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基于ACEPACK SiC模块和 STM32H743的50kW数字控 制DC-AC逆变器

Rain XU

Power & Energy
Competence
Center



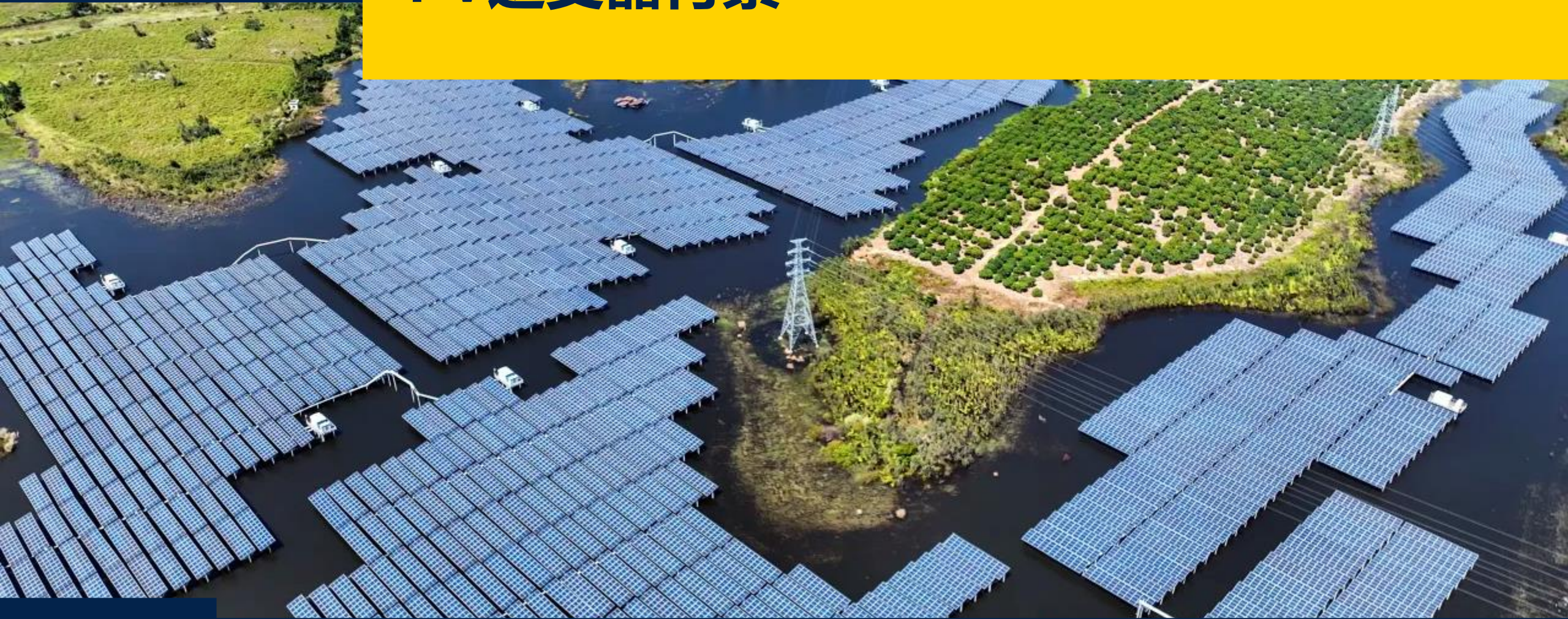
1 PV逆变器背景

2 ST PV数字解决方案

3 ST PV板性能

4 总结

PV逆变器背景



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PV逆变器

住宅设施

通常 < 5 kW



商业和工业建筑

5 kW-1 MW



地面安装的发电厂

1-100 MW

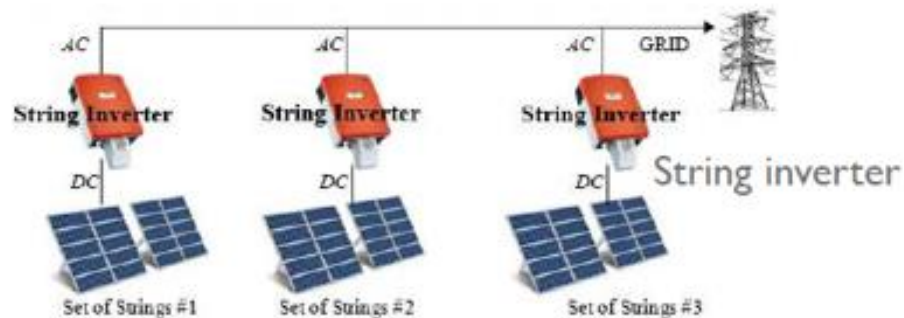


PV inverters

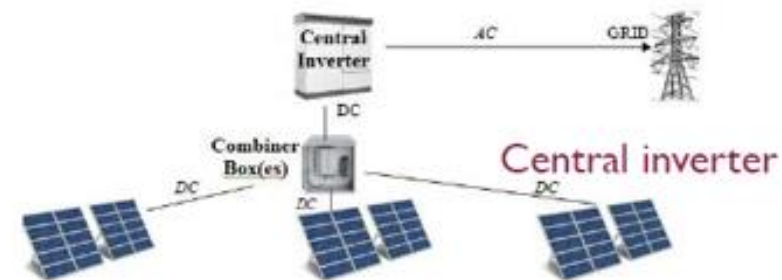


Micro-inverter

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



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



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



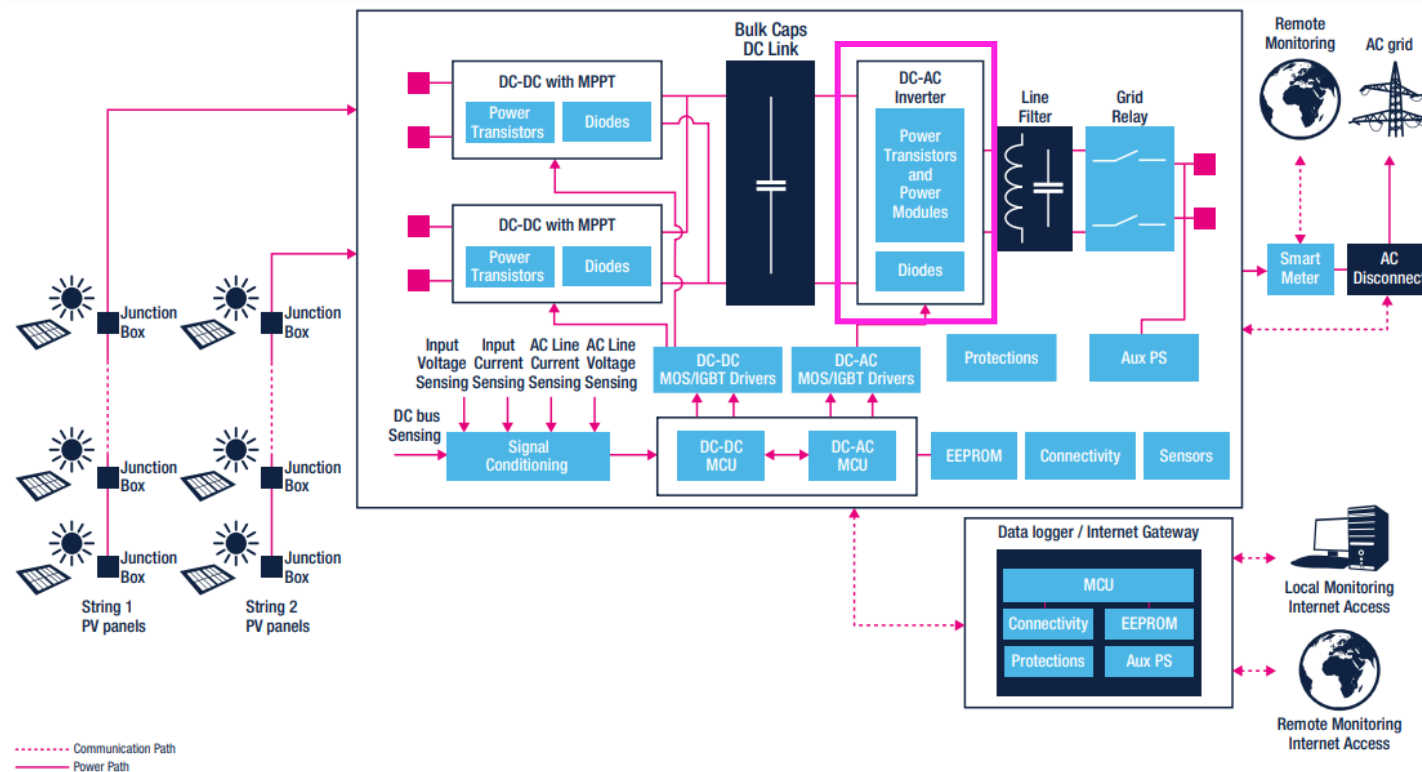
组串式逆变器

输入规格与要求

输入电压	200-1100 Vdc
正常电压	600 Vdc
输入电流	最大120 A @450 V
MPPT电压	200-1000 Vdc
MPPT数	4

输出规格与要求

输出电压	312~480 V L-L
频率	50 Hz / 45~55 Hz
输出功率	50 kW额定 (最大55 kW)
Thd	< 3 %
功率因数	0.8 ~ -0.8
Eff	98.5%



SiC的优势

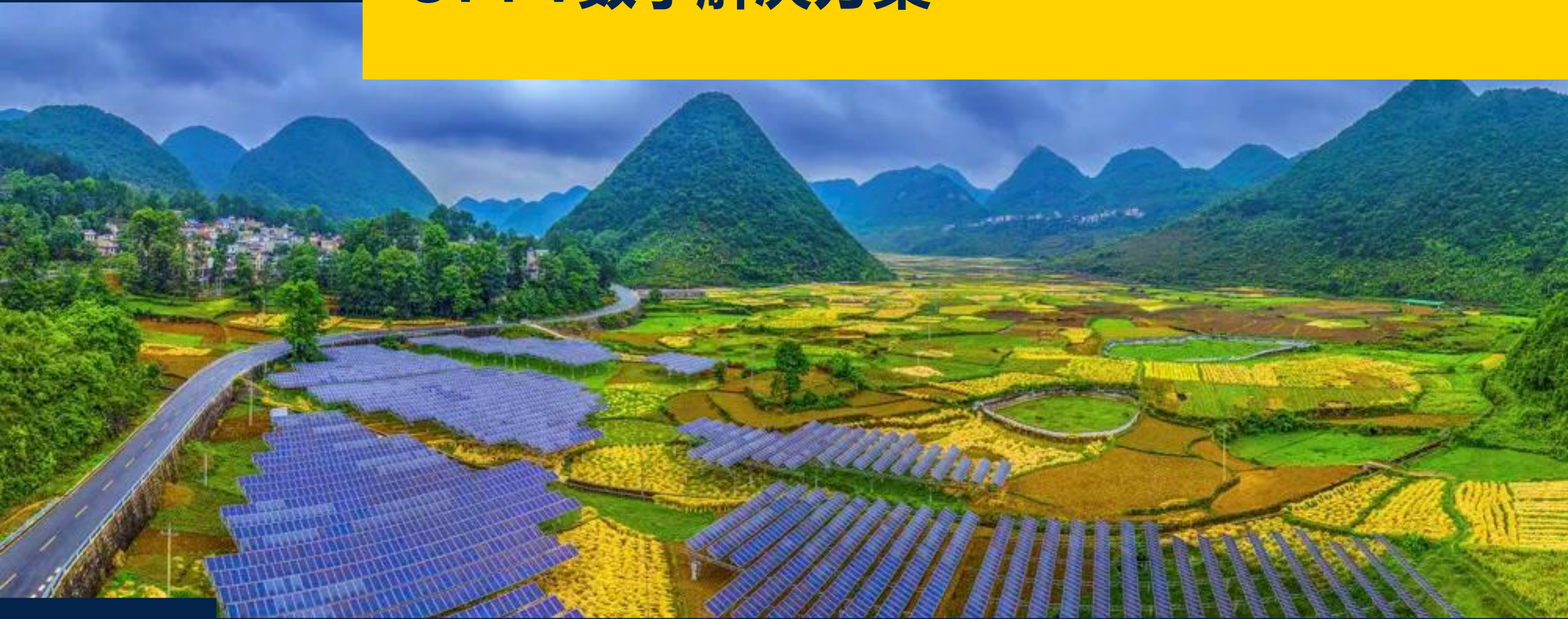
极低的开关损耗和超低的RDS(on)

良好的热性能

易于驱动

稳健的超快速本体二极管

ST PV数字解决方案



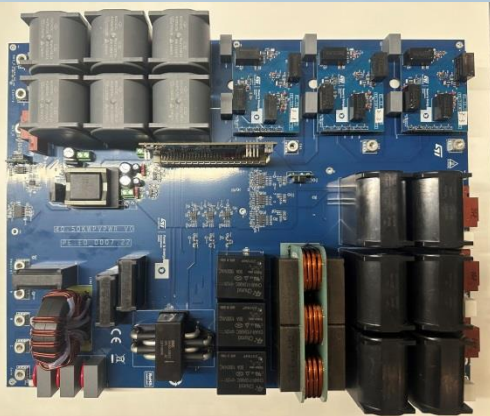
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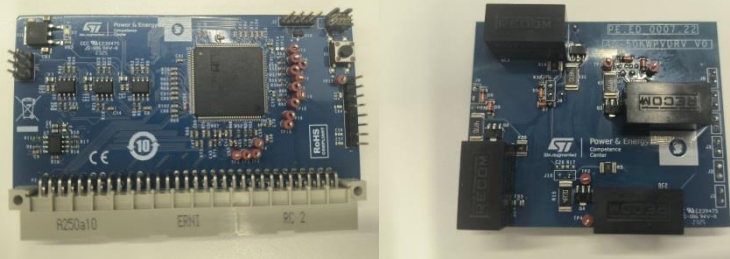
50 kW T型DC-AC PV逆变器



解决方案板可提供



T型三电平DC-AC，带ACEPACK模块



应用关键特性:

- 直流输入电压800 VDC，额定输出功率50 kW，开关频率40 kHz
- 输出AC电压：三相380 VAC，频率45 Hz至55 Hz
- 最大输出电流：84 ARMS
- 峰值效率98.89% (800Vdc)
- 0.99功率因数，THD低于3% @满载运行时
- STM32H743ZGT6

主要产品

STM32H743ZGT6
A2U8M12W3-FC*3 (9.5mΩ 1200 V & 6mΩ 750 V SiC模块)
STGAP2SICSC (电气隔离栅极驱动器)
IPC产品: L6565, ISOSD61, (L6983i)
肖特基二极管: STPS1150A, STPS2H100A, STPS2L60A
GPA: TSV914IDT, LD29080S33R, STLM20W87F, LD29080DT50R

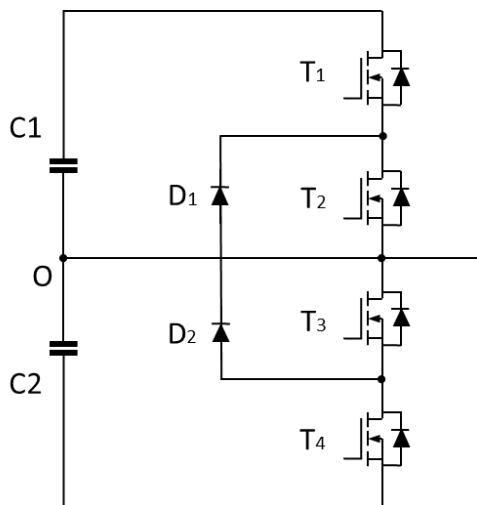
主要优势

- 基于SiC模块实现了更高的效率
- 40 kHz频率的低输出LCL滤波器成本
- 更高的可靠性、更低的设计复杂性



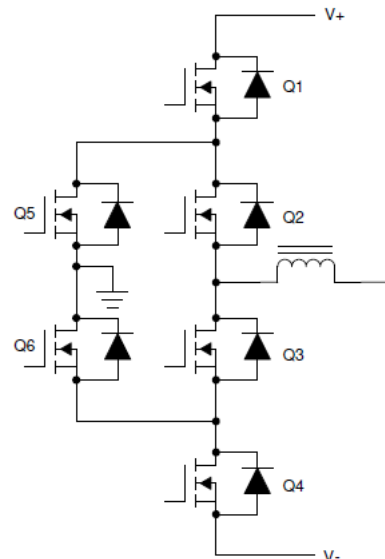
拓扑比较

INPC



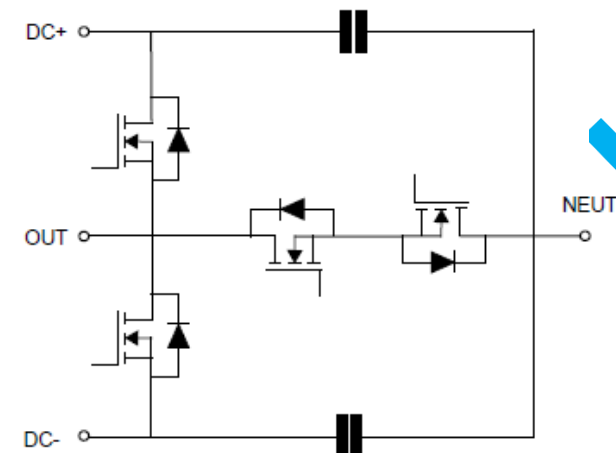
- + 适用于高母线电压
- + 三电平拓扑
- 击穿问题
- 控制复杂度：中-高
- 元件数：高
- 主电流路径中的2个设备

ANPC



- + 适用于高母线电压
- + 更适合散热
- + 三电平拓扑
- 击穿问题
- 控制复杂度：高
- 元件数：高
- 主电流路径中的2个设备

TNPC



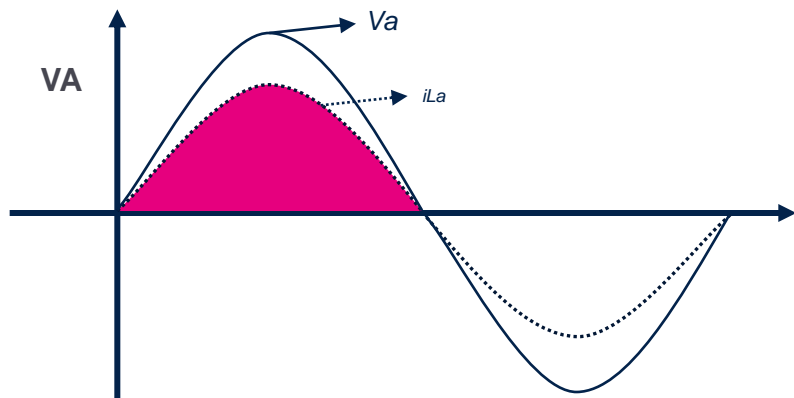
- + 元件数：低
- + 主电流路径中的2个设备
- + 三电平拓扑
- 击穿问题
- 控制复杂度：中-高
- 适用于母线电压 ≤ 850 V

T型三电平通常用作30-100kW PV逆变器中的DC-AC拓扑。

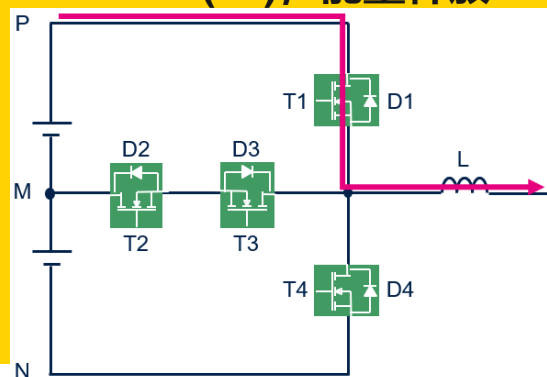


T型三相运行SiC MOS

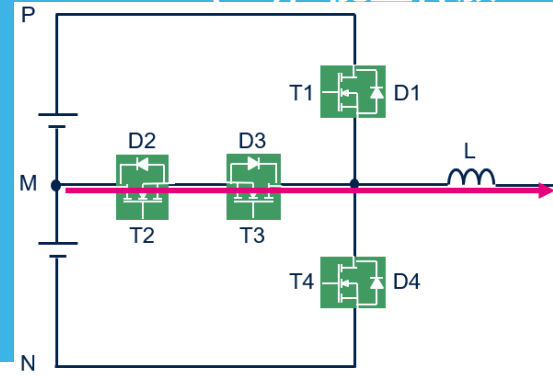
$V_a > 0, i_{La} > 0$



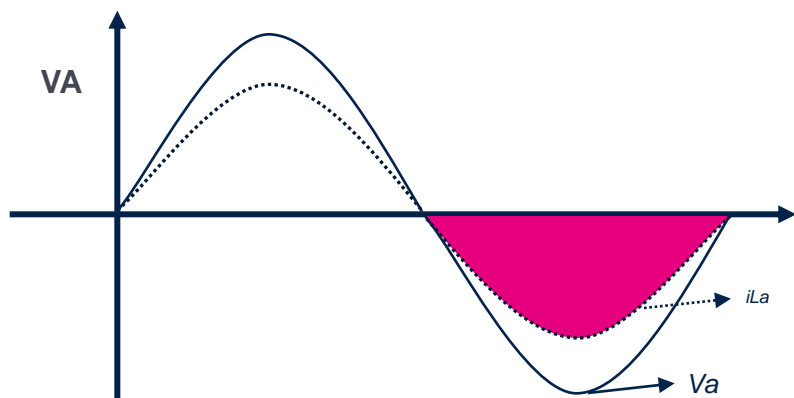
T1 on (=1), 能量释放



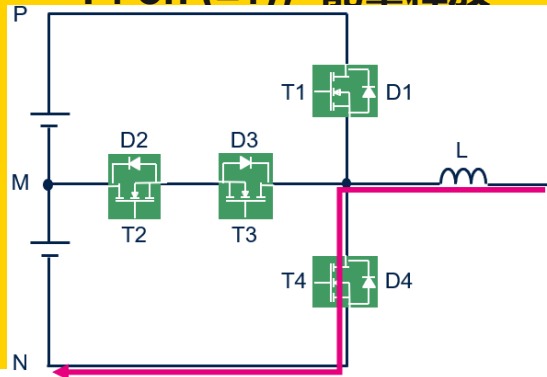
T3 on (=1), 能量释放



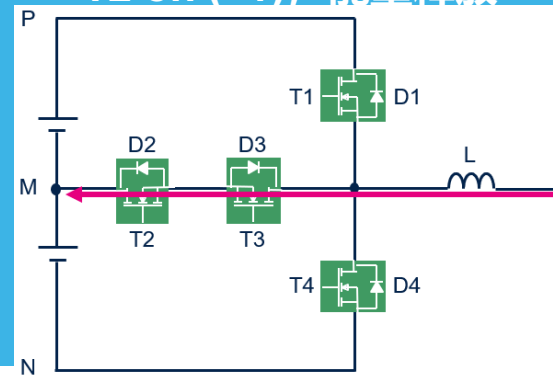
$V_a < 0, i_{La} < 0$



T4 on (=1), 能量释放



T2 on (=1), 能量释放



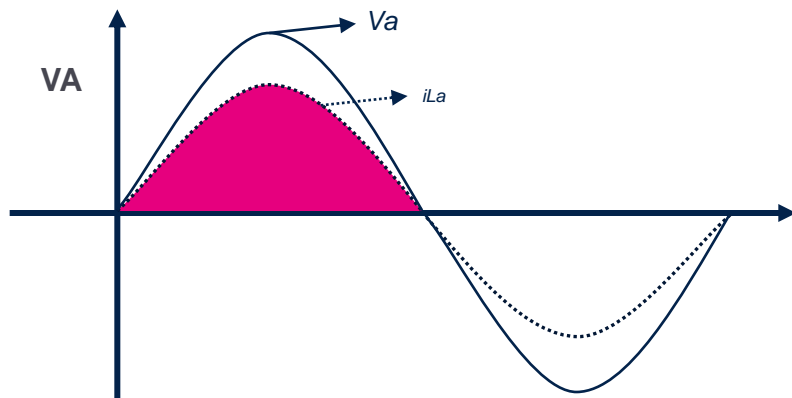
- 通过MOS T1或T4从BUS CAP到电感器的电流
- 从BUS CAP到电感器和输出的能量

- 通过MOS T2和T3从输出端到M点和电感器的电流
- 从输出到M点和电感器的能量

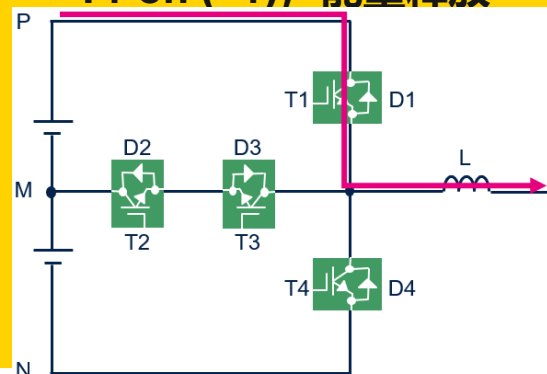


T型三相运行Si IGBT

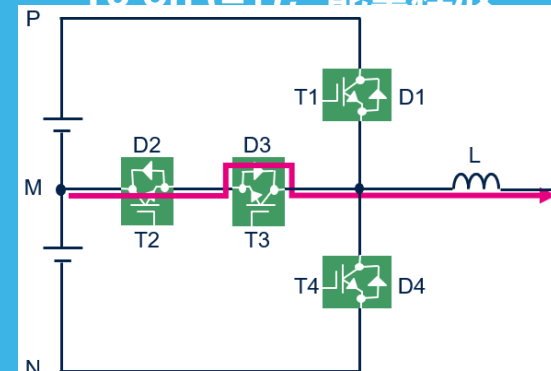
$V_a > 0, i_{La} > 0$



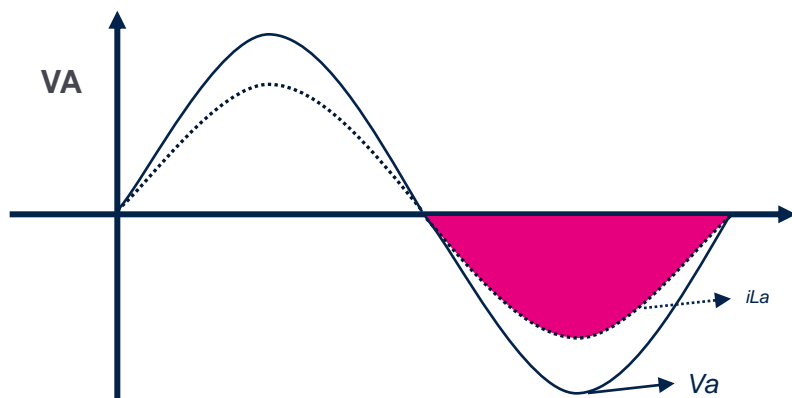
T1 on (=1), 能量释放



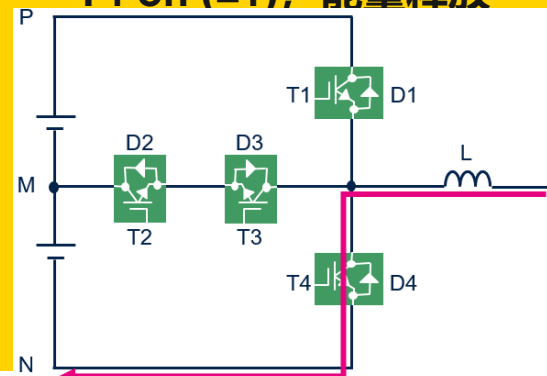
T3 on (=1), 能量释放



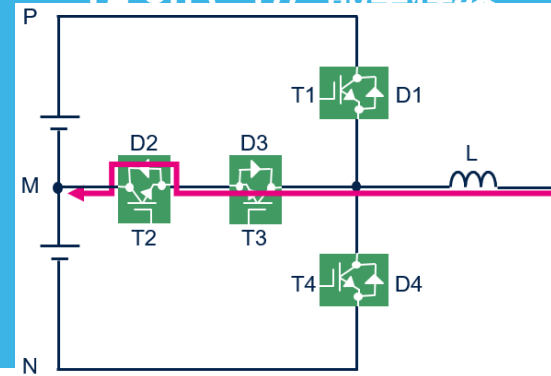
$V_a < 0, i_{La} < 0$



T4 on (=1), 能量释放



T2 on (=1), 能量释放



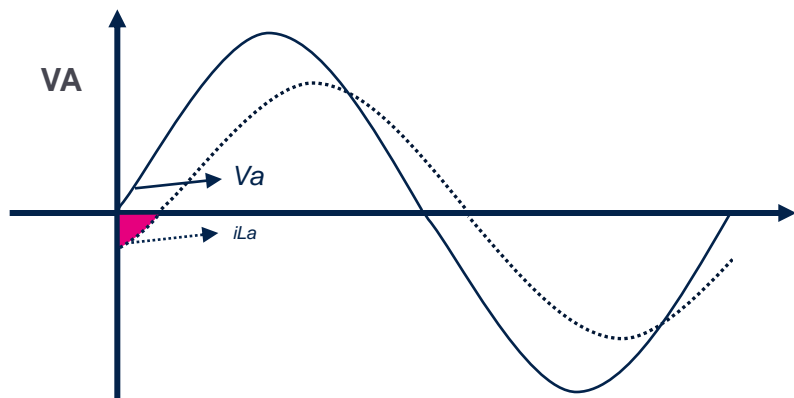
- 通过MOS T1或T4从BUS CAP到电感器的电流
- 从BUS CAP到电感器和输出的能量

- 从输出到M点和电感器的电流通过MOS T2和二极管D3或MOS T3和二极管D2
- 从输出到M点和电感器的能量

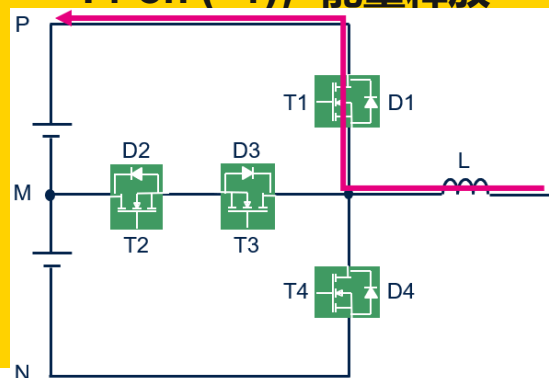


T型三相运行SiC MOS

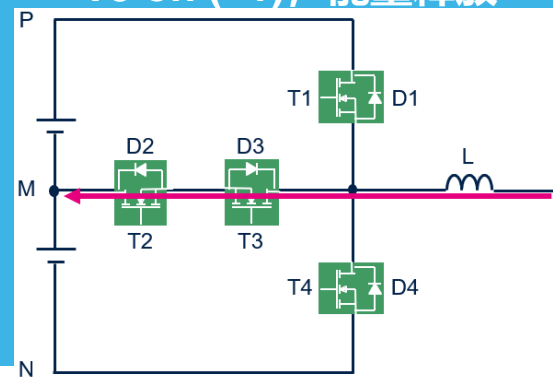
$$V_a > 0, i_{La} < 0$$



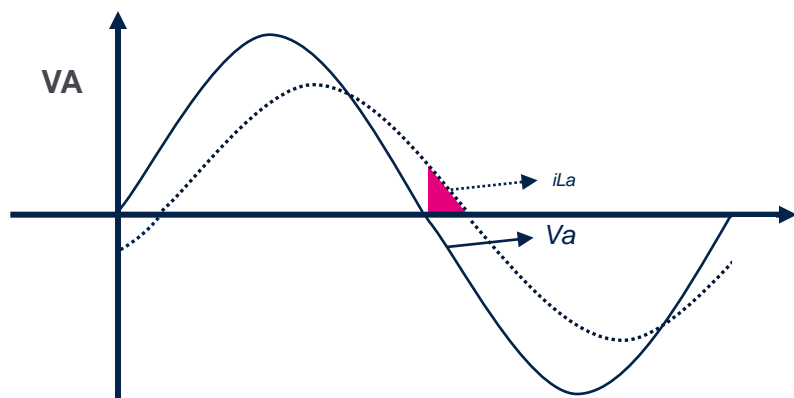
T1 on (=1), 能量释放



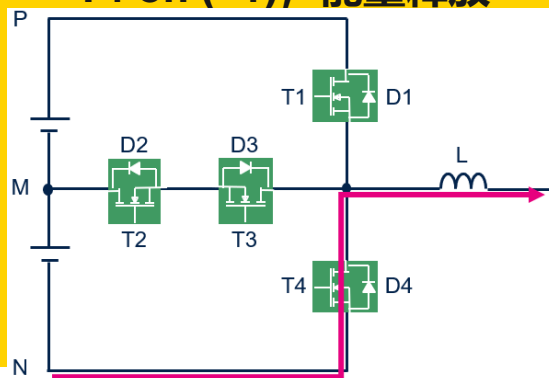
T3 on (=1), 能量释放



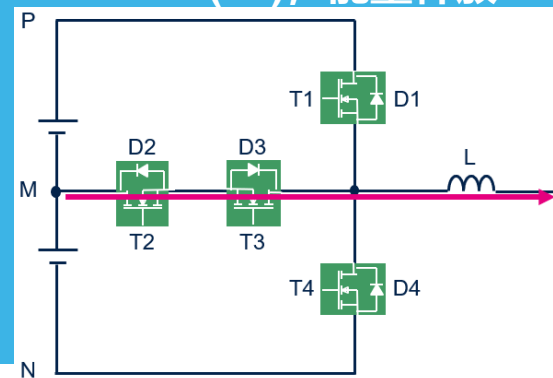
$$V_a < 0, i_{La} > 0$$



T4 on (=1), 能量释放



T2 on (=1), 能量释放



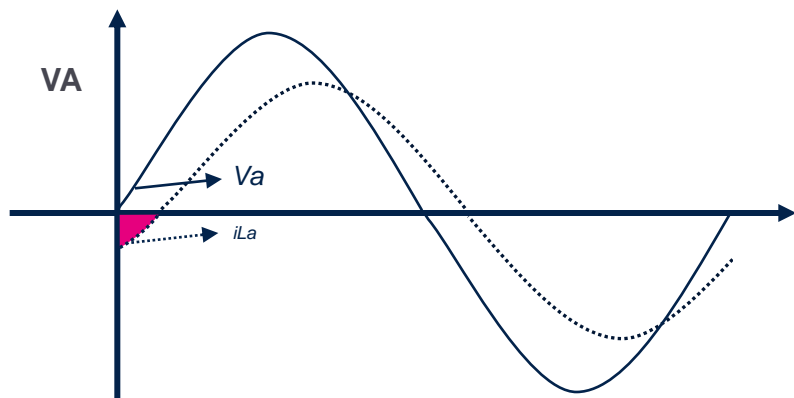
- 通过MOS T1或T4从电感器到BUS CAP的电流
- 从输出端和电感器到BUS CAP的能量

- 通过MOS T2和T3从输出端到M点和电感器的电流
- 从输出到M点和电感器的能量

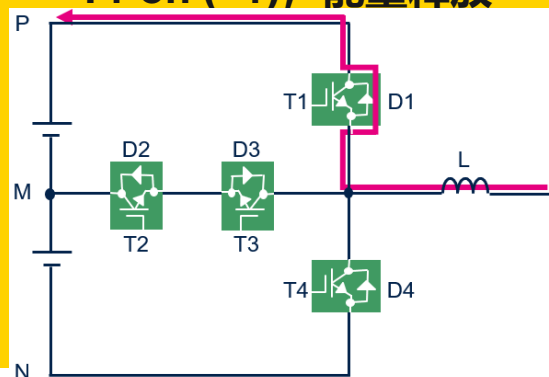


T型三相运行Si IGBT

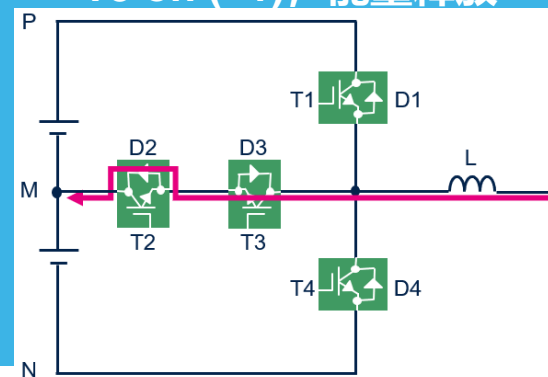
$$V_a > 0, i_{La} < 0$$



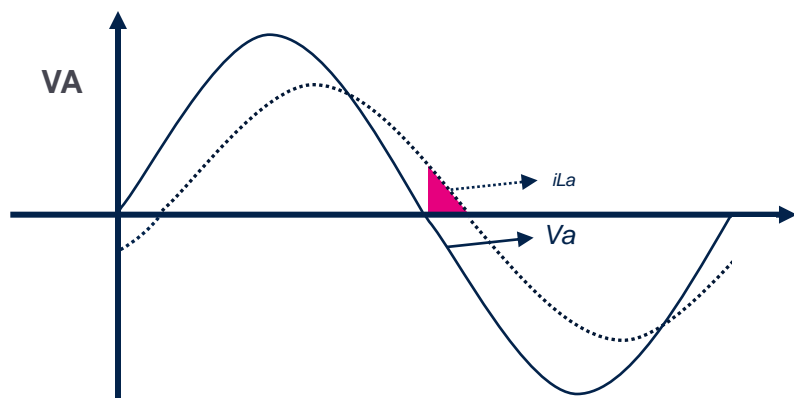
T1 on (=1), 能量释放



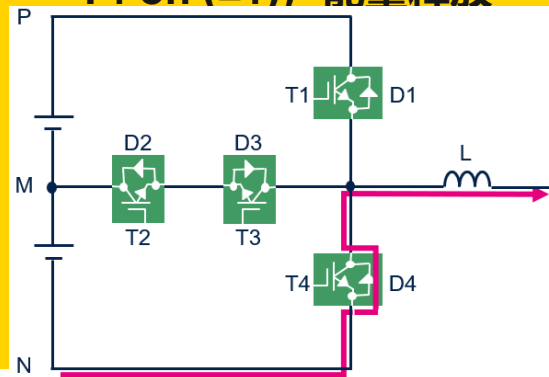
T3 on (=1), 能量释放



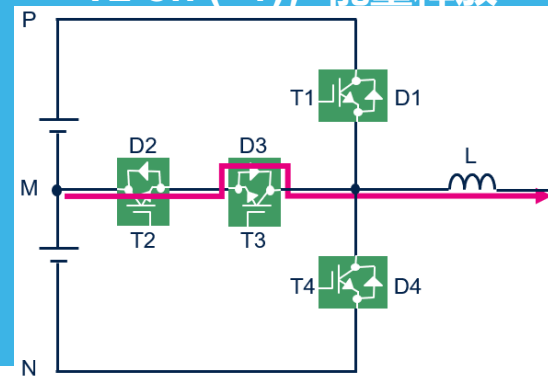
$$V_a < 0, i_{La} > 0$$



T4 on (=1), 能量释放



T2 on (=1), 能量释放

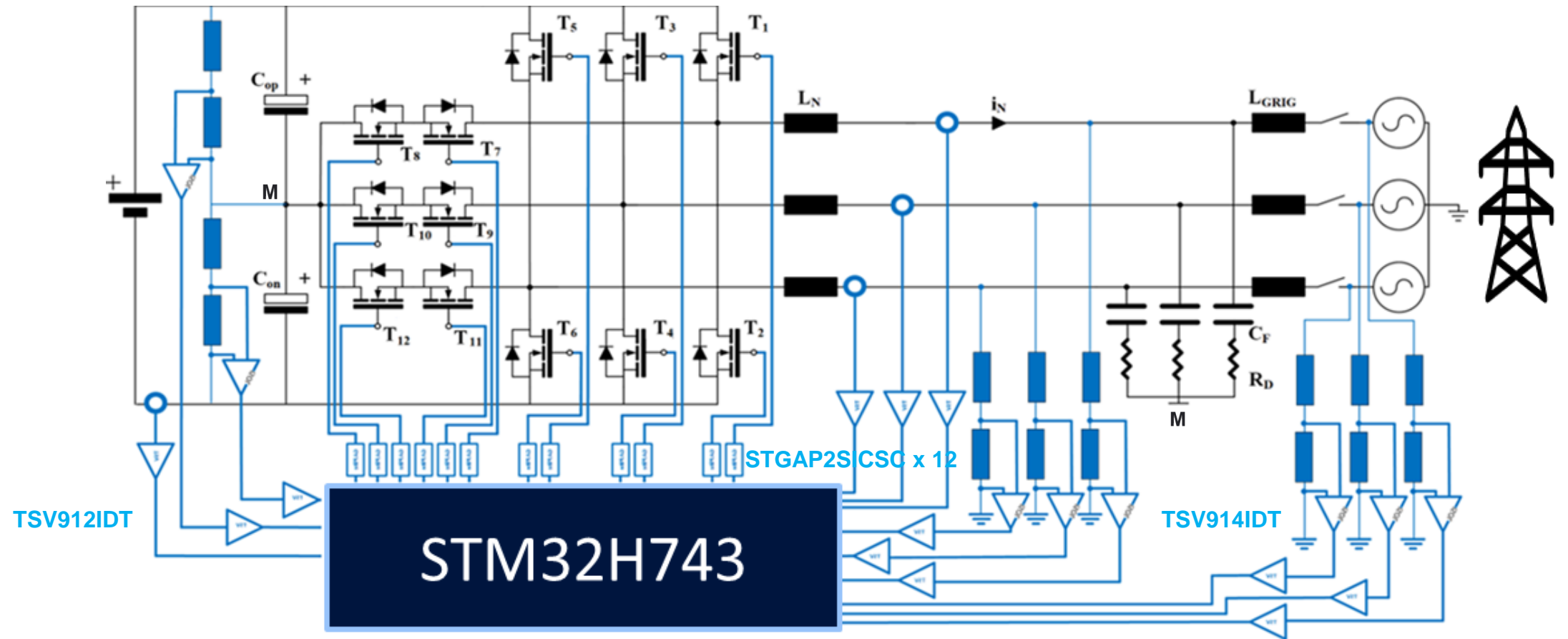


- 通过二极管D1或D4从电感器到BUS CAP的电流
- 从输出端和电感器到BUS CAP的能量

- 从输出到M点和电感器的电流通过MOS T3和二极管D2或MOS T2和二极管D3
- 从输出到M点和电感器的能量



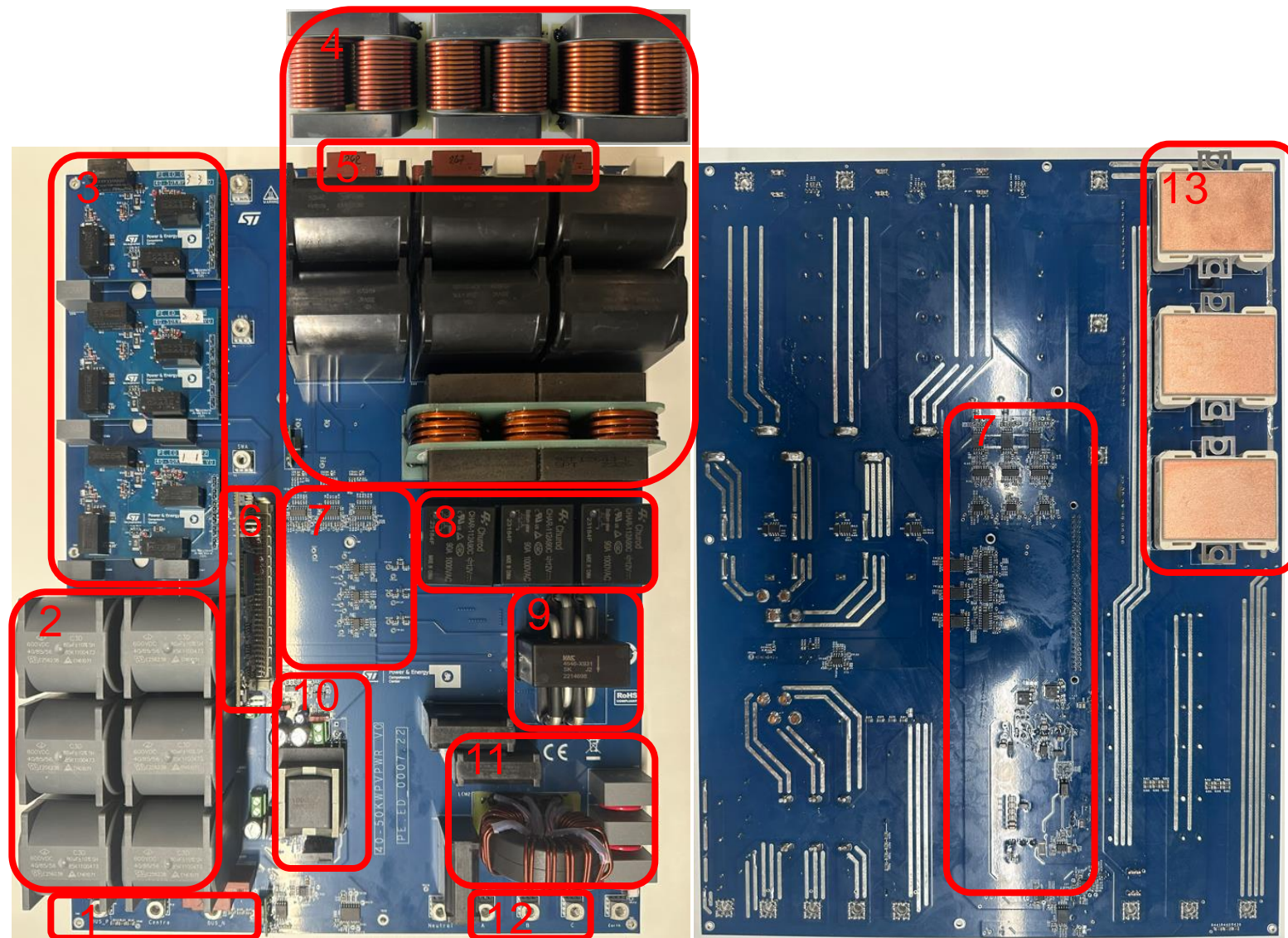
A2U8M12W3-FC x 3





电路板整体组装

- 1.DC输入连接器
- 2.BUS CAP
- 3.驱动板
- 4.LCL滤波器
- 5.电感电流传感器
- 6.控制板
- 7.检测电路
- 8.继电器
- 9.漏电流传感器
- 10.辅助电源电路
- 11.EMI滤波器
- 12.AC输出连接器
- 13.SiC模块

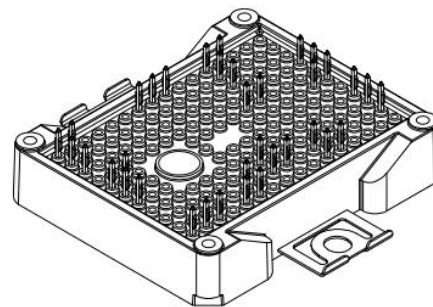


WxLxH:300 x 400 x 70 mm

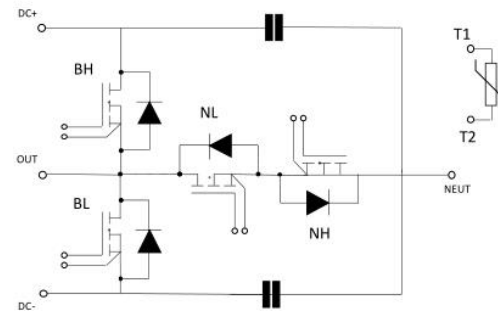


SiC模块-A2U8M12W3

ACEPACK 2功率模块，基于碳化硅功率MOSFET的三电平拓扑：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

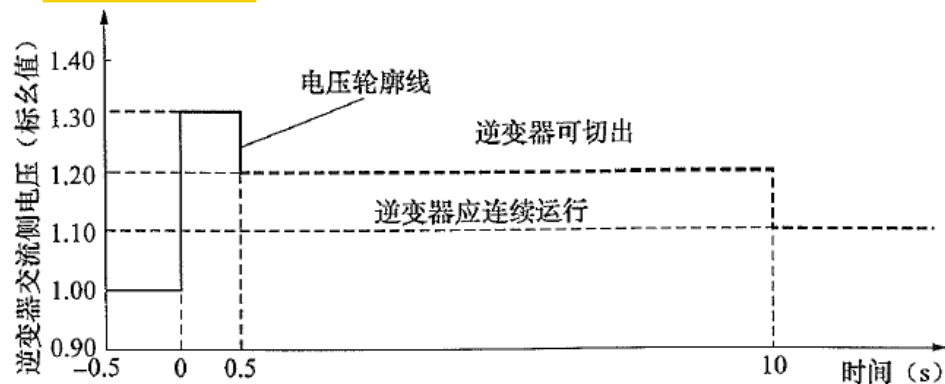
- DC-DC converters



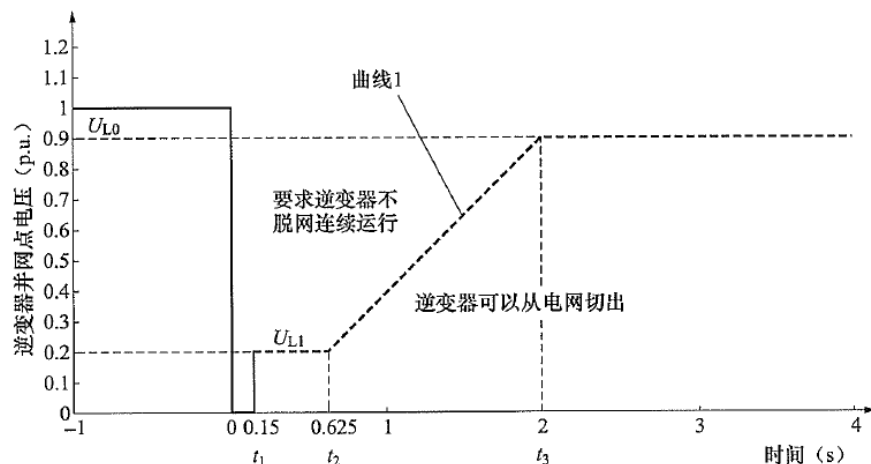
SiC模块-A2U8M12W3

运行

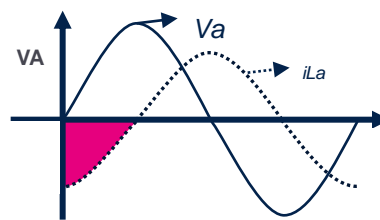
HVRT



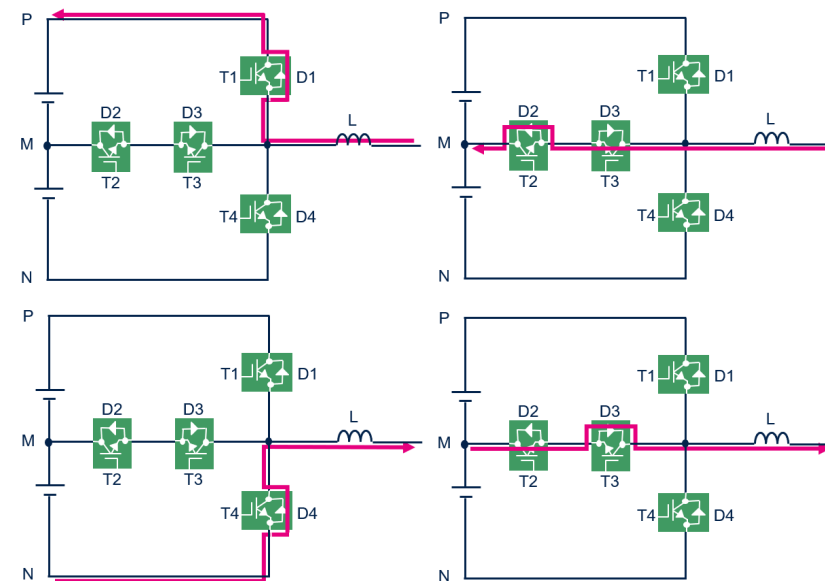
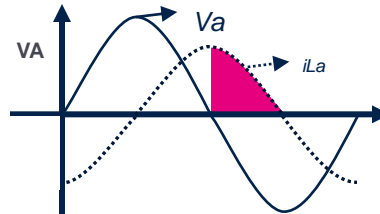
LVRT



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



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

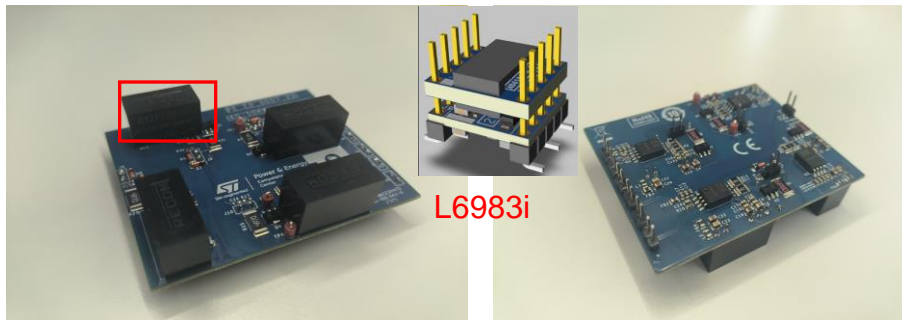


三相对称LVRT或HVRT故障:

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

Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_{SD}	Forward on voltage drop	$V_{GS} = -5V, I_{SD} = 100A$	-	5.2	-	V
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_{SD}	Forward on voltage drop	$V_{GS} = -5V, I_{SD} = 100A$	-	4.15	-	V

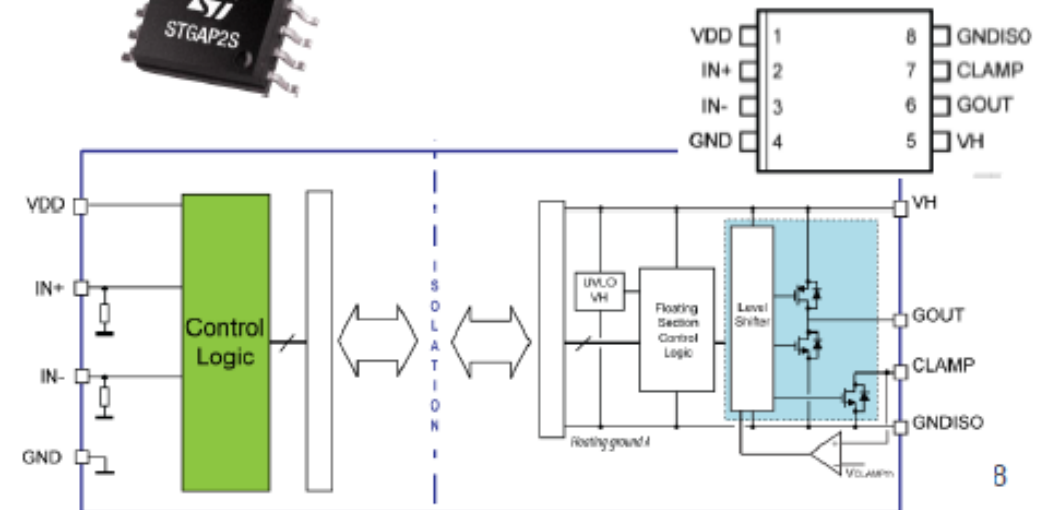
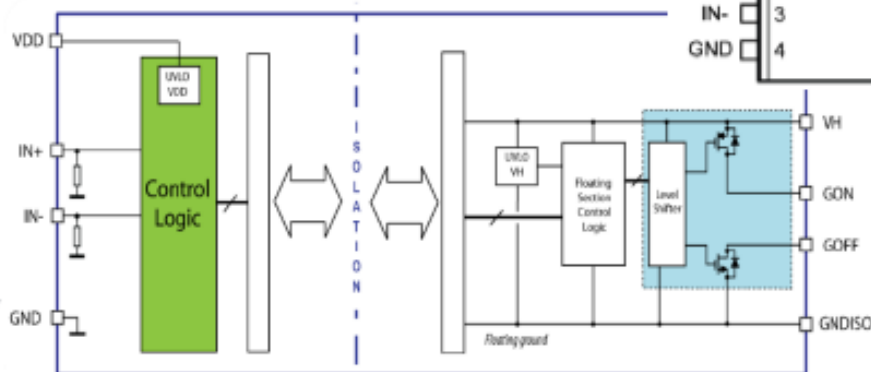
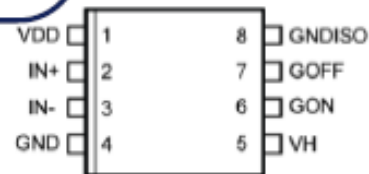
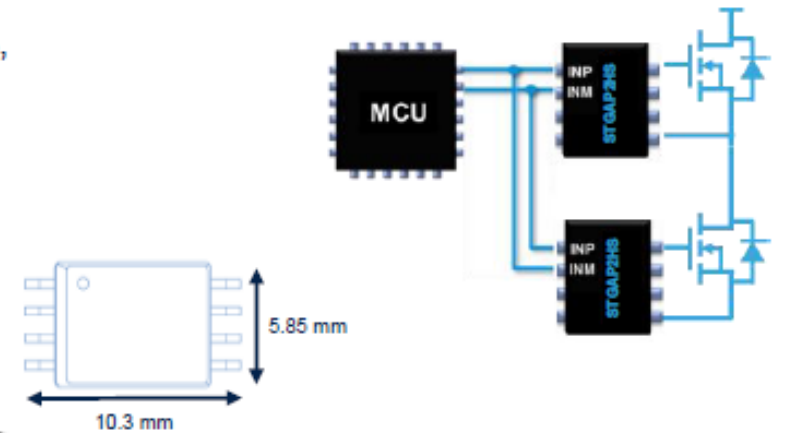
STGAP2电气隔离



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)

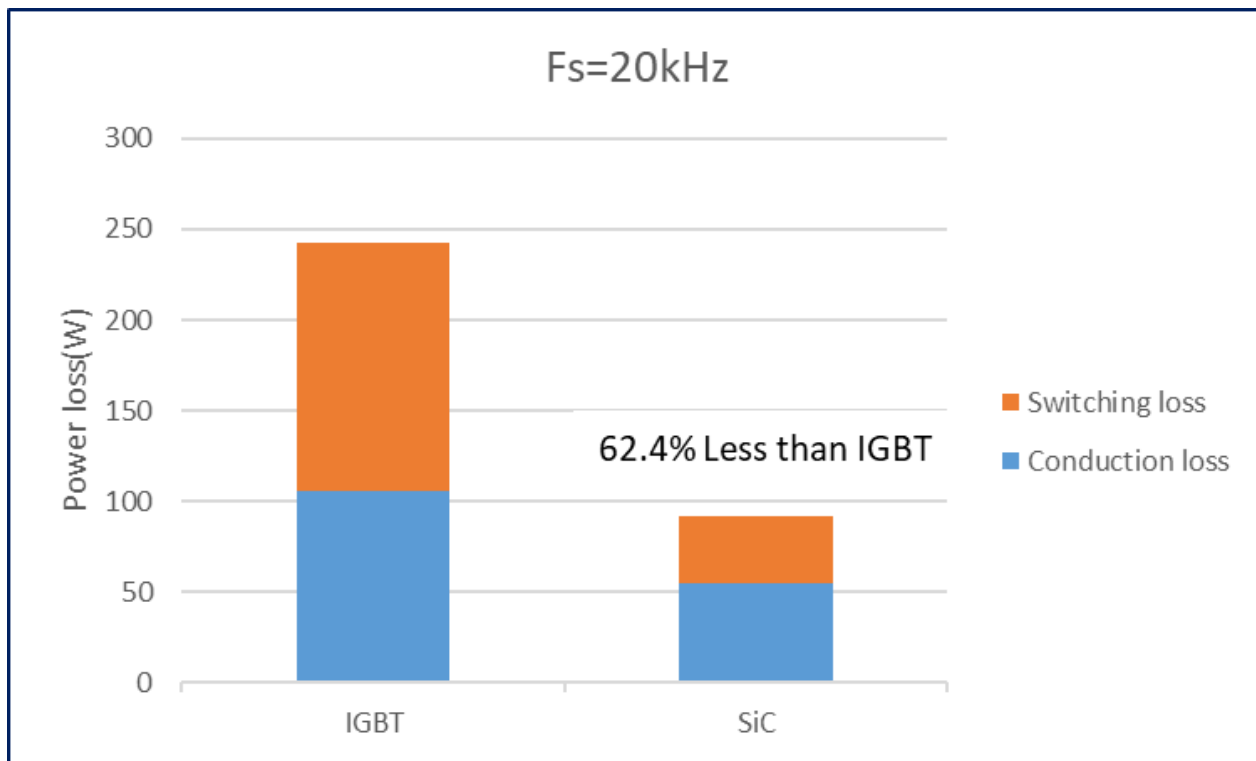




满载时的功率损耗对比

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%

更低的传导损耗
更低的开关损耗

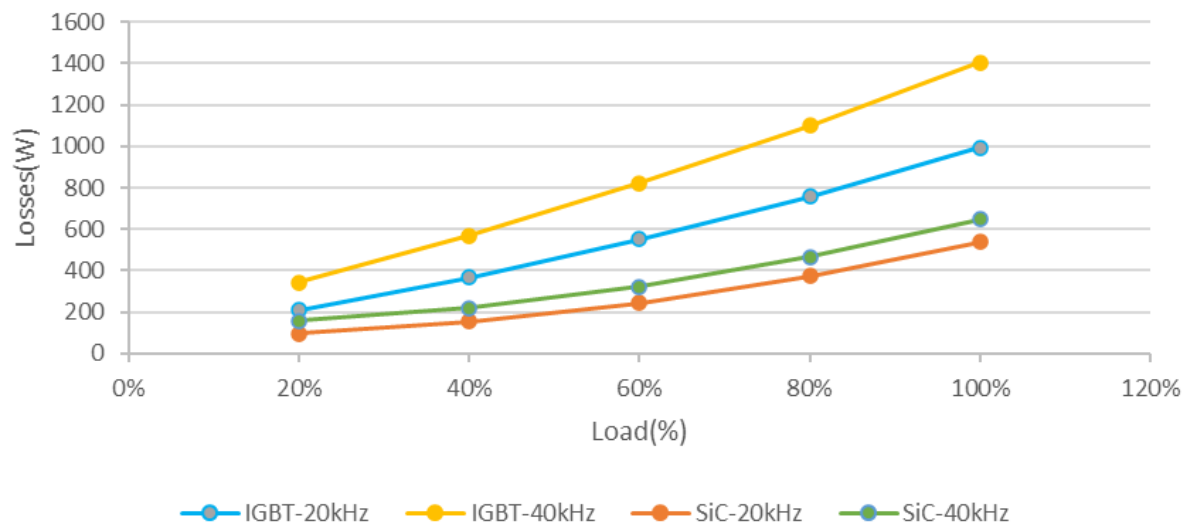


低47.56%
低73.72%



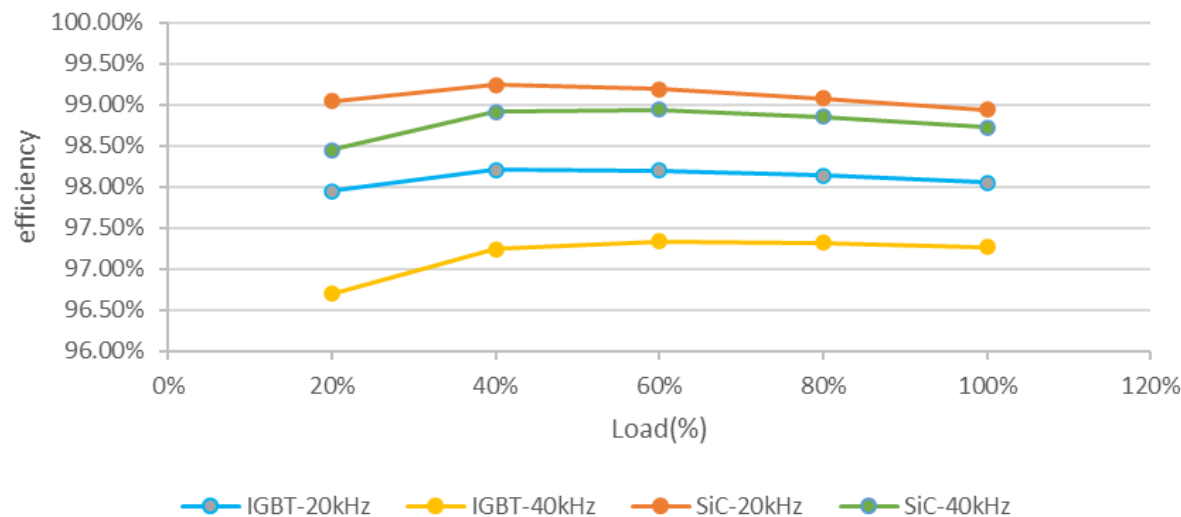
SiC: 损耗更低, 效率更高

Inverter losses vs %load



SiC MOSFET模块在整个负载范围内显示出更低的损耗

Inverter efficiency vs %load



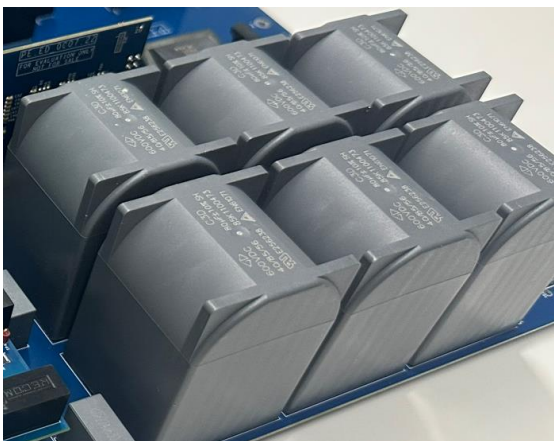
SiC MOSFET模块在整个负载范围内显示出更高的效率

更低的损耗意味着体积更小的冷却系统; 而更高的效率则意味着更好的性能



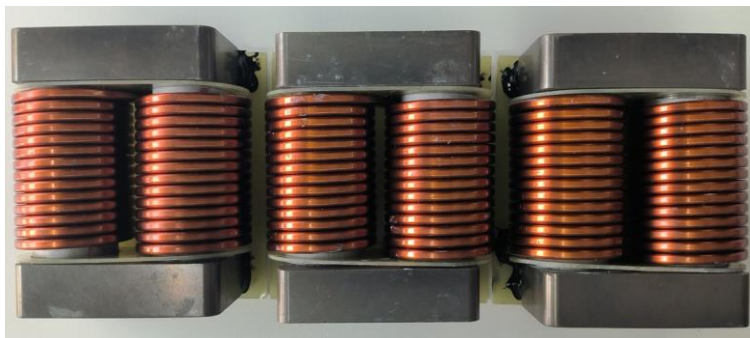
BUS CAP和LCL滤波器优化

BUS CAP



- + 高频率
 - + 低电容
- 120 μ F

逆变侧电感 L_f



- + 高频率
 - + 低电感
- 80 μ H

电网侧电感 L_g



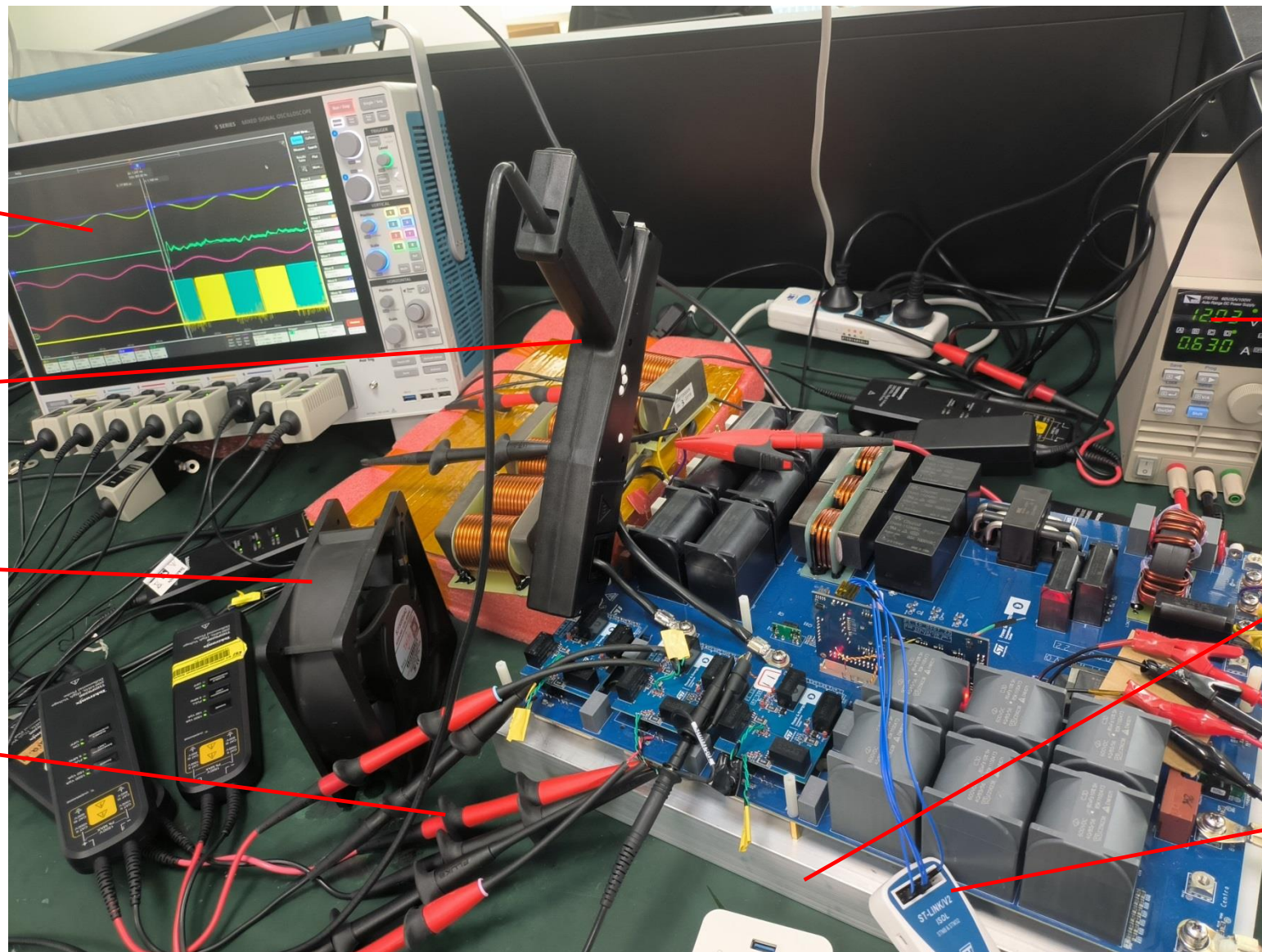
- + 高频率
 - + 低电感
- 6 μ H

ST PV板性能





50 kW PV测试平台



示波器

电流探头

风扇

差分电压探头

辅助电源

散热器

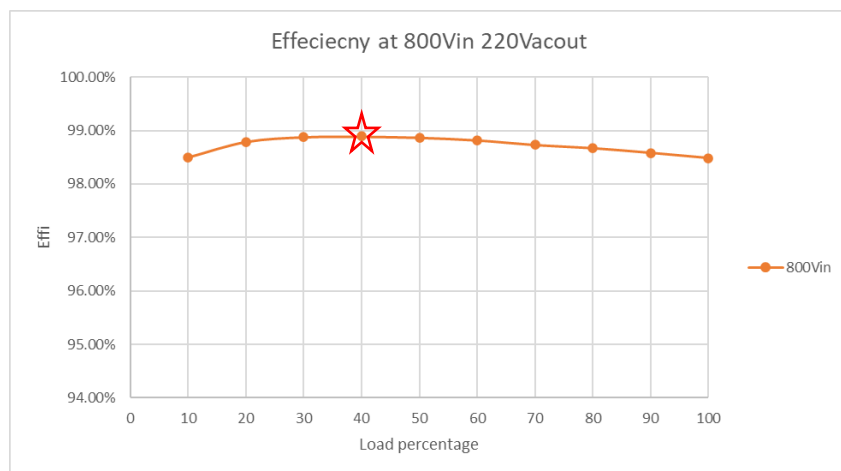
STLINK编程器



800Vin 220Vacout

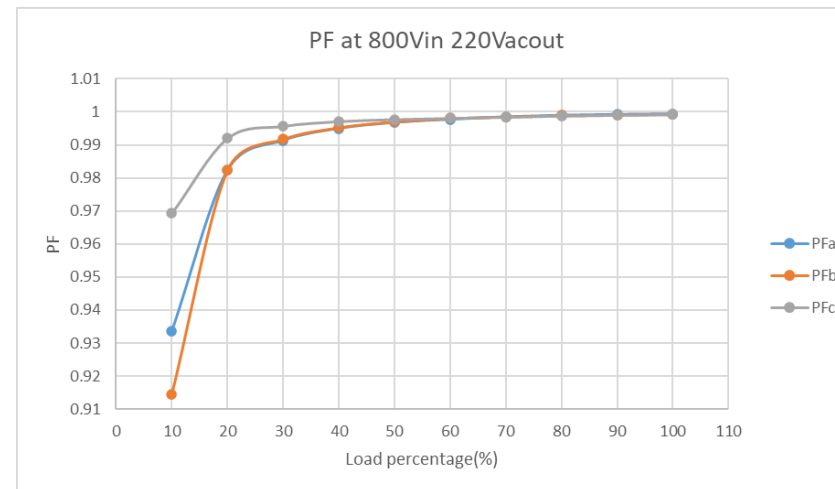
Load %	Effe	PF			thd		
		A	B	C	A	B	C
10	98.49%	0.93373	0.91461	0.9693	10.53%	15.63%	10.00%
20	98.79%	0.98242	0.98248	0.99199	5.60%	7.52%	4.61%
30	98.88%	0.99134	0.99176	0.99568	3.96%	5.38%	3.42%
40	98.89%	0.99499	0.9953	0.99711	3.12%	4.22%	3.09%
50	98.87%	0.99678	0.99708	0.99772	2.36%	3.35%	3.06%
60	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%

800Vin 220Vacout时的峰值效率为98.89%

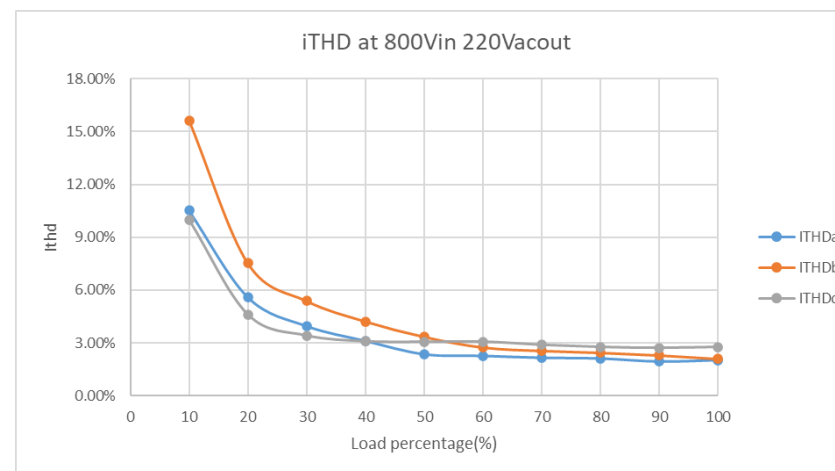


效率、功率因数和谐波

800Vin 220Vacout时的PF



满载时iTHD < 3%





50 kW T型DC/AC PV逆变器PF范围

800Vin 220Vacout 50kw

PF=0.8电压超前电流

VoutA →

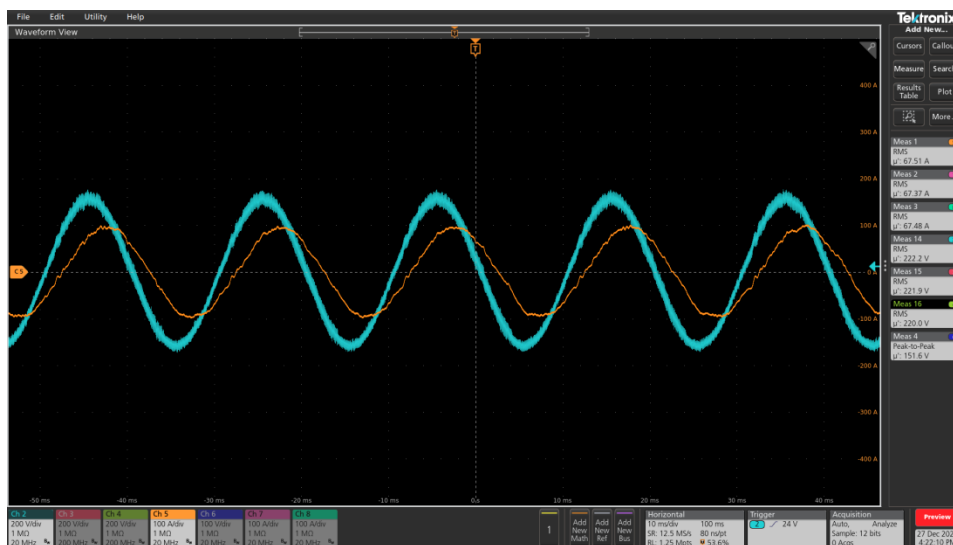
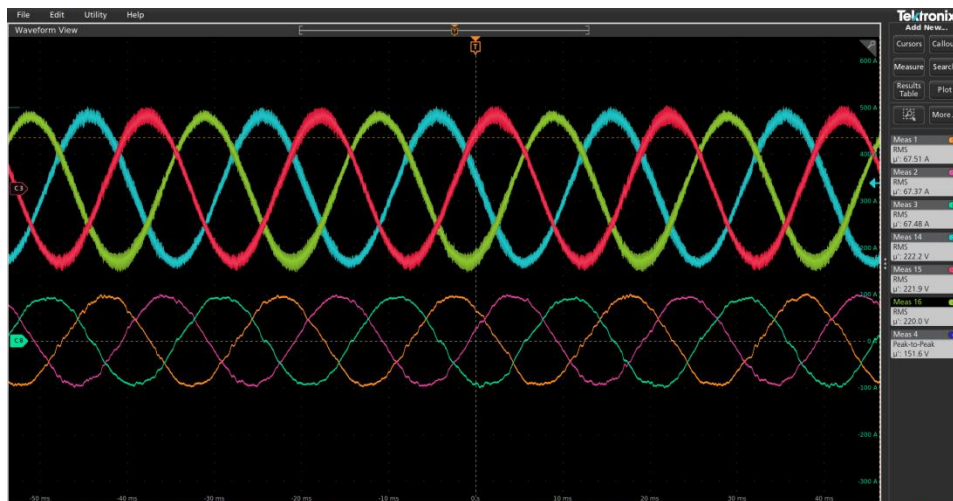
VoutB →

VoutC →

IoutA →

IoutB →

IoutC →



PF=0.8电压滞后电流

VoutA →

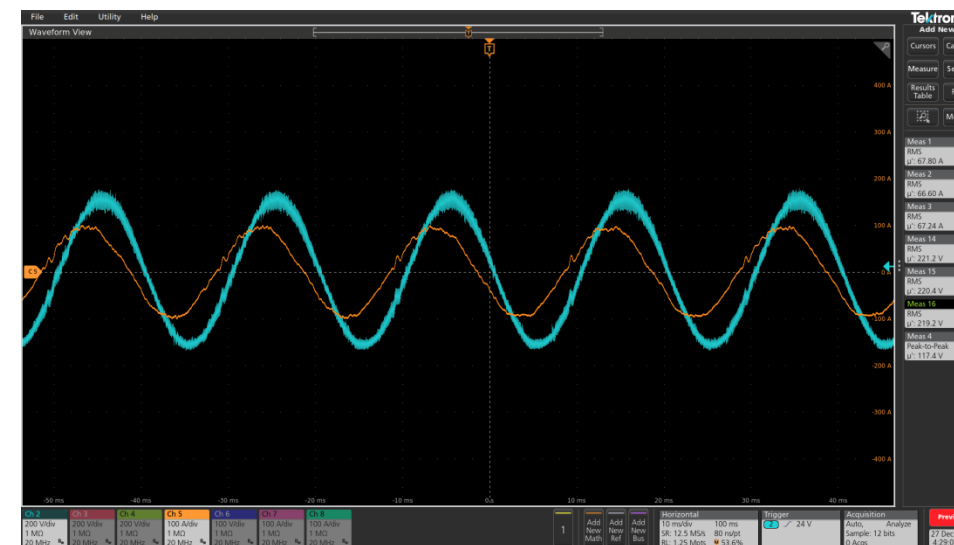
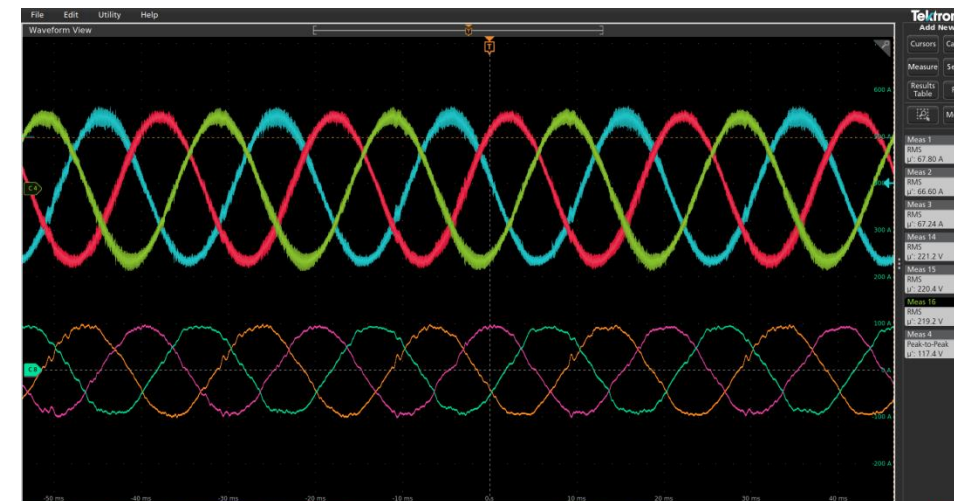
VoutB →

VoutC →

IoutA →

IoutB →

IoutC →





800Vin 220Vacout 50kw

50 kW T型DC/AC PV逆变器

频率范围

频率=45 Hz

VoutA →

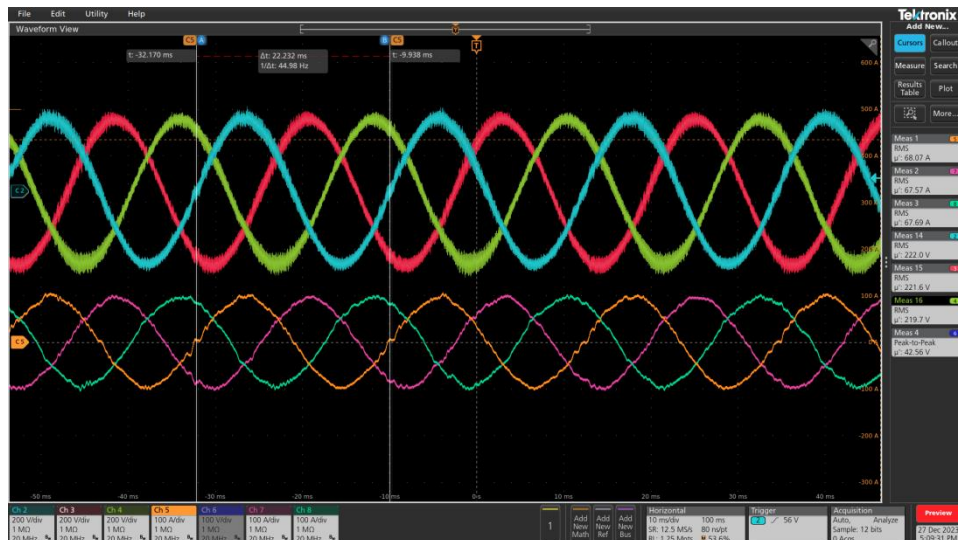
VoutB →

VoutC →

IoutA →

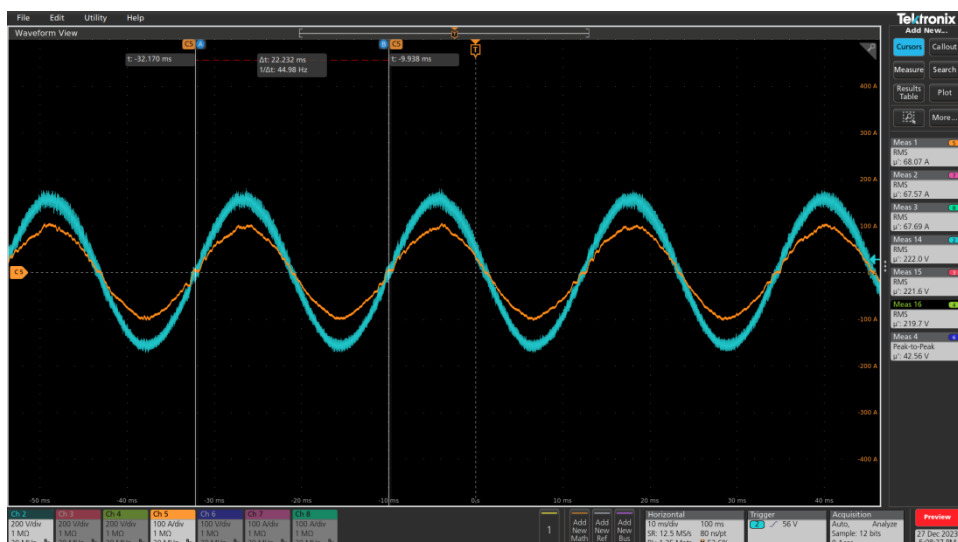
IoutB →

IoutC →



VoutA →

IoutA →



频率=55 Hz

VoutA →

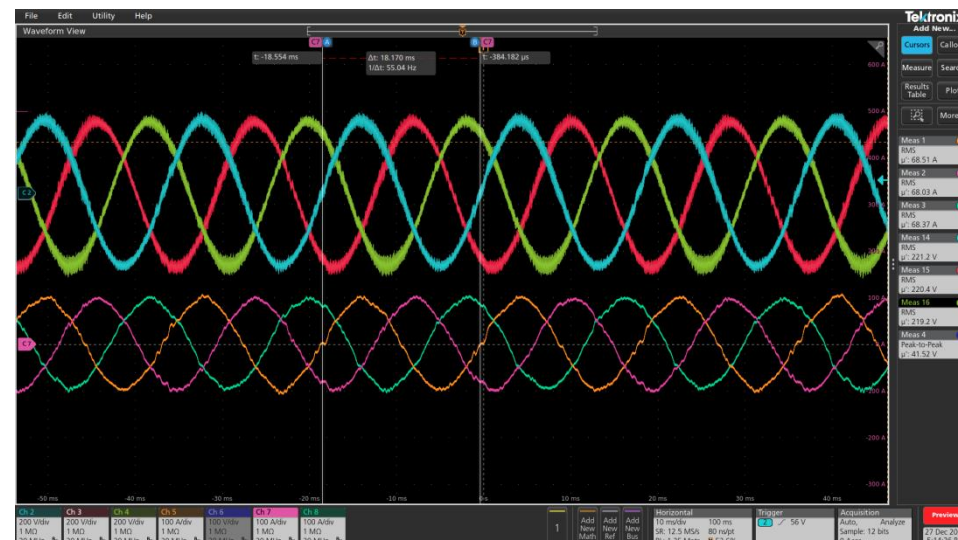
VoutB →

VoutC →

IoutA →

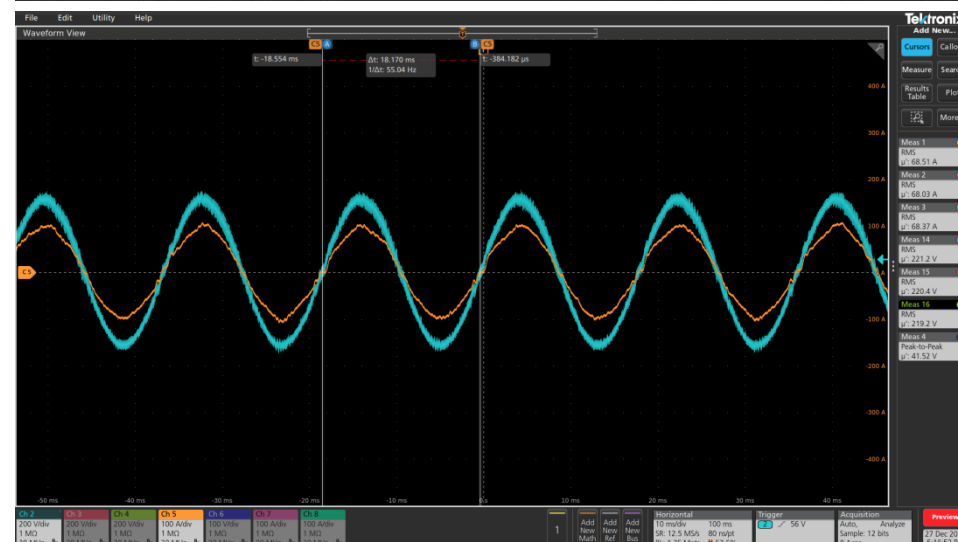
IoutB →

IoutC →



VoutA →

IoutA →





800Vin

50 kW T型DC/AC PV逆变器

Vout范围

Vout=310 V(L-L)

VoutA →

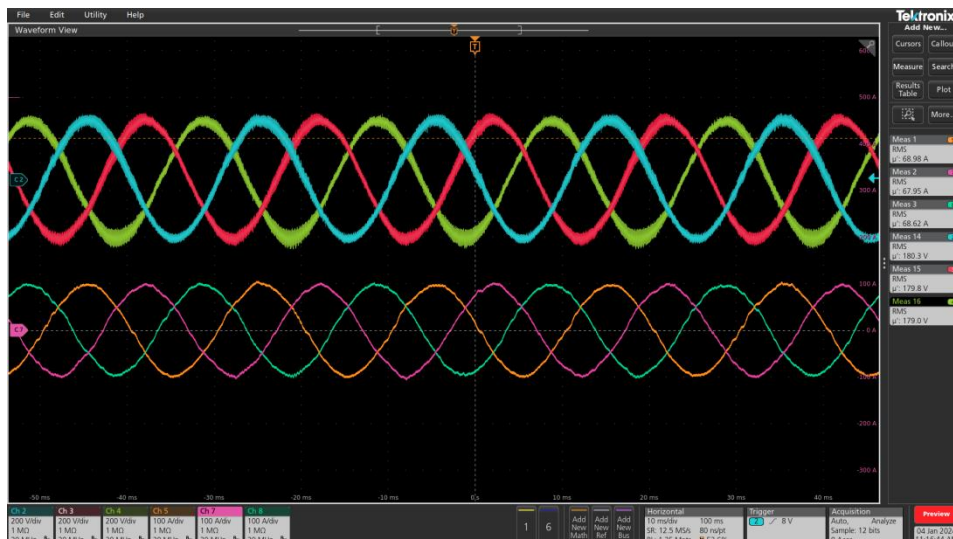
VoutB →

VoutC →

IoutA →

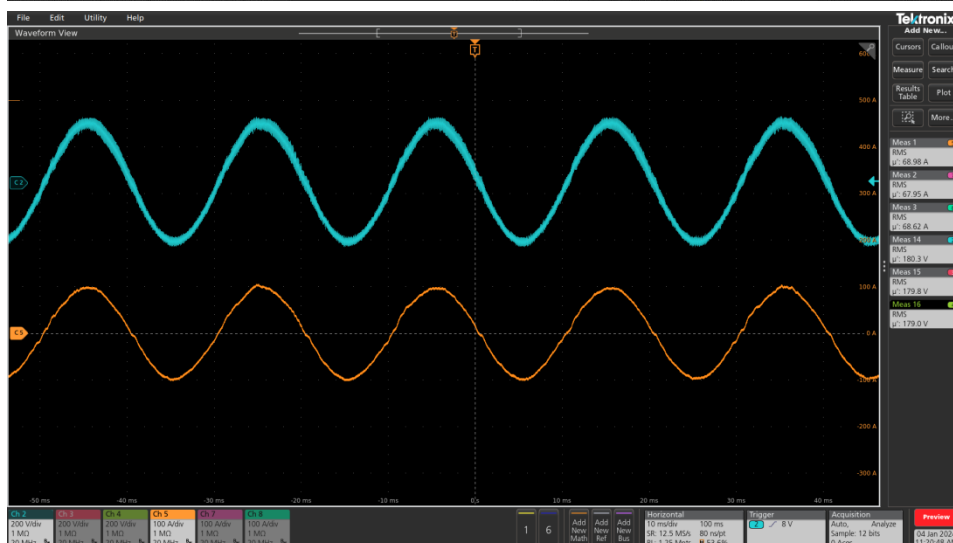
IoutB →

IoutC →



VoutA →

IoutA →



Vout=476 V(L-L)

VoutA →

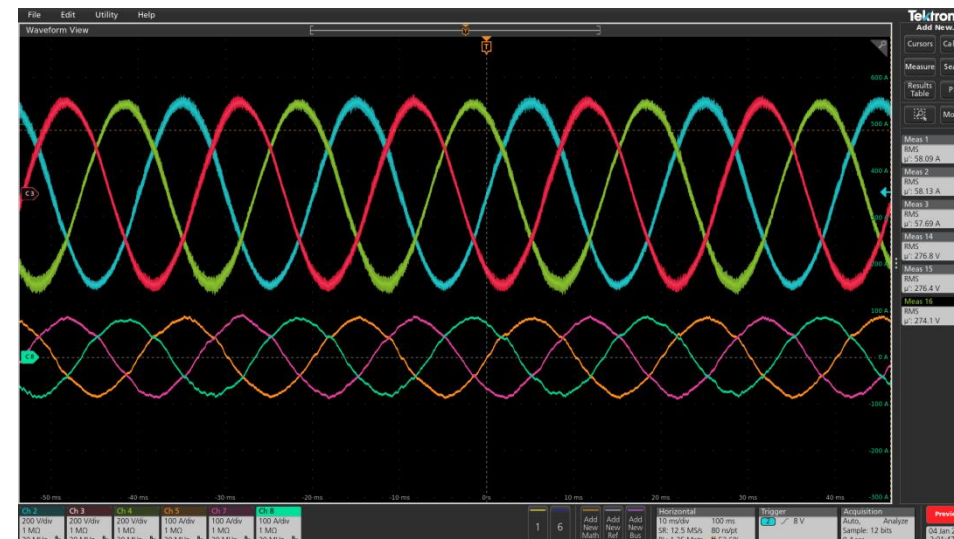
VoutB →

VoutC →

IoutA →

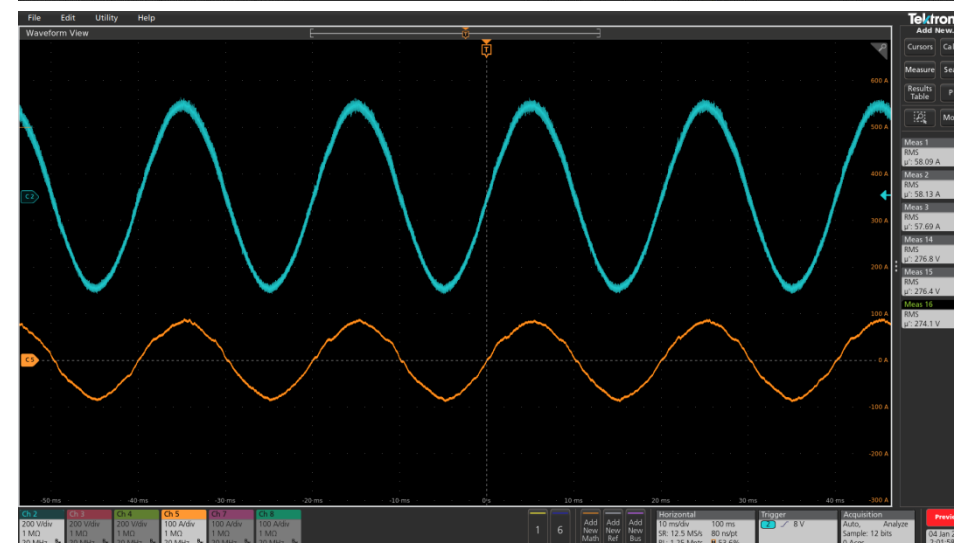
IoutB →

IoutC →



VoutA →

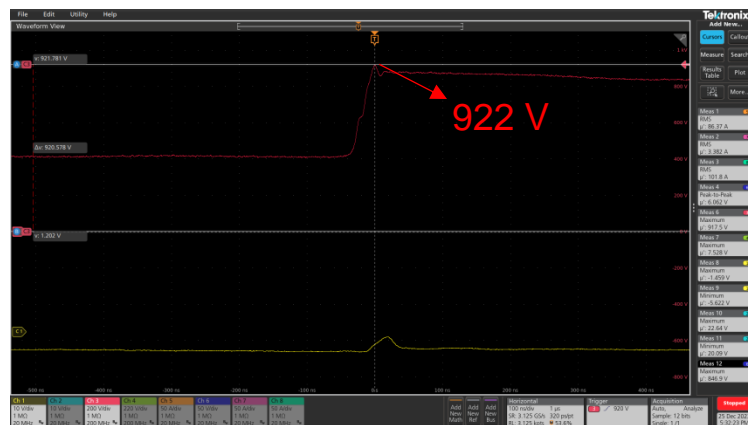
IoutA →



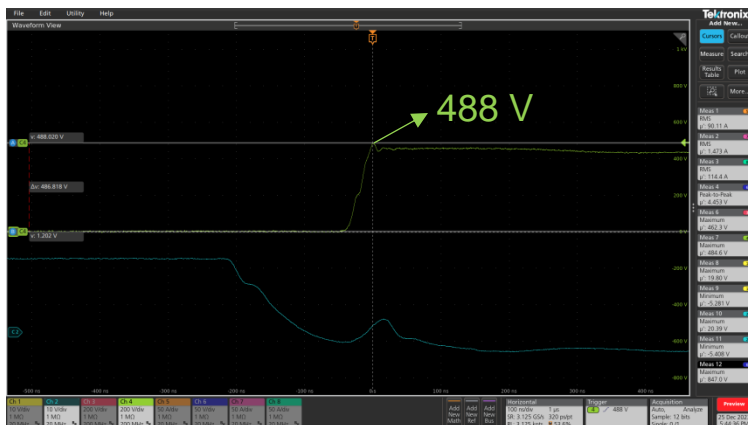


850Vin 220Vacout 50kw

竖桥臂 (PF=1)



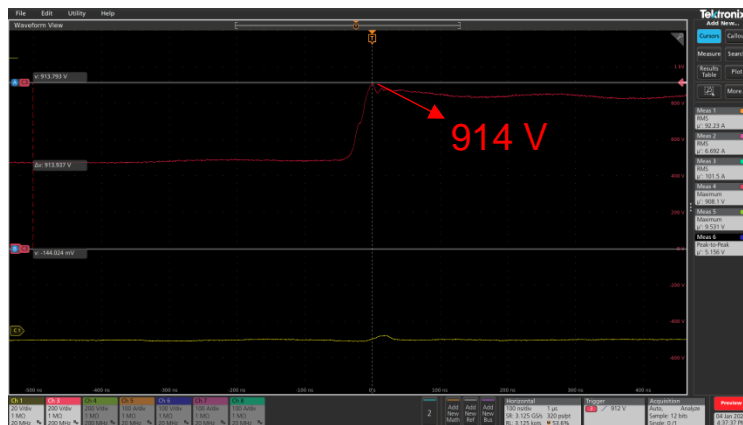
横桥臂 (PF=1)



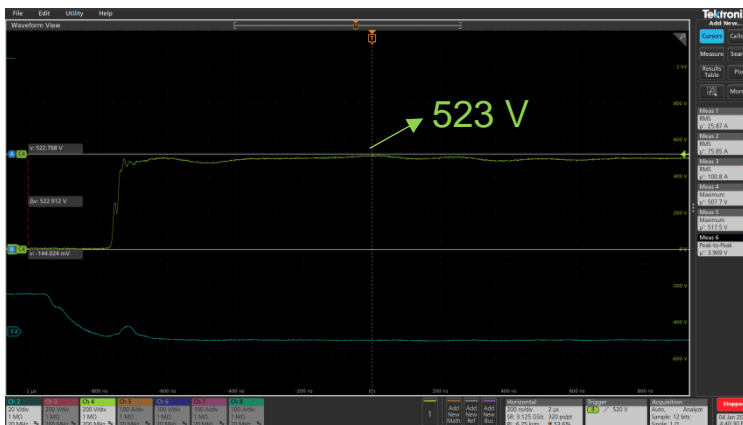
50 kW T型DC/AC PV逆变器

Vds尖峰

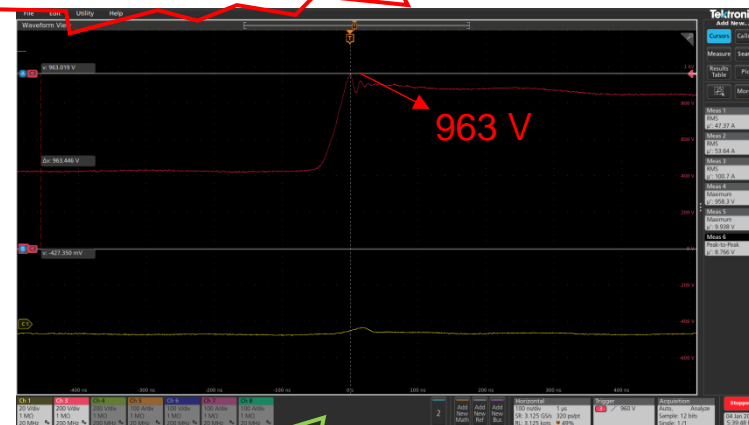
竖桥臂 (PF=0.8超前)



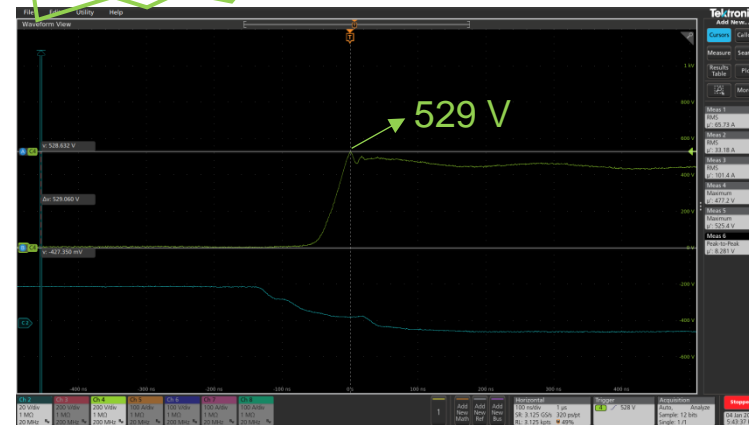
横桥臂 (PF=0.8超前)



竖桥臂 (PF=0.8滞后)



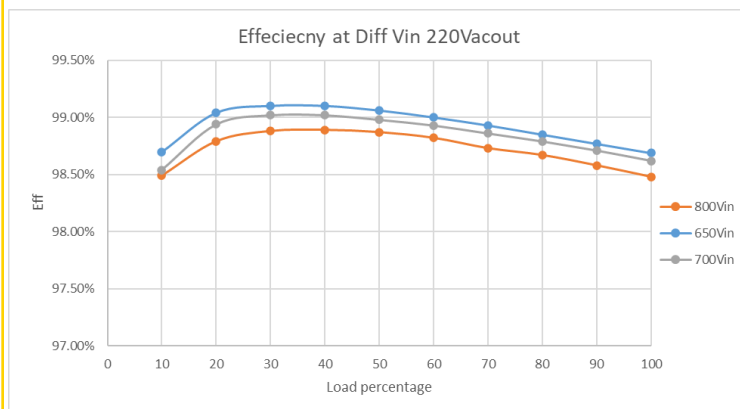
横桥臂 (PF=0.8滞后)



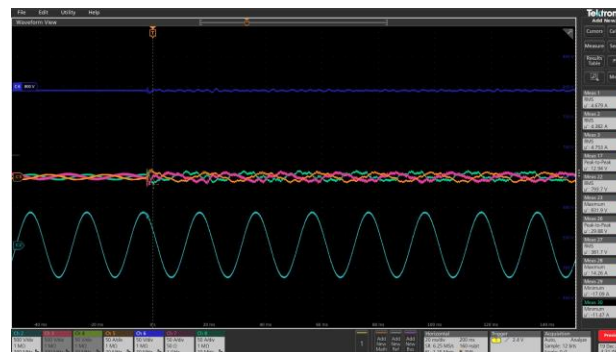


最终EVAL结果

效率

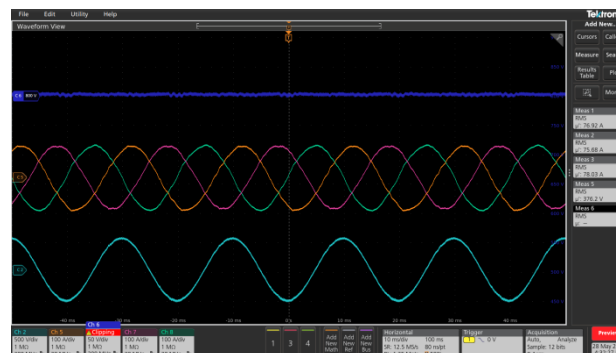


波形



CH5,7,8-ABC输出电流; CH6输入电压; CH2输出电压

启动



CH5,7,8-ABC输出电流; CH6输入电压; CH2输出电压

800 V 50 kW输出

关键性能结果

1. 650-850 V_{dc}输入电压; 310-476 V输出电压;
45-55 Hz输出频率; 50 kW输出最大功率
2. 峰值效率 99.10% @ 650 V_{dc}输入;
98.89% @ 800 V输入
3. 软件控制: PQ/PF控制

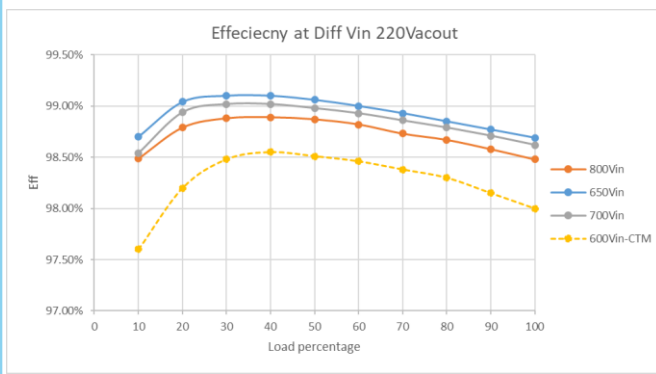


WxLxH: 300 x 400 x 70 mm

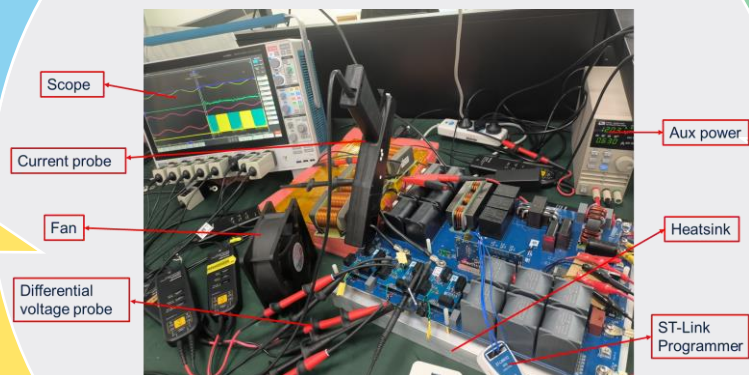


高效率

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



A2U8M12W3



高功率密度

- 75 W/in³

BUS CAP	Inverter Inductor Lf	Grid Inductor Lg
+ Lower Capacitance 120uF	+ Lower Inductance 80uH	+ Lower Inductance 6uH

高频率

- 40 kHz

可靠性高

- 第3代SiC技术
- ACEPACK2 封装
- 集成NTC
- AIN DBC



life.augmented

基于SiC ACEPACK和 STM32H743的50kW数字 DC-AC逆变器

Leah XIAO

Power & Energy
Competence
Center



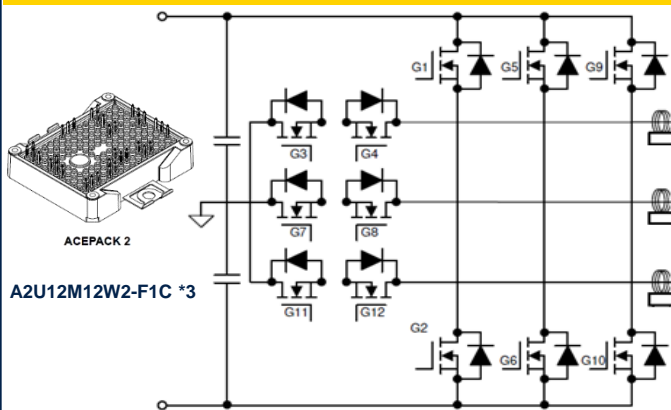


PV逆变器的50 kW DC/AC

PE.ED_ED_0007.22



三电平T型拓扑



PCBA



应用关键特性:

- 输入DC电压: 650Vdc-850VDC
- 输出AC电压: 380 VAC L-L
- 开关频率: 40 kHz
- 峰值效率: 98.89% (800 Vdc)
- 满载运行时 ≥ 0.99 PF且 $\leq 3\%$ THD
- 有功和无功功率控制
- 0.8超前到0.8滞后可调
- 配备STM32H7 MCU的全数字电源平台

主要产品

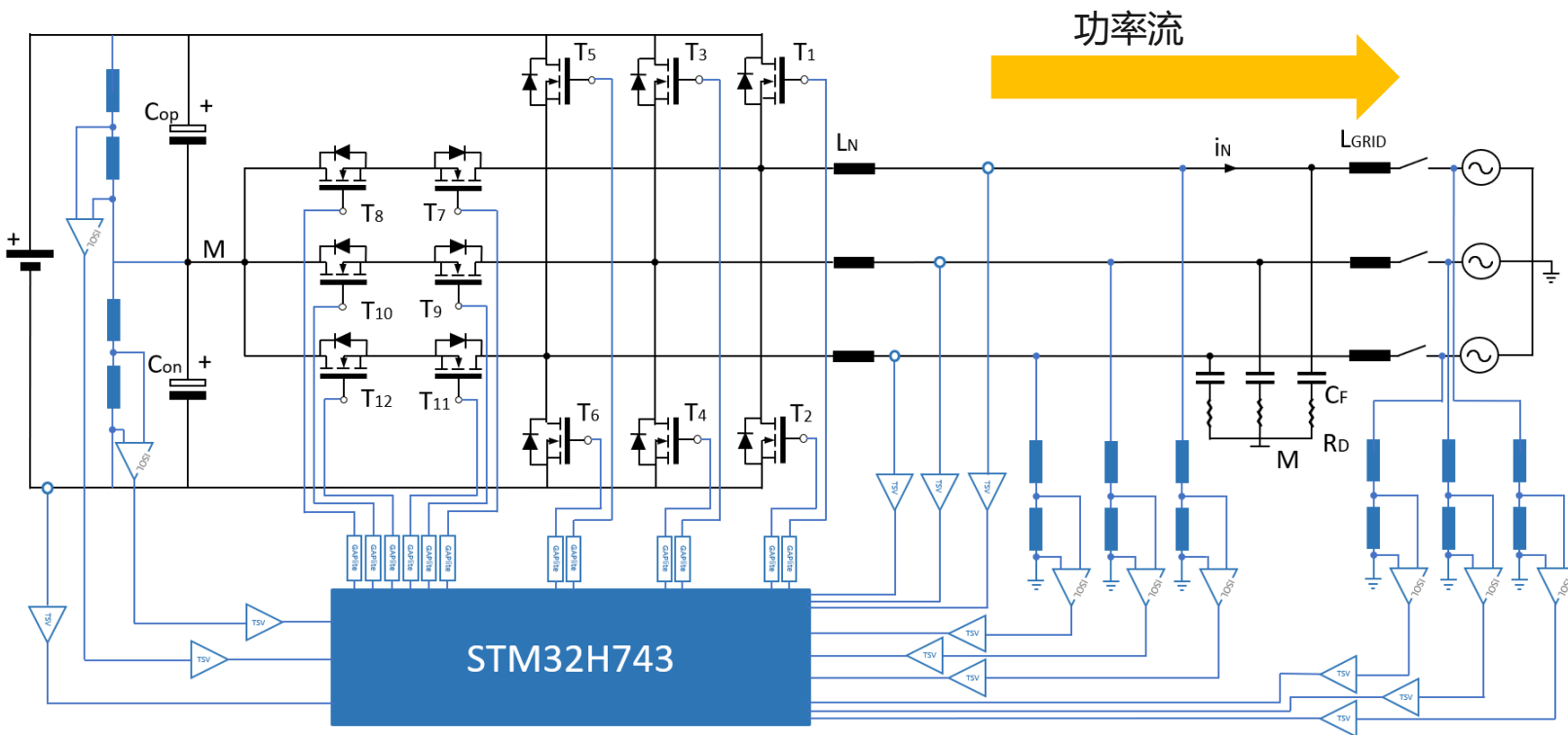
MCU: STM32H743ZGT6 (32位MCU, CPU频率为480 MHz)
SiC MOSFET: A2U8M12W3-FC*3 (9.5m Ω 1200 V & 6m Ω 750 V SiC模块)
栅极驱动器: STGAP2SICSC (电气隔离)
IPC & GPA: ISOSD61, LM393DT, TSV912IDT, TSV914IDT

主要优势

- ✓ 采用全数字功率控制的SiC模块化方法, 系统设计灵活性高
- ✓ 功率级开关频率高达40 kHz的紧凑型输出LCL滤波器
- ✓ 支持PVI产品设计参考的主要功能 (防孤岛、RCMU)



功能块& 主要固件特性



DC-AC

- DQ坐标系下的三相并网系统控制
- 有功和无功功率控制
- 过电压保护
- 过流保护
- 过温保护
- 防孤岛效应、漏电流检测
- 更高的工作频率
- 灵活的数字定制设计，满足客户特定需求
- 通信接口
(用于外部/内部通信的UART异步协议)



逆变器数字平台-STM32H743

数字逆变器上MCU关键功能的配置

Arm® Cortex®-M7 高达
480 MHz

浮点单元(FPU)

- 控制回路计算 (保留供将来使用)

64 KB ITCM RAM和128 KB
DTCM RAM

- 时间关键型例程的零等待状态

DFSDM 数字滤波器, 用于
 $\Sigma\Delta$ 调制器

- 配合外部隔离ADC使用

USART, SPI, CAN

- USART用于内部/外部通讯

高分辨率PWM
定时器

- 主要用于40 kHz的B相和C相MOSFET控制

高级PWM
定时器

- 主要用于40 kHz的A相MOSFET控制

多个ADC, 最大分辨率为
16位

- 三相电网电压、电感器电流、DC bus电压/电流和温度

比较器和DAC

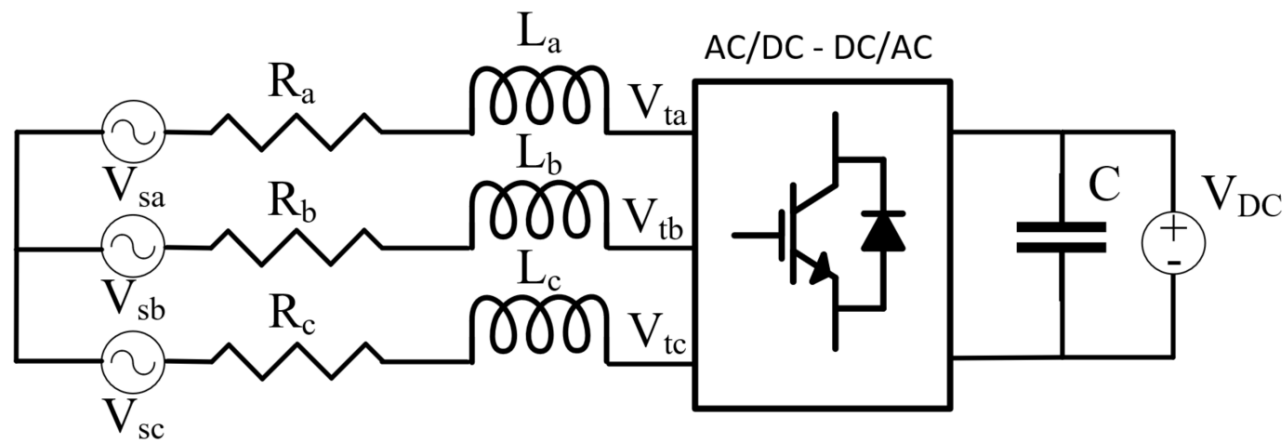
- 逆变器OVP/OCP





VSC模型 (建模)

电压源变流器 “VSC”模型



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

Clarke
 $abc \Rightarrow \alpha\beta$

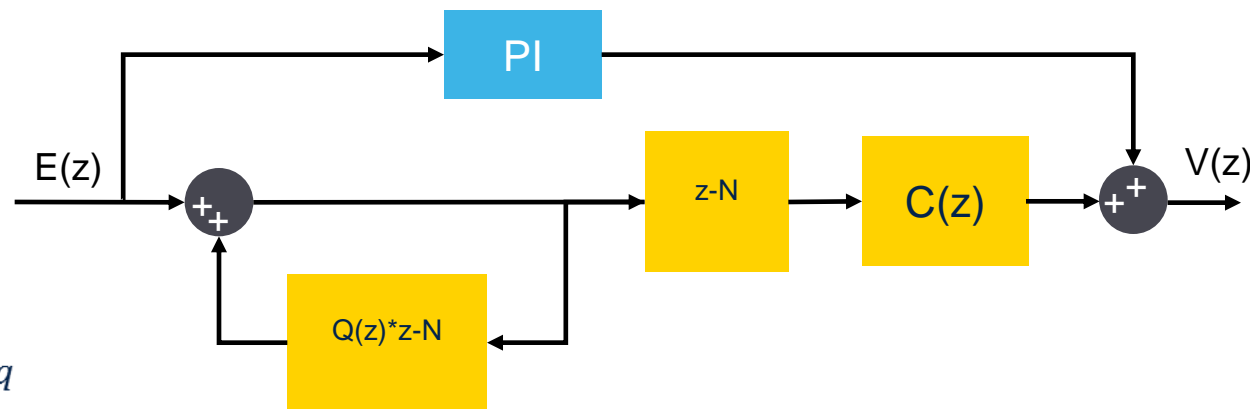
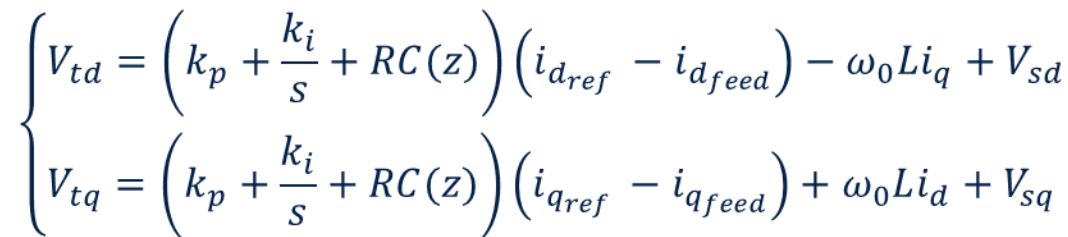
$$\begin{cases} L \frac{di_\alpha}{dt} + Ri_\alpha = V_{t\alpha} - V_{s\alpha} \\ L \frac{di_\beta}{dt} + Ri_\beta = V_{t\beta} - V_{s\beta} \end{cases}$$

Park
 $\alpha\beta \Rightarrow qd$

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



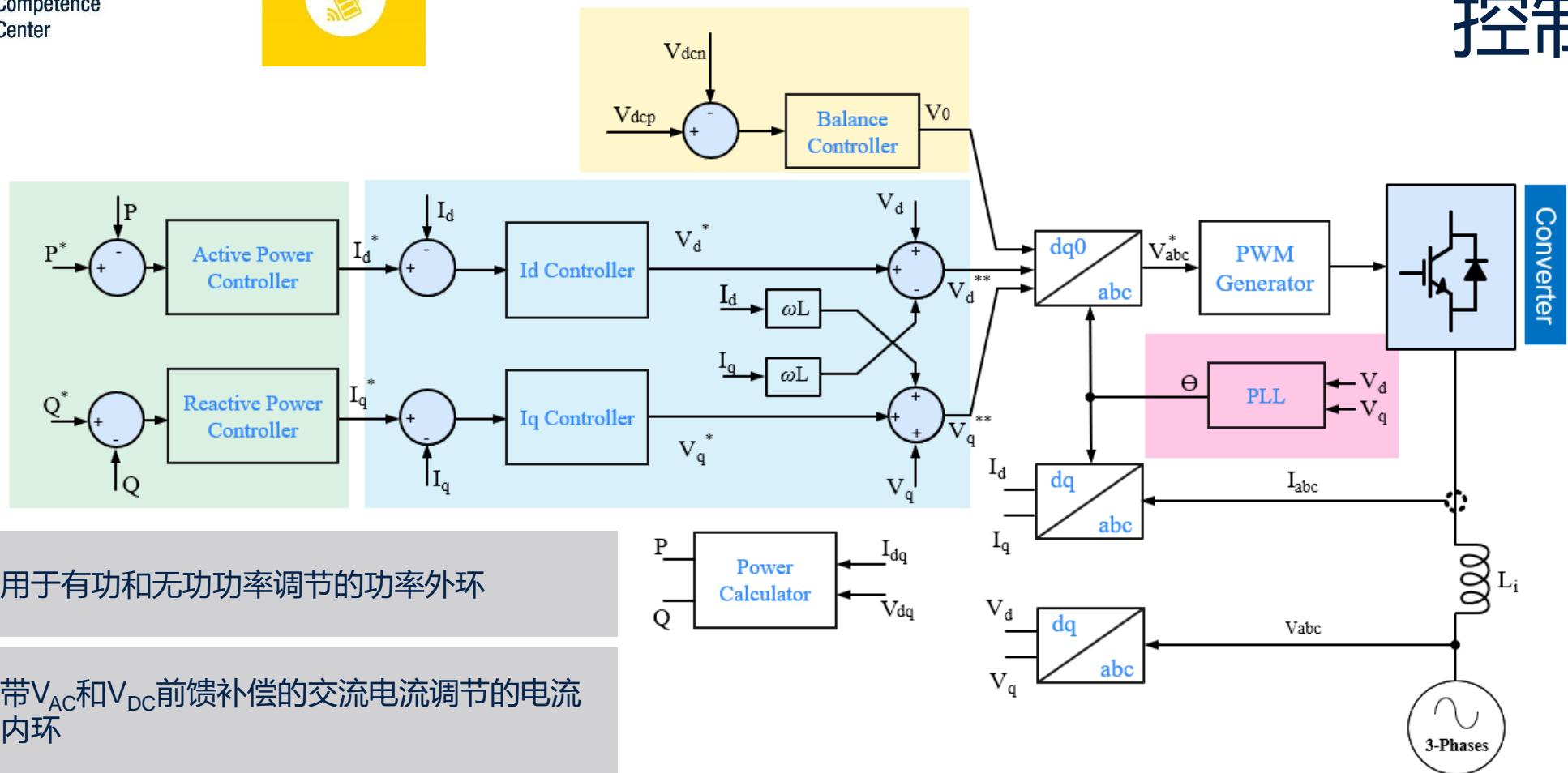
带解耦控制的电流环



采用PI+重复控制器，在电流控制方面实现了更好的静态和动态性能



控制框图



功率环

用于有功和无功功率调节的功率外环

电流环

带 V_{AC} 和 V_{DC} 前馈补偿的交流电流调节的电流内环

锁相环

PLL用于同步AC相位

母线均压环

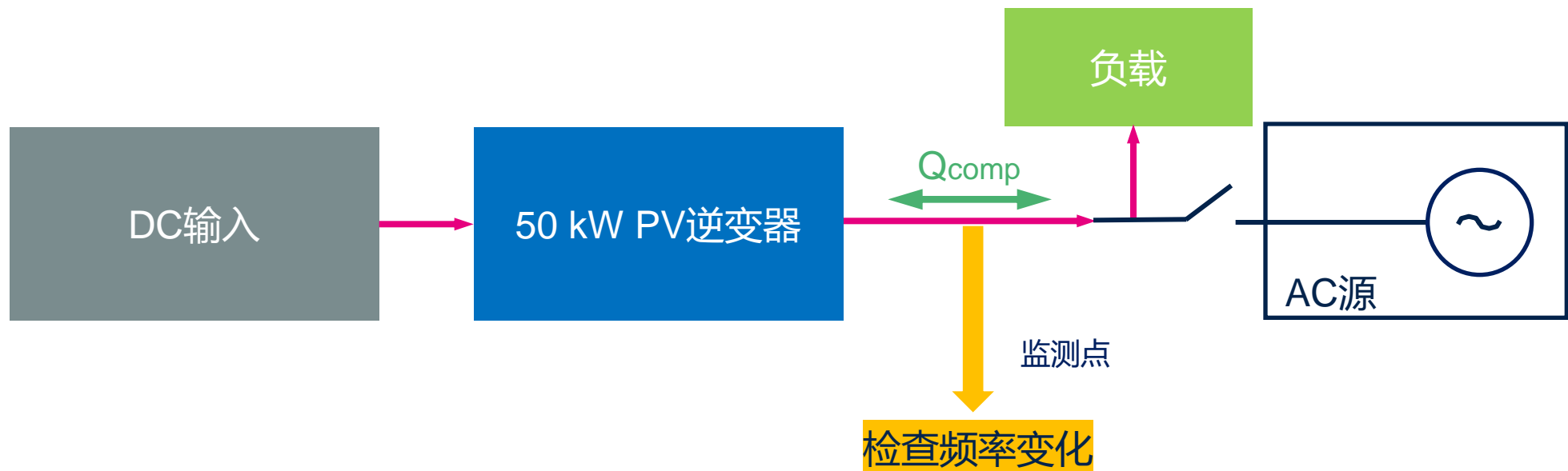
平衡三电平母线中性点

- 功率环: 20 kHz
- 电流环: 20 kHz
- 锁相环: 20 kHz
- 母线均压环: 20 kHz



主动检测-无功干扰补偿方法

- 注入变化的无功功率作为干扰信号，通过检查频率变化来检测交流电网的存在。
- 无功功率的干扰补偿 (Q_{comp}) 将被注入到具有配置变化范围 ($-Q_{comp}/0/+Q_{comp}$) 的控制回路输出端。

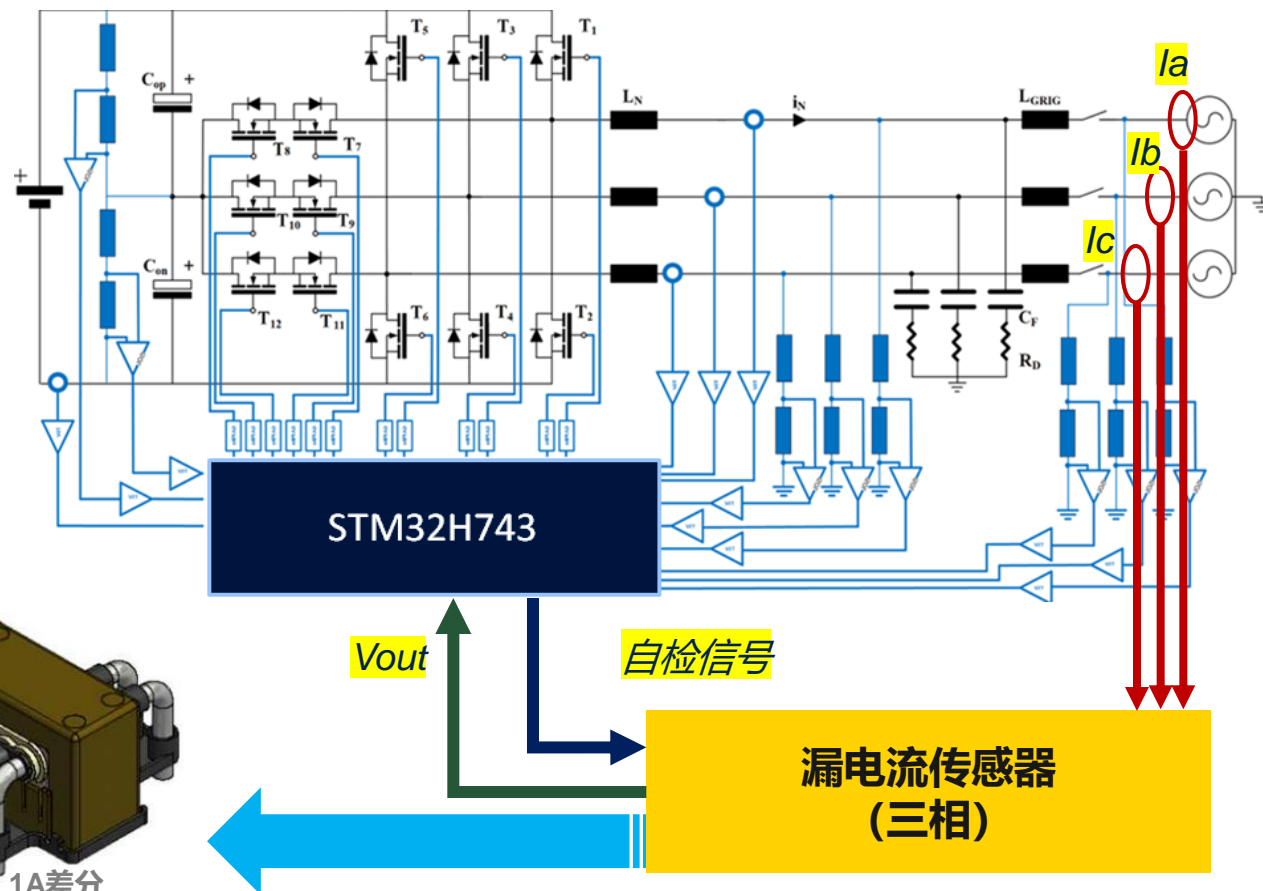
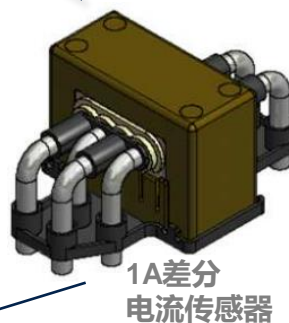
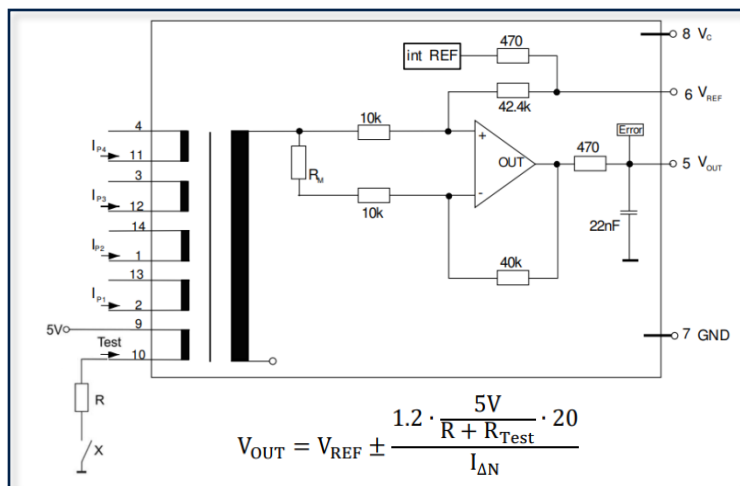




漏电流保护

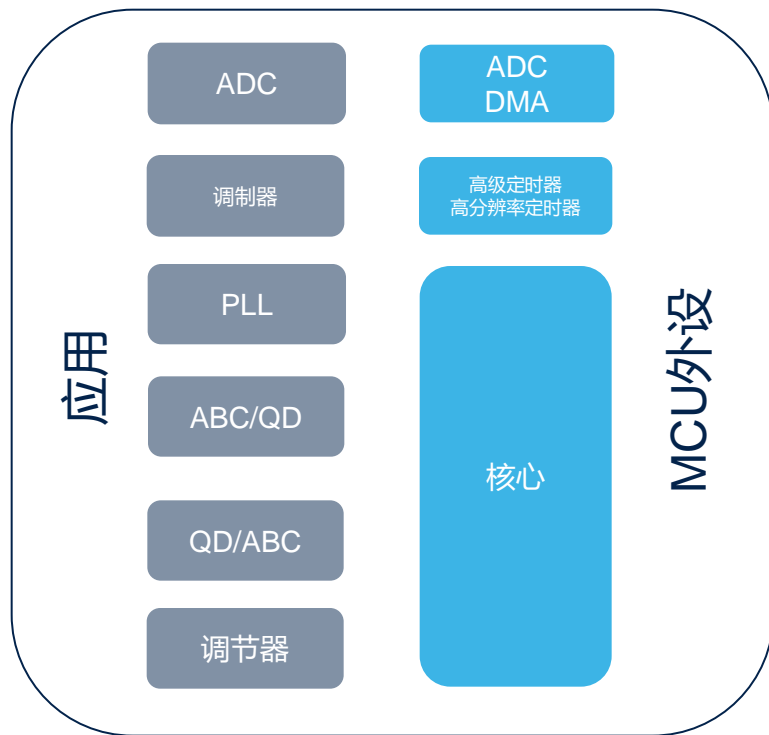
带自检功能的漏电流监测

- 自检功能:
在上电之前 (电网继电器打开), MCU发送“自检”信号以检查电流传感器的功能
- 漏电流检测:
在上电之后 (电网继电器闭合), MCU将继续监测漏电流 (在配置值内)





控制环路的MCU配置



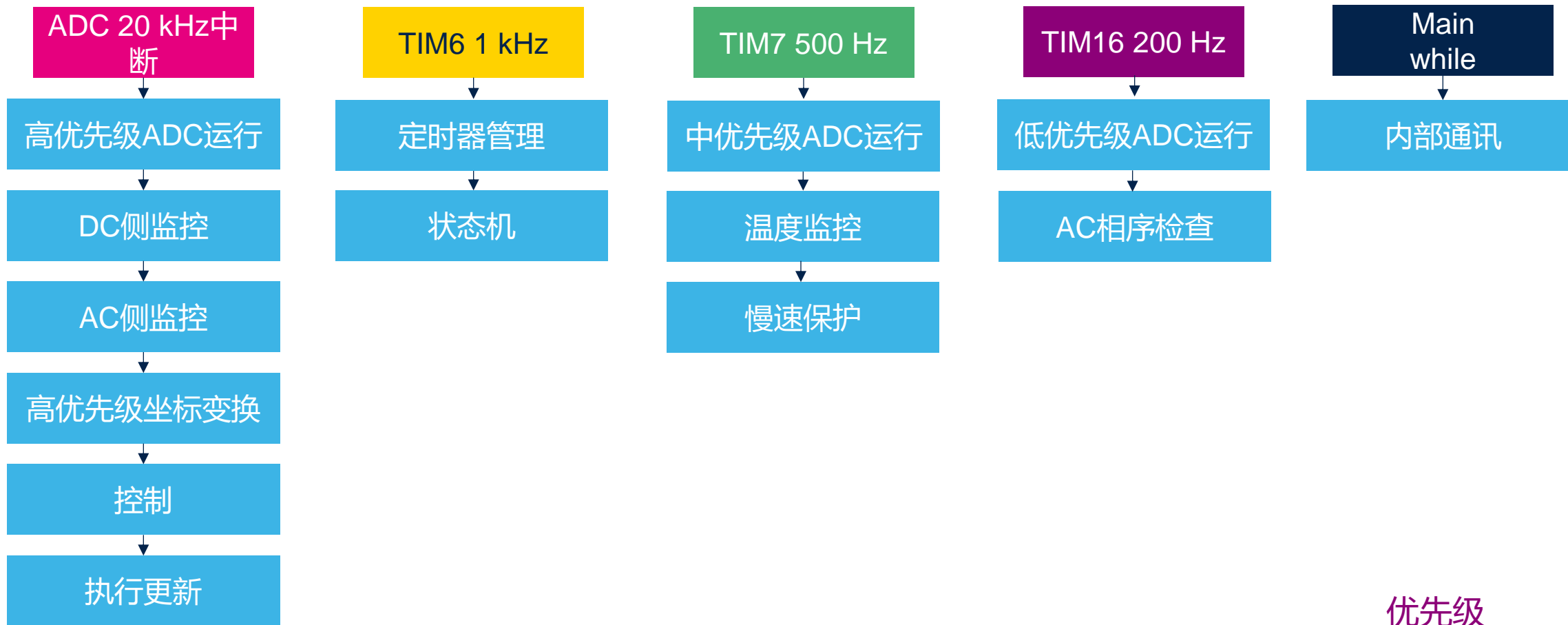
实现

工作	所用外设
外环和内环	基于ADC中断
调制器	高分辨率 + 高级定时器
采样	ADC & DMA

STM32H743	定时器	通道 (带DT)	输出
高级定时器	TIM1	2	4
高分辨率定时器	HRTIM	4	8

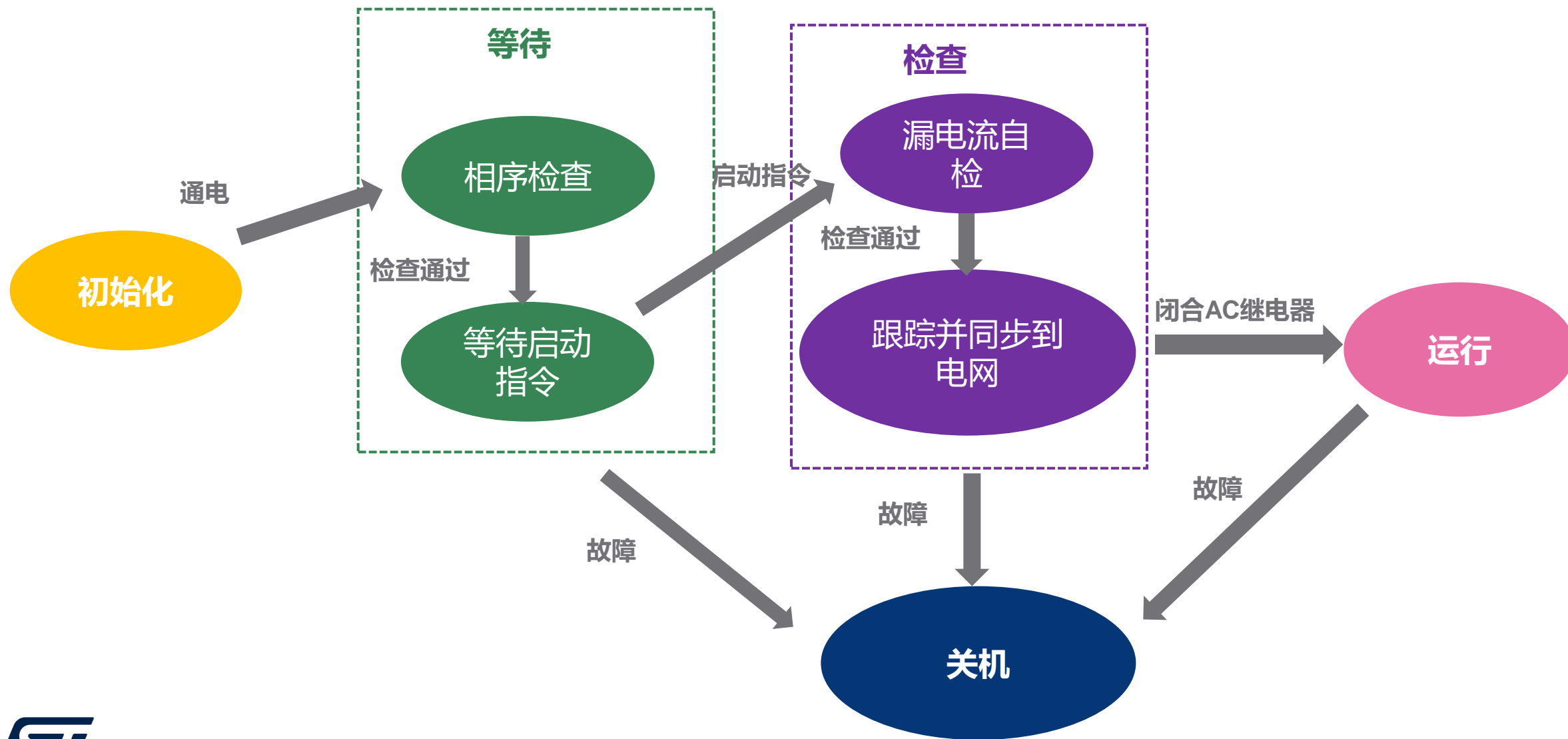


固件配置



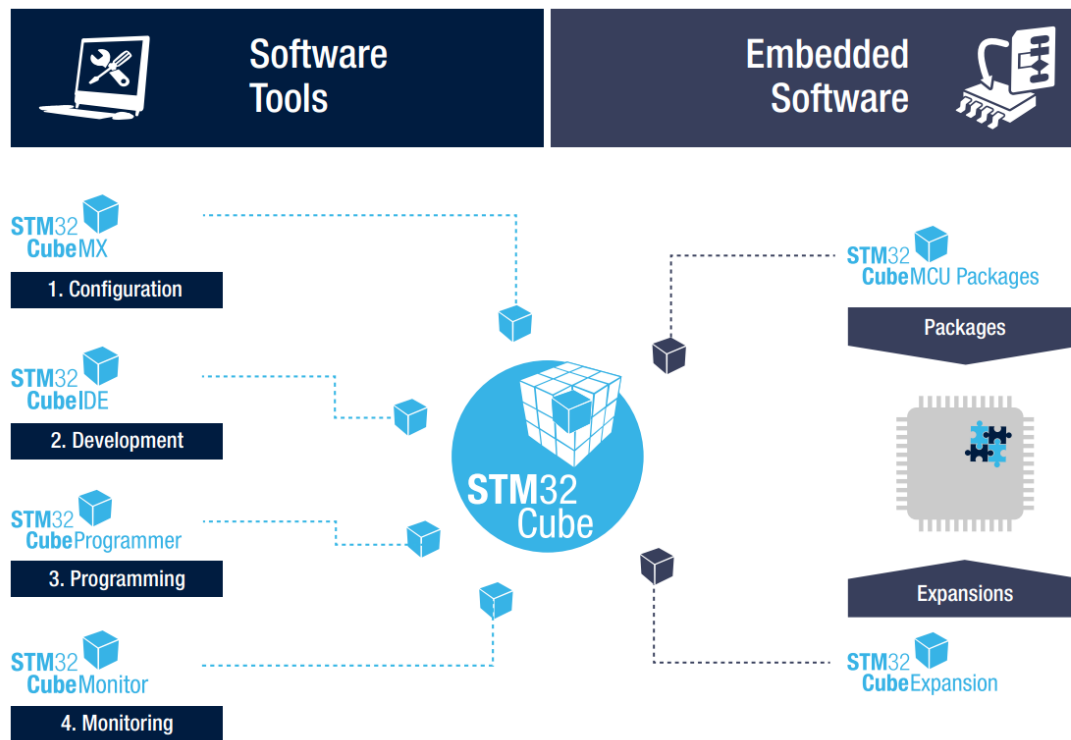


状态机





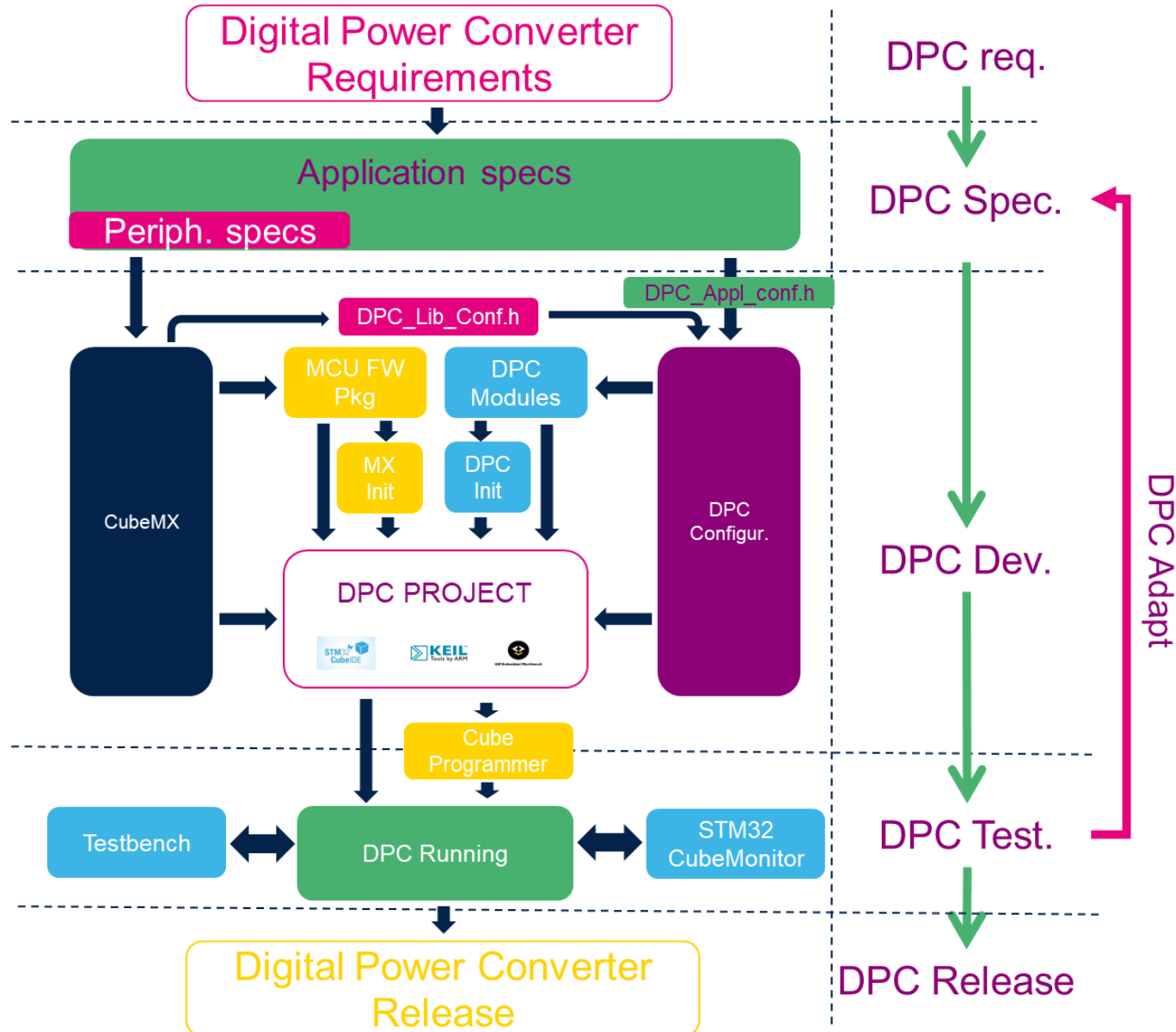
STM32Cube生态系统



STM32Cube生态系统是STM32微控制器和微处理器的软件解决方案，面向关注STM32微控制器和微处理器免费综合开发环境的设计者和寻求在其现有IDE（如Keil或IAR IDE）中整合STM32软件的用户。



DPC开发流程



总结





基于ST SiC和STM32H7的解决方案有助于实现高性能PV逆变器

随着高效和高功率密度的发展趋势，人们对于PV逆变器的要求越来越高

意法半导体为客户提供先进的元件和整体解决方案（SiC MOSFET/SiC二极管/STGAP/STM32）

ST 50 kW **T型逆变器**解决方案可实现峰值效率98.89% (800 Vdc)、99.10% (650 Vdc)

用户手册、BOM、SCH和PCB板现在都已准备就绪



工业峰会
资料下载中心



能以致励子网站



Our technology starts with You



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