48 V to 12 V DC-DC Switch Tank Converter in Zonal Architecture Design

User Guide

About this document

Scope and purpose

This document shall provide the audience with information on how to work with this reference design.

Intended audience

Electronics engineers

Reference Board/Kit

Product(s) embedded on a PCB with a focus on specific applications and defined use cases that may include software. PCB and auxiliary circuits are optimized for the requirements of the target application.

Note: *Boards do not necessarily meet safety, EMI, quality standards (for example UL, CE) requirements*

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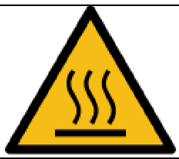
Safety precautions

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

Table 1 Safety precautions

	**Warning**: *The evaluation or reference board contains DC bus capacitors, which take time to discharge after removal of the main supply. Before working on the drive system, wait 5 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.*
	**Caution:** *The heat sink and device surfaces of the evaluation or reference board may become hot during testing. Hence, necessary precautions are required while handling the board. Failure to comply may cause injury.*
	**Caution:** *The evaluation or reference board 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.*

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1 The board at a glance

This reference design is developed to evaluate the performance of prospective DC-DC converters suitable for the new zonal controller unit (ZCU) in automotive application. Please note that for operating this evaluation kit, a TriBoard TC499A STD is needed. The TriBoard is not included in the evaluation kit and needs to be purchased separately. Please check our homepage www.infineon.com for TriBoard TC499 STD or contact your local Infineon sales office.

This reference design, as can be seen in Figure 1, consists of

- DC-DC converter board
- Interface board

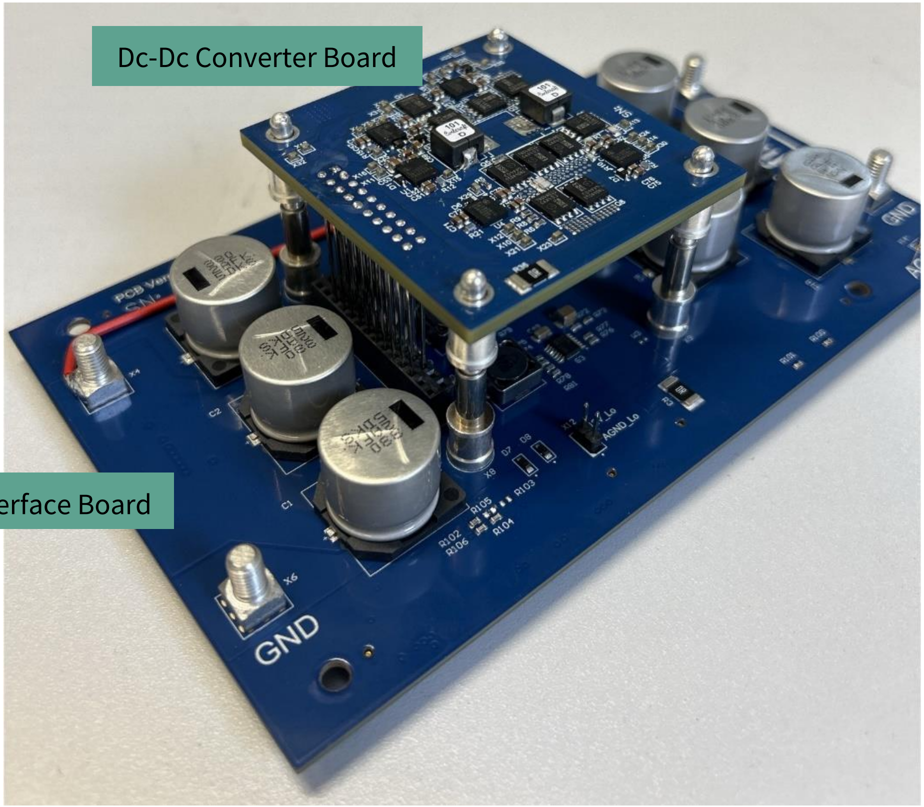

Figure 1 48V-12V DC-DC converter reference design

The DC-DC converter board is responsible for the voltage conversion functionality and the topology of choice is the 4 to 1 Switched Tank Converter (STC). The STC is chosen in order to achieve a high efficiency by means of soft switching of the switches and a small form factor, which is important in the zonal architecture design. The board is designed to output continuous power of 500 W and based on Infineon OptiMOS™ MOSFET in combination of EiceDRIVER™ MOSFET gate driver.

The interface board's main functions are protection of the 48 V and the 12 V sides from abnormal operation (e.g. over-/undervoltage and overcurrent) and to interface the DC-DC converter board with the Infineon AURIX™ TC4x - TriBoard.

1.1 Scope of supply

- 1 x DC-DC converter board
- 1 x interface board

1.2 Block diagram

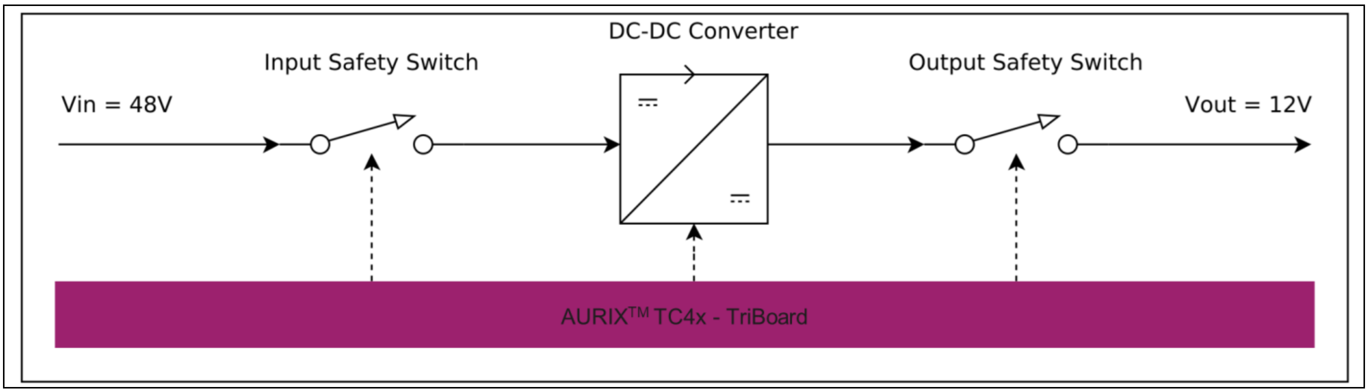

Figure 2 Block diagram of the 48V-12V DC-DC converter reference design

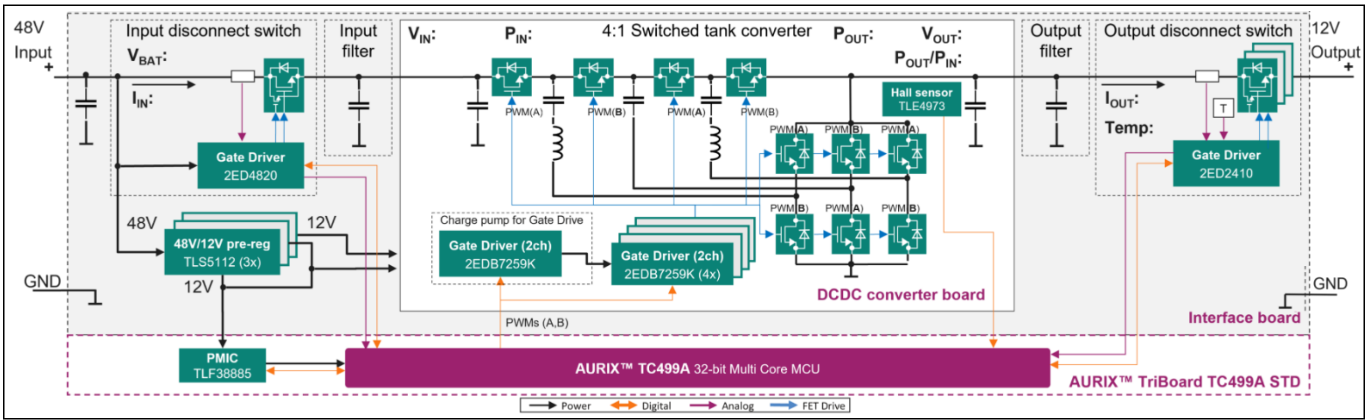

Figure 3 Detailed block diagram with Infineon components shown

1.3 Main features

The block diagram of the system can be seen in Figure 2.

Some of the main features of the system are as follows.

- Small form factor and high efficiency power conversion using Infineon OptiMOS™ MOSFET
- Safe pre-charge of the input filter capacitors using Infineon OptiMOS™ MOSFET
- Input and output protections using Infineon EiceDRIVER™
- Interactive Graphical User Interface (GUI) using Infineon OneEye

The Infineon components used in this reference design can be seen in Figure 3.

1. DC-DC converter board
   - IAUCN08S7N013 [1]: 80 V, N-Ch, 1.3 mΩ max, Automotive MOSFET, SSO8 (5x6), OptiMOS™ 7
   - IAUCN04S7N012 [2]: 40 V, N-Ch, 1.2 mΩ max, Automotive MOSFET, SSO8 (5x6), OptiMOS™ 7

- EiceDRIVER™ 2EDB7259K [3]: Dual-channel isolated gate-driver ICs in LGA package
- TLE4973-A075T5-S0001 [4]: XENSIV™ high accuracy coreless current sensor for internal current rail applications

2. Interface board
   - EiceDRIVER™ APD 2ED4820-EM [5]: 48 V smart high-side MOSFET gate driver with SPI
   - EiceDRIVER™ APD 2ED2410-EM [6]: 12 V / 24 V smart analog high-side MOSFET gate driver
   - IAUTN08S5N012L [7]: 80 V, N-Ch, 1.15 mΩ or 9.0 mΩ, Automotive MOSFET, TOLL (10x12), OptiMOS™ 5
   - TLS5112C0EPV: 48 V synchronous step-down regulator

1.4 Board parameters and technical data

Due to the DC-DC converter topology selection (i.e. switched tank converter), the output voltage of the converter is always (i.e. assuming no voltage drop) a quarter of the input voltage, i.e. $V_{out} = V_{in}/4$. Some important parameters of the reference design can be found in Table 1.

Table 1 Parameter

Parameter	Symbol	Min.	Typical	Max.	Unit	Notes
Nominal input voltage	V_{in}	36	48	60	V	
Input undervoltage lockout	$V_{in,UVLO}$		36		V	
Input overvoltage lockout	$V_{in,OVLO}$		60		V	
Absolute maximum input voltage	$V_{in, abs}$			75	V	
Output voltage	V_{out}	9	12	15	V	$V_{out} = V_{in}/4$ (no load)
Output power	P_{out}			500	W	Heat sink is needed to operate at 500W continuously
Switching frequency	f_{sw}		160		kHz	
Dead time	t_d	100			ns	Minimum dead time is provided by the gate driver

2 System and functional description

2.1 Getting started

The system requires a nominal input voltage of 36 V to 60 V to power the whole set-up. The input voltage is applied to V_{in}+ and V_{in}- as can be seen in Figure 4 below. When the system is up and running, a 9 V to 15 V output will be observed (assuming no load) at the output terminals V_{out}+ and V_{out}- as indicated in Figure 4 below.

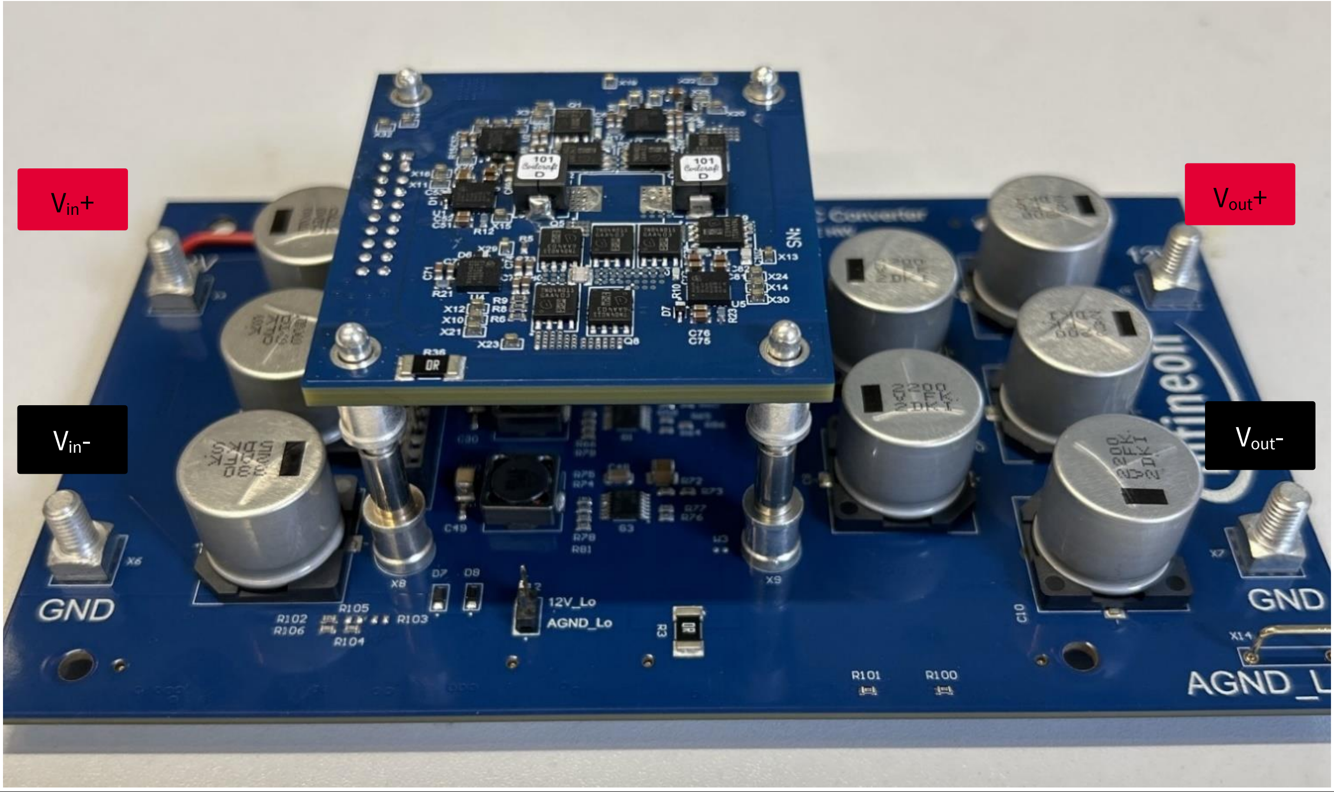

Figure 4 48V-12V DC-DC converter reference design - TOP view

To prepare the set-up, do the following

- Connect the DC-DC converter board with the top side of the interface board (see Figure 4).
- Connect the bottom side of the interface board (as indicated in Figure 5 below) with the Infineon AURIX™ TC4x – TriBoard.
- Connect the interface board with a 48 V power supply.

Some additional equipment that would be important to have for the operation of the reference design is as following

- Power supply with operating power > 500 W and voltage 0 V – 60 V with appropriate cables (current up to 15 A)
- Electronic load with operating power > 500 W and voltage 0 V – 20 V with appropriate cables (current up to 50 A)
- Connectors to the Würth Elektronik M5 terminals (part number: 7461001)
- 12 V / 2 A power adapter for flashing the TriBoard

- MicroUSB – USB-A cable for establishing connection between the TriBoard and your PC

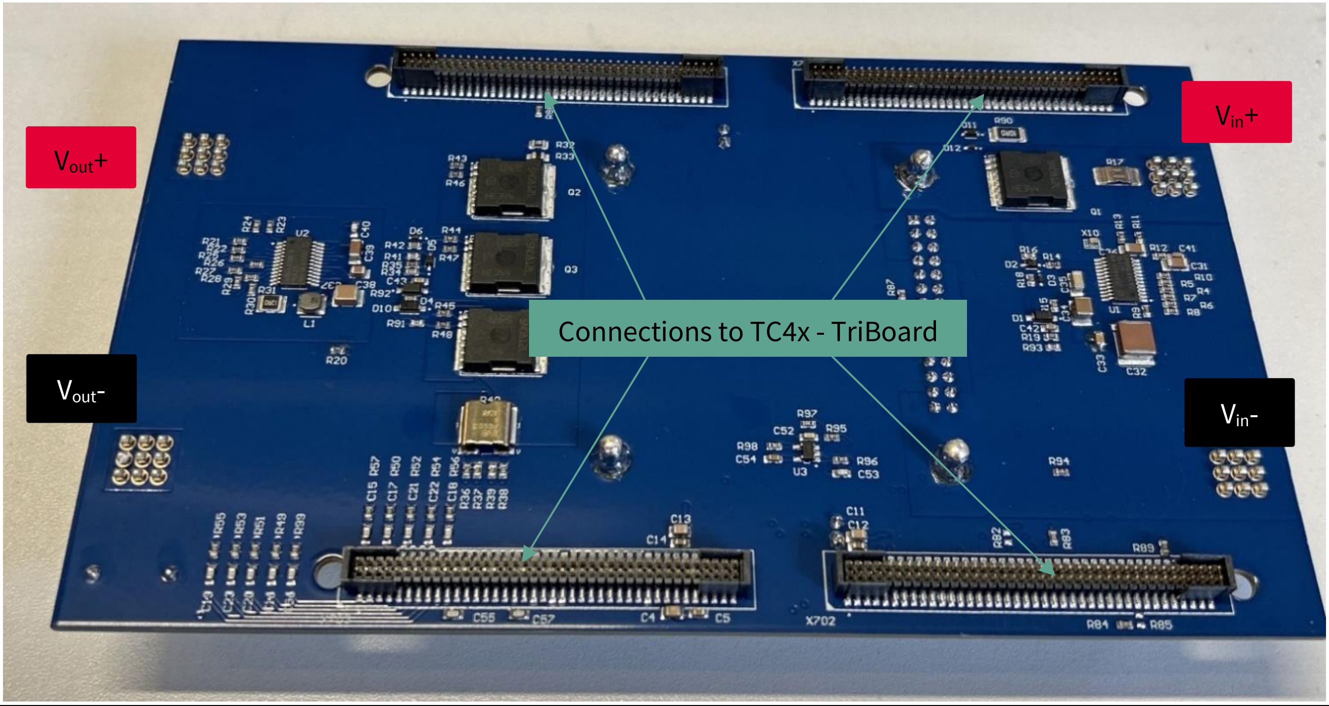

Figure 5 48V-12V DC-DC converter reference design - BOTTOM view

2.2 Description of the functional blocks

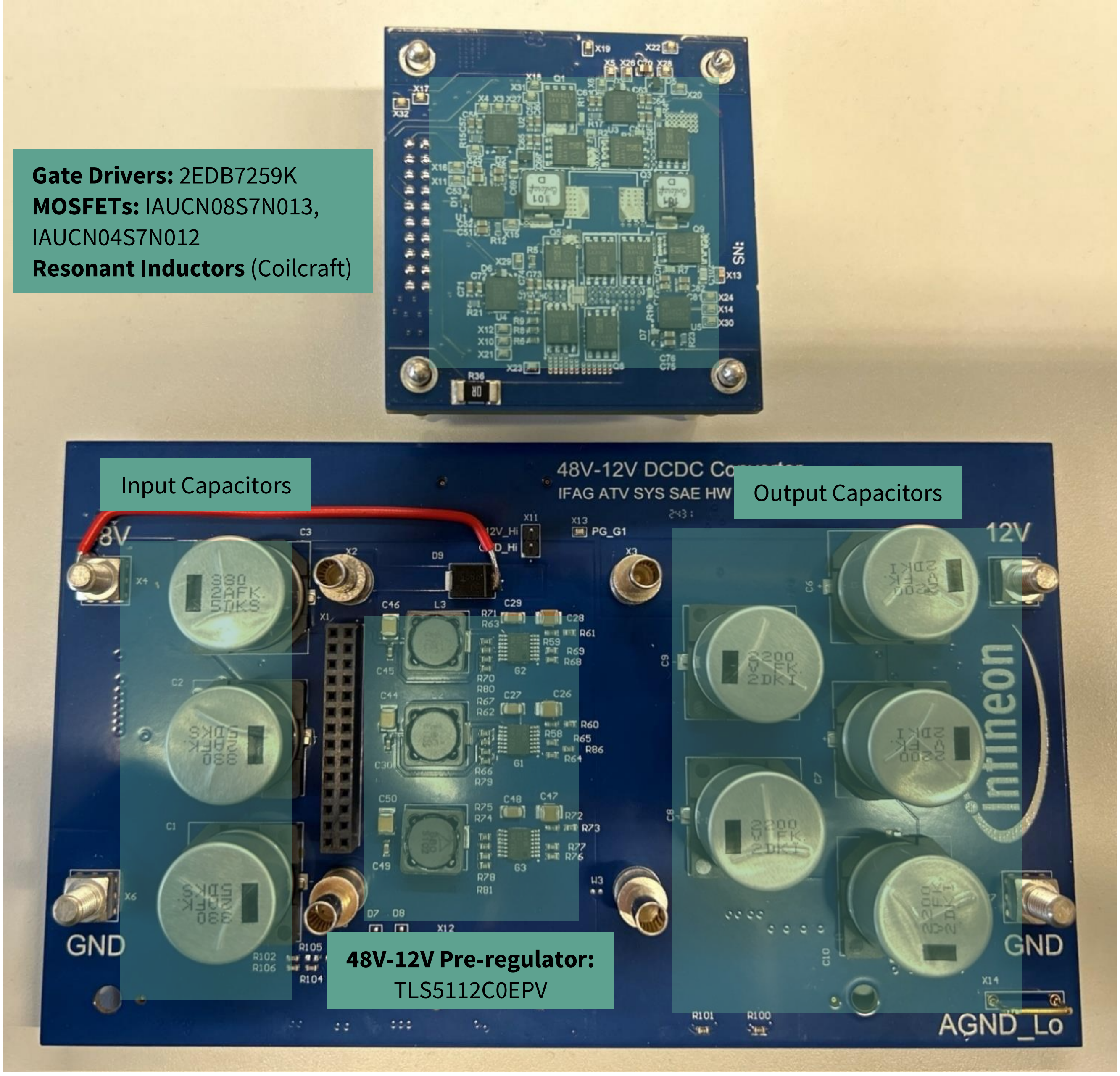

Figure 6 Functional blocks on the TOP side

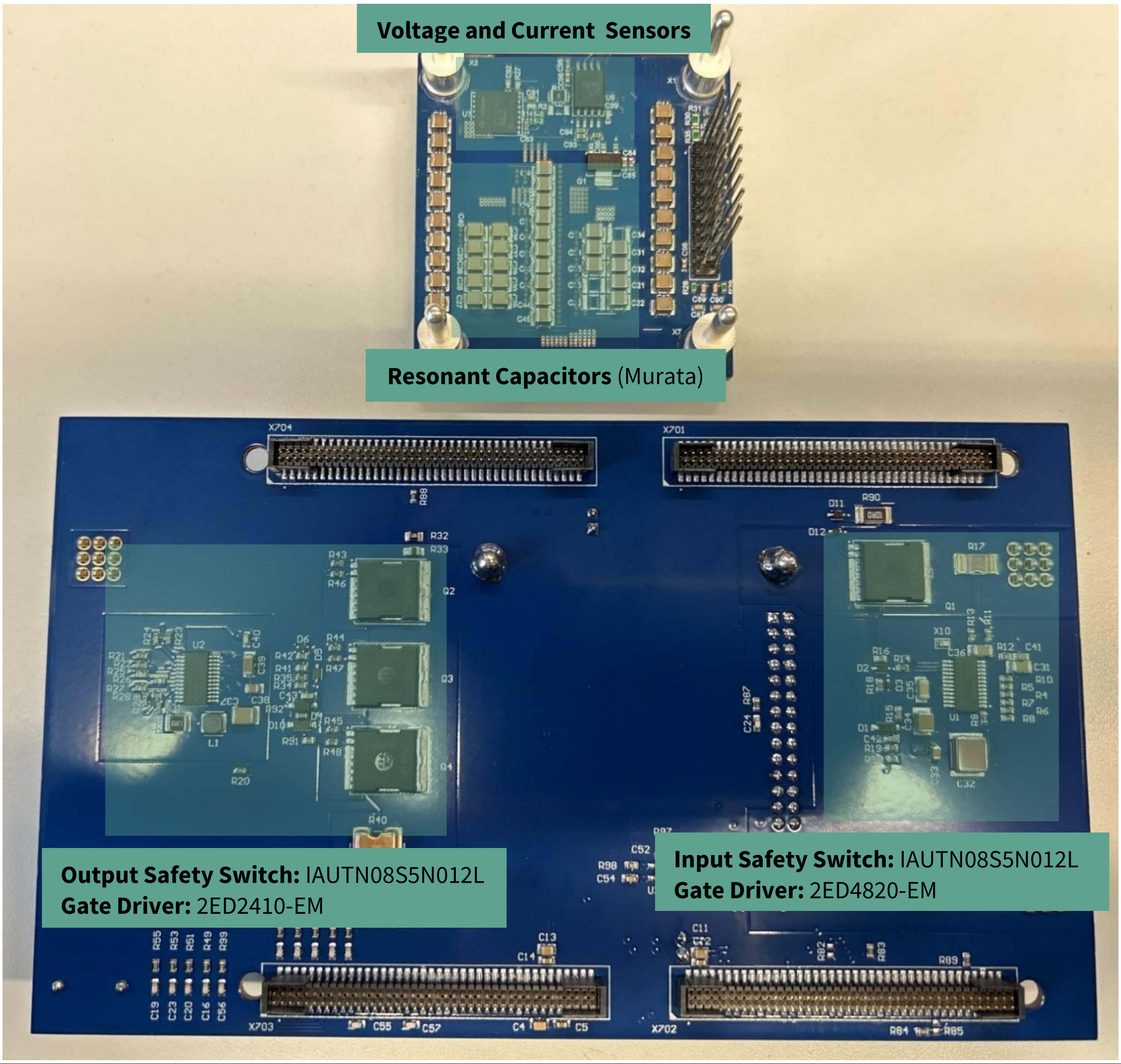

Figure 7 Functional blocks on the BOTTOM side

2.2.1 DC-DC converter board

The voltage conversion from 48 V to 12 V happens on the DC-DC converter board. The switches, gate drivers, and resonant inductors are placed on the top side (see Figure 6), whereas the input/output filter capacitors, resonant capacitors, and sensors are placed on the bottom side (see Figure 7).

For this switched tank converter topology, switches from the OptiMOS™ 7 in SSO8 (5x6) package are chosen. Two IAUCN08S7N013 (80 V, 1.3 mΩ) are used for the first two flying switches in the configuration (Q1 and Q2 in Figure 20) and IAUCN04S7N012 (40 V, 1.2 mΩ) for the rest including the synchronous rectifier switches (Q3 – Q10 in Figure 20).

To drive the switches, the dual-channel EiceDRIVER™ 2EDB7259K gate drivers are used. Bootstrap circuits are needed to drive the synchronous rectifier switches, whereas charge pump circuit is used to drive the four flying switches.

Three measurements are done on the board, i.e. input voltage, output voltage, and output current measurements. For the output current measurement, the XENSIV™ current sensor TLE4973-A075T5-S0001 is used. The input voltage measurement is done by using an isolated op-amp and the output voltage measurement by a simple resistive voltage divider. The measurement signals will be sent to the Infineon AURIX™ TC4x – TriBoard.

There are two physical resonant tanks in a 4 to 1 switched tank converter topology, which consist of inductance originating mainly from the discrete inductors and the stray inductance of the PCB traces and capacitance of the MLC capacitors (MLCCs). It is assumed that the stray capacitance is negligible for the resonant operation. It is of high importance that the resulting resonant frequencies of both the resonant tanks are close to each other. The switching frequency of the switches should then be set close to the resonant frequencies of the resonant tanks for optimum operation of the DC-DC converter.

2.2.2 Interface board

The input and output safety switches alongside their respective dedicated drivers are located on the bottom side of the board (see Figure 7), while the input and output bulk capacitors and the pre-regulators can be found on the top side (see Figure 6). The pre-regulators TLS5112C0EPV are the power supply of the system, i.e. they will convert the input voltage to 12 V to supply both the DC-DC converter board and the Infineon AURIX™ TC4x – TriBoard.

The switches used for the input and output safety switches are the OptiMOS™ 5 IAUTN08S5N012L dual gate MOSFETs (80 V, 1.15 mΩ). One MOSFET for the input safety switch and three MOSFETs in parallel for the output safety switches because of the higher output current requirement.

The gate driver for the input safety switch is the EiceDRIVER™ APD 2ED4820-EM. SPI communication is used to control this gate driver. Because a dual gate MOSFET is used, both outputs of the 2ED4820 (GA and GB) are utilized. The gate driver for the output safety switches is the EiceDRIVER™ APD 2ED2410-EM. Similar to the input side, both outputs of the 2ED2410-EM (GA and GB) are utilized. Both gate drivers have built-in current sensing functionality and provide many diagnostic functions.

2.3 Basic operation

The software is implemented in Simulink on the Infineon AURIX™ TC4x – TriBoard with the help of the Hardware Support Package [8]. To obtain the software and information on how to flash it, please contact your local Infineon sales office for support.

2.3.1 State machine

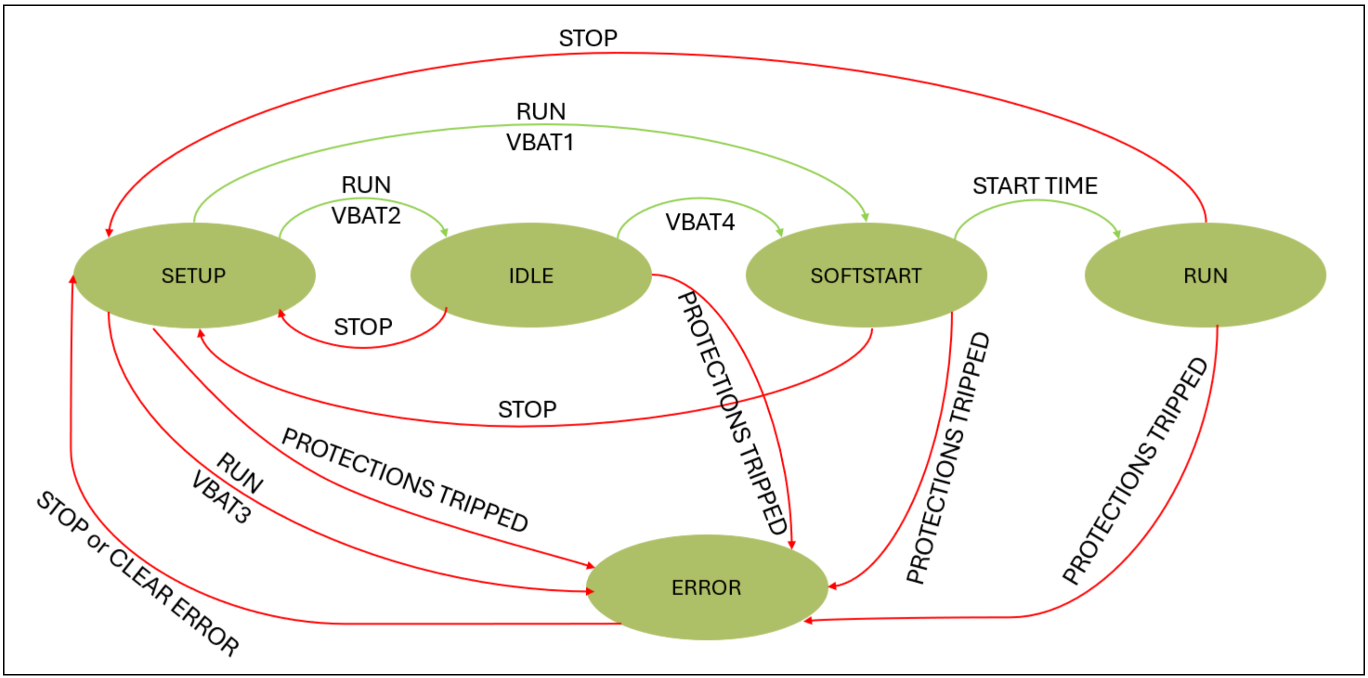

Figure 8 State machine behind the system

To start operating the system, apply input voltage V_{in} at the input terminal. The voltage applied needs to be at least higher than 15 V, so the 12 V output from TLS5112C0EPVs can supply the Triboard. Once the Triboard is supplied the state machine can start (see Figure 8).

After running the initial setup code, the state machine waits in the SETUP state for the RUN command to be issued. If the RUN command is issued, depending on the value of the input voltage, three outcomes are possible. If the input voltage is between 36 V and 60 V, (VBAT1 in Figure 8), the state machine switches to the SOFTSTART state. If the input voltage is less than the input undervoltage lockout of 36 V, but higher than 35 V or higher than the input overvoltage lockout of 60 V but less than 61 V, (VBAT2 in Figure 8) the converter will be in the IDLE state waiting for the input voltage to reach a value of at least 37 V for the lower limit, or at least 59 V for the higher limit, (VBAT4 in Figure 8) before advancing to the SOFTSTART phase. If the input voltage is less than 35 V or over 61 V (VBAT3 in Figure 8), an input undervoltage, respectively overvoltage error is thrown, and the state machine will go in the ERROR state. Pressing STOP at any moment will return the state machine in the SETUP state.

The SOFTSTART state takes around 80 ms. The first part of this state consists of using the input gate driver 2ED4820-EM to control the input dual-gate MOSFET IAUTN08S5N012L. The dual gate MOSFET comprises two interleaved transistors on the same silicon chip, with a common drain and source, but separate gates that are individually accessible through dedicated pins. One gate represents the ONFET, which delivers a low $R_{DS(ON)}$ for steady-state operation, while the other gate represents the LINFET, which offers excellent SOA and linear operation performance, making it suitable for controlling charging capacitors inrush current and active clamping after short-circuit turn-off. In this state 20 pulses are sent to shortly activate the linear FET of the dual-gate switch and pre-charge the circuit. After the pulsing phase the low $R_{DS(ON)}$ FET is activated. At this moment the input voltage of the converter nodes should be equal to the input V_{BAT}. After this step two complementary PWM signals are activated to control the switches on DC-DC converter board and start the power conversion. In this state, only if the output voltage, i.e. output capacitors voltage (C6 to C10), is at least 8 V, the linear FET of only one of the 3 parallel connected output dual-gate MOSFET IAUTN08S5N012L switches is turned on using the 2ED2410-EM. After this pre-charge phase, if the voltage hasn't dropped under 8 V, the 3 parallel low $R_{DS(ON)}$ FETs of the safety output switches are activated, the linear FET is turned off, and the converter will move to the RUN state. If the output voltage is less than 8 V, the output undervoltage error flag is active, and the converter goes in the ERROR state.

There are 8 error flags defined that can make the converter go into the ERROR state. In the case of any tripped active protection, the system will go to the ERROR state, e.g. in the SOFTSTARTUP state the output undervoltage protection is not active, as this voltage in this state is still ramping up to the nominal value. To go back to the SETUP state, send the ERROR RESET or STOP command. In the case of ERROR RESET, if the proper conditions are met, the converter starts without issuing again the RUN command. In the case of the STOP command, the state machine will wait in the SETUP state for the RUN command to be issued.

The total number of 8 protections is active during the RUN State when the system checks that the input and output voltage is between the under and over voltage lockout limits and that the input and output current are less than the limits set for the overcurrent protection as well as monitoring the interrupt pins on both 2ED4820-EM and 2ED2410-EM gate drivers for determining faults detected by these two circuits.

2.3.2 Operating the GUI on a PC

The GUI is used to visualize data coming from the hardware and to control the parameters through Aurix, OneEye GUI illustrated in Figure 9 is being used. The USB connection is used for the communication between PC and the onboard Aurix™.

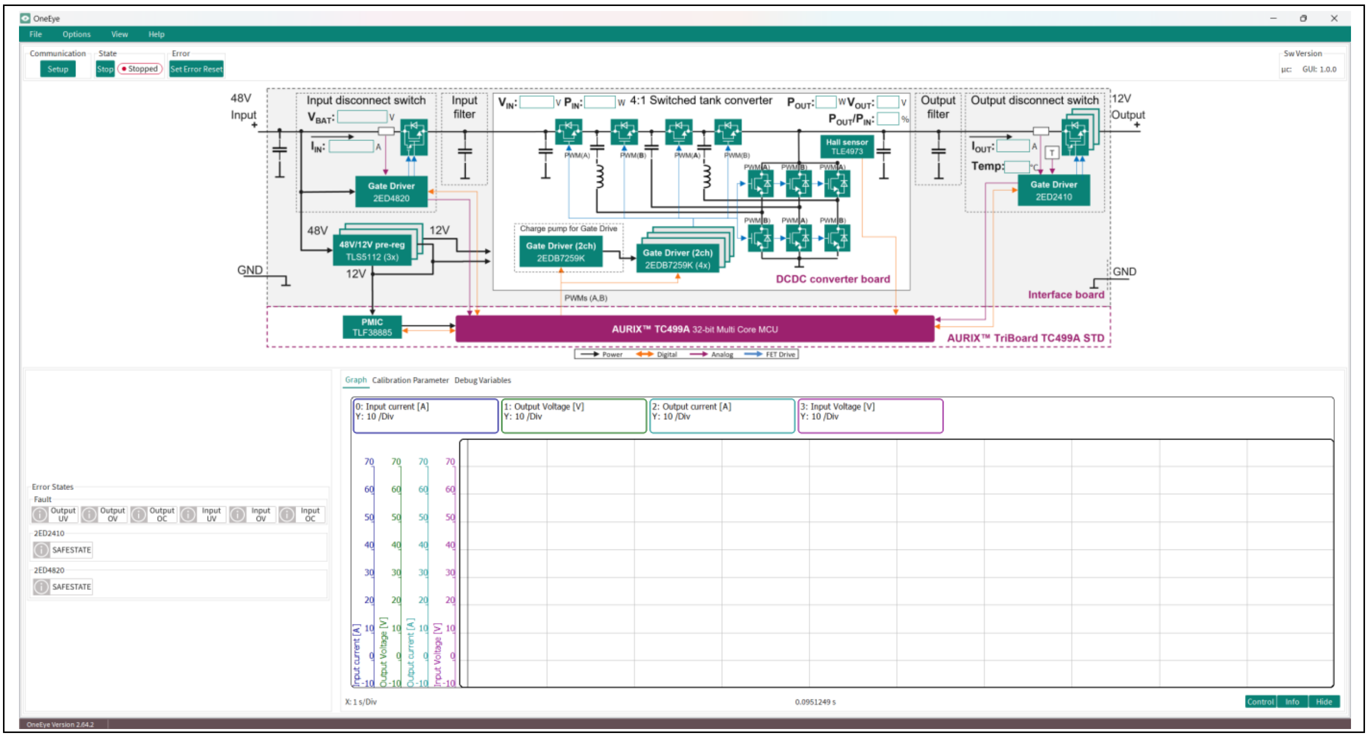

Figure 9 GUI overview

2.3.2.1 Installation of GUI

As first step, the Infineon Developer Center Launcher as shown in Figure 10 needs to be installed. To install OneEye GUI, navigate to Manage Tools section and search for application in search bar.

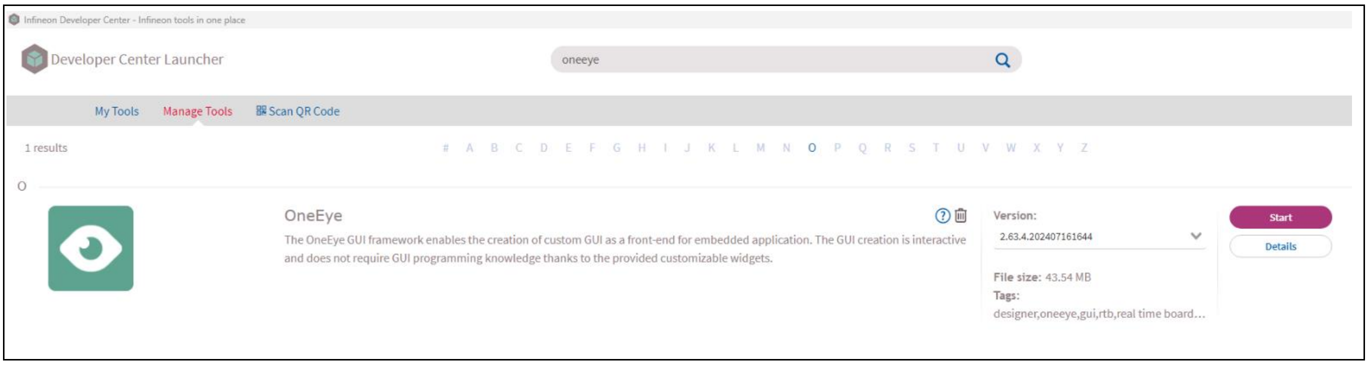

Figure 10 Infineon Developer Center Launcher

2.3.2.2 Start workflow of the GUI

As first step OneEye GUI needs to be started, and the configuration file shall be loaded, as shown in the Figure 11.

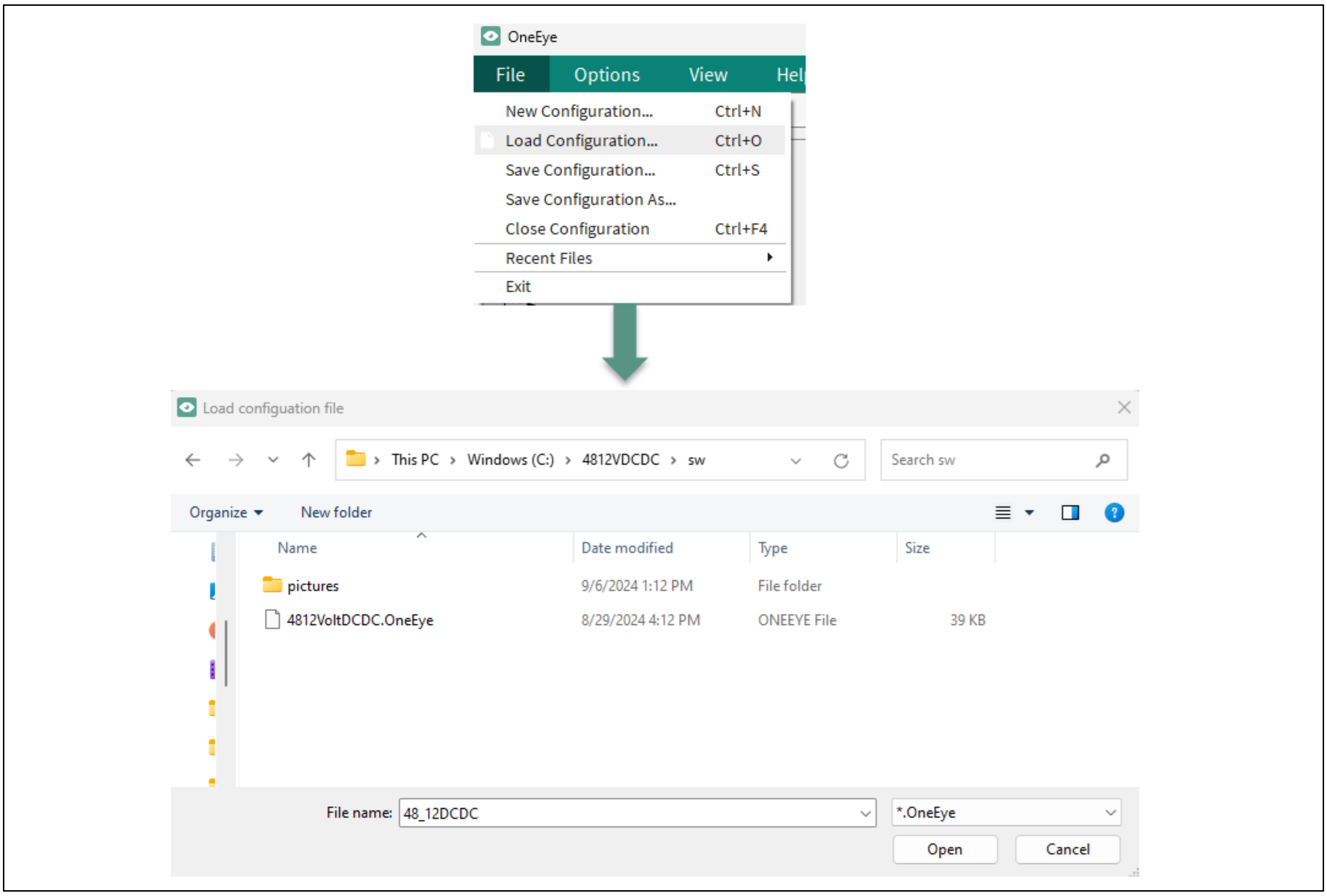

Figure 11 GUI software start

To establish communication between the PC and the TriBoard, first connect the board to the PC using a USB cable, and then click the setup button as shown in Figure 12 after loading the configuration files as described above. Once communication is successfully established, the LED beside the setup button, as shown in Figure 12, will begin blinking alternately green and gray. Additionally, the 'Log box is available for viewing logs to debug any connection-related or other issues. To open the Log box, click on the 'View' menu and select 'Log box', as depicted in Figure 13.

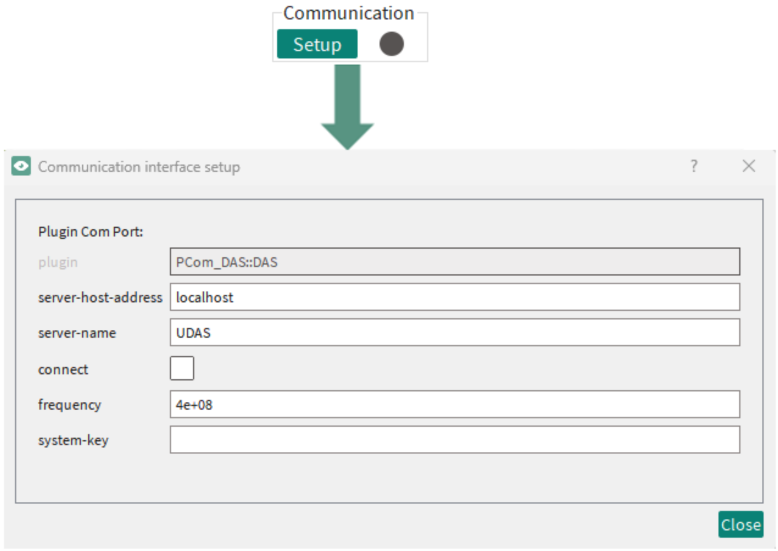

Figure 12 Communication settings

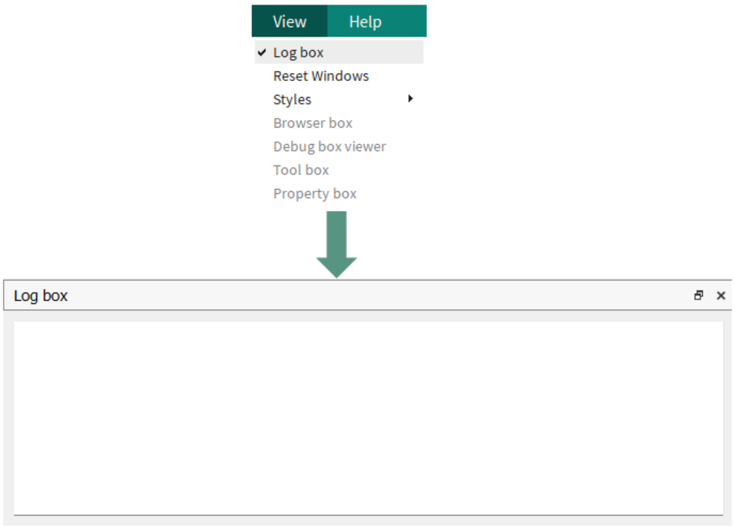

Figure 13 Log box

Once the communication is running successfully, click on the run button as shown in the Figure 14.

Figure 14 Run button and current state indicator on the GUI

2.3.2.3 Starting the System: Run Button Actions and Firmware States

Upon launching the GUI, the default 'Stopped' state is displayed, indicating that the firmware is in the IDLE state with no active processes, as this is the standard state when the system is not running.

Pressing the 'Start' button, depicted in Figure 14, triggers the SOFTSTART and Setup phases on the TriBoard firmware, which are presented as the 'Starting' state on the GUI, as detailed in Table 2. Once the startup process completes successfully, the firmware advances to the RUN state, mirrored on the GUI as the 'Running' state, also detailed in Table 2. In the event of an error, as described in 2.3.2.4, the firmware enters the ERROR state. To gain a deeper understanding of the firmware's state machine, please see Figure 8.

Table 2 - Correlation between GUI indicators and firmware states

States in firmware	States in GUI
IDLE	● Stopped
SOFTSTART	● Starting
RUN	● Running
ERROR	● Error
SETUP	● Stopped

2.3.2.4 Error States and Notifications

The GUI displays various error notifications including input over/under voltage, output over/under voltage, and input/output overcurrent, as visualized in Figure 15 within the fault section.

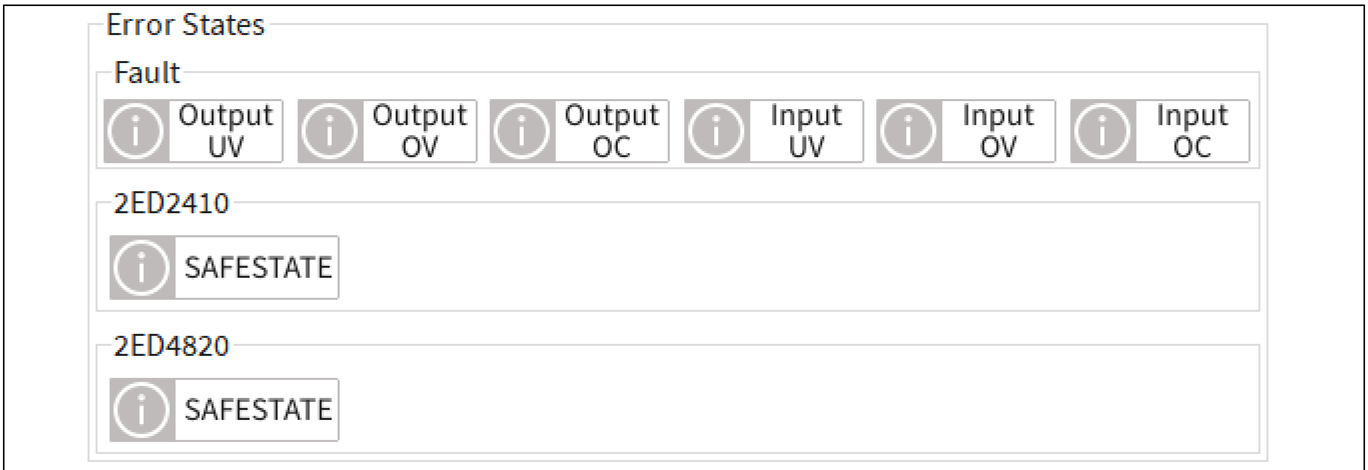

Figure 15 GUI error states notifications

These errors are often short-lived, appearing for only a few milliseconds, making them difficult for users to detect. To improve visibility, the GUI captures and displays these fleeting errors for user awareness. Pressing the 'Clear Error Reset' button, as shown in Figure 16, will revert the errors to their current state—if no errors are present at the time of pressing, the notifications will clear. If the errors do not exist during the time when button is pressed, it will disappear.

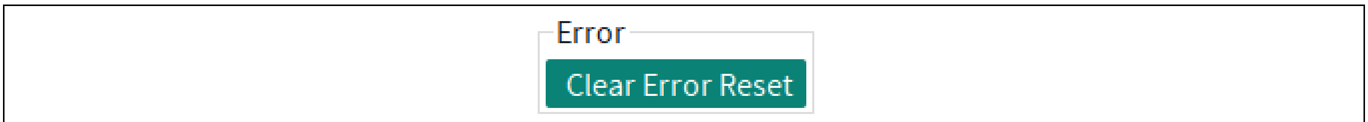

Figure 16 Clear Error Reset button

Table 3 illustrates the difference between the 'Active error state' and the 'No error state' with respective graphics. Additionally, errors related to gate drivers, such as the 2ED2410-EM and 2ED4820-EM, are displayed in Table *3* under their respective sections. Should any errors occur within these gate drivers, the 'SAFESTATE' will enter an 'Active error state'. For comprehensive details regarding these gate driver errors, please consult the user manuals for each model.

Table 3 - Active and inactive error states

Active error state	
No error state	

2.3.2.5 Operating the Graph

The graph as depicted in Figure 17 is used as a visual tool for monitoring input/output voltage and current levels. To closely examine specific data, position the cursor within the graph's canvas area and use the mouse wheel to zoom in or out. The y-axis, located on the graph's left side, displays values ranging from -10 V/A to +70 V/A, which are the default range settings for visualization. To visualize broader view of the data, utilize the zoom feature. The x-axis is measured in seconds, and by default, ten divisions are visible. This enables the simultaneous visualization of a ten-second data span.

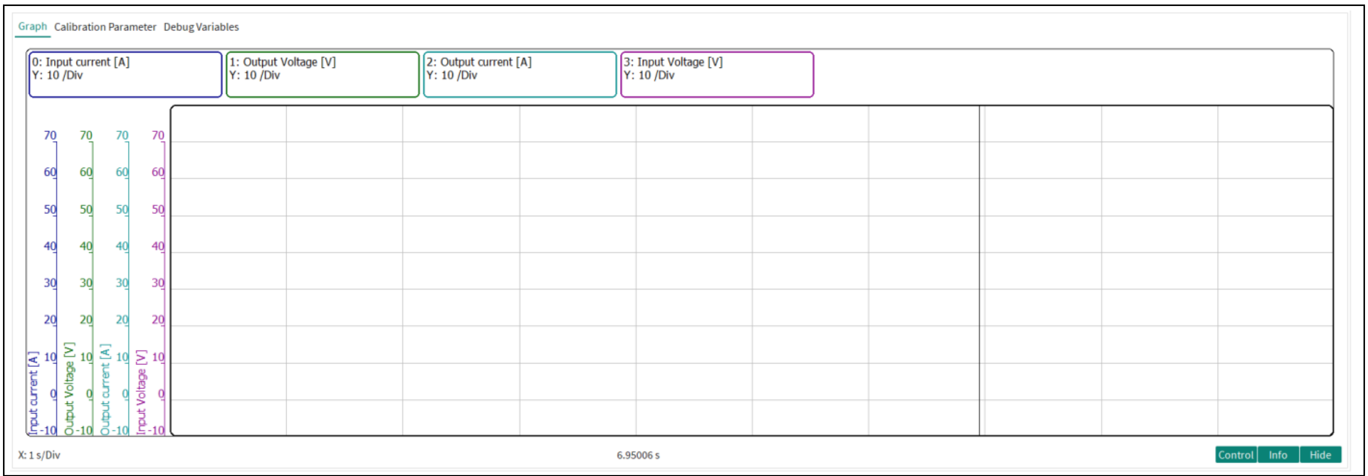

Figure 17 Interactive graph for voltage and current visualization

2.4 Improving measurements results

The current sensing amplifier on 2ED4820-EM will introduce a large measurement unreliability for currents below 5 A considering the measurement shunt used of 1 mΩ. To improve the accuracy of the current sensing, a calibration method will be described next. The output of the current sensing amplifier is almost linearly dependent of input supply voltage, in this application from 36 V to 60 V, and of input current. We consider a bilinear interpolation of input supply voltage and of input current to obtain a result with a better precision. For performing the calibration, a voltmeter measuring the input voltage and an ammeter measuring the input current are necessary. For this example, the indication on the power supply was used for this purpose. To find the necessary coefficients, 4 measurements should be performed. At 36 V for two different currents and at 60 V for two different currents. For ease we can consider the load in constant power output and we set it for 100 W and 300 W respectively. The user should input in the Calibration section of the GUI the value returned from the internal ADC and also the measured input current value.
In Figure 18, the user should enter in y11 the value of the current read from the ammeter and in the cell y11adc the current value read from the internal ADC from cell. The values should be entered monotonically with index 11 for 36 V and 100 W, index 12 for 36 V and 300 W, index 21 60 V and 100 W, and index 22 60 V and 300 W.

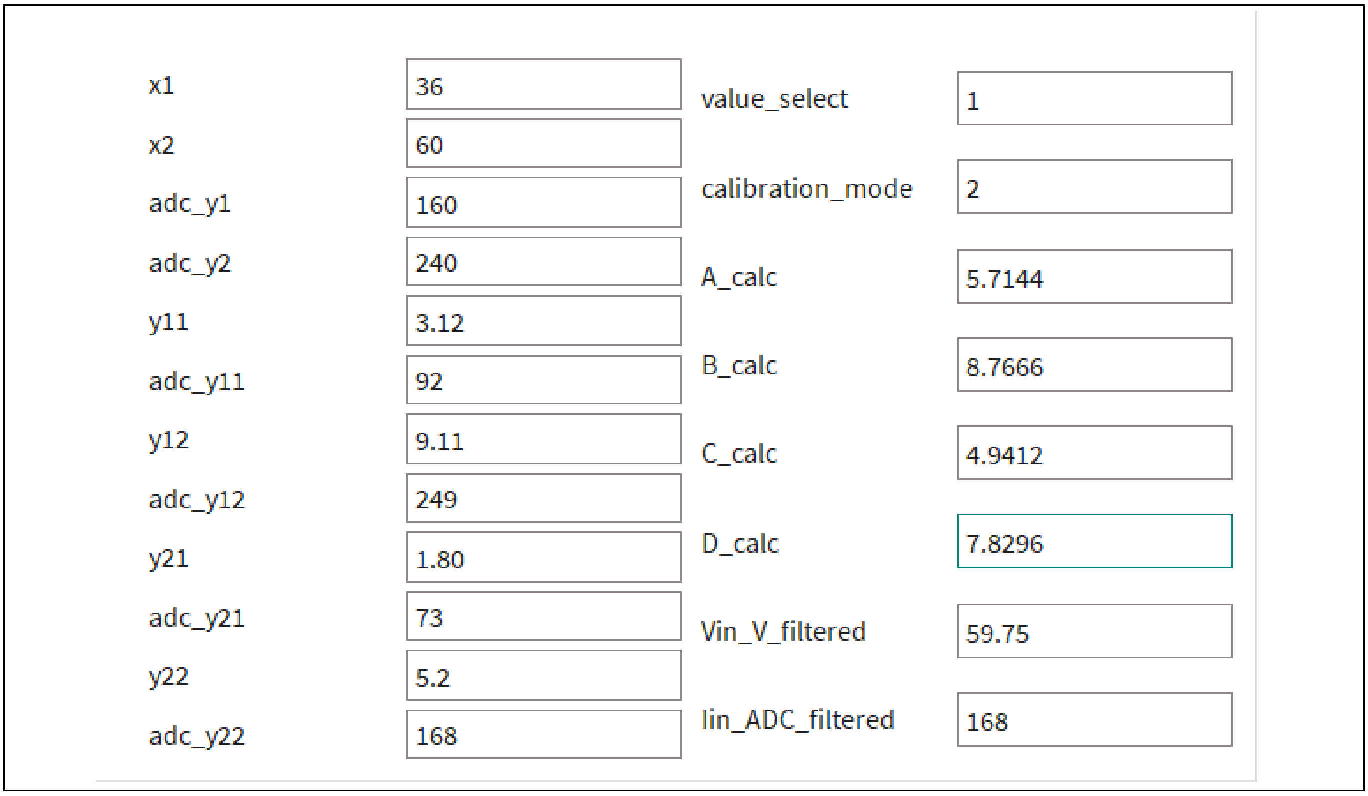

Figure 18 OneEye GUI cells used for calibration

Using these recommended values the values read from the ammeter should be close to the ones presented in Figure 18. The coefficients for the interpolation are automatically calculated in the cells on the right. Using these coefficients the read value should be in an interval of ±0.1A of the value read on the ammeter used to do the calibration. To make these four values in A_calc, B_calc, C_calc and D_calc persistent, the configure board script provided in the software package should be used by selecting option “2. Add a new interface board SN and calibration parameters”. Using the same tool the user can also revert to the default values, or use an existing calibration dataset.

3 System design

3.1 Schematics

3.1.1 Schematics of DC-DC converter board

3.1.1.1 Top_Level.SchDoc

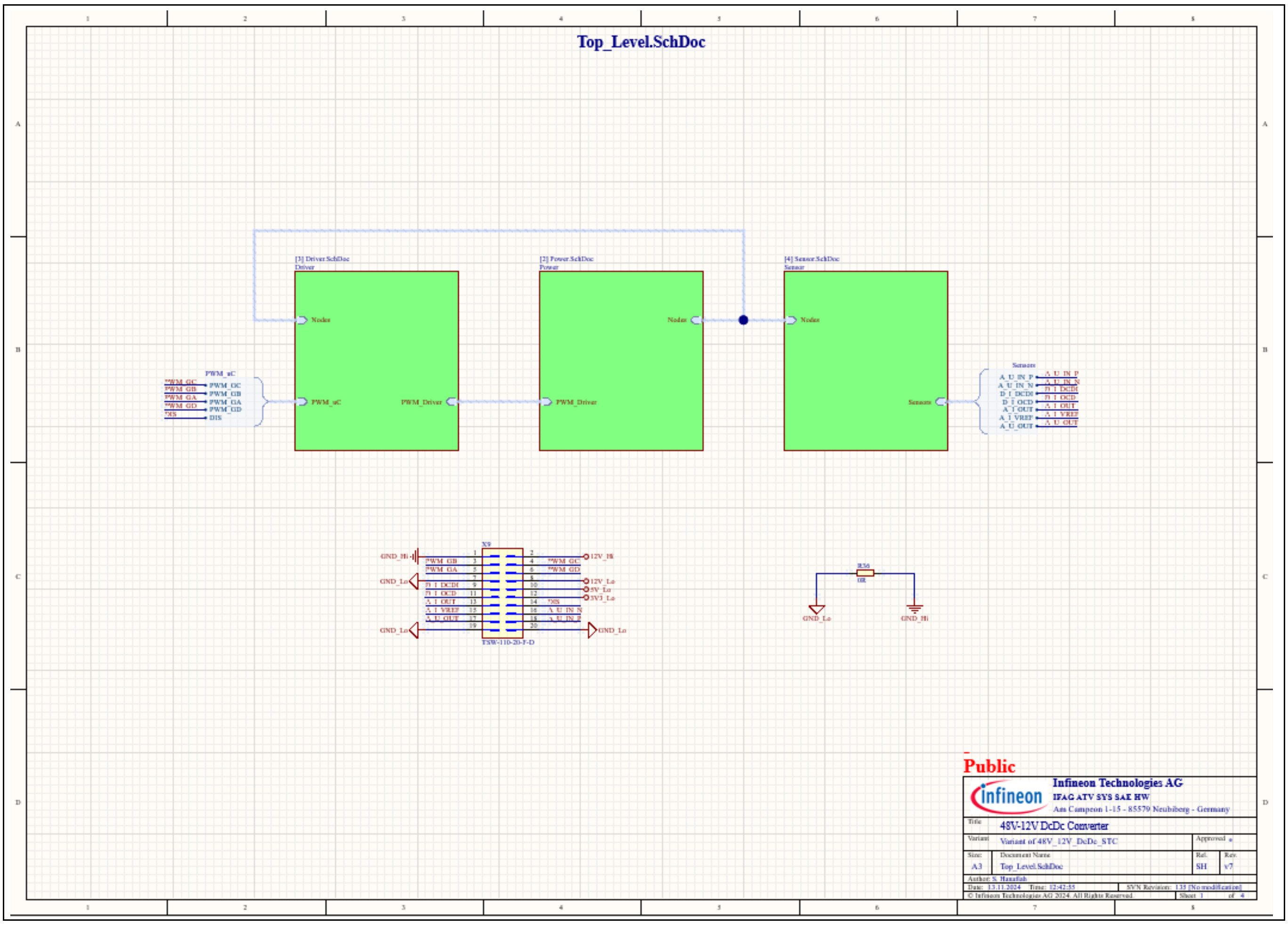

Figure 19 Schematics Top_Level.SchDoc

3.1.1.2 Power.SchDoc

The topology chosen for this ZCU application is the 4 to 1 Switched Tank Converter (STC) topology (see Figure 20) originally proposed by Google for data center application [9]. The topology consists of four flying switches and six synchronous rectification (SR) switches. The two physical resonant tanks must be designed in such a way so that their resonant frequencies are approximately equal. The switching frequency is then set slightly below the lowest resonant frequencies of both the resonant tanks to ensure zero current switching (ZCS) of the SR switches.

The stray inductances (coming from the PCB traces) of the two resonant tanks in our design differ by more than 100% where the lowest simulated stray inductance at close to the switching frequency is about 21 nH and the highest is about 55 nH. This difference makes it difficult to design resonant tanks that have similar resonant frequencies. To alleviate this problem, a discrete inductor which inductance value is higher (e.g. 100 nH in our design) than the stray inductance is added to each resonant tank. With the addition of the discrete inductor, the difference between the minimum and maximum resonant inductances becomes roughly 30%.

STC topology requires two different PWM signals, i.e. PWM_GA and PWM_GB. There are also two different modes, i.e. mode 1 when PWM_GA = 1 and PWM_GB = 0 and mode 2 when PWM_GA = 0 and PWM_GB = 1. In mode 1, the resonant capacitor of tank 1 consists of only capacitors connected to NODE_3. The resonant capacitor of tank 2 consists of a series connection of capacitors connected to NODE_2 and NODE_1. In mode 2, the resonant capacitor of tank 1 consists of a series connection of capacitors connected to NODE_3 and NODE_2. The resonant capacitor of tank 2 consists of only capacitors connected to NODE_1. For this reason, it is very important to have capacitance connected to NODE_2 (a lot) higher than the capacitance connected to either NODE_1 or NODE_3 so that the resonant capacitances of both resonant tanks would be similar in both modes. This will at the end ensure similar resonant frequencies of both resonant tanks. It is also very important to consider the dc bias characteristic of the MLCCs when designing the resonant tanks.

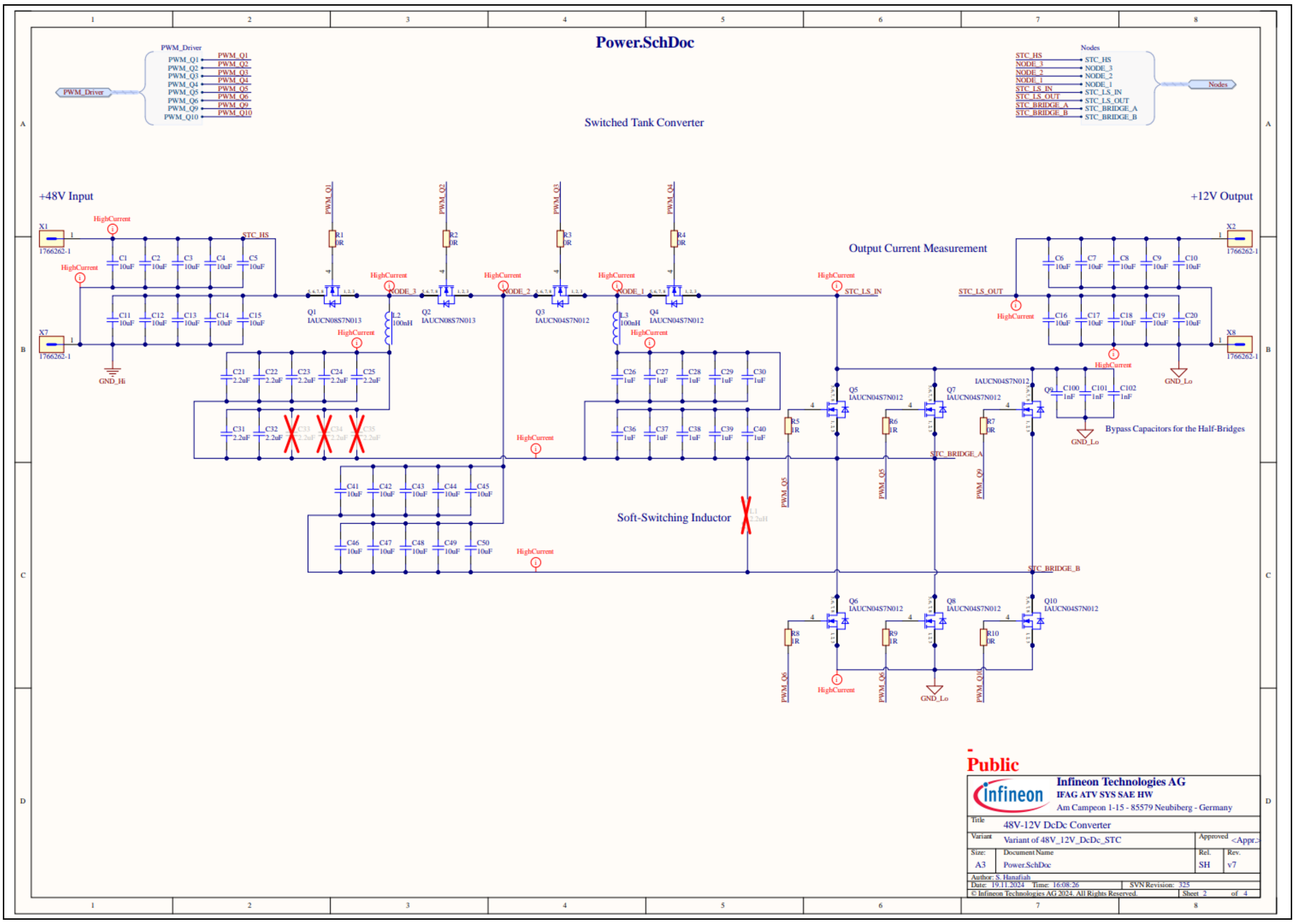

Figure 20 Schematics Power.SchDoc

3.1.1.3 Driver.SchDoc

To drive the four flying switches, a charge pump circuit is implemented (see Figure 21). For the SR switches, bootstrap circuit is implemented. Because switches Q5 and Q7 (also switches Q6 and Q8) are connected in parallel, a single gate driver is used to drive both SR half-bridges.

As mentioned before, two complementary PWM signals are needed to operate an STC. According to a research paper [10], it is possible to phase-shift the PWM signals of MOSFET Q1 and Q4 to improve the efficiency of the converter, i.e PWM_GC and PWM_GD. This strategy has not been implemented in the current software version.

The bootstrap diode of the first bootstrap circuit D2 shall be a 100 V Schottky diode to prevent potential damage to it. During start-up, when all the node voltages are still equal to 0 V, D2 will see the full input voltage.

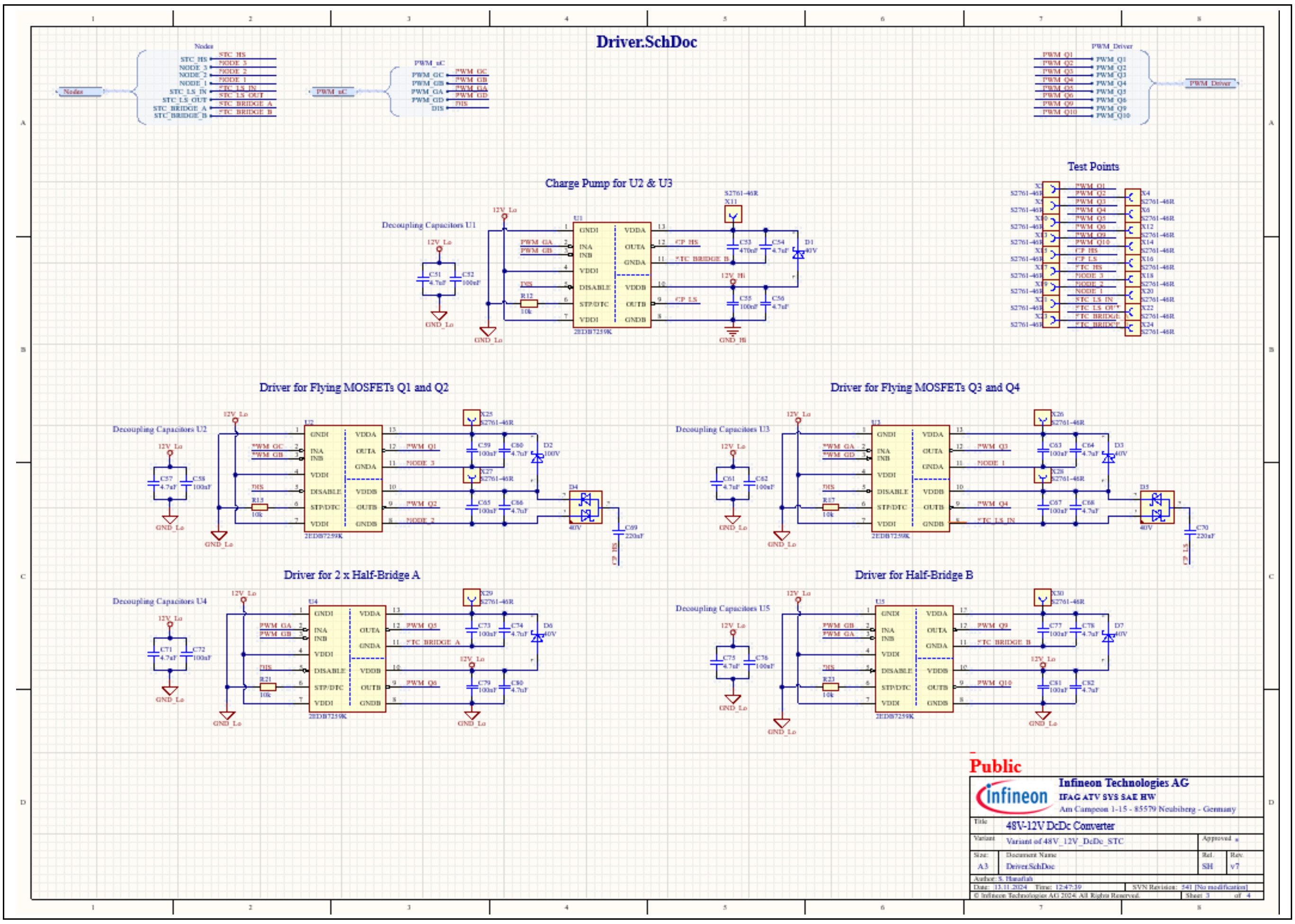

Figure 21 Schematics Driver.SchDoc

3.1.1.4 Sensor.SchDoc

For the input voltage measurement, an isolated operational amplifier (op-amp) is used (see Figure 22). In case of failure at the input side, the microcontroller will still be protected. The supply voltages of the input side and output side of the operational amplifier, i.e. 5V_Hi and 5V_Lo, are separated to provide further isolation. The 5V_Hi is obtained by using Infineon voltage regulator TLE4264.

For the output voltage measurement, a simple voltage divider is implemented.

For the output current measurement, a high accuracy coreless current sensor from Infineon TLE4973 is used to measure the dc output current. The current sensor can be calibrated by using the SENXIV™ TLx4973 Current Sensor Programmer. At the moment, no information from the current sensor is used in both the hardware and software of this reference design.

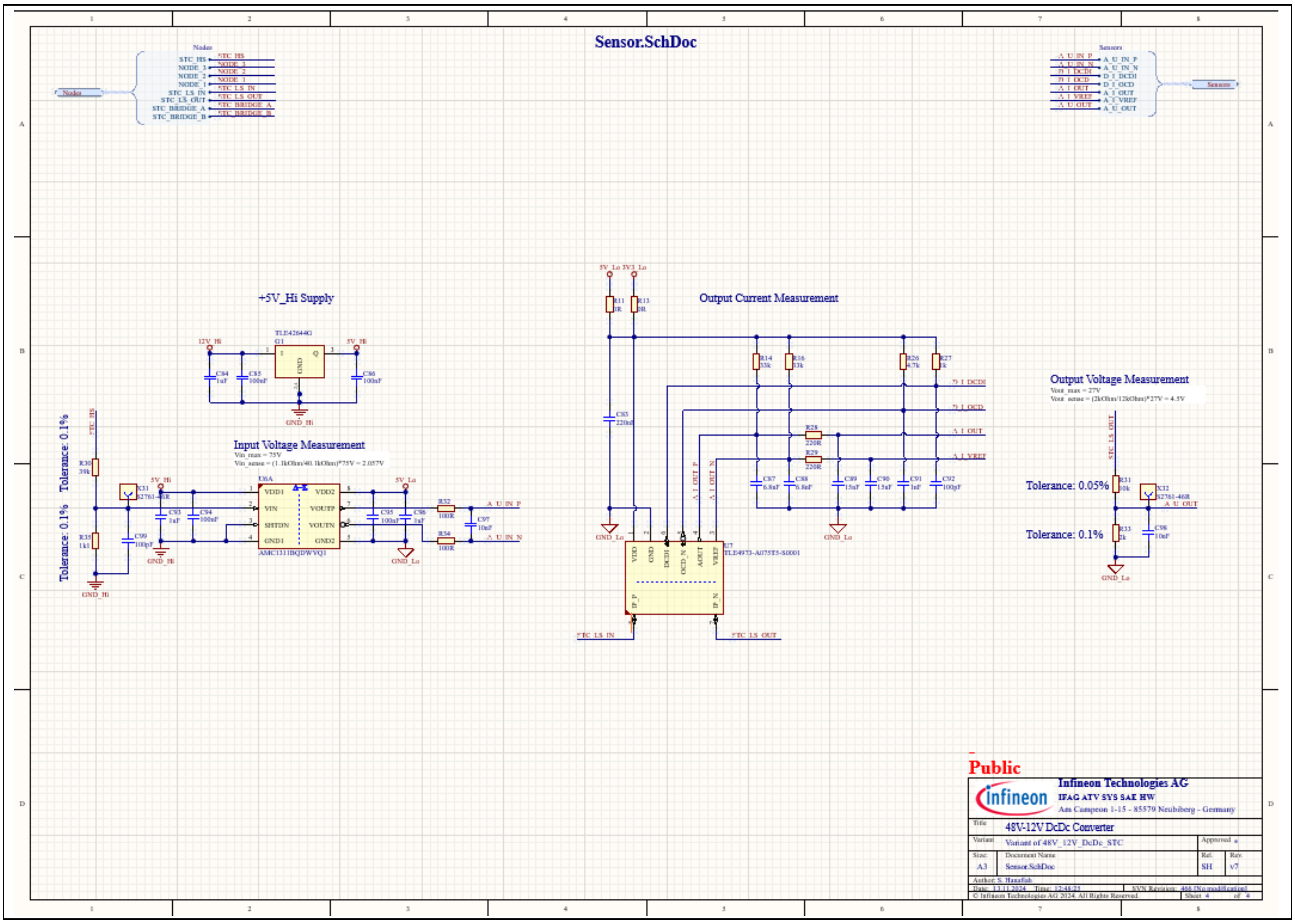

Figure 22 Schematics Sensor.SchDoc

3.1.2 Schematics of interface board

3.1.2.1 Top_Level.SchDoc

The Infineon AURIX™ TC4x – TriBoard requires 12 V supply provided by the interface board. On the other hand, the 5 V supply for the DC-DC converter board, i.e. 5V_Lo, will be provided by the TriBoard (X703 pin 69).

A hardware over-current detection (OCD) is implemented on the interface board. This OCD signal is coming from the TLE4973 current sensor on the DC-DC converter board. To avoid wrong detection of an over-current event, this functionality is deactivated by unsoldering R105 (see Figure 23).

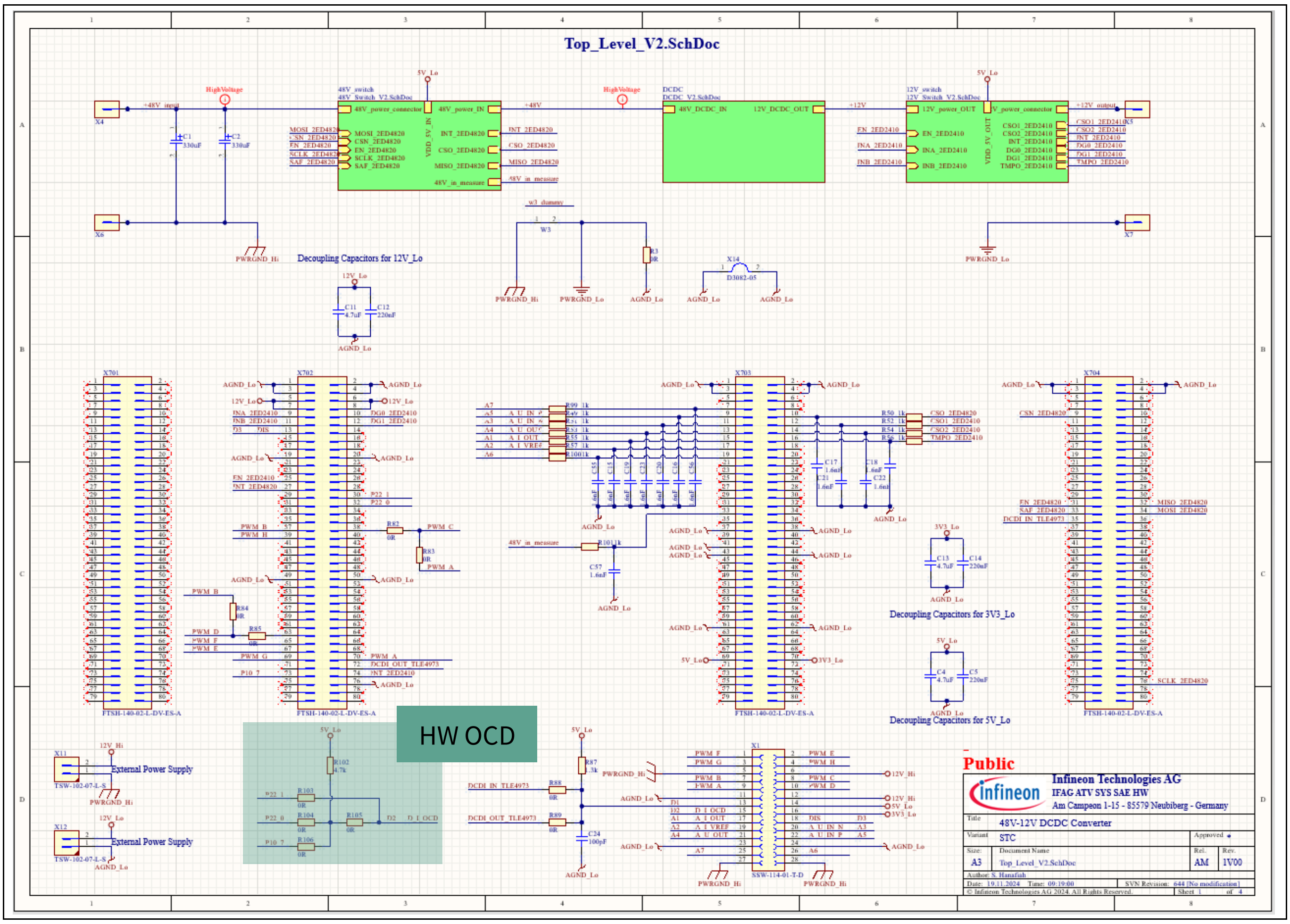

Figure 23 Schematics Top_Level_V2.SchDoc

3.1.2.2 48V_Switch.SchDoc

The input safety switch is driven by the dedicated safety gate driver from Infineon 2ED4820-EM. SPI is used for communication between the gate driver and the microcontroller (MOSI_2ED4820, MISO_2ED4820, SCLK_2ED4820, and CSN_2ED4820).

To be able to measure the input voltage before the MOSFET, an operational amplifier circuit is implemented (see Figure 24). This input voltage measurement is used in the state machine.

The dc input current measured by the 2ED4820-EM is displayed on the GUI and used in the software to limit the input current the system is able to draw.

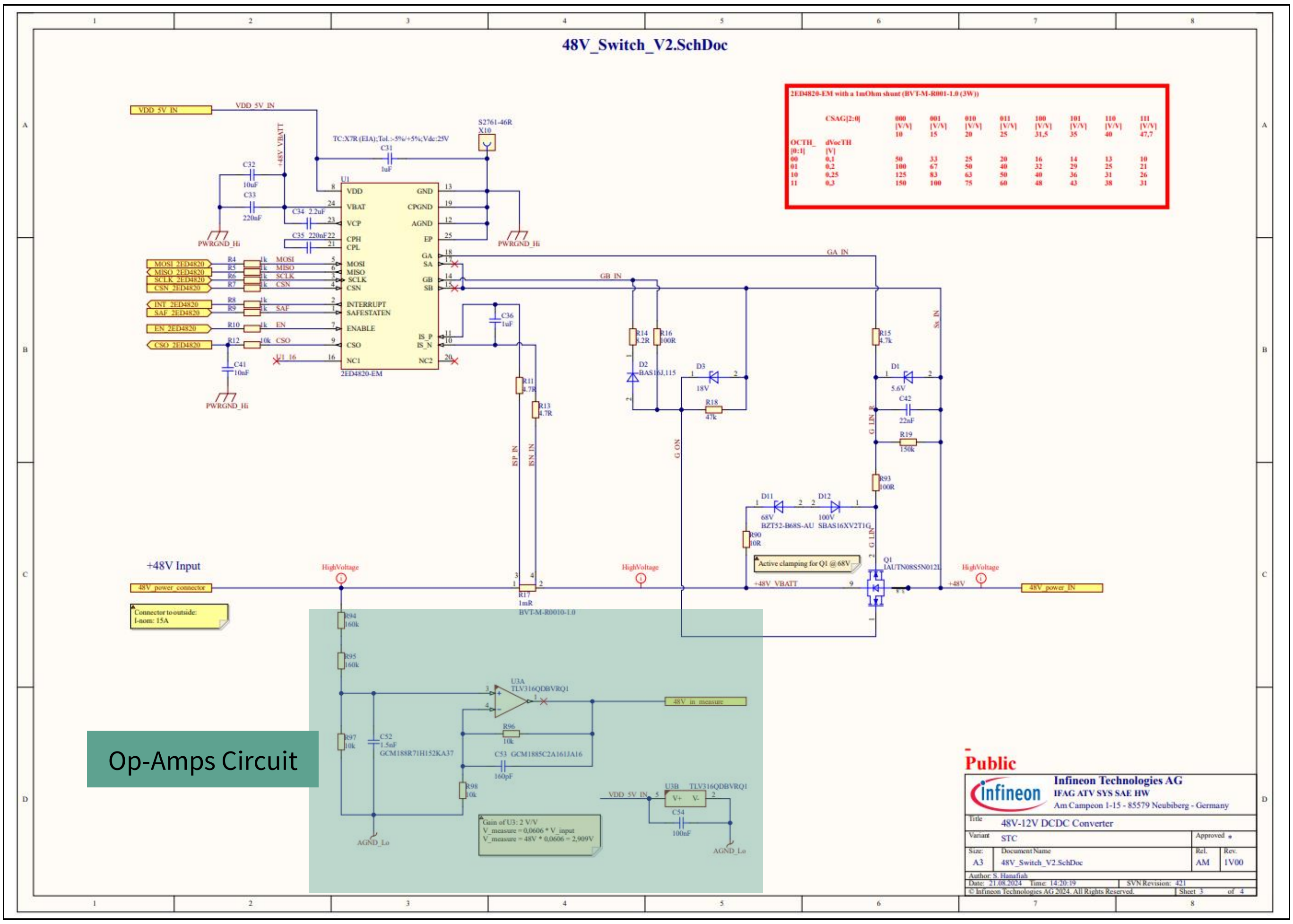

Figure 24 48V_Switch_V2.SchDoc

3.1.2.3 DCDC.SchDoc

To provide the 12 V supply for the whole system, three power supply ICs from Infineon TLS5112C0EPV are used. Each IC can supply about 1 A. One IC is used to supply 12 V to the DC-DC converter board and two ICs in parallel are used to supply 12 V to the TriBoard. An electrical connection between the input terminal X4 and the cathode of D9 is provided physically on the interface board (see the red cable in Figure 6 and compare it with Figure 25) so that the start-up of the system can work properly.

The output capacitors (C6-C10) 11 mF are meant to represent capacitive load of the 12 V network.

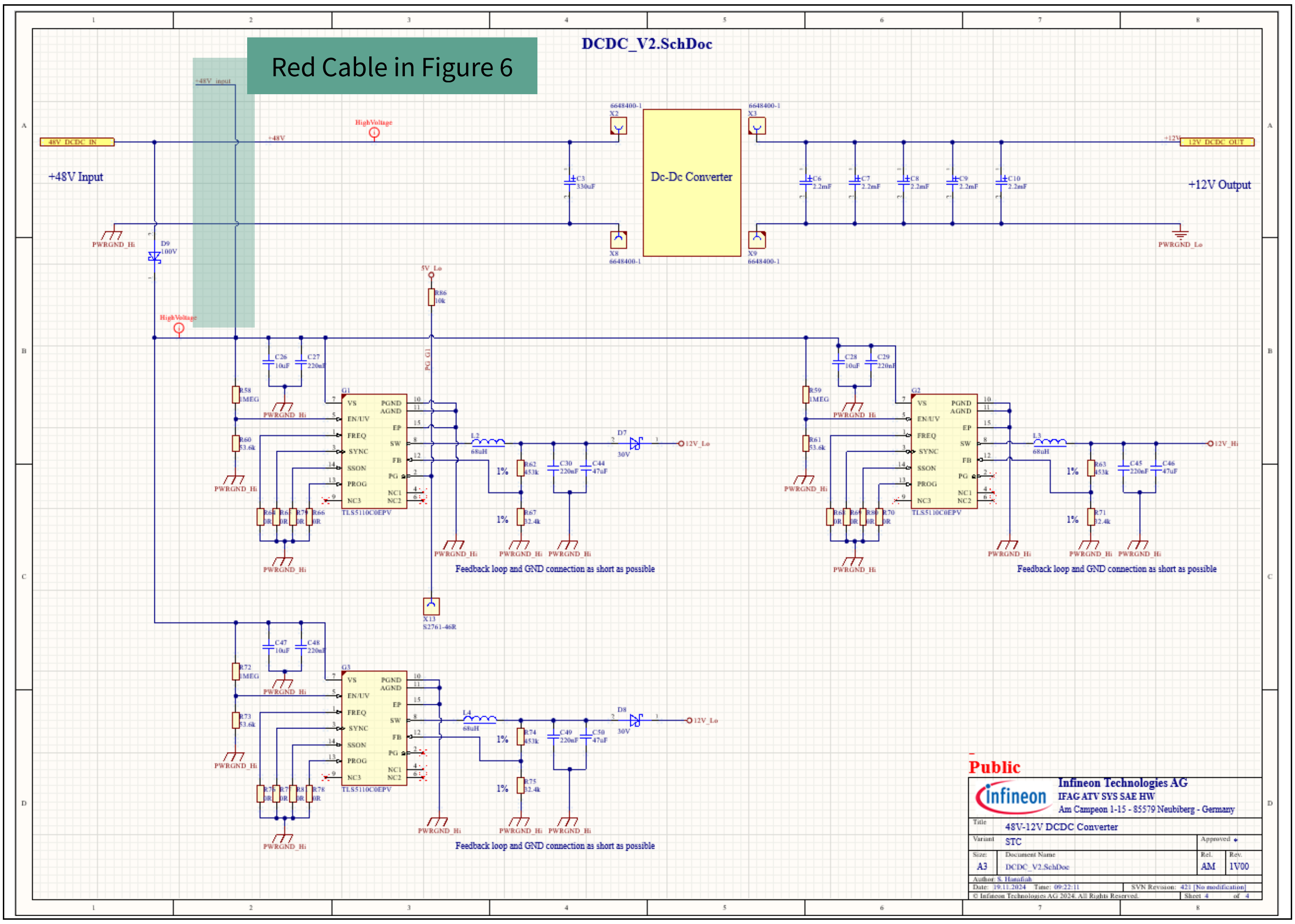

Figure 25 Schematics DCDC_V2.SchDoc

3.1.2.4 12V_Switch.SchDoc

The output safety switch with three MOSFETs connected in parallel are driven by a single dedicated safety gate driver from Infineon 2ED2410-EM. Only enable signal (no SPI communication) from the microcontroller is required to drive the switches.

The dc output current measured by the 2ED2410-EM is displayed on the GUI and used in the software to limit the output current the load is able to draw.

The temperature of the interface board is measured by using an NTC (see Figure 26) placed close to one of the dual gate MOSFETs.

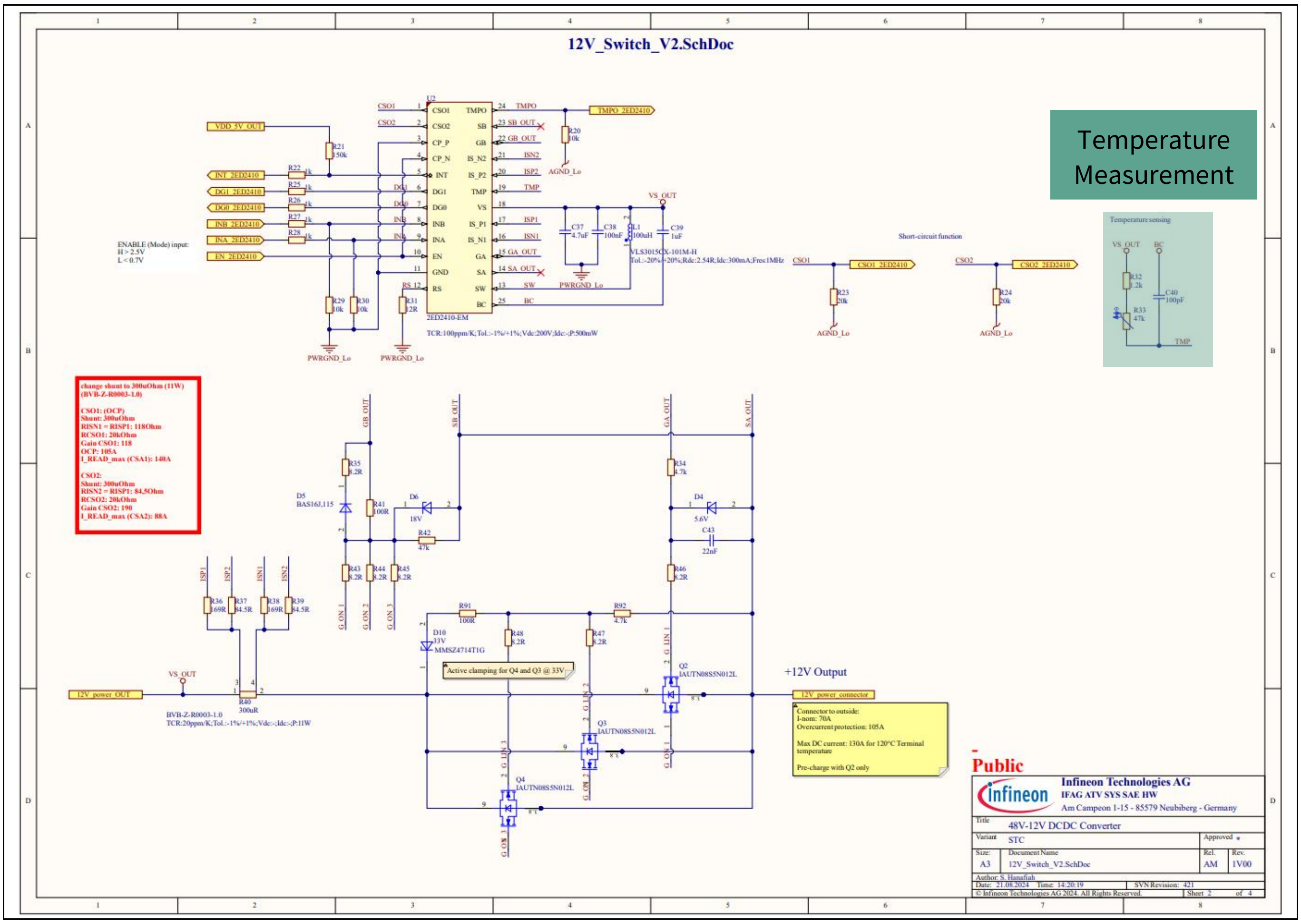

Figure 26 Schematics 12V_Switch_V2.SchDoc

3.2 Layout

3.2.1 Layout of DC-DC converter board

The PCB of the DC-DC converter board consists of 10 layers. The layer stack can be seen below in Figure 27. Layer 1 to layer 4 are used mainly for the power path of components located on the top side (see Figure 28, whereas layer 7 to layer 10 are used mainly for the power path of the components located on the bottom side (see Figure 30). Gate signals are mainly routed on layer 5, whereas the return paths of the gate signals are routed directly below them on layer 6 (see Figure 29).

The thickness of the outer copper layers is 4 oz / 140 µm, whereas the thickness of the inner copper layers is 5 oz / 175 µm. The outer copper layers are made thinner on purpose because many of the active components (e.g. MOSFETs and gate drivers) do not have the minimum required spacing between pads to accommodate a 5 oz / 175 µm layer design (i.e. for a 5 oz / 175 µm layer design, the distance between the pads should be wider). The inner copper layers are kept 5 oz / 175 µm to accommodate the high current requirement of the application.

The placement of the top side components can be seen in Figure 31 and the bottom components in Figure 32.

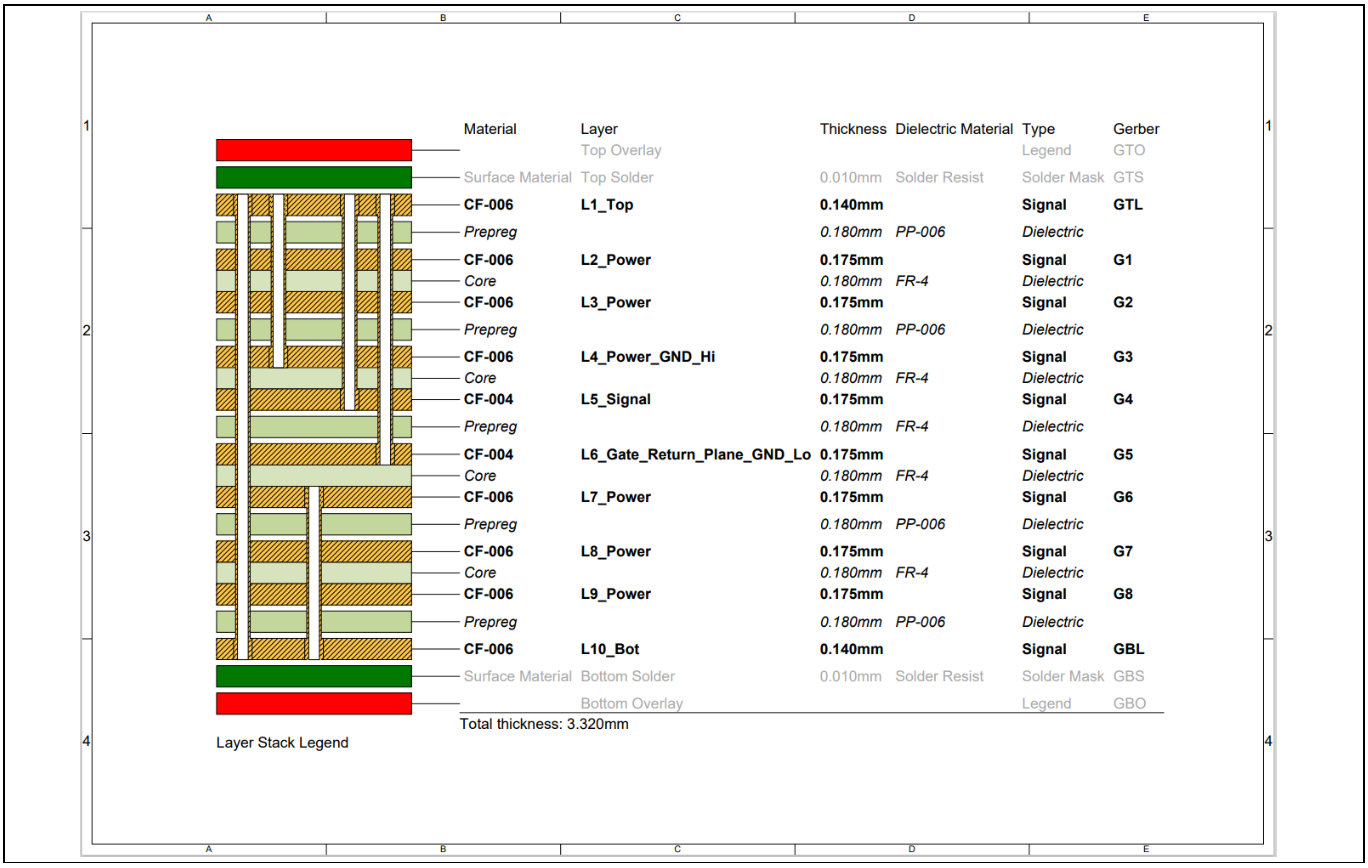

Figure 27 Layer stack of the DC-DC converter

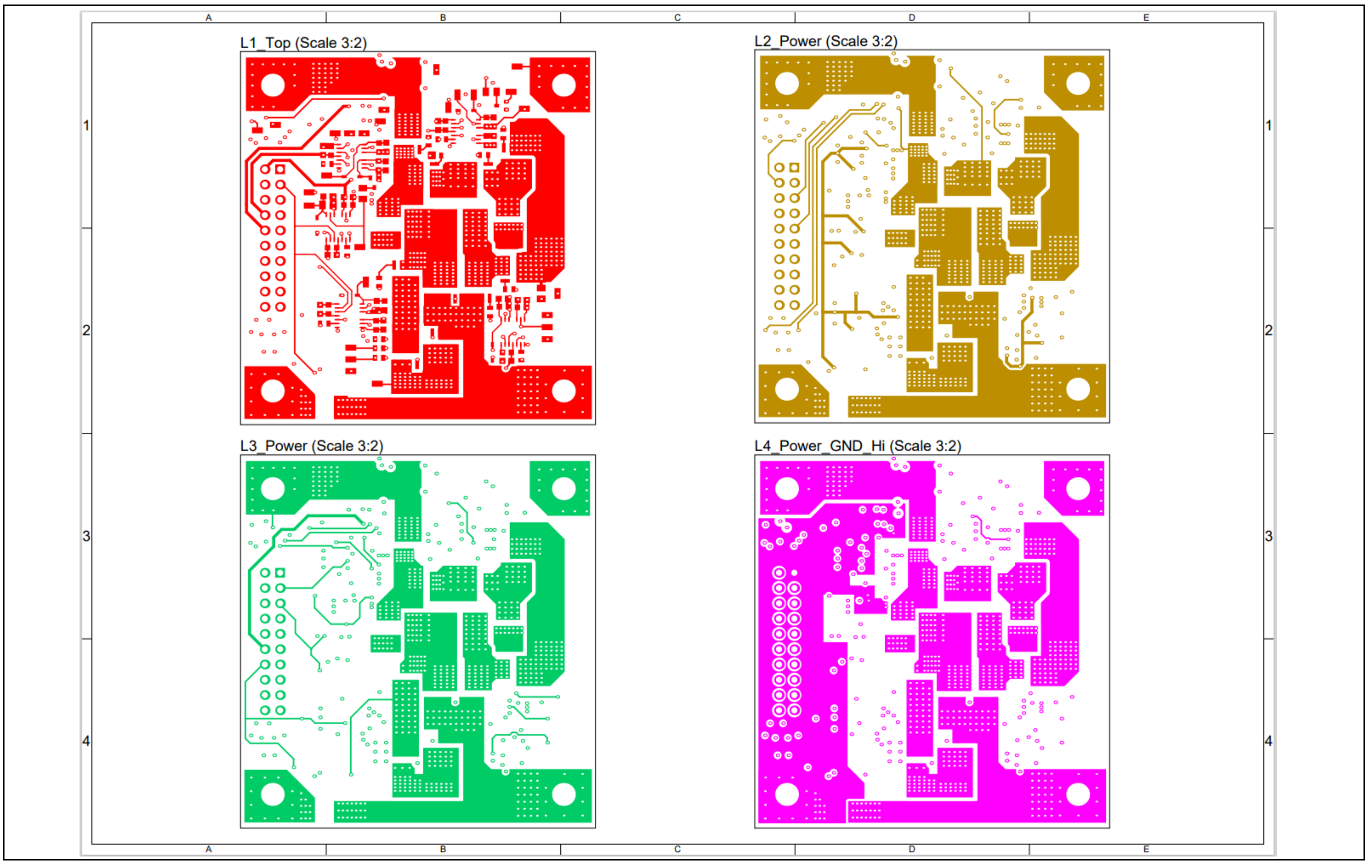

Figure 28 PCB layout of the DC-DC converter layer 1-4

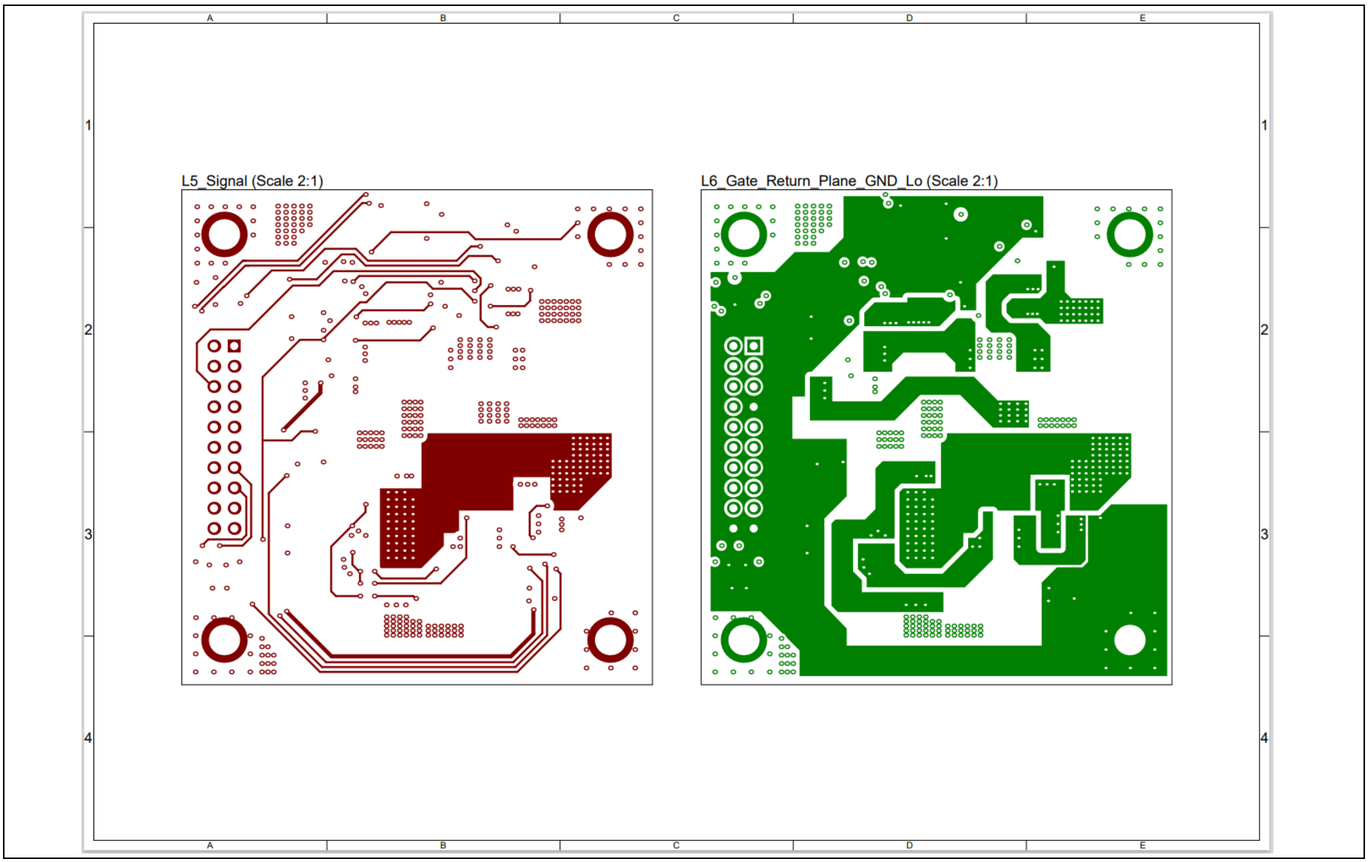

Figure 29 PCB layout of the DC-DC converter layer 5 and 6

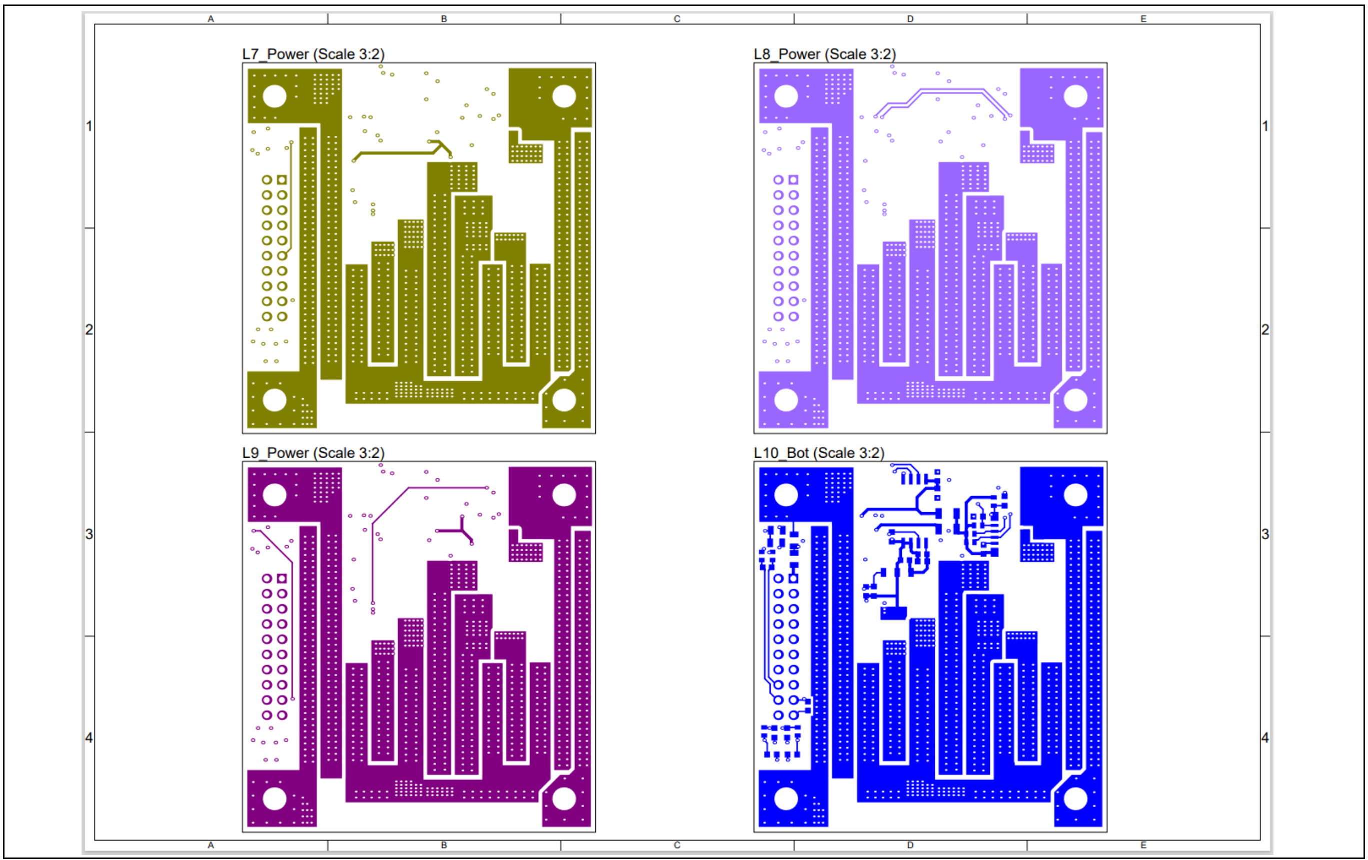

Figure 30 PCB layout of the DC-DC converter layer 7-10

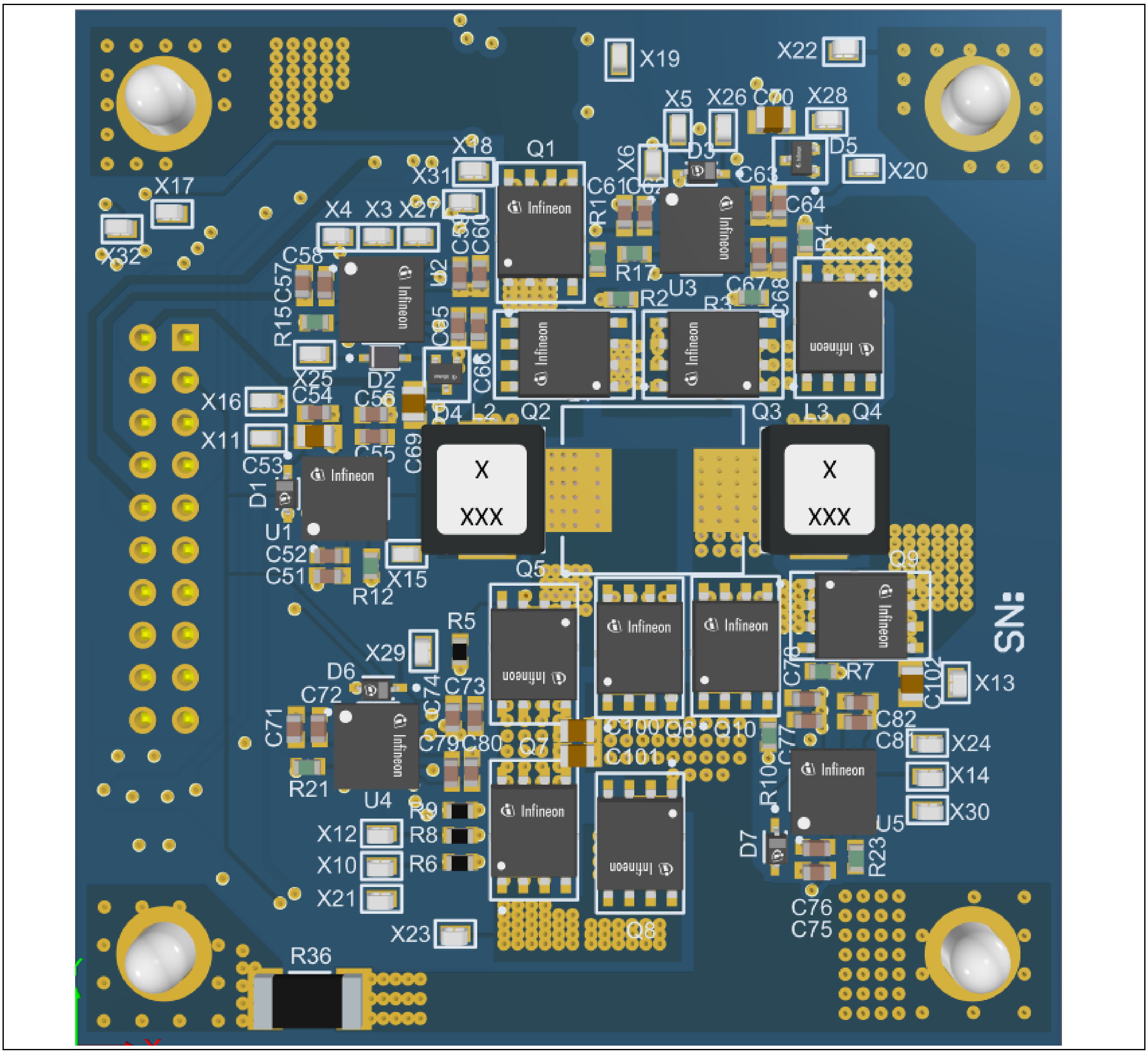

Figure 31 Placement of the top side components

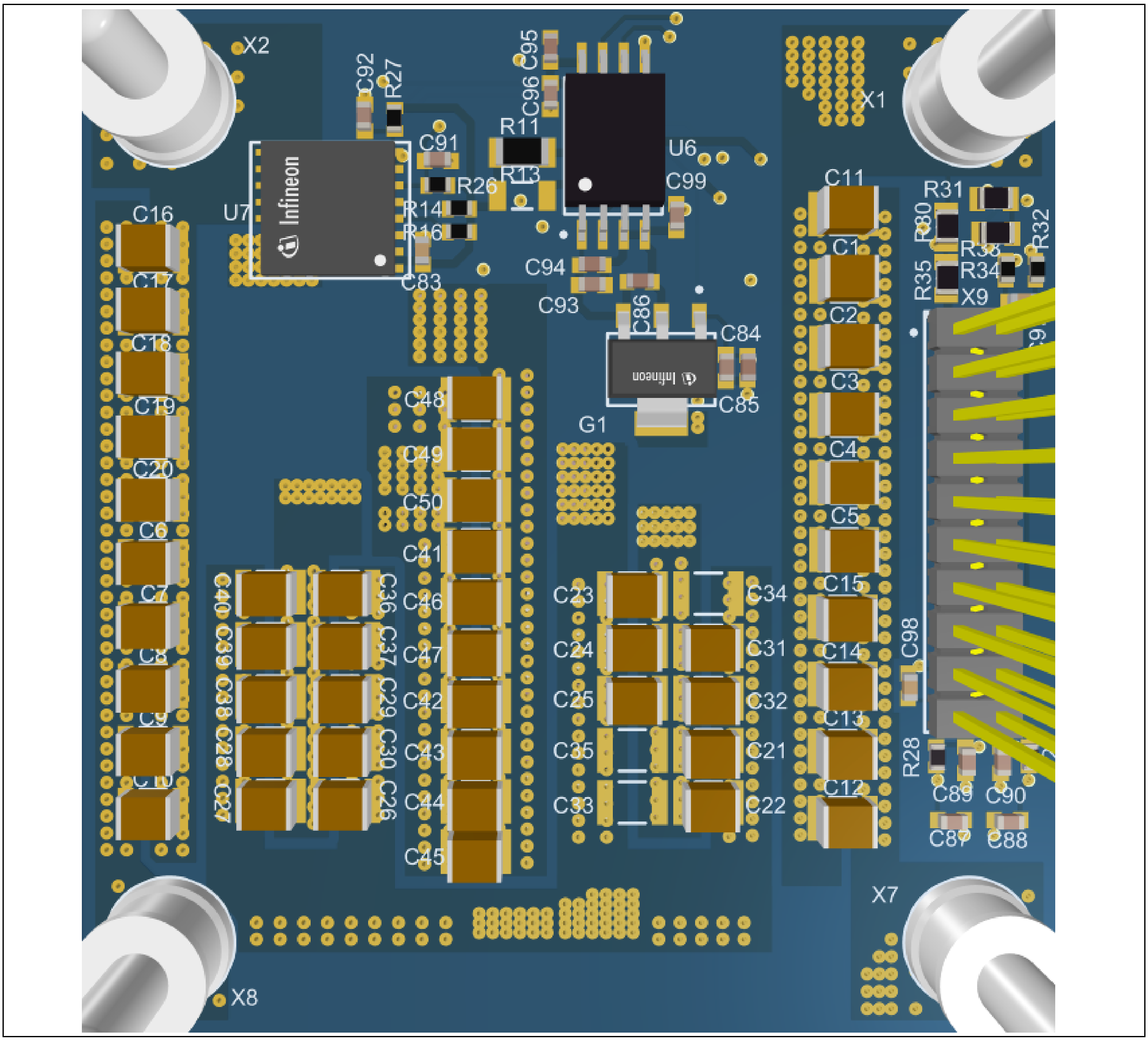

Figure 32 Placement of the bottom side components

3.2.2 Layout of interface board

The PCB of the interface board consists of 6 layers as can be seen below in Figure 33. Layer 1 and layer 2 are used for the power paths of components located on the top side (see Figure 34), while layer 5 and layer 6 are used mainly for the power paths of components located on the bottom side (see Figure 36). Signals are mainly routed on layer 3 and layer 4 (see Figure 35). All the layers have copper thickness of 3 oz / 105 µm.

The placement of the top side components can be seen in Figure 37 and the bottom side components in Figure 38.

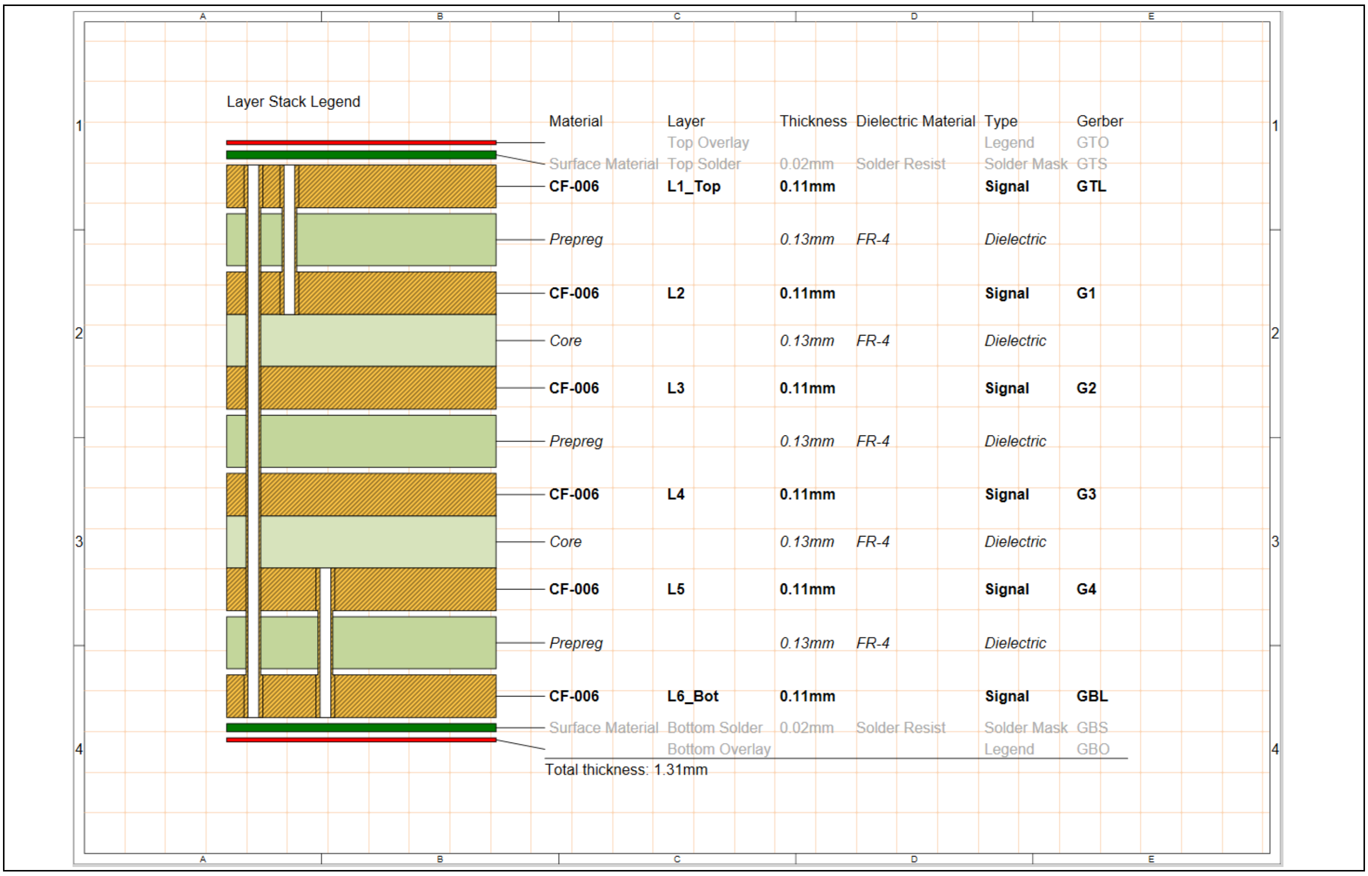

Figure 33 Layer stack of the interface board

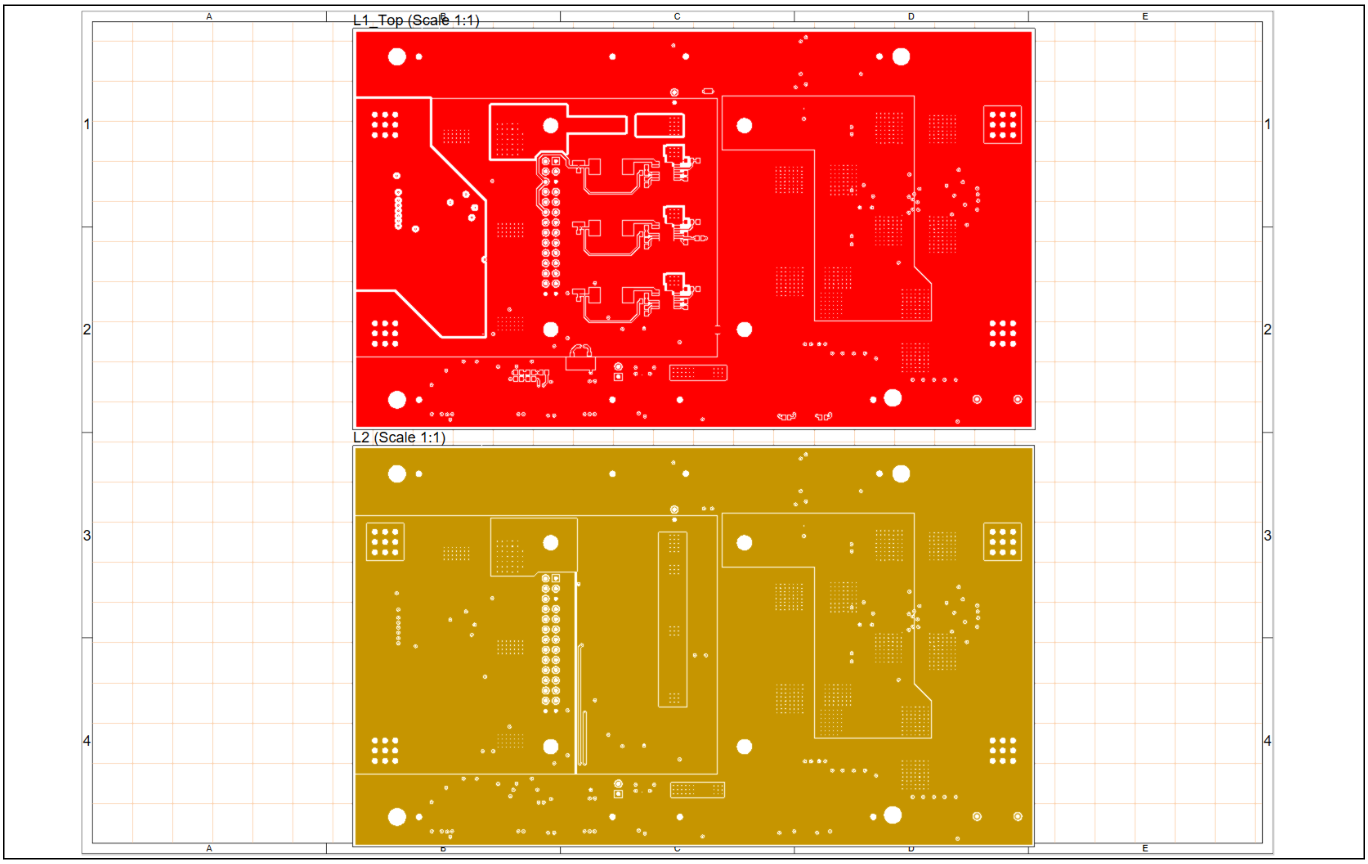

Figure 34 PCB layout of the interface board layer 1 and 2

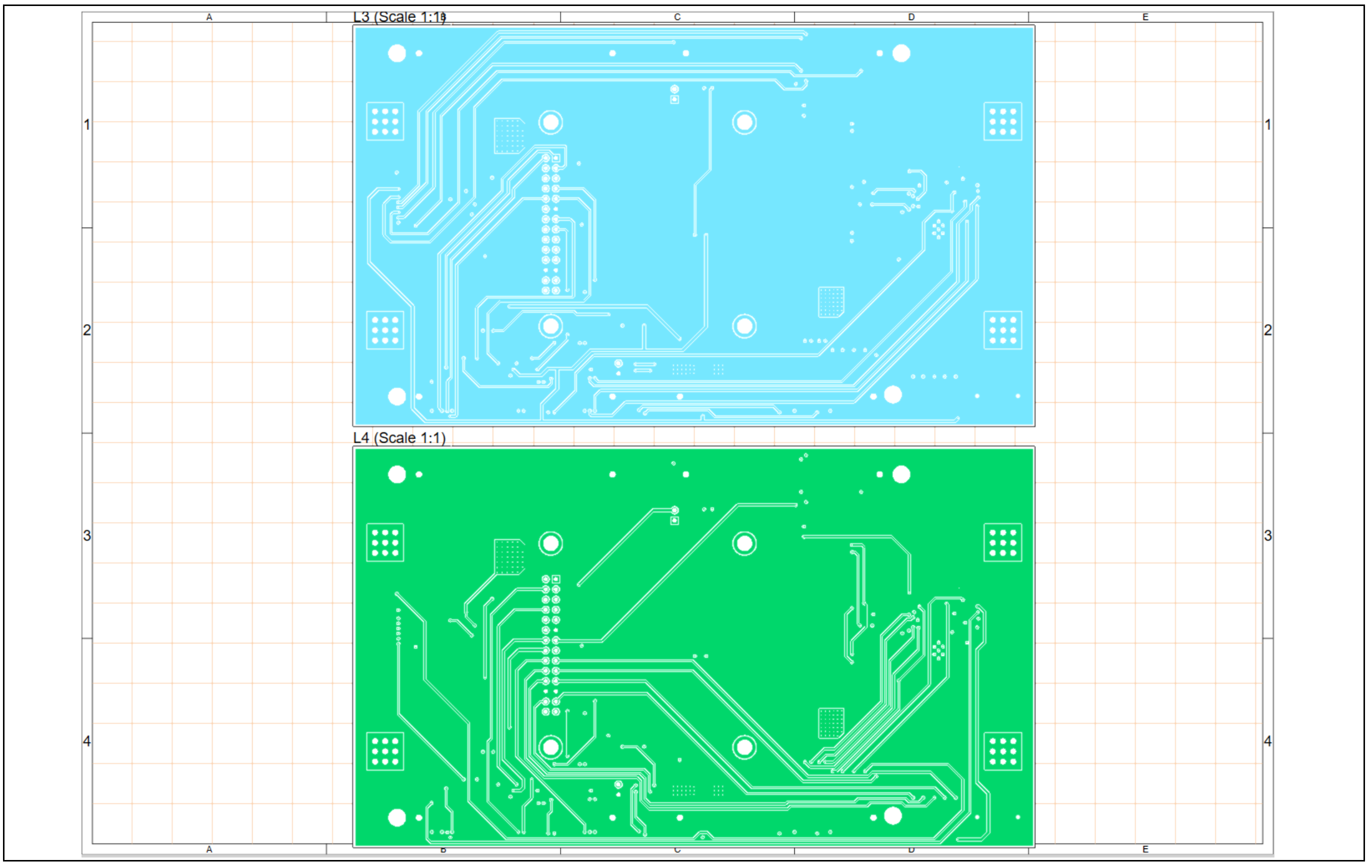

Figure 35 PCB layout of the interface board layer 3 and 4

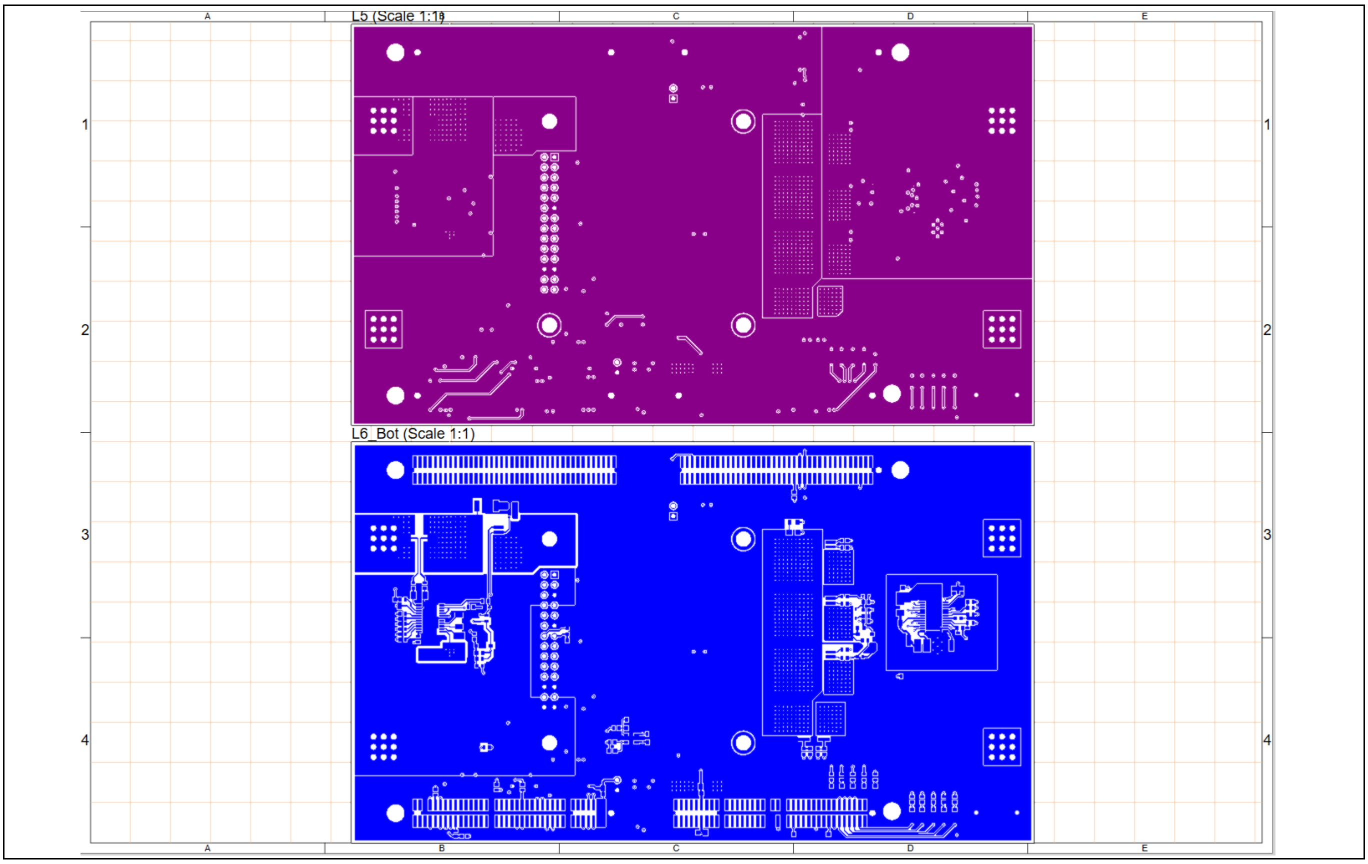

Figure 36 PCB layout of the interface board layer 5 and 6

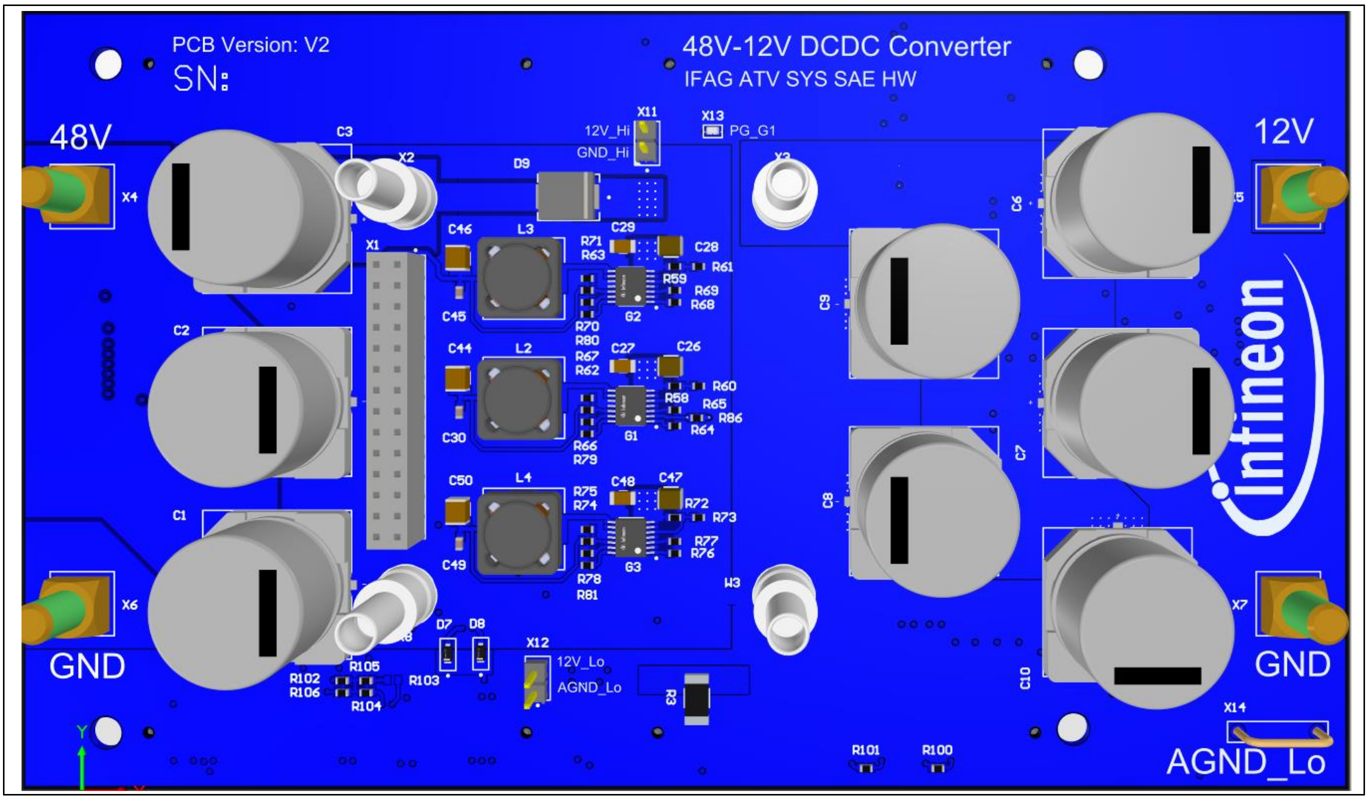

Figure 37 Placement of the top side components

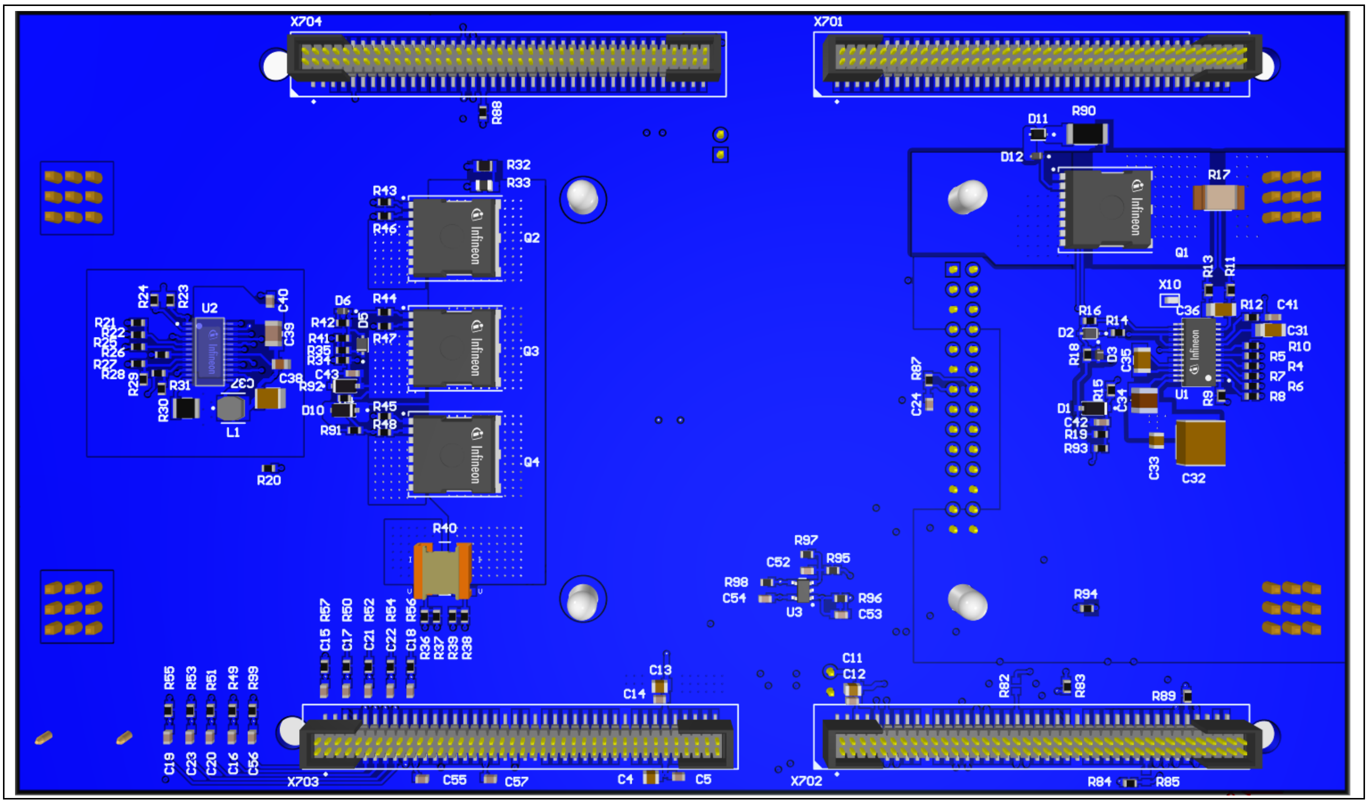

Figure 38 Placement of the bottom side components

3.3 Bill of material (BOM)

The complete bill of material is available on the download section of the Infineon homepage. A log-in is required to download this material.

Table 4 - BOM of the most important/critical parts of the DC-DC converter board

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N	Populated
5	C41, C42, C43, C44, C45, C46, C47, C48, C49, C50	10 µF 50 V X7R	Murata	GCM32EC71H106KA03L	Yes
6	C26, C27, C28, C29, C30, C36, C37, C38, C39, C40	1 µF 50 V X7R	Murata	GCM32ER71H105KA37L	Yes
8	Q1, Q2	OptiMOS™ 7 80 V	Infineon	IAUCN08S7N013	Yes
9	Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10	OptiMOS™ 7 40 V	Infineon	IAUCN04S7N012	Yes
10	L2, L3	100 nH	Coilcraft	SLC7649S-101KLC	Yes
14	U1, U2, U3, U4, U5	Dual-channel isolated gate driver	Infineon	2EDB7259K	Yes
44	C21, C22, C23, C24, C25, C31, C32	2.2 µF 50 V X7R	Taiyo Yuden	MCJCH32MAB7225KPPA01	Yes

Table 5 - BOM of the most important/critical parts of the interface board

S. No.	Ref Designator	Description	Manufacturer	Manufacturer P/N	Populated
24	G1, G2, G3	Step down regulator	Infineon	TLS5112C0EPV	Yes
27	Q1, Q2, Q3, Q4	OptiMOS™-5 Power-Transistor 80 V	Infineon	IAUTN08S5N012L	Yes
49	U1	48 V gate driver	Infineon	2ED4820-EM	Yes
50	U2	12 V gate driver	Infineon	2ED2410-EM	Yes

3.4 Connector details

Table 6 – DC-DC converter board screw terminals

PIN	Label	Function
X1	V_{in}+	Positive supply to the DC-DC converter board
X2	V_{out}+	Positive output voltage of the DC-DC converter board

PIN	Label	Function
X7	V_{in}-	Negative supply to the DC-DC converter board
X8	V_{out}-	Negative output voltage of the DC-DC converter board

Table 7 – DC-DC converter board pin header

PIN	Label	Function
1	GND_Hi	Ground connection of the DC-DC converter board (equal to GND_Lo)
2	12V_Hi	12 V supply of the DC-DC converter (equal to 12V_Lo)
3	PWM_GB	PWM signal from the interface board
4	PWM_GC	PWM signal from the interface board
5	PWM_GA	PWM signal from the interface board
6	PWM_GD	PWM signal from the interface board
7	GND_Lo	Ground connection of the DC-DC converter board (equal to GND_Hi)
8	12V_Lo	12 V supply of the DC-DC converter (equal to 12V_Hi)
9	D_I_DCDI	DCDI communication interface from TLE4973
10	5V_Lo	5 V supply of the DC-DC converter
11	D_I_OCD	Over-current detection output from TLE4973
12	3V3_Lo	3V3 supply of the DC-DC converter (current not used)
13	A_I_OUT	Analog output from TLE4973
14	DIS	Disable signal for the gate driver from the interface board
15	A_I_VREF	Reference voltage from TLE4973
16	A_U_IN_N	Input voltage measurement – inverting analog output
17	A_U_OUT	Output voltage measurement
18	A_U_IN_P	Input voltage measurement – noninverting analog output
19	GND_Lo	Ground connection of the DC-DC converter board (equal to GND_Hi)
20	GND_Lo	Ground connection of the DC-DC converter board (equal to GND_Hi)

Table 8 - Interface board screw terminals

PIN	Label	Function
X4	V_{in}+	Positive supply to the interface board
X5	V_{out}+	Positive output voltage of the interface board

PIN	Label	Function
X6	V_{in}-	Negative supply to the interface board
X7	V_{out}-	Negative output voltage of the interface board

Table 9 – Interface board pin socket

PIN	Label	Function
1	-	Reserved for the next DC-DC converter
2	-	Reserved for the next DC-DC converter
3	-	Reserved for the next DC-DC converter
4	-	Reserved for the next DC-DC converter
5	PWRGND_Hi	Power ground connection of the interface board (equal to AGND_Lo)
6	12V_Hi	12 V supply to the DC-DC converter board
7	PWM_B	PWM signal to the DC-DC converter board
8	PWM_C	PWM signal to the DC-DC converter board
9	PWM_A	PWM signal to the DC-DC converter board
10	PWM_D	PWM signal to the DC-DC converter board
11	AGND_Lo	Analog ground connection of the interface board (equal to PWRGND_Hi)
12	12V_Hi	12 V supply to the DC-DC converter board
13	D1	Digital pin interface between DC-DC converter board and TriBoard
14	5V_Lo	5 V supply to the DC-DC converter board
15	D2	Digital pin interface between DC-DC converter board and TriBoard
16	3V3_Lo	3V3 supply to the DC-DC converter board
17	A1	Analog pin interface between DC-DC converter board and TriBoard
18	D3	Digital pin interface between DC-DC converter board and TriBoard
19	A2	Analog pin interface between DC-DC converter board and TriBoard
20	A3	Analog pin interface between DC-DC converter board and TriBoard
21	A4	Analog pin interface between DC-DC converter board and TriBoard
22	A5	Analog pin interface between DC-DC converter board and TriBoard
23	AGND_Lo	Analog ground connection of the interface board (equal to PWRGND_Hi)
24	AGND_Lo	Analog ground connection of the interface board (equal to PWRGND_Hi)

PIN	Label	Function
25	-	Reserved for the next DC-DC converter
26	-	Reserved for the next DC-DC converter
27	-	Reserved for the next DC-DC converter
28	-	Reserved for the next DC-DC converter

4 System performance

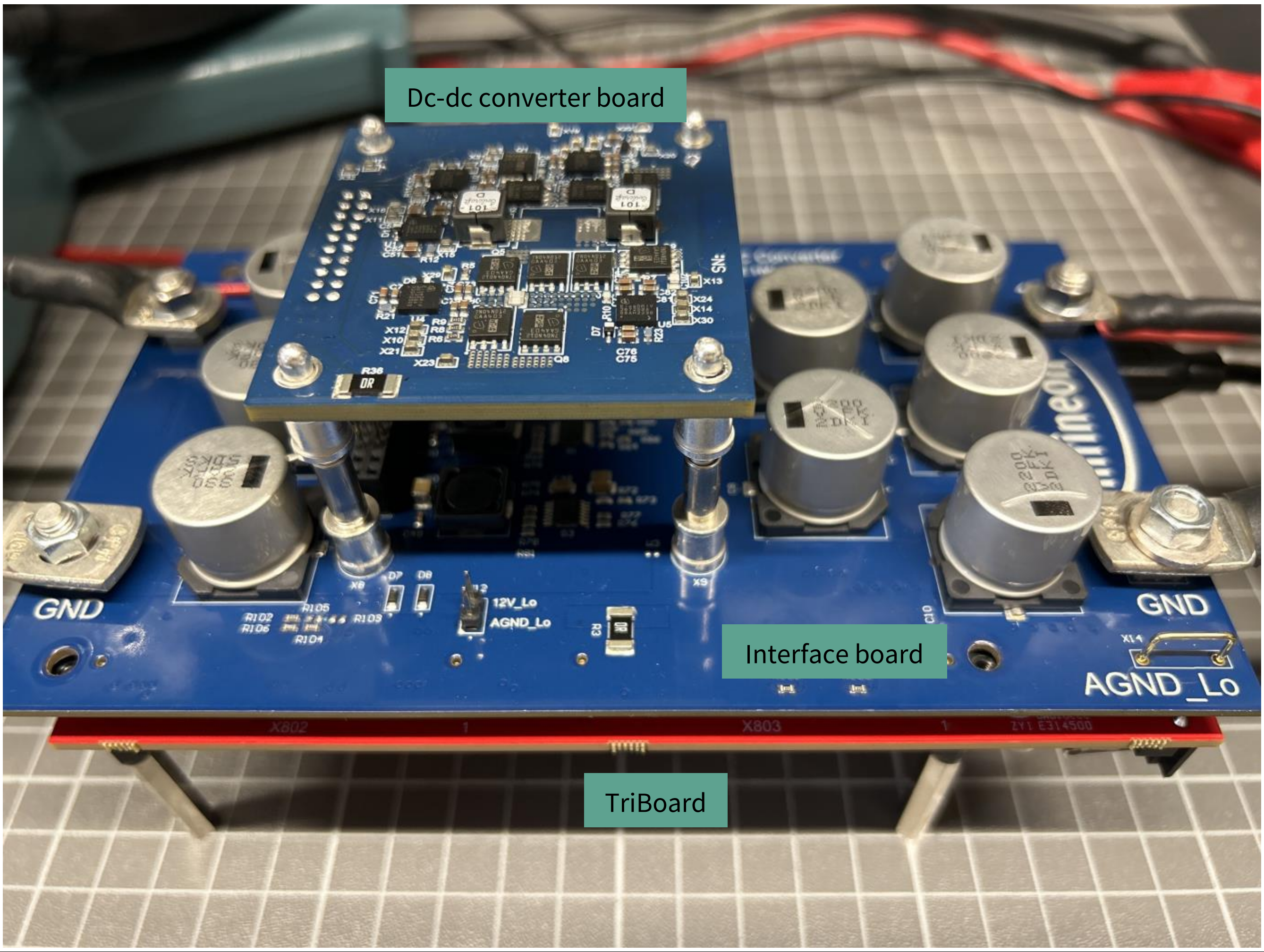

Figure 39 Test set-up

A typical test set-up of the reference design can be seen in Figure 39.

Green: operation without heatsink

Orange: operation with heatsink

Red: no operation due to very high output current / board temperature

Table 10 - Operation at 36 V

V_{in} = 36 V	100 W	200 W	300 W	400 W	500 W
V_{in}	35.928 V	35.846 V	35.748 V		
I_{in}	3 A	6.1 A	9.5 A		
V_{out}	8.826 V	8.622 V	8.408 V		
I_{out}	11.4 A	23.7 A	37.5 A		
η	93.4 %	93.5 %	92.8 %		

Table 11 - Operation at 48 V

V_{in} = 48 V	100 W	200 W	300 W	400 W	500 W
V_{in}	47.942 V	47.884 V	47.821 V	47.752 V	47.679 V
I_{in}	2.3 A	4.4 A	6.8 A	9.2 A	11.8 A
V_{out}	11.869 V	11.726 V	11.563 V	11.391 V	11.182 V
I_{out}	8.5 A	17.2 A	26.6 A	36.3 A	46.8 A
η	91.5 %	95.7 %	94.6 %	94.1 %	93.0 %

Table 12 - Operation at 60 V

V_{in} = 60 V	100 W	200 W	300 W	400 W	500 W
V_{in}	59.453 V	59.405 V	59.356 V	59.305 V	59.252 V
I_{in}	1.8 A	3.55 A	5.4 A	7.2 A	9.15 A
V_{out}	14.764 V	14.642 V	14.512 V	14.376 V	14.166 V
I_{out}	6.8 A	13.7 A	21 A	28.3 A	36.1 A
η	93.8 %	95.1 %	95.1 %	95.3 %	94.3 %

4.1 Thermal

The temperature of the PCBs and the components increases with increasing output load (i.e. output current). The maximum temperature of the DC-DC converter board reaches about 105 °C after operation of 5 minutes at V_{in} of 60 V and I_{out} of about 28 A (which corresponds to P_{out} of about 400 W) as can be seen below in Figure 40. The hottest spot is the gate driver that drives the two rectifier half-bridges. It is advised not to operate the system, i.e. the DC-DC converter, at I_{out} of higher than 28 A without any means of cooling it irrespective of the operating voltages V_{in} or V_{out}.

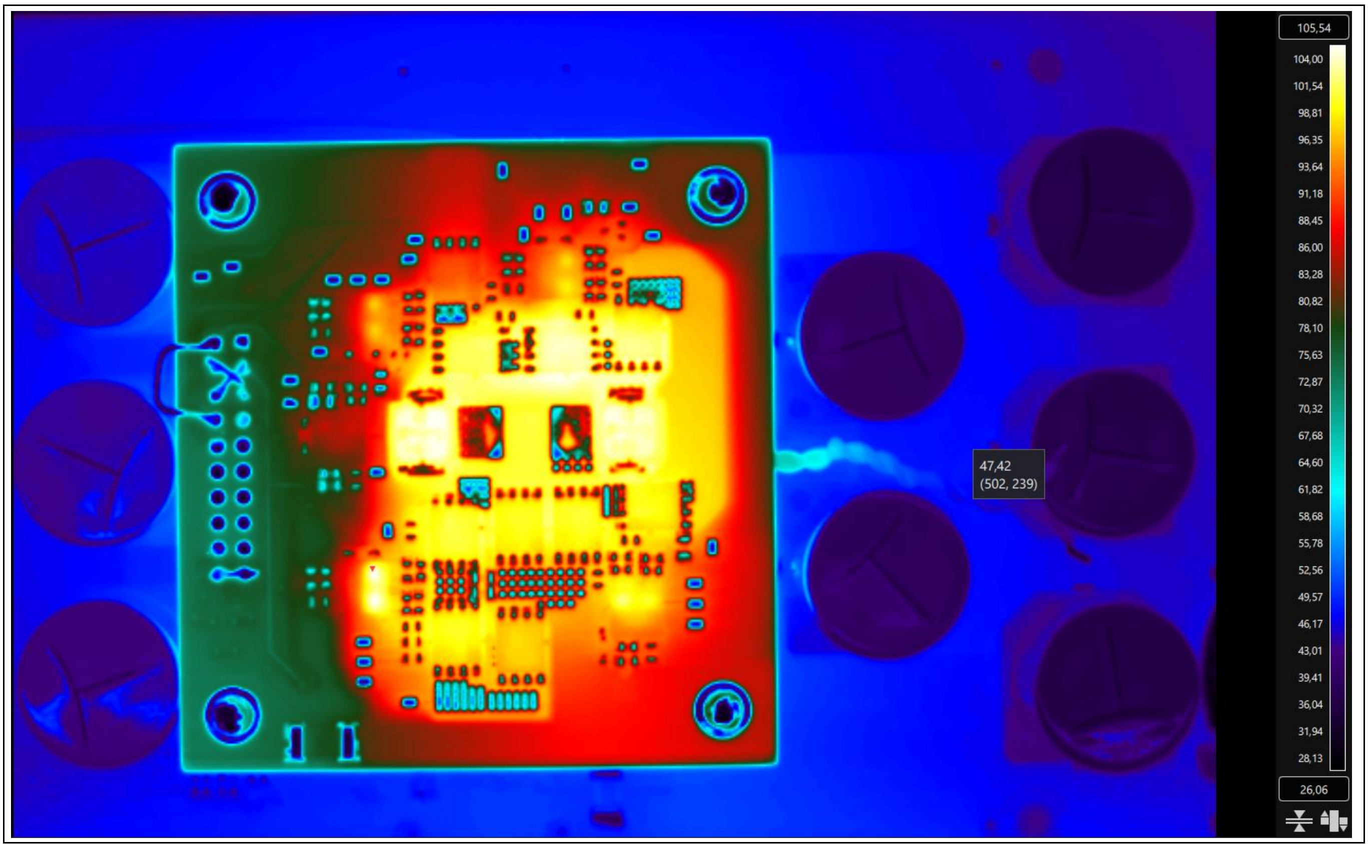

Figure 40 Operation at Vin = 60 V and Pout = 400 W

To operate the system at higher I_{out}, a heat sink can be attached to the surface of the DC-DC converter board as shown in Figure 41. The amount of heat that can be dissipated by the heat sink heavily depends on its properties, e.g. material, shape, thickness, etc. It is recommended to constantly check the temperature of the boards when operating the system outside of the green operating points shown in Table 10, Table 11, and Table 12 to prevent any damage to the system.

Thermal pads are applied in between the heat sink and the components on the top side of the DC-DC converter, as can be seen in Figure 41. Due to the height of the resonant inductors, a 3 mm thermal pad must be used to thermally connect all the MOSFETs and the gate drivers on the top side of the PCB to the heat sink. The thermal pad from t-Global Technology is used here with thermal conductivity of 6.2 W/mK.

For the heat sink, we use the pin heat sink from Fischer Elektronik GmbH & Co. KG with part number of ICK S 50x50x50. The heat sink has a maximum thermal resistance of 4.05 K/W. Since there is most likely no air or liquid cooling in the ZCU, it is of very high importance to provide a proper cooling mechanism by means of conduction.

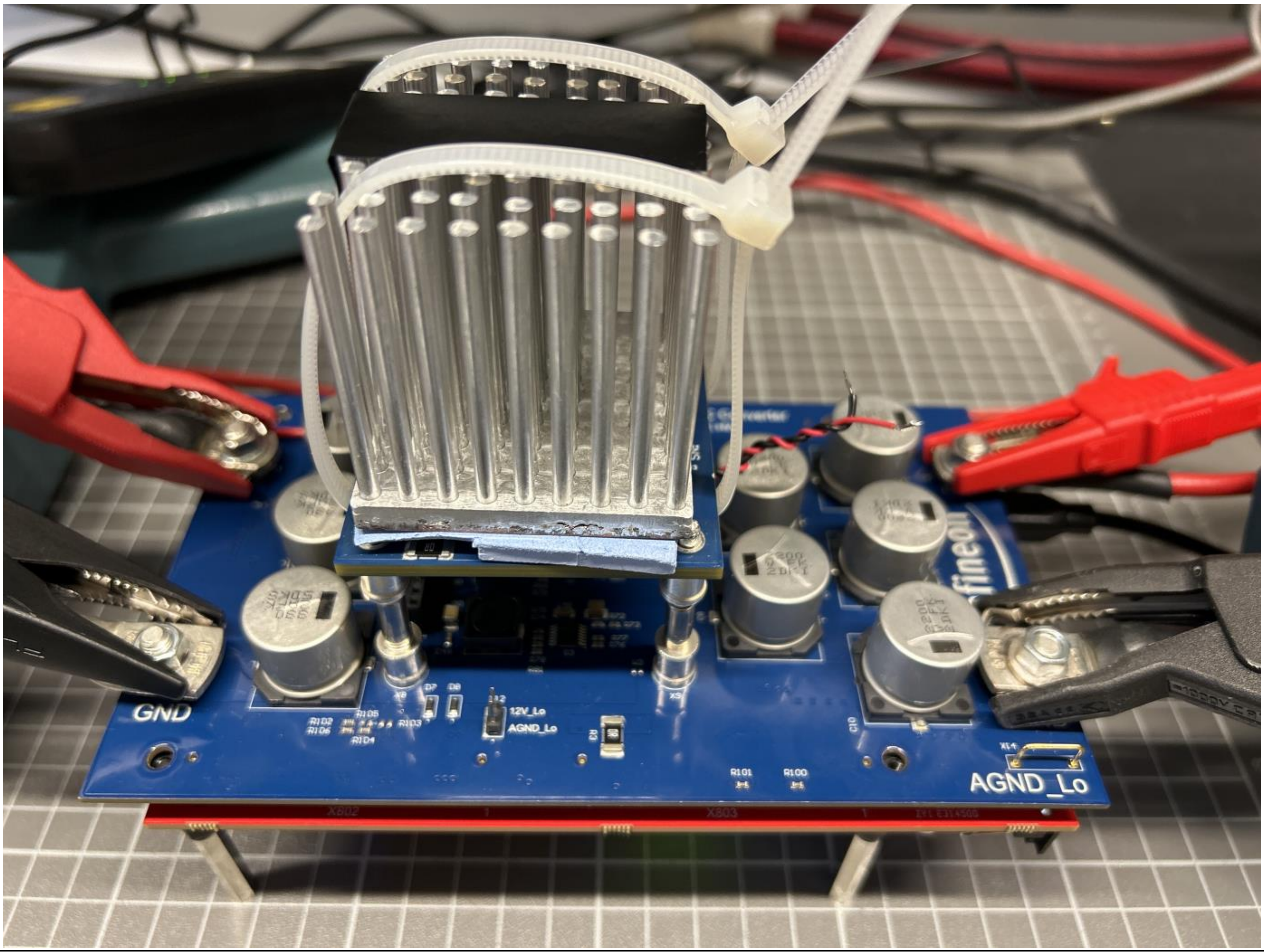

Figure 41 Test setup with added heat sink

With the heat sink, we can operate the board at higher I_{out} (i.e. P_{out}) as indicated by the orange columns in Table 10, Table 11, and Table 12. Below are some temperature measurements at three different operating points for a duration of at least 5 minutes: V_{in} of 36 V P_{out} of 300 W (see Figure 42), V_{in} of 48 V P_{out} of 500 W (see Figure 43), and V_{in} of 60 V P_{out} of 500 W (see Figure 44).

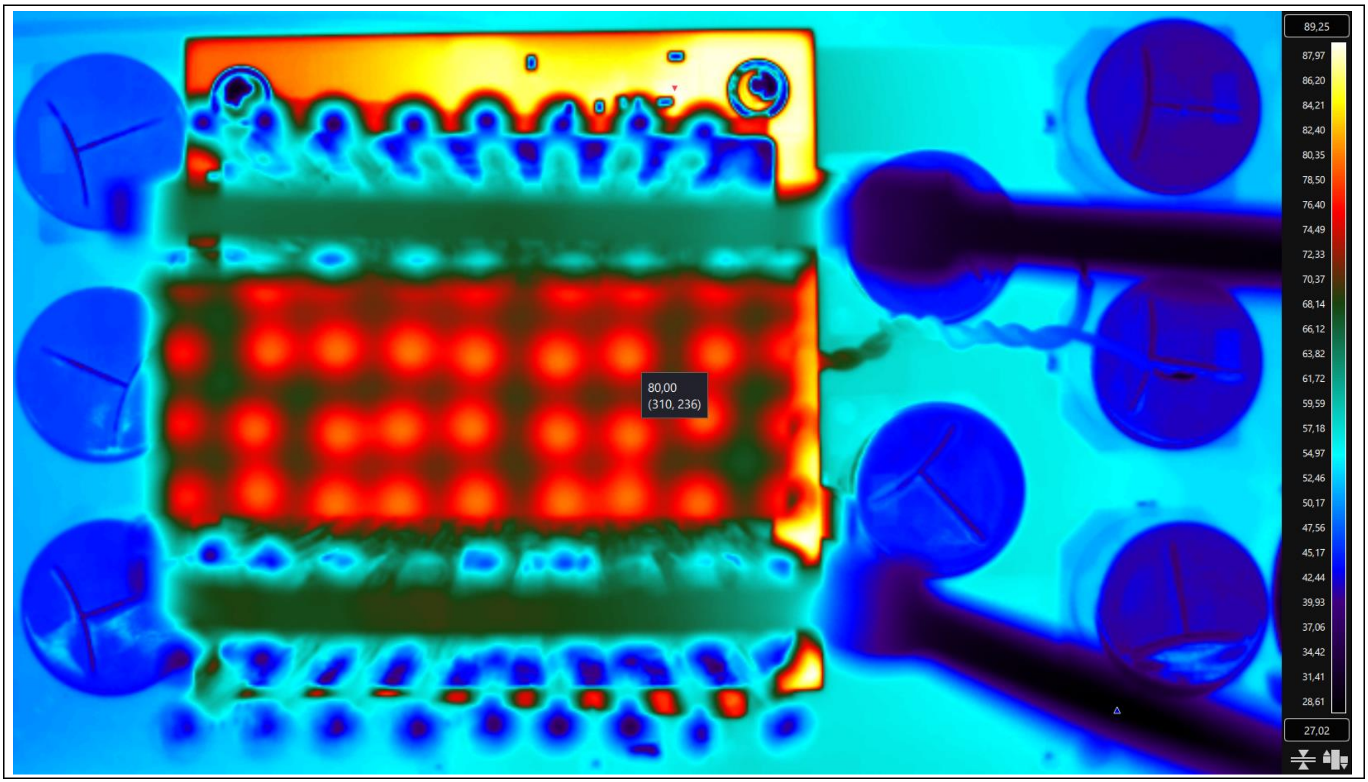

Figure 42 Operation at V_{in} = 36 V and P_{out} = 300 W

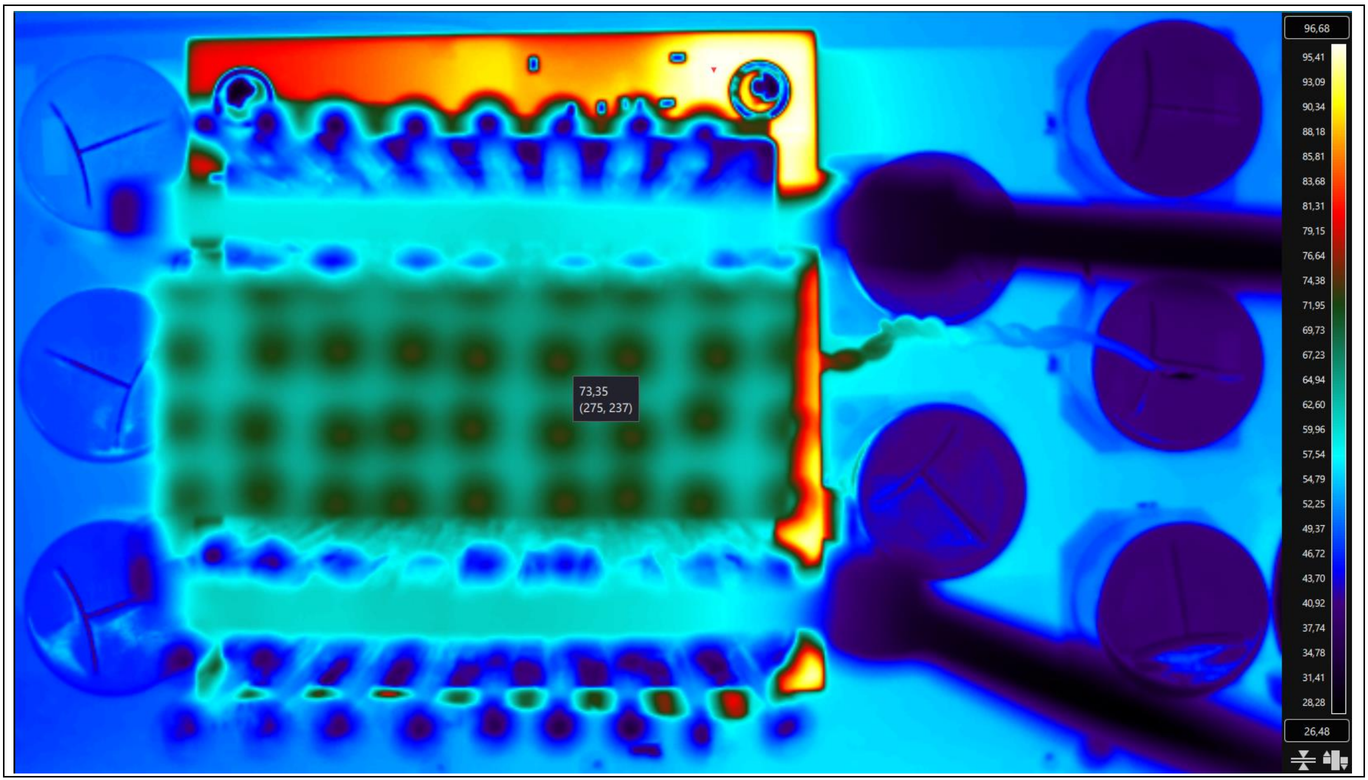

Figure 43 Operation at V_{in} = 48 V and P_{out} = 500 W

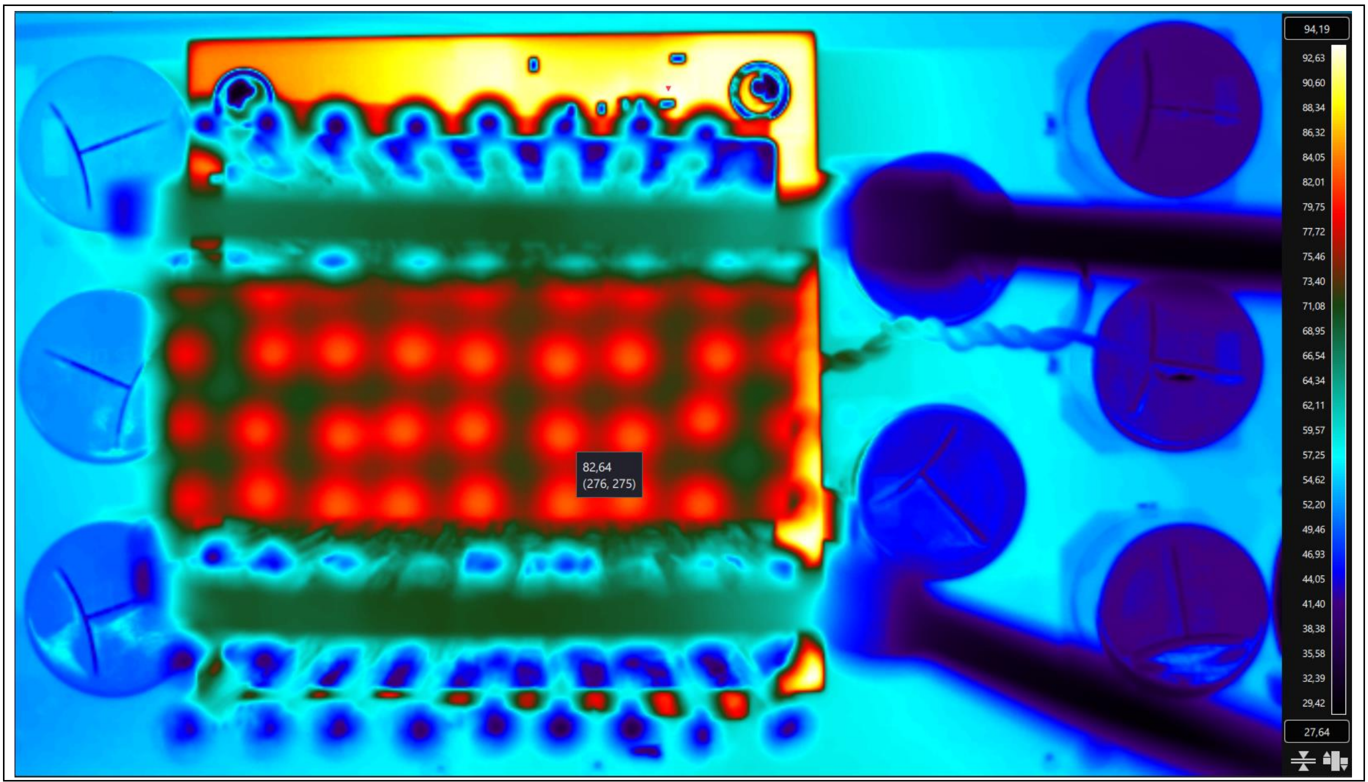

Figure 44 Operation at V_{in} = 60 V and P_{out} = 500 W

4.2 Voltage conversion

Since the switched tank converter is an open-loop topology, whenever the converter is connected to a load and a dc current is drawn, there will always be a voltage drop at the output voltage. The output voltage drop of this reference design is depicted in a curve as shown below in Figure 45.

According to the PCB simulation done in Ansys Q3D Extractor, the resistance of the PCB traces in our reference design plays a big role (up to 10 mΩ) in the amount of output voltage drop of the DC-DC converter. Another possibility to improve the output voltage drop of the DC-DC converter is to use lower $R_{DS(ON)}$ MOSFETs since conduction loss is dominating in this STC topology. As can be seen in the next section, the output voltage drop correlates strongly with the efficiency of the DC-DC converter itself.

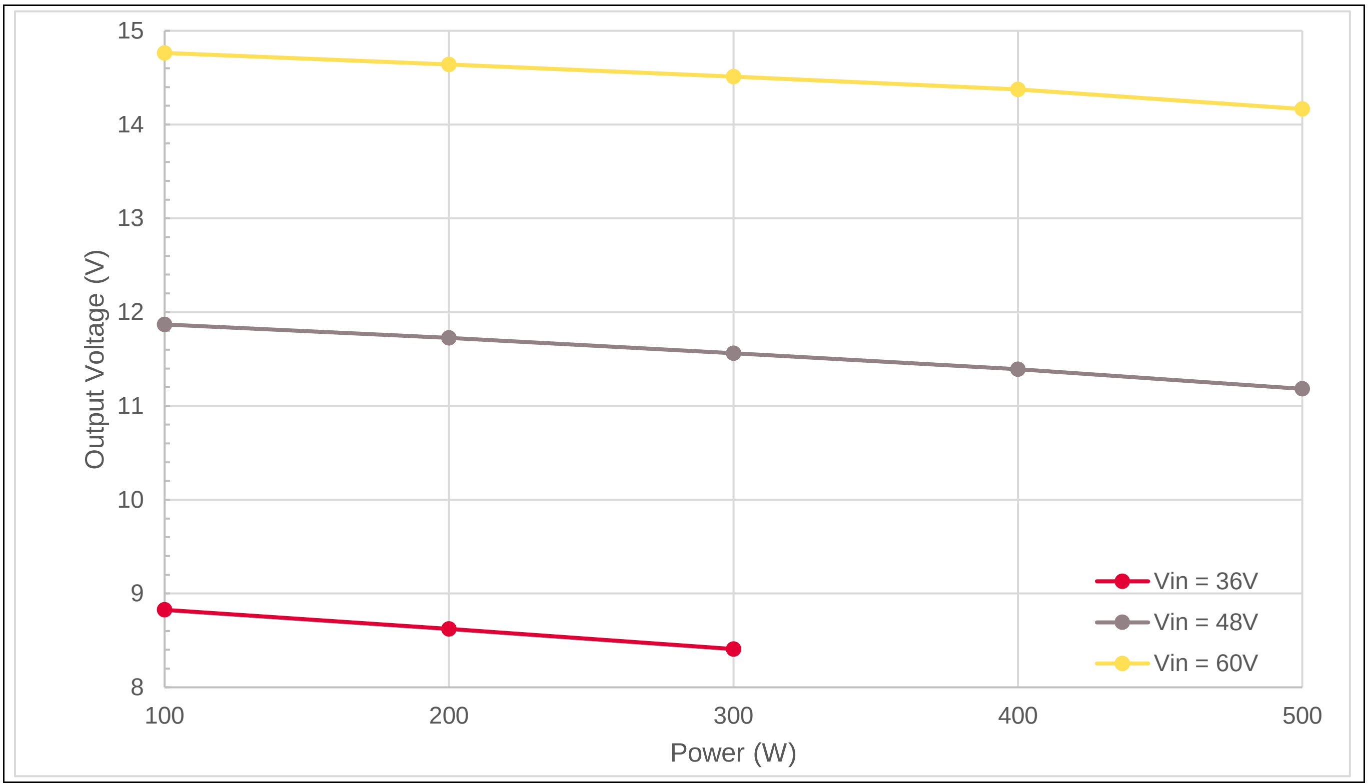

Figure 45 Output voltage drop curves

4.3 Efficiency

The maximum efficiency achieved by the system (i.e. DC-DC converter board, interface board, and TriBoard) is 95.7 % when input voltage V_{in} is equal to 48 V and output power P_{out} is 200 W as can be seen in Figure 46. In general, the high load efficiency of the system improves with increasing output (or input) voltage. At low output voltage, the output current increases dramatically with load and the conduction loss becomes dominant.

By tuning the switching frequency closer to the resonant frequencies of the resonant tanks, it is possible to improve the efficiency and output voltage drop of the DC-DC converter. It is important to note that due to the dc bias characteristic of the MLCCs, it is difficult to achieve the optimum efficiency just by having a single switching frequency (i.e. the optimum switching frequency is dependent on the input voltage V_{in}).

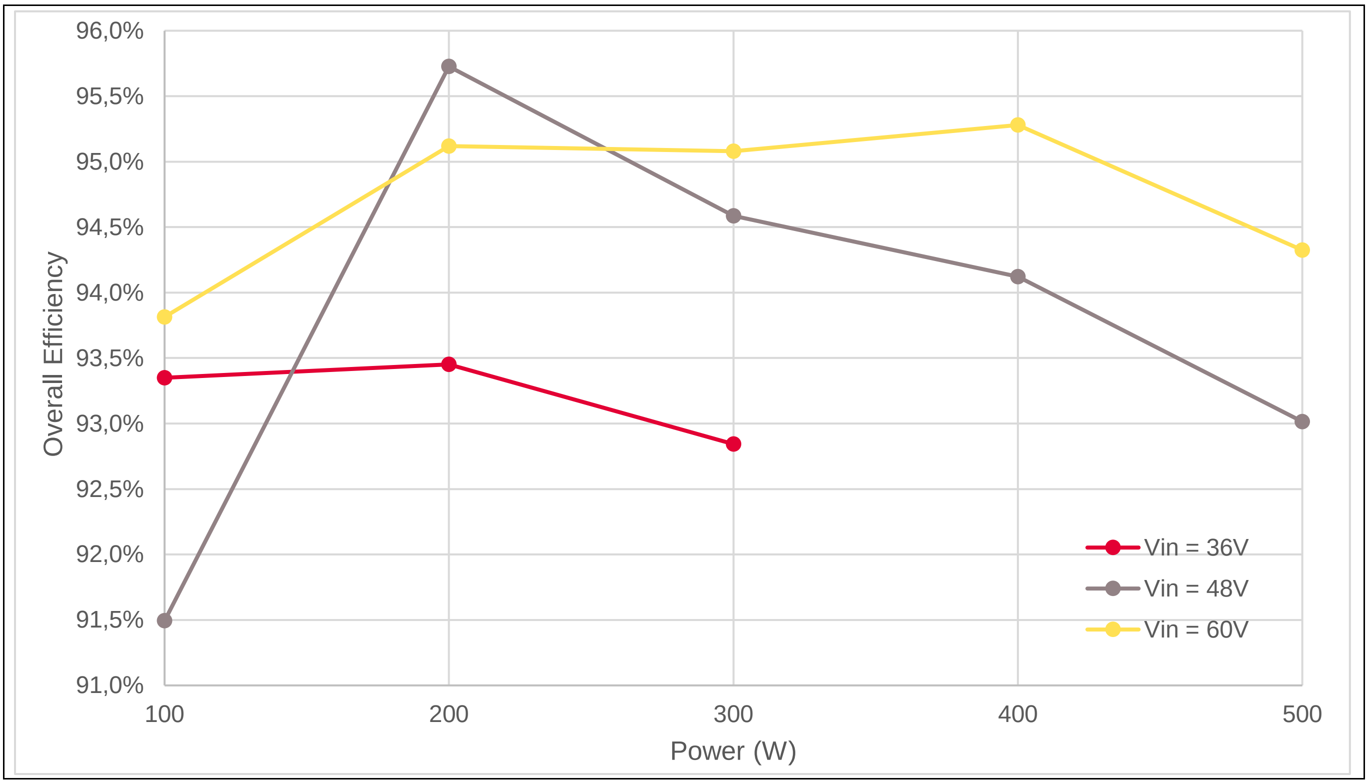

Figure 46 Efficiency curves of the whole systems

4.4 Dynamics

The switched tank converter has an excellent dynamic performance when subjected to an output load jump. In the experiment below, the system is subjected to a load jump of higher than 1 kA/ms. The DC-DC converter is trying to maintain the 4:1 ratio of output and input voltages, as can be seen in Figure 47. We can observe that there is no overshoot of the output voltage as long as the input voltage is also stable.

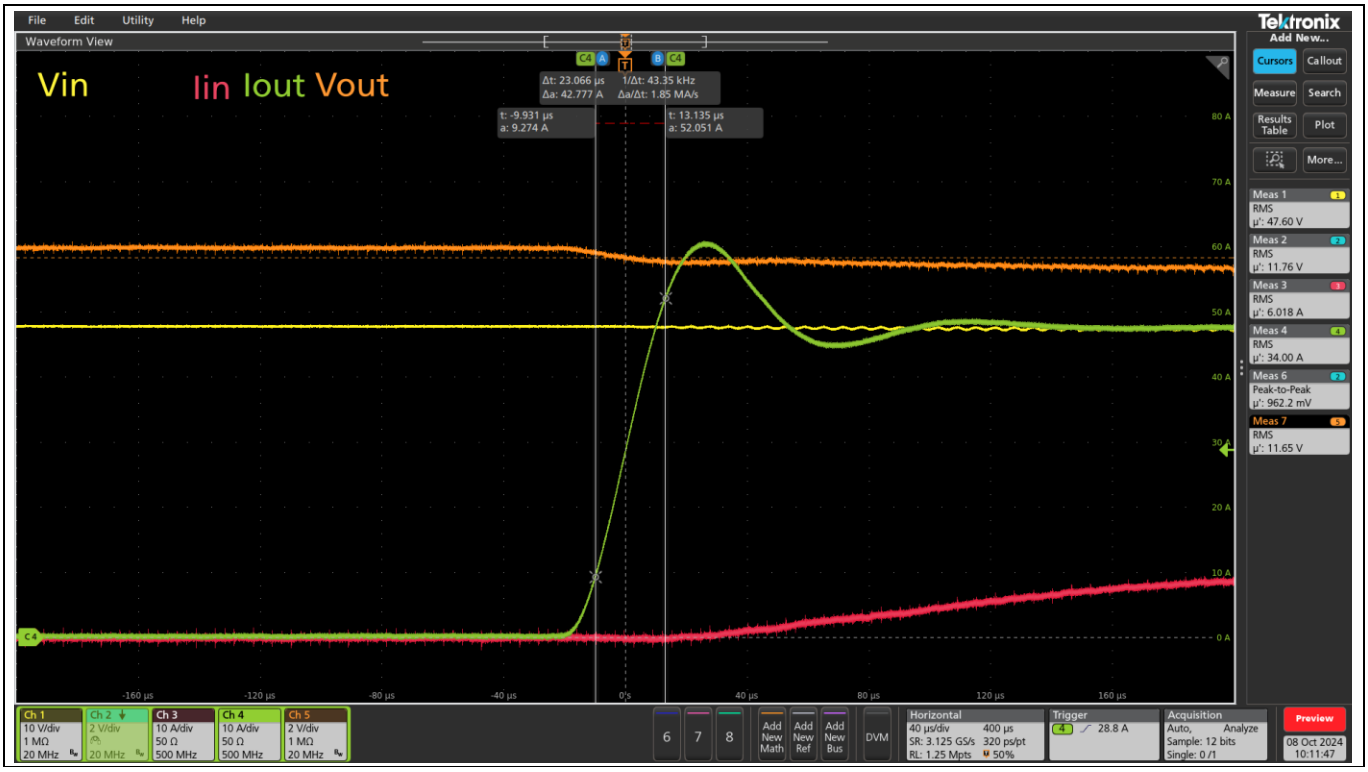

Figure 47 The system is subjected to a load jump

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