Igniting Potential: SiC-Powered 6.6kW Isolated Bidirectional Energy Storage Designed with CLLLC Topology

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- Arrow-ST Industrial Joint Lab
- Energy Storage – Bidirectional 6.6kW/ 60-90Vdc
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    - Topology Selection
    - Designing Introduction
    - Testing Result
    - Main issues

Arrow-ST Industrial Joint Lab solutions

Power & Energy Lab

Bidirectional Charger 250-450V/19.6A, 6600W for EV, PFC

P/N : 2021P004, 2020P003

	Charger for EV	Qty
PTD	SCTW40N120G2VAG->	
PTD	SCT040W120G3-4AG	16
IPC	STGAP2SiCS	12
GPA	A6986I*	12
IPC	VIPER31*	1
ADG	STL8N10LF3*	6
MDG	STM32G474VBT6	1

Energy Storage (ESS) bi-directional 60-80V/82.5A Output, 6600W, PFC & DC-DC

P/N : 2021P005, 2021P006

	Energy Storage	Qty
PTD	SCTWA60N120G2-4 ->	16
PTD	SCT040W120G3-4AG	
IPC	STGAP2SiCS	8
GPA	A6986I	12
ADG	STP75NF20	32
IPC	VIPER319HDTR	1
DFD	STPS1150A	2
IPC	STISO621WTR	2
ADG	STL8N10LF3*	6
DFD	HDMIULC6-4SC6Y	3
DFD	ESDCAN03-2BWY	2
MDG	STM32G474VBT6	2

15 kW Bidirectional PFC

NEW

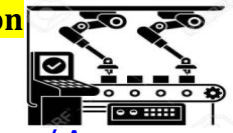
P/N : 2022P001

	15kW PFC	Qty
PTD	SCT070W120G3-4AG	6
PTD	SCT055W65G3-4AG	6
MDG	STM32G474RET6	1
IPC	STGAP2HSCM	12
IPC	VIPER26HD	1
GPA	TSV912IDT	10
GPA	TSV914IDT	6

Automation Lab

Factory Automation

IO-link Master



IO-link Slave – Sensors/ Actuators

8-CH Master w/ Arrow MCU

P/N : 2021W001

	8-CH IO-link Master	Qty
	ARW-IOLM4P-STM32L4	
MDG	STM32L431RBT6	2
MDG	M24256-BRDW6TP	2
DFD	USBLC6-4SC6	1
GPA	L7986ATR	1
GPA	LD1117S33TR	1
GPA	LD39050PU33R	1
MDG	M93C66-RMC6TG	1
IPC	IPS161H	8
IPC	L6360	8
DFD	SPT01-335DEE	8
MDG	STM32F746ZGT6	1
GPA	STG3693QTR	2

8-CH Digital Input

P/N : 2021W002

	DI Module	Qty
DFD	SM15T33CA	1
DFD	SMA4F5.0A	1
MDG	STM32G071RBT6	1
IPC	STISO621WTR	2
DFD	CLT01-38SQ7-TR	1
GPA	L7986ATR	1
DFD	SPT01-335DEE	1
GPA	LD39050PU33R	1
IPC	L6364Q	1
DFD	STPS140Z	8
DFD	STPS3L60UFN	1
DFD	STPS340AFN	1

8-CH Master w/ Ethernet IP

P/N : 2021W004

	8 CH IOLM	Qty
MDG	STM32H743ZIT6	1
IPC	VN808-32-E	1
IPC	L6360	8
MDG	M24256-BRDW6TP	1
GPA	L7986A	1
DFD	SLVU2.8-4A1	2
DFD	SMA4F28A	24

8-CH Digital Output

P/N : 2021W003

	DO Module	Qty
DFD	STPS3L60UFN	1
DFD	STPS340AFN	1
DFD	SM15T33CA	1
DFD	SMA4F5.0A	1
GPA	L7986ATR	1
DFD	SPT01-335DEE	1
GPA	LD39050PU33R	1
IPC	L6364Q	1
IPC	ISO8200AQ	1
MDG	STM32G071RBT6	1

Building Automation

KNX

*Partner module

	KNX	Qty
IPC	STKNX	1
MDG	STM32G070CBT6	1

Tower-light CTRL

P/N : 2021W005

	Tower light	Qty
IPC	IPS4260L	1
IPC	L6364Q	1
MDG	STM32G071	1
MDG	M24C08	1
DFD	SMB15F24A	2
GPA	STG3157CTR	1

Motor Control Lab

Air-conditioning Compressor

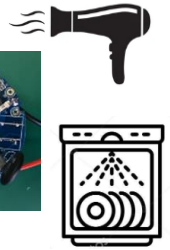
P/N : 2019M002 Customization

STEVAL-CTM010V1

	HVAC – 2kW	Qty
PTD	STGIB15CH60TS-L	1
MDG	STM32F302RBT6	1
PTD	STP4LN80K5	2
IPC	PM8834	1
DFD	STTH30AC06C	2
DFD	T435-800B	1
IPC	STSPIN820	1

110 krpm BLDC Motor Driver

P/N : 2021M001



	Fast Hair Dryer	Qty
IPC	STSPIN32F0601Q	1
PTD	STN6N60M2	6
IPC	VIPER222	1
GPA	LD1117S33TR	1
DFD	BAT41ZFILM	1
DFD	STTH1L06A	2
DFD	T1635T-8FP	1

1kW Servo Motor Driver

P/N : 2022M001

	Servo	Qty
IPC	STSPIN32G4	1
ADG	STL110N10F7	6
IPC	VIPER319HDTR	1
DFD	STPS1H100A	3
GPA	ST1S40IDR	2
GPA	LD1117S12TR	1
DFD	ETP01-1621RL	4
DFD	ETP01-1621RL	2

Power & Energy

Power & Energy solutions

Bidirectional Power Converter for EV (6600W)

PFC
Released
P/N : 2021P004

DC-DC
Released
P/N : 2020P003

Unidirectional Power Converter for EV (30kW) – designed by ST Power & Energy CC

PFC
Released
P/N :STDES-30KWVRECT

DC-DC
Soon to Release
P/N : STDES-#####

Bidirectional Energy Storage System (ESS) PFC & DC-DC (6600W)

On-grid PFC
Released
P/N : 2021P005

DC-DC
Soon to Release
P/N : 2021P006

3 Phase 3 Level T-Type Bidirectional Power Converter (15kW)

PFC
In Development
P/N : 2022P001

Bidirectional Power Converter for ESS – AC/DC

Feature

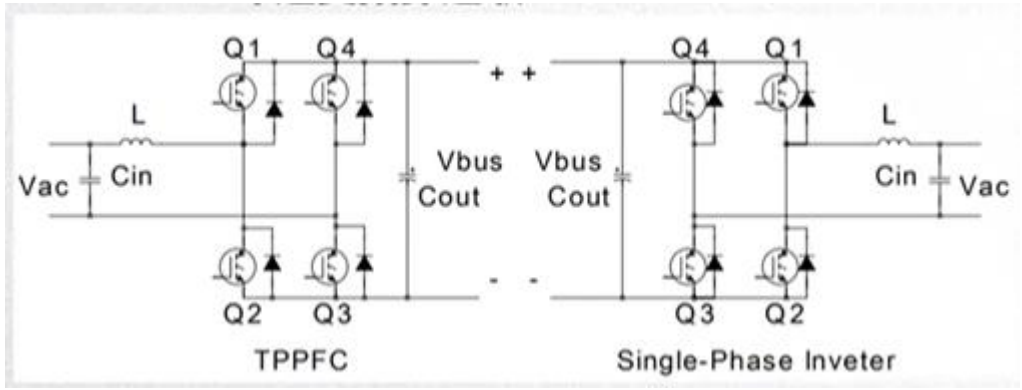
- Max. **6.6kW** Bidirectional Power Conversion
- Power factor >0.99 @ R load
- THDi < 3% @Full load
- Peak Efficiency >**98%**
- Input Voltage: 200-265 VAC 50Hz
- Output voltage: 390~550VDC
- Inversion Rated Input: 390~550VDC
- Inversion Rated Output: 220VAC 50Hz
- Dimension: 450mmx150mmx100mm (LxWxH)

Functions

1) PFC (AC to DC)

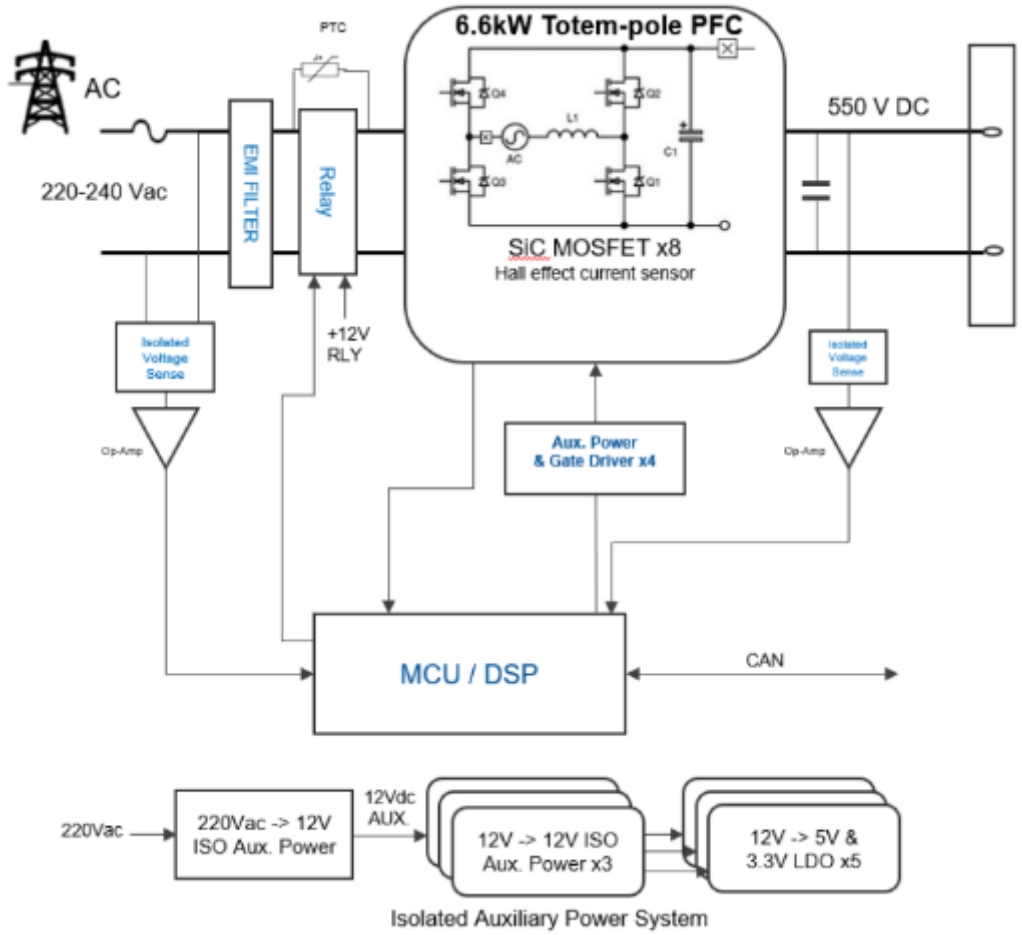
2) Off Grid Inverter(DC to AC)

3) On Grid Inverter(DC to AC)



- Switch Frequency 100KHz
- Unipolar PWM
- 4*SiC

Bidirectional Power Converter for ESS - AC/DC



Core Chip

- MCU control:
  - **ST** STM32G474VBT6
- SiC MOS:
  - **ST** SCTWA60N120G2-4
  - -> SCT040W120G3-4AG
- Isolated gate driver:
  - **ST** STGAP2SiCS
- Isolated DC-DC module:
  - **ST** L6986I
  - **ST** VIPER329HDTR
- CAN:
  - **ST** L9616
- ESD protection:
  - **ST** HDMIULC6-4SC6Y
  - **ST** ESDCAN03-2BWY
- Hi-Precision OP-AMP:
  - **ST** TSZ181IYLT
- Current sensor:
  - **Allegro** ACS772LCB-050B-PFF-T
  - **Allegro** ACS772LCB-100B-PFF-T
- Relay:
  - **TE** T9VV1K15-12S
- Magnetic component:
  - **knitter-switch** ICSI15312700LVJ61
  - **knitter-switch** ICSI28175700LVK14
  - **knitter-switch** ICST75311000LVK61
  - **knitter-switch** ICSC30330600LVS2
  - **knitter-switch** ICSC64415600LHS61
  - **knitter-switch** ICST90211100SHSST61

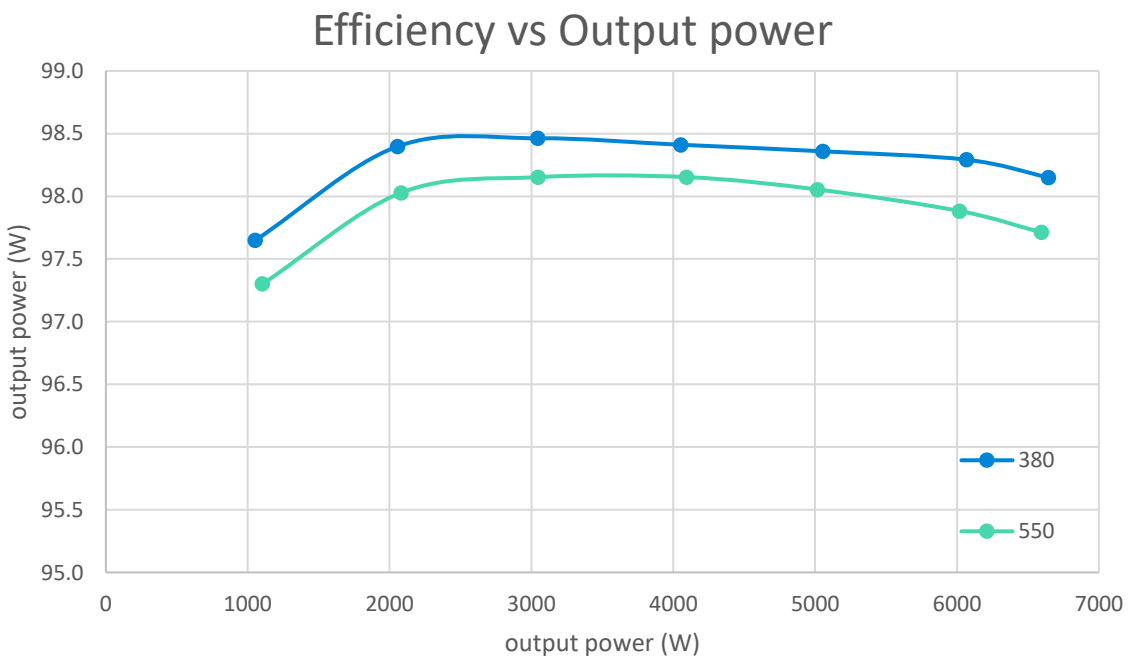
Bidirectional Power Converter for ESS - AC/DC

- **Charging mode@380V output**

Input voltage (VAC)	Input current (A)	Input power (W)	PF	Athd (%)	Output voltage (VDC)	Output current (A)	Output power (W)	Eff. (%)
229.7	4.7	1079.3	0.994	4.91	379.8	2.8	1053.9	97.7
228.0	9.2	2091.3	0.998	3.02	379.7	5.4	2057.8	98.4
226.4	13.7	3093.0	0.999	2.46	379.8	8.0	3045.5	98.5
224.8	18.4	4120.1	0.999	2.16	379.9	10.7	4054.6	98.4
223.0	23.1	5140.7	0.999	2.06	380.0	13.3	5056.3	98.4
221.0	28.0	6173.3	0.999	2.04	380.1	15.9	6067.8	98.3
219.7	30.8	6770.6	0.999	2.02	380.2	17.4	6645.4	98.2

- **Charging mode@550V output**

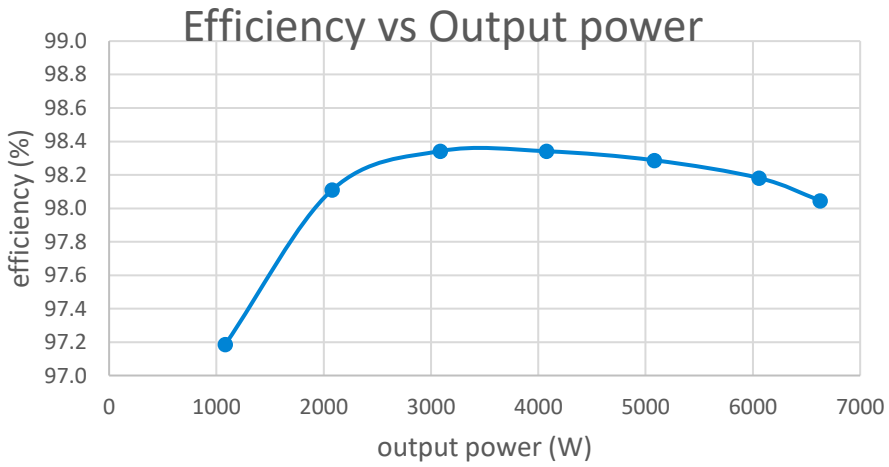
Input voltage (VAC)	Input current (A)	Input power (W)	PF	Athd (%)	Output voltage (VDC)	Output current (A)	Output power (W)	Eff. (%)
229.5	5.0	1134.2	0.994	5.40	548.5	2.0	1103.6	97.3
228.0	9.3	2123.9	0.998	3.35	548.6	3.8	2082.0	98.0
226.5	13.7	3106.1	0.999	2.54	548.6	5.6	3048.7	98.2
224.84	18.6	4172.3	0.999	2.04	548.7	7.5	4095.2	98.2
223.2	23.0	5117.4	0.999	1.73	548.7	9.1	5017.8	98.1
221.4	27.8	6149.1	0.999	1.50	548.6	11.0	6018.9	97.9
220.0	30.7	6749.7	0.999	1.42	548.8	12.0	6595.2	97.7



Bidirectional Power Converter for ESS - AC/DC

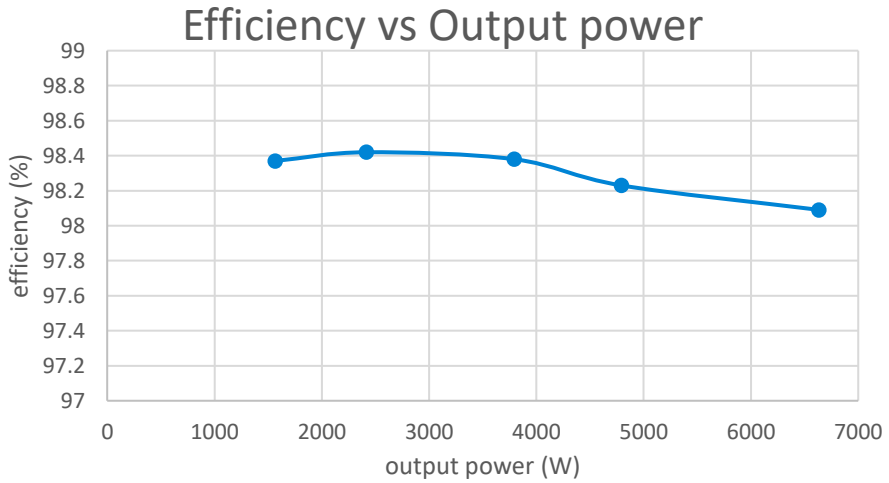
- **Off grid Inversion mode**

Input voltage (VDC)	Input current (A)	Input power (W)	PF	Vthd (%)	Output voltage (VAC)	Output current (A)	Output power (W)	Eff. (%)
550.2	2.0	1112.3	0.998	0.85	225.7	4.8	1081.0	97.2
550.1	3.9	2118.1	0.999	0.84	225.5	9.2	2078.2	98.1
550.0	5.7	3139.0	0.999	0.88	225.3	13.7	3086.9	98.3
550.0	7.5	4146.0	0.999	0.88	225.2	18.1	4077.2	98.3
549.6	9.4	5171.4	0.999	0.99	224.9	22.6	5083.1	98.3
548.5	11.3	6170.5	0.999	1.14	224.6	27.0	6058.5	98.2
547.3	12.4	6760.3	0.999	1.33	224.5	29.5	6628.3	98.1



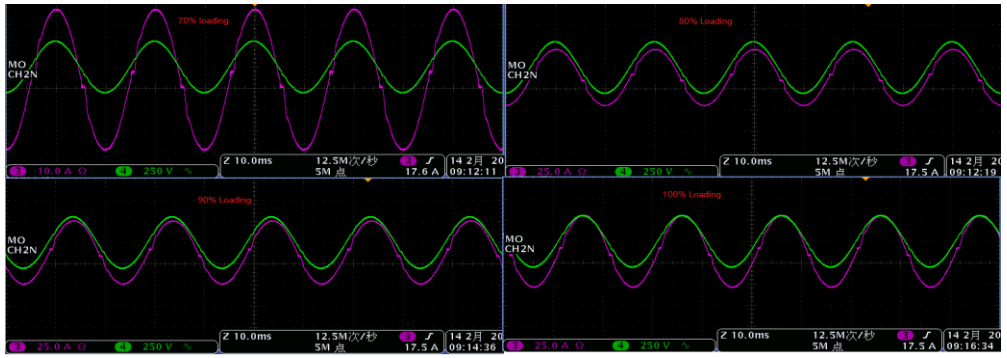
- **On grid Inversion mode**

Input voltage (VDC)	Input current (A)	Input power (W)	PF	Vthd (%)	Output voltage (VAC)	Output current (A)	Output power (W)	Eff. (%)
550.1	2.9	1590.0	0.991	0.55	211.0	7.5	1564.2	98.4
550.0	4.5	2452.8	0.996	0.54	211.5	11.5	2414.0	98.4
549.9	7.0	3857.2	0.998	0.51	213.7	17.8	3794.6	98.4
549.5	8.9	4879.7	0.999	0.47	214.1	22.4	4793.1	98.23
547.4	12.4	6762.8	0.999	0.43	217.4	30.5	6633.9	98.1

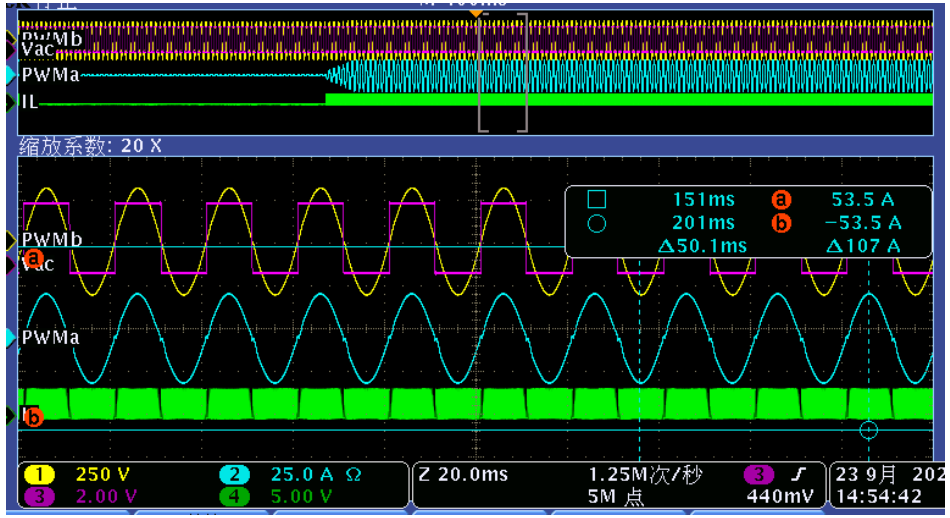


Bidirectional Power Converter for ESS - AC/DC

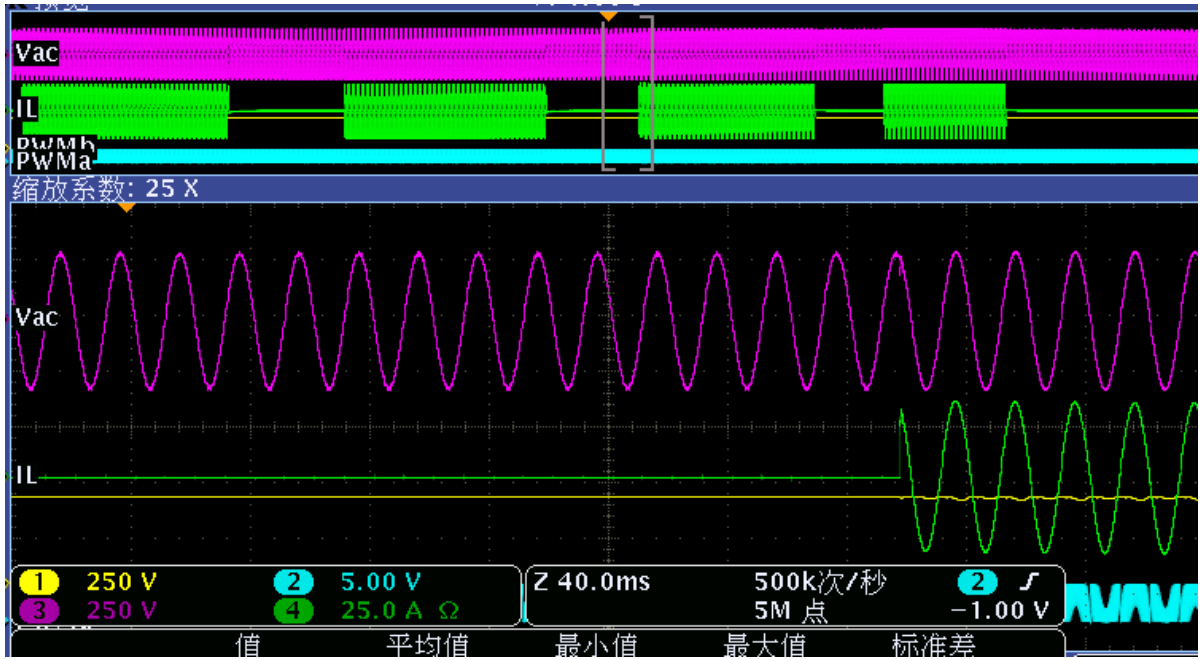
- Test Waveform



PFC



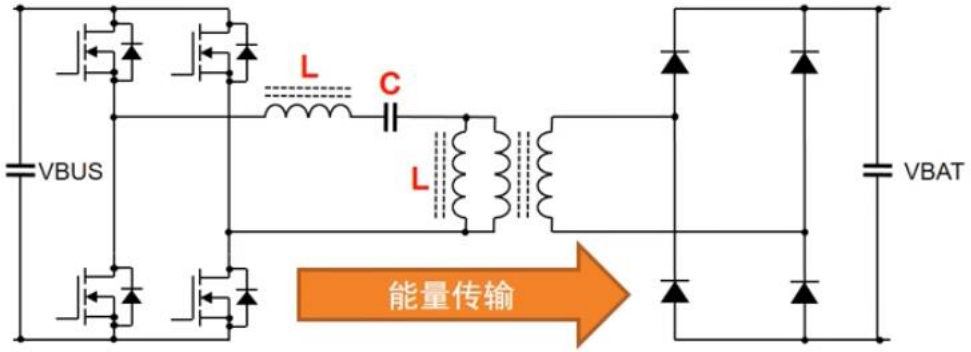
On Grid inverter



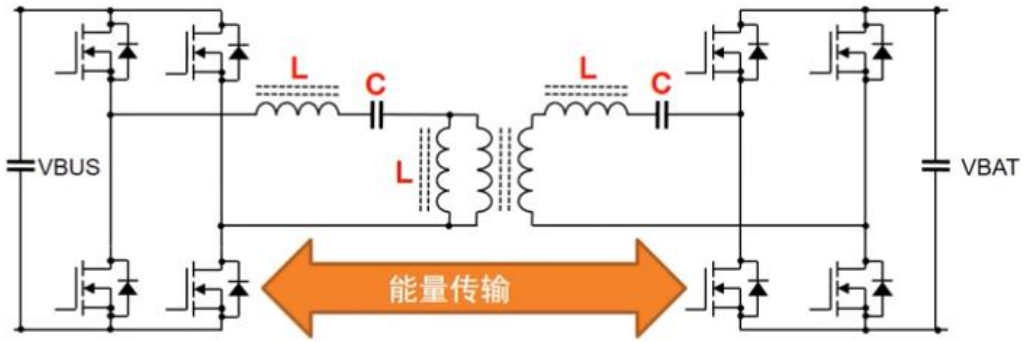
Off Grid inverter

Bidirectional Power Converter for ESS – DC/DC

- **Topology Selection**



LLC



CLLLC

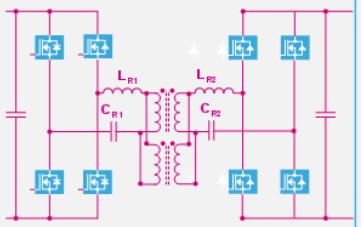
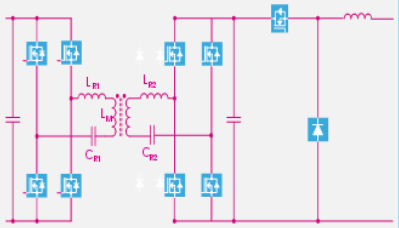
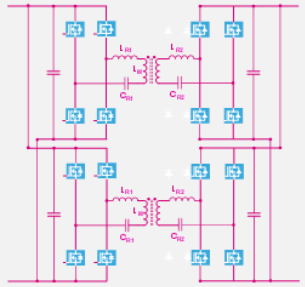
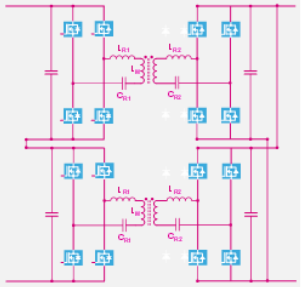
➢ **Advance**:
- High Effciency
- Full Range Soft Switch
- Low EMI at low voltage side

➢ **Challenge**:
- The gain adjustment range is small
- Cost
- High Power

Bidirectional Power Converter for ESS – DC/DC

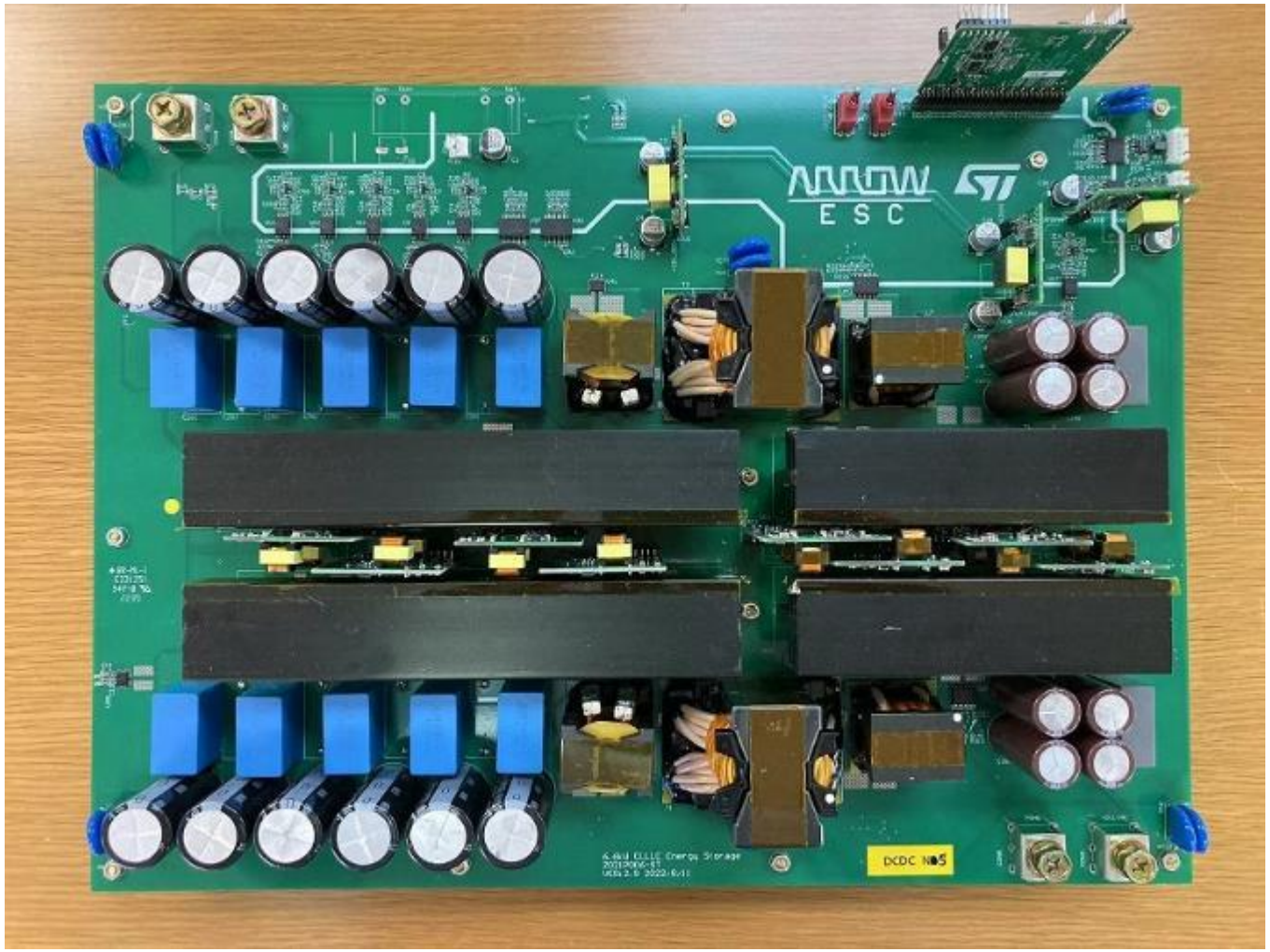
- **Topology Selection**

S: Taking as reference
+: Better than reference
-: Worse than reference

★ Key feature				
Efficiency	-	- -	S	-
Power density	=	-	S	+
Cost	=	-	S	=
Firmware complexity	+	+	S	-
Hardware complexity	-	+	S	=
Resource needed	=	+	S	=
Delivery time	=	+	S	-
Reliability	-	+	S	=

Bidirectional Power Converter for ESS – DC/DC

Coming Soon!



- **Feature**
- Dual Symmetric CLLLC DCDC converter
- Max. **6.6kW** Bidirectional Power Conversion
- Efficiency >**96%**
- Input Voltage: 420~650VDC
- Output voltage: 60-90VDC
- Inversion Rated Input: 80VDC
- Inversion Rated Output: 550VDC
- Dimension: 450mmx330mmx100mm (LxWxH)

Arrow Design ID: 2021P006

Bidirectional Power Converter for ESS – DC/DC

- Auxiliary Power & Gate Driver

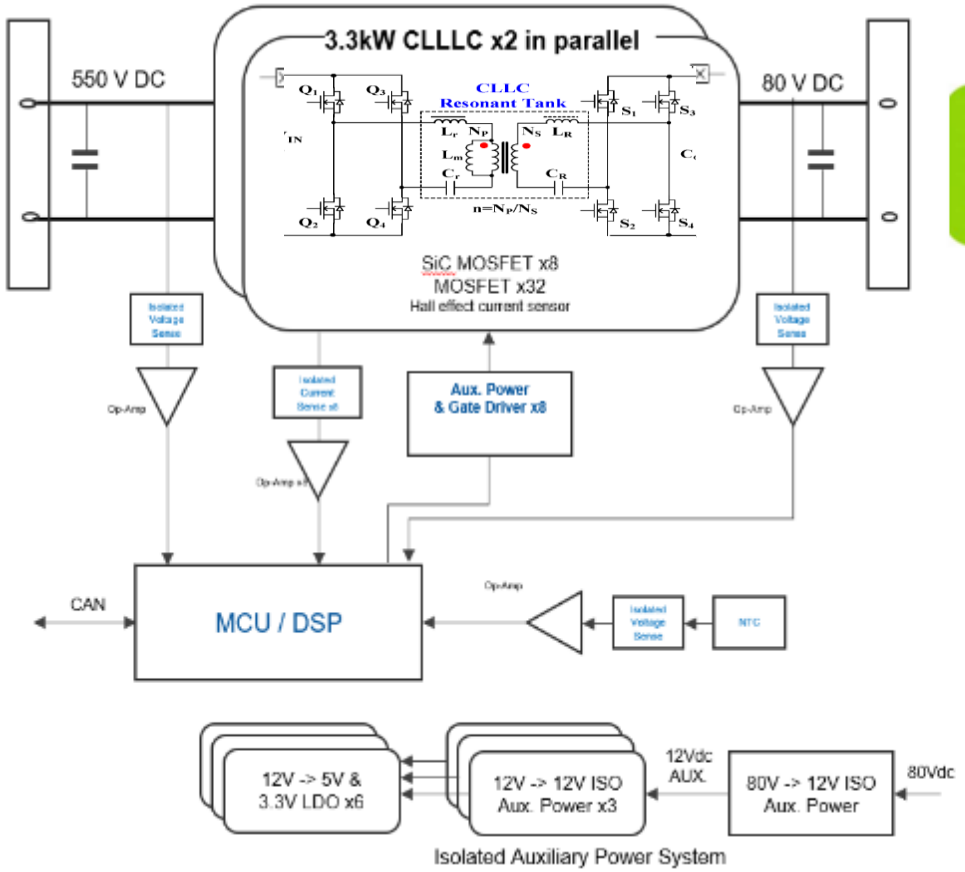
AC to 12V isolated auxiliary power board

12V to 12V isolated auxiliary power board

Isolated gate driver board with DCDC module

Isolated gate driver board with iso-buck converter

Bidirectional Power Converter for ESS – DC/DC

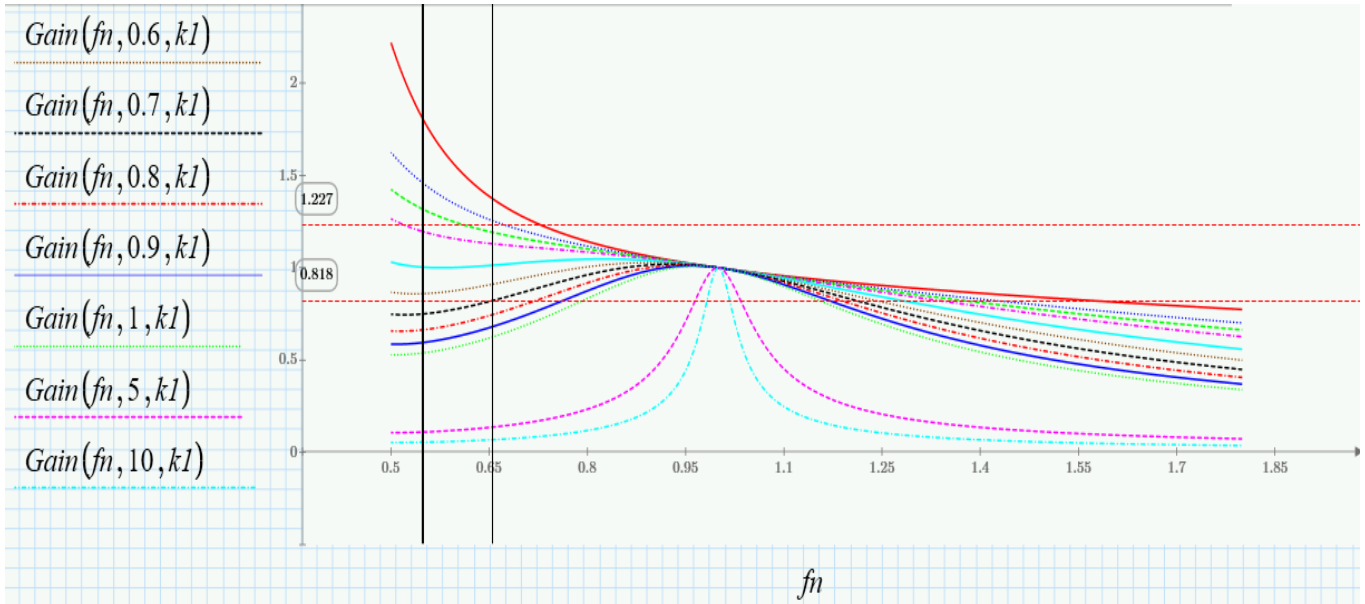


Core Chip

- MCU control:
  - **ST** STM32G474VBT6
- SiC MOS:
  - **ST** SCTWA60N120G2-4
  - -> SCT040W120G3-4AG
- Isolated gate driver:
  - **ST** STGAP2SiCS
  - **ST** STGAP2SM
- Isolated Aux. Power:
  - **ST** A6986I
- CAN:
  - **ST** L9616
- ESD protection:
  - **ST** HDMIULC6-4SC6Y
  - **ST** ESDCAN03-2BWY
- Hi-Precision OP-AMP:
  - **ST** TSZ181IYLT
- Current sensor:
  - **Allegro** ACS37002LMABTR-050B5-M
  - **Allegro** ACS72981LLRATR-100B5
- Magnetic component:
  - **knitter-switch** ICSI15312700LVJ61
  - **knitter-switch** ICSI28175700LVK14
  - **knitter-switch** ICST75311000LVK61
  - **knitter-switch** ICSC30330600LVS2
  - **knitter-switch** ICSC64415600LHS61
  - **knitter-switch** ICST90211100SHSST61

Bidirectional Power Converter for ESS – DC/DC

- Parameter Design



$gmin := 0.656$

$Fmin := gmin \cdot fr = 131200$

Found the real gmin from the curve with Q=0.35 to see that is 0.656.
0.656 * fr = Fmin
so the minimum frequency should be = 131kHz

Parameters design

$Iomax := \frac{Pomax}{Vomin} = 55$ maximum output current

$RLmin := \left(\frac{Vomin}{Iomax}\right) = 1.091$ minimum output resistance

$fnmin := \frac{fsmin}{fr} = 0.5$ minimum fs/fr ratio

$fnmax := \frac{fsmax}{fr} = 2$ maximum fs/fr ratio

$Gmin\_assume := 0.85$ Assuming minimum voltage gain is 0.85, which is limited by the ratio of Lm/Lr

$n\_ratio\_cal := \frac{Vinmin \cdot Gmin\_assume}{Vomin} = 7.792$ Assuming minimum voltage gain is 0.75, which is limited by the ratio of Lm/Lr

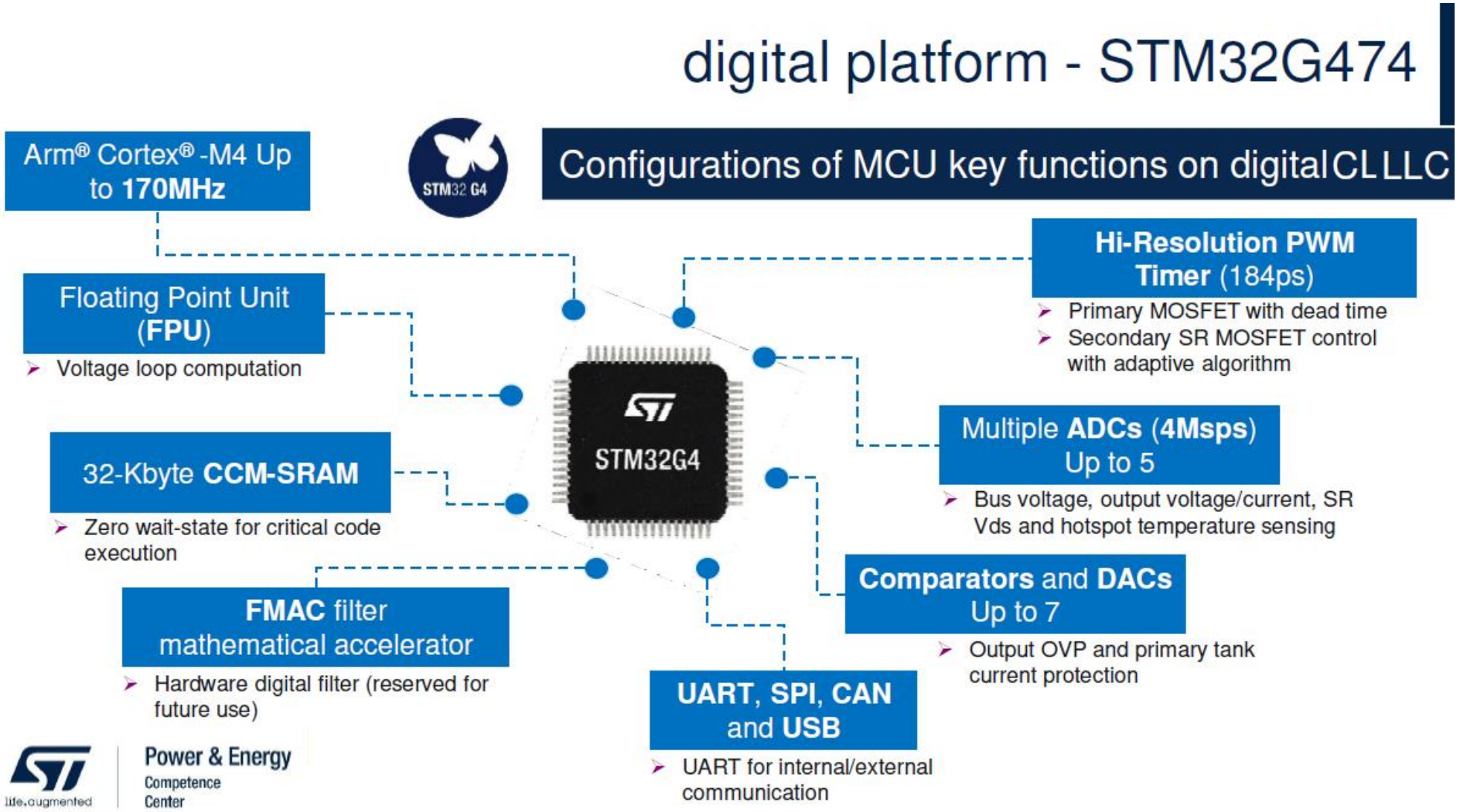
$n\_ratio := 7.5$ *** Manual set the n ratio

$Gmax := \frac{Vomax \cdot n\_ratio}{Vinmax} = 1.227$ Maximum gain

$Gmin := n\_ratio \cdot \frac{Vomin}{Vinmin} = 0.818$ Minimum gain

Bidirectional Power Converter for ESS – DC/DC

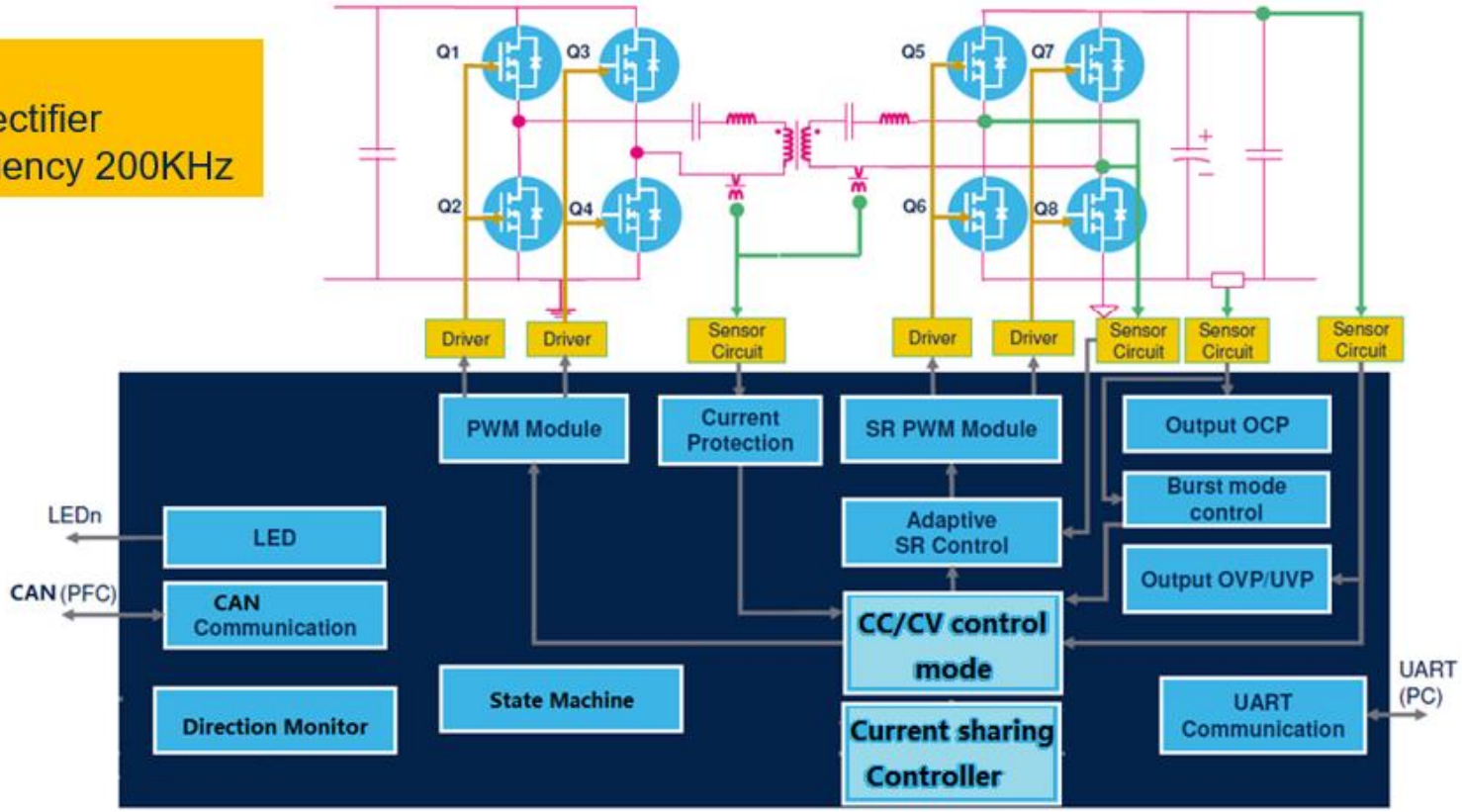
- MCU



Bidirectional Power Converter for ESS – DC/DC

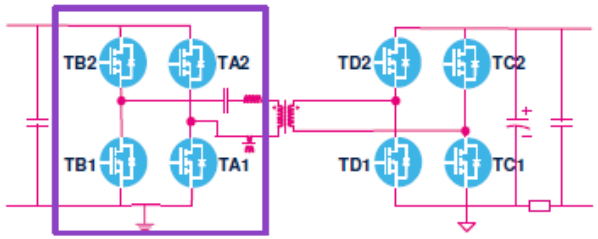
- functional block diagram

- Bidirectional
- Synchronous rectifier
- Resonant frequency 200KHz



Bidirectional Power Converter for ESS – DC/DC

- PWM configuration

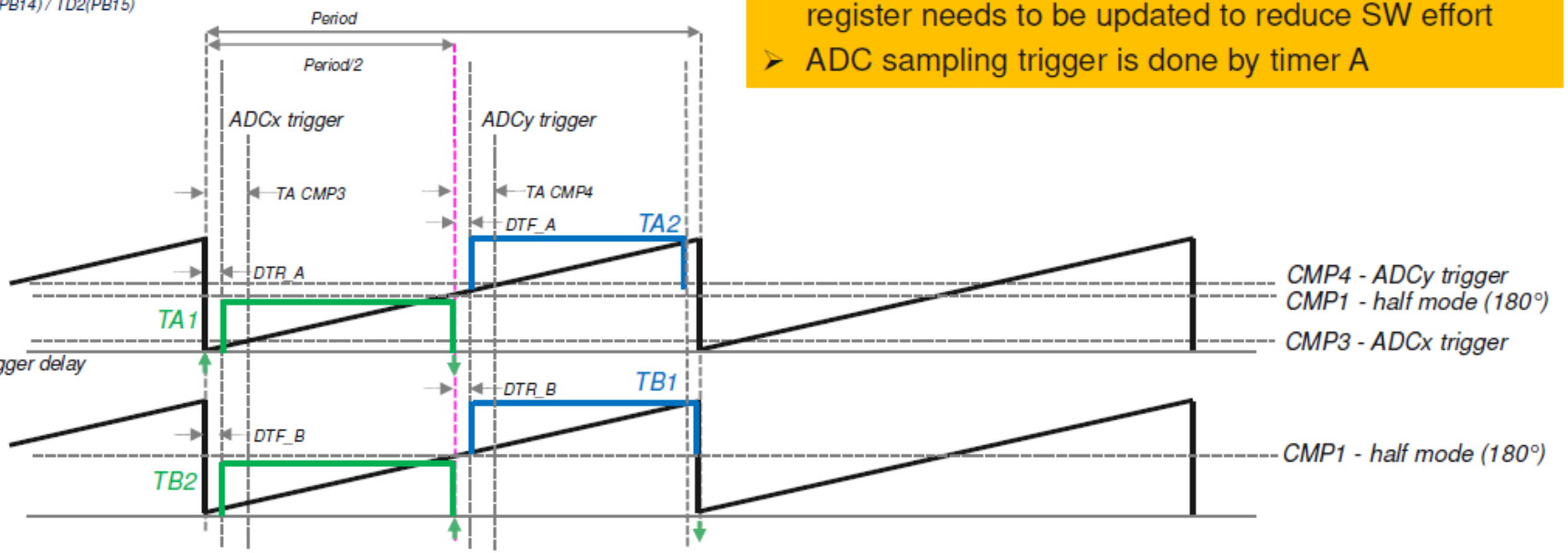


Primary side (Active) MOSFETs

Primary: TA1(PA8) / TA2(PA9) / TB1(PA10) / TB2(PA11)
Secondary: TC1(PB12) / TC2(PB13) / TD1(PB14) / TD2(PB15)

PWM configuration by using HRTIM

- Switches are driven two-by-two (TA1-TB2 and TB1-TA2) with 50 percent PWM duty cycle and an appropriate dead time
- By using powerful HRTIM (half mode), only PERIOD register needs to be updated to reduce SW effort
- ADC sampling trigger is done by timer A



Timer A

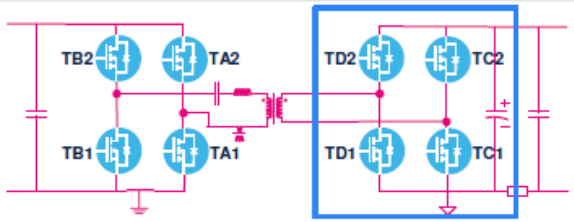
- *Half mode*
- *Dead time insertion enabled*
- *TA CMP3 = ADC trigger delay*
- *TA CMP4 = Period/2 + ADC trigger delay*

Timer B

- *Half mode*
- *Dead time insertion enabled*

Bidirectional Power Converter for ESS – DC/DC

- PWM configuration

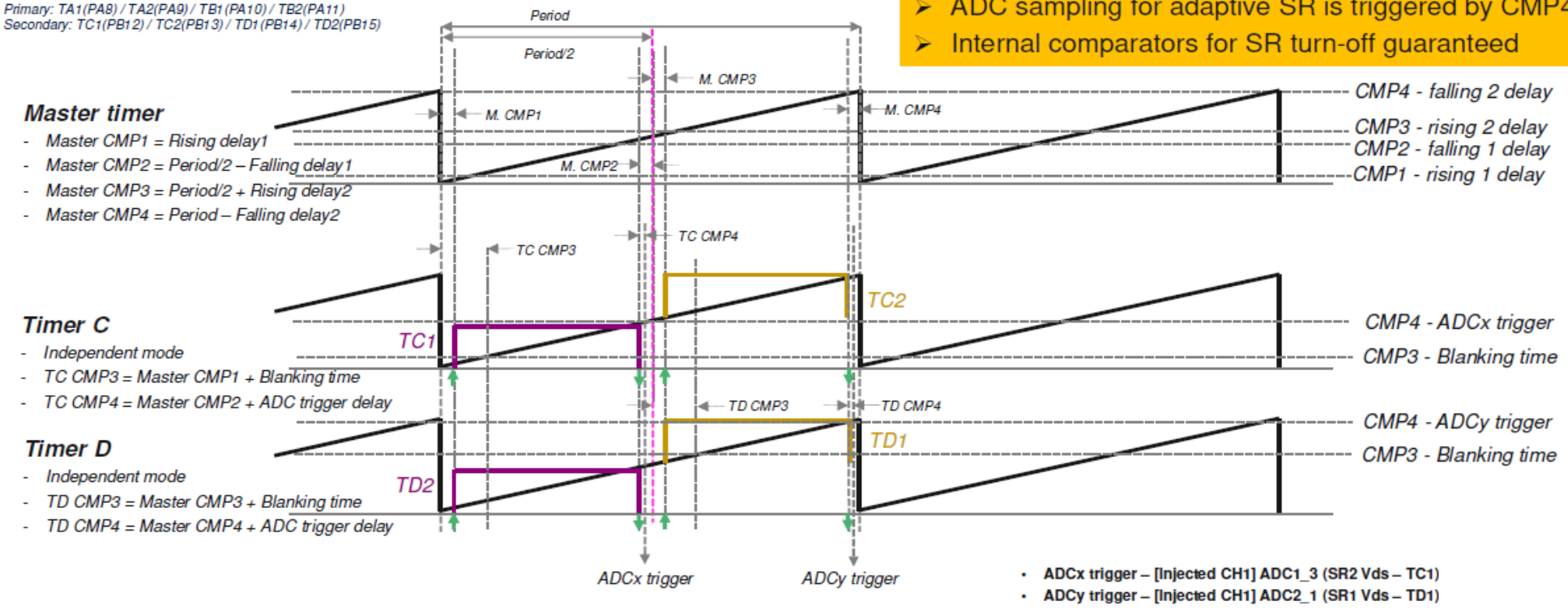


PWM configuration by using HRTIM

- The SR ON/OFF (set/reset) with dead time / adaptive algorithm are controlled by master timer
- Blanking time by CMP3 for avoiding false trigger
- ADC sampling for adaptive SR is triggered by CMP4
- Internal comparators for SR turn-off guaranteed

Secondary side (SR) MOSFETs

Primary: TA1(PA8) / TA2(PA9) / TB1 (PA10) / TB2(PA11)
Secondary: TC1(PB12) / TC2(PB13) / TD1 (PB14) / TD2(PB15)

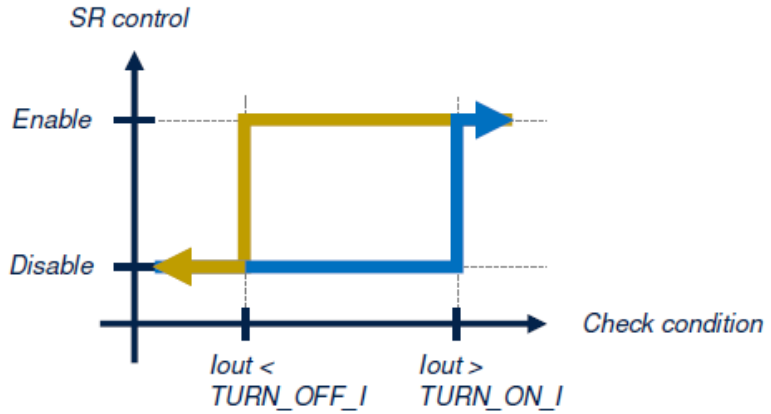


- **ADCx trigger – [Injected CH1] ADC1_3 (SR2 Vds – TC1)**
- **ADCy trigger – [Injected CH1] ADC2_1 (SR1 Vds – TD1)**

Bidirectional Power Converter for ESS – DC/DC

- SR Control

- SR enable/disable



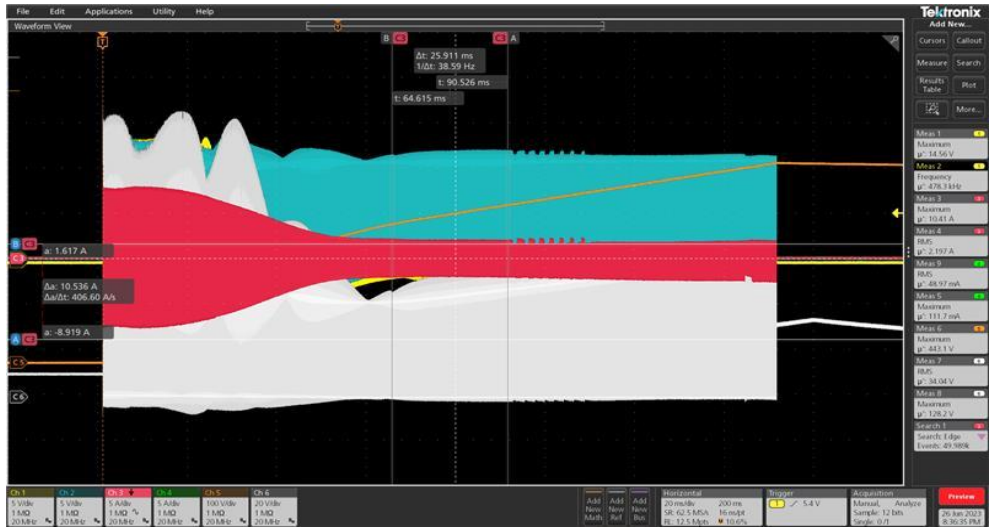
- **SR control**

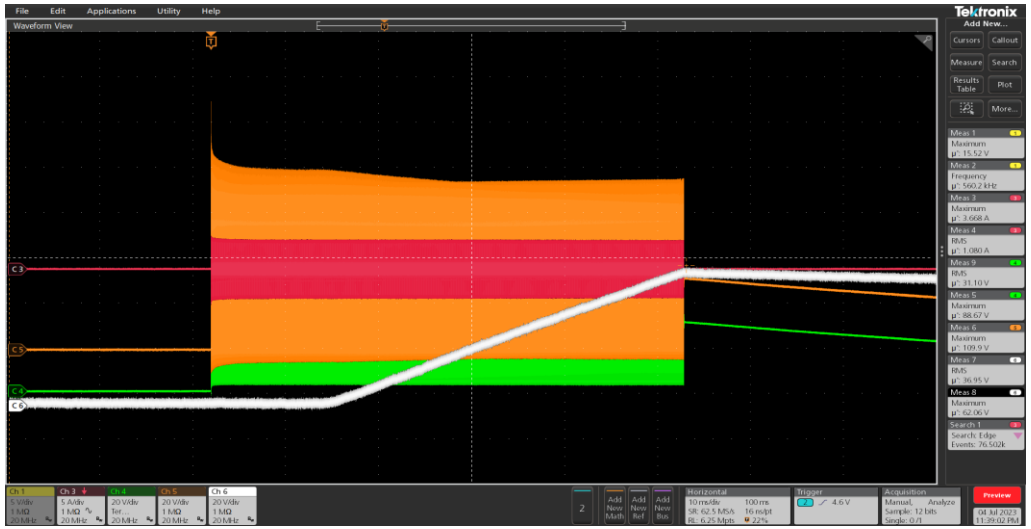
<= Fr: Fixed pulse width for SR

>Fr： Increased Deadtime

Bidirectional Power Converter for ESS – DC/DC

- Soft start





- Discharging startup Vds stress

Software :Step 1: 500kHz, duty from 10% to 15%; Step 2: 500kHz, duty=15% for 10ms.

Step 3: 500kHz, duty from 15% to 30%, 200ms. Step 4: 500kHz -> 300khz

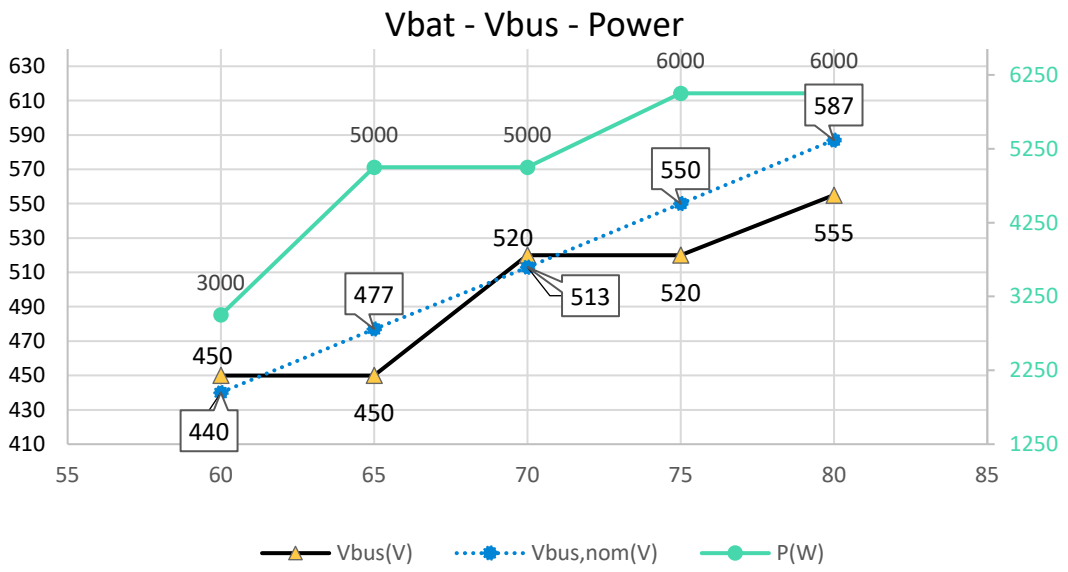
Note: a) Capacitors provides the nearest path for voltage spikes

b) The software method reduced the current of resonant current at start- up

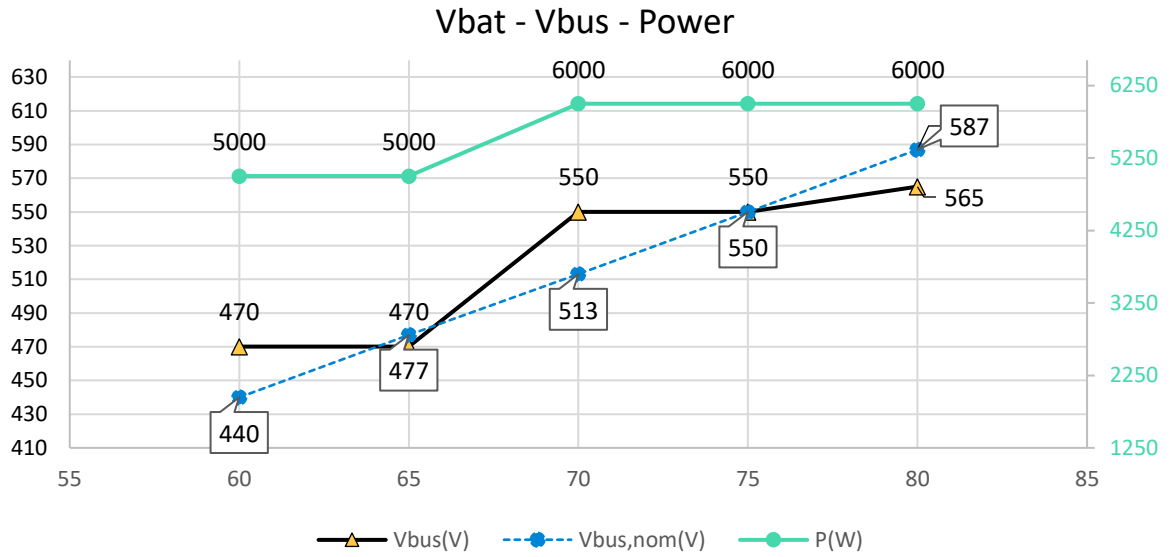
Bidirectional Power Converter for ESS – DC/DC

- Power load capacity test

■ Discharging mode



■ Charging mode

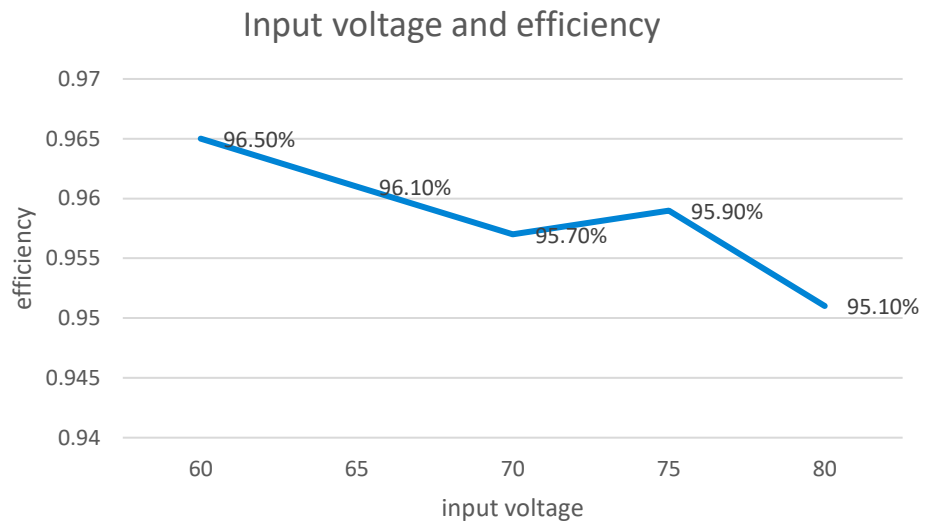


Note: For Discharging mode and charging mode, at low voltage input, the output power should be derated

Bidirectional Power Converter for ESS – DC/DC

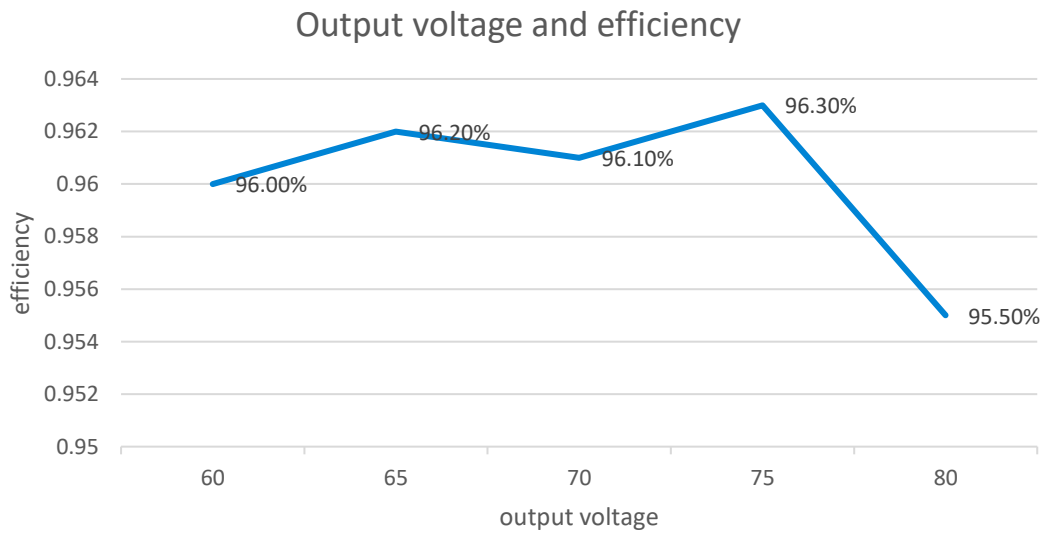
● Efficiency

■ Discharging mode at different input voltage



Discharging mode efficiency

■ Charging mode at different output voltage



Charging mode efficiency

Bidirectional Power Converter for ESS – DC/DC

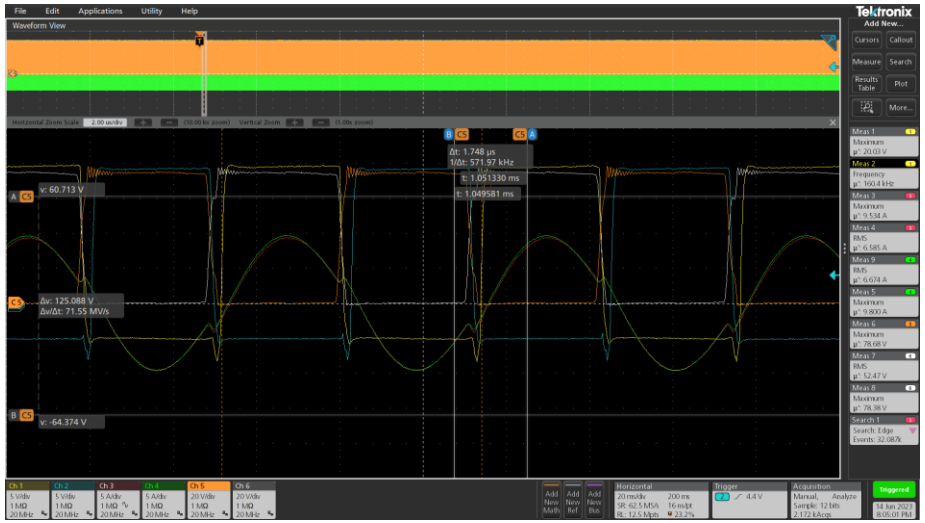
- **6.6kW bidirectional CLLLC can implement bidirectional charging mode and discharging mode. Already finished key items as following list:**

Mode	Items	Test results
Discharge	The voltage spike of MOS under different input voltage	$V_{spike\text{-}80V}$=124V
Discharge	Under different input voltage , Power load capacity test	Power derating
Discharge	Under different input voltage , Efficiency test	η_{max}=96.7%
Discharge	Current sharing test	ΔI_{max}=4.2A
Discharge	Thermal stress test(normal temperature)	T_{mosmax}=81°C
Charge	The voltage spike of MOS under different input voltage	$V_{spike\text{-}80V}$=100V
Charge	Under different input voltage , Power load capacity test	Power derating
Charge	Under different output voltage , Efficiency test	η_{max}=97.1%
Charge	Current sharing test	ΔI_{max}=3.5A

Bidirectional Power Converter for ESS – DC/DC

- **Charging mode**

测试条件	1、LLC2+LLC1闭环测试 2、Lm更该为200uH											
输出电流	输出电压	输入电压	输入电流	输出功率	输入功率	Ploss		LLC1-rms	LLC2-rms	fs	SR	ΔI
22.896	75.373	550.28	3.29	1725.74	1810.421	84.68099	95.32%	2.342	2.349	174	off	0.051333
26.696	75.432	550.24	3.83	2013.733	2107.419	93.68653	95.55%	2.632	2.626	170	off	-0.044
26.696	75.423	550.24	3.78	2013.492	2079.907	66.41479	96.81%	2.648	2.65		on	0.014667
40.096	75.434	550.21	5.66	3024.602	3114.189	89.58694	97.12%	3.546	3.593		on	0.344667
49.796	75.404	550.2	7.03	3754.818	3867.906	113.0884	97.08%	4.303	4.237	167.6	on	-0.484
53.396	75.393	550.2	7.54	4025.685	4148.508	122.8234	97.04%	4.505	4.566	166.6	on	0.447333
61.196	75.376	550.18	8.66	4612.71	4764.559	151.8491	96.81%	5.108	5.154	164.5	on	0.337333
66.896	75.366	550.18	9.47	5041.684	5210.205	168.5207	96.77%	5.564	5.582	163	on	0.132
73.696	75.357	550.17	10.45	5553.509	5749.277	195.767	96.59%	6.116	6.094	162	on	-0.16133
77.096	75.338	550.16	10.94	5808.258	6018.75	210.492	96.50%	6.401	6.342	161	on	-0.43267
80.396	75.331	550.16	11.42	6056.311	6282.827	226.5161	96.39%	6.677	6.591	160.4		-0.63067
83.096	75.318	550.16	11.81	6258.625	6497.39	238.7651	96.33%	6.899	6.782	160		-0.858



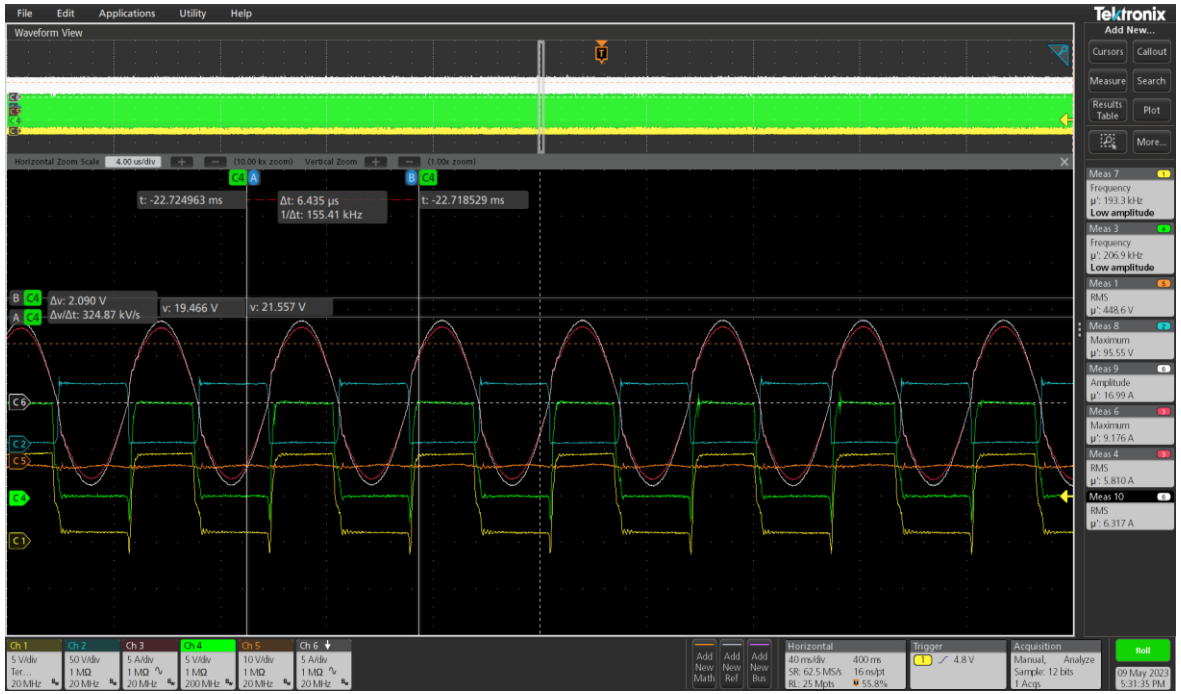
- **Discharging mode**

LLC2+LLC1	闭环测试	闭环测试	将LLC1的Lm更该为200uH									
输出电流	输出电压	输入电压	输入电流	输出功率	输入功率	Ploss		LLC1-rms	LLC2-rms	fs	SR	ΔI
2.505	449.37	60.014	20.09	1125.67	1205.68	80.0094	93.36%	1.447	1.892	152	off	3.26333
3.005	449.24	59.978	23.99	1349.97	1438.87	88.906	93.82%	1.702	2.231	145	off	3.87933
3.216	449.29	59.964	25.61	1444.92	1535.68	90.7614	94.09%	1.824	2.36	142	off	3.93067
3.216	449.29	59.968	25.4	1444.92	1523.19	78.2706	94.86%	1.992	2.196	167	on	1.496
3.516	449.32	59.945	27.71	1579.81	1661.08	81.2668	95.11%	2.13	2.4	162	on	1.98
4.015	449.11	59.913	31.52	1803.18	1888.46	85.2811	95.48%	2.358	2.778	156	on	3.08
4.516	448.89	59.881	35.31	2027.19	2114.4	87.2109	95.88%	2.56	3.188	148	on	4.60533
5.006	448.84	59.848	39.13	2246.89	2341.85	94.9592	95.95%	2.82	3.49	142	on	4.91333
5.615	448.32	59.804	43.91	2517.32	2625.99	108.677	95.86%	3.2	3.86	138	on	4.84
6.736	446.91	59.729	52.67	3010.39	3145.93	135.541	95.69%	3.92	4.56	135	on	4.69333

Bidirectional Power Converter for ESS – DC/DC

- **The current waveform of resonant tank**

Input 60V, output 450V



Input 65V, output 450V

Bidirectional Power Converter for ESS – DC/DC

- **Challenges**

description	Solution	Effect
Discharging mode, the low side MOS Vds stress at the steady-state operate and no load situation	the primary inductance of transformer increase to 200uH.	Voltage stress decreased 25%,and efficiency increase 6%~7%
Discharging mode, Vds stress issue at startup	PWM + PFM hybrid control +C@DS+C@input port	Voltage stress decreased 27%, Vmax=124V@80V
Discharging mode, excessive temperature of resonant capacitor(96°C@2100W)	The model changed to mkp21224/400VDC	Temperature of resonant capacitor 65°C@3000W
Discharging mode , the working frequency suddenly changes near 180kHz, and the gain curve is not monotonic.	SRMOS fixed turn-on time frequency point below180 kHz	Gain curve is monotonic
Charging mode ,working state is asymmetry in positive and negative half-cycle	changed MOS model	Working state is the same


Thank you!