22 kW power converter demonstration system for bidirectional DC EV chargers

About this document

Scope and purpose

This user guide describes the 22 kW power converter demonstration system REF-EV22KIZSICSYS, which provides a pre-developed design solution proposal for applications with bidirectional power flow, such as DC electric vehicle (EV) chargers or energy storage systems. It combines a 3-phase, active front-end (AFE) converter with a 3-phase, dual active bridge (DAB) converter and uses a broad range of Infineon products.

Intended audience

This document is meant to support engineers who want to design their own bidirectional DC EV charger product, for example a 22 kW DC wallbox. Providing a design example for the usage and combination of, for example, 1200 V and 1700 V CoolSiC™ MOSFETs with EiceDRIVER™ driver ICs in such a challenging application shall reduce development times and efforts at our customers.

Hardware demonstration system

This demonstration system is not a qualified and certified commercial product. It is intended for evaluation purposes only within a controlled laboratory environment and does not fully comply with all requirements of the EV charging standard IEC 61851-23, which is designed for end product level compliance.

The printed circuit boards (PCBs) of the system do not necessarily meet any safety, EMI, or quality standard (for example, UL, CE) requirements.

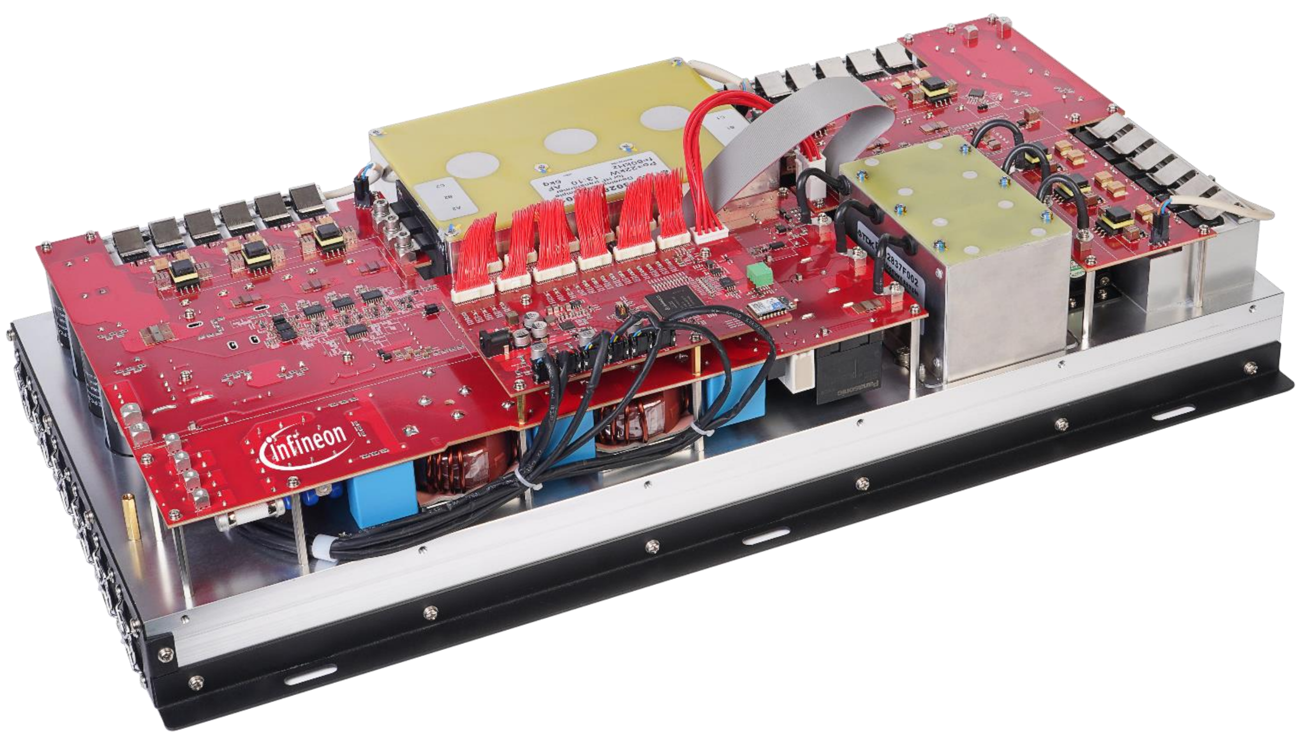

Figure 1 22 kW power converter demonstration system for bidirectional DC EV chargers

Please read the "Important notice" and "Safety precautions" of this document

Important notice

"Evaluation Boards and Reference Boards" shall mean products embedded on a printed circuit board (PCB) for demonstration and/or evaluation purposes, which include, without limitation, demonstration, reference and evaluation boards, kits and design (collectively referred to as "Reference Board").

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Safety precautions

Please note the limited scope of operation and specific environmental constraints associated with this hardware demonstrator:

1. **Operational Limitation**: The hardware demonstration system is designed for demonstration and evaluation purposes only within a laboratory setting and is not intended for deployment in real-world applications or environments.
2. **Controlled Environment**: The operation of this hardware demonstration system is restricted to a controlled laboratory environment with regulated parameters for humidity, dust levels, altitude, and temperature, as outlined below:
    - *Humidity*: Maintained within the operation in controlled lab environment to ensure optimal performance and prevent moisture-related issues.
    - *Dust Level*: Compliant with electrical laboratory environment, minimizing the risk of contamination and equipment damage.
    - *Altitude*: Operated within the laboratory's specific elevation parameters, considering potential impacts on dielectric strength and equipment performance.
    - *Temperature*: Controlled within the range of typical electrical workshop environment to maintain stable operating conditions for the hardware demonstrator.

Please note the following warnings regarding the hazards associated with development systems:

Table 1 Safety precautions

	Warning: *The DC link potential of this demonstration system is up to 1000 VDC. When measuring voltage waveforms by oscilloscope, high voltage differential probes must be used. Failure to do so may result in personal injury or death.*
	Warning: *This demonstration system contains DC bus capacitors which take time to discharge after removal of the main supply. Before working on the system, wait five minutes for capacitors to discharge to safe voltage levels. Failure to do so may result in personal injury or death. Darkened display LEDs are not an indication that capacitors have discharged to safe voltage levels.*
	Warning: *The demonstration system is connected to the grid input during testing. Hence, high-voltage differential probes must be used when measuring voltage waveforms by oscilloscope. Failure to do so may result in personal injury or death. Darkened display LEDs are not an indication that capacitors have discharged to safe voltage levels.*
	Warning: *Remove or disconnect power from the system before you disconnect or reconnect wires, or perform maintenance work. Wait five minutes after removing power to discharge the bus capacitors. Do not attempt to service the system until the bus capacitors have discharged to zero. Failure to do so may result in personal injury or death.*
	Caution: *The heat sink and device surfaces of the demonstration system may become hot during testing. Hence, necessary precautions are required while handling the hardware. Failure to comply may cause injury.*
	Caution: *Only personnel familiar with the hardware, power electronics and associated machinery should plan, install, commission and subsequently service the system. Failure to comply may result in personal injury and/or equipment damage.*
	Caution: *The demonstration system contains parts and assemblies sensitive to electrostatic discharge (ESD). Electrostatic control precautions are required when installing, testing, servicing or repairing the assembly. Component damage may result if ESD control procedures are not followed. If you are not familiar with electrostatic control procedures, refer to the applicable ESD protection handbooks and guidelines.*
	Caution: *A system that is incorrectly applied or installed can lead to component damage or reduction in product lifetime. Wiring or application errors such as supplying an incorrect or inadequate AC supply or excessive ambient temperatures may result in system malfunction.*
	Caution: *The demonstration system is shipped with packing materials that need to be removed prior to installation. Failure to remove all packing materials that are unnecessary for system installation may result in overheating or abnormal operating conditions.*

Table of contents

1 The system at a glance

This power converter demonstration system consists of a 3-phase, active front-end (AFE) converter and a 3-phase, dual active bridge (DAB) converter. It has been tested intensively at Infineon, which is the basis for the specification and measurement results mentioned in this document.

PCB design files and hardware of the power converter is available on demand, but not the lab software which was used for the internal measurements.

The combination of 1200 V CoolSiC™ MOSFETs in a TO247-4 package with best-fitting EiceDRIVER™ 1ED compact gate driver ICs unleashes the advantages of SiC technology, such as high power conversion efficiency in both energy flow directions, lower component part count, and enhanced system reliability.

The AURIX™ TC3xx platform meets the requirements of the most demanding embedded control system applications like DC EV charging, where competing issues of price/performance, real-time responsiveness, computational power, data bandwidth, and power consumption are key design elements.

The integration of even more Infineon products and technologies such as voltage regulators, XENSIV™ current sensors, memory and communication chips helps to develop a cost-effective power converter design with high reliability in a short time.

Figures 2 - 5 show the placement of the main components on the individual boards of the demonstration system.

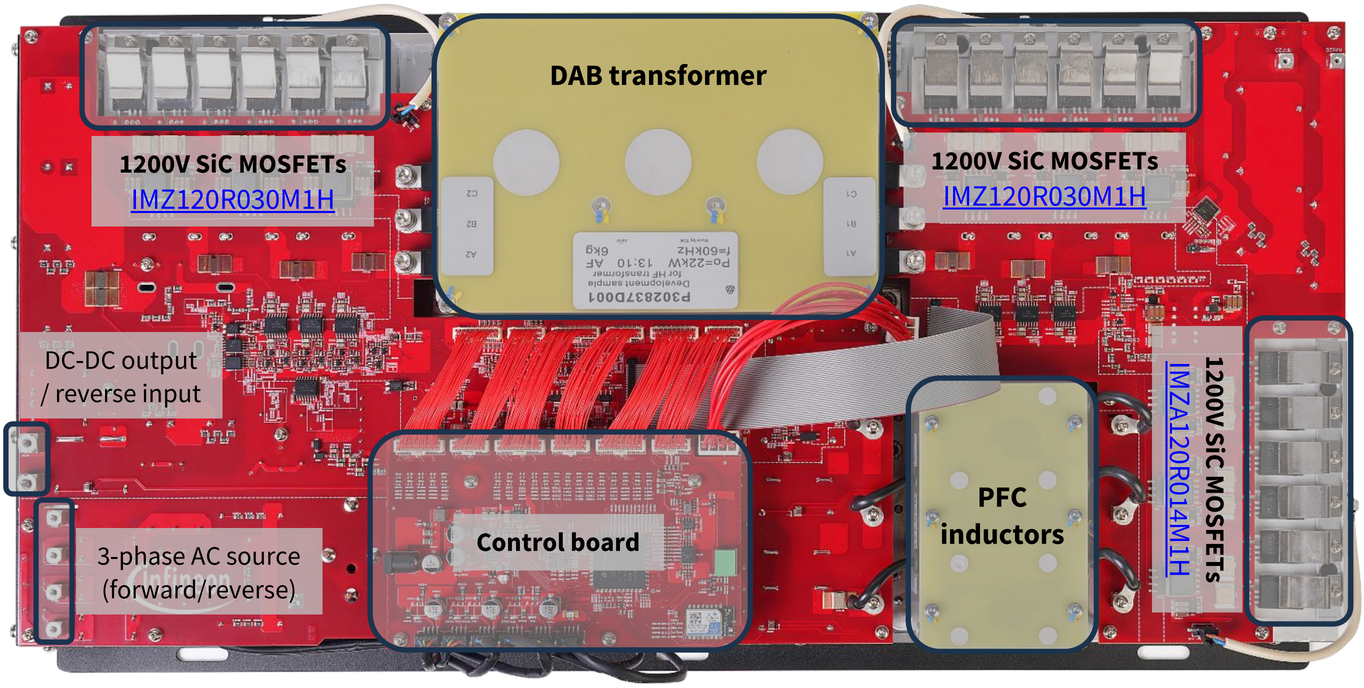


Figure 2 Power conversion board (top view)

The system at a glance

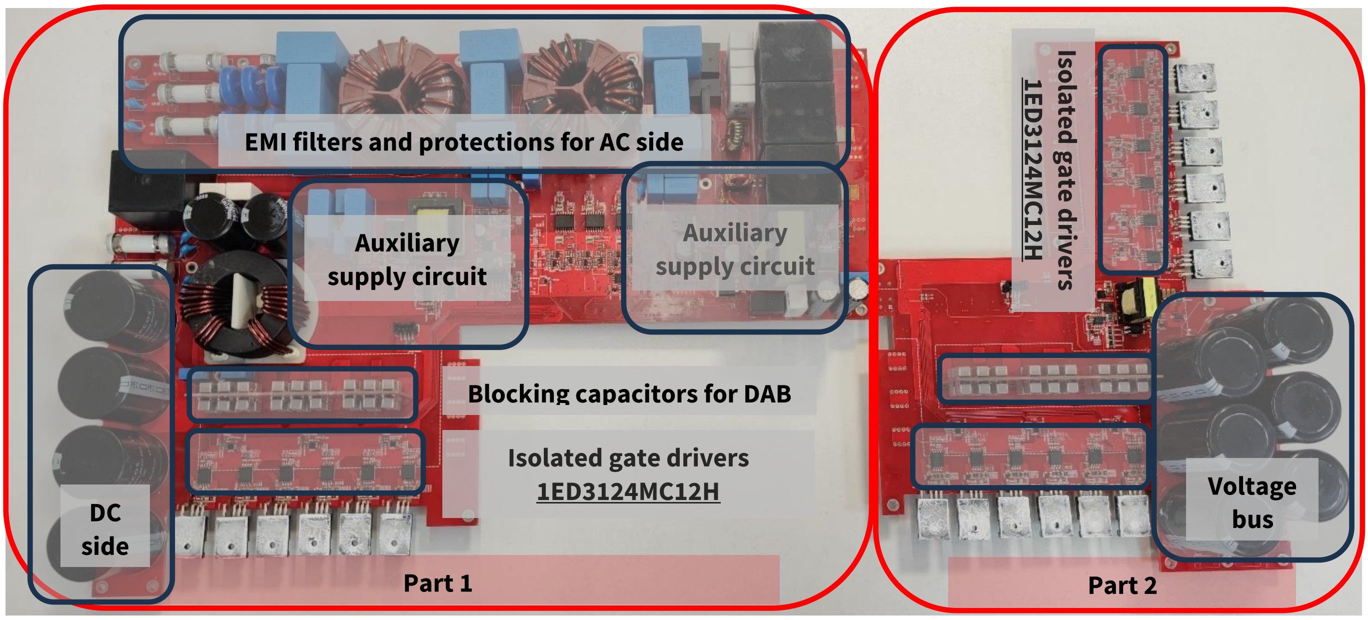


Figure 3 Power conversion board (bottom view)

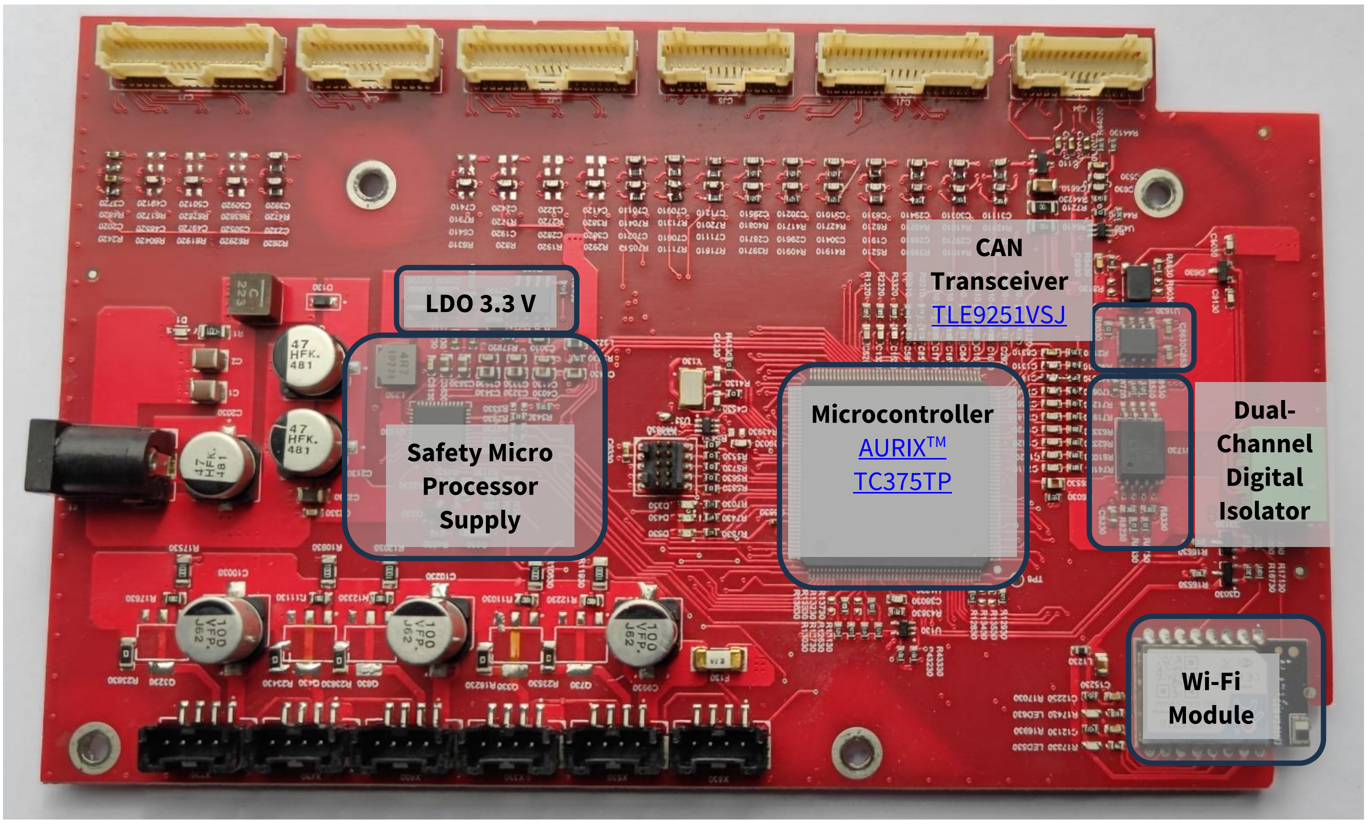


Figure 4 Power control board (top view)

The system at a glance

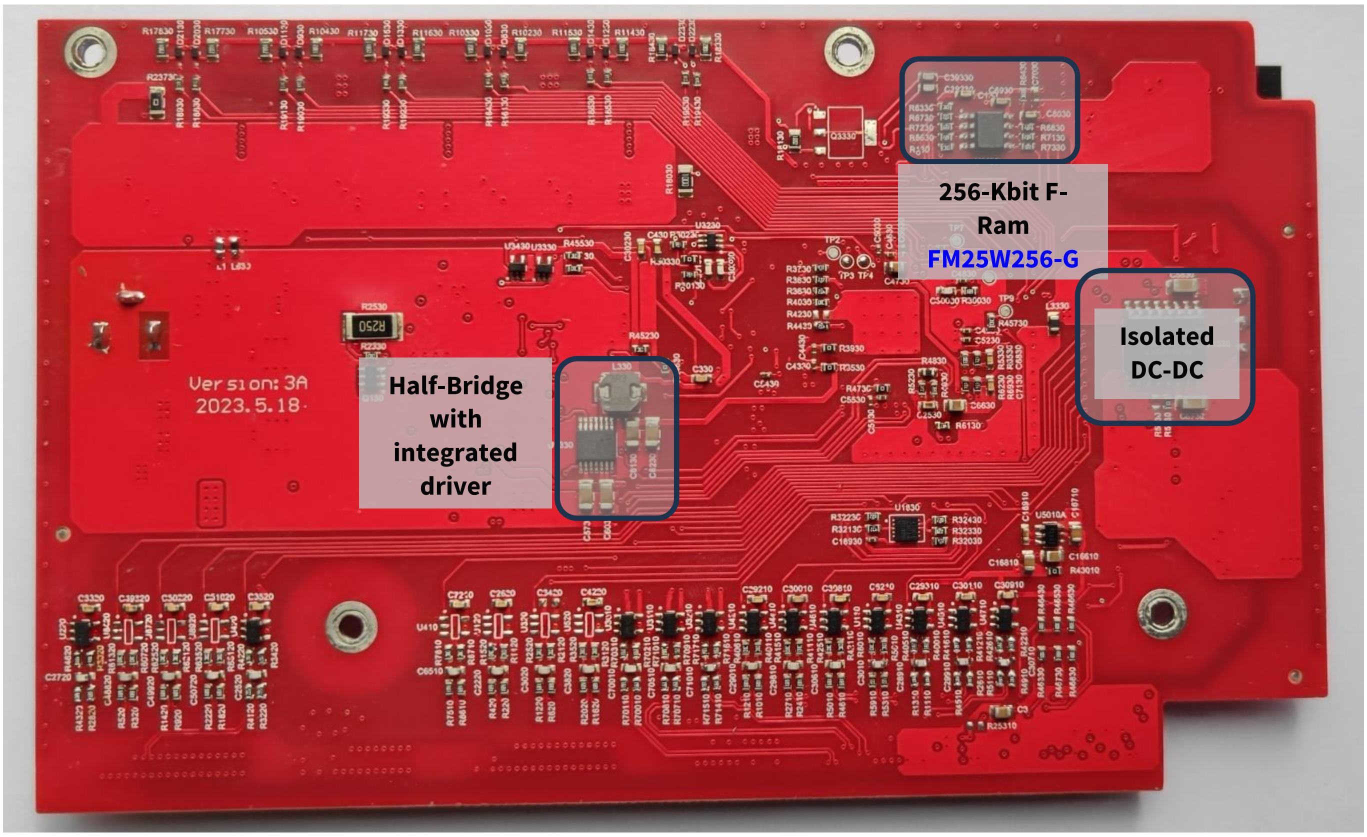


Figure 5 Power control board (bottom view)

1.1 Key Infineon products

This demonstration system uses the following Infineon products:

Main power conversion board:

- 1200 V CoolSiC™ discrete MOSFETs – IMZ120R030M1H/ IMZA120R014M1H
- 1200 V EiceDRIVER™ single-channel, isolated gate driver IC in a wide body package –1ED3124MC12H
- XENSIV™ high-precision, coreless current sensors for industrial applications – TLI4971

Auxiliary power supply:

- 1700 V CoolSiC™ MOSFET discrete – IMBF170R1K0M1
- PWM-QR (quasi resonant) flyback controller ICs – ICE5QSAG
- Step-down (buck) switching voltage regulator – IFX91041EJV50

Power control board:

- Infineon microcontroller with three CPU cores – AURIX™ TC375TP
- High-speed CAN transceiver generation – TLE9251VSJ
- 256 KB (32K × 8) serial (SPI) F-RAM - FM25W256-G

More information about these products is available on their individual pages at www.infineon.com.

1.2 Block diagram

The functional block diagram of the 22 kW power converter demonstration system is shown in Figure 6.

A B6, full-bridge rectifier is used as the active power-factor corrector (PFC) for the AC-DC power stage.

The DC-DC power stage is realized by a 3-phase DAB converter to transfer high power with high efficiency. Furthermore, the 3-phase DAB is capable of bidirectional power flow and a wide voltage regulation range.

Thanks to the discrete 1200 V SiC MOSFETs, the AC-DC and DC-DC power conversion stages are very compact and highly efficient.

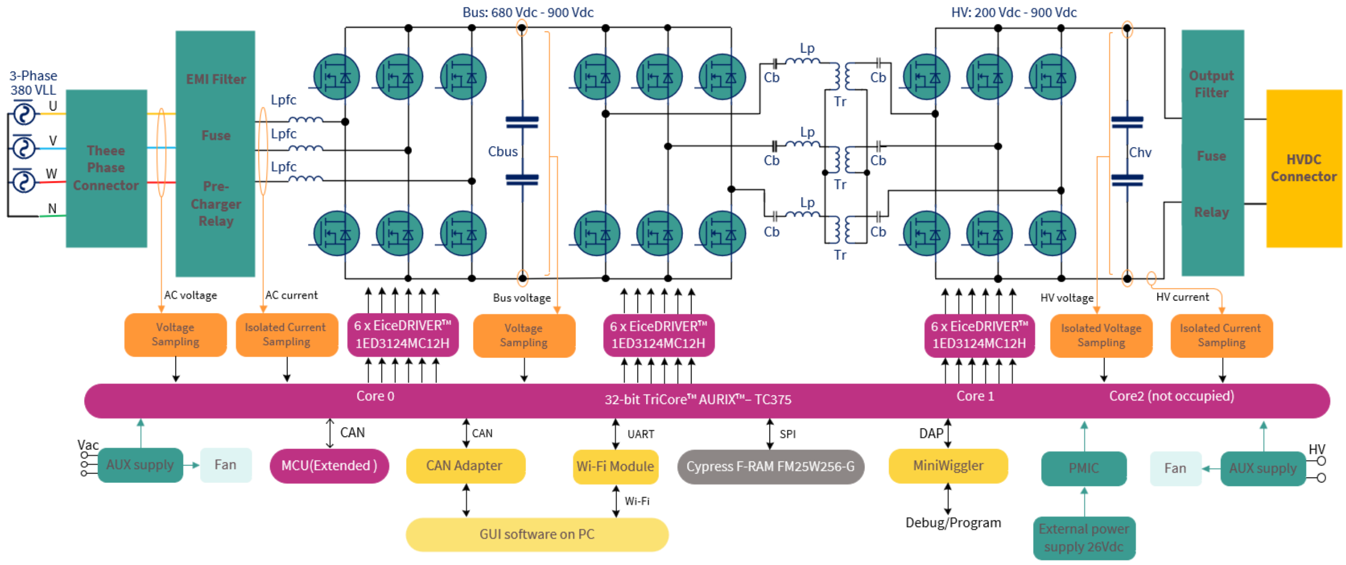


Figure 6 Functional block diagram

Figure 7 shows the mechanical block diagram. Here, the power board consists of two parts that are connected to each other through the 3-phase DAB transformer, the PFC inductor, and two signal cables. The control board communicates with the power boards via six signal cables. Furthermore, the control board supplies and controls six fans.

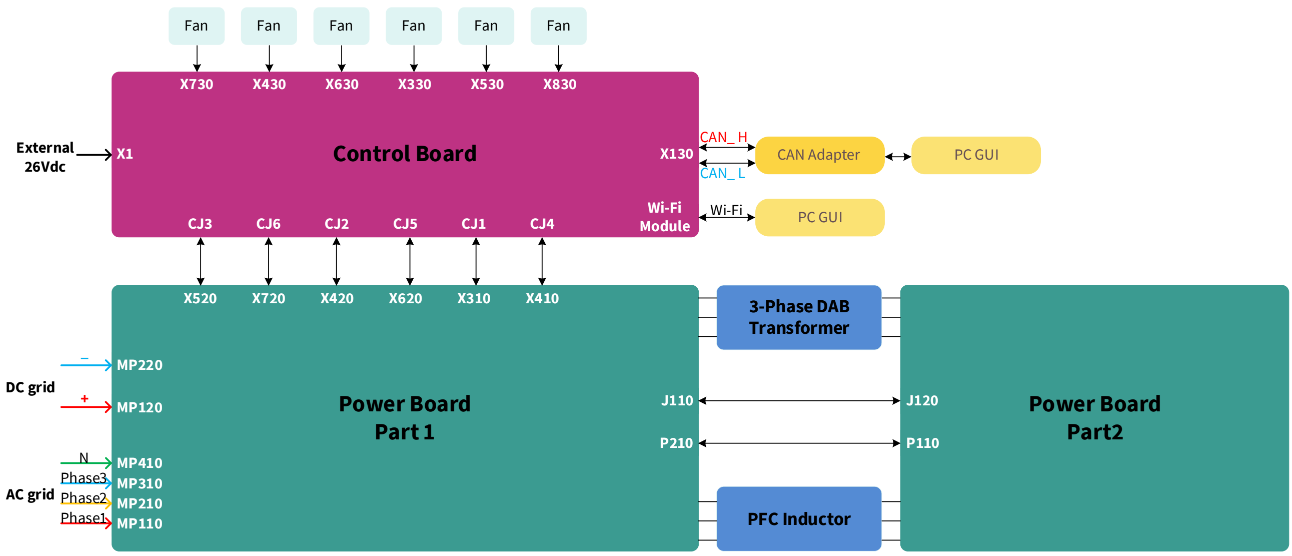


Figure 7 Mechanical block diagram

1.3 Main features

The main power circuits are implemented based on 1200 V CoolSiC™ MOSFETs to increase the efficiency of the system and to achieve a compact design.

The AC-DC converter comes with a low total harmonic distortion (THD) and a power factor close to 1 in both power flow directions. The 3-phase DAB DC-DC converter provides galvanic isolation, highly efficient bidirectional power flow, and wide output voltage range. The isolation level of the 3-phase DAB transformer is 3000 V AC. Using intelligent, digitally controlled algorithms are utilized to regulate output voltage and control bidirectional power flows.

The power control system of the demonstration system uses an Infineon AURIX™ TC375TP microcontroller. The AURIX™ TC3xx platform is a family of high-performance microcontrollers with multiple TriCore™ CPUs, program and data memories, buses, bus arbitration, interrupt system, DMA controller, and a powerful set of on-chip peripherals.

1.4 System parameters and technical data

Table 2 and Table 3 show the specifications of the demonstration system in forward and reverse mode, respectively, based on measurements at Infineon.

Table 2 Specification of the 22 kW power converter demonstration system in forward mode

Item	Parameter	Symbol	Min.	Typ.	Max.	Unit
AC side (Input)	Line voltage	V_{line}		380		V
	Phase current	I_{phase}		35		A
	Line frequency	f_{line}		50		Hz
	Power factor	cosθ		≥0.95		
	Total harmonic distortion (Tested at V_{line} = 380 V AC, V_{DC} = 530 V, P = 22 kW)	THD		3	5	%
	Switching frequency	f_{sw}		40		kHz
DC side (Output)	DC voltage (standard mode)	V_{DC}	200	530	750	V
	DC voltage (high voltage mode)	V_{DC}	500	700	900	V
	DC current	I_{DC}			50	A
	Power	P			22	kW
	Switching frequency	f_{sw}		60		kHz
Other	Cooling		Forced air			
	Size	L x W x T	650 x 290 × 140			mm
	Efficiency (Tested at V_{line} = 380 V AC, V_{DC} = 530 V, P = 22 kW)	η		96		%

Table 3 Specification of the 22 kW power converter demonstration system in reverse mode

Item	Parameter	Symbol	Min.	Typ.	Max.	Unit
DC side (Input)	DC voltage	V_{DC}		530		V
	DC current	I_{DC}			22	A
	Switching frequency	f_{sw}		60		kHz
AC side (Output)	Line voltage	V_{line}		380		Vac
	Phase current	I_{phase}			17.5	A
	Power	P			11	kVA
	Power factor	cosθ		≥0.95		
	THD (Tested at V_{line} = 380 V AC, V_{DC} = 530 V, P = 11 kVA)	THD		7		%
	Switching frequency	f_{sw}		40		kHz
Other	Cooling	Forced air				
	Module size	L x W x T	650 x 290 × 140			mm
	Efficiency	η		96		%

The system at a glance

Item	Parameter	Symbol	Min.	Typ.	Max.	Unit
DC side (Input)	DC voltage	V_{DC}		530		V
	DC current	I_{DC}			22	A
	Switching frequency	f_{sw}		60		kHz
AC side (Output)	Line voltage	V_{line}		380		Vac
	Phase current	I_{phase}			17.5	A
	Power	P			11	kVA
	Power factor	cosθ		≥0.95		
	THD (Tested at V_{line} = 380 V AC, V_{DC} = 530 V, P = 11 kVA)	THD		7		%
	Switching frequency	f_{sw}		40		kHz
	(Tested at V_{line} = 380 V AC, V_{DC} = 530 V, P = 11 kVA)					

Output power and current of the demonstration system are limited to 22 kW and 50 A, respectively, due to limitations of the selected components. Therefore, with an increase or decrease in the DC voltage, the power of the converter decreases.

Figure 8 shows the maximum operating power versus voltage of the DC side in standard and high voltage modes. To optimize efficiency, voltage of the DC bus (V_{BUS}) between the AC-DC and DC-DC stages was varied and depends on the voltage of the DC side, as shown in Figure 9. The difference between standard and high voltage modes is the modulation technique of the DAB converter. Symmetric and complementary PWMs are utilized, respectively, in the standard and the high voltage mode. To extend the high voltage range, the complementary PWM allows for a voltage boost in the DC voltage. However, that increases power losses due to the high current stress in the MOSFETs. The maximum power of the converter, therefore, is limited in the high voltage mode to avoid overheating the power devices.

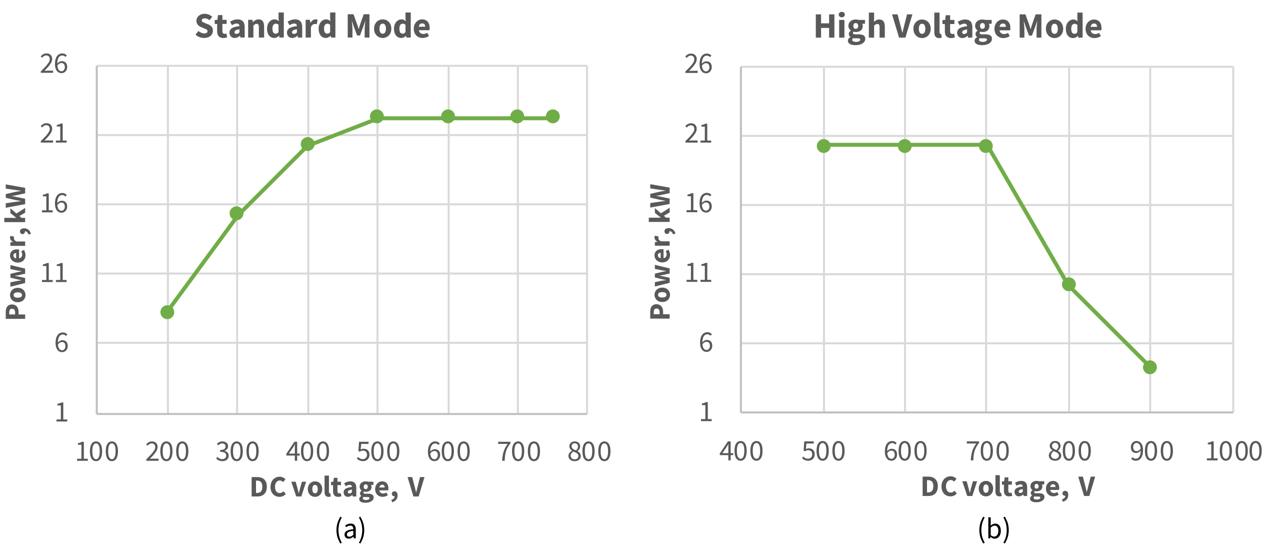
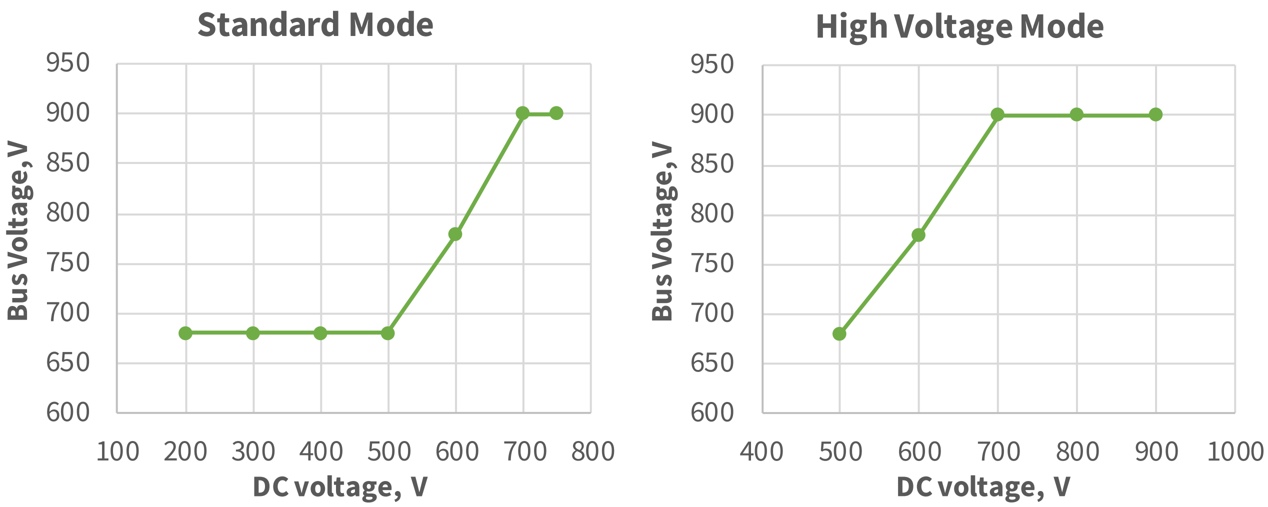


Figure 8 **Maximum power versus voltage of the DC side in (a) standard and (b) high voltage mode**

The system at a glance



(a) (b)

Figure 9 **Bus voltage versus voltage of the DC side in (a) standard and (b) high voltage mode**

The control system of the converter includes various protections, as listed in Table 4.

Table 4 **Protection levels in the control system**

Item	Parameter	Value	Recovery value	Unit
AC side	Over-phase voltage	275	268	V
	Under-phase voltage	140	147	V
	Phase current	45		A
	Line frequency	< 45 or > 65		Hz
	Imbalance voltage	±15%	±10%	
DC side	Over-DC voltage (forward mode)	990	970	V
	Over-DC voltage (inverse mode)	690	670	V
	Under-DC voltage (forward, standard mode)	150		
	Under-DC voltage (forward, High voltage mode)	450		
	Under-DC voltage (reverse mode)	510		
	DC current (forward mode)	80	79	A
	DC current (reverse mode)	-80	-79	A
DC Bus	Overvoltage	1050	840	V
Temperature	Over-temperature: PCB, MOSFETs, ambient	110	100	°C

2 System and functional description

2.1 Getting started

2.1.1 Setting up the hardware

For testing the 22 kW power converter demonstration system, the following equipment is recommended:

- Bidirectional, 3-phase AC power supply (400 V, > 24 kVA)
- Bidirectional DC power supply (1000 V, > 24 kW) or DC load for forward mode and unidirectional DC power supply for inverse mode
- Auxiliary power supply (26 V/2 A)
- Oscilloscope with voltage and current probes

Connecting to the demonstration system

1. Connect the power board to a 3-phase AC power supply and a DC power supply (or the DC load) using the cables and terminals on the power board (see Figure 10).
2. Connect a protective earth (PE).
3. Connect the external auxiliary power supply (26 V/2 A) to the control board using the connector as shown in Figure 11.

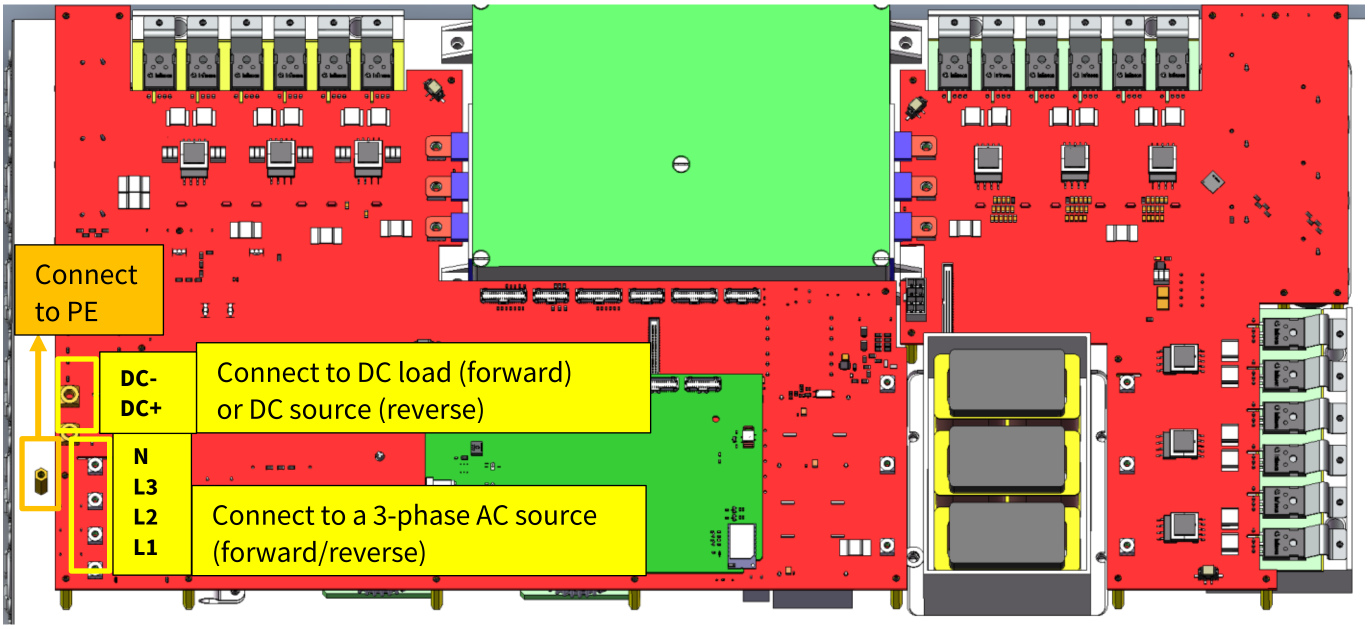


Figure 10 Power board setup

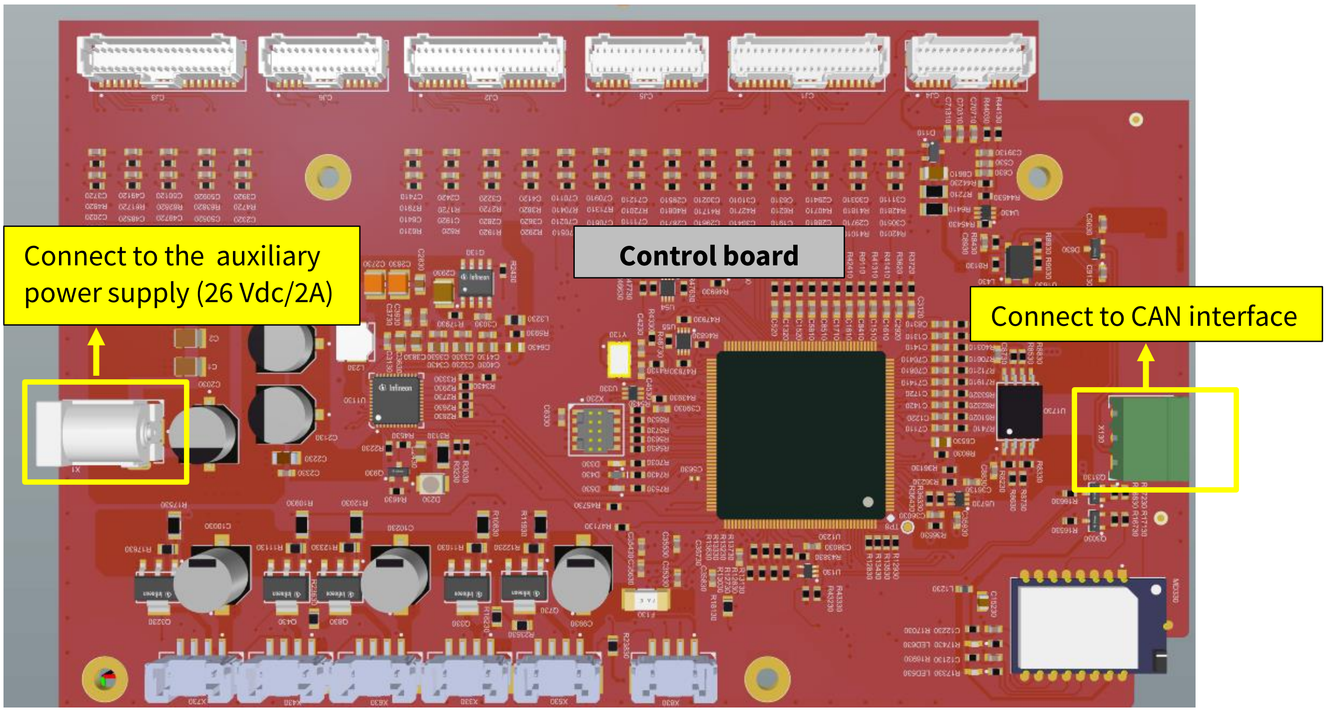


Figure 11 **Control board setup**

Note: *Exercise caution during operation when the unit is connected to the grid, to avoid potential electrical hazards.*

2.1.2 Options to connect with the control board

Users can connect their personal computer with the control system based on the AURIX™ TC375TP microcontroller through a Wi-Fi module or CAN interface.

For using the CAN interface, an additional USB-CAN converter is required.

2.2 Description of functional blocks

2.2.1 Active front-end AC-DC converter

In the demonstration system, conventional B6 inverter topology is used for the active front-end AC-DC converter. The AC-DC was operated as a boost circuit; therefore, it was able to raise and regulate voltage of the DC bus in the range of 680 V to 900 V to optimize performance. The AC-DC converter also was forming a sinusoidal current in the grid with a constant switching frequency. At the same time, the 3-phase inductor and EMI filter reduce the high-frequency current ripple.

A sinusoidal modulation has been considered for better closed loop control and reduction in harmonics, which improves the total harmonic distortion (THD).

2.2.2 The 3-phase DAB converter

A 3-phase, dual active bridge (DAB) converter is used for the DC-DC stage of the demonstration system. It provides bidirectional power flow capability, galvanic isolation, and regulates the output DC voltage in the forward mode and the DC current in both modes. The DAB is based on 1200 V CoolSiC™ MOSFETs and a 3-phase planar transformer. In addition, the DAB has blocking capacitors on both sides of the transformer to avoid DC bias current in the transformer.

2.2.3 Auxiliary supply circuit

The auxiliary supply circuit of the demonstration system uses a 1700 V CoolSiC™ MOSFET and a PWM-QR flyback controller ICE5QSAG in a single-ended flyback topology. It provides an output voltage of 24 V with up to 32 W of power supply to all components of the demonstration system. The auxiliary power circuit is connected to the HV DC side; therefore, it operates in a wide input voltage range from 200 V to 900 V. This guarantees a stable operation.

A flyback converter is the most typical topology for a low-power supply, such as an auxiliary supply. However, the flyback converter features high voltage stress on a switching device that requires a semiconductor device with a high blocking voltage. The IMBF170R1K0M1 1700 V CoolSiC™ MOSFET from Infineon is an excellent choice for high input voltage of up to 1000 V (see Figure 13). Compared to 1500 V silicon MOSFETs, the 1700 V CoolSiC™ MOSFET has a low on-state resistance ($R_{DS(on)}$) and low output capacitance (C_{OSS}), which result in low power losses. TO-263-7L is a compact surface-mounted device (SMD) package with a 7 millimeter (mm) wide creepage distance between the drain and the source. Therefore, safety standards are easily met. More information about the auxiliary supply circuit can be found in another Infineon reference design [2].

System and functional description

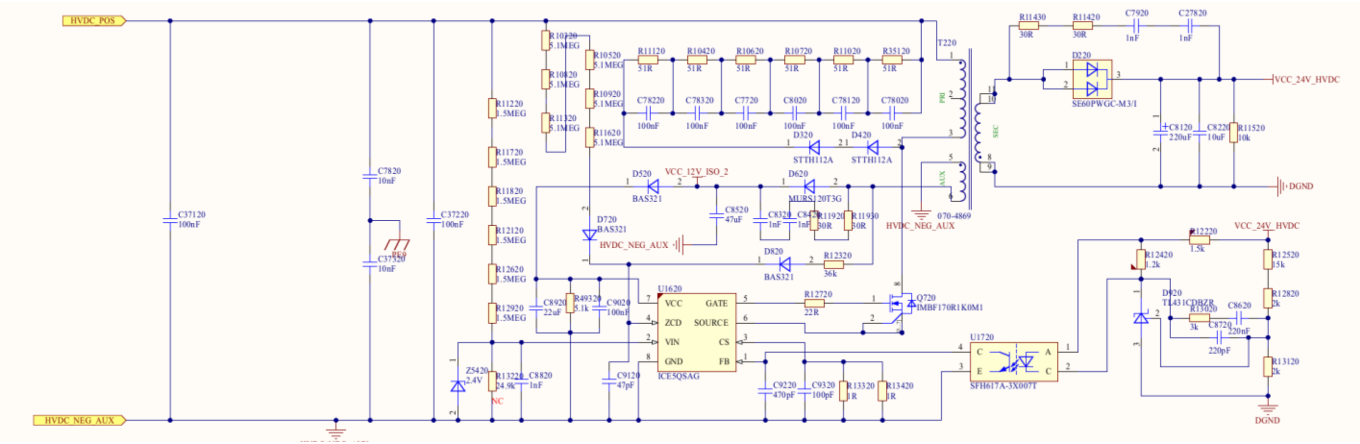


Figure 12 **Schematic of the auxiliary supply circuit**

Figure 13 **1700 V CoolSiC™ MOSFET**

The PWM-QR flyback controller (see Figure 14) helps the flyback converter operate in a quasi-resonant mode to reduce switching losses and EMI noise. This controller does not require additional circuit for driving the 1700 V CoolSiC™ MOSFETs, which helps simplify the auxiliary supply circuit design.

Figure 14 **PWM-QR flyback controller ICE5QSAG**

2.2.4 Switching devices

The CoolSiC™ 1200 V MOSFETs IMZ120R030M1H and IMZA120R014M1H in TO247-4 package, using a state-of-the-art trench semiconductor process, are optimized to combine performance with reliability. Compared to traditional silicon (Si)-based switches, such as IGBTs and MOSFETs, the CoolSiC™ MOSFET offers a series of advantages such as:

- The lowest gate charge and device capacitance levels seen in 1200 V switches
- No reverse recovery losses in the internal, commutation-proof body diode
- Temperature independent low switching losses
- Threshold-free, on-state characteristics

1200 V CoolSiC™ MOSFETs from Infineon are ideal for hard-switching and resonant-switching topologies such as 3-phase, bidirectional AC-DC converters and the isolated DAB converter. Its benefits are:

- Improved efficiency
- Enables higher switching frequency
- Increased power density
- Reduced cooling effort
- Reduced system complexity and cost

Figure 15 1200 V SiC Trench MOSFET

2.2.5 Gate drivers

Infineon's 1ED3124MC12H gate driver belongs to the EiceDRIVER™ compact 1ED31xx family. It is a single-channel isolated gate driver with a two-level output signal. The sinking and sourcing peak output current is up to 14 A in a DSO-8, wide-body package with a large creepage distance (> 8 mm). 1ED3124MC12H offers short-circuit clamping to limit the gate voltage during short circuit. It can operate over a wide range of supply voltage, either unipolar or bipolar, for IGBTs, MOSFETs, and SiC MOSFETs.

The driver, 1ED3124MC12H, provides:

- Separate sink and source outputs
- Accurate and stable timing

- Active shutdown to ensure a safe transistor off-state in case the output chip is not connected to power
- Short-circuit clamping to limit the gate voltage during a short circuit

Gate drivers are used to drive CoolSiC™ 1200 V SiC MOSFETs and hence, provide isolation between the high voltage and low voltage circuit. The 1200 V SiC MOSFET is driven with a bipolar gate drive voltage of +18 V/-2.4 V. Figure 16 shows the circuit reference for the gate drive IC 1ED3124MC12H. More information about the gate driver circuit can be found in another Infineon reference design [3].

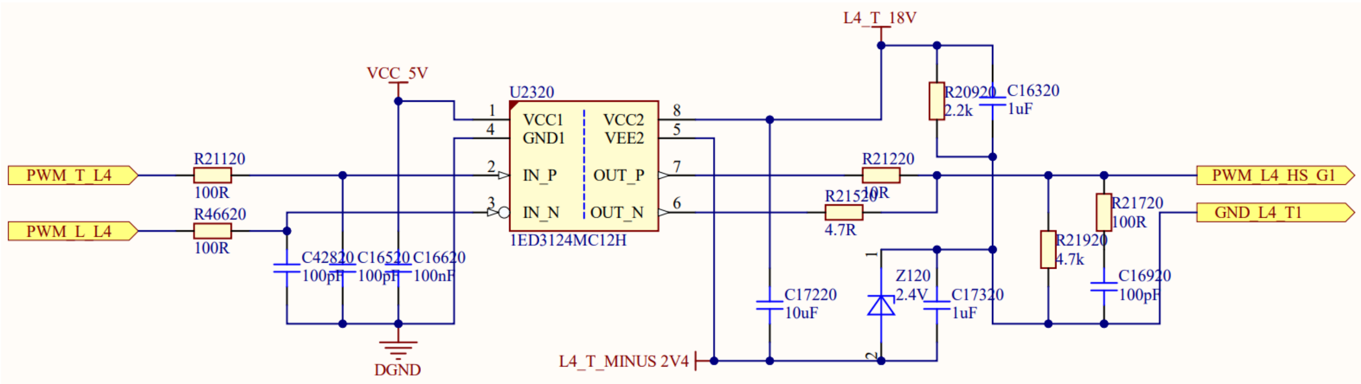


Figure 16 Reference circuit for gate driver 1ED3124MC12H

2.2.6 Microcontroller

The AURIX™ TC375TP microcontroller is based on the AURIX™ TC3xx platform with multiple TriCore™ CPUs, program and data memories, buses, bus arbitration, interrupt system, DMA controller, and a powerful set of on-chip peripherals. The AURIX™ TC3xx platform offers several versatile on-chip peripheral units such as serial controllers, timer units, and analog-to-digital converters. Within the AURIX™ TC3xx platform, all these peripheral units are connected to the TriCore™ CPUs/system via a system peripheral bus (SPB) and a shared resource interconnect (SRI). A number of I/O lines on the AURIX™ TC3xx platform ports are reserved for these peripheral units to communicate with the external world. The TriCore™ processor architecture combines three powerful technologies within one processing unit, achieving new levels of power, speed, and economy for embedded applications:

- Reduced instruction set computing (RISC) processor architecture
- Digital signal processing (DSP) operations and addressing modes
- On-chip memories and peripherals

DSP operations and addressing modes provide the computational power necessary to efficiently analyze complex real-world signals. The RISC load/store architecture provides high computational bandwidth with low system cost. On-chip memory and peripherals are designed to support even the most demanding high bandwidth, real-time embedded control system tasks. Figure 18 shows a block diagram of the AURIX™ TC375TP microcontroller.

System and functional description

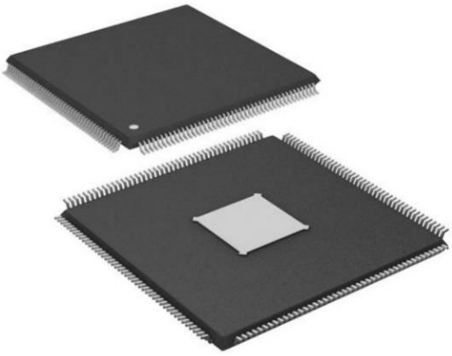


Figure 17 Infineon AURIX^{TM} TC375TP microcontroller

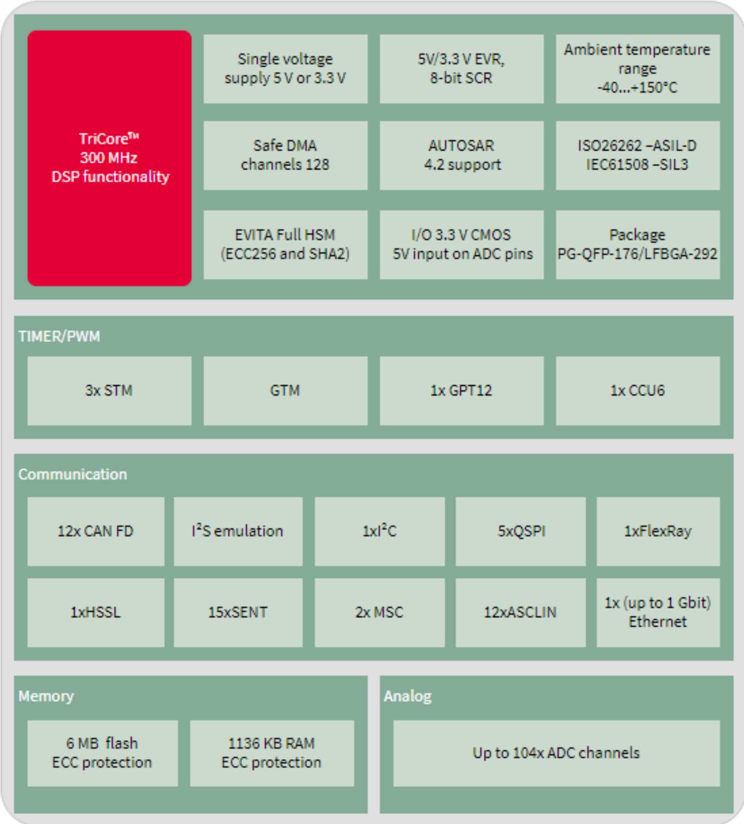


Figure 18 Block diagram of the AURIX^{TM} TC375TP microcontroller

The AURIX^{TM} TC375TP microcontroller includes the following features:

- Three 32-bit super-scalar TriCore^{TM} CPUs (TC1.6.2P), each having the following features:
  - Fully integrated DSP capabilities
  - A multiply-accumulate unit capable of sustaining 2 MAC operations per cycle
  - Fully pipelined floating point unit (FPU)
  - Up to 300 MHz operation at full temperature range
  - Up to 240/96 KB data scratchpad RAM (DSPR)
  - Up to 64 KB instruction scratchpad RAM (PSPR)
  - 32 KB instruction cache (ICACHE)
  - 16 KB data cache (DCACHE)

System and functional description

- Lockstep shadow cores for up to two TC1.6.2P
- Multiple on-chip memories
  - All embedded NVM and SRAM are ECC protected
  - Up to 6 MB program flash memory (PFLASH)
  - Up to 384 KB data flash memory (DFLASH) usable for EEPROM emulation
- 128-channel DMA controller with safe data transfer
- Sophisticated interrupt system (ECC protected)
- High performance, on-chip bus structure
  - 64-bit cross bar interconnect (SRI) providing fast, parallel access between bus masters, CPUs, and memories
  - 32-bit system peripheral bus (SPB) for on-chip peripheral and functional units
  - SRI to SPB bus bridges (SFI bridge)
- Optional hardware security module (HSM) on some variants
- Safety management unit (SMU) to handle safety monitor alarms
- Memory test unit with ECC, memory Initialization, and MBIST functions (MTU)
- Versatile on-chip peripheral units
  - 12 asynchronous/synchronous serial channels (ASCLIN) with hardware LIN support (V1.3, V2.0, V2.1, and J2602) up to 50 MBaud
  - Five queued SPI interface channels (QSPI) with master and slave capability of up to 50 Mbit/s
  - One high speed serial link (HSSL) for serial inter-processor communication of up to 320 Mbit/s
  - Two serial microsecond bus interfaces (MSC) for expanding serial ports to external power devices
  - Two MCMCAN modules with four CAN nodes for highly efficient data handling via FIFO buffering
  - 15 single edge nibble transmission (SENT) channels for connecting to sensors
  - One FlexRay™ module with two channels (E-Ray) supporting V2.1
  - One generic timer module (GTM) providing a powerful set of digital signal filtering and timer functionality for autonomous and complex input/output management
  - One capture/compare 6 module (two kernels CCU60 and CCU61)
  - One general purpose 12-timer unit (GPT120)
  - Two channel peripheral sensor interface conforming to V1.3 (PSI5)
  - One peripheral sensor interface with serial PHY (PSI5-S)
  - One inter-integrated circuit bus interface (I2C) conforming to V2.1
  - One IEEE802.3 ethernet MAC with RMII and MII interfaces (ETH)
  - Four/five wire JTAG (IEEE 1149.1) or device access port (DAP) interfaces
- Versatile successive approximation ADC (VADC)
  - Cluster of 12 independent ADC kernels
  - Input voltage range from 0 V to 5.5 V (ADC supply)
- Delta-Sigma ADC (DSADC)
- Multi-core debugging, real time tracing, and calibration
- Clock generation unit with system PLL and peripheral PLL
- Temperature range from -40°C to 150°C

More information about the microcontroller is available on Infineon's website.

3 System design

The complete Altium Designer project file of the power and control board is available on demand.

3.1 Bill of materials

Table 5 is listing up the key Infineon products and the most important/critical parts of the demonstration system.

Table 5 BOM of the most important/critical parts of the reference board

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N
1	D830, D930, D1030, D1130, D1230, D1330, D1430, D1530, D2030, D2130, D2230, D2330	TVS Diode, Ultra Low Clamping Bidirectional ESD/Transient /Surge Protection Diode, VRWM-5.5 V	Infineon Technologies	ESD206-B1-02V
2	G130	Low Dropout, Low Noise, Linear Voltage Post Regulator, 3.3V, 500 mA	Infineon Technologies	TLS205B0EJV33
3	U1130	Multi Voltage Safety Micro Processor Supply (5.0V Variant)	Infineon Technologies	TLF35584QVVS1
4	U1230	32-Bit Single-Chip Microcontroller, 3 TriCore™ running at 300 MHz	Infineon Technologies	SAL-TC375TP-96F300W AA
5	U1330	2.5A Half-Bridge with integrated driver and level shifter	Infineon Technologies	TLF11251EP
6	U1630	High Speed CAN Transceiver	Infineon Technologies	TLE9251VSJ
7	G110	1.8A DC/DC Step-Down Voltage Regulator – 5 V Output Voltage	Infineon Technologies	TLE8366E V50
8	G310	Micropower, low noise, low dropout voltage regulator	Infineon Technologies	TLS203B0EJ V33
9	Q110, Q210, Q310, Q410, Q510, Q610	Insulated-Gate Field-Effect Transistor (IGFET), N-Channel	Infineon Technologies	IMZA120R014M1H
10	Q120, Q220, Q320, Q420, Q520, Q620, Q820, Q920, Q1020, Q1120, Q1220, Q1320	Insulated-Gate Field-Effect Transistor (IGFET), N-Channel	Infineon Technologies	IMZ120R030M1H
11	Q720	CoolSiC™ Trench Silicon Carbide MOSFET	Infineon Technologies	IMBF170R1K0M1
12	Q1510	OptiMOS™ 2 Power-Transistor,120V	Infineon Technologies	BSC080N12LS G
13	Q1520	OptiMOS™ Small-Signal-Transistor	Infineon Technologies	2N7002
14	U910, U1010, U1110, U1210, U1310, U1410, U2320, U2420, U2520, U2620, U2720,	EiceDRIVER™ 1ED312xMU Compact Single channel isolated IGBT gate driver IC	Infineon Technologies	1ED3124MC12H

System design

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N
	U2820, U2920, U3020, U3120, U3220, U3320, U3420			
15	U1620, U3110	Quasi-Resonant PWM Controller	Infineon Technologies	ICE5QSAG
16	U1920	A high precision miniature coreless magnetic current sensor for AC and DC measurements with analog interface and two fast over-current detection outputs	Infineon Technologies	TLI4971-A120T5-E0001
17	D8230, D8330, D8430	TVS Diode, Ultra Low Clamping Bidirectional ESD/Transient /Surge Protection Diode, VRWM-5.5V	Infineon Technologies	ESD206-B1-02V
18	Q1710	CoolSiC™ Trench Silicon Carbide MOSFET	Infineon Technologies	IMBF170R450M1
19	C1, C2, C3, C4, C9, C10, C11, C12, C17, C18, C19, C20, C25, C26, C27, C28, C33, C34, C35, C36, C41, C42, C43, C44, C49, C50, C51, C52, C57, C58, C59, C60, C65, C66, C67, C68	CAP / CERA / 300nF / 630V / 5% / C0G (EIA) / NP0 / 2220 (5750) / SMD /	TDK Corporation	CAA573C0G2J304J640LH
20	C110, C210, C310, C1010, C1110, C1210	Bus Capacitors CAP / 390uF / 500V / 20% / Aluminiumelectrolytic / THT /	TDK Corporation	B43544A6397M060
21	C1620, C1820, C8520, C17120, C18520, C21210, C21610, C22010, C25710, C25910, C26910, C27110, C28110, C28310, C30720, C30920, C32120, C32320, C33520, C33720, C34920, C35120	CAP / CERA / 47uF / 100V / 20% / X7S (EIA) / -55 °C to 125 °C / 2220 / SMD / -	TDK Corporation	CAA573X7S2A476M640LH
22	C410, C510, C610, C620, C710, C720, C810, C820, C910, C920, C1020, C1120, C10920, C11120, C11220, C11720, C11820, C11920	(Capacitors between the drain and source) CAP / CERA / 250nF / 900V / 20% // SMD /	TDK Corporation	B58031I9254M062
23	C3510, C4510, C5510, C24920, C32020,	CAP / CERA / 6.8nF / 100V / 5% / C0G (EIA) / NP0 / 0805 / SMD /	TDK Corporation	C2012C0G2A682J125AA

System design

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N
	C35620, C43920, C44920, C45920			
24	C7820, C11420, C12120, C37320	CAP / FILM / 10nF / 1.5kV / 20% / THT /	TDK Corporation	B32021A3103M000
25	C8910, C9010, C10020, C53010	CAP / CERA / 10uF / 75V / 10% / X7R (EIA) / / 3225 (1210) / SMD /	TDK Corporation	C3225X7R1N106K250AC
26	C10010, C35110, C38010, C38110, C38910, C39010, C39210	(Y Capacitor) CAP / FILM / 4.7nF / 20% /THT	TDK Corporation	B81123C1472M000
27	C9410, C9510, C9610, C9710, C9810, C9910, C34810, C34910, C35010,	(X Capacitor) 3.3uF, EMI suppression capacitor(X2), 18.0*33.0*31.5	TDK Corporation	B32924J3335
28	C10620, C12720	(HV output filter capacitor) CAP / ELCO / 100uF / 550V / 20% / Aluminiumelectrolytic	TDK Corporation	B43544D7107M060
29	C10720, C10820, C12520, C12620	(HV output filter capacitor) CAP / ELCO / 330uF / 500V / 20% / Aluminiumelectrolytic	TDK Corporation	B43544B6337M067
30	C19010	CAP / CERA / 100uF / 25V / 20% / X7R (EIA) / 2220 (5750) / SMD /	TDK Corporation	CKG57NX7R1E107M500JH
31	C22110, C22210	CAP / CERA / 10uF / 100V / 10% / X7S (EIA) / 2220 / SMD / -	TDK Corporation	C5750X7S2A106K230KB
32	C34010	CAP / FILM / 47nF / 1kV / 5% /	TDK Corporation	B32672L0473J000
33	C37120, C37220	CAP / FILM / 100nF / 1.25kV / 10% / MKP (Metallized Polypropylene) /	TDK Corporation	B32653A7104K
34	L510	P302837F001, PFC inductor, 44A	TDK Corporation	P302837F001
35	L710	IND / STD / 47uH / 4.4A / 20% / 121.2mR / SMD / Inductor; 2 pin / SMD /	TDK Corporation	SPM10054T-470M-HZ
36	L410, L1210	IND / STD / 3mH / 45A / 50% / 4.8mR / THT / Common Mode Choke, THT, 6 pin, 70mm Dia X 39mm H body /	Würth Elektronik	744839003450
37	R11610, R11710, R12110, R12710, R12810, R12910	RES / VDR / 1kV / 1W / 10% / THT	TDK Corporation	B72220P3621K101
38	T120	3-phase HF transformer for 22kW, 43:55 A, 9:7, 60…100 kHz, 85 °C	TDK Corporation	P302837D001
39	T110	EE20/10/6 (EF20) 10-Term., THT, Vertical	Würth Elektronik Midcom	750345004

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N
40	T210, T310, T320, T410, T420, T520, T620, T720, T820	EE13/7/4 (EF12.6), 9-Term. EXT, SMT, Horizontal	Würth Elektronik Midcom	750345005
41	T220	Transformer 12-Terminal , THT, Horizontal, ER Style Bobbins, ER28/14	Würth Elektronik Midcom GmbH	750345011
42	T810	PQ3230 12-Term. EXT, THT, Vertical	Würth Elektronik	750345002

3.2 Connector details

Table 6 lists the main connectors used on the power board and the control board. To operate the microcontroller and drivers, an auxiliary power supply 26 V/2 A must be connected through the 5.5 x 2.1 mm DC jack (X1) on the control board. A 3-phase AC power supply is connected through four terminals (MP110, MP210, MP310, and MP410) on the power board using M3 screws. A DC load or DC power supply are connected through two terminals (MP120 and MP220) on the power board using M5 screws.

Table 6 Description of connectors

Ref Designator	Description	Manufacturer P/N	Function
X1	DC Jack 5.5x2.1 mm	EJ503A MDP	Auxiliary supply for the control board
X310, X420, X520	Pico-Clasp Wire-to-Board PCB Header	501190-4027 Molex	Connection of the power board and the control board
X410, X620, X720	Pico-Clasp Wire-to-Board PCB Header	501190-3027 Molex	Connection of the power board and the control board
X330, X430, X530, X630, X730, X830	Micro-Lock Plus Wire-to-Board Connector System	505575-0471 Molex	Connection of fans to the control board
P110, P21	WR-MPC4 4.2mm Male Dual Row Vertical Header, 8pins	64900821122 Wurth Elektronik	Connection of two parts of the power board, providing auxiliary supply
J110, J120	WR-BHD Male Box Header, SMT Straight, pitch 1.27mm, 50pins	62732020621 Wurth Elektronik	Connection of two parts of the power board, providing digital and analog signals
MP110, MP210, MP310, MP410	WP-BUTR REDCUBE PRESS-FIT with internal thread, 7x7mm, height 6mm, M3x5mm, 100A	7461057 Wurth Elektronik	Connection of three-phase AC power supply to the power board
MP120, MP220	WP-BUTR REDCUBE PRESS-FIT with internal thread, 9x9mm, height 7mm, M5x6mm, 160A	7460305 Wurth Elektronik	Connection of HV DC power supply or DC load to the power board
X130	3.50mm Horizontal PCB Header WR-TBL	691322110003 Wurth Elektronik	Connection of CAN interface between the control board and PC

Tables 7 and 8 list the connectors between the boards.

Table 7 Connectors between the control and power boards

Control board connector	Connector description	Power board connector
CJ1	ADC sense signals from AFE	X310
CJ2	ADC sense signals from DAB (bus-side voltage)	X420
CJ3	ADC sense signals from DAB (bus-side voltage)	X520
CJ4	PWM and digital signals for AFE	X410
CJ5	PWM and digital signals from DAB (bus-side voltage)	X620
CJ6	PWM and digital signals from DAB (bus-side voltage)	X720

Table 8 Connectors between power boards

Power board (part1) connector	Connector description	Power board (part2) connector
J110	Signal connection	J120
P210	Power connection	P110

3.3 Description of microcontroller pins

Table 9 lists the input and output signal pins of the microcontroller for controlling the power boards.

Table 9 Signal pins of the microcontroller

Pin #	GPIOs	Signal name	Signal description	Configuration	Purpose
43	AN25/P40-1	VAC1_SNS	AC voltage sampling	I	ADC
49	AN17/P40-10	VAC2_SNS	AC voltage sampling	I	ADC
57	AN11	VAC3_SNS	AC voltage sampling	I	ADC
41	AN27/P40.3	VAC1_SNS_GRID	GND(AC side)	I	ADC
40	AN28/P40.13	VAC2_SNS_GRID	GND(AC side)	I	ADC
39	AN29/P40.14	VAC3_SNS_GRID	GND(AC side)	I	ADC
60	AN7	VBUS_SNS	Bus voltage sampling	I	ADC
42	AN26/P40.2	IPH1_SNS	AC current sampling	I	ADC
48	AN18/P40.11	IPH2_SNS	AC current sampling	I	ADC
56	AN12	IPH3_SNS	AC current sampling	I	ADC
46	AN20	HVDC_SNS	HV voltage sampling	I	ADC
47	AN19/P40.12	ILEG3_SNS	HV current sampling	I	ADC
71	P33_1	PWM_T_L1_PM1	Signal of PFC PWM	O	PWM
76	P33_6	PWM_B_L1_PM1	Signal of PFC PWM	O	PWM

77	P33_7	PWM_T_L2_PM1	Signal of PFC PWM	O	PWM
87	P32_3	PWM_B_L2_PM1	Signal of PFC PWM	O	PWM
90	P23_1	PWM_T_L3_PM1	Signal of PFC PWM	O	PWM
93	P23_4	PWM_B_L3_PM1	Signal of PFC PWM	O	PWM
96	P22.1	DR_PRE_RLY1	Relay control signal (AC)	O	GPIO
97	P22.2	DR_PRE_RLY2	Relay control signal (AC)	O	GPIO
95	P22.0	DR_PRE_RLY3	Relay control signal (AC)	O	GPIO
98	P22.3	DR_PRE_RLY4	Relay control signal (AC)	O	GPIO
94	P23.5	DR_PRE_RLY5	Relay control signal (AC)	O	GPIO
105	P21.0	DR_PRE_RLY6	Relay control signal (Aux power)	O	GPIO
106	P21.1	DR_PRE_RLY7	Relay control signal (HV)	O	GPIO
137	P15.4	PWM_T_L1_PM2	Signal of DAB primary PWM	O	PWM
138	P15.5	PWM_B_L1_PM2	Signal of DAB primary PWM	O	PWM
136	P15.3	PWM_T_L2_PM2	Signal of DAB primary PWM	O	PWM
133	P15.0	PWM_B_L2_PM2	Signal of DAB primary PWM	O	PWM
131	P20.13	PWM_T_L3_PM2	Signal of DAB primary PWM	O	PWM
130	P20.12	PWM_B_L3_PM2	Signal of DAB primary PWM	O	PWM
16	P00.5	CTRL_FAN_INSIDE	Fan control signal	O	PWM
1	P02.0	CTRL_FAN1	Fan control signal	O	PWM
4	P02.3	CTRL_FAN2	Fan control signal	O	PWM
13	P00.2	CTRL_FAN3	Fan control signal	O	PWM
17	P00.6	CTRL_FAN4	Fan control signal	O	PWM
161	P11.3	CTRL_FAN5	Fan control signal	O	PWM
15	P00.4	CTRL_FAN6	Fan control signal	O	PWM
5	P02.4	PWM_T_L1_PM3	Signal of DAB secondary PWM	O	PWM
2	P02.1	PWM_B_L1_PM3	Signal of DAB secondary PWM	O	PWM
160	P11.2	PWM_T_L2_PM3	Signal of DAB secondary PWM	O	PWM
159	P13.3	PWM_B_L2_PM3	Signal of DAB secondary PWM	O	PWM
158	P13.2	PWM_T_L3_PM3	Signal of DAB secondary PWM	O	PWM
143	P14.1	PWM_B_L3_PM3	Signal of DAB secondary PWM	O	PWM

4 System performance

4.1 Efficiency

The efficiency plots shown in Figure 19 have been measured in forward mode under different voltages at the HV DC side. The maximum current circulating through the DAB converter is limited due to the losses of the DAB MOSFETs. Therefore, the power of the converter is limited at low and high voltage. The maximum power of the converter can be achieved in the range of 450 to 750 V. A Yokogawa WT1800 high-precision power analyzer was used to capture the efficiency plots. The maximum efficiency of the demonstration system is 96.8% at V_{DC} = 523 V, P_{DC} = 14 kW.

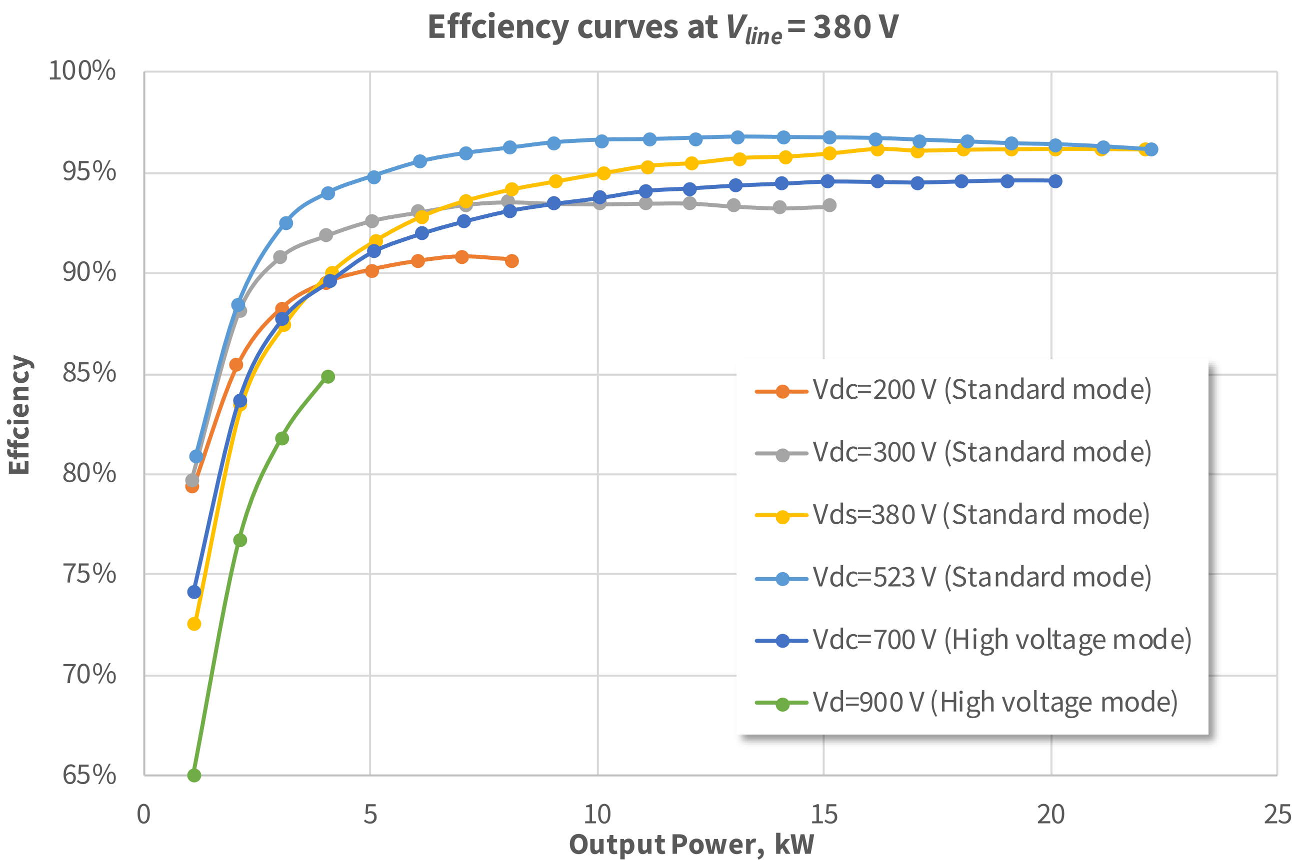


Figure 19 Efficiency test result for the whole converter in forward mode

Figure 20 shows separated efficiency curves for the AC-DC and the DAB converters in forward mode at V_{DC} = 530 V and V_{BUS} = 680 V. In this mode, the AC-DC converter operates as an active front-end rectifier. The maximum efficiency of the AC-DC and the DAB converters equals 98.3% and 98.7%, respectively, at P = 13 kW.

Note: V_{BUS} is the voltage of the bus between the AC-DC and the DAB converter. The voltage bus has variable voltage.

System performance

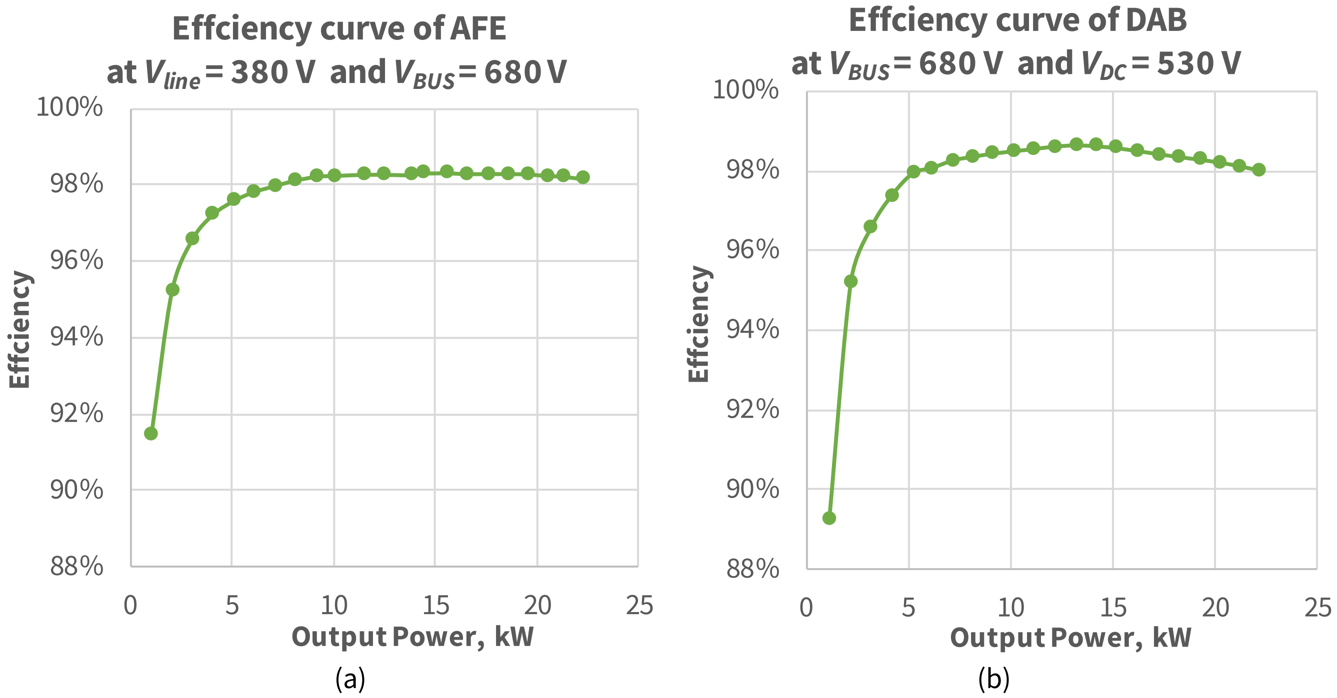


Figure 20 **Efficiency test result for (a) AC-DC and (b) DAB stage**

In the reverse power flow, the demonstration system has been tested at power up to 11 kVA due to limitations of the available equipment (see Figure 21). The maximum efficiency is 96.5% at P = 11 kW.

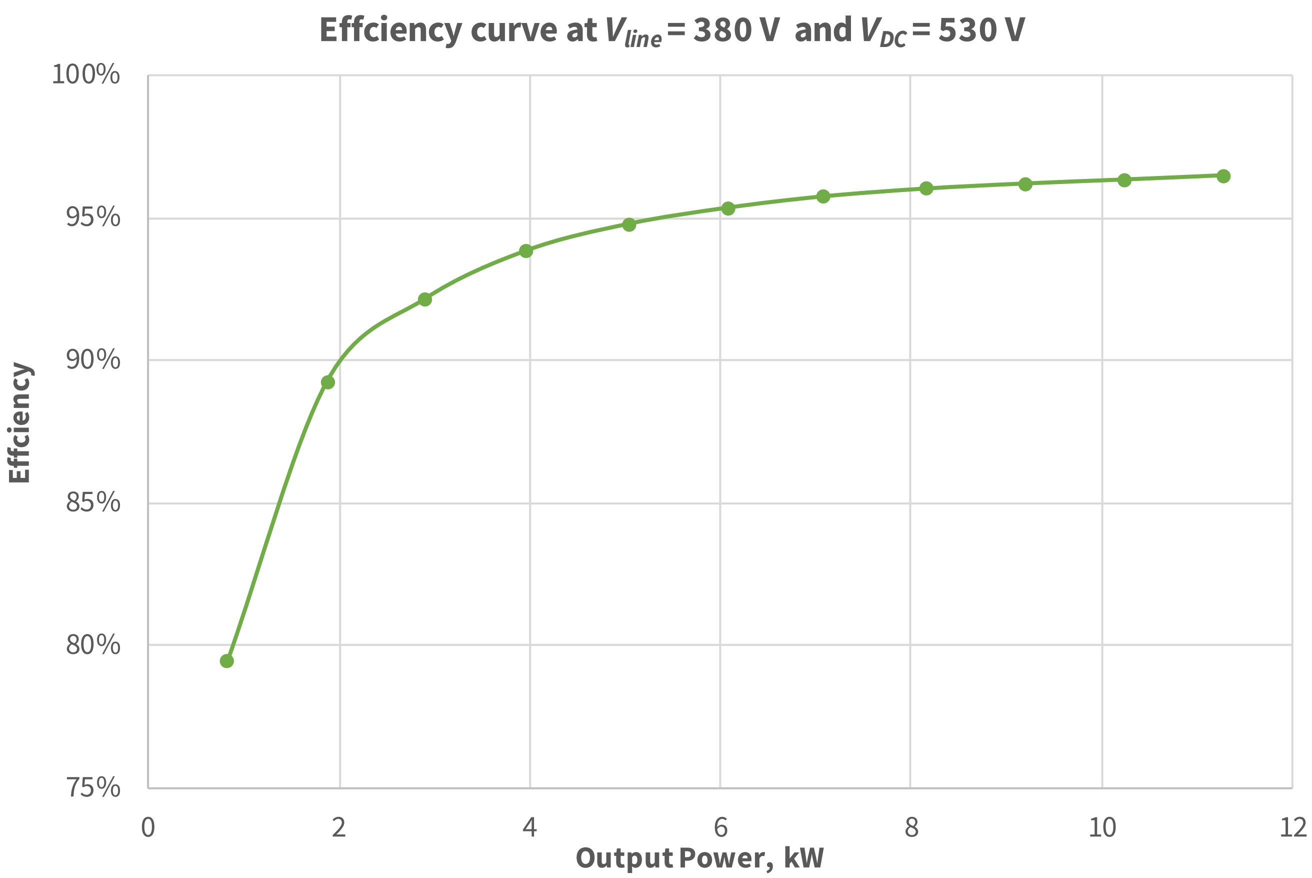


Figure 21 **Efficiency test result for the whole system in the reverse mode**

4.2 Steady-state waveforms of the AC side

Steady-state waveforms of the AC input current and voltage in forward mode at *P* = 22 kW and reverse mode at *P* = 11 kVA are shown in Figures 22 and 23, respectively:

- Channel C5 (grey) is the voltage of phase A (120 V/div)
- Channel C6 (violet) is the current of phase C (20 A/div)
- Channel C7 (red) is the current of phase A (20 A/div)
- Channel C8 (orange) is the current of phase B (20 A/div)

In both tests, the HV DC voltage was equal to 530 V.

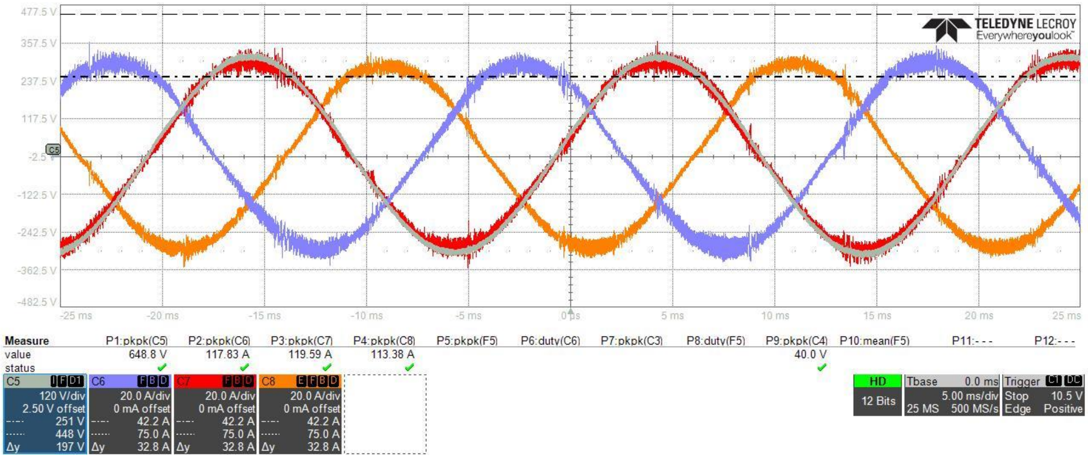


Figure 22 Steady-state waveforms of the AC input current and voltage in forward mode at 22 kW

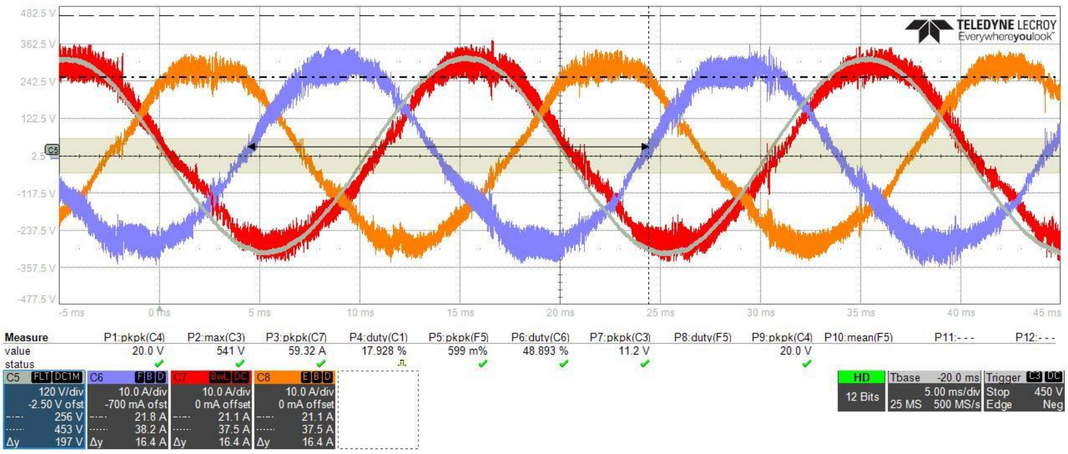


Figure 23 Steady-state waveforms of the AC input current and voltage in reverse mode at 11 kW

Figures 24 and 25 show measured voltage, current, efficiency, power factor, and THD in forward mode at *P* = 22 kW and reverse mode at *P* = 11 kW. A Yokogawa WT1800 high-precision power analyzer was used for these tests. As shown in Figures 24 and 25, the power factor is about 0.99 and the current THD equals 2.2% and 4.8% in forward and inverse mode, respectively. The results achieved corresponded to the requirements.

System performance

Figure 24 Current, voltage, power, and THD in forward mode at 22 kW

Figure 25 3-phase AC input current and voltage in reverse mode at 11 kW

4.3 Steady-state waveforms of the AC-DC converter

Figures 26 and 27 show steady-state waveforms of the AD-DC converter operating in forward mode as an active front-end (AFE) converter at $P = 22$ kW, $V_{DC} = 530$ V; and $P = 4$ kW, $V_{DC} = 900$ V, respectively:

- Channel C1 (yellow) is the gate-source voltage of the top switch in the leg (10 V/div)
- Channel C2 (red) is the drain-source voltage of the top switch in the leg (200 V/div)
- Channel C7 (red) is the gate-source voltage of the bottom switch in the leg (10 V/div)

System performance

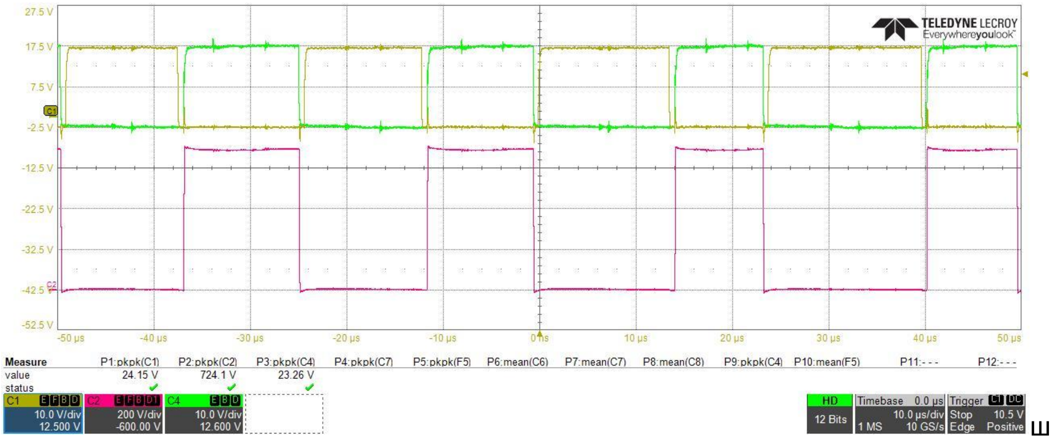


Figure 26 Steady-state waveforms of the AC-DC converter at P = 22 kW, V_{DC} = 530 V

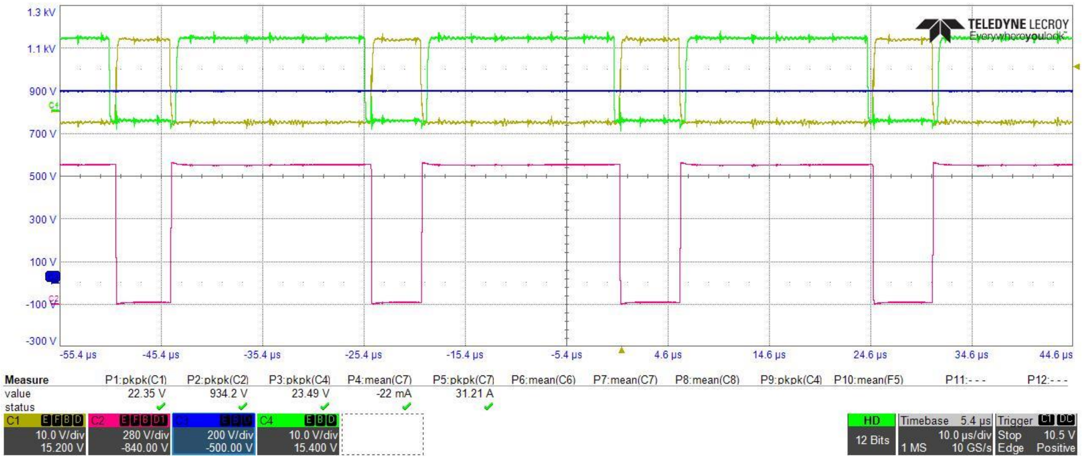


Figure 27 Steady-state waveforms of the AC-DC converter at P = 4 kW, V_{DC} = 900 V

4.4 Steady-state waveforms of the DAB converter

Figures 28 and 29 show steady-state waveforms of transformer currents on the primary and secondary sides of the 3-phase DAB converter operating in the forward mode at P = 22 kW, V_{DC} = 530 V.

- Channel C6 (violet) is the current of phase C of the 3-phase DAB (20 A/div)
- Channel C7 (red) is the current of phase A of the 3-phase DAB (20 A/div)
- Channel C8 (orange) is the current of phase B of the 3-phase DAB (20 A/div)

System performance

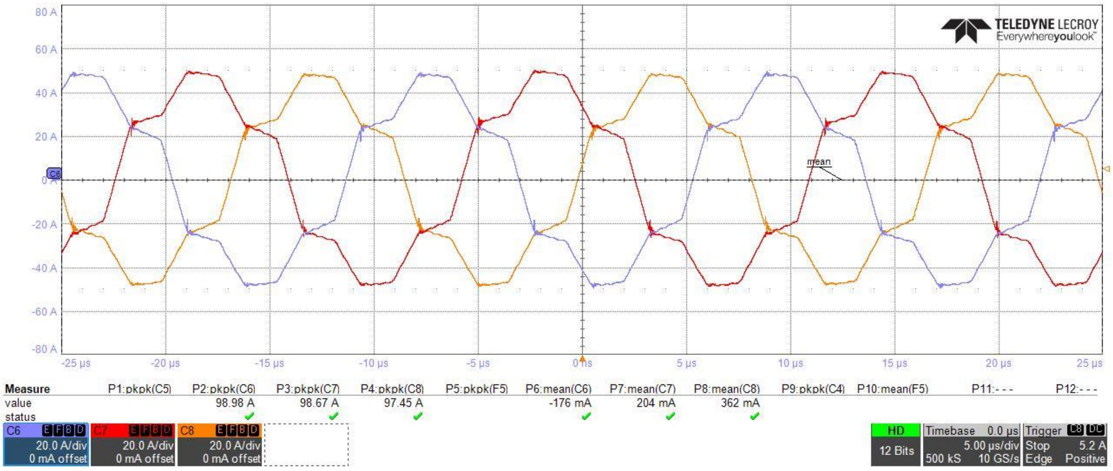


Figure 28 **Steady-state waveforms of the currents on the primary side of the 3-phase DAB converter at $P = 22$ kW, $V_{DC} = 530$ V**

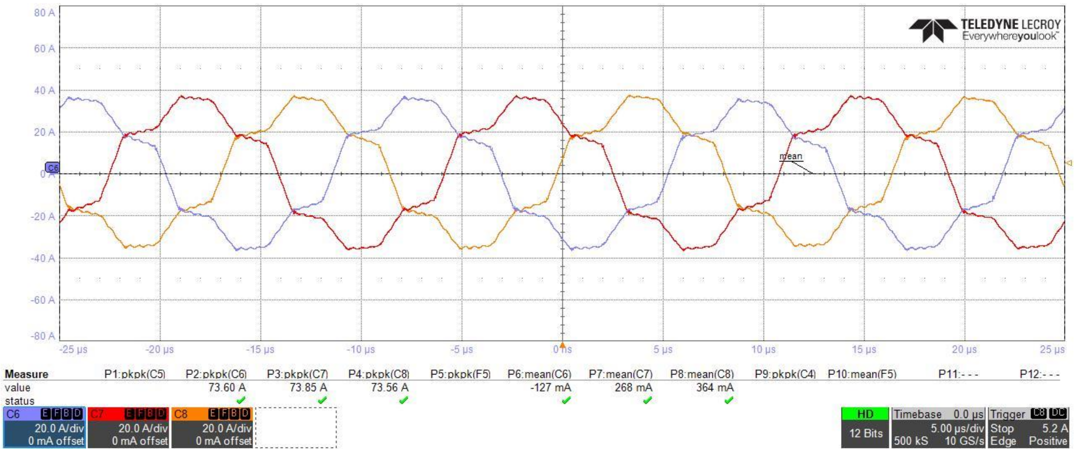


Figure 29 **Steady-state waveforms of the currents on the secondary side of the 3-phase DAB converter at $P = 22$ kW, $V_{DC} = 530$ V**

Figures 30 and 31 show steady-state waveforms of the switches' voltage on the primary and secondary sides of the 3-phase DAB converter operating in forward mode at $P = 22$ kW, $V_{DC} = 530$ V.

- Channel C1 (yellow) is the gate-source voltage of the top switch (10 V/div)
- Channel C2 (pink) is the drain-source voltage of the top switch (10 V/div)
- Channel C4 (green) is the gate-source voltage of the bottom switch (10 V/div)
- Channel C7 (red) is the current of phase A (20 A/div)

System performance

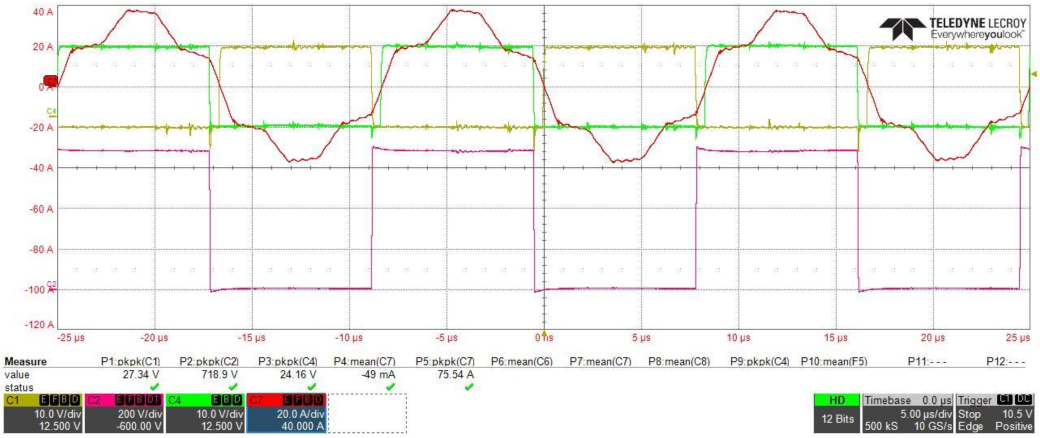


Figure 30 Steady-state waveforms of the current and voltage on the primary side of the 3-phase DAB converter at P = 22 kW, V_{DC} = 530 V

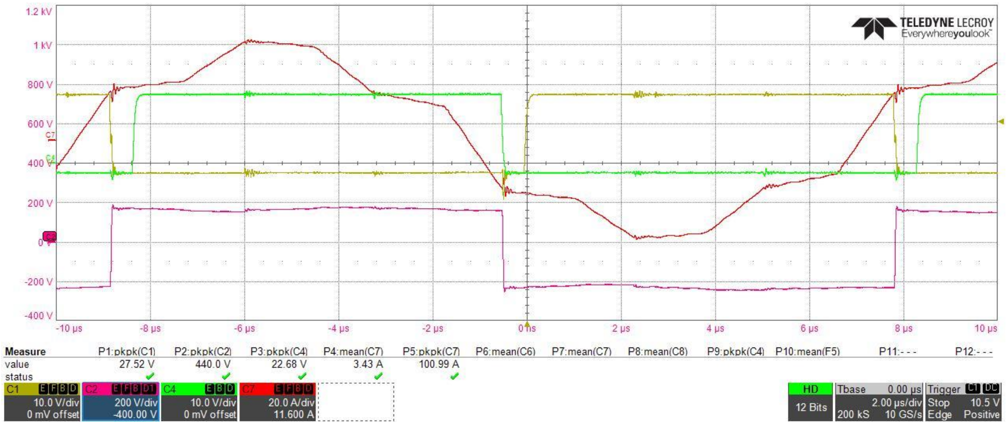


Figure 31 Steady-state waveforms of the current and voltage on the secondary side of the 3-phase DAB converter at P = 22 kW, V_{DC} = 530 V

5 Appendices

5.1 Abbreviations and definitions

Table 10 Abbreviations

Abbreviation	Meaning
AC	Alternative current
DC	Direct current
THD	Total harmonic distortion
DAB	Dual active bridge
AFE	Active front-end
PWM	Pulse-width modulation
QR	Quasi resonant
MOSFET	Metal oxide semiconductor field effect transistor
SiC	Silicon carbide
CAN	Controller area network interface

Appendices

Table 12 Special notes

#	Sorts	Description
1	Isolation	Clearance and creepage distances do not fully comply with IEC62477-1 2022 regulations. For example, the distance between the MOSFET clamps to the heatsink, or the DAB primary side to secondary side distance.
2	Connectors	All the connectors including the 26 V auxiliary power supply connector, AC input connector, DC output connector, CAN bus connector must not be touched whenever the system is connected to the grid or during any kind of operation.
3	DC link voltage	As there is no discharge circuit for the DC link voltage, it is recommended to discharge the output DC voltage to safety voltage with DC load after the module is switched off.
4	Current control loop	To avoid the module go to constant current control loop, it is recommended not to limit the output current and power through GUI, or limit the current to > 55A, limit power to > 22kW in GUI, and on the other hand to limit the output DC load current.
5	Equipment used	**1) AC Source:** BSA 30-300-46 / BRISYS / 30KVA -300VAC-46A bi-directional AC-AC source **2) DC load:** Resistive load 30 kW / 1000 V (resistor changeable) Resistive load DC-RSF-100-1000V-200A -30KW (Factory) DC Load: ELR 11500-60 4U / EA / 1500V – 60A – 30kW **3) DC source:** PSI 11500-60 4U / EA / 1500V–60A–30 kW BTLA-PMA060-A011-HL / 380VAC input-680V-1000VDC output (Factory) **4) Power analyzer:** WT1804E / Yokogawa **5) 26 V external auxiliary power supply:** ITech IT6721 / 60V–8A isolated AC-DC high accuracy digital power supply.

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2.0	31.05.2024	Updated disclaimer and additional notes

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