; 98.89%@800 V input
3. PQ/PF control method in SW control

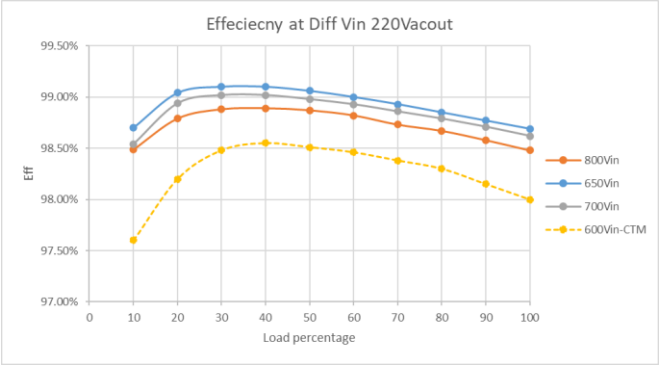


WxLxH:300 x 400 x 70 mm

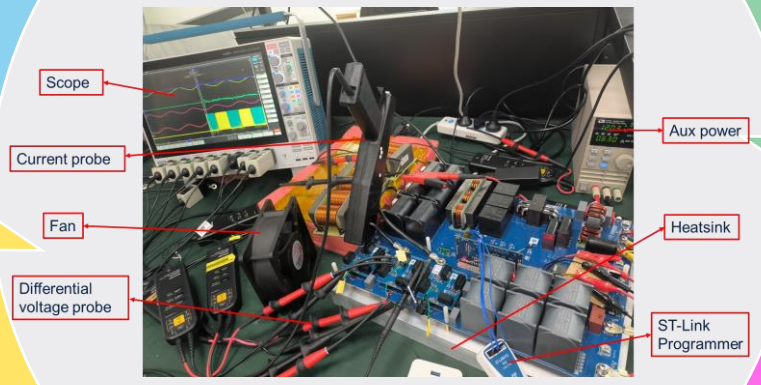
Summary

High efficiency

- 98.89% @ 800 Vdc
- 99.10% @ 650 Vdc



A2U8M12W3



High power density

- 75 W/in^3

High frequency

- 40 kHz

High reliability

- Gen 3 SiC technology
- ACEPACK2 package
- Integrated NTC
- AlN DBC

life.augmented

50 kW Digital DC-AC Inverter Based on SiC ACEPACK and STM32H743

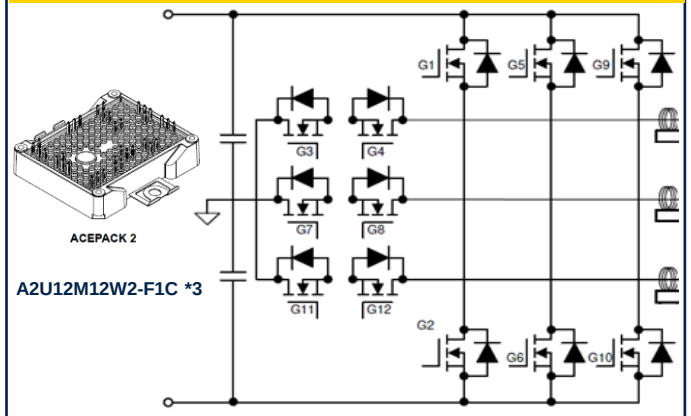
Leah XIAO

Power & Energy
Competence
Center

Power & Energy Competence Center

50kW DC/AC for PV Inverter PE.ED_ ED_0007.22

3-level t-type topology



PCBA outlook

Application key features:

- Input DC voltage: 650Vdc-850VDC
- Output AC voltage: 380 VAC L-L
- Switching frequency: 40 kHz
- Peak efficiency: 98.89% (800 Vdc)
- ≥0.99 PF and ≤3% THD @ full load operation
- Active and reactive power control
- 0.8 leading to 0.8 lagging adjustable
- Fully digital power Stage with STM32H7 MCU

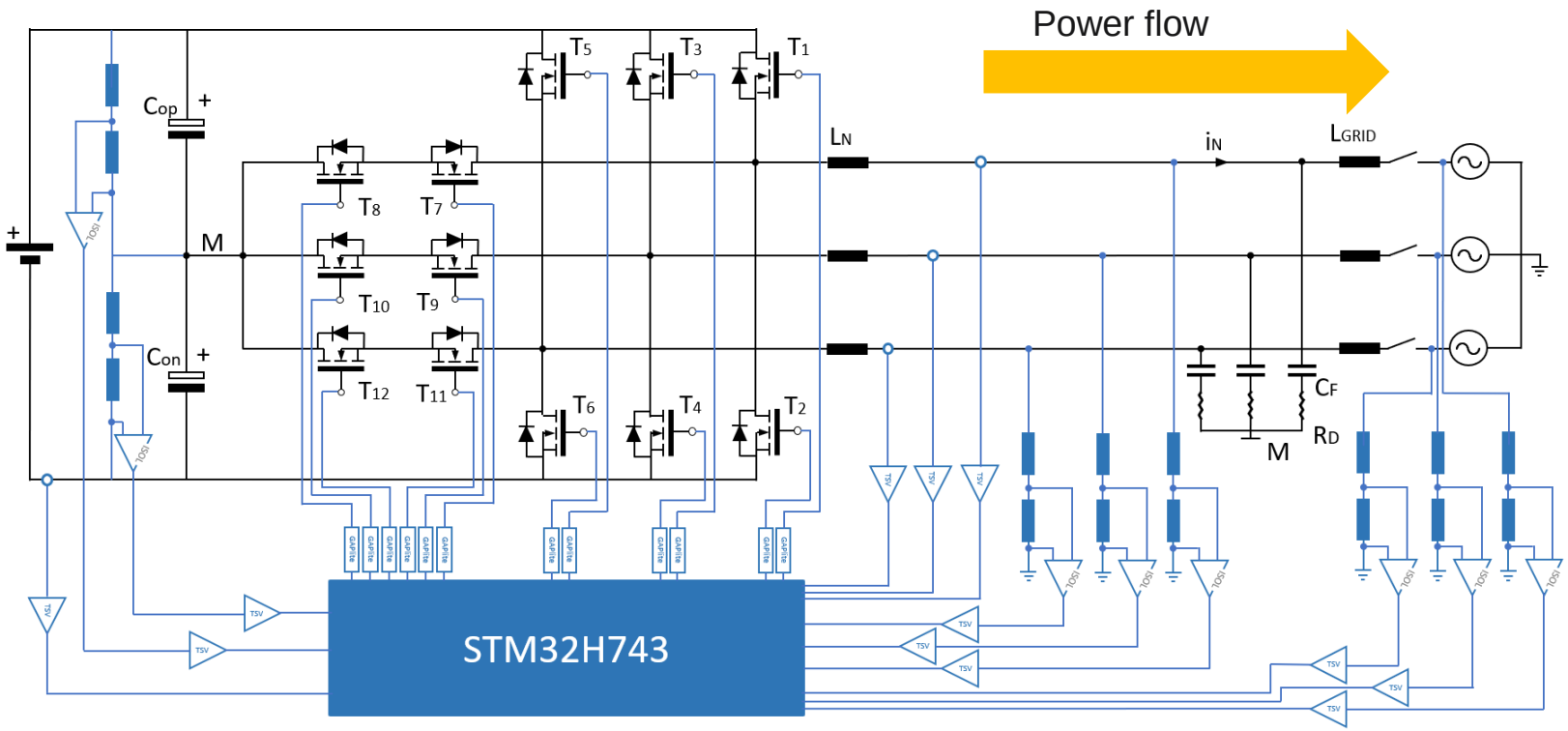
Key products

MCU: STM32H743ZGT6 (32-bit MCU with 480 MHz CPU frequency)
SiC MOSFET: A2U8M12W3-FC*3 (9.5mΩ 1200 V & 6mΩ 750 V SiC module)
Gate driver: STGAP2SICSC (galvanic insulated)
IPC & GPA: ISOSD61, LM393DT, TSV912IDT, TSV914IDT

Key benefits

- ✓ SiC modular approach with full digital power control for high flexibility in system design
- ✓ Compact output LCL filter with switching frequency up to 40 kHz on power stage
- ✓ Support major functions (anti-islanding, RCMU) for PVI product design reference

Functional Block & Main Firmware Features



DC-AC

- **3-phase grid-connection controlled by DQ**
- **Active and reactive power control**
- **Overvoltage protection**
- **Overcurrent protection**
- **Thermal protection**
- **Anti-islanding, residual current detection**
- **Higher operating frequency**
- **Flexible digital design customization to meet specific customer needs**
- **Communication interfaces**
  (UART asynchronous protocol for external/internal communications)

Inverter Digital Platform - STM32H743

Configurations of MCU key functions on digital inverter

Arm® Cortex® -M7 up to 480 MHz

Floating-point unit (FPU)

- Control loop computation (reserved for future use)

64-Kbyte ITCM RAM and128-Kbyte DTCM RAM

- Zero wait state for time critical routines

DFSDM digital filters for sigma delta modulator

- To work with external isolated ADC

USART, SPI, CAN

- USART for internal/external communication

Comparators and DACs

- Inverter OVP / OCP

Multiple ADCs with 16-bit max resolution

- Three-phase grid voltage, inductor current, DC bus voltage/current and temperature

Advanced-control PWM Timer

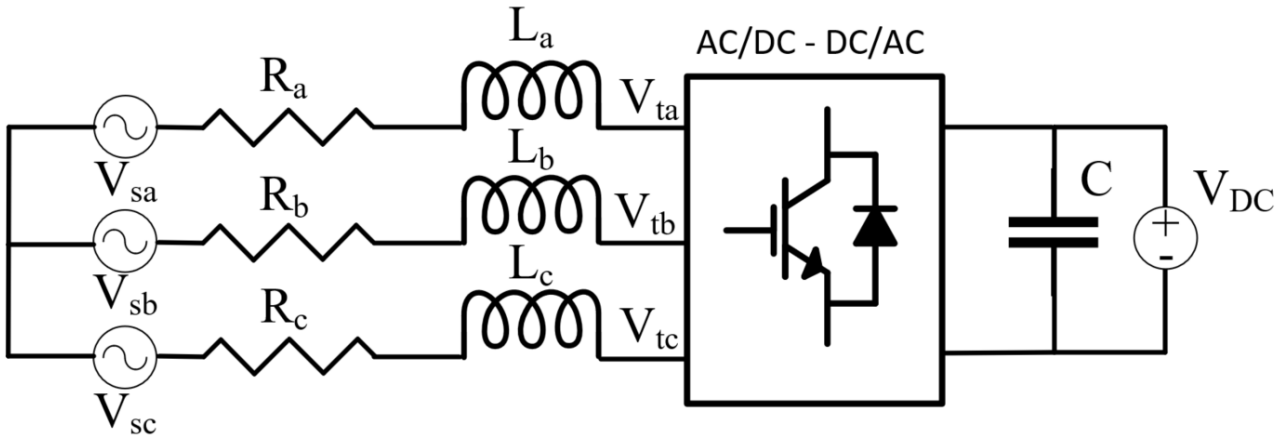
- Mainly for phase A MOSFET control at 40 kHz

Hi-Resolution PWM Timer

- Mainly for phase B and phase C MOSFET control at 40 kHz

VSC Model (Plant)

Model of voltage source converter “VSC”



$$\begin{cases} L\frac{di_a}{dt} + Ri_a = V_{ta} - V_{sa} \\ L\frac{di_b}{dt} + Ri_b = V_{ta} - V_{sb} \\ L\frac{di_c}{dt} + Ri_c = V_{ta} - V_{sc} \end{cases}$$

Clarke
abc ⇒ $\alpha\beta$

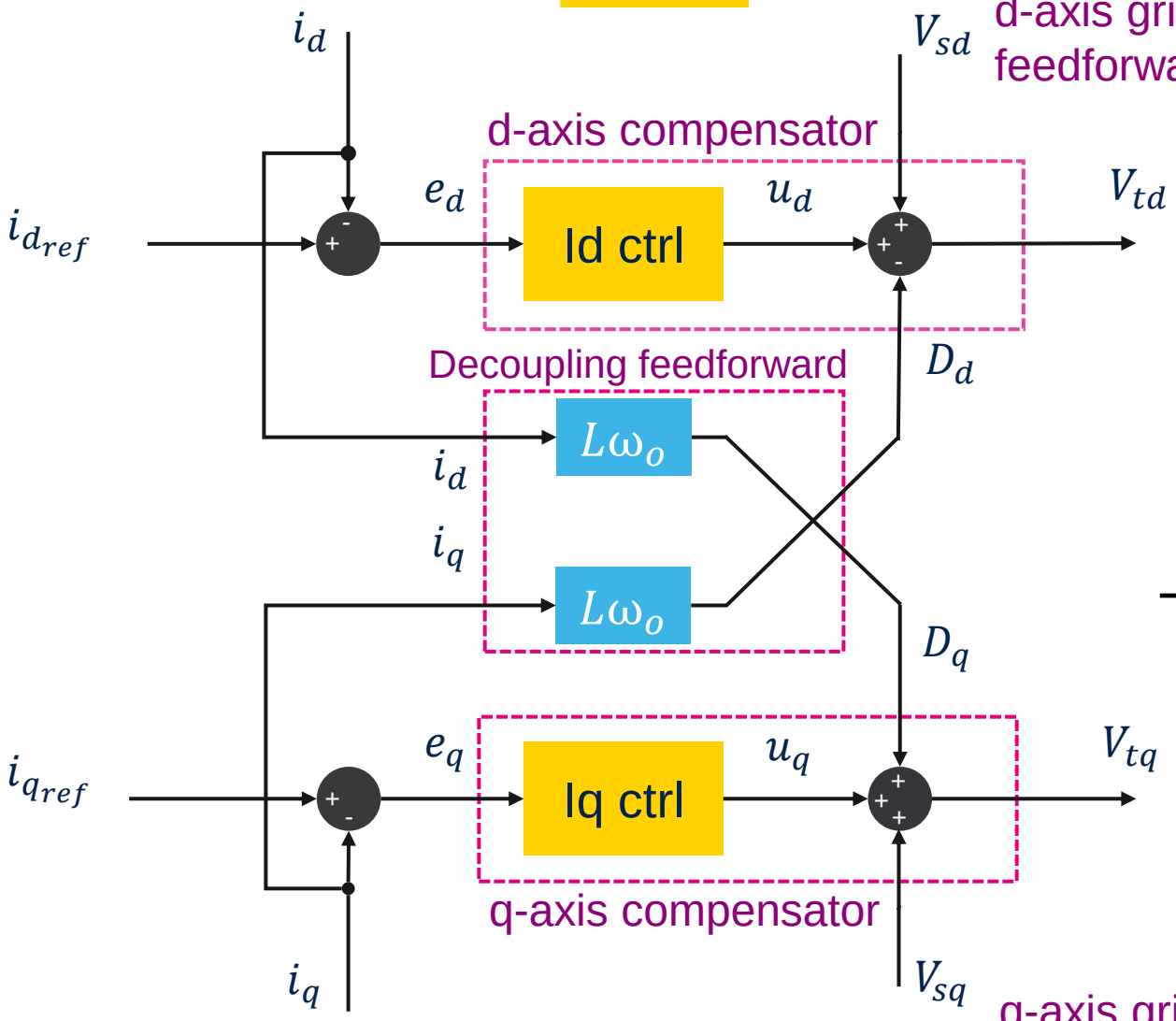
$$\begin{cases} L\frac{di_\alpha}{dt} + Ri_\alpha = V_{t\alpha} - V_{s\alpha} \\ L\frac{di_\beta}{dt} + Ri_\beta = V_{t\beta} - V_{s\beta} \end{cases}$$

Park
$\alpha\beta$ ⇒ qd

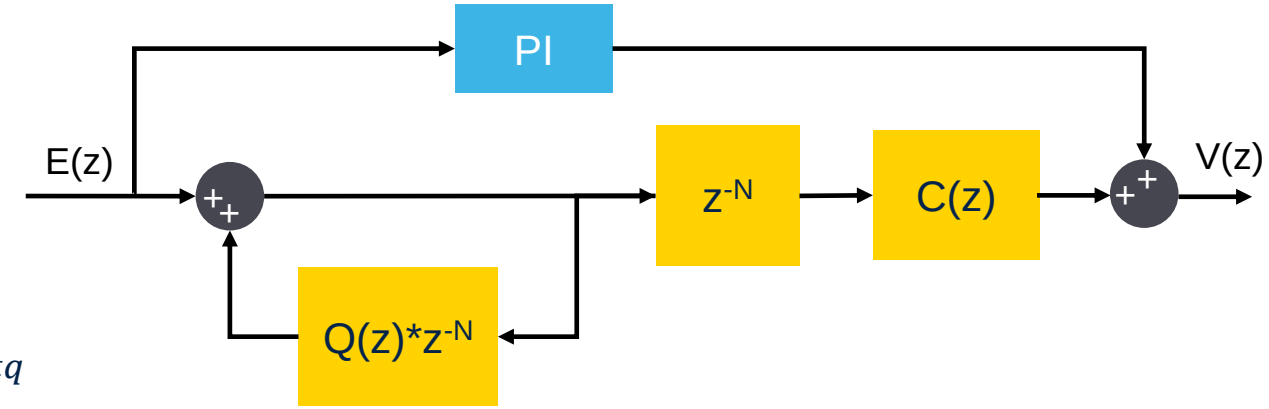
$$\begin{cases} L\frac{di_d}{dt} + Ri_d - \omega(t)Li_q = V_{td} - V_{sd} \\ L\frac{di_q}{dt} + Ri_q + \omega(t)Li_d = V_{tq} - V_{sq} \\ \frac{d\rho}{dt} = \omega(t) \end{cases}$$

Hp. $\begin{cases} e_a + e_b + e_c = 0 \\ i_a + i_b + i_c = 0 \end{cases}$

Current Loop With Decoupling Control

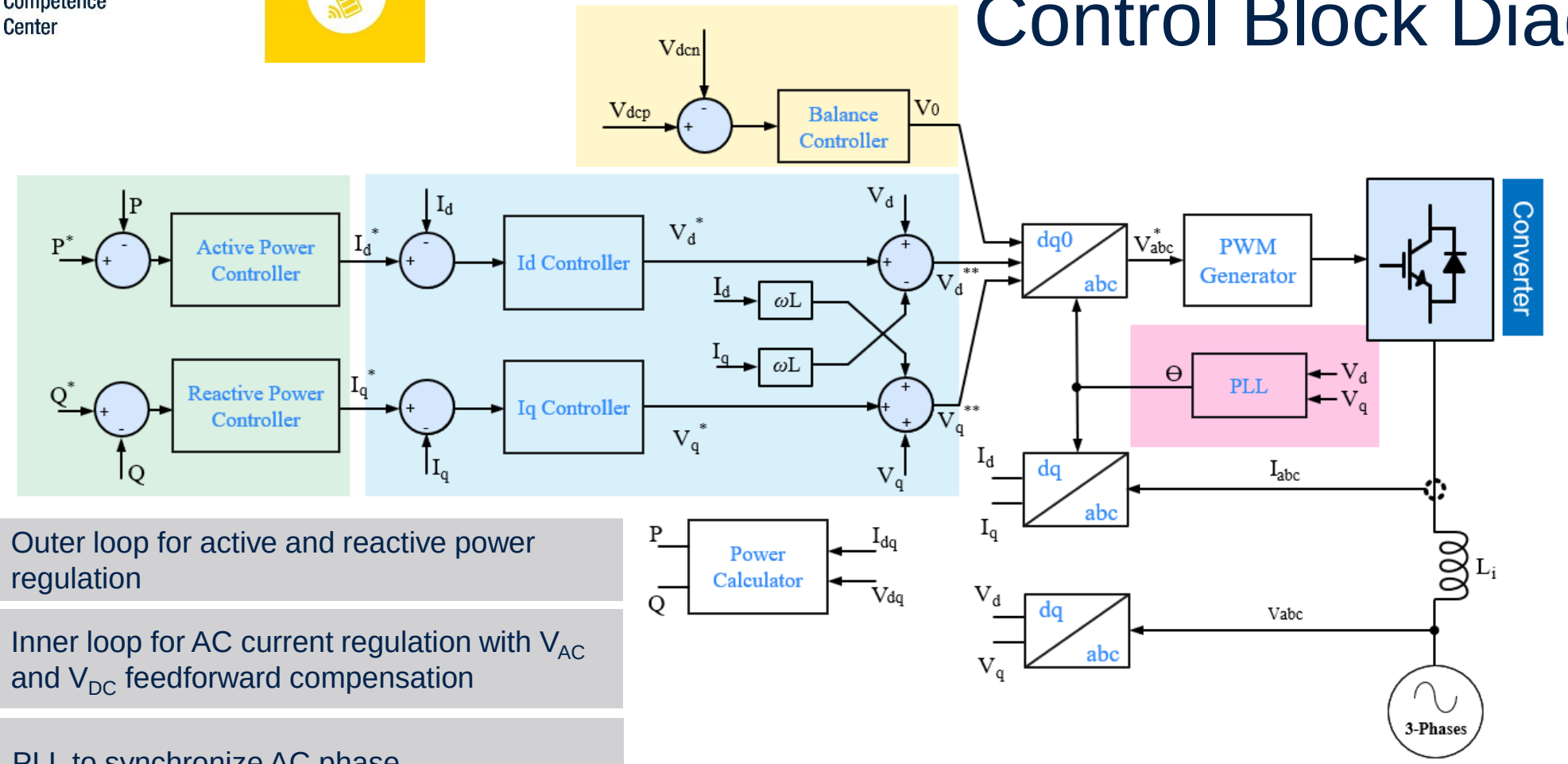


$$\begin{cases} V_{td} = \left(k_p + \frac{k_i}{s} + RC(z)\right)\left(i_{d_{ref}} - i_{d_{feed}}\right) - \omega_0 L i_q + V_{sd} \\ V_{tq} = \left(k_p + \frac{k_i}{s} + RC(z)\right)\left(i_{q_{ref}} - i_{q_{feed}}\right) + \omega_0 L i_d + V_{sq} \end{cases}$$



PI + repetitive controller is applied to achieve better static and dynamic performance on current controlling

Control Block Diagram



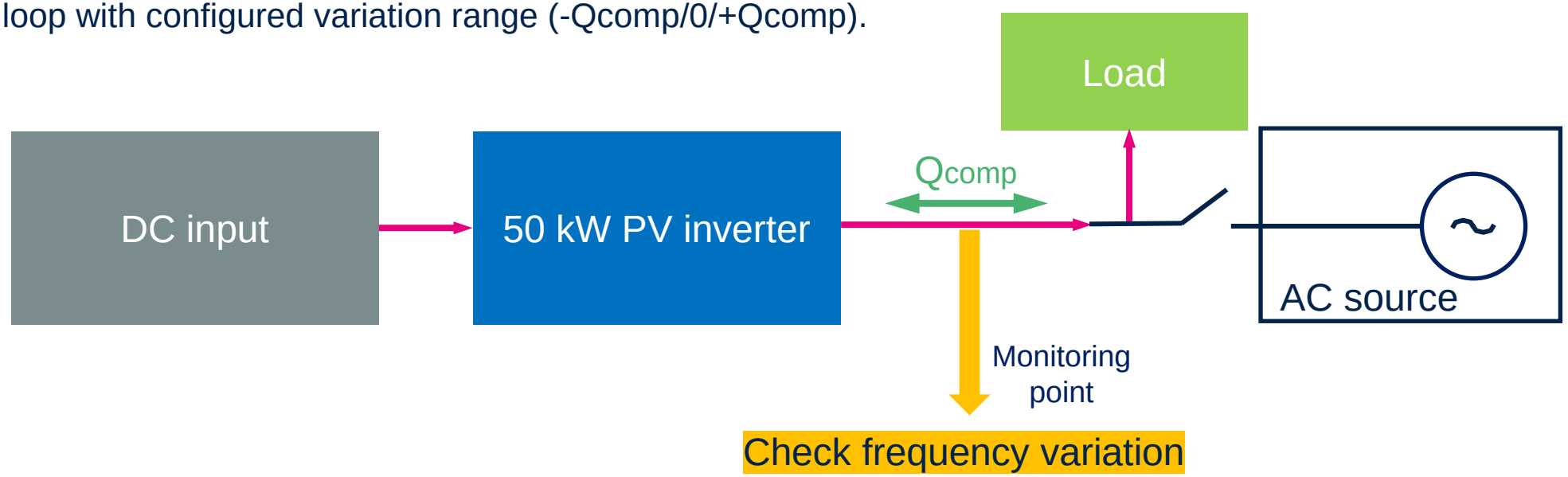
Power loop	Outer loop for active and reactive power regulation
Current loop	Inner loop for AC current regulation with V_{AC} and V_{DC} feedforward compensation
PLL loop	PLL to synchronize AC phase
Bus balance loop	Balance three-level bus neutral-point

- Power loop: 20 kHz
- Current loop: 20 kHz
- PLL loop: 20 kHz
- Bus balance control: 20 kHz

Anti-islanding

Active detection - reactive disturbance compensation method

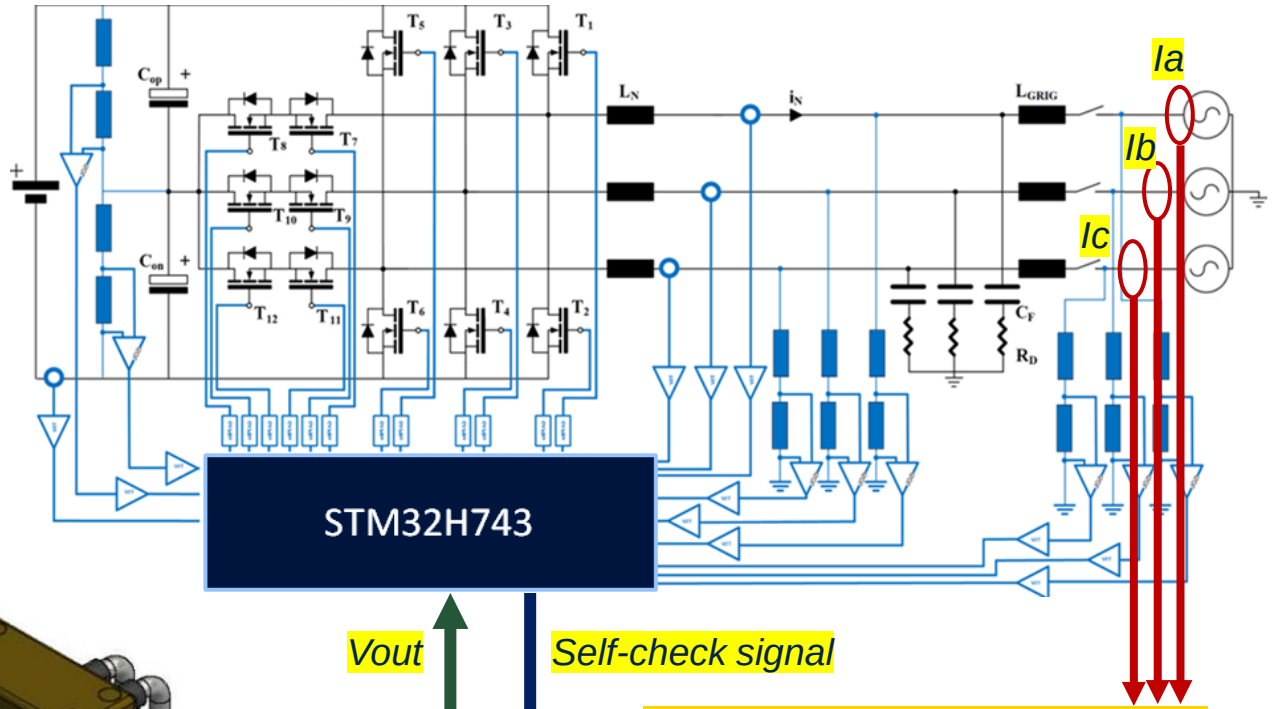
- By variation of reactive power as disturbance signal, the existence of AC grid could be detected by checking frequency variation.
- The disturbance compensation of reactive power (Qcomp) will be injected to the output of control loop with configured variation range (-Qcomp/0/+Qcomp).

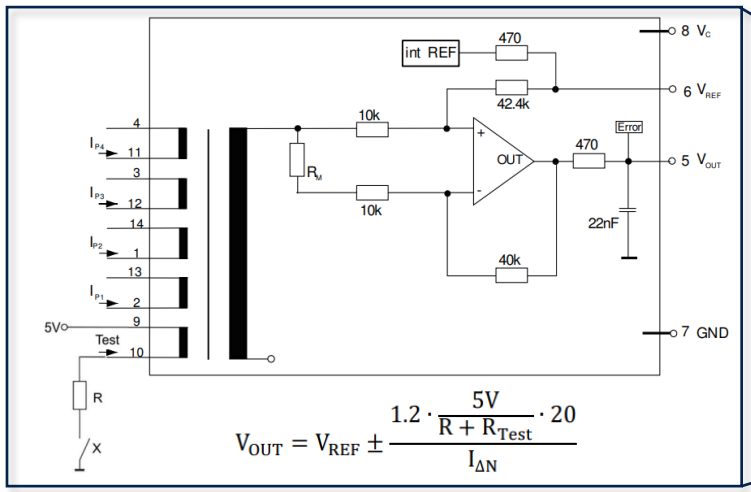


Residual Current Protection

Residual current monitoring with self-checking

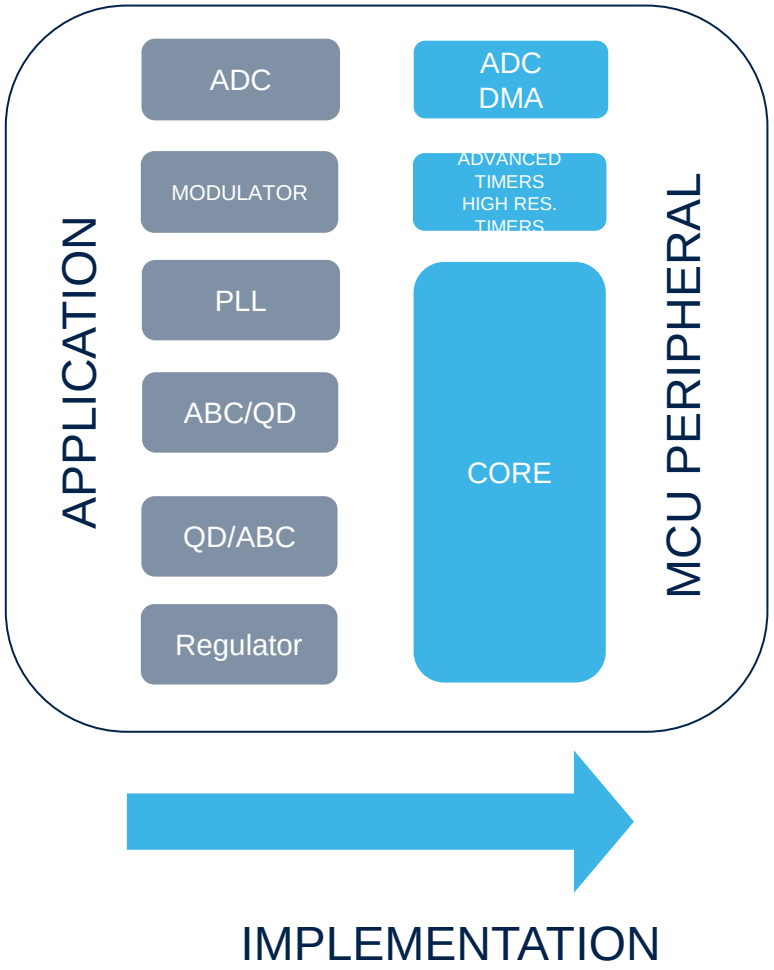
- Self-checking feature:
  Before powering up (grid relay off), MCU sends a “self-check” signal to check the functionality of current sensor
- Residual current detection:
  After powering up (grid relay on), the MCU will keep monitoring the residual current (within a configured value)





Power & Energy Competence Center

MCU Configuration For Control Loop



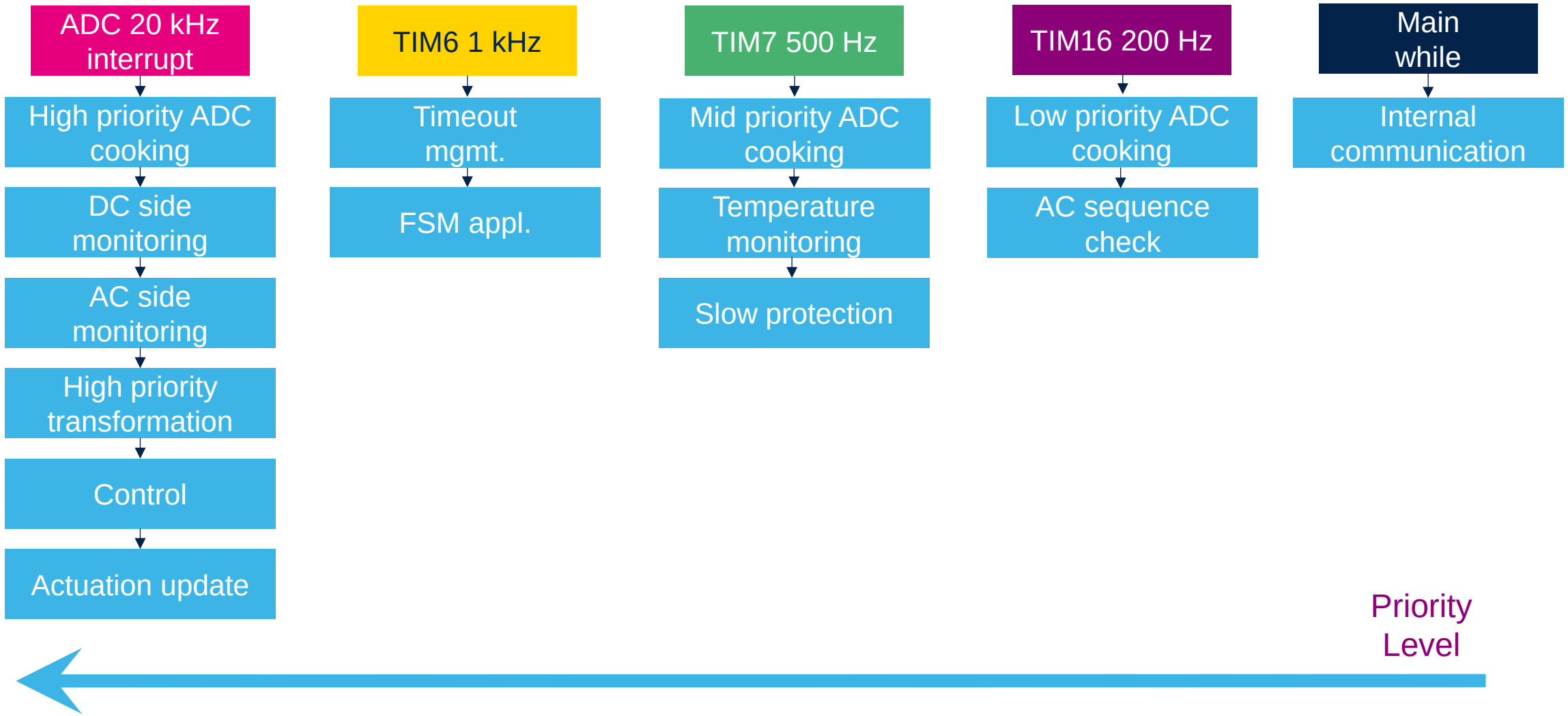
Task	Used peripherals
Outer loop & inner loop	ADC based interrupt
Modulator	High resolution + advanced timers
Sensing	ADC & DMA

STM32H743	Timer	Channel w DT	Output
Advanced timers	TIM1	2	4
High-resolution timers	HRTIM	4	8

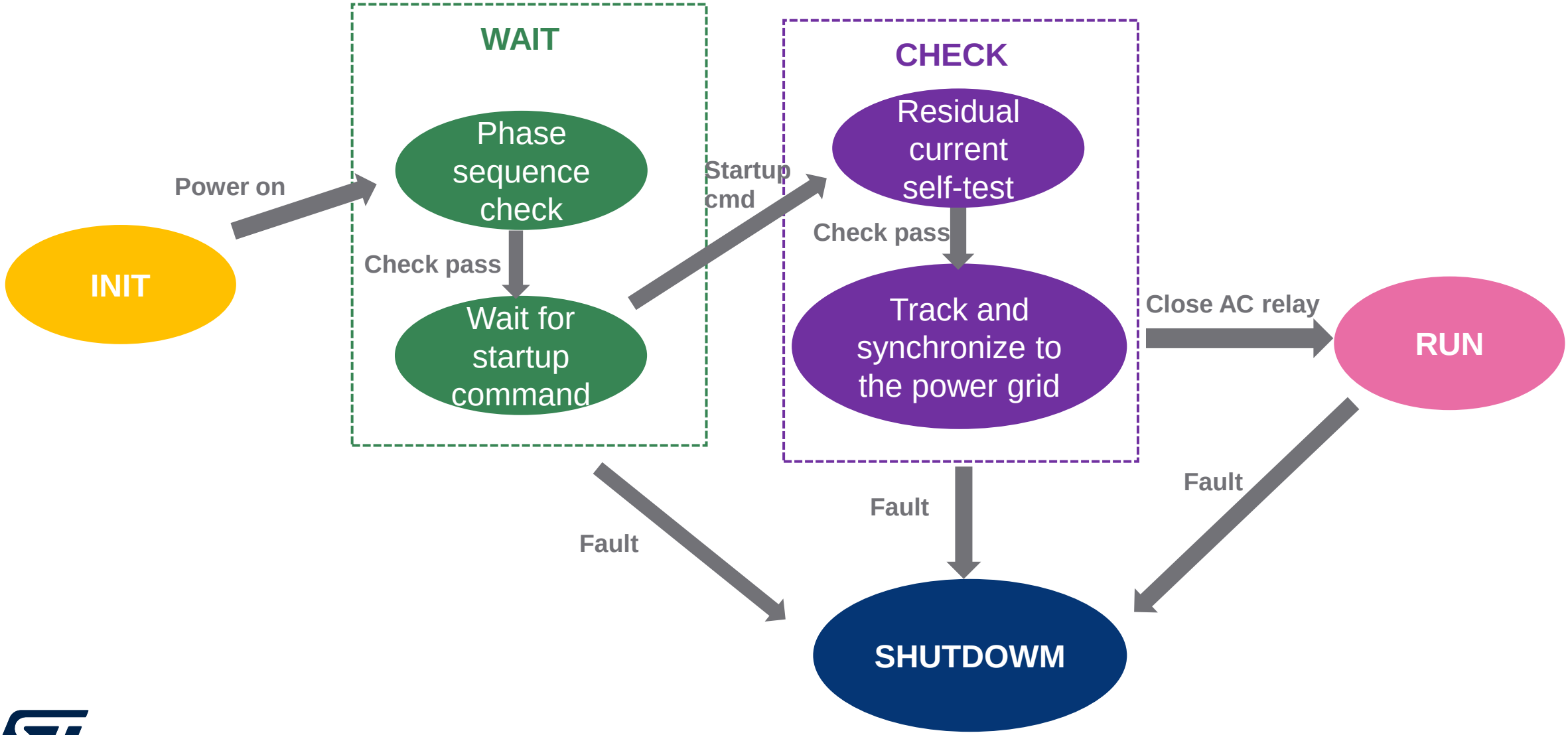
life.augmented

Power & Energy Competence Center

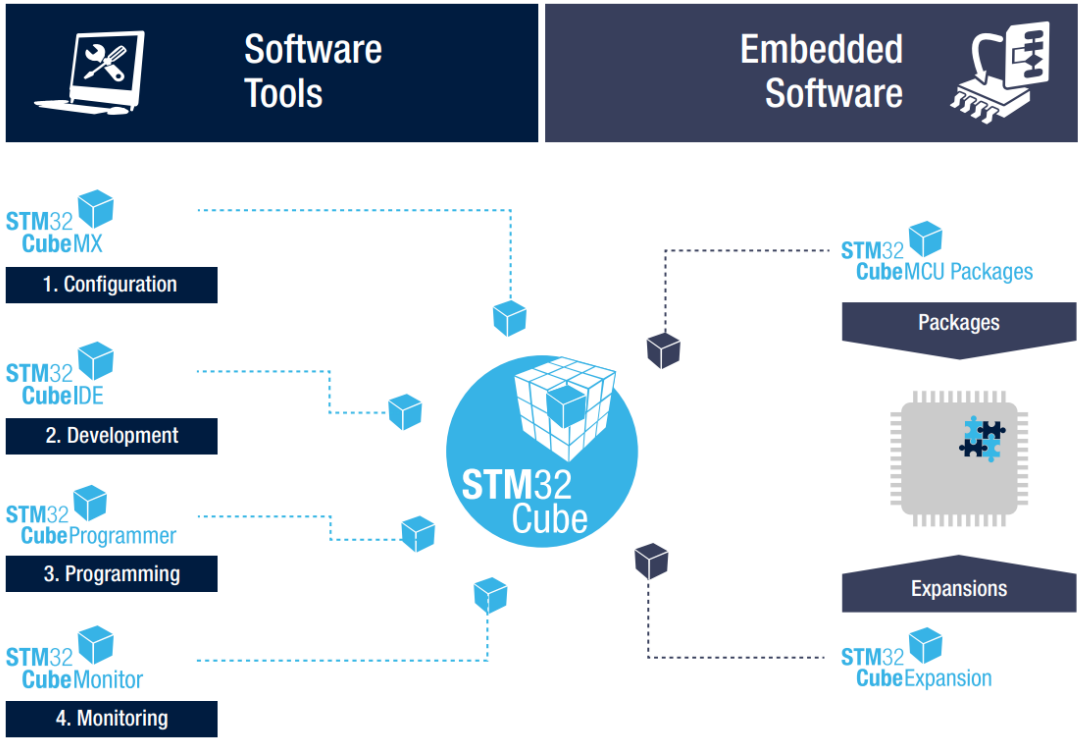
Firmware Configuration



State Machine

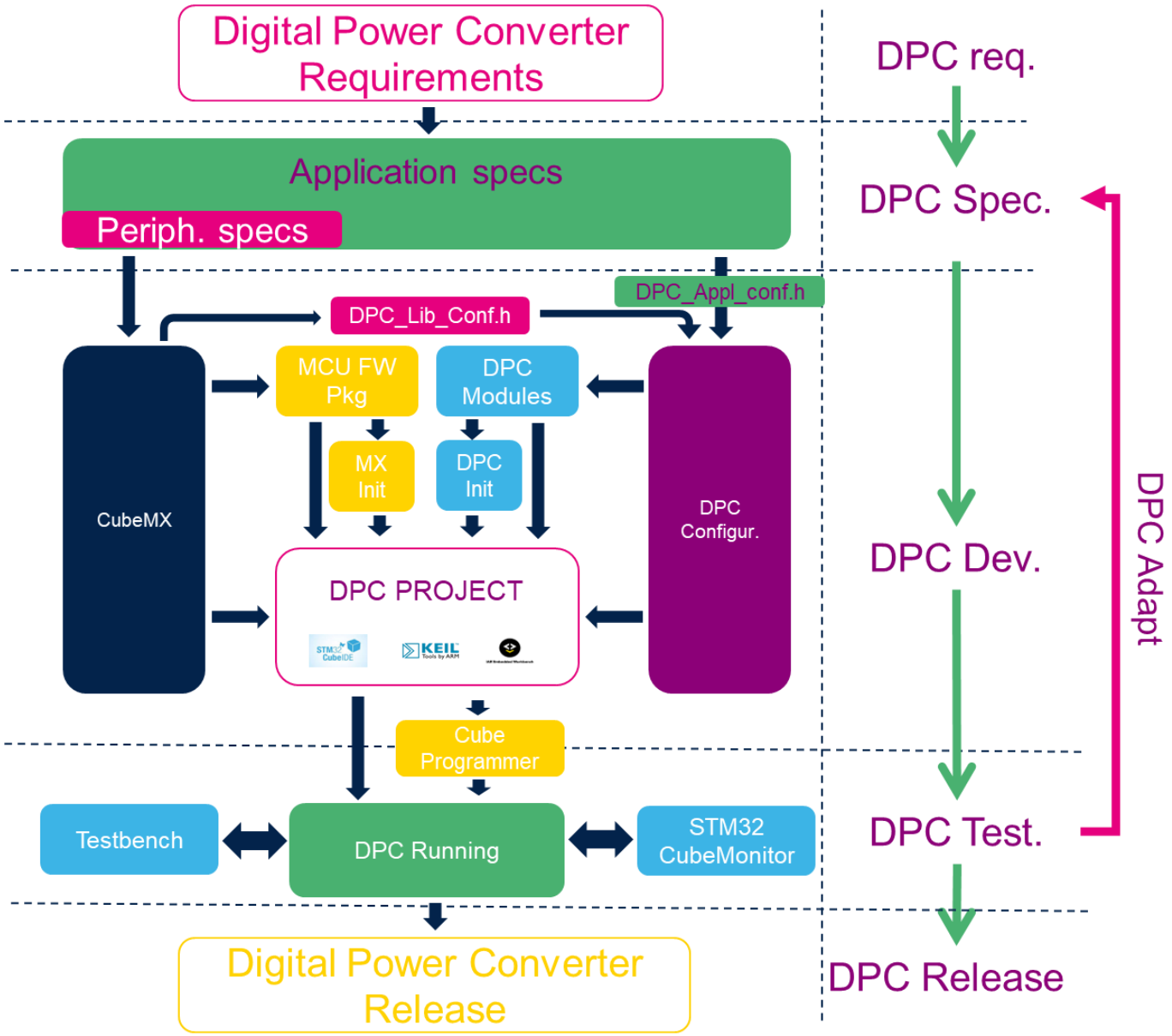


STM32Cube Ecosystem

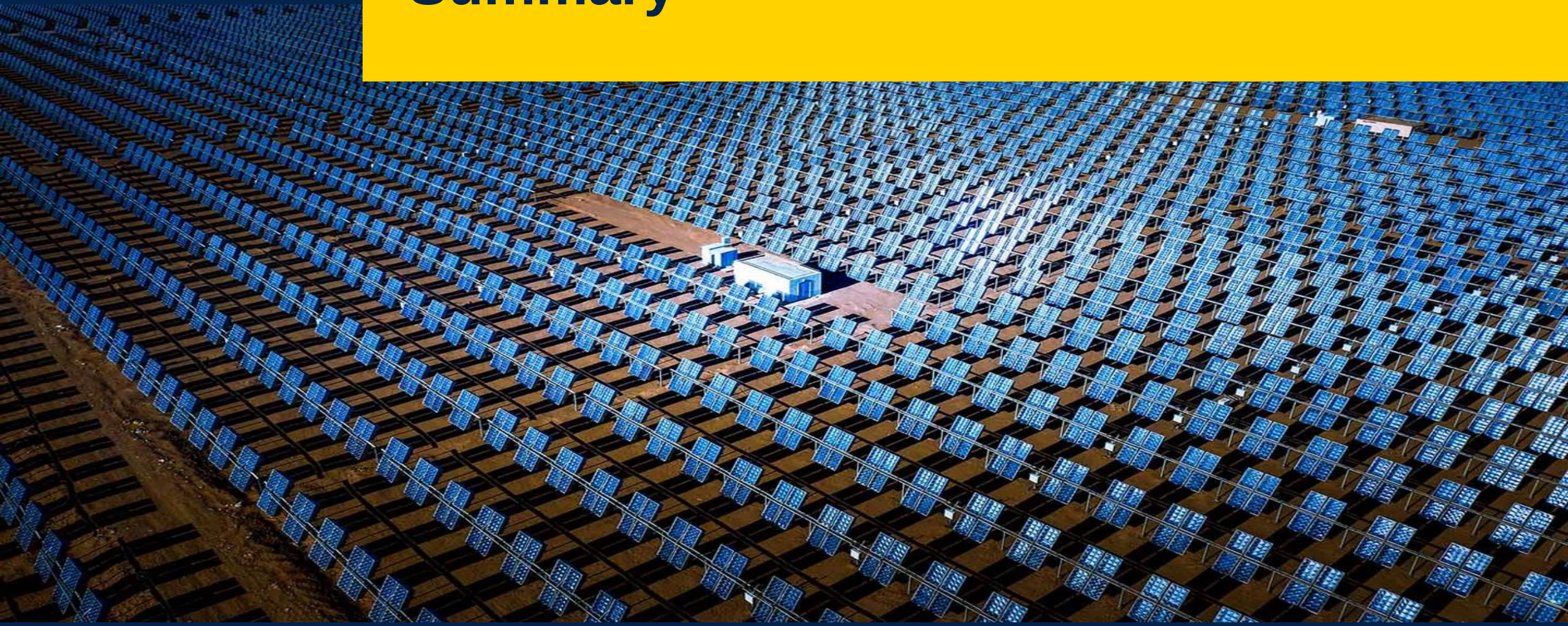


The STM32Cube ecosystem is a software solution for STM32 microcontrollers and microprocessors, created for both designers interested in a free comprehensive development environment for STM32 microcontrollers and microprocessors, and for users looking to integrate STM32 software in their existing IDE, such as Keil or IAR IDEs.

DPC Dev. Flow


Digital Power Converter Requirements
Application specs
Periph. specs
DPC_Appl_conf.h
DPC_Lib_Conf.h
CubeMX
MCU FW Pkg
DPC Modules
MX Init
DPC Init
DPC Configur.
DPC PROJECT
Cube Programmer
Testbench
DPC Running
STM32 CubeMonitor
Digital Power Converter Release
DPC req.
DPC Spec.
DPC Dev.
DPC Test.
DPC Release
DPC Adapt

Summary



life.augmented

Summary

ST SiC and STM32H7 based solution help achieve high performance PV inverters

With high efficiency & high power density trends, more requirements to PV inverter

ST provides advanced components & total solution to customers（SiC MOSFETs/SiC diode/STGAP/STM32)

ST 50 kW **T-type inverter** solution can achieve peak efficiency 98.89%(800 Vdc), 99.10%(650 Vdc)

User manual & BOM & SCH & PCB boards have all been ready now

Industrial Summit
download center

ST Power & SPIN
microsite (CN Only)

life.augmented

Our technology starts with You

Find out more at www.st.com

life.augmented