150 W water pump reference design with SiP

User guide

Z8F80905570

About this document

Design overview

The reference design guide describes the 150 W Water Pump Reference Design with SiP using the TLE9954QSW40-33 MOTIX™ MCU System in package (SiP). The 3-phase bridge driver TLE9954QSW40-33 is used for automotive motor control for example auxiliary pumps and fans in thermal management systems. The reference design is designed to drive 150 W loads at a battery voltage of 12 V.

The guide includes the schematics of the design, electrical, thermal, and *electromagnetic compatibility (EMC)* measurements according to the CISPR25 standard.

Highlighted components

1. MOTIX™ MCU TLE9954QSW40-33
2. OptiMOS™ 7 IAUZN04S7N026

Applications

- Auxiliary water pump
- Oil pump

Highlighted design aspects

- Space optimization
- Cost optimization
- EMC optimization
- Thermal optimization

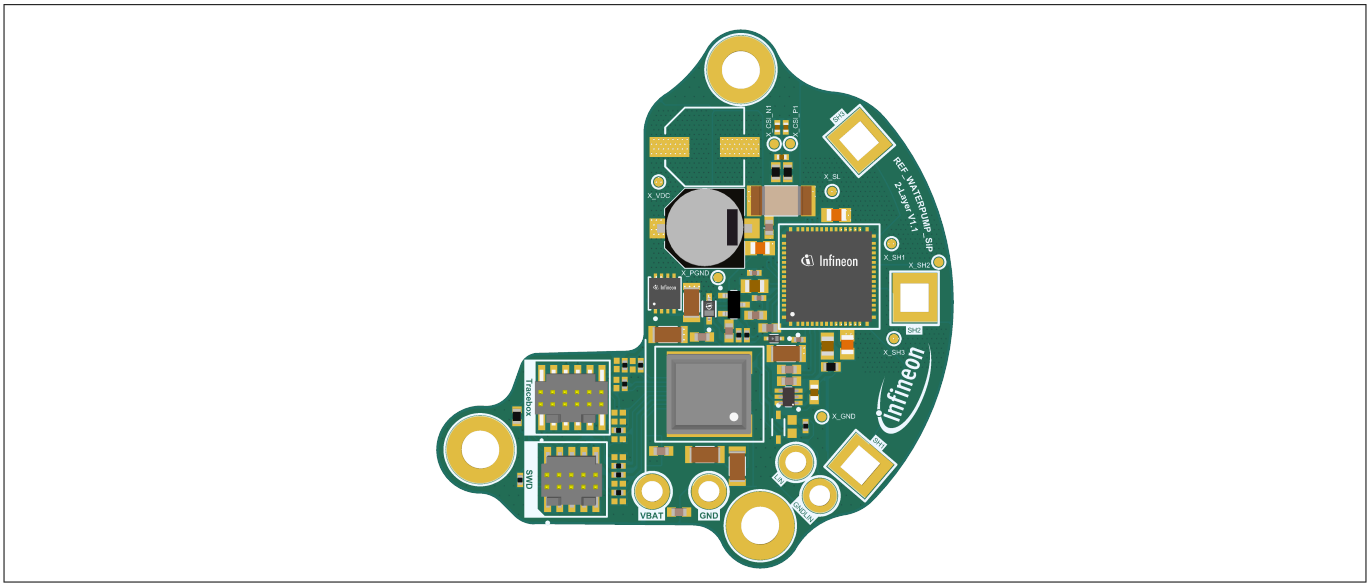


Figure 1 Reference design

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Table of contents

About this document . . . 1
Important notice . . . 2
Table of contents . . . 3
1 System offerings . . . 5
2 Two reference designs for two different purposes with MOTIX™ MCU TLE9954QSW40-33 . . . 6
2.1 Value of moving from discrete MOSFETs to System-in-Package . . . 6
2.2 Utilizing MOTIX™ MCU TLE9954QSW40-33 for extremely space constraint environments in comfort applications . . . 7
2.3 Key takeaway . . . 7
3 In detail: 150 W water pump reference design with SiP . . . 8
3.1 Design specifications . . . 8
3.2 Highlighted products . . . 9
3.2.1 OptiMOS-7™ 40 V IAUZN04S7N026 MOSFET . . . 9
3.2.2 MOTIX™ MCU | 32-bit motor control SiP with integrated 3-phase bridge driver . . . 9
4 Hardware design guide . . . 10
4.1 General component selection . . . 10
4.2 Input filter and reverse polarity protection circuit . . . 11
4.2.1 Input filter . . . 11
4.2.2 Reverse polarity protection circuit . . . 13
4.3 Motor control components . . . 14
4.3.1 Interfaces . . . 14
4.3.2 External components for MOTIX™ SiP TLE9954QSW40-33 . . . 16
4.3.2.1 Decoupling and buffer capacitors on supply pins . . . 16
4.3.2.2 Charge pump circuit . . . 17
4.4 Power stage . . . 18
4.4.1 DC-link capacitors . . . 18
4.4.2 Snubbers . . . 19
4.5 Measurement components . . . 20
4.5.1 Shunt measurement circuit . . . 20
4.5.2 Shunt resistor selection . . . 21
5 Placement and layout . . . 22
5.1 Components and interfaces . . . 22
5.2 Layout and current flow . . . 22
6 Getting started with REF_WATERPUMP_SIP . . . 24
7 System performance . . . 26
7.1 System test setup . . . 26
7.2 Electrical test result . . . 28

Table of contents

7.2.1 Switching characteristics 28
7.3 Thermal behavior 32
7.3.1 Water cycles in thermal management 32
7.3.2 Thermal testing test setup 32
7.3.3 Thermal analysis results 34
7.3.4 Thermal behavior conclusion 39
7.4 EMC 39
7.4.1 EMC test setup 39
7.4.2 Conducted emission with motor in on-state 40

8 Project collaterals 45
8.1 Schematics 45
8.2 Bill of materials 50
8.3 Layout 55

Glossary 57

Revision history 59

Disclaimer 60

1 System offerings

Infineon's system offering for automotive water pumps with TLE9954QSW40-33 System-in-Package device encompasses a range of components that work together to provide a comprehensive solution.

Key Components:

- **TLE9954QSW40-33 DUT board:** A robust hardware foundation for efficient integration with a MOTIX™ MCU TLE9954QSW40-33, a OptiMOS™ 7 MOSFET, on board debugger, and several other interfaces
- **REF_WATERPUMP_SiP:** An optimized *printed circuit board (PCB)* for size, thermal and *EMC* performance. It highlights the size and PCB cost improvements against a traditional gate driver with discrete MOSFETs
- **REF_MINI_CMFRT_SiP:** Compact automotive solution with Infineon's fully integrated System-in-Package, optimized for minimal PCB size, and faster time-to-market
- **MOTIX™ TLE994_5x SDK Evaluation edition:** Evaluation edition of Software Development Kit (SDK) for MOTIX™ TLE994x and 995x including Peripheral Driver Library (PDL), Code examples, and Device Configurator settings. CMSIS Pack file
- **Infineon Automotive Power Explorer:** The Infineon Automotive Power Explorer is a powerful tool designed to provide a comprehensive and detailed analysis of Infineon products, enabling users to make informed decisions and optimize their designs. It offers a range of analysis features that enable users to evaluate and compare the performance of different products under various operating conditions
- **MOTIX™ MCU Solution Designer** The MOTIX™ MCU Solution Designer is a graphical configuration tool to analyze, debug, and tune your motor control application. The intuitive *graphical user interface (GUI)* helps to develop a field-oriented motor control application based on Infineon's MOTIX™ MCU families

2 Two reference designs for two different purposes with MOTIX™ MCU TLE9954QSW40-33

There are two reference designs for TLE9954QSW40-33 in the list above. Both reference designs are designed very differently and serve very different purposes.

2.1 Value of moving from discrete MOSFETs to System-in-Package

The REF_WATERPUMP_SiP was designed as a 1 to 1 replacement for the REF_WATERPUMP150W. The REF_WATERPUMP150W uses the traditional architecture with MOTIX™ MCU TLE995x and OptiMOS™ 7 integrated half-brigde MOSFETs. The integration of the MOSFETs allows for different improvements on the *PCB* listed below:

- **Reduction of PCB area by 40%:** Both PCBs were designed for the identical water pump and identical feature set. On the REF_WATERPUMP_SiP, the unutilized PCB space was cut away to show the saving in PCB area which resulted in a 40% reduction in PCB area. At the same time, both reference designs are capable of driving 150 W of continuous power
- **Simplification of 4 layer PCB down to 2 layer PCB:** The easier layout of the REF_WATERPUMP_SiP allows a good PCB layout on only 2 layers. This results in a cheaper PCB
- **Simplified layout:** As the routing in the commutation path is already integrated in the package of the System-in-Package, the layout gets much easier. First-time-right design with optimized *EMC* performance can be achieved due to low parasitic inductance

Below figure shows both REF_WATERPUMP150W (left) and REF_WATERPUMP_SiP (right) side by side

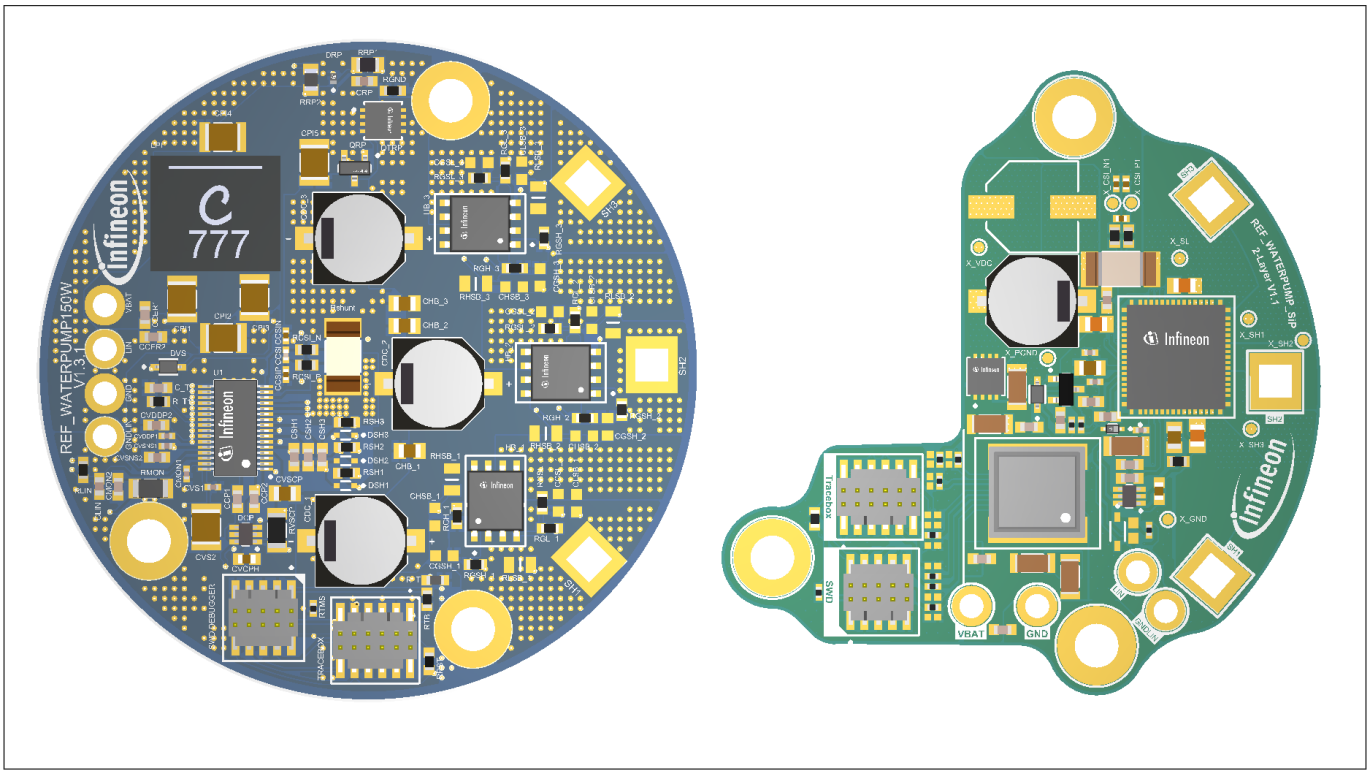


Figure 2 Comparison of REF_WATERPUMP150W (left) and REF_WATERPUMP_SiP (right)

2.2 Utilizing MOTIX™ MCU TLE9954QSW40-33 for extremely space constraint environments in comfort applications

Utilizing MOTIX™ MCU TLE9954QSW40-33 for extremely space constraint environments in comfort applications

The REF_MINI_CMFRT_SIP was designed to reduce the *PCB* size as much as possible. To achieve this small size of 30 mm x 17 mm, a double-sided assembly on a 4-layer board was utilized. The device is cooled via the topside of the mold compound of the MOTIX™ MCU TLE9954QSW40-33.

The figure below shows the REF_WATERPUMP_SiP (left) next to the REF_MINI_CMFRT_SIP (right) in correct relative scale.

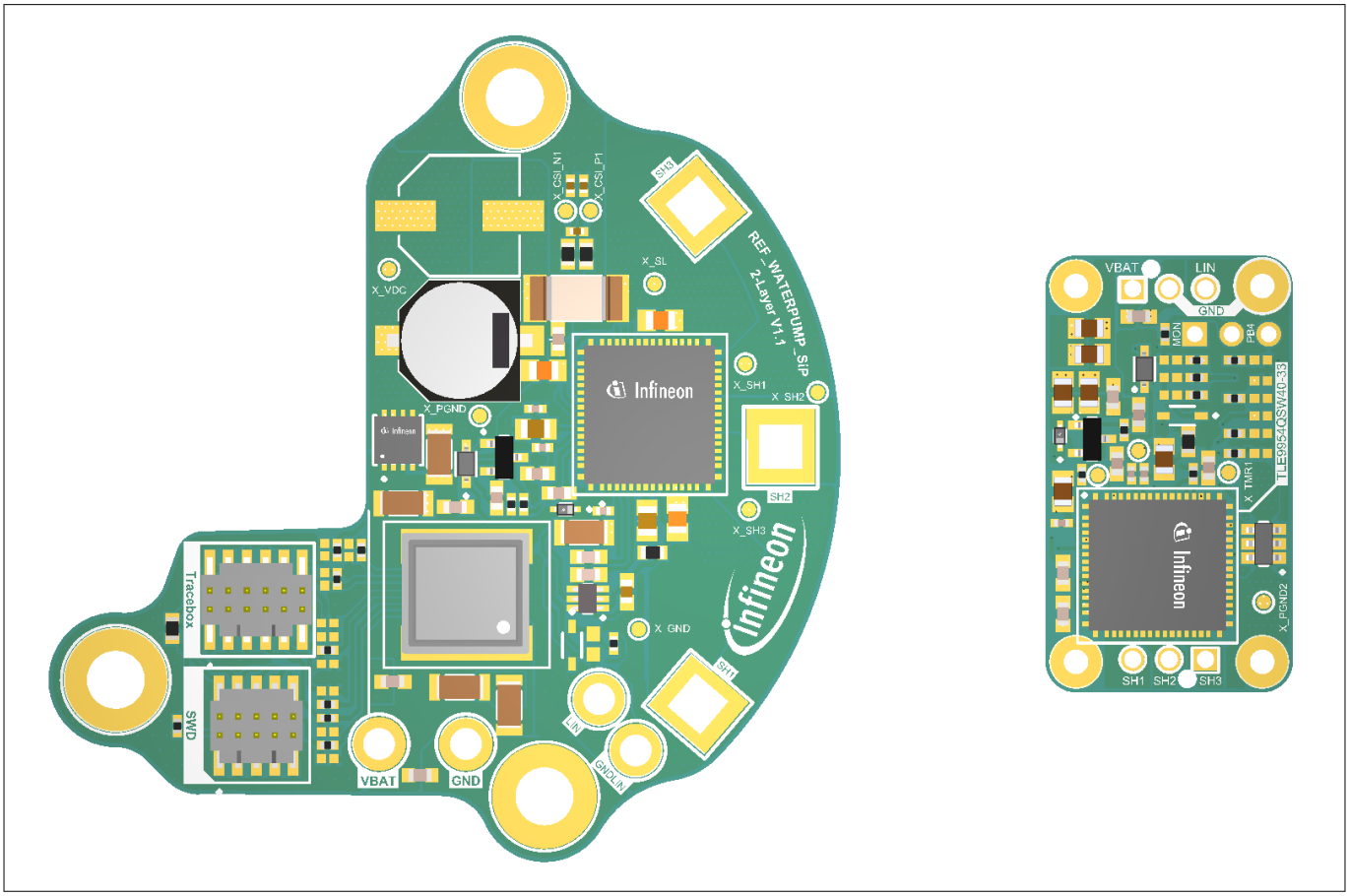


Figure 3 Comparison of REF_WATERPUMP_SiP (left) and REF_MINI_CMFRT_SIP(right)

To reduce the power losses even further, this design does not use a shunt resistor for current sensing. Instead the XENSIV™ TLE5572 *tunnel magnetoresistance (TMR)* current sensor is used to measure the current flowing through the copper planes inside the PCB is used.

For more details on the REF_MINI_CMFRT_SIP, refer to the board user guide of REF_MINI_CMFRT_SIP.

2.3 Key takeaway

Both *PCB* size and reduction in layers have a positive impact on the total costs of the PCB. This user guide shows that the impact of reduction of PCB size and number of layers on performance is very small and therefore the REF_WATERPUMP_SiP can be used in the same applications with tighter space constraints. Additionally, a simplified layout will result in a faster PCB development.

3 In detail: 150 W water pump reference design with SiP

REF_WATERPUMP_SIP is a reference design for 150 W water pump applications. The design could also be used as a reference for other *brushless DC motor (BLDC motor)* applications. The board of the reference design is developed using standard *PCB* materials and processes.

The reference design uses MOTIX™ TLE9954QSW40-33 SiP integrated with a B6-bridge. The board has one OptiMOS™ 7 IAUZN04S7N026 MOSFET for reverse polarity protection. The design is supplied with power via the 12 V battery terminal connection. The reference design consists of an input PI filter and supports *local interconnect network (LIN)* communication. Measurement of current flowing through the bridge is possible via single shunt resistor. The flash and debug communication to the microcontroller can be established via the debug connectors.

3.1 Design specifications

The design specifications are related to the assembled components and design considerations. They should not differ from the product datasheet recommendations. In case of deviations, the datasheet values of the products are valid.

Table 1 Design specifications

Parameter	Symbol	Values			Unit	Comment
		Min.	Typ.	Max.		
System parameters						
Function input voltage	V_{IN}	8	13.5	18	V	Specified according to water pump specification
Peak input current	I_{IN}	-	-	20	A	Peak current (<10 s)
Nominal input current	I_{IN}	-	11	-	A	2000 rpm
LIN interface	V_{BUS}	-40	-	40	V	
Phase voltage 1, 2, 3	V_{SH}	-8	-	48	V	
Thermal						
Operating temperature	T_A	-40	25	125	°C	Specified by design
Electromagnetic compatibility						
Conducted emissions				Class 5		CISPR25, 150 kHz-108 MHz
Mechanical specification						
Dimensions PCB	54 mm x 57 mm (Width x Length)					

3.2 Highlighted products

3.2.1 OptiMOS-7™ 40 V IAUZN04S7N026 MOSFET

A high-current, low $R_{DS(on)}$ power MOSFET in a 3x3 mm^2 advanced leadless package with a Cu-Clip for low package R_{ON} and minimal stray inductance, offering high power density, low conduction losses, and optimized switching behavior, with a reduced form factor compared to traditional leaded packages, ideal for automotive applications, for example power distribution, body control modules, and electric motors. For further information, see IAUZN04S7N026.

3.2.2 MOTIX™ MCU | 32-bit motor control SiP with integrated 3-phase bridge driver

TLE9954QSW40-33 belongs to the TLE995x family of 32-bit motor control SiPs with integrated 3-phase bridge driver and support for *LIN*. The potential applications of TLE995x include automotive motor control for auxiliary drives like pumps and fans in thermal management. In addition, *microcontroller unit (MCU)* system clock frequency supporting a wide range of motor control algorithms, either sensor-based or sensorless. Further information of the product can be found here.

4 Hardware design guide

The battery supply of the reference design has an input PI filter and a reverse polarity protection circuit. The *direct current (DC)* link voltage is buffered via a combination of one hybrid and multiple ceramic capacitors. Further, the bridge driver TLE9954QSW40-33 is supplied by a 2-stage charge pump. The main component of the reference design, MOTIX™ SiP TLE9954QSW40-33 runs the motor control algorithm and drives the motor. The design allows load current measurement using a single shunt resistor. For debugging and flashing purposes, Tracebox and SWD Debug connectors are available.

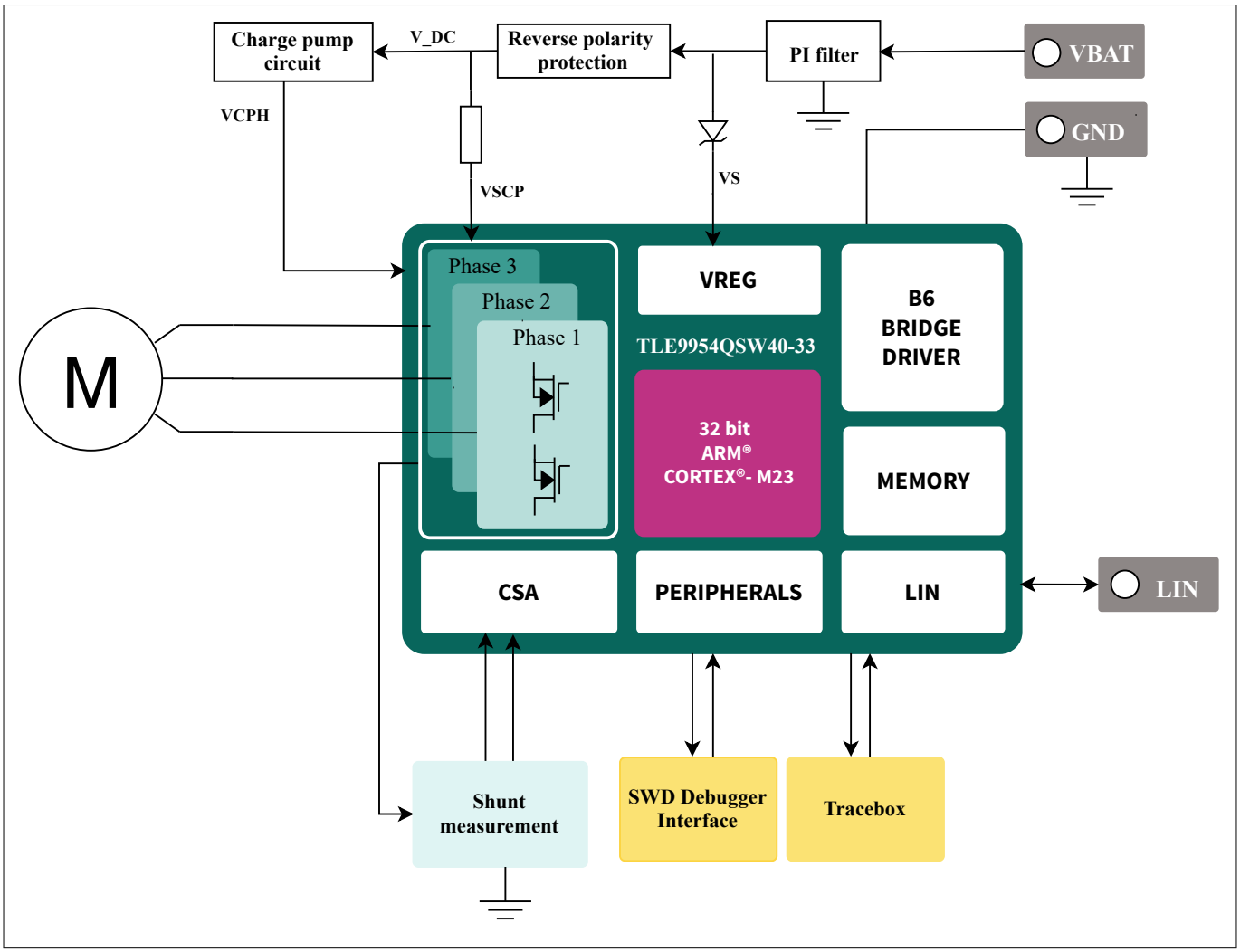


Figure 4 Reference design overview

4.1 General component selection

In general, the components for the reference design are selected to provide optimum performance. Wherever available, automotive qualified components were selected. Further information about the components used can be found in the following sections.

4.2 Input filter and reverse polarity protection circuit

4.2.1 Input filter

The reference design has an on-board input filter. The filter used is a PI filter, which consists of ceramic input capacitors CPI1-3, a power inductor LPI and output capacitors CPI4-6. It is designed to filter the low-frequency noise caused by *pulse-width modulation (PWM)* operation. An additional low capacitance filter CCER1 placed directly at the power connectors is used to filter high-frequency noise. The schematic and the component placement of the PI filter are depicted in the following figures.

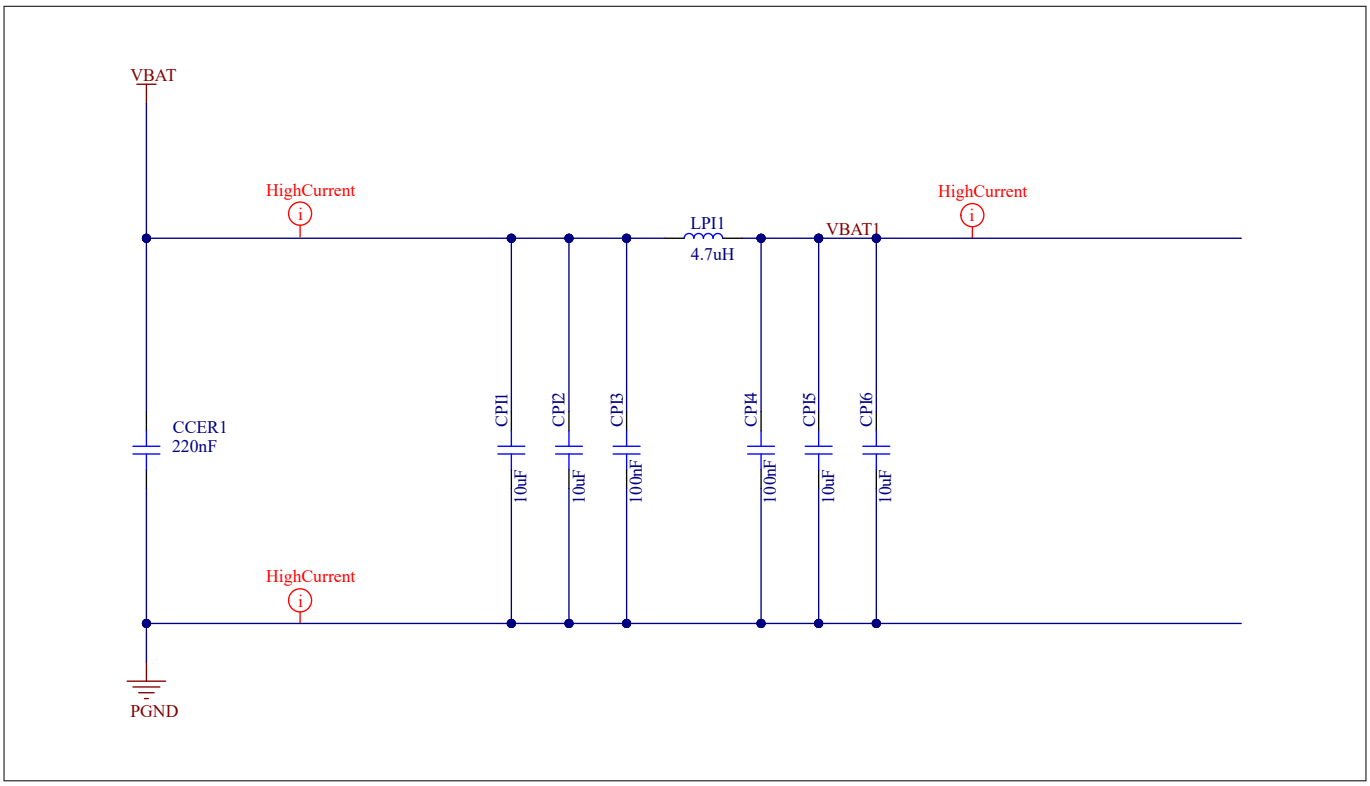


Figure 5 PI-filter schematic

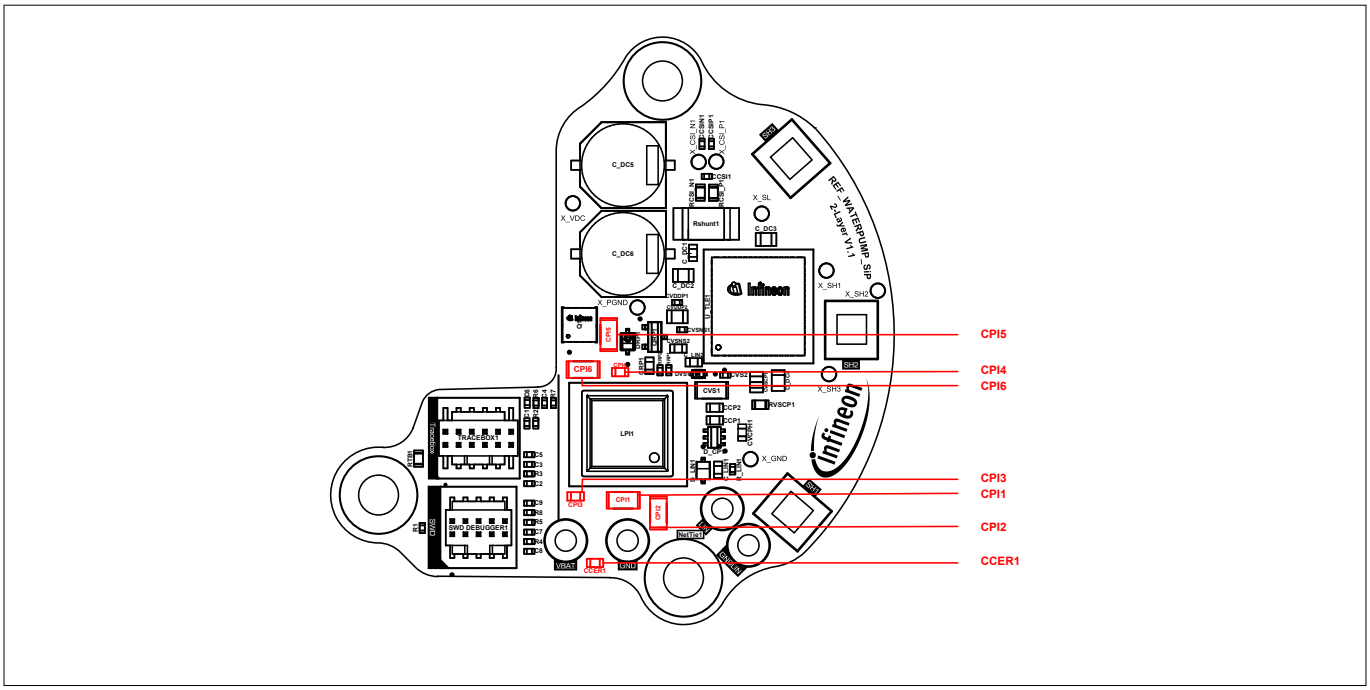


Figure 6 PI-filter component placement

4.2.2 Reverse polarity protection circuit

The reverse polarity protection is designed according to the "Reverse Polarity Protection for Embedded Power ICs" application note. The reverse polarity MOSFET Q1 (IAUZN04S7N026) is driven by the charge pump voltage VCPH as depicted in the reverse polarity circuit. The schematic and the component placement of the reverse polarity protection circuit are depicted in the following figures.

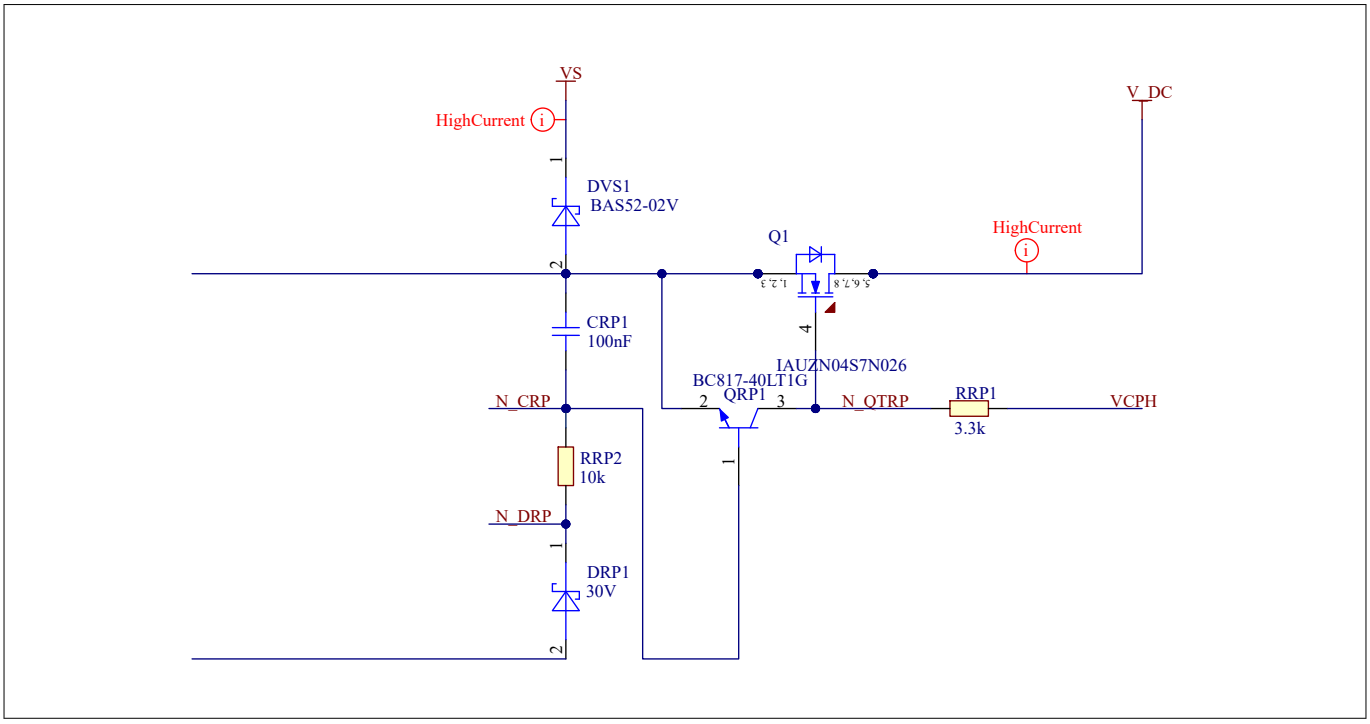


Figure 7 Reverse polarity protection schematic

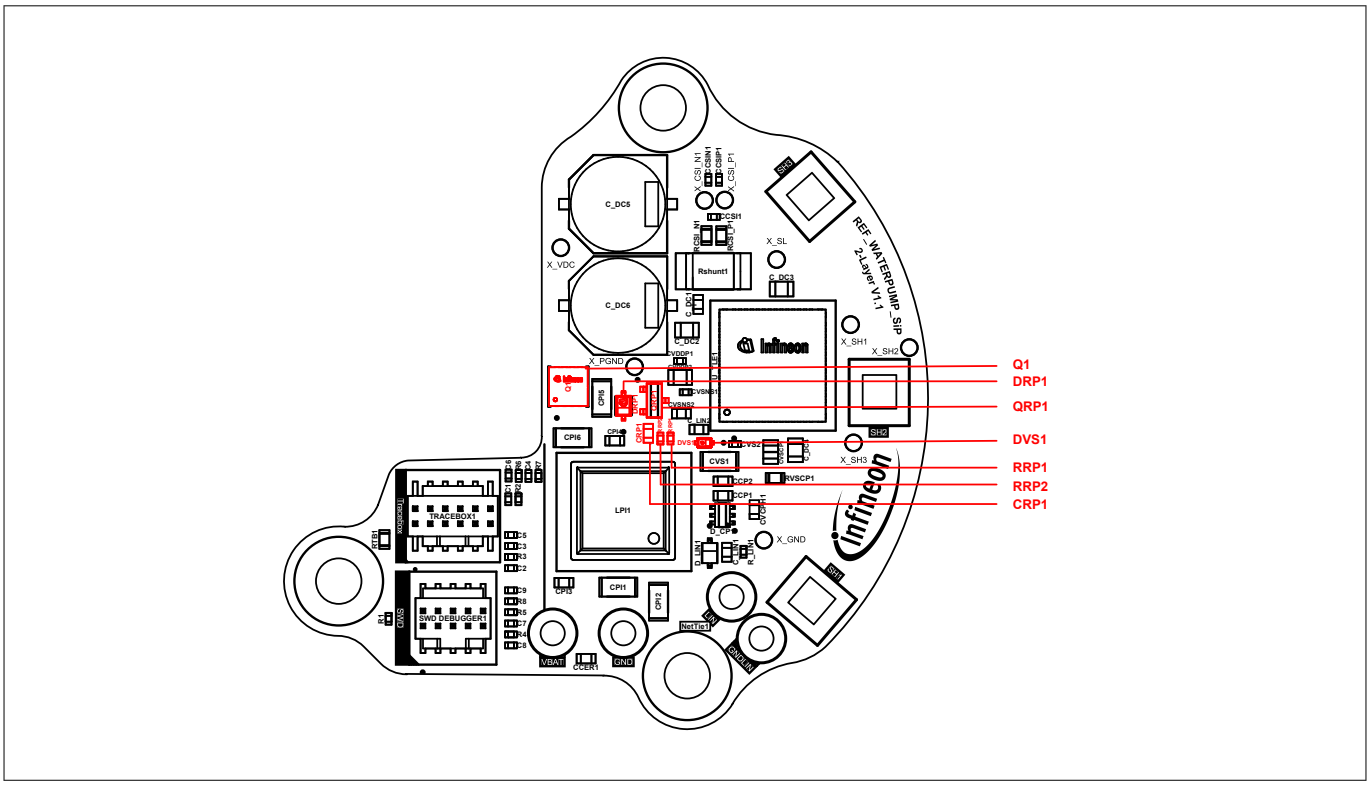


Figure 8 Reverse polarity protection component placement

4.3 Motor control components

4.3.1 Interfaces

The reference design has 2 debugger connectors - Tracebox and SWD debugger on board for debugging and flashing the device. The debugger connector is a standard 10-pin connector which can be used for external debuggers like ARM® KEIL ULINK or an XMC™ Link. The Tracebox connector is a 12-pin connector specifically intended to be used with Tracebox, available from Moteon. When connecting the XMC™ link to the Tracebox connector via the provided adapter board, the solution designer can be used to control the MOTIX™ motor control library during operation.

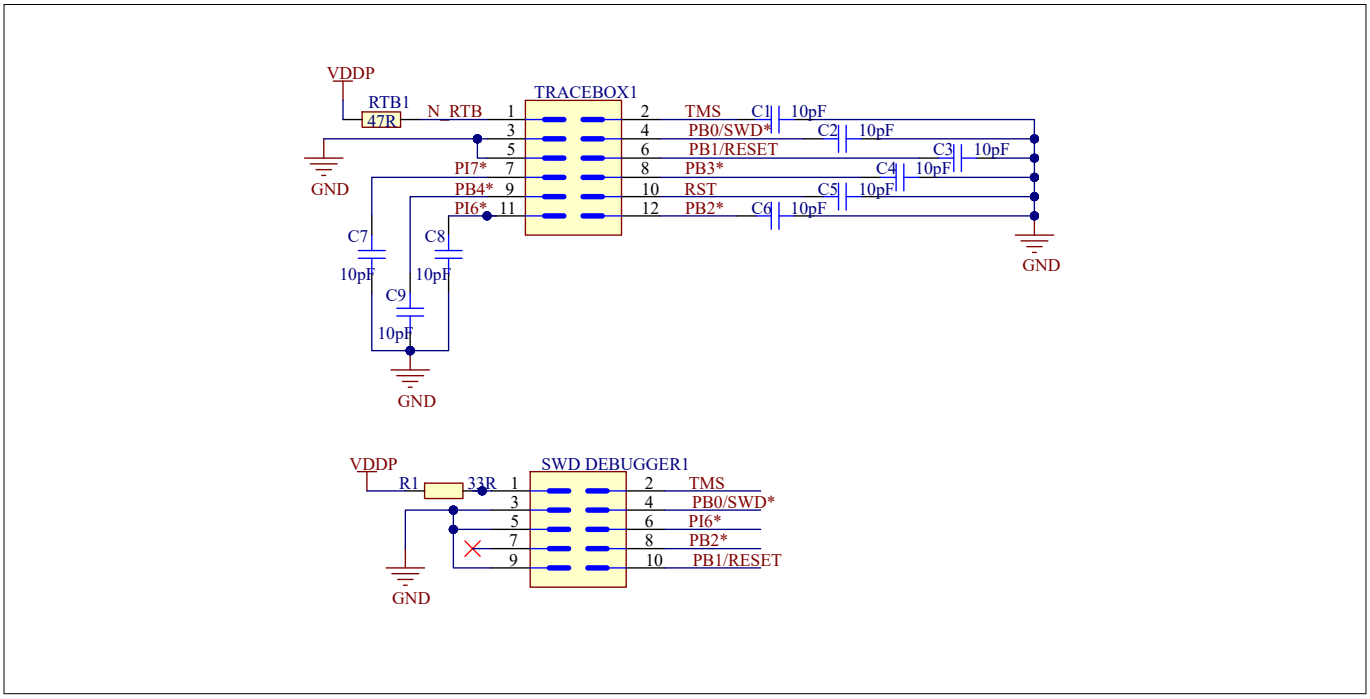


Figure 9 **Tracebox and SWD Debugger schematic with filter capacitor placement options. These capacitors are not populated by default**

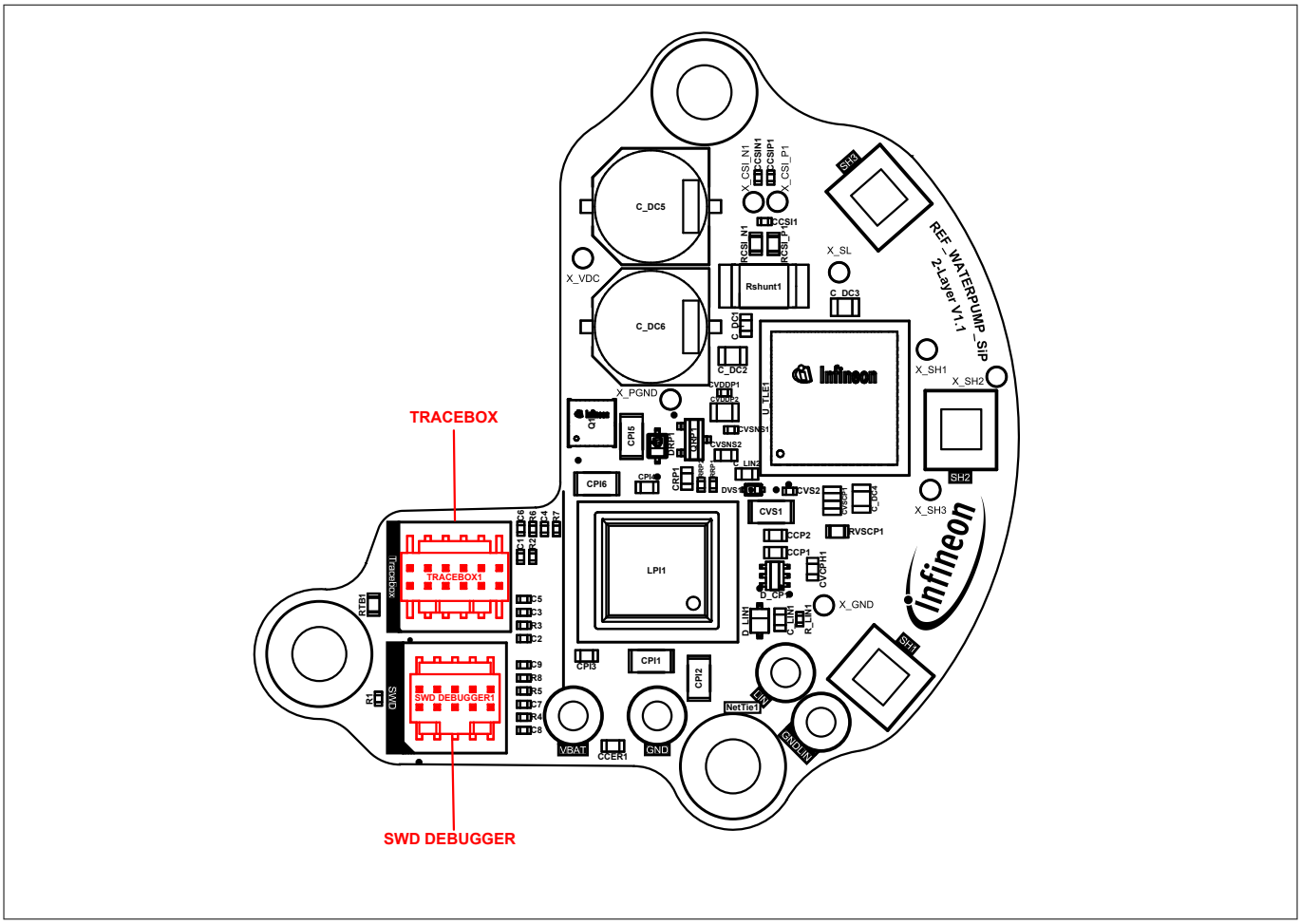


Figure 10 Tracebox and SWD Debugger component placement

4.3.2 External components for MOTIX™ SiP TLE9954QSW40-33

4.3.2.1 Decoupling and buffer capacitors on supply pins

The decoupling and buffer capacitors are used to filter noise from the supply and provide a steady voltage to the circuit. The decoupling capacitors are ceramic capacitors with a typical value of 100 nF while the buffer capacitors have values that are application-dependent. The schematic and the component placement of the decoupling and buffer capacitors are depicted in the following figures.

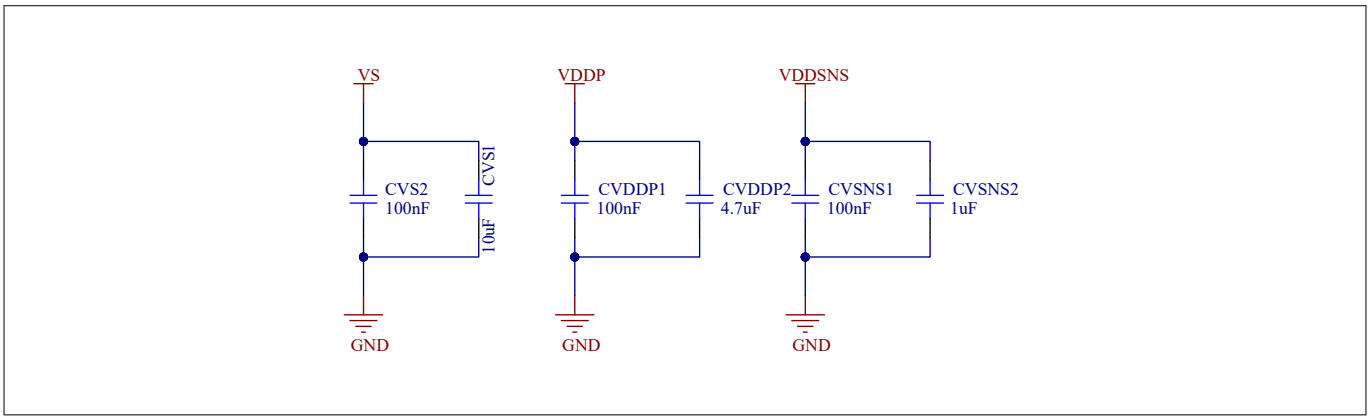


Figure 11 Decoupling and buffer capacitors schematic

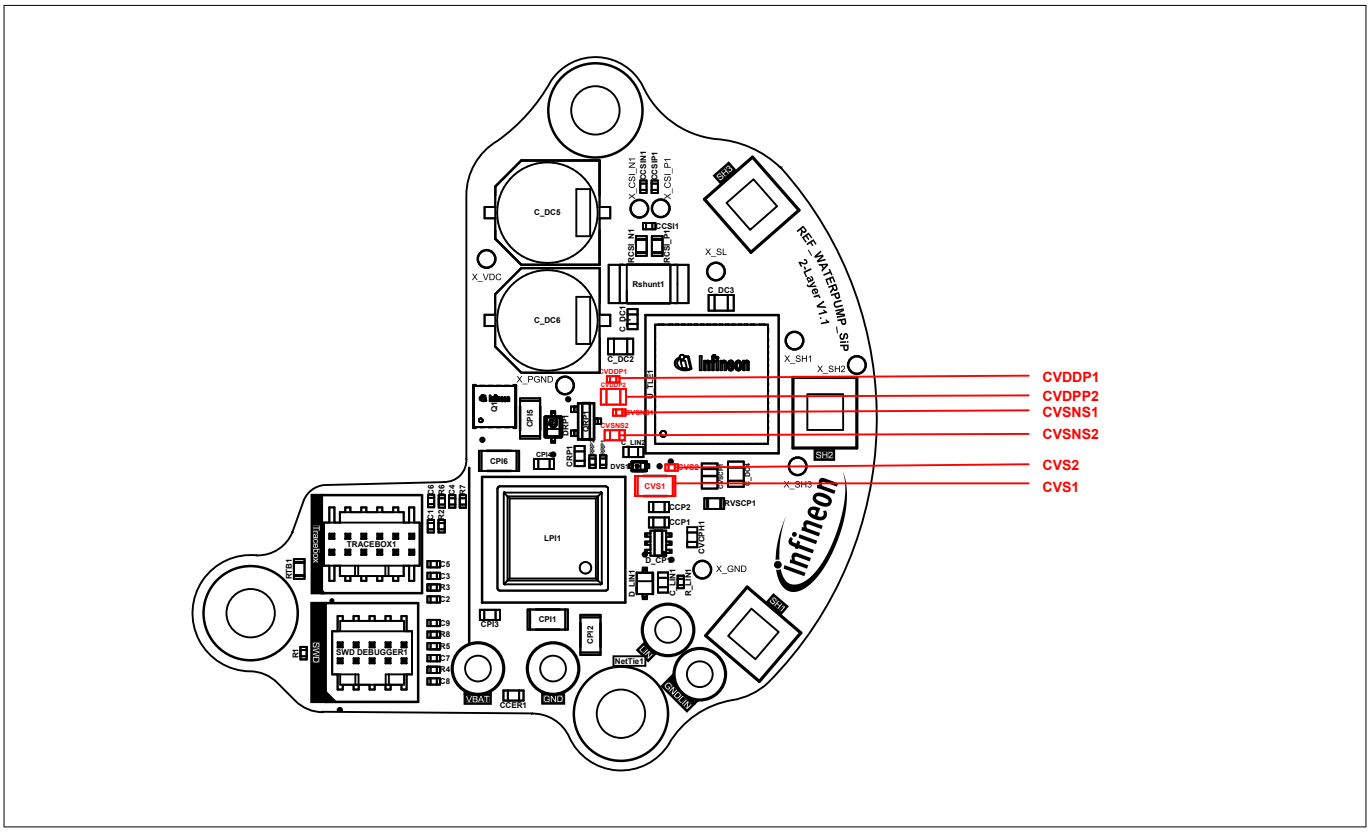


Figure 12 Decoupling and buffer capacitors component placement

4.3.2.2 Charge pump circuit

The bridge driver is supplied by a 2-stage charge pump for low-voltage operation and static MOSFET gate control. The default configuration of the charge pump requires two external buffer capacitors, two external flying capacitors, and four external diodes. The schematic and the component placement of the charge pump circuit are depicted in the following figures:

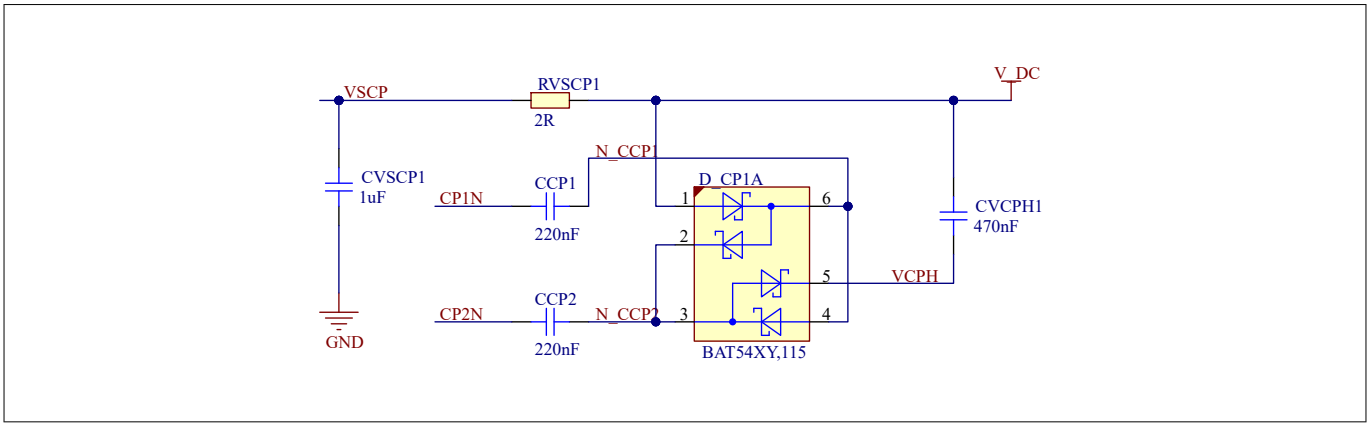


Figure 13 Charge pump circuit schematic

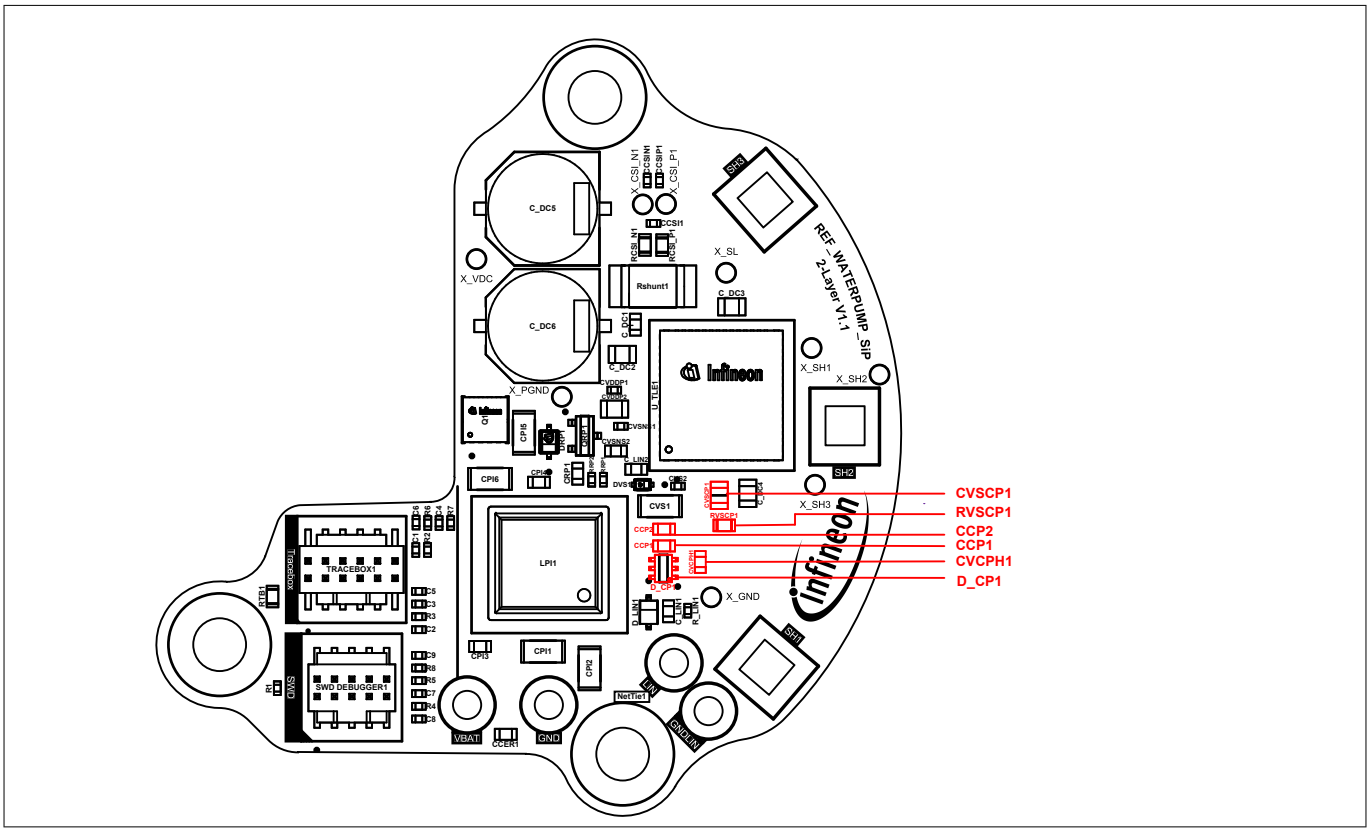


Figure 14 Charge pump circuit component placement

4.4 Power stage

4.4.1 DC-link capacitors

The board comes with a single 220 uF hybrid capacitor C_DC6 by default. Alternatively, another 220 uF hybrid capacitor C_DC5 can be added. There are two ceramic 4.7 uF capacitors placed between VDC and SL left and right to give the best possible buffering as close as possible to the device during switching. The 100 nF capacitor is used for high-frequency switching noise. The schematic and the component placement of the *DC* link capacitors are depicted in the following figures:

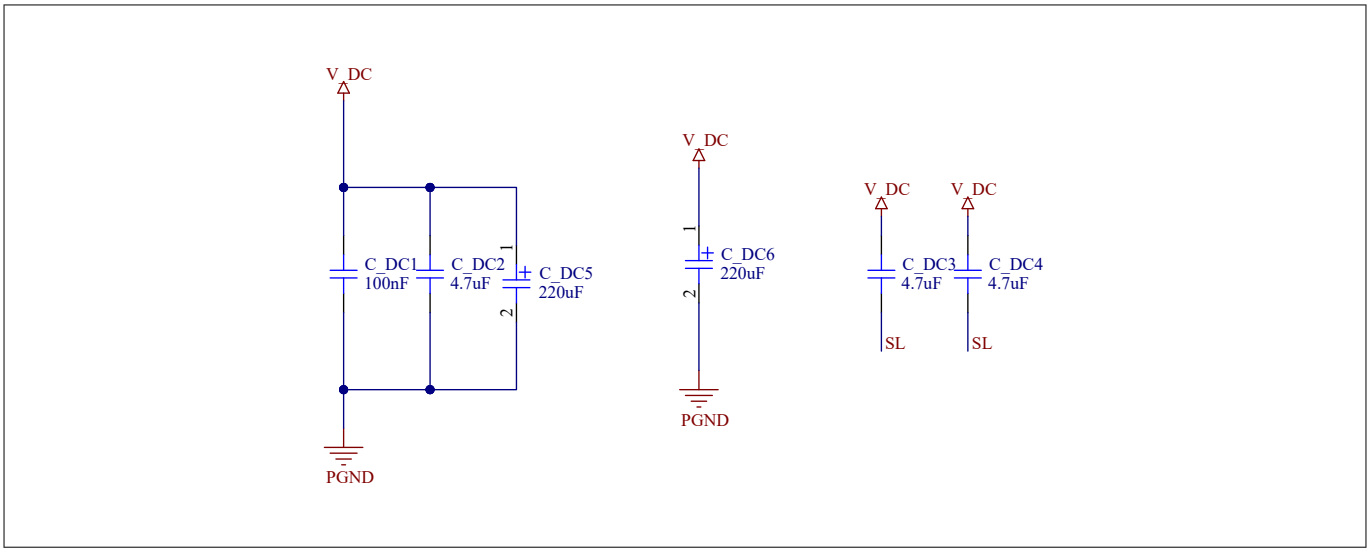


Figure 15 DC link capacitor schematic

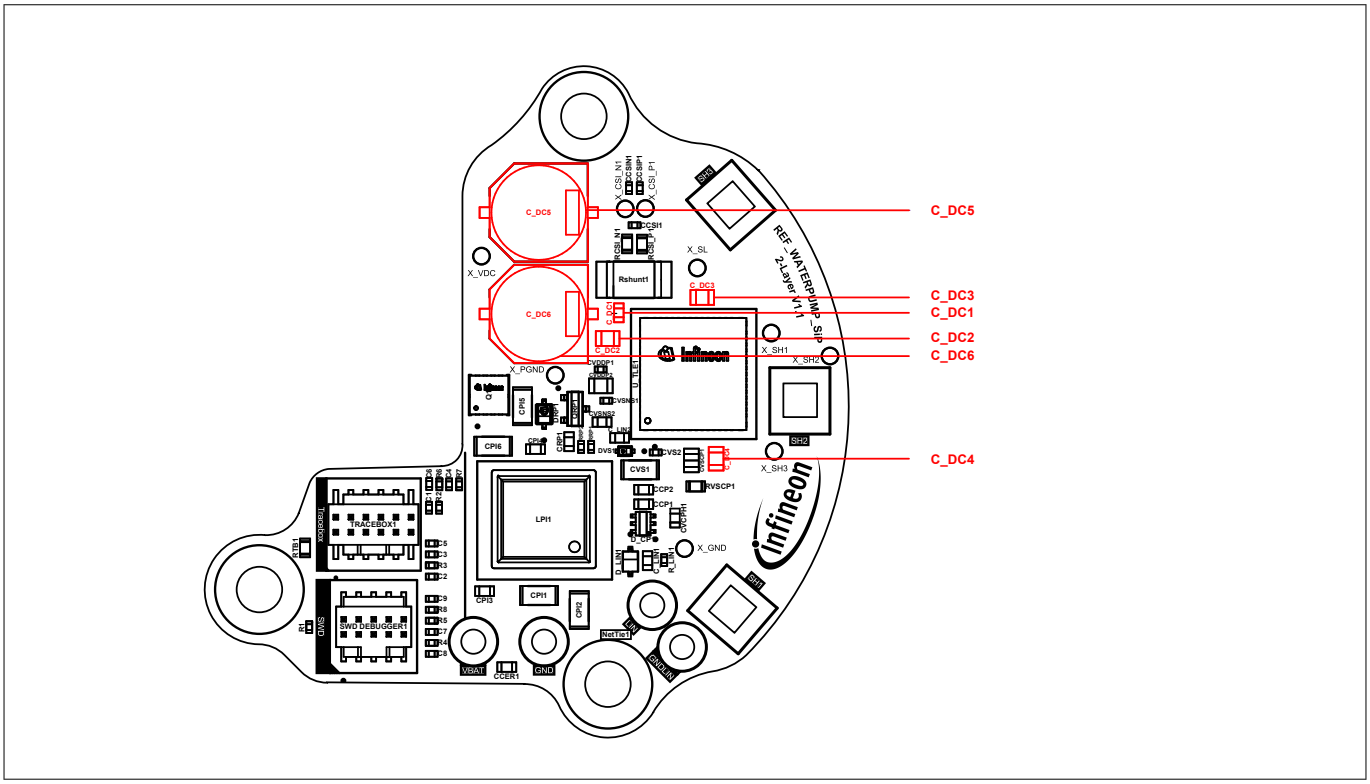


Figure 16 DC link capacitor component placement

4.4.2 Snubbers

Snubbers have not been used in the design. Due to the MOSFETs being integrated in the system package, there is no need for additional filter components. This comes from the very low parasitic inductance in the commutation path resulting in very good electrical and *EMC* characteristics. For further details, refer to System performance.

4.5 Measurement components

4.5.1 Shunt measurement circuit

The shunt measurement circuit is used for load current measurement using a 2 mΩ shunt resistor. A smaller resistance value is being used to ensure smaller power losses. The 2 mΩ shunt is selected for its very low parasitic inductance of less than 2 nH. A single shunt resistor R_SHUNT is placed on the board between the SL pin of the device and *ground (GND)*. It enables the indirect measuring of the motor current. This is done via the CSIP and CSIN pins of the device, together with R-C networks for filtering. The Shunt_P/Shunt_N and CSI_P/CSI_N measurement signals need to be routed differentially for optimum measurement quality. The schematic and the component placement of the shunt measurement circuit are depicted in the following figures:

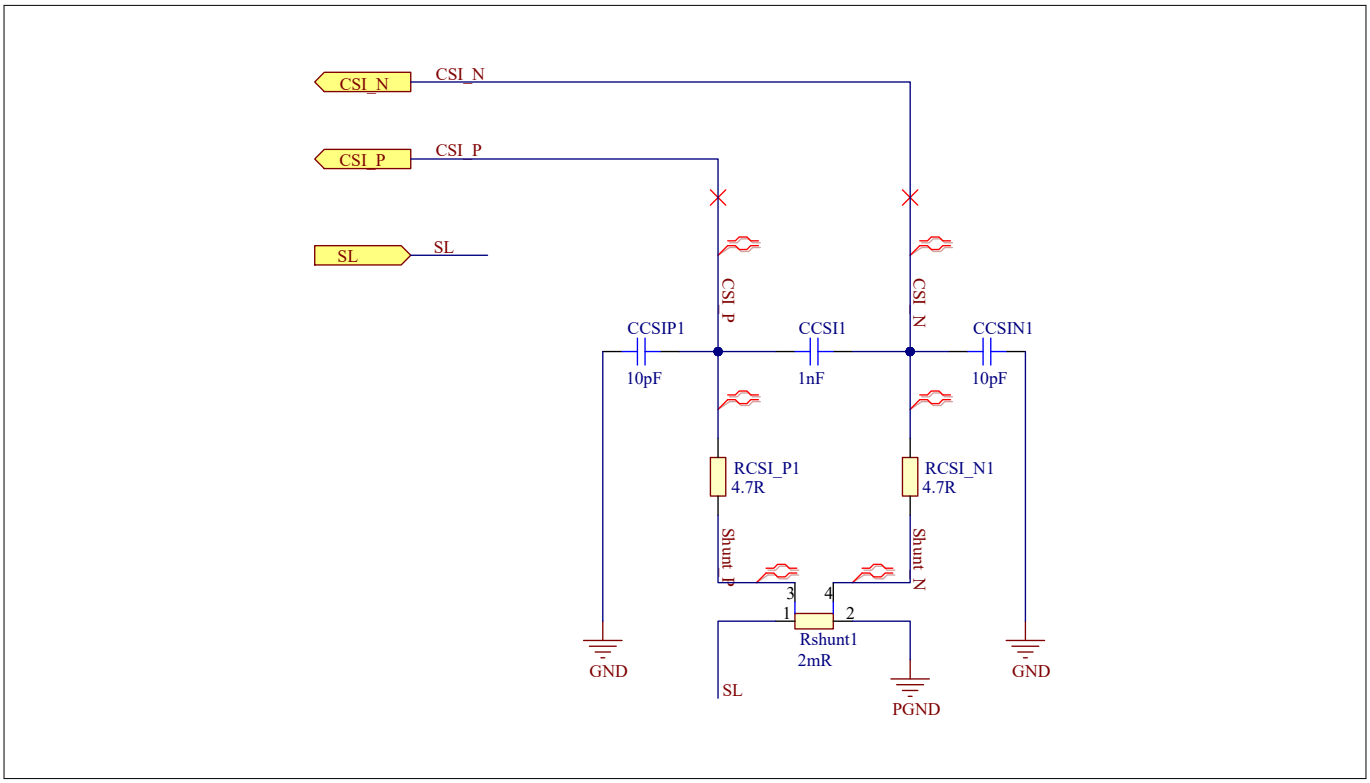


Figure 17 Shunt measurement schematic

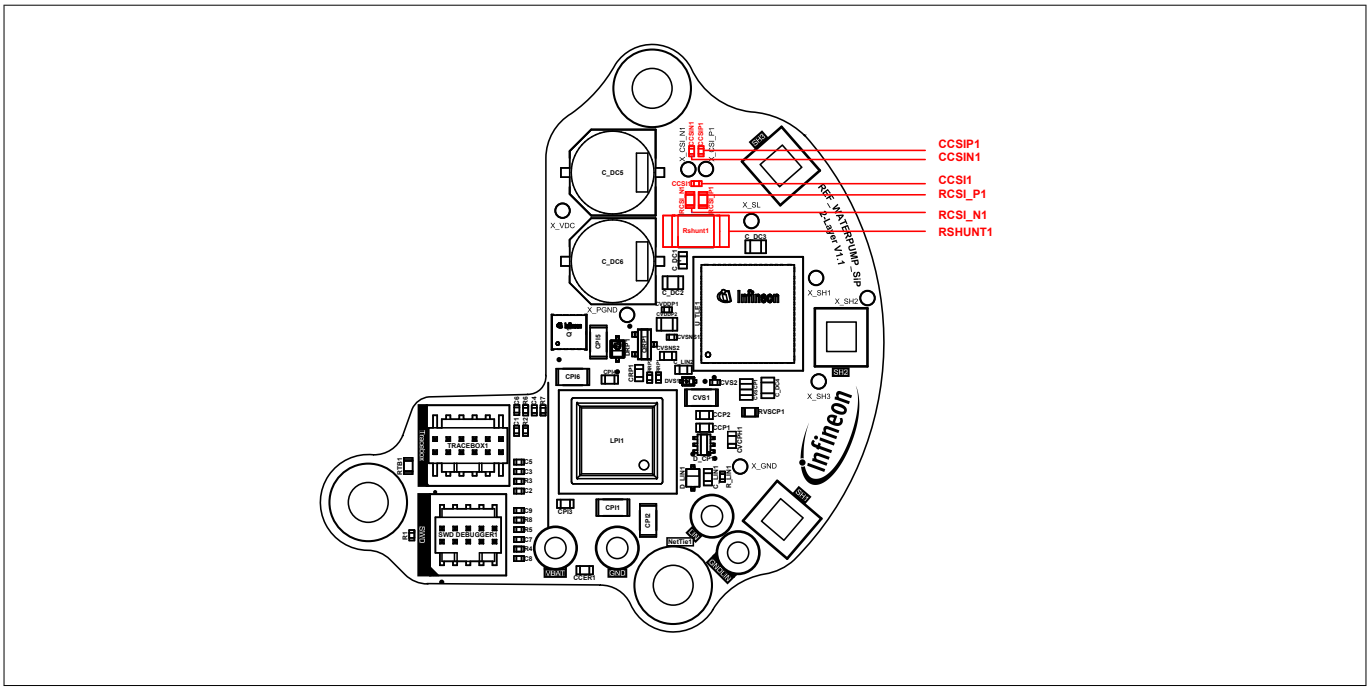


Figure 18 Shunt measurement component placement

4.5.2 Shunt resistor selection

The shunt resistor is placed between the SL pin of the device and the *GND*. The shunt resistor enables measurement of motor currents. The resistance, tolerance, temperature coefficient, wattage, derating, form-factor, stray-inductance, and environmental robustness are the main parameters to consider when choosing a shunt resistor. The value of the shunt resistor can be determined considering the targeted maximum shunt current.

When it comes to the 150 W water pump reference design with SiP, the power dissipation of the shunt resistor can make a significant portion of the overall power consumption. The reference design has a 3 W/2 mΩ resistor below the low-side MOSFETs. Considering a power derating down to 15% of the 3 W at $155°C$, the maximum power of the shunt resistor is 0.45 W. According to the resistor specification, the resistance is expected to rise by 50 ppm/K, giving a total shunt resistance equal to ((155-25) °C x 50 ppm/K) + 2 mΩ = 2.0065 mΩ. Thus, the power dissipation at 12 A rms current is: $(12A)^2 \quad x \quad 2.0065 \quad m\Omega \quad = \quad 0.289W.$

Keeping the *DC*-link loop inductance low is essential to let the system run with fast switching times, which allows low switching losses, noise and stable gate driving. Therefore, having low-stray inductance of the shunt resistors is important for an application that involves high-speed switching.

5 Placement and layout

5.1 Components and interfaces

The reference design has a compact structure with a reduced surface area providing optimum functionality. The reference design has the battery terminals towards the bottom of the board. Towards the right, 3-phase outputs of the motor bridge driver are oriented towards to the phase connector locations of the motor. *LIN* communication port can be found at the bottom of the board. Tracebox and SWD debugger can be found towards the left of the board. TLE995QSW40-33 is located at the center. Test points are provided on the *PCB* for measuring the switching performance.

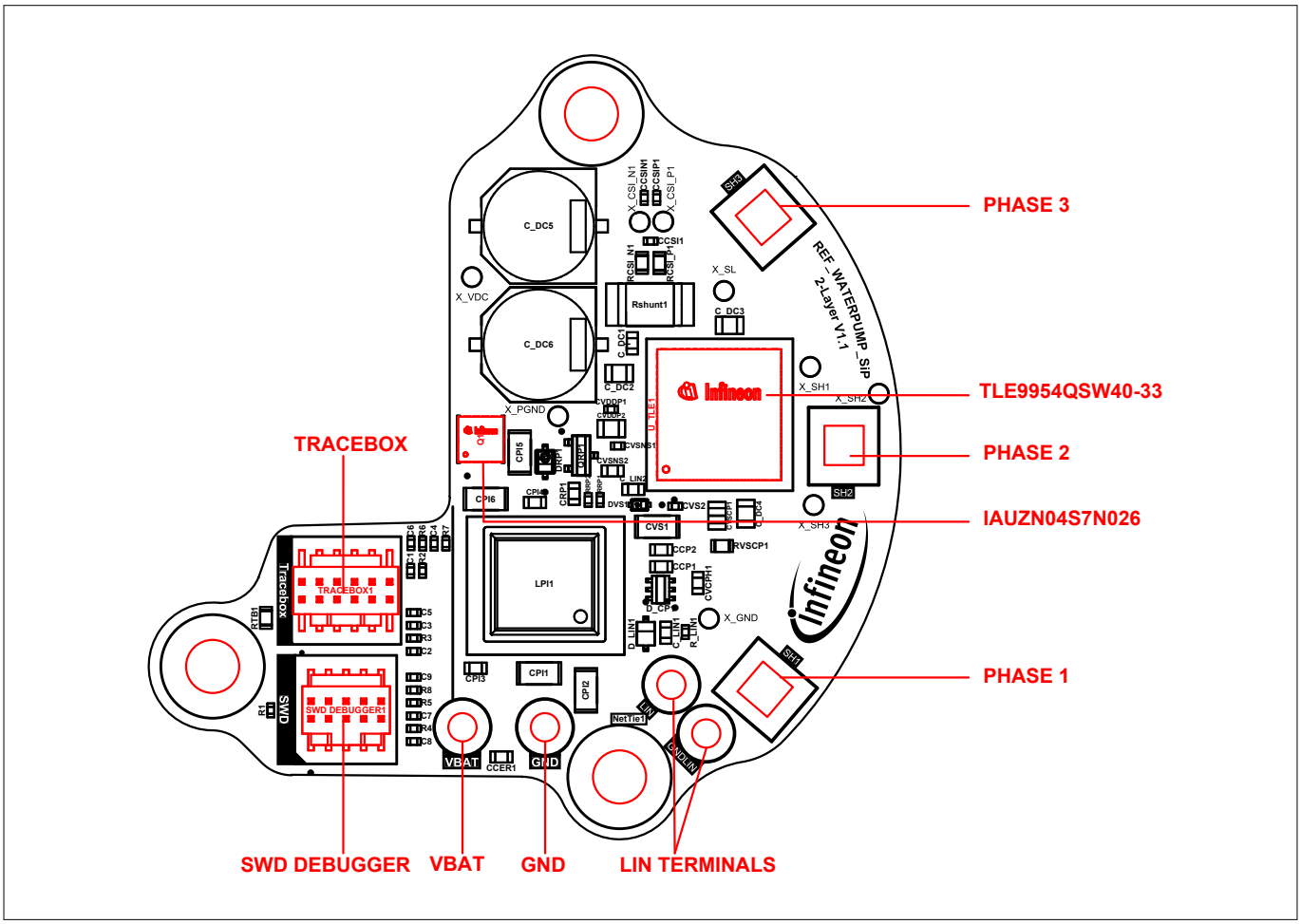


Figure 19 Reference design

5.2 Layout and current flow

The fact that the B6 bridge is integrated in the TLE9954QSW40-33 device allows for a very compact layout even with a two-layer *PCB*. Figure 20 illustrates the current flow from the *DC*-link capacitors to the TLE9954QSW40-33 and back to the DC-link capacitor via the shunt resistor. The arrows represent the direction of the currents while the yellow areas show the copper polygons in the PCB that are carrying the current.

On the left, you can see the VDC polygon on the bottom layer which connects the DC-link capacitor to the VDC pad of the TLE9954QSW40-33. In the center, you can see the SL polygon taking the return current towards the shunt. You can see that the polygon spreads away from the TLE9954QSW40-33 device in two directions. This was done to optimize the heat distribution through the PCB for better cooling. On the right side, you can see

the power ground polygon connecting the shunt to the ground side of the DC-link capacitor. The arrows on the right picture also illustrate the very compact circle that the commutation path surrounds.

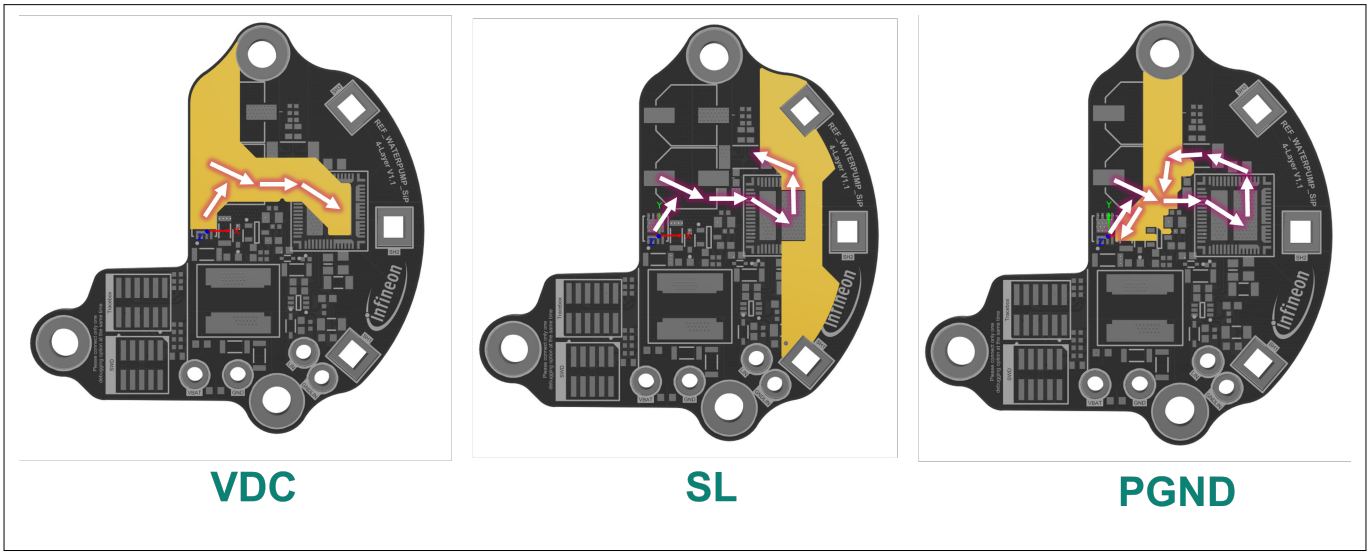


Figure 20 Drawing of current flowing through commutation path

6 Getting started with REF_WATERPUMP_SIP

Tool installation guide

To get the reference design ready and running, there are certain tools and software required. The software toolchain can be installed by following these instructions.

Content of the packaging

The box contains the following components:

- 150 W water pump reference design with SiP
- XMC™ link isolated debug probe
- Connector board
- Tracebox cable with 12 pin Tracebox connector

Connecting the PCB for usage with Solution Designer

The reference design is supplied by soldering two supply cables to the battery and *GND* terminals. The *BLDC motor* is connected by soldering the three phases of the motor to the 3-phase output of the *PCB*. The reference design can be connected to the PC through the connector board using an XMC™ Link. Connect the Tracebox cable to the 12-pin Tracebox connector on the Reference Design to the DUT Connector on the connector board. Then connect the bigger 8-pin connector on the XMC™ Link to the XMC_LINK_UART connector on the connector board. This allows to both flash and debug, and to control the motor control algorithm through the MOTIX™ MCU Solution Designer during runtime.

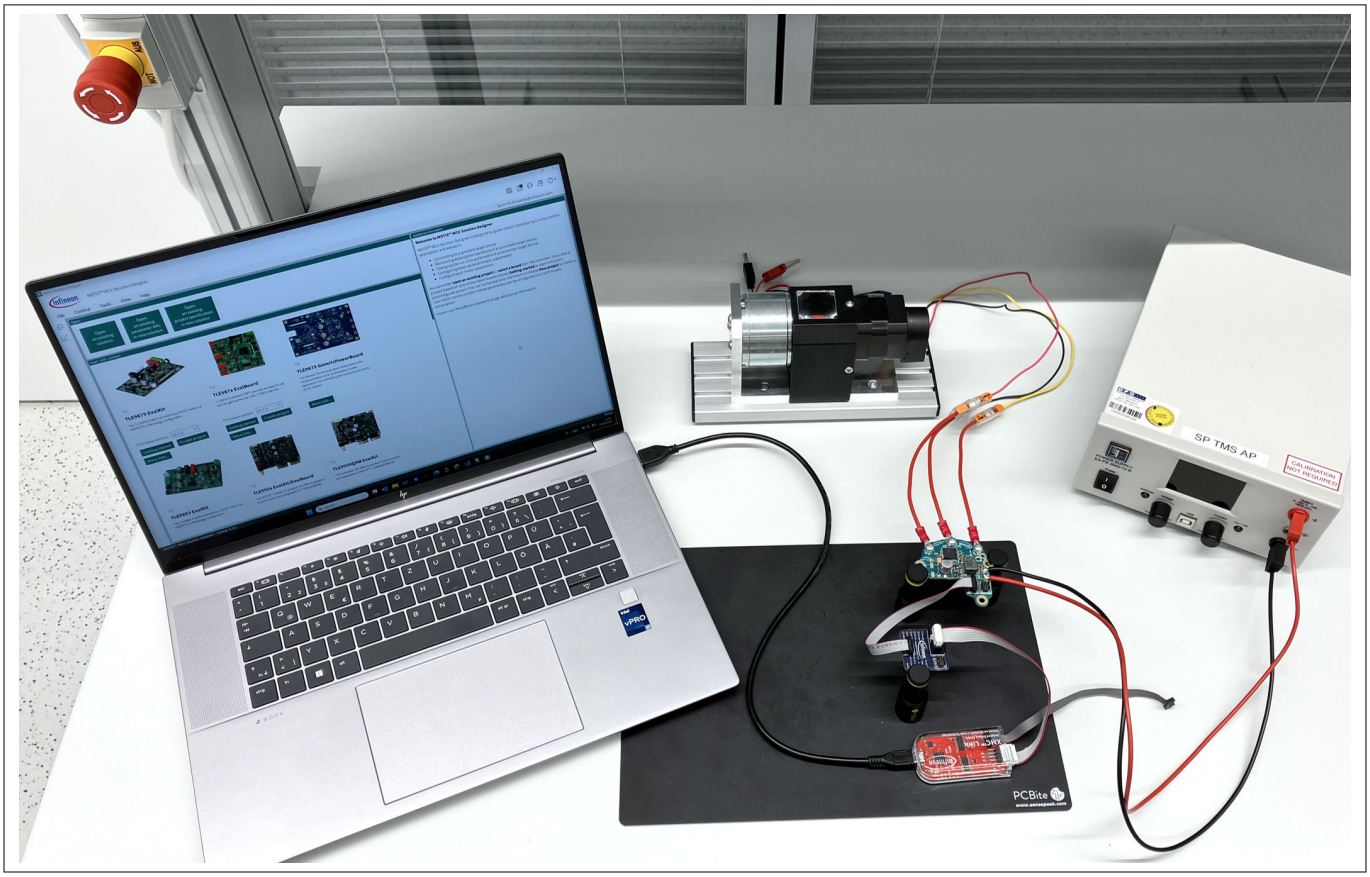


Figure 21 Assembly picture of connected board

Connecting the PCB for flashing and debugging only

For flashing and debugging only, the 10-pin SWD cable can directly be connected to the 10-pin SWD connector on the reference design. Any Arm® Debugger like XMC™ Link, Segger J-Link, or Segger U-Link can be used.

In this use case, the connector board is not mandatory but can be utilized to access some *general purpose input output (GPIO)*s of the TLE9954QSW40-33 for example, to connect external sensors.

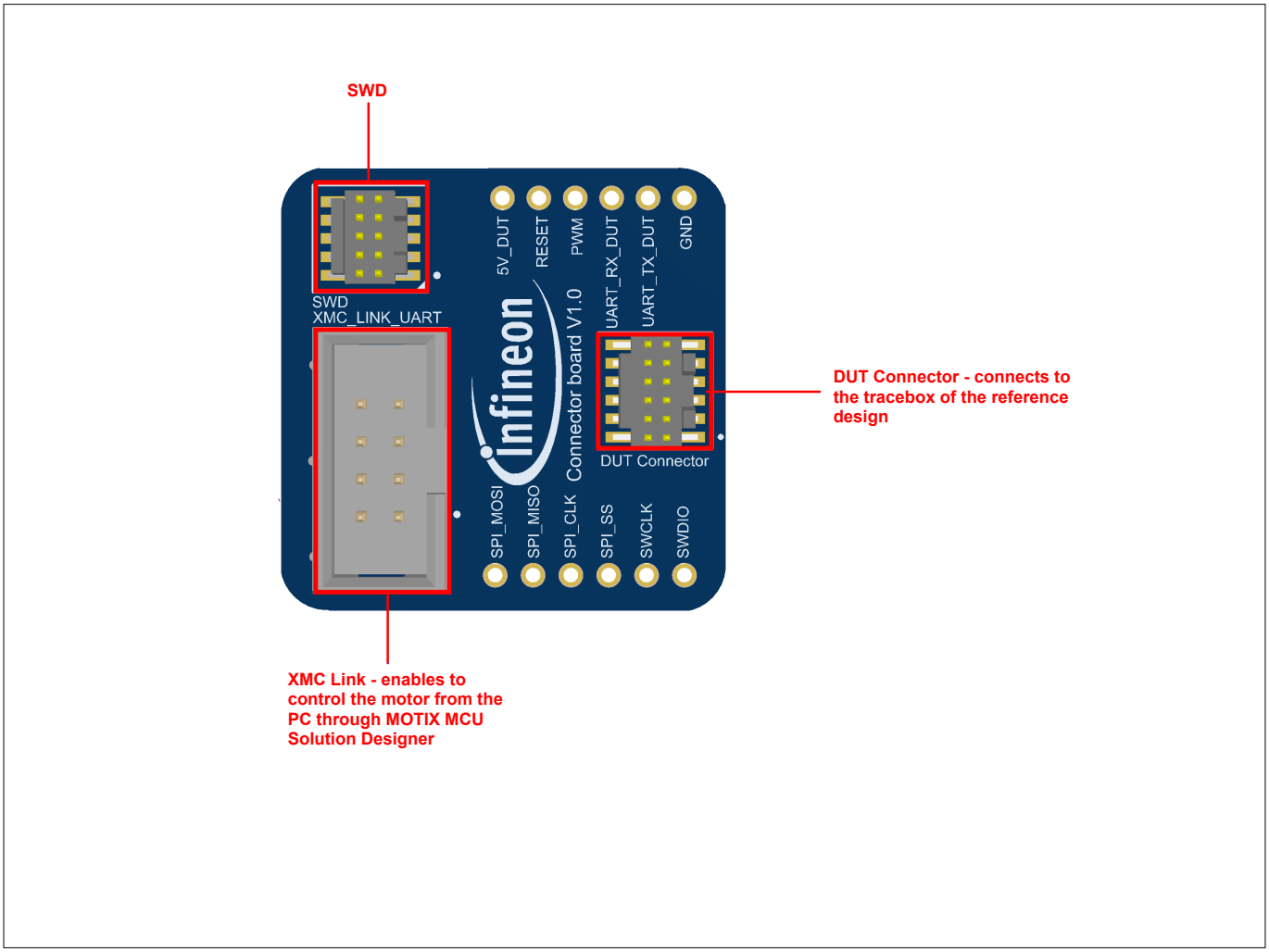


Figure 22 Connector board

7 System performance

The reference design is offered to provide a reference about the performance that can be achieved with the TLE9954QSW40-33 SiP device. The performance of the reference design is shown in the following sections and covers details on the test setup, electrical behavior, *EMC* performance and thermal performance.

The tests were conducted by either attaching the water pump to an emulated water circuit with a water tank setup or by using a simple *BLDC motor* attached to a hysteresis brake. All the tests performed, the test setup, conditions, and results were documented. The default test configuration is assumed to be the following, unless mentioned otherwise:

- Electrical power = ~ 150 W
- Battery voltage = 13.5 V
- Nominal speed (Waterpump) = ~3600 rpm
- Nominal speed (Nanotec DB59C024035R-A motor) = 2000 rpm

7.1 System test setup

The reference design, REF_WATERPUMP_SiP, was tested with two different setups. In one setup with a water pump and load emulation, and one with a standard *BLDC motor* and hysteresis brake as a load.

Water pump setup

The reference design, REF_WATERPUMP_SiP, drives an automotive *brushless direct current (BLDC)* water pump. The pump is directly connected to a system constituting of different tubes and an expansion tank to ensure that the system is free of air. Water is filled in the system to emulate the load of an automotive thermal management water cycle. The *PCB* is mounted directly to the metal body of the pump as shown in Figure 24. The load is controlled by increasing or decreasing the rotational speed of the pump.

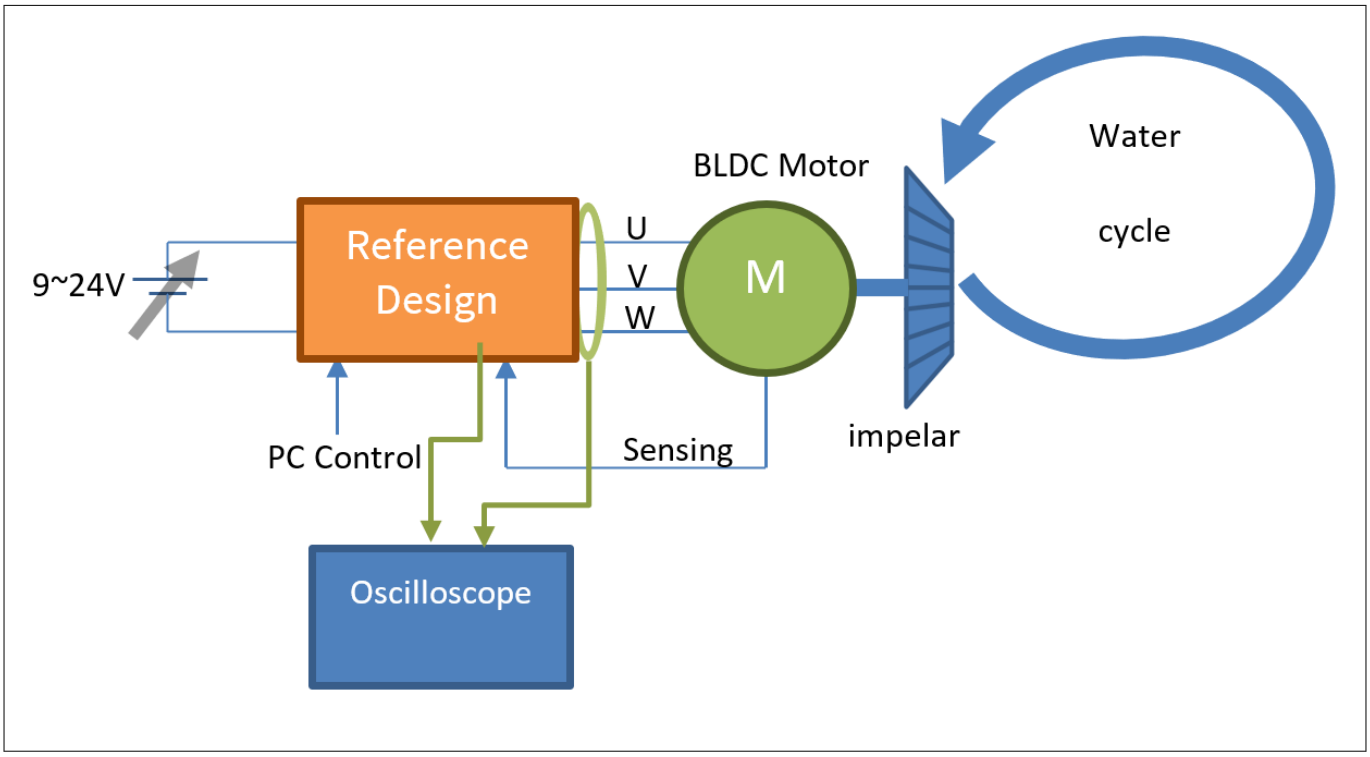


Figure 23 Water pump test setup block diagram

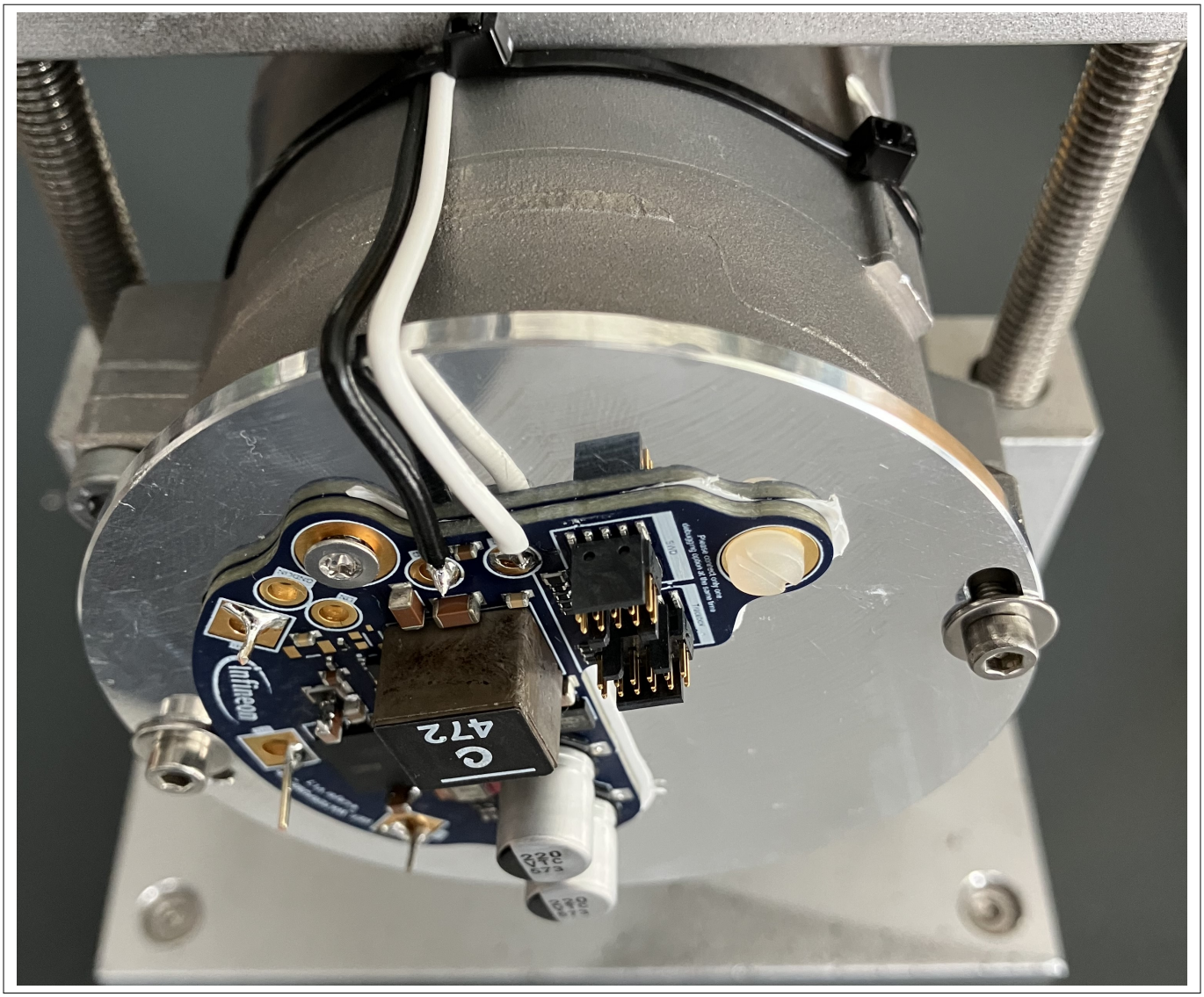


Figure 24 Assembly of PCB mounted on water pump

Hysteresis brake setup

On the second setup, the PCB is connected to the Nanotec DB59C024035R-A motor via cables. This way, different cooling conditions can be realized with and without heat sinks. The shaft of the pump is connected to a hysteresis brake via a coupling. The load to the motor can be controlled via the current into the hysteresis brake while keeping the rotational speed at around 2000 rpm.

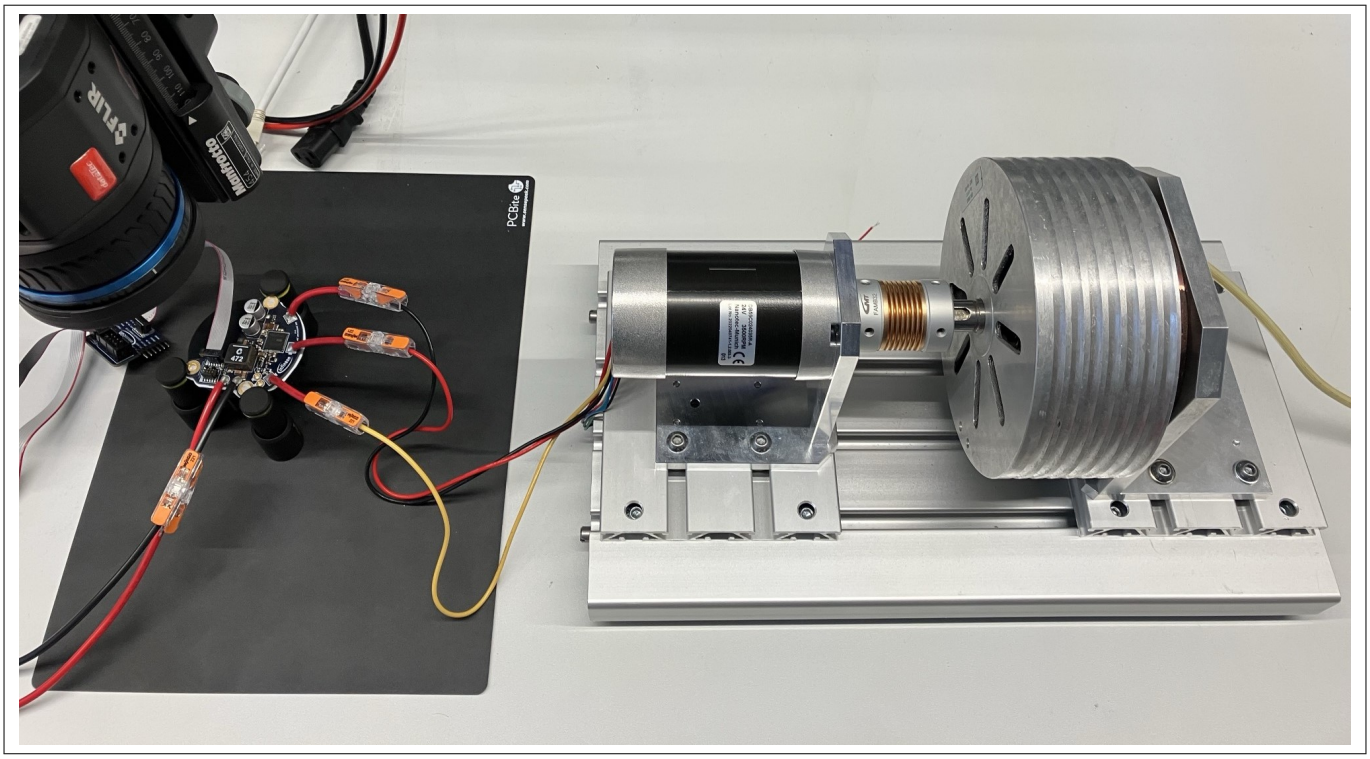


Figure 25 Picture of DB59C024035R-A and hysteresis brake setup

7.2 Electrical test result

7.2.1 Switching characteristics

The main advantage of the TLE9954QSW40-33 device is the high integration due to all B6-MOSFETs being placed inside of the package. This way the parasitic inductance in the commutation path will be reduced significantly. A lower parasitic inductance will allow for a faster switching transition.Figure 26 illustrates the difference in typical switching time ranges between both a traditional discrete solution and the TLE9954QSW40-33 System-in-Package solution.

You can see that typical switching times are ranging between 100 ns and 200 ns. In most cases, the target is to switch as fast as possible to reduce switching losses, to keep the dead-time as short as possible and to acquire current readings as quickly as possible after switching. The limiting factor are the *EMC* emission and maximum ratings of the gate driver due to over- and underswing on the output voltage. Both are mostly impacted by the parasitic inductance in the commutation path. This is the reason why it is possible to switch much faster with the TLE9954QSW40-33 device. A switching time of only 60 ns should be achievable in most applications. In some cases it is even possible to go down to 14 ns. For further details, refer to Conducted emission with motor in on-state.

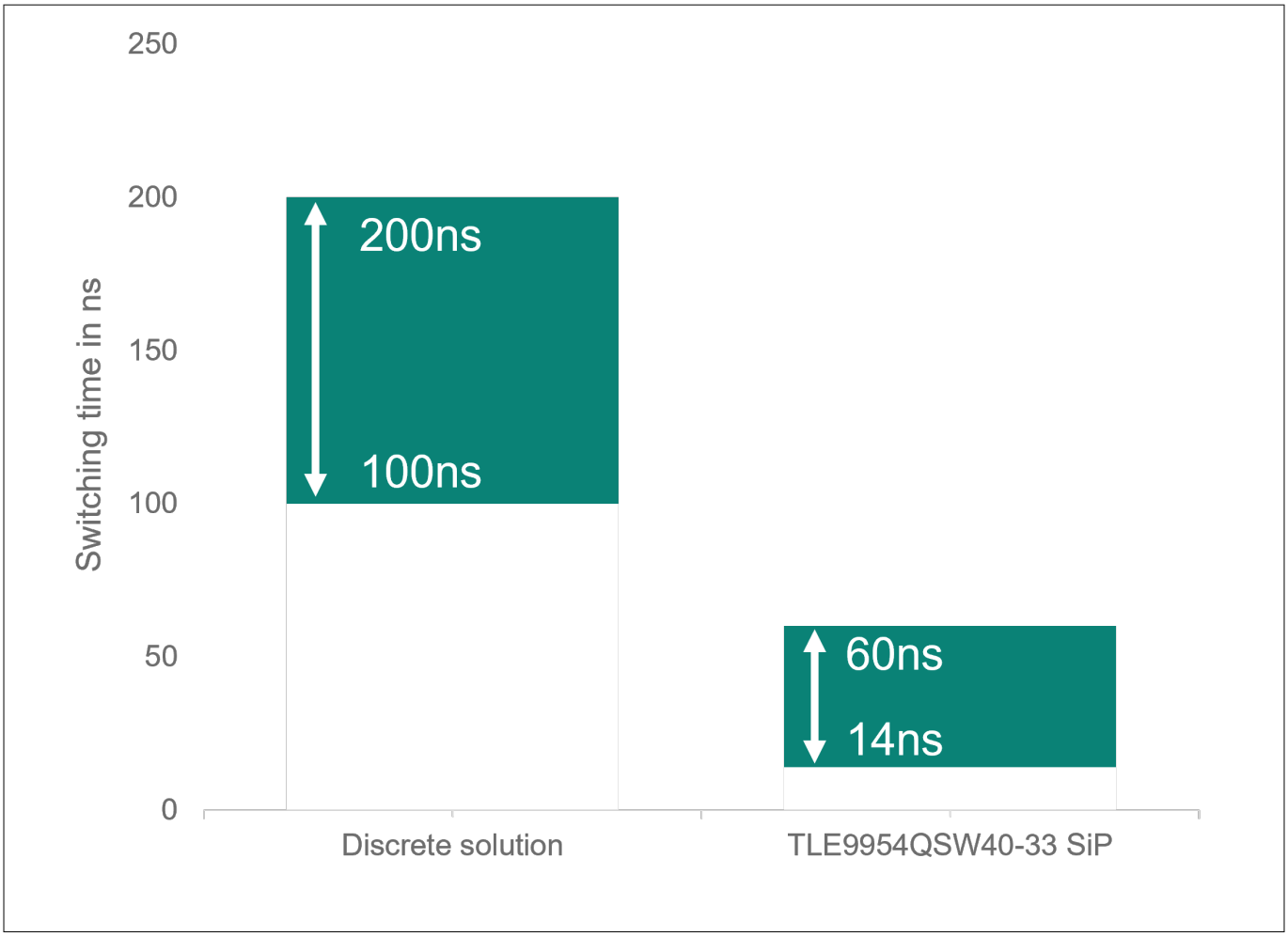


Figure 26 Comparison of traditional switching speeds in discrete solutions vs. TLE9954QSW40-33 switching speeds

To find the ideal switching speed, three main aspects must be considered.

- Power losses in the MOSFET during switching
- EMC emission due to switching
- Maximum rating of the device

Generally a faster switching transition is desired to reduce the power loss in the MOSFET. On the down side, faster switching will also lead to higher EMC emission. The EMC emission will be worse with higher parasitic inductance in the commutation path. Additionally, the combination of fast switching and parasitic inductance will lead to positive and negative spikes on the outputs during the switching event. These spikes might exceed the maximum rating of the gate driver and must be avoided at all costs. In most cases, the maximum rating to look at is the maximum negative voltage at SHx. There will be a negative voltage spike at SHx during the High-Side turn-off switching event.

Figure 27 and Figure 28 show a scope capture of the high-side and low-side switching behavior of the REF_WATERPUMP_SIP. The gate driver was configured to maximum gate current. In the scope capture, the low-side MOSFET has a rise and fall time of 19.7 ns and 14 ns respectively which is very fast. The high side MOSFET is switching slightly slower with 25.2 ns and 23.6 ns. It can be observed in Figure 29 that the negative spike is not even exceeding the -5 V mark which is way withing the maximum rating.

Switching as fast as shown in the below figures comes with the following advantages:

- Very low switching losses
- Very short dead-time which gives more time for phase current measurements

- Changing application conditions (voltage, current, temperature) and production spread will cause only minor deviations in switching times
- High accuracy in switching timings through application conditions and production deviations

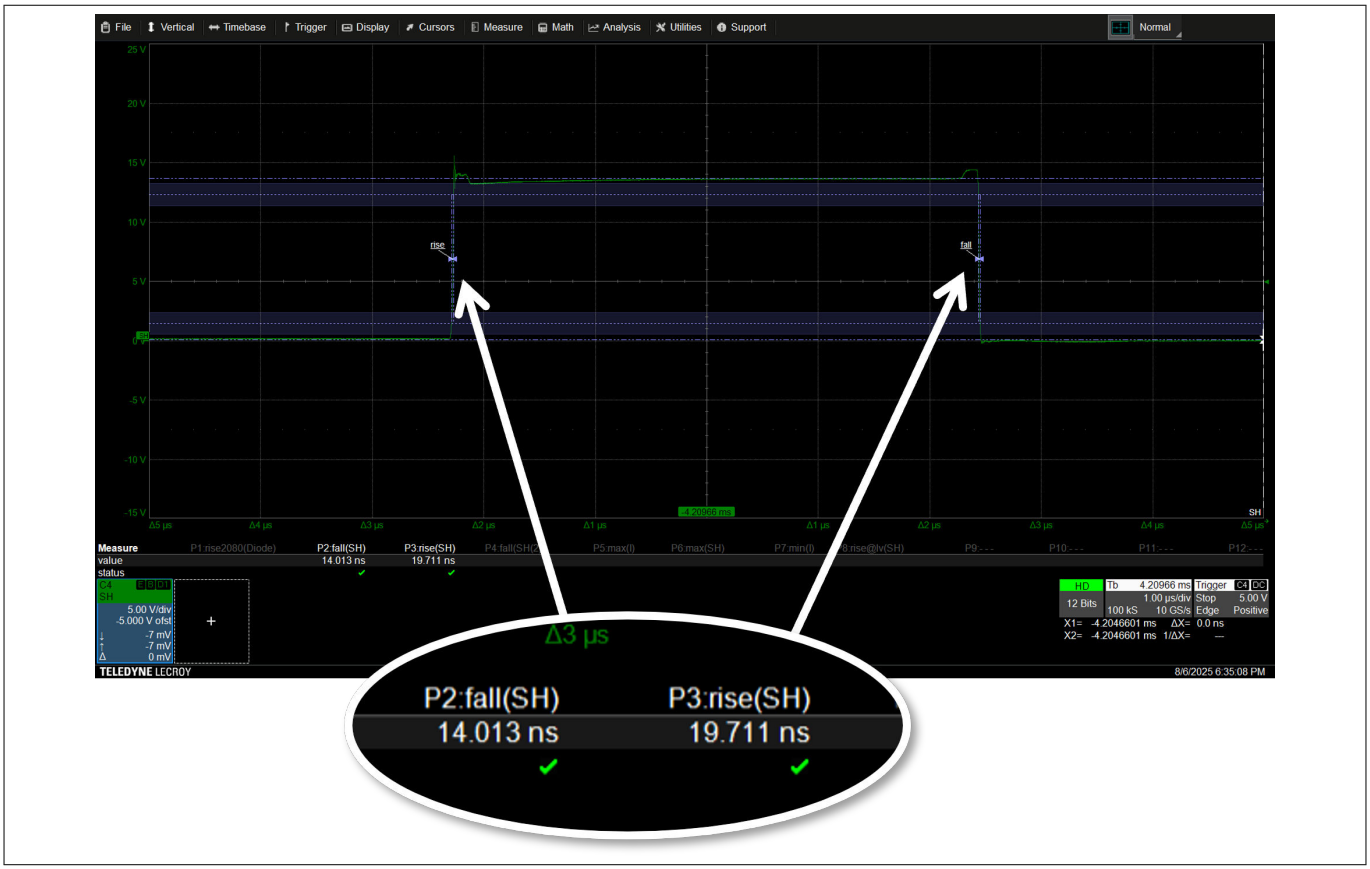


Figure 27 Low-side switching behavior

7 System performance

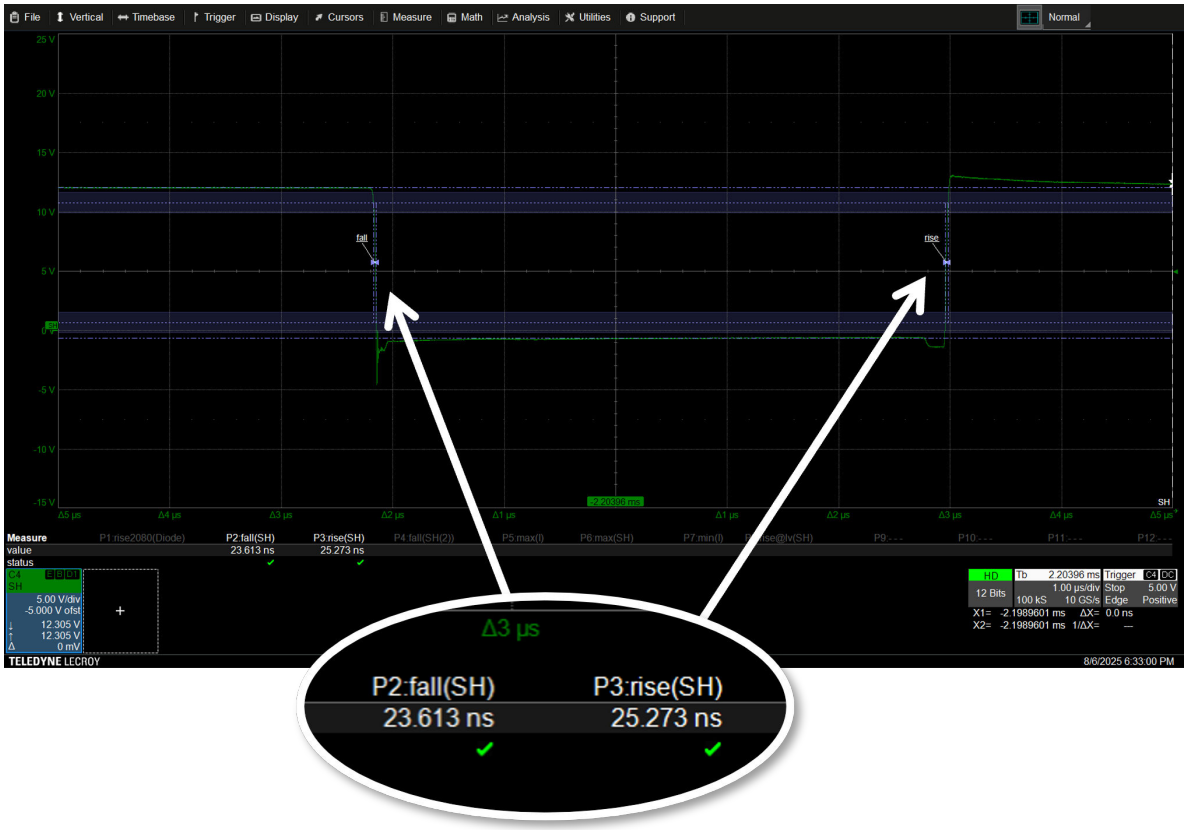


Figure 28 High-side switching behavior

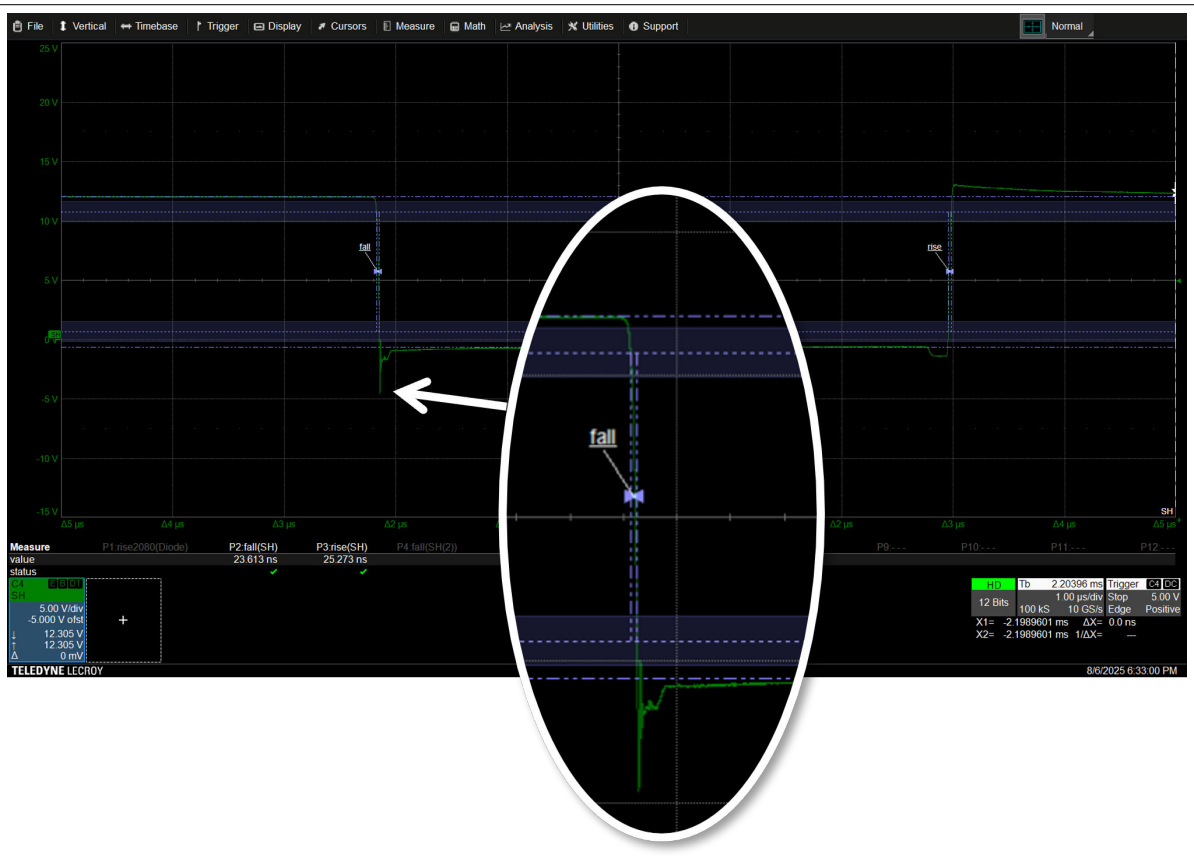


Figure 29 Negative spike during high side turn-off

7.3 Thermal behavior

7.3.1 Water cycles in thermal management

The thermal performance of a water pump *electronic control unit (ECU)* in an automotive thermal management system is essential due to high operating temperature conditions. Since the water pump is a part of an automotive thermal management system, the part is exposed to varying temperature ranges spanning from -40°C to 85°C.

Therefore, it is important to understand the thermal energy dissipated by the active components to understand the thermal performance and reliability of the reference design in application scenarios. The main limiting factor will be the self-heating of the MOSFETs which are inside of the TLE9954QSW40-33 device. The target of a good thermal design is to draw the dissipated heat away from the device as efficiently as possible.

7.3.2 Thermal testing test setup

In order to evaluate the heat generated by the active components on the reference design, a thermal camera was used to capture the temperature profile of the key active components at a room temperature of 25°C. The reference design was directly coupled onto the pump in the water circuit. To make sure the *PCB* has full contact to the pump when the phase terminals are connected to the 3-phase outputs of the PCB, a metal adapter plate was used. Figure 30 illustrates the assembly of the PCB on the water pump. Figure 31 illustrates the total test setup including the water cycle.

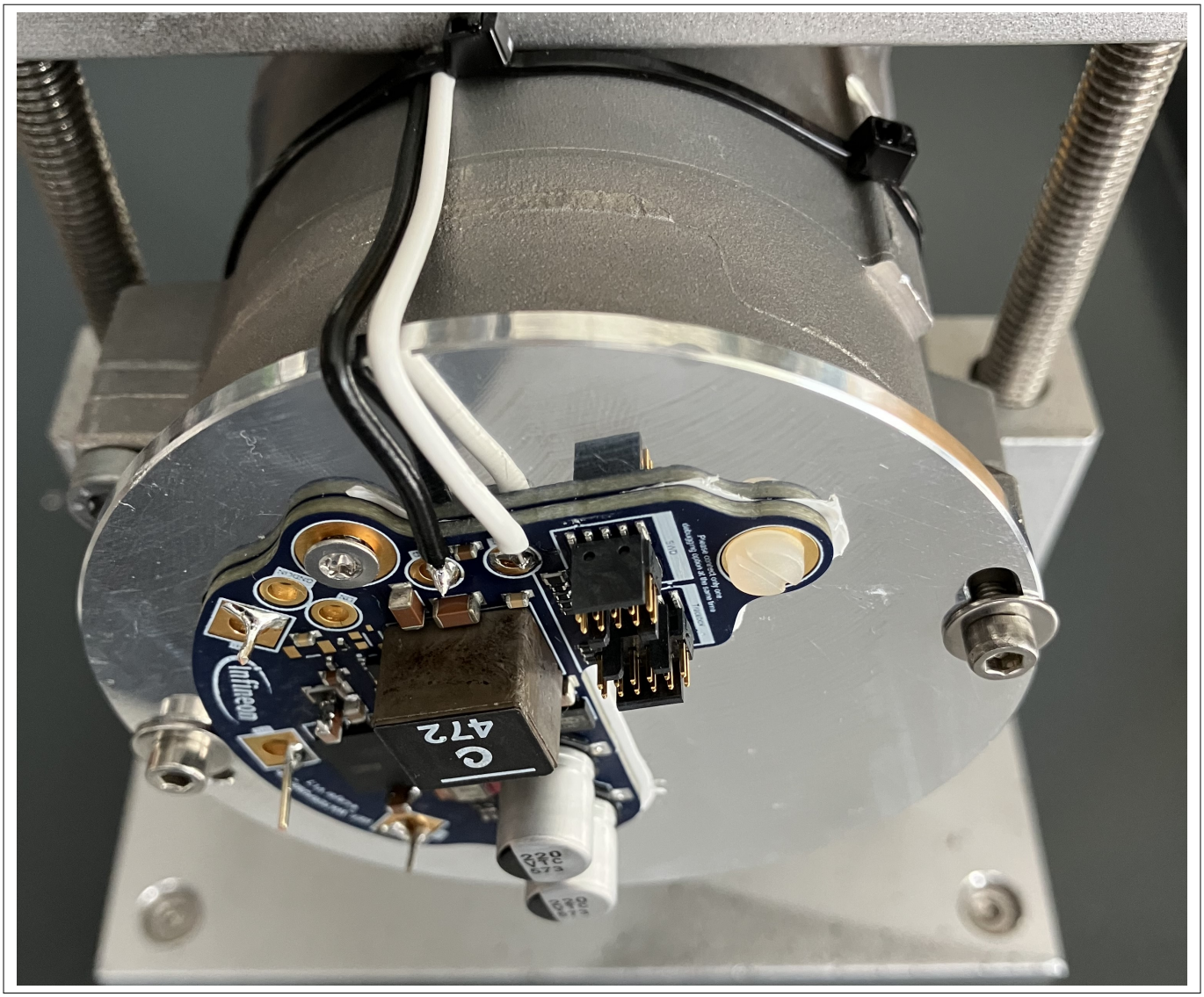


Figure 30 Image of PCB coupled to water pump

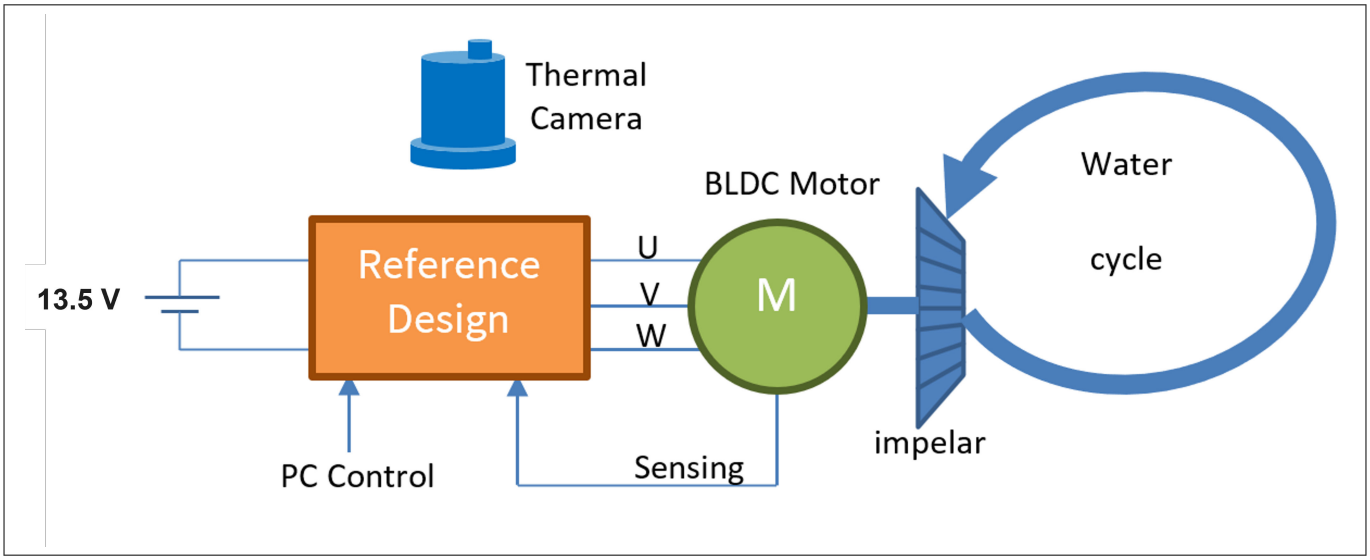


Figure 31 Thermal testing test setup block diagram

Additionally to the water pump setup, some tests were also performed with the bare PCB in natural convection and the PCB assembled to a heat sink in natural convection. Figure 32 shows the specification of the aluminum heat sink from https://www.fischerelektronik.de/.

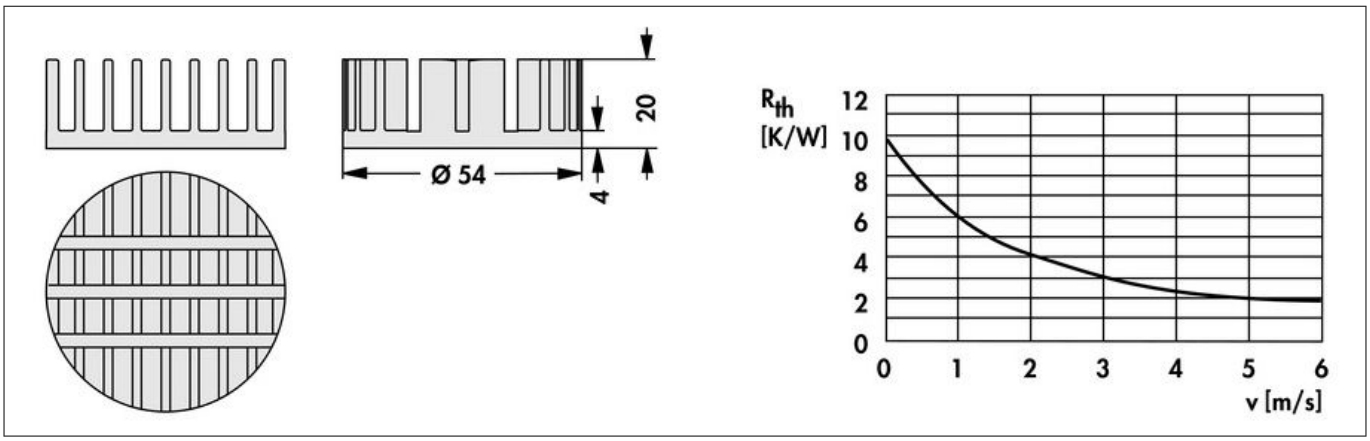


Figure 32 Mechanical specification of aluminum heat sink

7.3.3 Thermal analysis results

Temperature measurement on a PCB

The temperatures on the reference design are measured via an infrared camera. The values described in this chapter are referring to the hotspot on top of the mold compound of the *integrated circuit (IC)*. In Figure 33, you can see one example of the *impact rating (IR)* camera reading. The camera's emissivity is configured to take precise readings on the mold compound of each IC of the *PCB*. Other components or the PCB surface will give imprecise reading as the emissivity of the materials is different to the mold compound. Nevertheless, they can give a rough indication about the temperature distribution through the PCB.

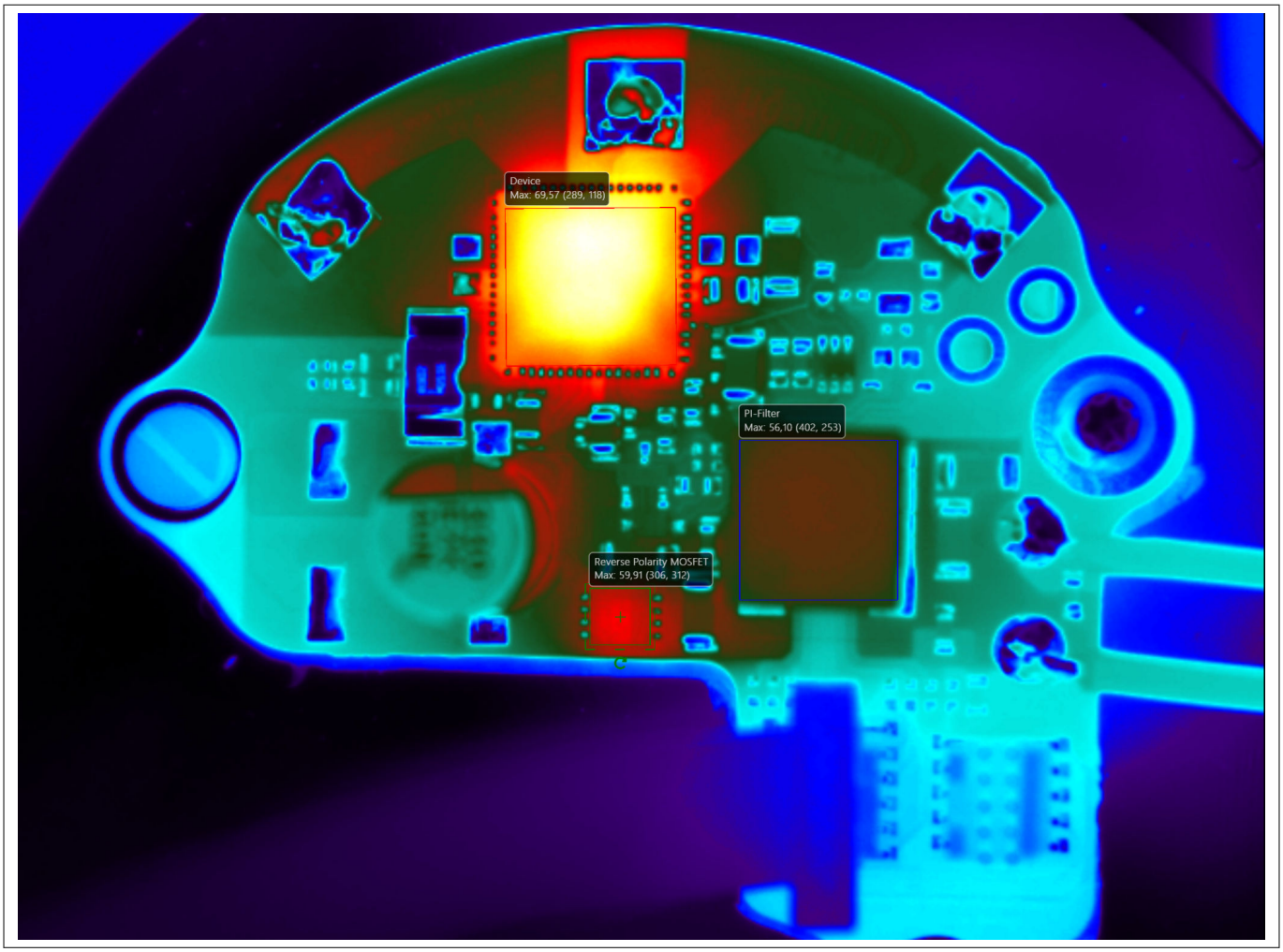


Figure 33 IR-camera recording of temperature distribution on PCB

Heating curve of the device

Figure 34 shows the heating curve of the mold compound hotspot on the TLE9954QSW40-33 (red) and reverse polarity MOSFET (green) in the previously described water cycle setup. It shows the heating curves over a time of ~17 minutes.

You can see that the majority of the heating happens in the first 3 minutes. This is roughly the time that is needed to heat up the PCB itself. Afterwards the heating curve transitions into a rather linear increase. This comes from the pump slowly heating up. At the same time, the pump is cooled via the water circulating through it. Therefore, the steady heating after the first few minutes is following the water temperature which is not being actively cooled.

In the next section, different cooling concepts are compared. For better compatibility of the temperatures in the previously mentioned setup which is cooled via the circulating water are described as the delta temperatures against the water temperature. The other cooling concepts are cooled via the surrounding air and therefore the temperatures are taken as a delta against the air temperature.

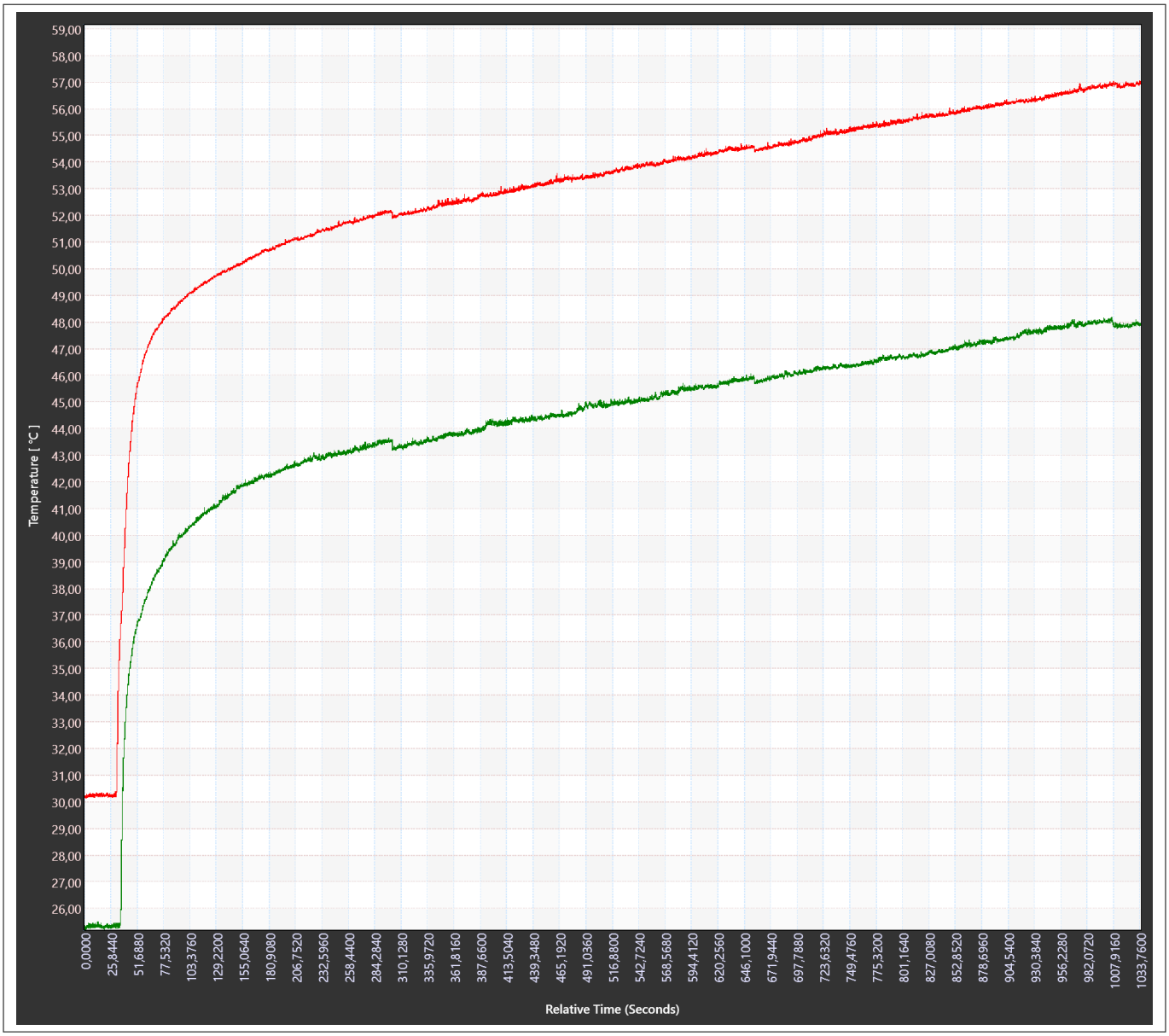


Figure 34 **Plot of temperatures on TLE9954QSW40-33 (red) and reverse polarity MOSFET (green) over time**

Comparison of different cooling concepts

Figure 35 shows a comparison between different cooling concepts. It shows the ΔT at steady state after driving the motor for 1 hour at 150 W continuously. The green bars show the results with a gate driver configuration for fastest switching times and the gray bars show the results at 60 ns switching time.

The bar charts on the left and in the middle show the temperatures for natural convection, once with a small aluminum heat sink and once without any heat sink. You can see that the use of a heat sink decreases resulting temperatures by 32°C and 34°C respectively.

The bar on the right shows the settling temperatures in the water pump setup. As the device temperature in this setup correlates to the water temperature, the values displayed here are the ΔT between water temperature and device temperature. You can see that in the water pump setup the ΔT drops down by another 21°C compared to the heat sink setup.

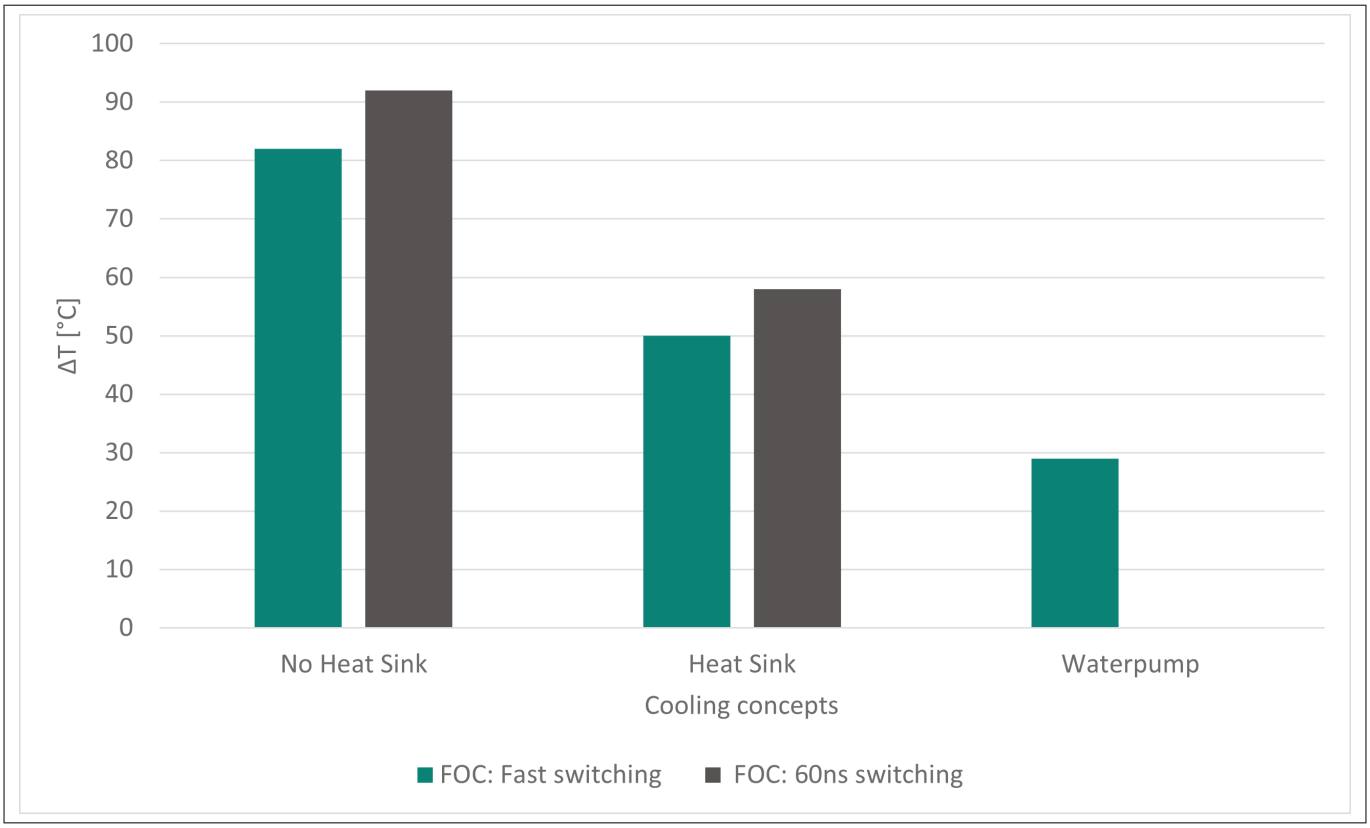


Figure 35 Bar chart comparing different cooling concepts

Overall you can see that the resulting temperature depends highly on the cooling setup. When the motor or pump is kept on a certain temperature through the water in the system, there is only a ΔT of 29°C against the water at 150 W of electrical power.

Comparison of different motor control schemes

Figure 36 shows a comparison of the impact of different motor control schemes on the thermal performance.

For fast switching times, FOC control gives the best performance due to the very low impact of switching losses. When switching slower, 12-step block commutation gives the best results due to significantly less switching events compared to FOC.

The bar chart shows again that switching as fast as possible brings great value to the thermal performance of the system. Therefore it is highly recommended to make use of the very high integration of the TLE9954QSW40-33 device and increase the switching speed as much as possible.

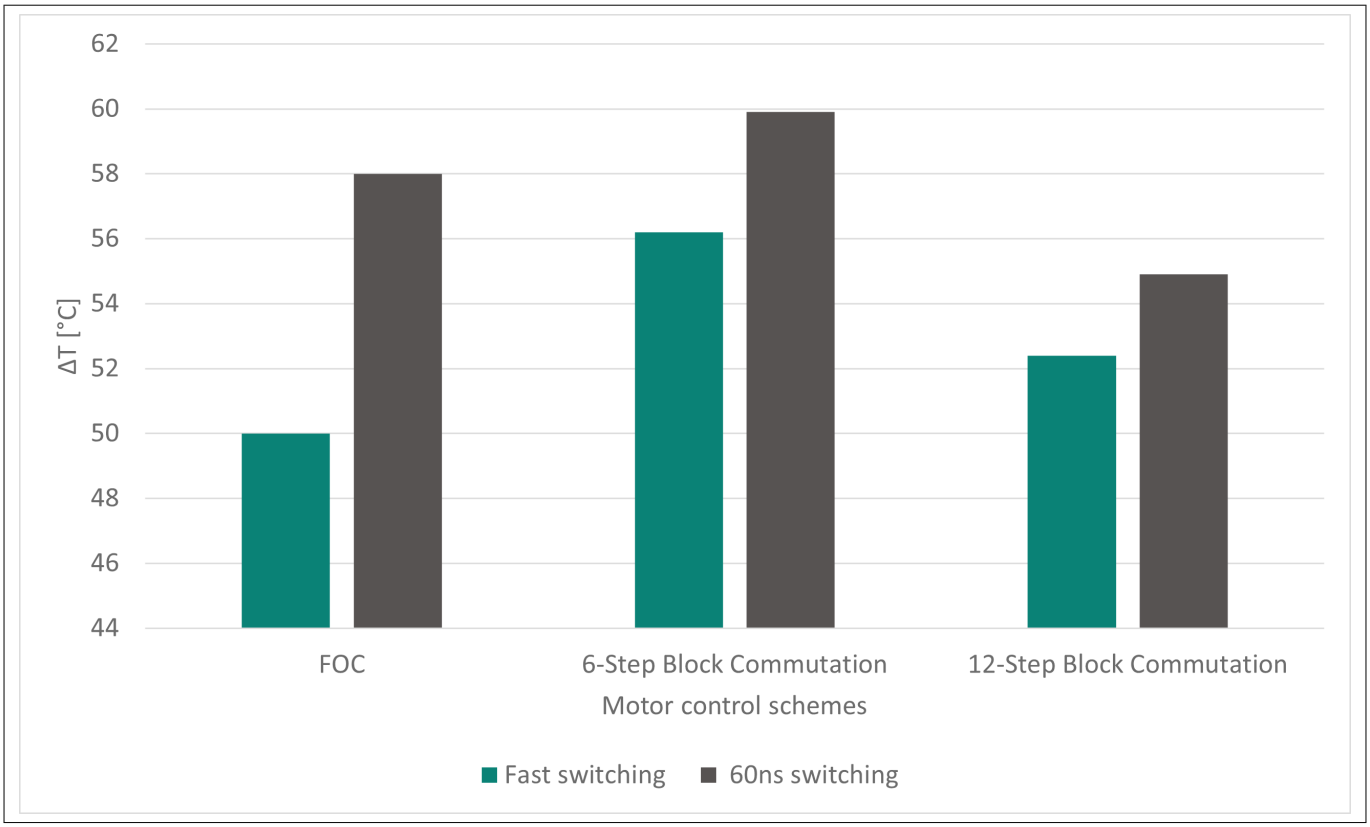


Figure 36 Bar chart comparing different motor control schemes

Comparison of 2-layer and 4-layer PCB

To give a better indication on the pros and cons of the proposed low-cost 2-layer PCB concept, the identical PCB was also developed as a 4-layer variant and tested under the same conditions. The impact on the 4-layer PCB are a higher copper mass in thePCB due to additional copper planes and reduced resistive losses in the PCB as most high current planes are routed in two layers in parallel instead of only one layer on the 2-layer PCB. Figure 37 shows the results of the 2-layer PCB (green) vs. the 4-layer PCB (gray) for fast and slow switching and with and without heat sink.

You can see that the 4-layer PCB does perform better when no heat sink is used, but as soon as any kind of heat sink is utilized, the impact of 4-layer PCB can be nearly neglected. This comes from the fact that in both PCBs the heat from the components is directly transferred vertically through the PCB through a large number of thermal vias into the metal heat sink. Therefore, the two additional copper layers do not generate additional value to the cooling performance.

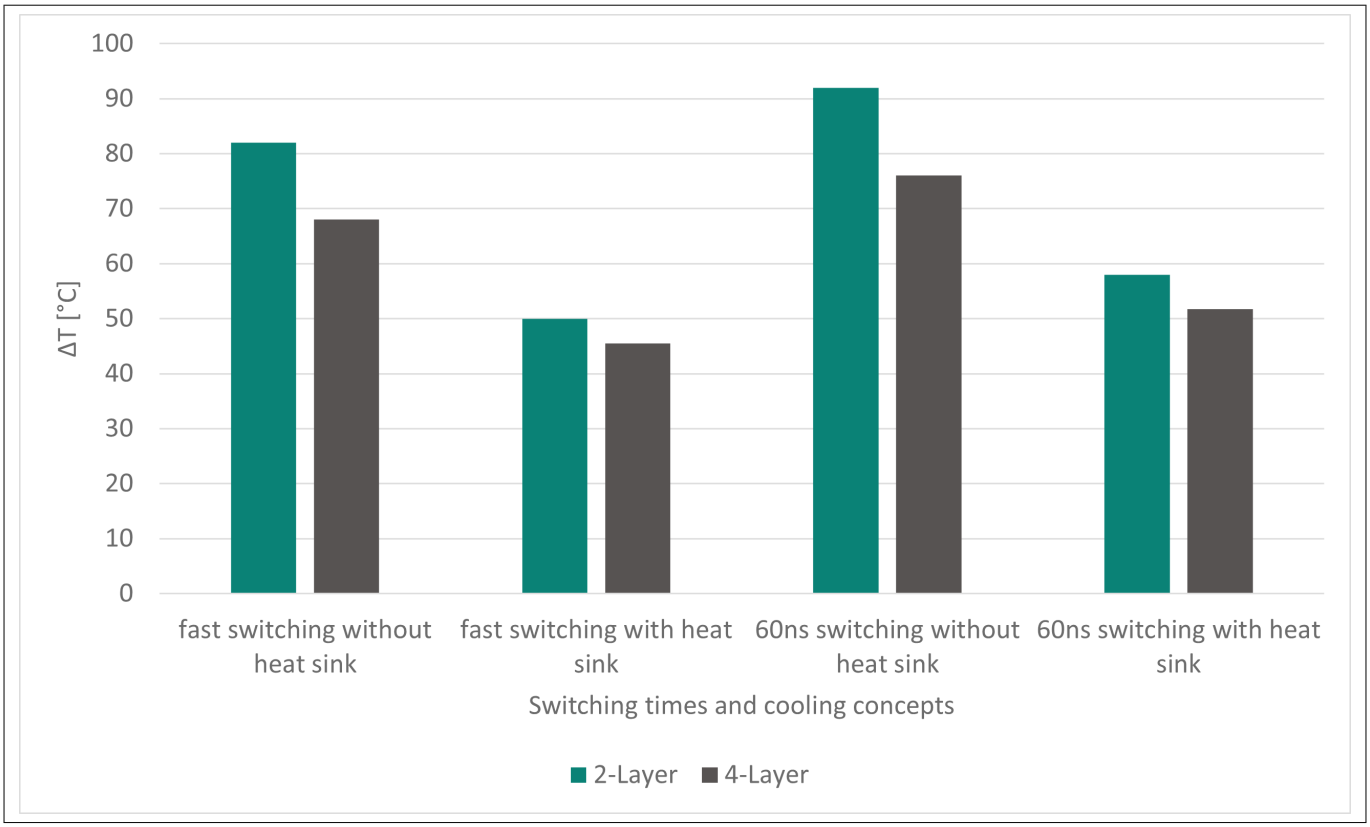


Figure 37 Bar chart comparing 2-layer and 4-layer PCB

7.3.4 Thermal behavior conclusion

In most applications, the *PCB* will be mounted to some kind of metal housing or heat sink and therefore, the PCB costs can easily be saved by building a 2-layer PCB only, without sacrificing thermal performance reduction in output power.

The TLE9954QSW40-33 device allows very fast switching speeds due to high integration. Making use of the switching speeds will result in significant reduction of switching losses, allowing to drive more power at the same thermal performance.

7.4 EMC

7.4.1 EMC test setup

Figure 38 illustrates the setup that was used for the *EMC* tests. The same water pump load as in the thermal analysis was used. On the supply side, an LISN network was connected to emulate the 12 V board net and the conducted emission on the supply lines was measured. All tests were performed at 150 W continuous load.

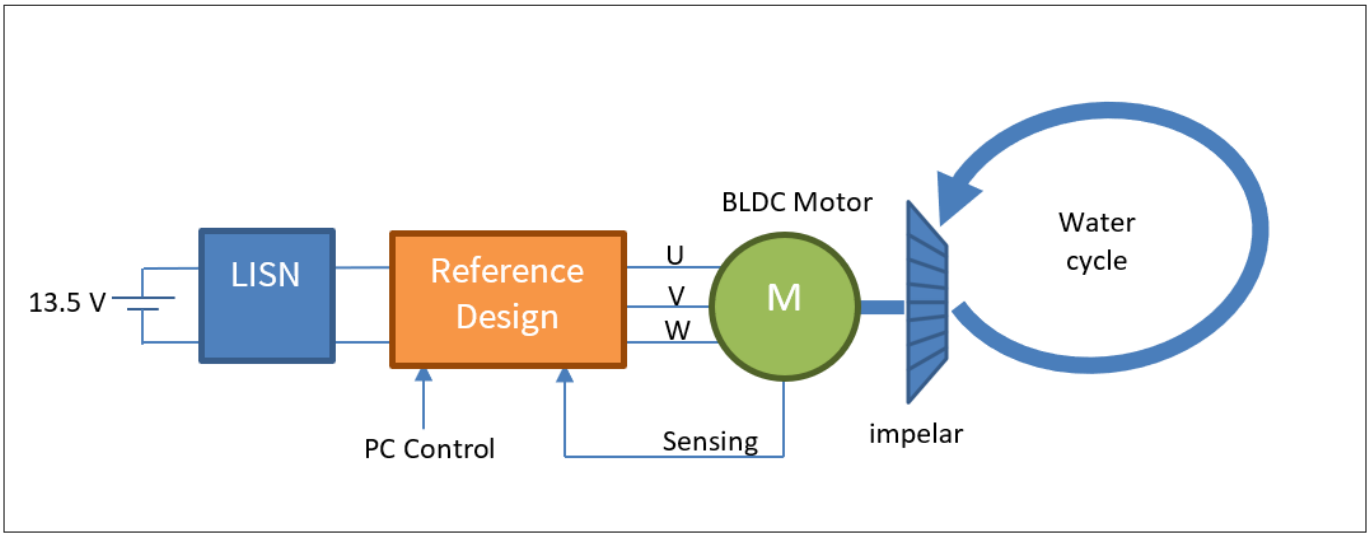


Figure 38 Diagram of EMC test setup

7.4.2 Conducted emission with motor in on-state

Figure 39 and Figure 40 show the *EMC*–conducted emission results for peak and average measurements. The blue, green, and red curves show the emission for fastest (14 ns), medium (60 ns), and slow (110 ns) switching speeds. You can see that even at 14 ns, the class 5 limits are just being touched in the high-frequency range and as soon as you go down to 60 ns there is a significant margin of >5dBµV to the class 5 limits.

Overall you can definitely achieve class 4 with the fastest switching speed and maybe even class 5 depending on the *PCB* layout and measurement setup. When switching with 60 ns, reaching class 5 should be possible in most cases.

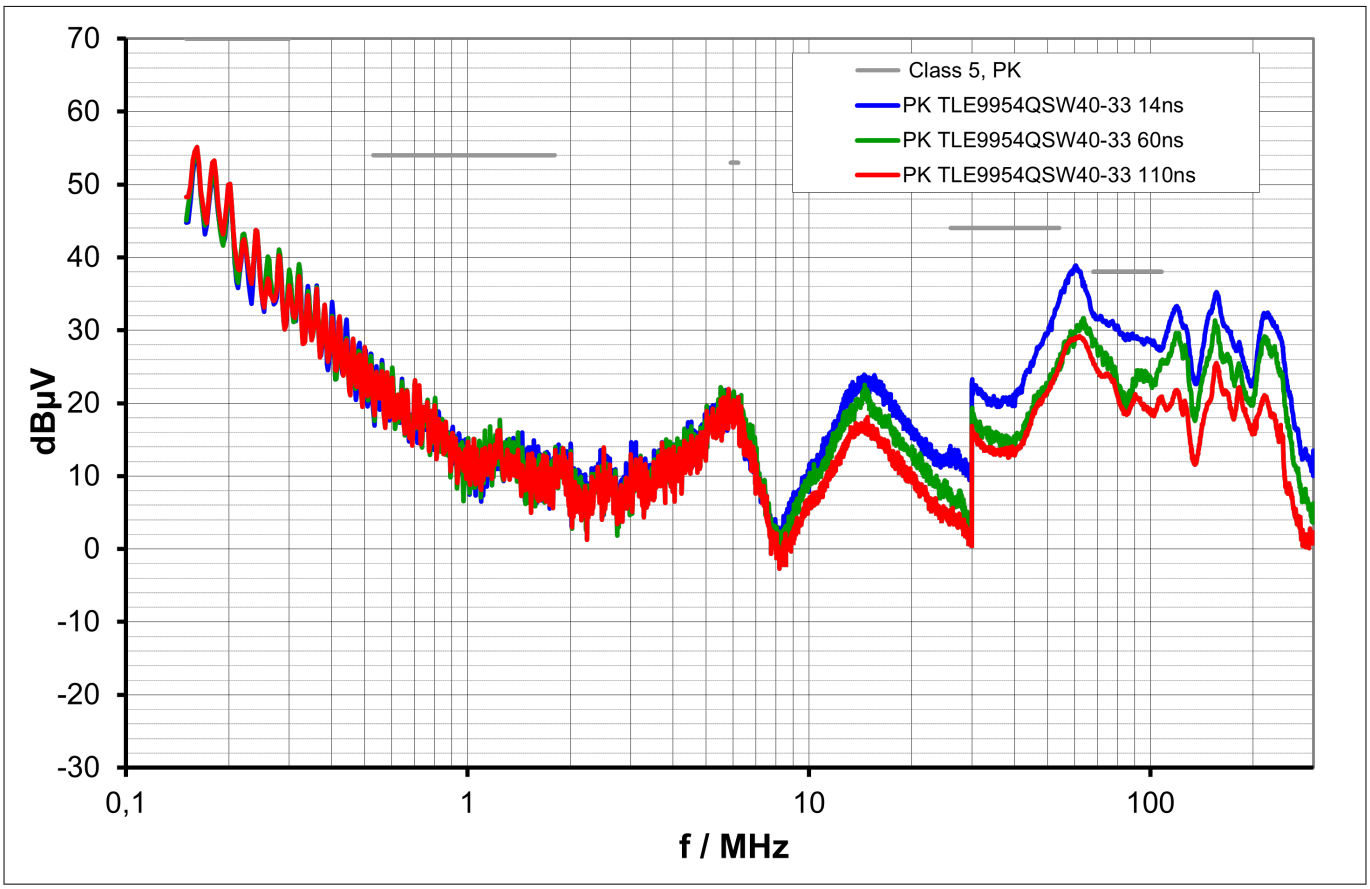


Figure 39 EMC peak measurements

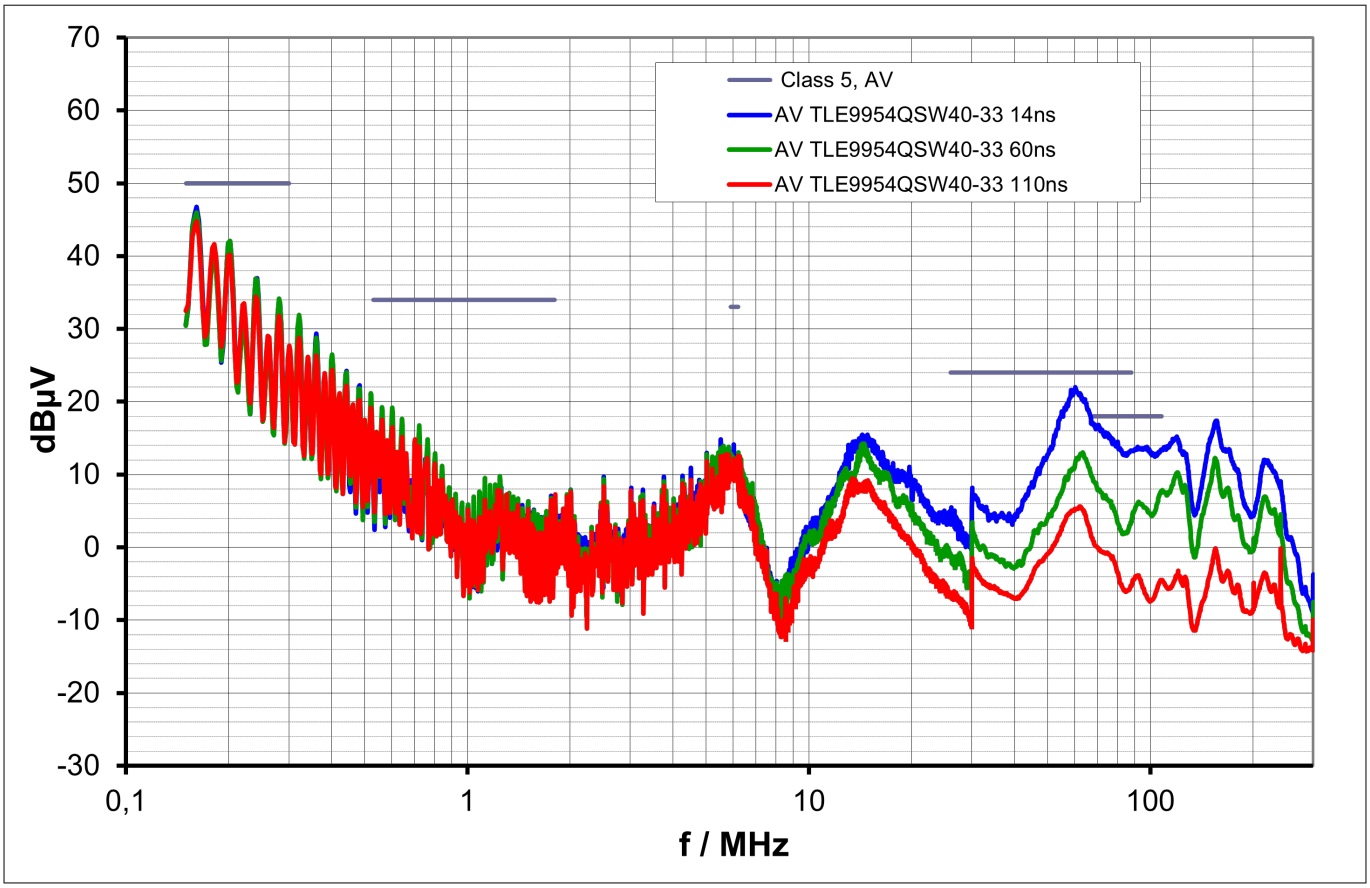


Figure 40 EMC average measurements

TLE9954QSW40-33 SiP vs. discrete integrated half-bridge solution

For better comparability the EMC results of TLE9954QSW40-33 are compared against a discrete gate driver setup. The discrete setup uses the REF_WATERPUMP150W reference design that utilizes the TLE995x device together with OptiMOS® 7 integrated half-bridge MOSFETS. This setup is a perfect comparison because both board use the same technology for gate driver and MOSFETs and are designed for the same pump for the same power class.

Below picture shows both PCBs side by side. You can see that the discrete solution on the left uses more space. The System-in-Package solution on the right has integrated the same feature set. The same circular shape was taken as a reference and all PCB area that is not needed was cut away to give some indication about the possible space saving when using the System-in-Package.

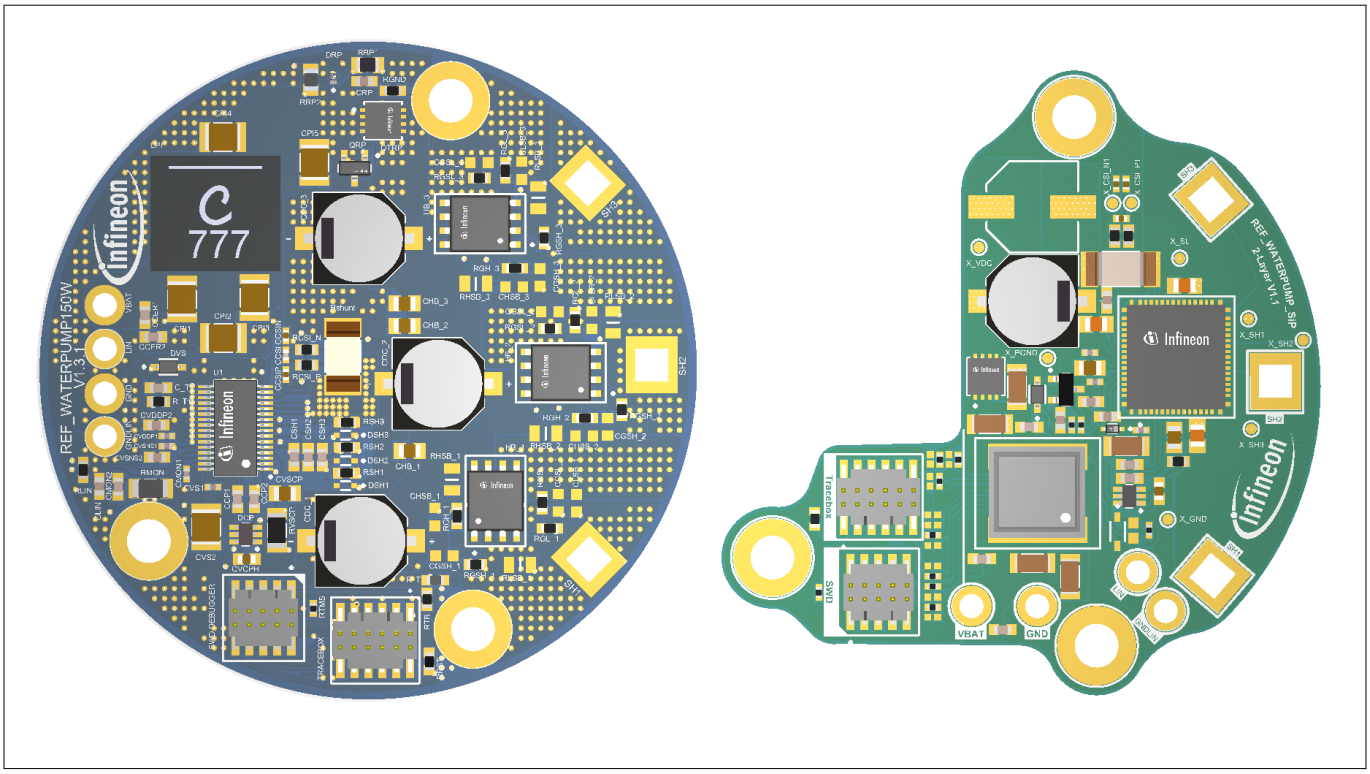


Figure 41 SiP vs. integrated half-bridge board comparison

Figure 42 and Figure 43 show the EMC conducted emission results for peak and average measurements. The blue graph shows the discrete results and the green graph shows the System-in-Package results. On the discrete setup, a 200 ns switching speed was used for the test. On the System-in-Package setup, the goal was to take a switching speed that gives a roughly similar EMC emission and 60 ns was selected.

You can see that the shapes look different and in the higher frequency the System-in-Package has slightly higher EMC emission. This comes from the difference in PCB layout which have high impact on the shape of the EMC emission. The difference in higher frequency could come from the discrete PCB having 4-layers which provides better possibility for a good ground concept, while the System-in-Package measurements were taken on the 2-layer PCB.

When comparing both curves against the class 5 EMC limits, both have a good margin against the limits over all frequency ranges. So overall you can conclude that the System-in-Package solution can be switched around 3.3x faster than the discrete solution while achieving similar EMC performance.

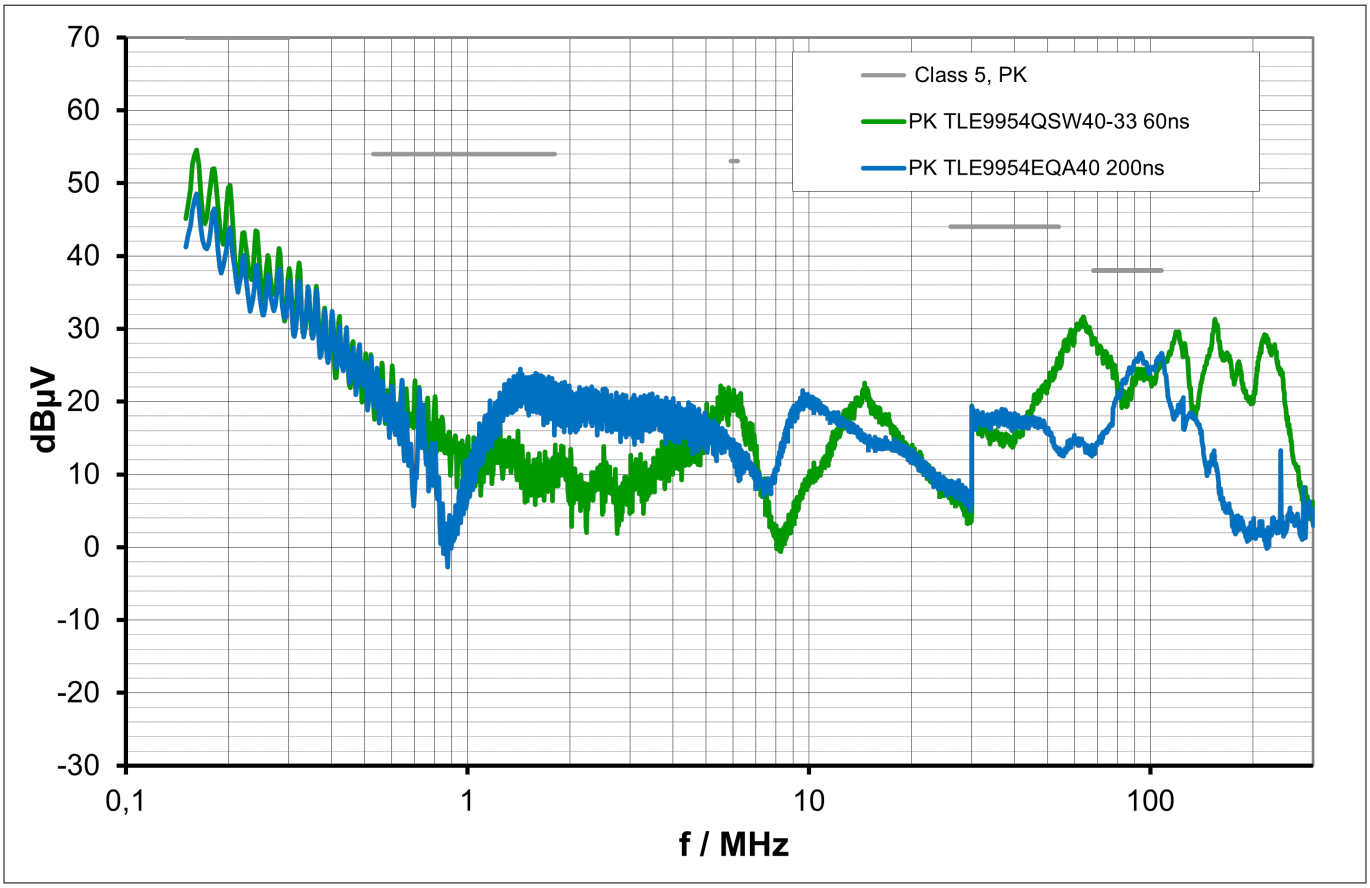


Figure 42 **EMC peak comparison of TLE9954QSW40-33 SiP vs. discrete integrated half-bridge**

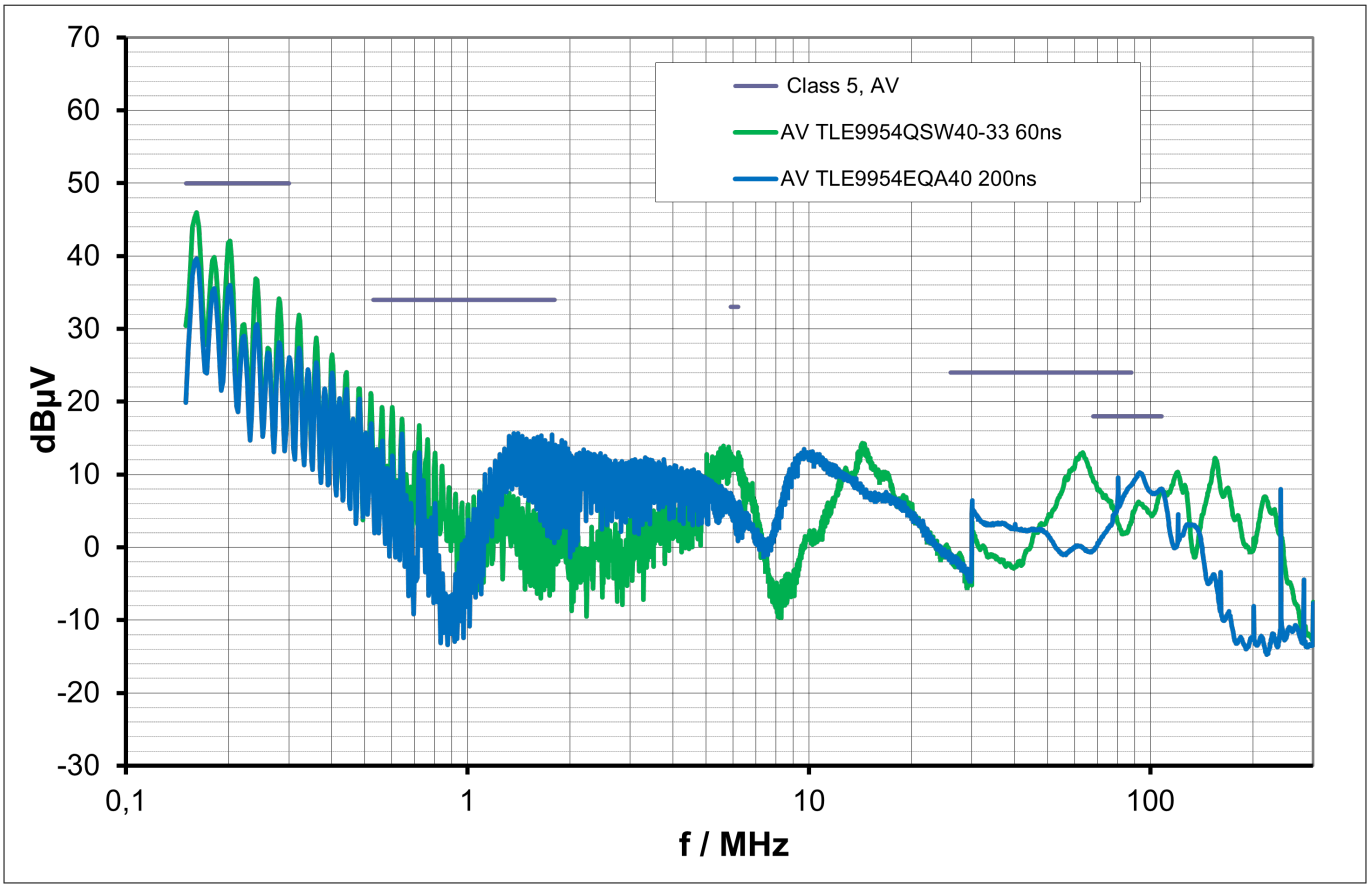


Figure 43 **EMC average comparison of TLE9954QSW40-33 SiP vs. discrete integrated half-bridge**

8 Project collaterals

8.1 Schematics

REF_WATERPUMP_SiP schematics

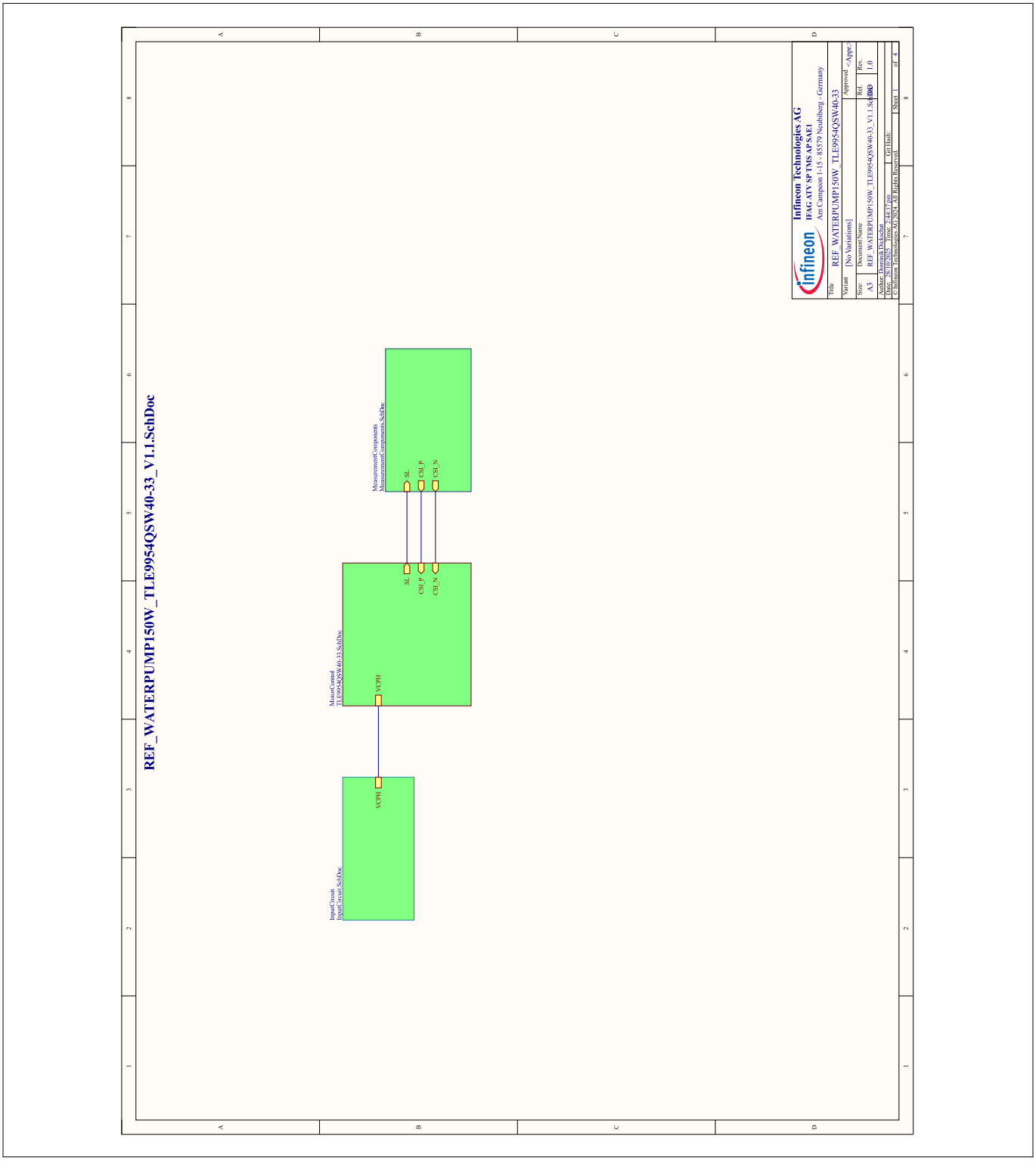


Figure 44 REF_WATERPUMP_SiP overview

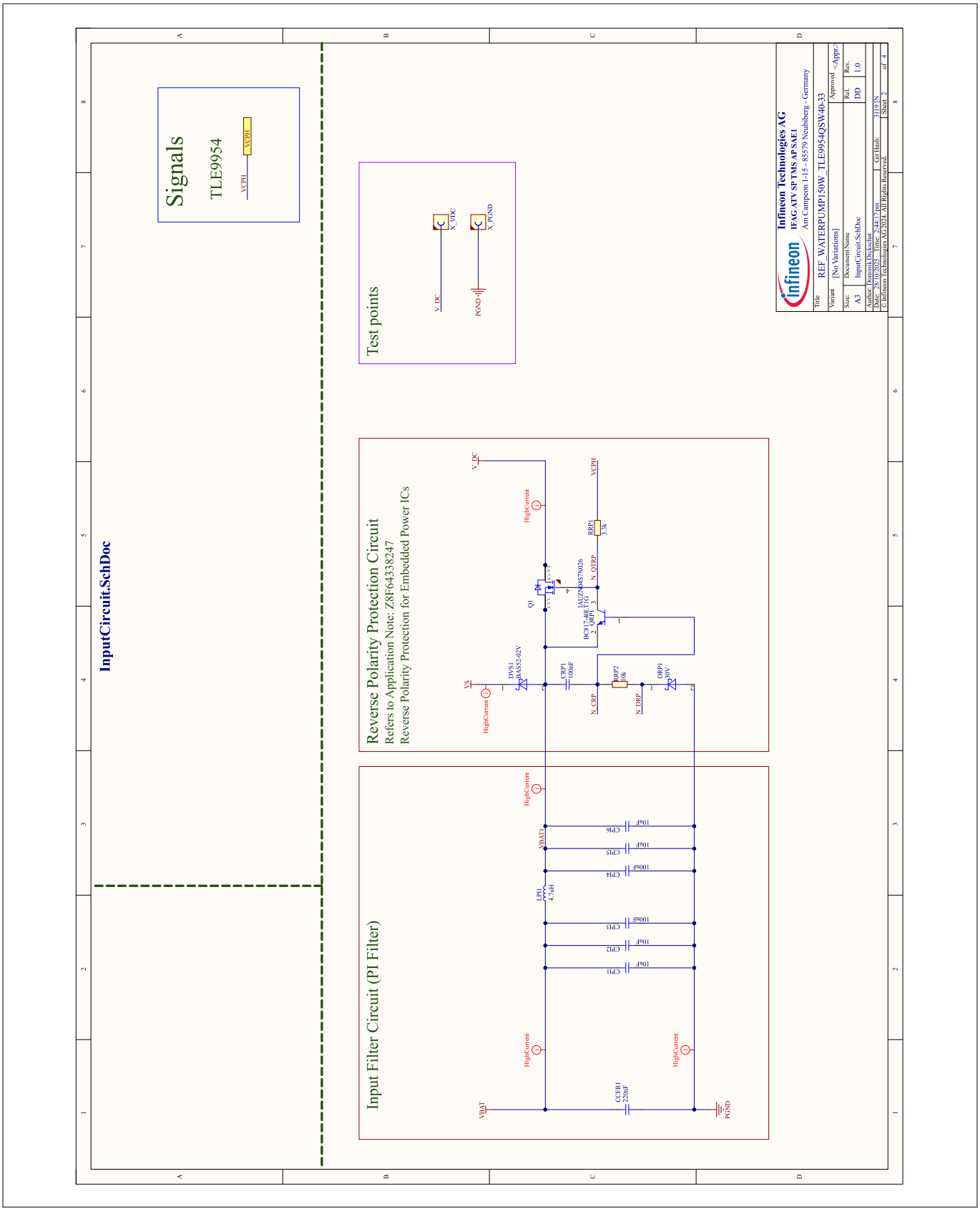


Figure 45 Input circuit

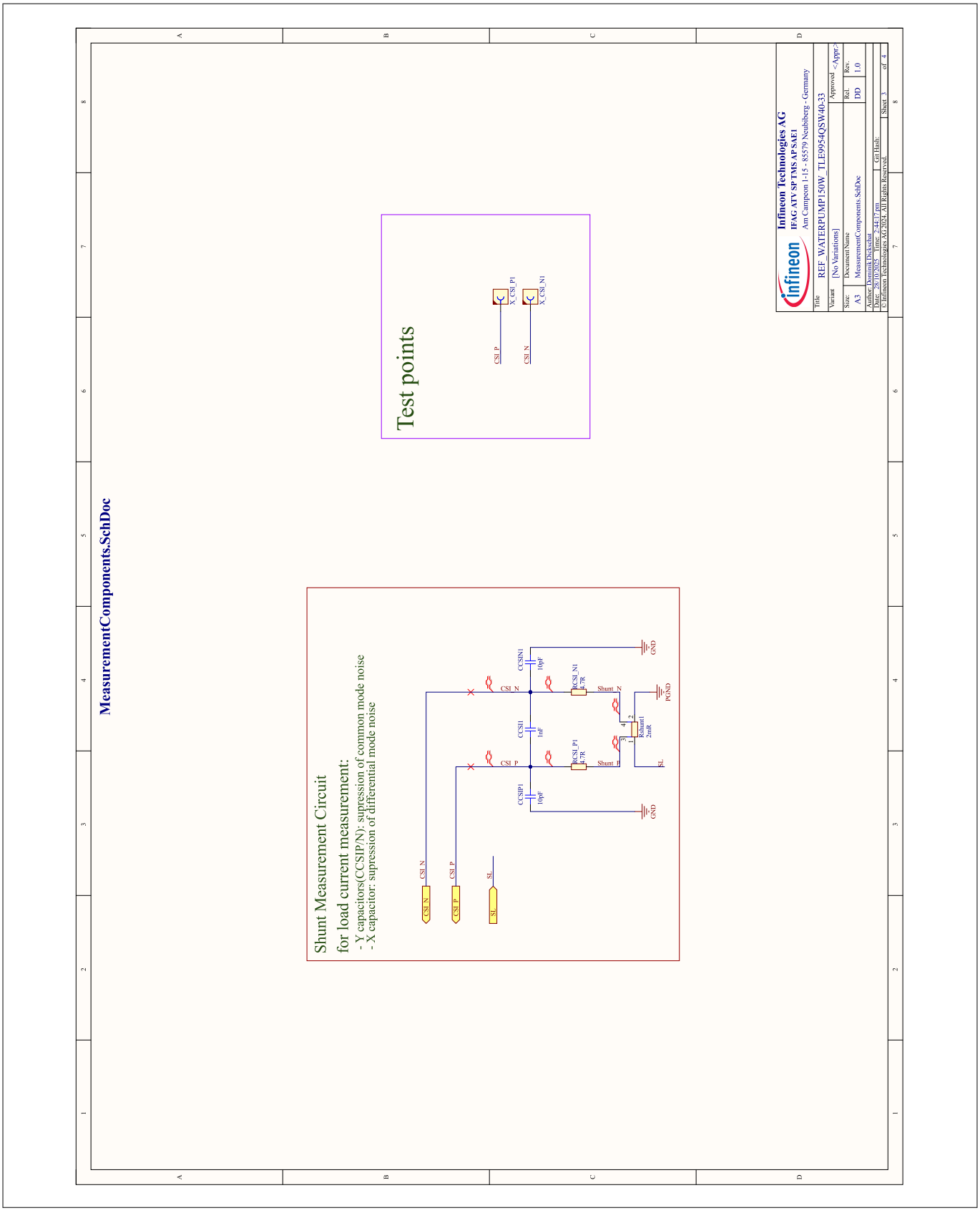


Figure 46 Measurement components

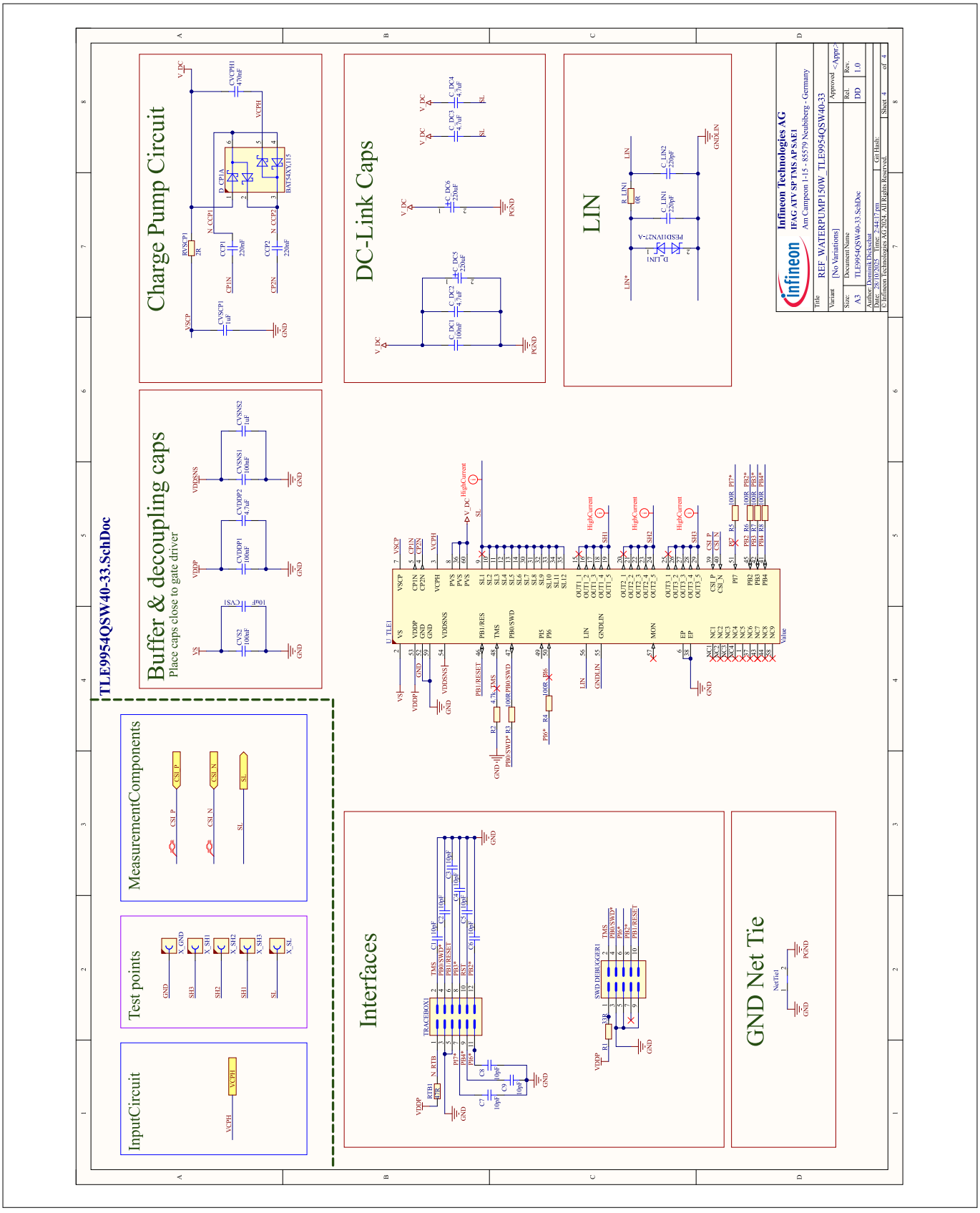


Figure 47 Motor control

Connector board schematics

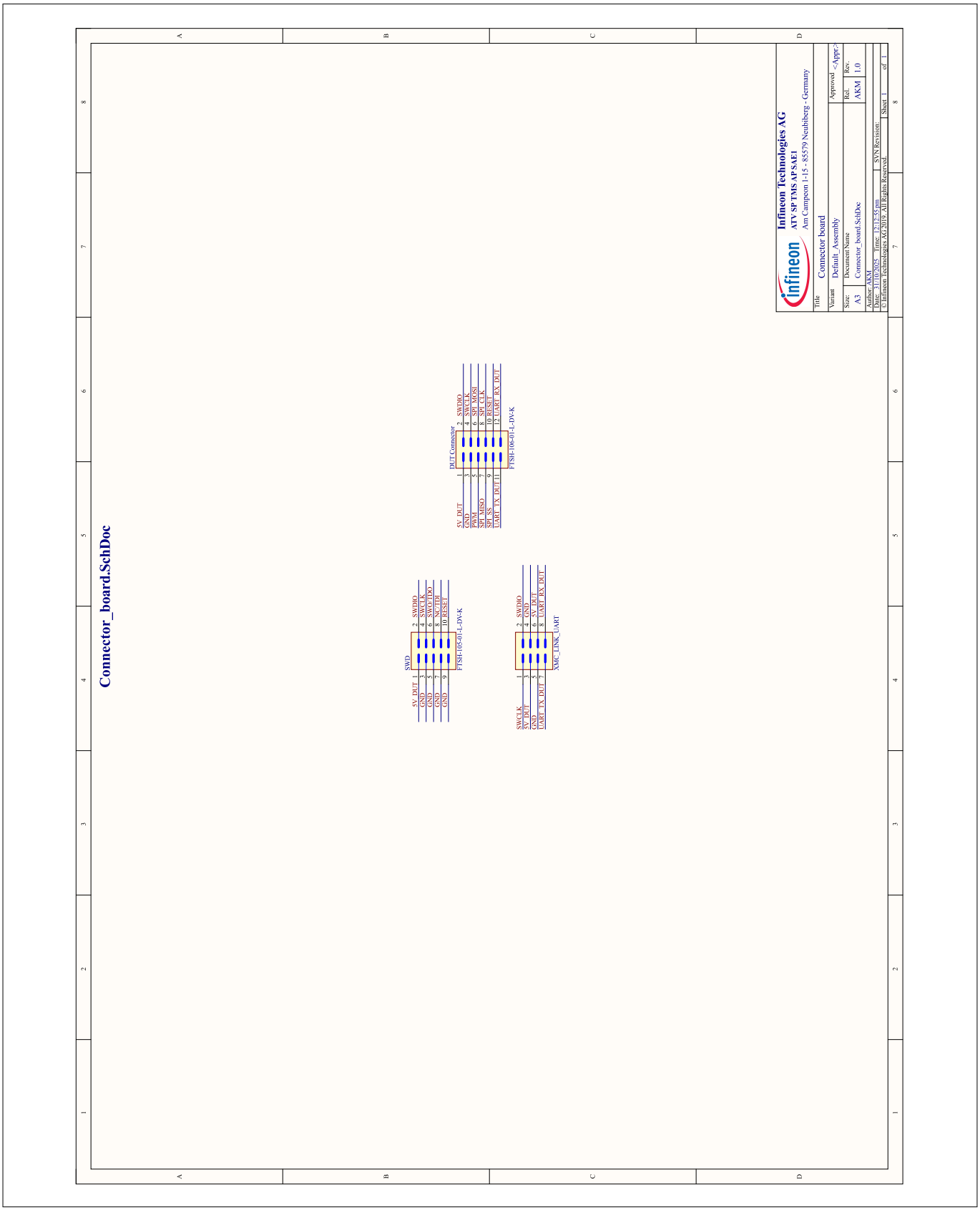


Figure 48 Connector board

8.2 Bill of materials

Table 2 Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
C_DC1, CRP1	100nF	CAP/CERA/ 100nF/50V/10 % / X8R (EIA) / -55°C to 150°C/ 0603(1608) / SMD / -	2	CGA3E3X8R1H 104K080AB	AEC Q200	Fitted
C_DC2, C_DC3, C_DC4	4.7uF	CAP/CERA/ 4.7uF/50V/10 % / X7R (EIA) / -55°C to 125°C/ 0805(2012) / SMD / -	3	CGA4J1X7R1H 475K125AE	AEC Q200	Fitted
C_DC6	330uF	CAP/ELCO/ 330uF/25V/20 % / Aluminiumelectrolytic / -55°C to 125°C/ 8.30mm L X 8.30mm W X 10.50mm H/SMD / -	1	EEHZK1E331UP	AEC Q200	Fitted
C_LIN2	220pF	Multilayer Ceramic Chip Capacitors, Automotive Grade, General, 220pF, 50 V, 5%, 50V, C0G, 0603	1	CGA3E2C0G1H221J080AA	AEC Q200	Fitted
CCER1, CCP1, CCP2	220nF	CAP/CERA/ 220nF/50V/10 % / X7R (EIA) / -55°C to 125°C/ 0603(1608) / SMD / -	3	GCM188R71H 224KA64	AEC Q200	Fitted

(table continues...)

Table 2 (continued) Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
CCSI1	1nF	CAP/ CERA/1nF/50V /5% / C0G (EIA) / NP0 / -55°C to 125°C/ 0402(1005) / SMD / -	1	GRM1555C1H 102JA01	AEC Q200	Fitted
CCSIN1, CCSIP1	10pF	CAP/CERA/ 10pF/50V/5% / C0G (EIA) / NP0 / -55°C to 125°C/ 0402(1005) / SMD / -	2	GRM1535C1H 100JDD5	AEC Q200	Fitted
CPI1, CPI2, CPI5, CPI6, CVS1	10uF	CAP/CERA/ 10uF/50V/10% / X7R (EIA) / -55°C to 125°C/ 1206/SMD / -	5	CGA5L1X7R1H 106K160AC	AEC Q200	Fitted
CPI3, CPI4	100nF	CAP/CERA/ 100nF/50V/10 % / X8L (EIA) / -55°C to 150°C/ 0603(1608) / SMD / -	2	GCM188L81H1 04KA57	AEC Q200	Fitted
CVCPH1	470nF	CAP/CERA/ 470nF/50V/10 % / X7R (EIA) / -55°C to 125°C/ 0603(1608) / SMD / -	1	CGA3E3X7R1H 474K080AE	AEC Q200	Fitted
CVDDP1, CVS2, CVSNS1	100nF	CAP/CERA/ 100nF/50V/10 % / X7R (EIA) / -55°C to 125°C/ 0402(1005) / SMD / -	3	CGA2B3X7R1H 104K050BB	AEC Q200	Fitted

(table continues...)

Table 2 (continued) Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
CVDDP2	4.7uF	CAP/CERA/ 4.7uF/50V/10 % / X7R (EIA) / -55°C to 125°C/ 0805(2012) / SMD / -	1	GRM21BZ71H 475KE15L	AEC Q200	Fitted
CVSCP1	1uF	CAP/ CERA/1uF/50V /10% / X7R (EIA) / -55°C to 125°C/ 0805(2012) / SMD / -	1	GRM21BR71H 105KA12L	AEC Q200	Fitted
CVSNS2	1uF	CAP/ CERA/1uF/16V /10% / X7R (EIA) / -55°C to 125°C/ 0603(1608) / SMD / -	1	CGA3E1X7R1C 105K080AC	AEC Q200	Fitted
D_CP1	BAT54XY,115	Schottky Barrier Quadruple Diode, 30V, 200mA	1	BAT54XY,115	AEC Q200	Fitted
DRP1	30V	Medium Power AF Schottky Diode	1	BAS3010B-03 W	AEC Q200	Fitted
DVS1	BAS52-02V	Silicon Schottky Diode	1	BAS52-02V	AEC Q200	Fitted
LPI1	2.2uH	IND/STD/ 2.2uH/13A/20 % / -40°C to 125°C/ 3.7mR/SMD/ Inductor, SMD, 5.00 mm Pitch, 2 pin, 8.30 mm L X 8.80 mm W X 8.00 mm H body/SMD / -	1	78439358022	AEC Q200	Fitted

(table continues...)

Table 2 (continued) Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
Q1	IAUZN04S7N026	OptiMOS™ 7 Power Transistor, 114A, 40V	1	IAUZN04S7N026	AEC Q200	Fitted
QRP1	BC817-40LT1G	Bipolar (BJT) Transistor NPN 45V 500mA	1	BC817-40LT1G	AEC Q200	Fitted
R1	33R	RES/STD/33R/ 63mW/1% / 100ppm/K / -55°C to 155°C/ 0402(1005) / SMD / -	1	CRCW040233R0FK	AEC Q200	Fitted
R2	4.7k	RES/STD/ 4.7k/ 63mW/1% / 100ppm/K / -55°C to 155°C/ 0402(1005) / SMD / -	1	CRCW04024K70FK	AEC Q200	Fitted
R3, R4, R5, R6, R7, R8	100R	RES/STD/ 100R/ 63mW/1% / 100ppm/K / -55°C to 155°C/ 0402(1005) / SMD / -	6	CRCW0402100RFK	AEC Q200	Fitted
R_LIN1	0R	0R/50V	1	ERJ2GE0R00X	AEC Q200	Fitted
RCSI_N1, RCSI_P1	4.7R	RES/STD/ 4.7R/ 100mW/1% / 100ppm/K / -55°C to 155°C/ 0603(1608) / SMD / -	2	CRCW06034R70FK	AEC Q200	Fitted
RRP1	3.3k	RES/STD/ 3.3k/ 63mW/1% / 100ppm/K / -55°C to 155°C/ 0402(1005) / SMD / -	1	CRCW04023K30FK	AEC Q200	Fitted

(table continues...)

Table 2 (continued) Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
RRP2	10k	RES/STD/10k/ 63mW/1% / 100ppm/K / -55°C to 155°C/ 0402(1005) / SMD / -	1	CRCW040210 K0FK	AEC Q200	Fitted
Rshunt1	2mR	RES/STD/2mR /3W/1% / 50ppm/K / -55°C to 170°C/ 2512(6432) / SMD / -	1	BVT-I-R0020-1.0	AEC Q200	Fitted
RTB1	47R	RES/STD/47R/ 100mW/1% / 100ppm/K / -55°C to 155°C/ 0603(1608) / SMD / -	1	CRCW060347 R0FK	AEC Q200	Fitted
RVSCP1	2R	RES/STD/2R/ 100mW/1% / 100ppm/K / -55°C to 155°C/ 0603(1608) / SMD / -	1	CRCW06032R 00FK	AEC Q200	Fitted
SWD DEBUGGER1	FTSH-105-01-L-DV-K	SMT Micro Header, 1.27mm pitch, 10 pin, vertical, double row, keying shroud,DAP	1	FTSH-105-01-L-DV-K	AEC Q200	Fitted
TRACEBOX1	FTSH-106-01-L-DV-K	Connector Header Surface Mount 12 position 0.050 (1.27mm)	1	FTSH-106-01-L-DV-K	AEC Q200	Fitted
U_TLE1	TLE9954QSW40-33	Microcontroller with LIN and Motor Driver for BLDC Application	1	TLE9954QSW40-33	AEC Q200	Fitted

(table continues...)

Table 2 (continued) Bill of materials

Designator	Value	Description	Quantity	Manufacturer order number	Automotive qualified	Fitted
X_GND, X_PGND, X_SH1, X_SH2, X_SH3, X_SL, X_VDC	-	Testpad, SMD, 1.0 mm	7	-	AEC Q200	Fitted

8.3 Layout

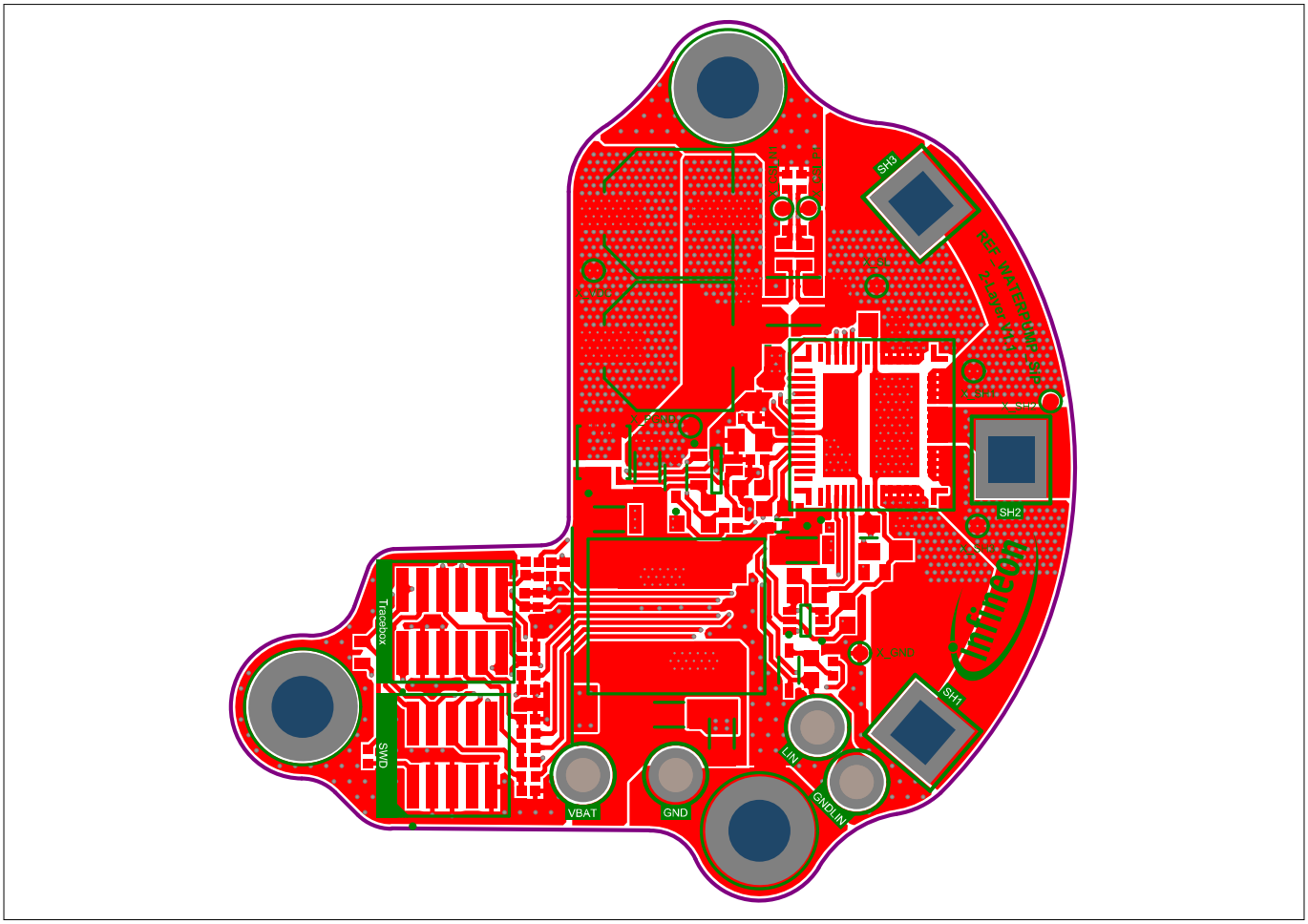


Figure 49 Top layer

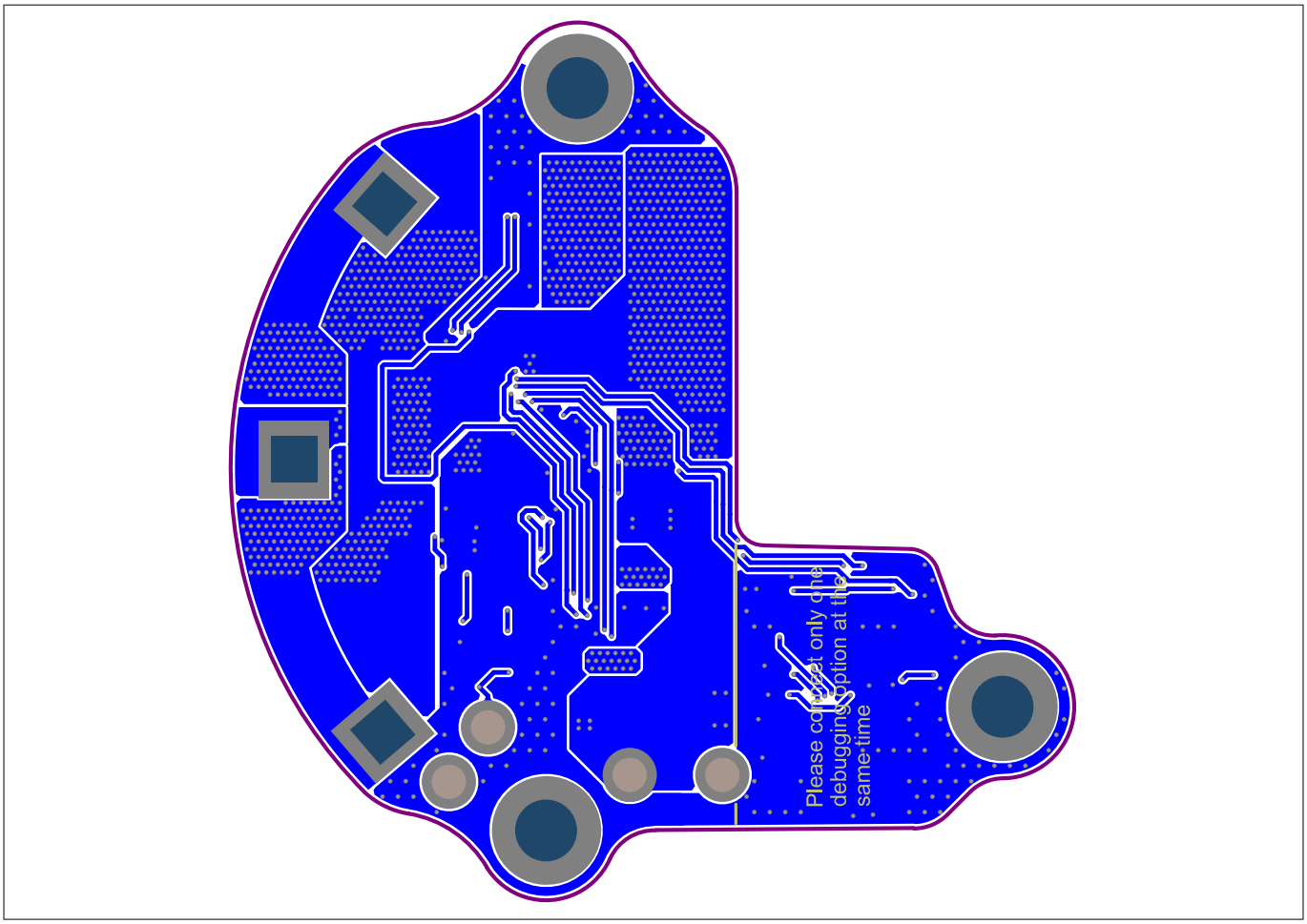


Figure 50 Bottom layer

Glossary

BLDC motor

brushless DC motor (BLDC motor)
A synchronous motor using a direct current electric power supply.

BLDC

brushless direct current (BLDC)

DC

direct current (DC)

One-directional flow of electric charge. An electrochemical cell is a prime example of DC power. Direct current may flow through a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current (AC).

ECU

electronic control unit (ECU)
An embedded system in automotive electronics that controls one or more of the electrical systems or subsystems in a car or other motor vehicle.

EMC

electromagnetic compatibility (EMC)
The ability of electrical equipment and systems to function acceptably in their electromagnetic environment, by limiting the unintentional generation, propagation and reception of electromagnetic energy which may cause unwanted effects such as electromagnetic interference (EMI) or even physical damage in operational equipment.

GND

ground (GND)

GPIO

general purpose input output (GPIO)

GUI

graphical user interface (GUI)

An interface that enables users to interact with electronic devices through icons and visual indicators.

IC

integrated circuit (IC)

A miniature electronic circuit built on the surface of a thin substrate of a semiconductor material.

impact rating

impact rating (IR)
Estimate of magnitude of damage or physical harm from a damage scenario (sever, major, moderate, negligible).

LIN

local interconnect network (LIN)

MCU

microcontroller unit (MCU)

A small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals.

PCB

printed circuit board (PCB)

A board that mechanically supports and electrically connects electronic components using conductive tracks, pads, and other features etched from copper sheets laminated onto a non-conductive substrate.

PWM

pulse-width modulation (PWM)

A technique to encode an analog value into the duty cycle of a pulsing signal with arbitrary amplitude.

TMR

tunnel magnetoresistance (TMR)

A magnetoresistive phenomenon that occurs in a magnetic tunnel junction, used for example, for sensors.

Revision history

Document version	Date of release	Description of changes
Rev. 1.00	2026-02-27	• Initial document release

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