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EVAL_TOLT_DC36V_2KW V 0.5 User Manual

Three-phase power inverter board using OptiMOS™ 5 60 V TOLT MOSFET

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About this document

Scope and purpose

This user manual presents a detailed description of the functionalities of the Infineon EVAL_TOLT_DC36V_2KW evaluation power board for battery-powered brushless direct current (BLDC) motor drives. This board is used to drive three-phase BLDC motors with three Hall sensors used for rotor position detection using pulse-width modulation (PWM) 6-step (block) commutation control to regulate the speed of the motor. The power board uses OptiMOS™ 5 60 V power MOSFET technology – TO-leaded top-side cooling (TOLT) MOSFET (IPTC007N06NM5) for each phase of the three-phase inverter – and the firmware is developed based on the **XMC1300 drive card**.

Intended audience

This document is intended for manufacturers of battery-powered power tools, and engineers familiar with three-phase motor drive systems and motor controls.

Infineon components featured

- **IPTC007N06NM5**, 60 V, 0.75 mΩ TOLT N-channel power MOSFET
- **IRLML6346TRPBF**, 30 V, 3.4 A, SOT-23, N-channel MOSFET
- **2EDL8124GXUMA1**, EiceDRIVER™ 100 V, +/-4 A half-bridge gate driver IC with true differential inputs
- **ILD8150EXUMA1**, buck regulator controller with integrated MOSFET
- **KIT_XMC1300_DC_V1**, motor drive control card

Figure 1 Isometric image of evaluation power board (EVAL_TOLT_DC36V_2KW V 1.0)

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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 DC link potential of this board is up to 100 V DC. Ensure the polarity is correct, otherwise the board will be damaged!* *When measuring voltage waveforms by oscilloscope, high-voltage differential probes are required. Failure to use correct probes may result in damage, personal injury or death.*
⚠	**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 five minutes for capacitors to discharge to safe voltage levels. Failure to do so may result in personal injury or death. Darkened display LEDs are not an indication that capacitors have discharged to safe voltage levels.*
⚠	**Warning:** *The evaluation or reference board is connected to the grid input during testing. Hence, high-voltage differential probes must be used when measuring voltage waveforms by oscilloscope. Failure to do so may result in personal injury or death. Darkened display LEDs are not an indication that capacitors have discharged to safe voltage levels.*
⚠	**Warning:** *Remove or disconnect power from the drive before you disconnect or reconnect wires, or perform maintenance work. Wait five minutes after removing power to discharge the bus capacitors. Do not attempt to service the drive until the bus capacitors have discharged to zero. Failure to do so may result in personal injury or death.*
⚠	**Caution:** *The heatsink 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:** *Only personnel familiar with the drive, power electronics and associated machinery should plan, install, commission and subsequently service the system. Failure to comply may result in personal injury and/or equipment damage.*
⚠	**Caution:** *The evaluation or reference board contains parts and assembly's sensitive to electrostatic discharge (ESD). Electrostatic control precautions are required when installing, testing, servicing or repairing the assembly. Component damage may result if ESD control procedures are not followed. If you are not familiar with electrostatic control procedures, refer to the applicable ESD protection handbooks and guidelines.*
⚠	**Caution:** *A drive that is incorrectly applied or installed can lead to component damage or reduction in product lifetime. Wiring or application errors such as undersizing the motor, supplying an incorrect or inadequate AC supply, or excessive ambient temperatures may result in system malfunction.*
⚠	**Caution:** *The evaluation or reference board is shipped with packing materials that need to be removed prior to installation. Failure to remove all packing materials that are unnecessary for system installation may result in overheating or abnormal operating conditions.*

Table of contents

1 Introduction

1.1 Overview

The EVAL_TOLT_DC36V_2KW evaluation power board uses OptiMOS™ 5 60 V power MOSFET technology TOLT devices for battery-powered medium-voltage BLDC motor drives suitable for high-power tools. This evaluation board is designed to be driven by the Infineon XMC1300 drive card **KIT_XMC1300_DC_V1** (or higher) loaded with the correct firmware. Both power board and drive card are needed for this application. A 32-pin male–female connector (MAB32B2-FAB32Q2) is needed to connect the power board and drive card, as shown in **Figure 2**.

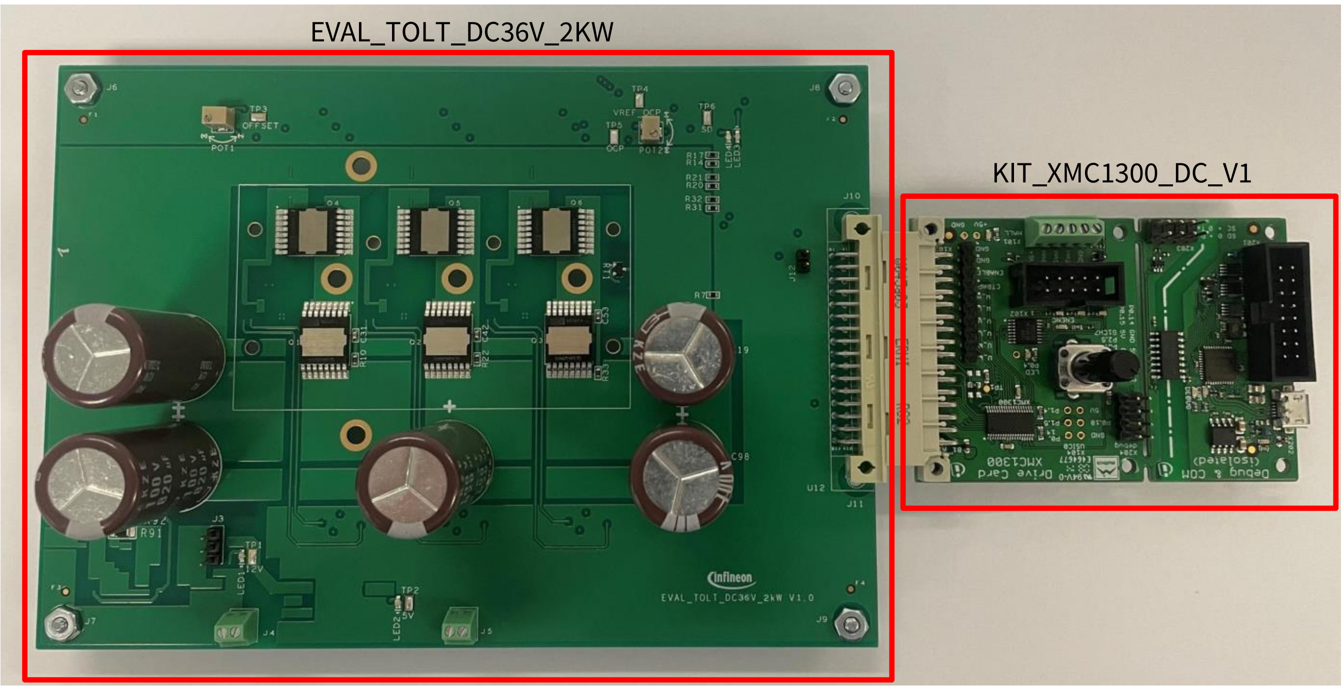

Figure 2 **Evaluation power board EVAL_TOLT_DC36V_2KW V1.0 and control card KIT_XMC1300_DC_V1 motor drive system**

The EVAL_TOLT_DC36V_2KW evaluation power board generates on-board 12.0 V and 5.0 V DC rails to power the gate driver ICs, and the microcontroller in the XMC1300 drive card. The power board also provides protection against overcurrent and overtemperature. The overcurrent threshold level can be changed by adjusting the potentiometer (POT2). Meanwhile, the overtemperature threshold can be changed only by firmware. Because this evaluation board is designed to be able to work with both 6-step block commutation control and field-oriented control (FOC) for three-phase BLDC motors there are three low-side shunt resistors to measure the current in the three phases of the inverter. The Hall sensors for the BLDC motors need to be connected to connector X101 on the XMC1300 drive card, as shown in **Figure 2**.

1.2 Board parameters and technical data

Table 2 includes the evaluation board parameters and technical details.

Table 2 Parameters

Parameter	Symbol	Conditions	Value	Unit
Input DC voltage	V_{IN}	DC voltage input	24~36	V
12 V output voltage	+12 V	Maximum 200 mA output current	12 ±5%	V
5 V output voltage	+5 V	Maximum 200 mA output current	5 ±5%	V
Max. switching frequency	f_{SW}	V_{CC} = 12 V	10	kHz
Max. output phase current	I_{phase_peak}	T_A = 20°C, T_C = 100°C, air cooling, f_{SW} = 10 kHz	100	A_{peak}
Maximum output power	P_{OUT}	Sufficient cooling applied to maintain heatsink temperature below 120°C	2000[1]	W
PCB characteristics				
Material		1.6 mm thickness, 2 oz. copper each layer, six layers	FR4	
Dimensions		Length x width x height	170 x 120 x 1.6	mm
System environment				
Max. ambient temperature	T_{amb}	Non-condensing, maximum RH 95%	40	°C

1.3 Main features

The main features of the EVAL_TOLT_DC36V_2KW evaluation power board using OptiMOS™ 5 60 V power MOSFET technology (TOLT MOSFET) for battery-powered motor drive applications are:

- Single MOSFET at each leg of the inverter
- Standard 32-pin male–female connector to interface power board and XMC1300 drive card
- 24.0 V to 36.0 V input voltage range
- 100.0 A_{peak} maximum phase current for each phase
- Latched shutdown overcurrent protection (OCP) by sensing the current through the shunt resistor of each phase
- Programmable overtemperature protection (OTP)
- 12.0 V and 5.0 V on-board power supplies for gate driver ICs and microcontroller, respectively
- Hardware supports both block commutation control and FOC control using Hall senors or back EMF

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[1] Continuous operation at full load may require forced air cooling. This is not recommended unless operating from a 36 V battery with short power cables.

1.4 Block diagram

A block diagram of the three-phase inverter board is shown in **Figure 3**. In this design, a buck (step-down) converter is used to convert the input voltage to 12.0 V for gate driver ICs. Alternatively, for ease of debugging, by changing the position of jumper J3, an external 12.0 V supply can be used. The 12.0 V rail is converted to 5.0 V by a linear drop-out (LDO) regulator to provide power to the analog circuits on the power board and to power the XMC™ drive card via the 32-pin connector. Moreover, by removing the resistor R1, an external 5.0 V supply can be used.

OCP is achieved by measuring the voltage drop across each shunt of each phase. The output of the current amplifier is also fed to the XMC™ drive card after passing through a low-pass RC filter for FOC control. OTP is achieved by using an on-board temperature sensor. The output voltage of the temperature sensor is also passed to the XMC™ drive card after filtering using an RC filter for OTP. Back EMF signals are provided to the XMC™ drive card after reducing the voltage below 5 V through the resistive divider for sensorless control. The Hall sensor signals are directly connected to the XMC™ drive card.

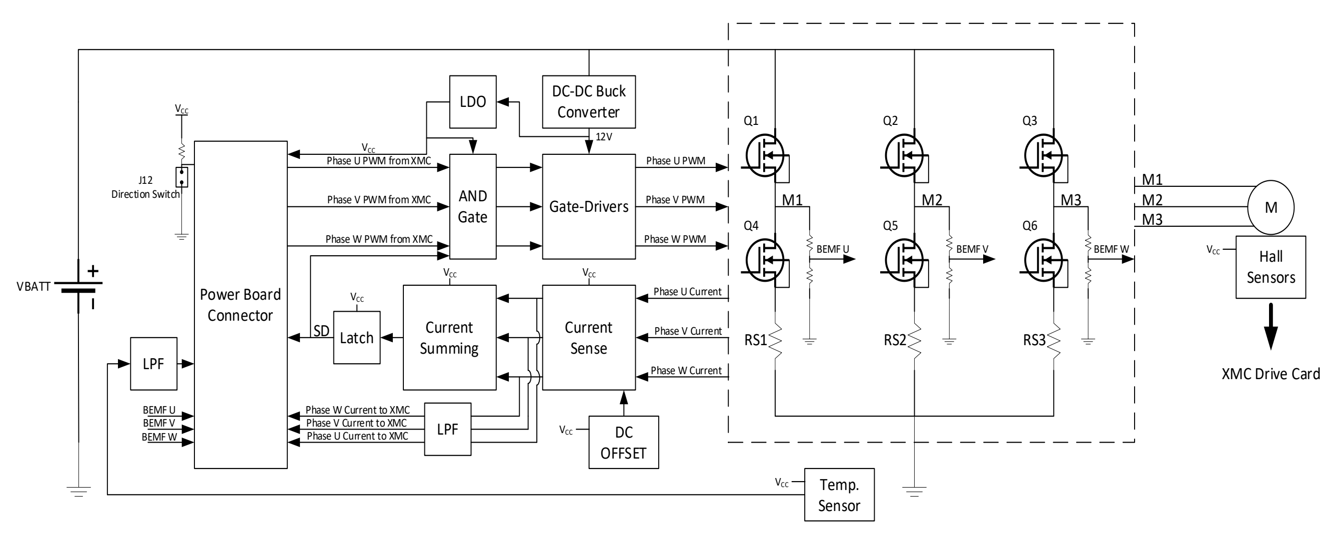


Figure 3 EVAL_TOLT_DC36V_2KW block diagram

2 Hardware description

Different sections of the evaluation board are shown in **Figure 4** and **Figure 5**. An aluminum heatsink is attached on top of the TOLT MOSFET to push more power to the load, because the maximum temperature rating of the FR4 PCB is 130°C. An insulator made of thermal insulating material (TIM) is placed between the heatsink and the MOSFETs. The heatsink is connected to ground to reduce electromagnetic interference (EMI).

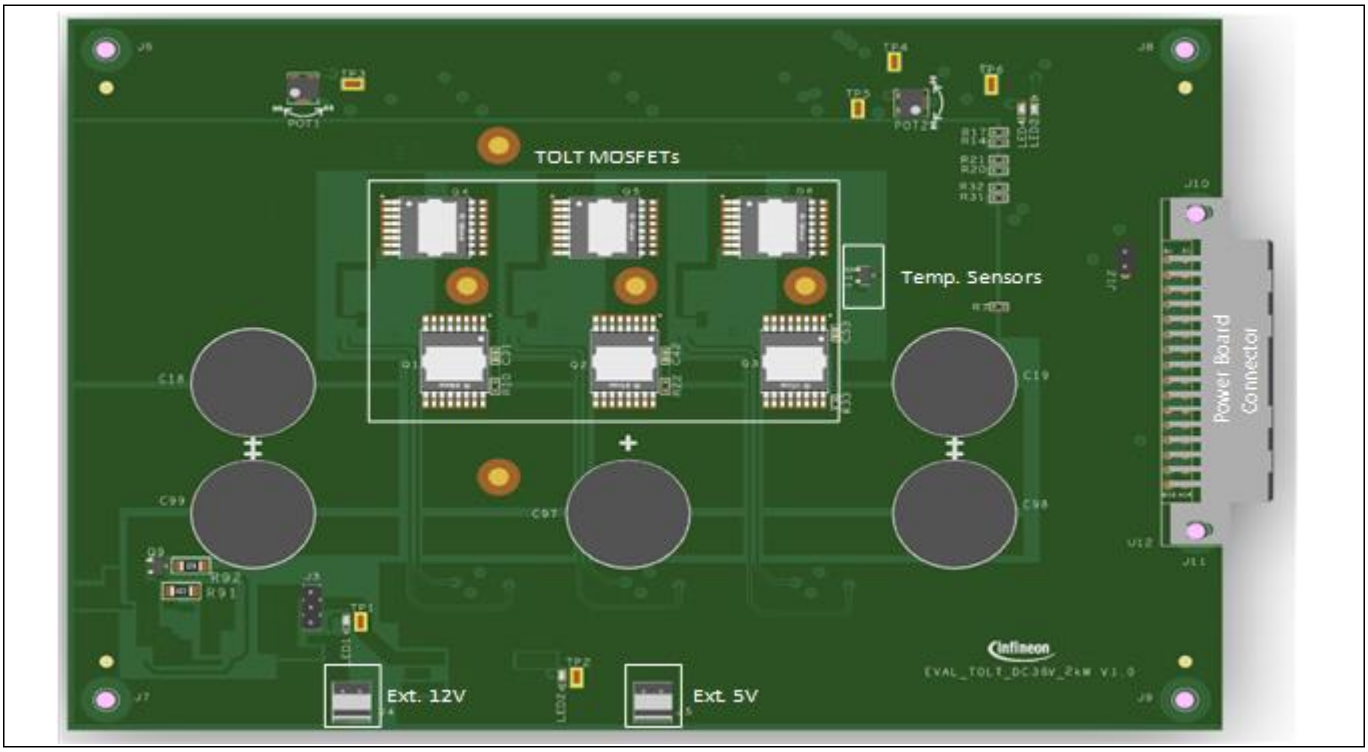


Figure 4 **Different sections of the demo board – top side**

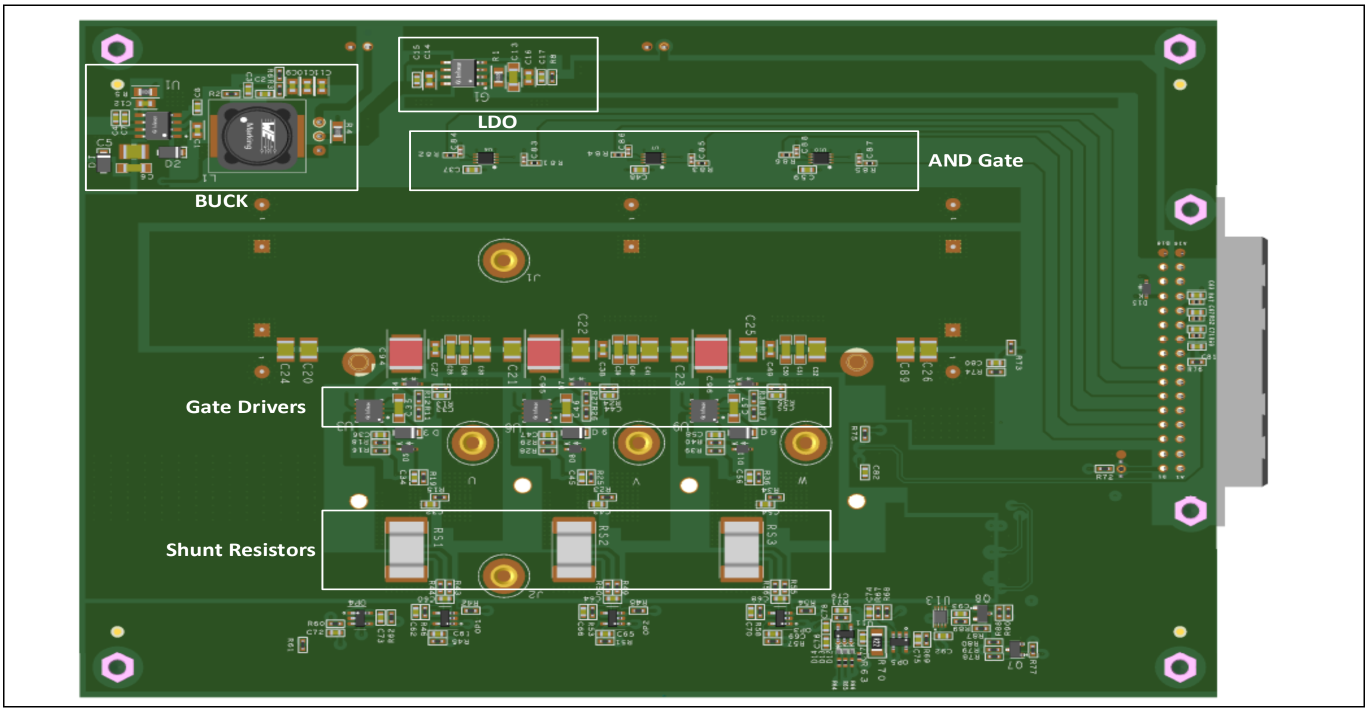


Figure 5 **Different sections of the demo board – bottom side**

2.1 Power supplies

The buck converter reduces the battery voltage (voltage range of 24 V~36 V) to a regulated value of 12 V to supply the gate driver ICs. For powering the microcontroller in the XMC™ drive card and other analog circuits in the power evaluation board, the 12 V is further reduced to 5 V by the LDO. The on-board power supply architecture is shown in **Figure 6**.

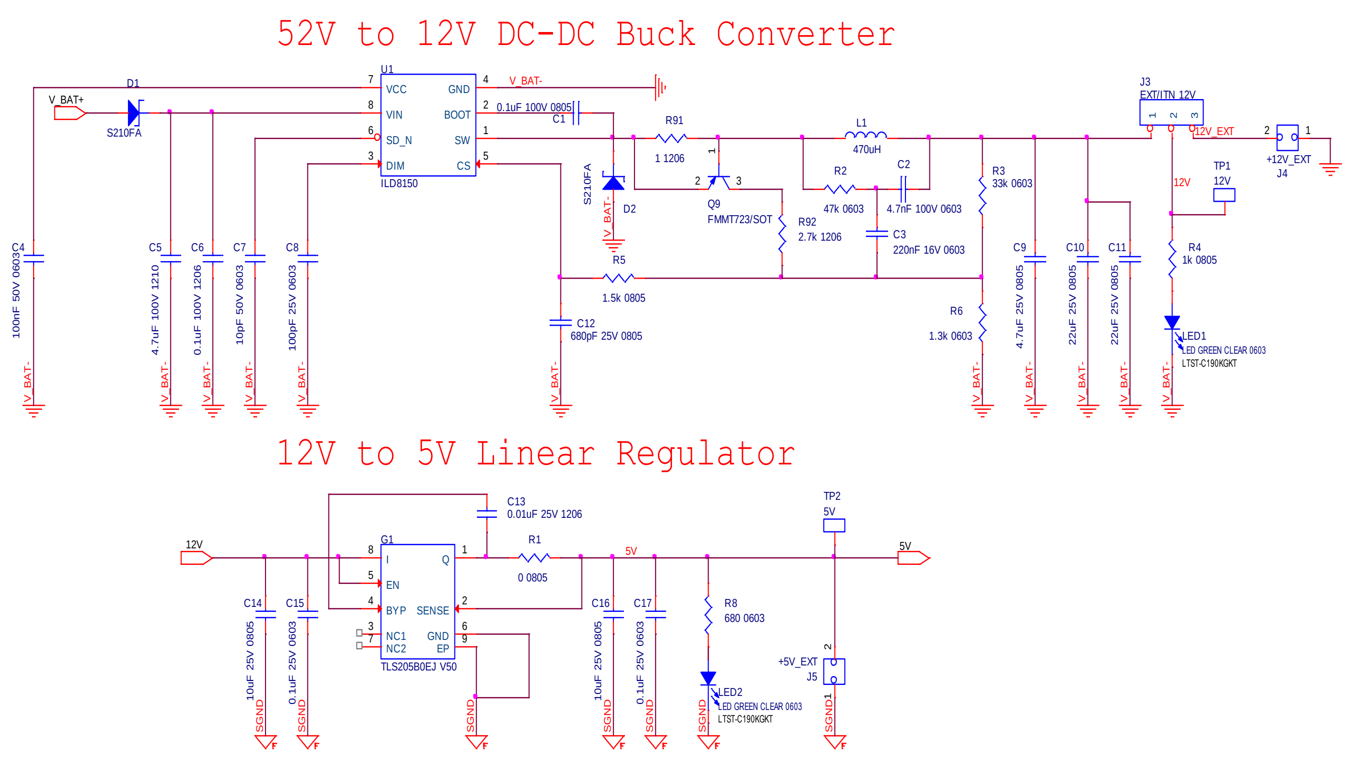


Figure 6 **Buck and LDO regulators used in the demo board**

Infineon's **ILD8150 buck LED driver IC** has been used in this design to reduce battery voltage to a regulated 12 V. The ILD8150, originally designed for constant current control in LED drivers, uses a hysteretic controller, which has been modified to provide constant voltage regulation at the output. The hysteretic control in the ILD8150 provides extremely fast regulation and stable output voltage combined with good EMI performance. The ILD8150 is rated to supply output current of up to 1.5 A.

The hysteretic controller stability depends on the ramp of the feedback voltage. The ramp of the feedback voltage should be large enough to reduce jitter. The ILD8150 implements two voltage thresholds V_{CSH} and V_{CSL}, so that when the feedback voltage crosses above the V_{CSH} threshold, the internal MOSFET turns off and when the feedback voltage crosses below the V_{CSL} threshold, the internal MOSFET turns on. The feedback ramp is largely dependent on the equivalent-series resistance (ESR) current of the inductor or from the external RC (R2, C2) components used to generate the ripple when a small ESR ceramic output capacitor is used. R5 and C12 act as a low-pass filter (LPF) to extract high-frequency noise. Additionally, to protect the LED driver IC from short-circuit, a simple circuit using a PNP BJT transistor (Q9) has been implemented, which limits the load current to 0.3 A. Therefore, as the load current is increased, it will create 0.7 V across R91, turning on the PNP transistor (Q9) and pulling the feedback pin high and dropping the output voltage low. As mentioned, an external power supply may also be used to provide 12 V to the gate driver Ics by changing the position of the jumper J3.

The TLS205B LDO (G1) provides a fixed 5 V power to the microcontroller in the XMC™ drive card and other analog circuits in the power board. An external bypass capacitor (C13) provides low output voltage ripple. This device is capable of supplying a maximum output current of 500 mA. By removing jumper R1, an external power supply can be used to provide 5 V to the microcontroller and the analog circuitry.

2.2 Gate drivers

Infineon's 2EDL8124G high-side and low-side gate driver IC has been implemented in this design for driving the three-phase inverter MOSFETs. The **2EDL8124G EiceDRIVER™** is a true differential input (Tdi) gate driver IC with enhanced noise immunity due to built-in hysteresis. The use of Tdi gate drivers is strongly recommended in high-current applications to avoid mis-triggering due to di/dt-induced transients, which can damage standard gate drivers. Additionally, the gate driver IC has a built-in 2 ns delay between the turn-on and turn-off of each MOSFET. The gate driver circuit for phase U is shown in **Figure 7**.

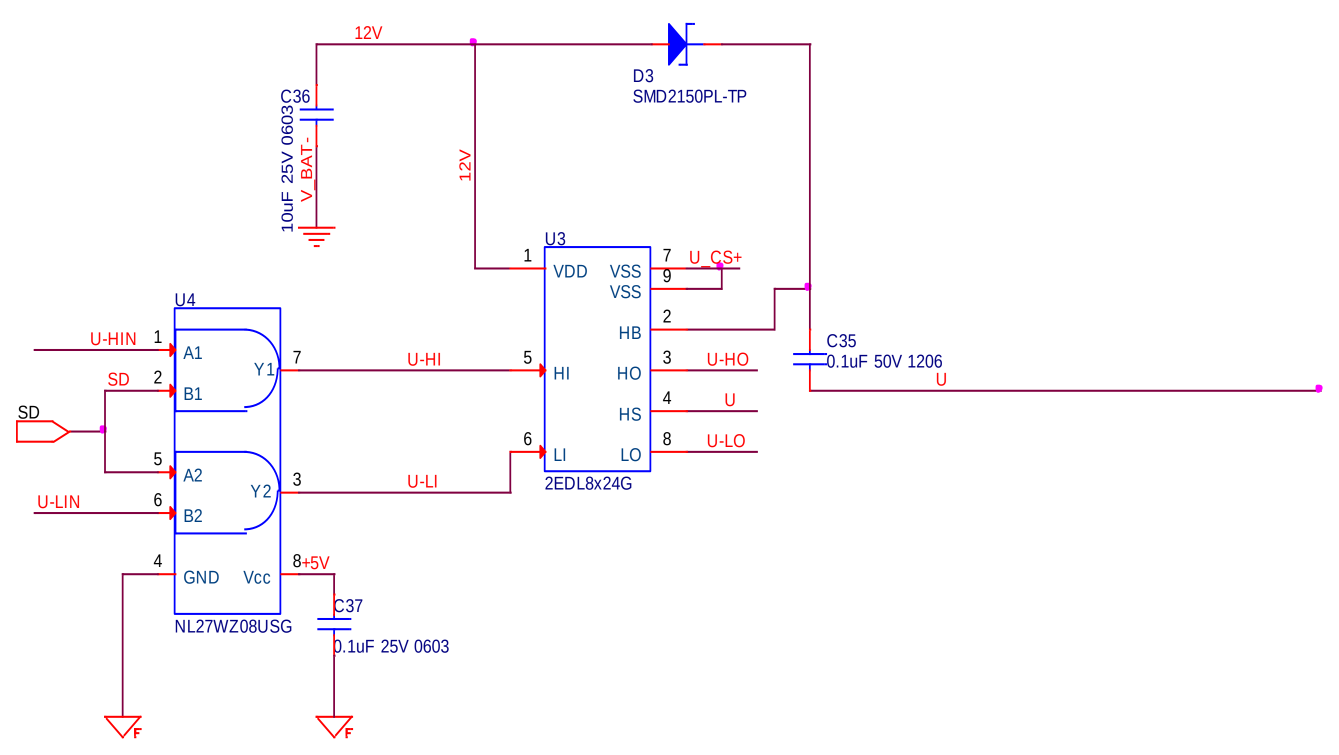


Figure 7 Gate driver circuit for phase U

For normal operation of the circuit, shutdown (SD) is high, which allows PWM signals (U-H and U-L) to pass through the dual-input AND gates generating PWM drive signals for the high-side and low-side MOSFETs (U-HO and U-LO). When there is overcurrent in any of the phases, SD is pulled low by the latch circuit and thus turns off the switching of the MOSFETs. Additionally, the firmware also has control of the SD signal via the driver enable signal ($\overline{DR\_EN}$). During normal operation of the circuit, the $\overline{DR\_EN}$ is pulled low and thus MOSFET Q7 is off. In this scenario, the green LED (LED3) is turned on and SD is pulled high. However, during an overcurrent situation, the microcontroller pulls $\overline{DR\_EN}$ high and the MOSFET Q7 is turned on and the SD is pulled low to provide firmware OCP which is set to 100 A_{peak}.

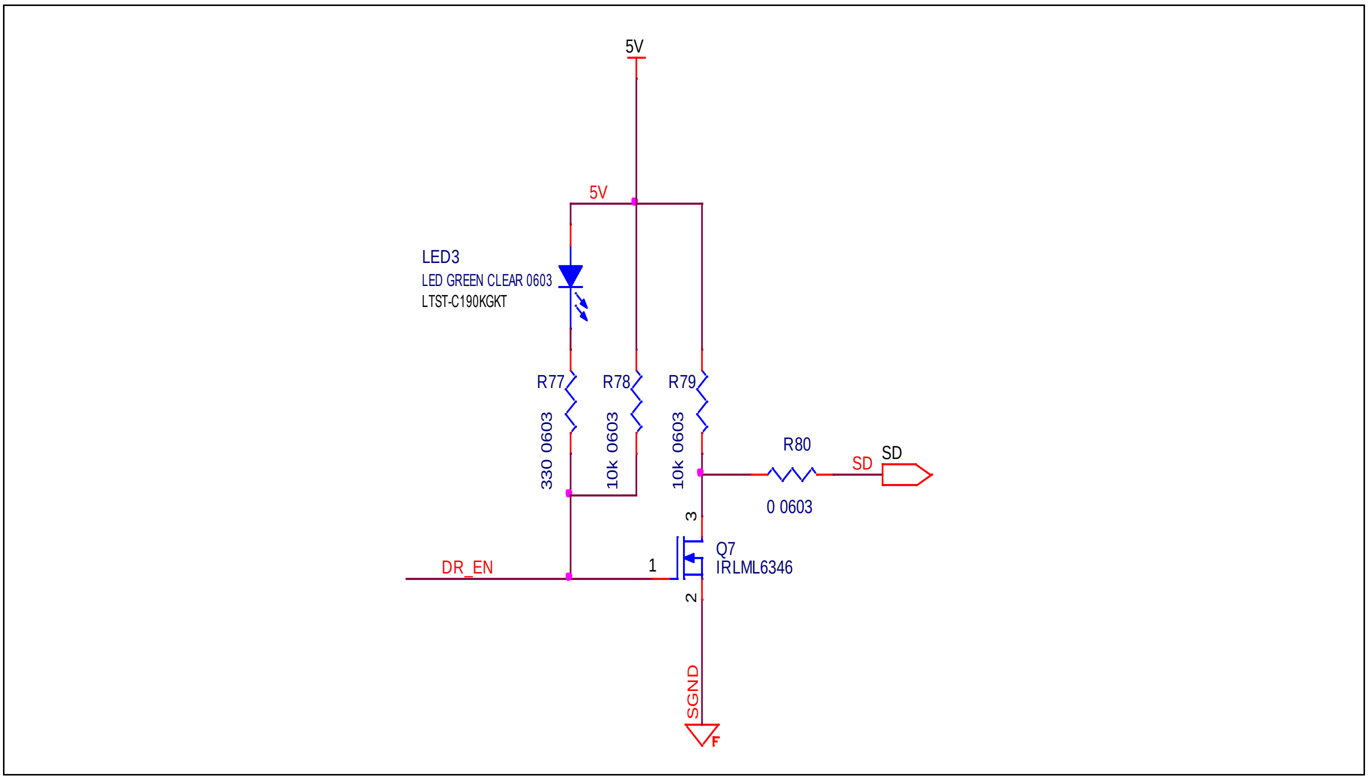


Figure 8 Firmware OCP circuit

2.3 TOLT MOSFET package

Infineon's **IPTC007N06NM5** TOLT MOSFET is used in the power inverter section of this design to drive the BLDC motor phases. The TOLT MOSFET is designed with a flipped leadframe inside the package, and the drain pad is exposed at the top of the package as shown in **Figure 9**. With an exposed drain pad, heat can be passed onto the heatsink through the TIM, enabling the inverter to push more power to the load. **Figure 10** shows the difference between the standard cooling technique (back-side) and top-side cooling.

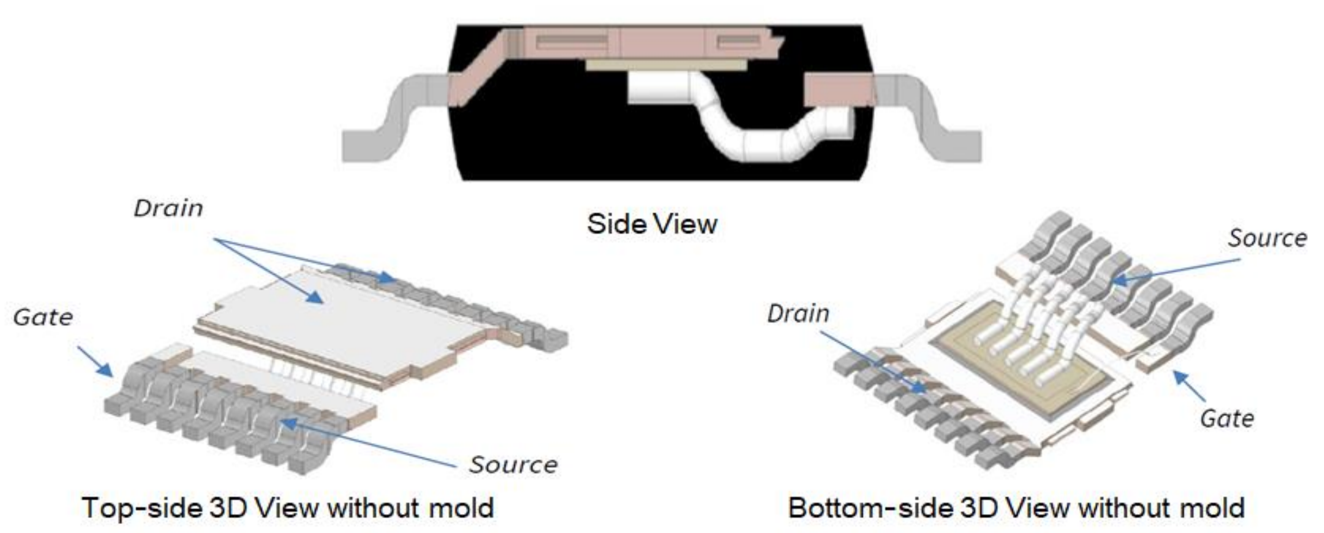
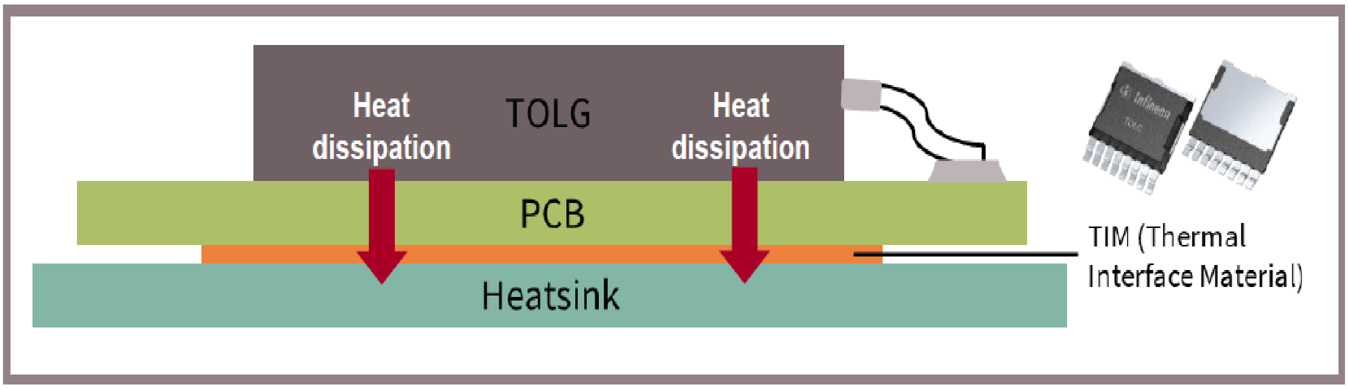
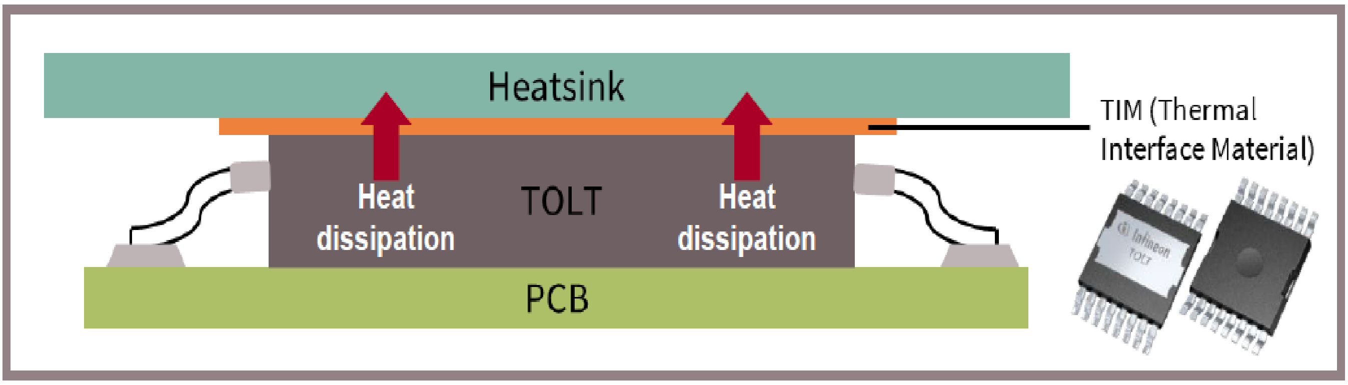


Figure 9 TOLT package structure



Back-side cooling



Top-side cooling

Figure 10 **Back-side vs. top-side cooling systems**

Main advantages of the TOLT packaged MOSFETs:

- Top-side cooling – cost savings in cooling systems and higher application power capability
- Sn-free exposed pad
- Components can be placed on the bottom side of the PCB because the heatsink is not mounted on the bottom as in a standard (not flipped) package MOSFET
- Distance between source and drain (creepage) is increased
- More efficient heat transfer is made possible by using a heatsink instead of transferring heat to the PCB and nearby components as in the back-side cooling system
- Negative standoffs

2.4 Heatsink and thermal insulating material

One of the major advantages of TOLT package MOSFETs is top-side cooling using a heatsink. For this design, a heatsink from Advanced Thermal Solutions (ATS-EXL110-300-R0) has been customized. Thermal resistance as a function of the airflow of EXL101 series heatsink for the entire extrusion is shown in **Figure 11**. **Figure 12** shows the dimensions of the heatsink.

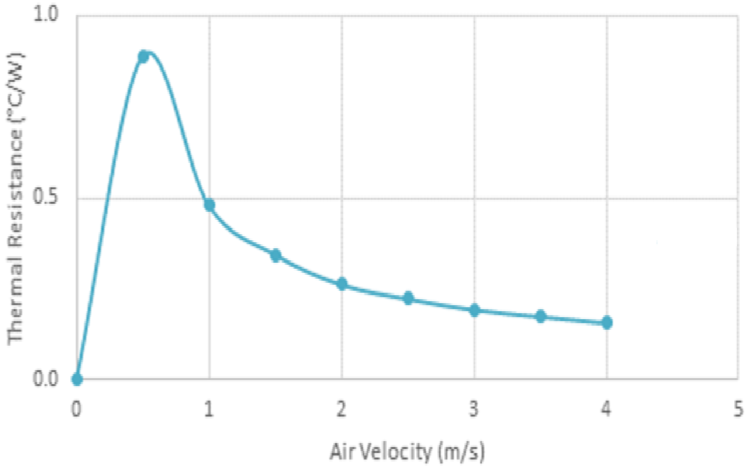


Figure 11 **Thermal resistance**

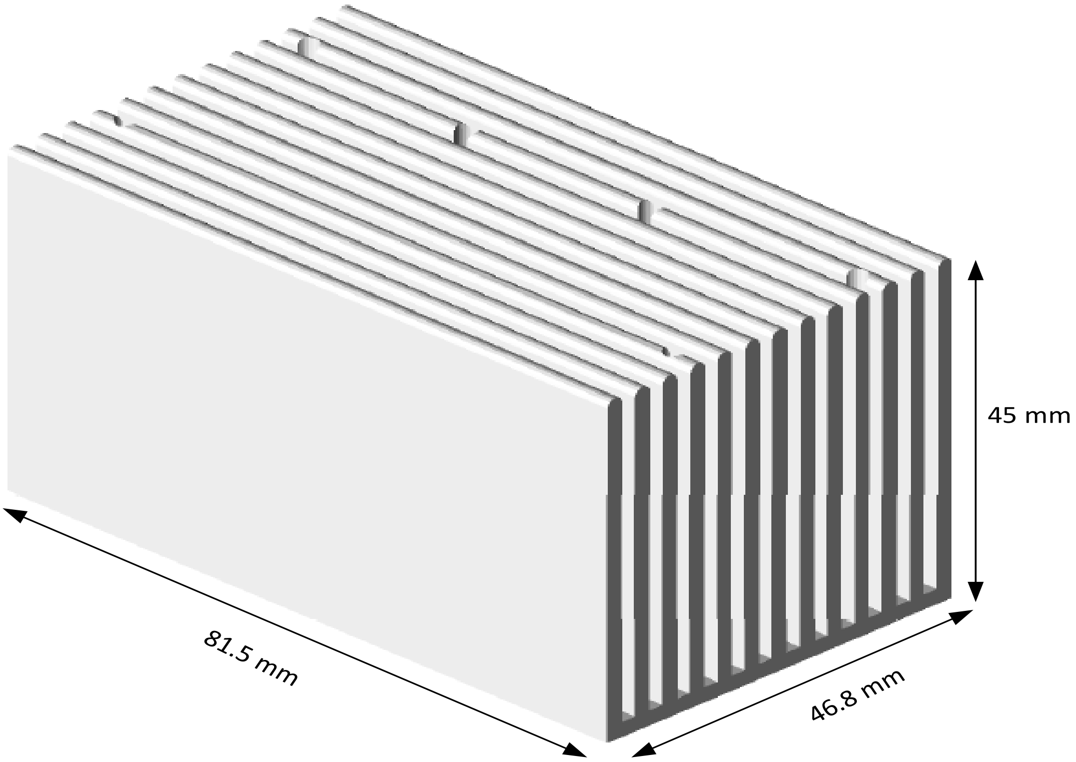


Figure 12 **Customized heatsink**

The heatsink is mounted to the top side of the board, with screws inserted from the bottom side. The heatsink is drilled and tapped to accept screw size 2-56 with the holes located to line up with the PCB holes. The torque setting for the screws is between 1 in-lbs to 2 in-lbs.

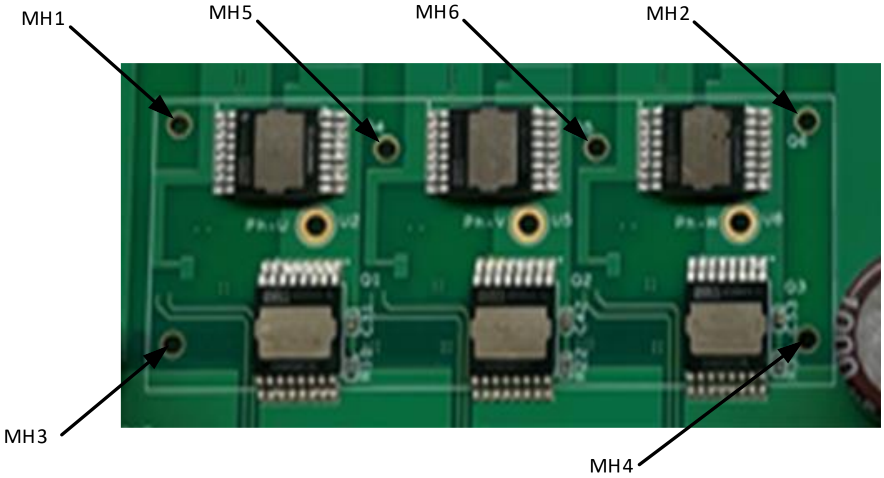
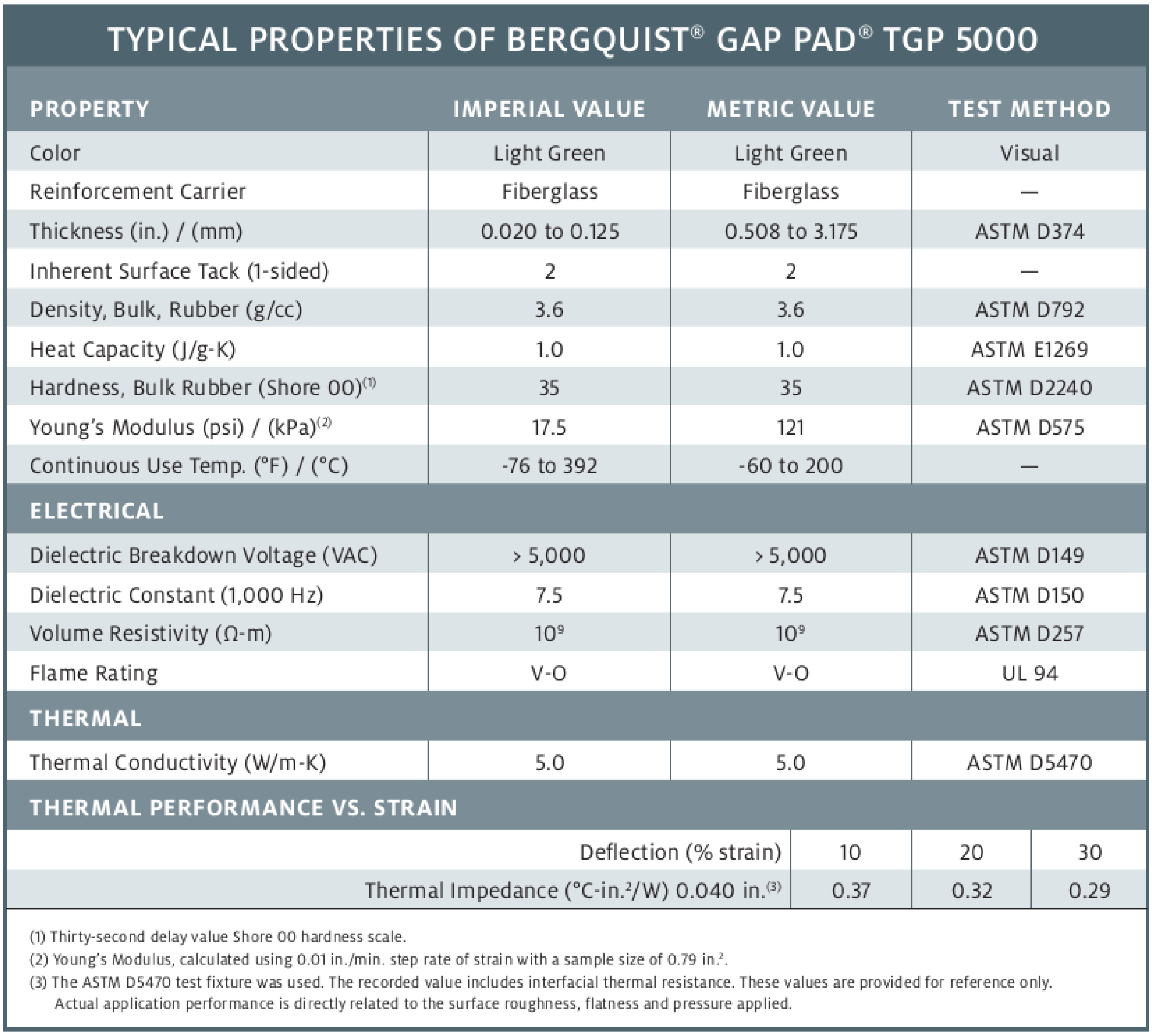


Figure 13 Heatsink mounting holes

For this design, a Bergquist® gap pad® TGP 5000 (gap pad® 5000S35) with 500 µm thickness and 5 W/m-K thermal conductivity is used for the TIM. **Figure 14** shows the typical properties of the selected TIM. Thermal resistance as a function of airflow of this TIM is shown in **Figure 15**.



TYPICAL PROPERTIES OF BERGQUIST® GAP PAD® TGP 5000

PROPERTY	IMPERIAL VALUE	METRIC VALUE	TEST METHOD
Color	Light Green	Light Green	Visual
Reinforcement Carrier	Fiberglass	Fiberglass	—
Thickness (in.) / (mm)	0.020 to 0.125	0.508 to 3.175	ASTM D374
Inherent Surface Tack (1-sided)	2	2	—
Density, Bulk, Rubber (g/cc)	3.6	3.6	ASTM D792
Heat Capacity (J/g-K)	1.0	1.0	ASTM E1269
Hardness, Bulk Rubber (Shore 00)(1)	35	35	ASTM D2240
Young's Modulus (psi) / (kPa)(2)	17.5	121	ASTM D575
Continuous Use Temp. (°F) / (°C)	-76 to 392	-60 to 200	—
ELECTRICAL			
Dielectric Breakdown Voltage (VAC)	> 5,000	> 5,000	ASTM D149
Dielectric Constant (1,000 Hz)	7.5	7.5	ASTM D150
Volume Resistivity (Ω-m)	10^9	10^9	ASTM D257
Flame Rating	V-O	V-O	UL 94
THERMAL			
Thermal Conductivity (W/m-K)	5.0	5.0	ASTM D5470

THERMAL PERFORMANCE VS. STRAIN

Deflection (% strain)	10	20	30
Thermal Impedance (°C-in.^{2}/W) 0.040 in.(3)	0.37	0.32	0.29

(1) Thirty-second delay value Shore 00 hardness scale.
(2) Young's Modulus, calculated using 0.01 in./min. step rate of strain with a sample size of 0.79 in.^{2}.
(3) The ASTM D5470 test fixture was used. The recorded value includes interfacial thermal resistance. These values are provided for reference only. Actual application performance is directly related to the surface roughness, flatness and pressure applied.

Figure 14 Typical properties of gap pad® TGP 5000

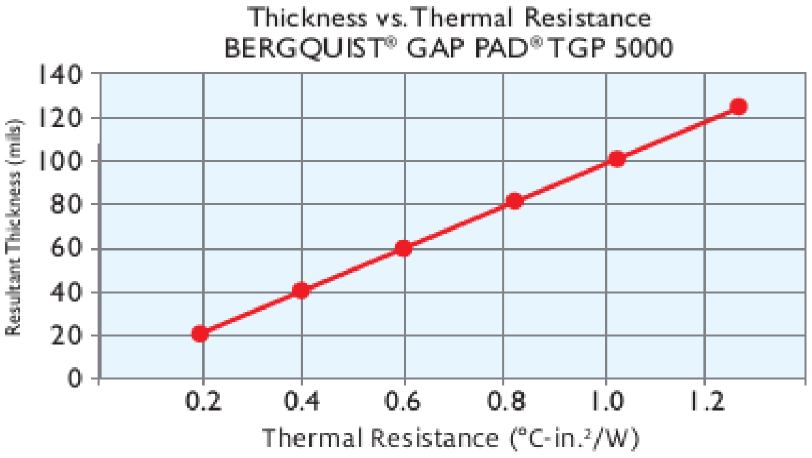


Figure 15 Thermal resistance of gap pad® TGP 5000

2.5 Protection circuitry

In order to protect the MOSFETs of the three-phase inverter from overcurrent, OCP circuitry is implemented in this design as shown in **Figure 16** and **Figure 17**. Each leg of the three-phase inverter has a 1 mΩ shunt resistor with respect to power ground, as shown in **Figure 3**. The voltage drop across the shunt resistor for phase U is measured using differential amplifier OP1 with a gain of 12.0 for phase U. To protect against leading-edge blanking, an integrator is implemented using R46 and C62. Because the voltage drop across the shunt resistor needs to be sensed by the microcontroller in the XMC™ drive card, there is a need to create an offset, as the voltage drop across the shunt resistor will be both positive and negative. Thus, OP2 is a buffer which applies a DC offset of 2.5 V to the differential amplifier OP1. The output of OP1 passes through an LPF and connects through the board connector to the microcontroller in the XMC™ drive card to be processed by the control algorithm and protection implemented in the firmware. Similar functions are performed by differential amplifiers OP2 and OP3 for phases V and W. The outputs of all the differential amplifiers of all the phases are summed together using diodes D12, D13, and D14 to detect the peak voltage. This peak voltage is compared against a reference voltage of 4.8 V by comparator U11. During normal operation, the output of this comparator will be low and thus the output of the D-flip-flop U13 remains low. However, during a short-circuit condition the output of the comparator goes high, as the detected peak voltage exceeds 4.8 V and thus the output of the U13 will transition high, turning on the MOSFET Q8 to pull SD low and turn off the inverter. With this setup the overcurrent trip level is set at 192 A_{peak}.

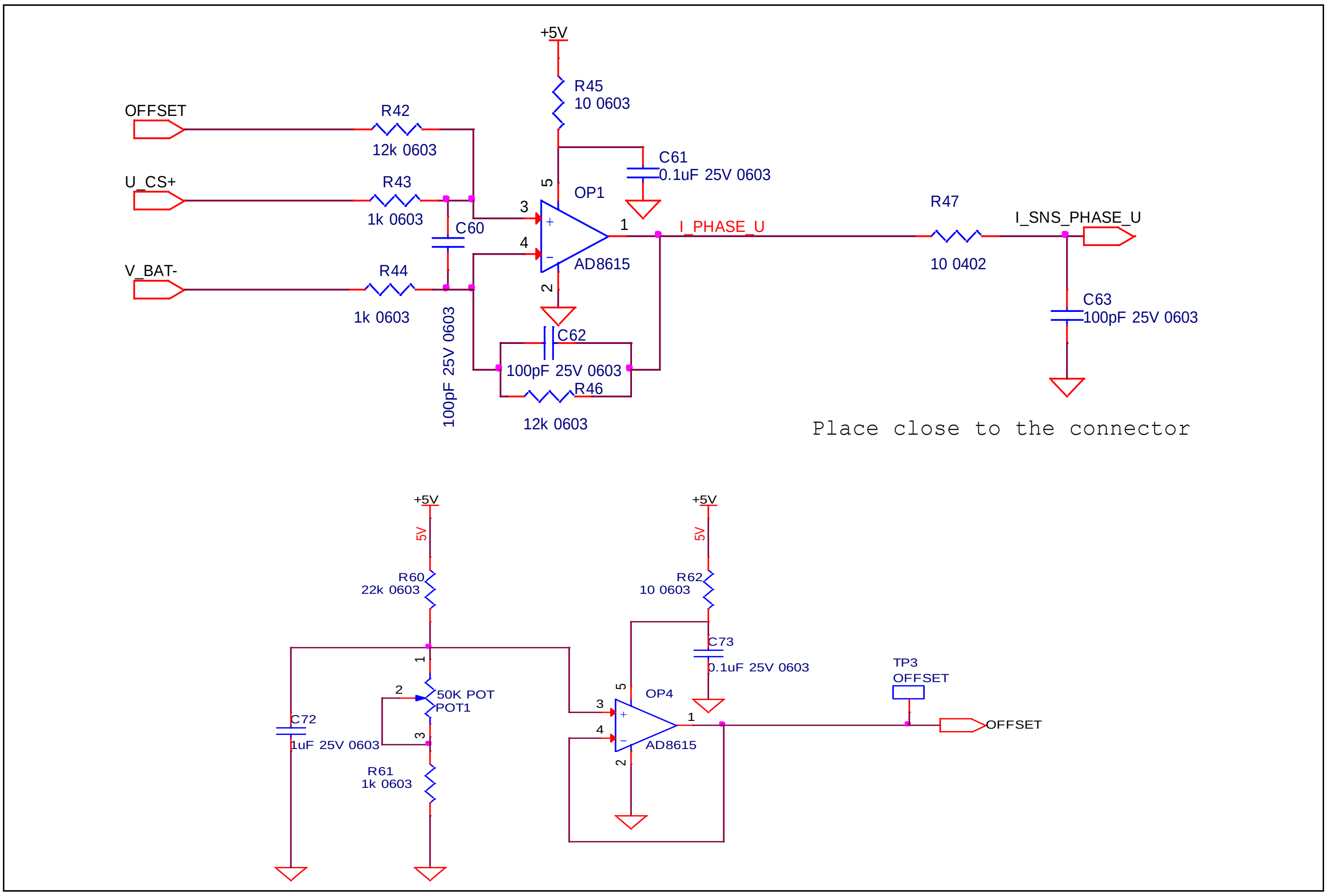


Figure 16 Current amplifier

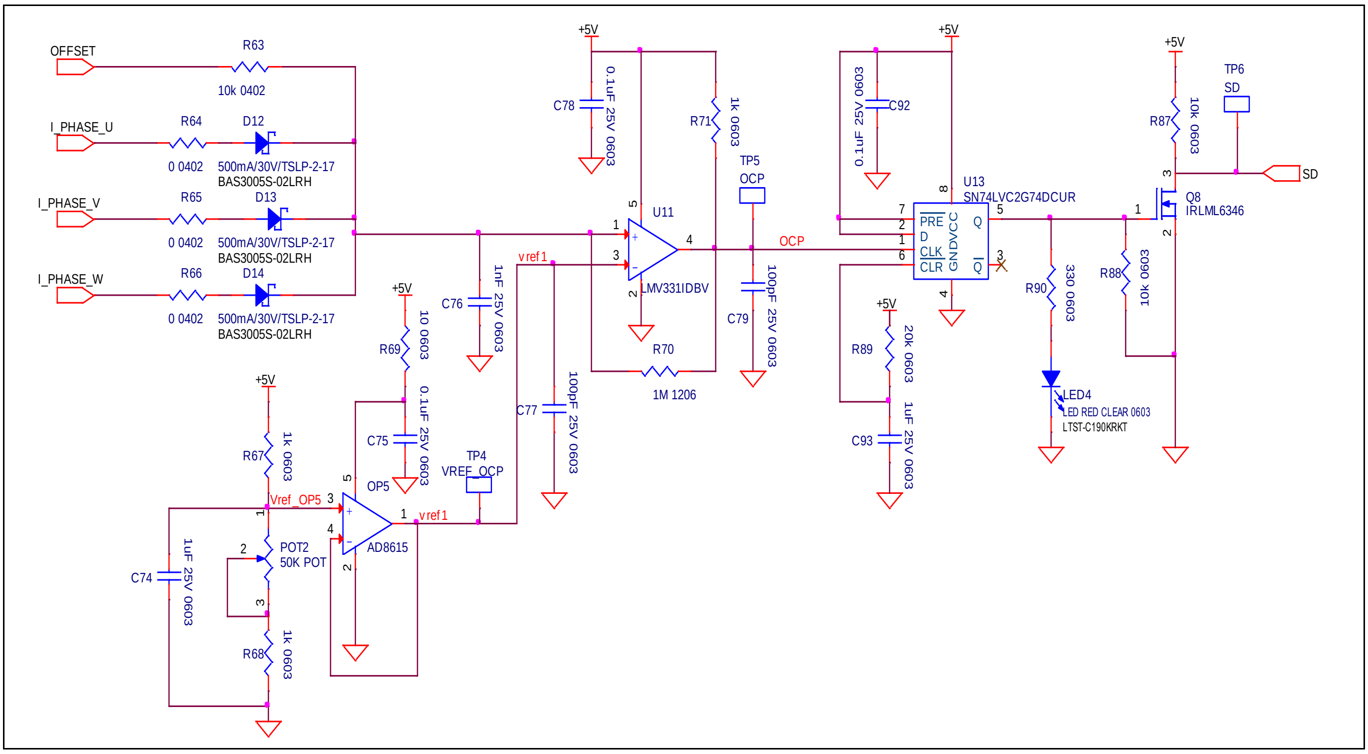


Figure 17 OCP circuitry

2.6 Power board connector

Figure 18 shows the interface using the 32-pin connector U12. The pin assignments are shown in **Table 3**.

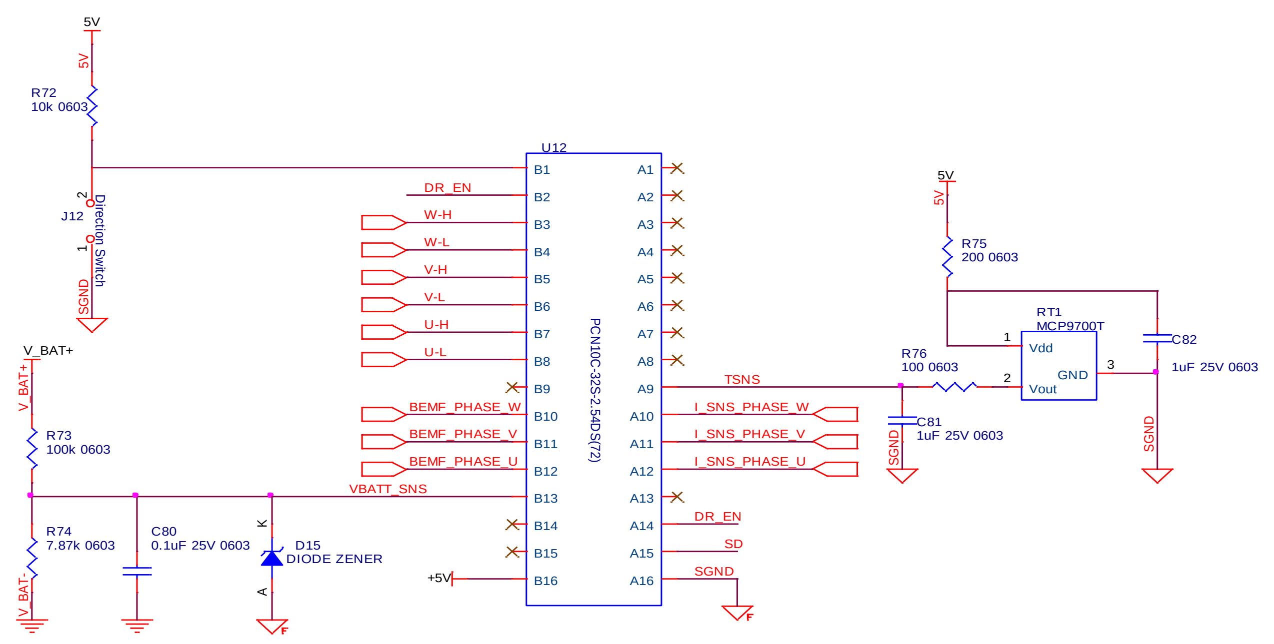


Figure 18 Power board connector

Table 3 Power board connector

X302 MAB32B2	U12 FAB32Q2	Function on power board	Port	Peripherals	
A1	A16	GND	VSS, VSSP		
A2	A15	SD	P0.5	CCU40.CC40	CMP2.OUT
A3	A14	$\overline{DR\_EN}$	P2.2	VADC0.G0CH7	ACMP2.INN
A4	A13	-	P2.4		VADC0.G1CH6
A5	A12	I_SNS_PHASE_U	P2.9	VADC0.G0CH2	VADC0.G1CH4
A6	A11	I_SNE_PHASE_V	P2.10	VADC0.G0CH3	VADC0.G1CH2
A7	A10	I_SNS_PHASE_W	P2.11	VADC0.G0CH4	VADC0.G1CH3
A8	A9	TSNS	P2.1	VADC0.G0CH6	
A9	A8	–	–		
A10	A7	–	–		
A11	A6	–	–		
A12	A5	–	–		
A13	A4	–	–		
A14	A3	–	–		
A15	A2	–	–		
A16	A1	–	–		
B1	B16	V_{CC}	VDD, VDDP		
B2	B15	–	–		
B3	B14	–	–		
B4	B13	VBATT_SNS	P2.3		VADC0.G1CH5
B5	B12	BEMF_U	P2.6	VADC0.G0CH0	
B6	B11	BEMF_V	P2.8	VADC0.G0CH1	VADC0.G0CH0
B7	B10	BEMF_W	P2.0	VADC0.G0CH5	

X302 MAB32B2	U12 FAB32Q2	Function on power board	Port	Peripherals	
B8	B9	–	P2.7		VADC0.G1CH1
B9	B8	U-L	P0.1	CCU80.OUT01	
B10	B7	U-H	P0.0	CCU80.OUT00	
B11	B6	V-L	P0.6	CCU80.OUT11	
B12	B5	V-H	P0.7	CCU80.OUT10	
B13	B4	W-L	P0.9 and P0.3	CCU80.OUT21	CCU80.OUT03
B14	B3	W-H	P0.8 and P0.2	CCU80.OUT20	CCU80.OUT02
B15	B2	$\overline{\mathrm{DR\_EN}}$	P0.12	CCU80.IN0A, IN1A, IN2A, IN3A	
B16	B1	Direction switch	P0.11	GPIO	

3 Control and firmware

3.1 Trapezoidal control also known as six-step or block commutation

In contrast to common synchronous machines, which are driven with sine wave voltages, BLDC motors are most commonly driven with a block-shaped voltage resulting in a trapezoidal-shaped current. Trapezoidal control is also known as block commutation or six-step control because there are six commutation intervals for each revolution, which are 60 degrees apart. This is the simplest BLDC motor control algorithm. Although performance is acceptable for power tools, block commutation is known to create a torque ripple with six times the frequency of the electrical rotary frequency of the three-phase motor. This leads to vibrations and acoustic noise due to the discrete switching between the phases such that the stator and rotor fields are not always perpendicular to each other. This generates high torque ripple, resulting in some inevitable vibration and noise.

In three-phase machines during each commutation step, a current path is formed between a pair of windings, leaving the third winding disconnected. The Hall sensor outputs are either high or low, depending on which pole of the rotor permanent magnet they are in proximity with, in the current position. During rotation, when one of the rotor north–south pole interfaces passes a Hall sensor, its output toggles and the controller then switches the DC voltage to the next phase (shown below as “A”, “B”, or “C”). The XMC1300 series microcontroller has sufficient processing power to execute this control algorithm. As shown below, the voltage has a rectangular shape, which results in a trapezoidal current and back-EMF shape in the machine.

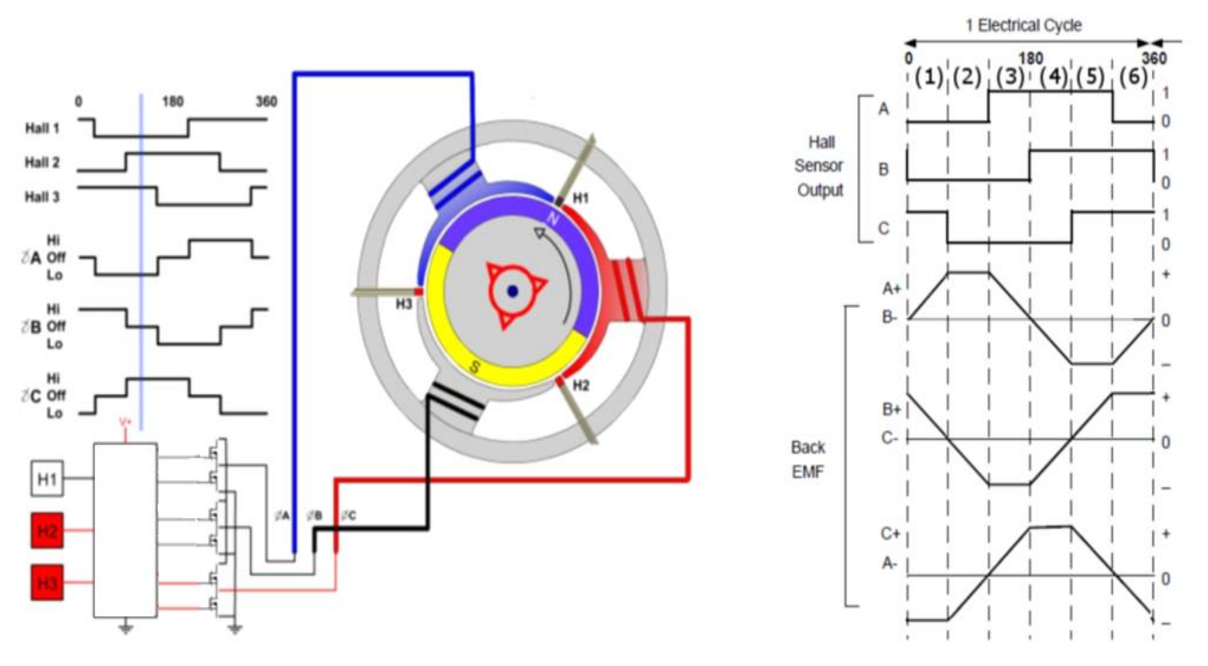


Figure 19 Control of a BLDC motor with Hall sensors

During each commutation step, one of the windings is energized with current entering into it, the second winding has current exiting it, and the third is in a non-energized open-circuit condition. The torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90 degrees to each other and falls off as the fields move together.

The block diagram of a typical BLDC trapezoidal control block commutation system with Hall sensors is shown below:

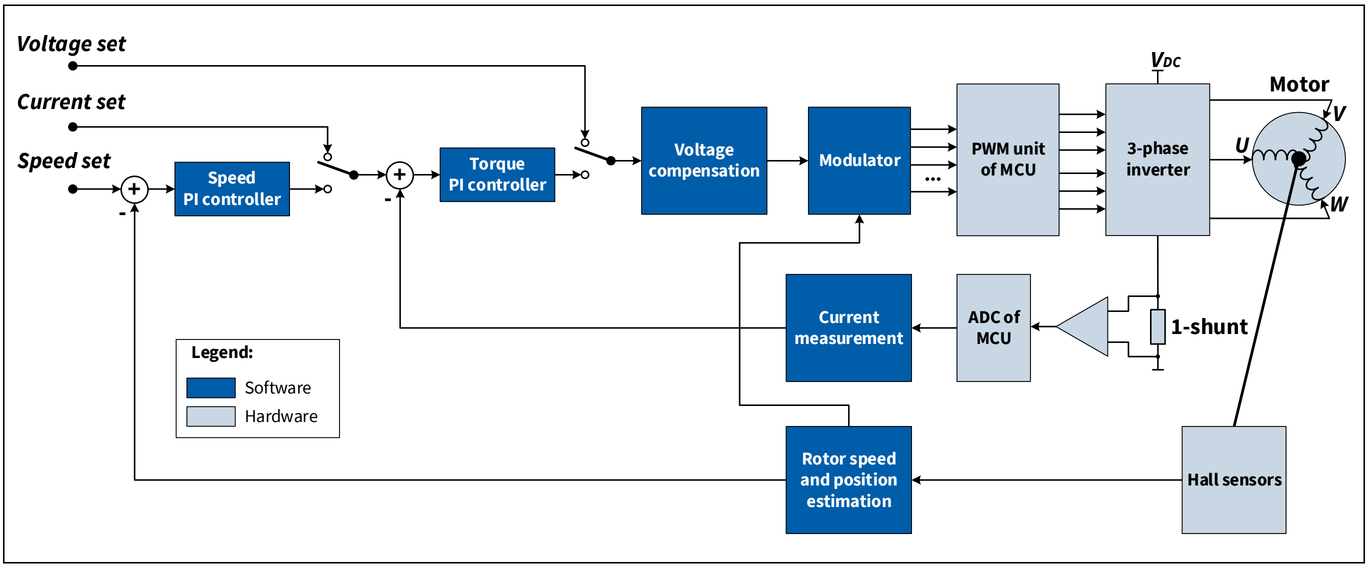


Figure 20 **Block diagram of trapezoidal/block commutation algorithm**

The switching patterns are shown in the diagram below. In the EVAL_TOLT_DC36V_2KW implementation, the 6PWM mode is used, where all of the high- and low-side gate drive pulses are generated by the microcontroller, which also senses the Hall sensor outputs. The firmware is based on the BLDC_SCALAR_HALL_XMC13 platform developed by Infineon and customized for the EVAL_TOLT_DC36V_2KW board.

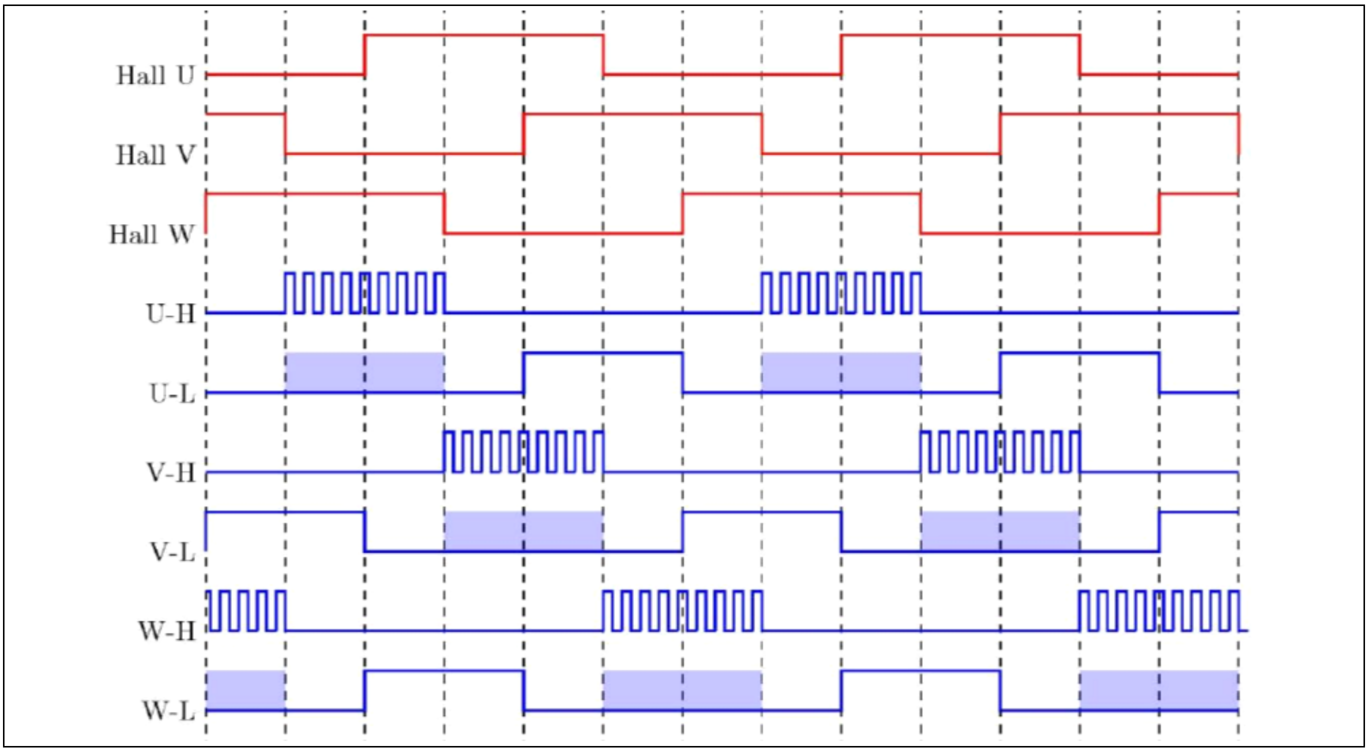


Figure 21 **Switching patterns for trapezoidal/block commutation**

3.2 P-I control

As illustrated in the block diagram above, a closed-loop control system is used to regulate the speed. A command value is applied to the system through the potentiometer on the XMC1300 drive card board. The firmware implements a proportional-integral (P-I) control loop, as shown:

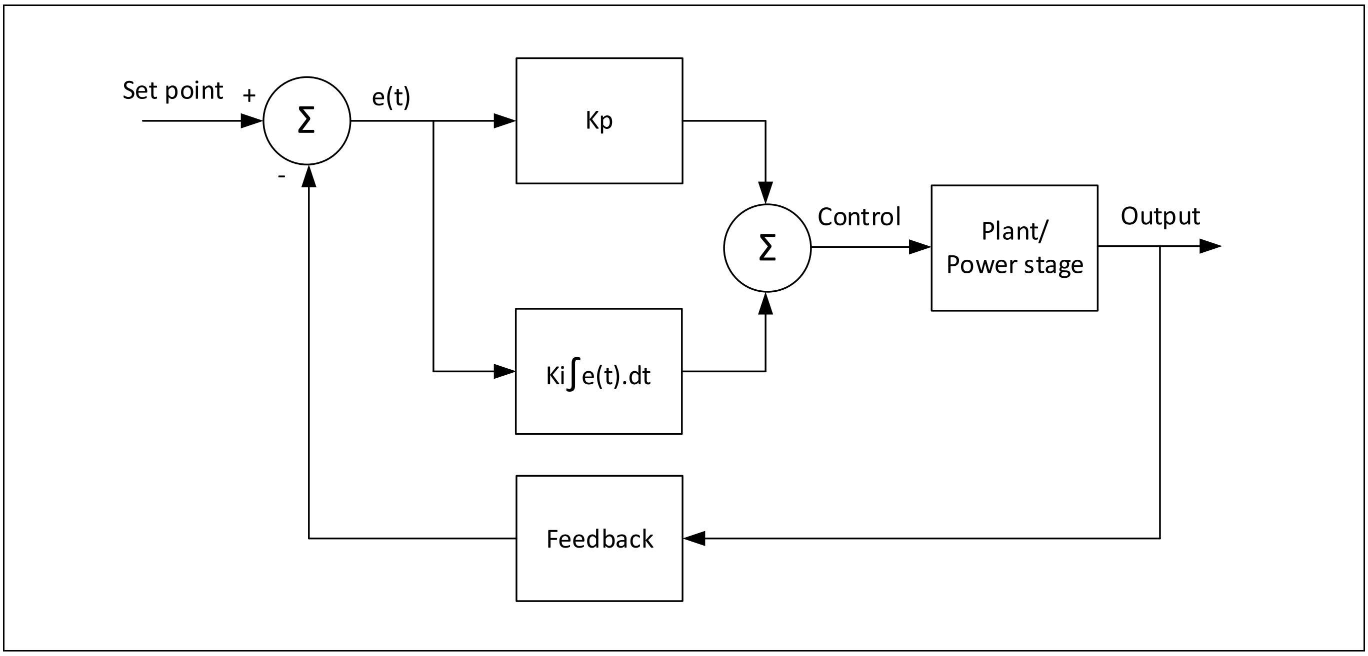


Figure 22 **P-I control block diagram**

The P-I controller is a widely used feedback control mechanism, which continuously calculates an error value e(t) that is the difference between the setpoint of the measured output quantity (here, speed in RPM) and the actual measured value. In this case the speed is derived by the firmware from the Hall sensor input signals. The error value is fed to the proportional calculator, where it is multiplied by K_P, and to the integral calculator, where it is integrated with respect to time and the result multiplied by K_I. These two results are then summed together to provide a control value, which is applied to the power stage to provide a correction that will adjust the output to match the setpoint. The goal is to optimize the values of K_P and K_I for the specific system (inverter and motor) to achieve minimal delay and overshoot when changes are made to the commanded speed.

4 System operation

4.1 System startup

The motor speed is set by adjusting POT1/R103 in the drive card. **Figure 23** shows the three-phase power board connected to an XMC1300 drive card.

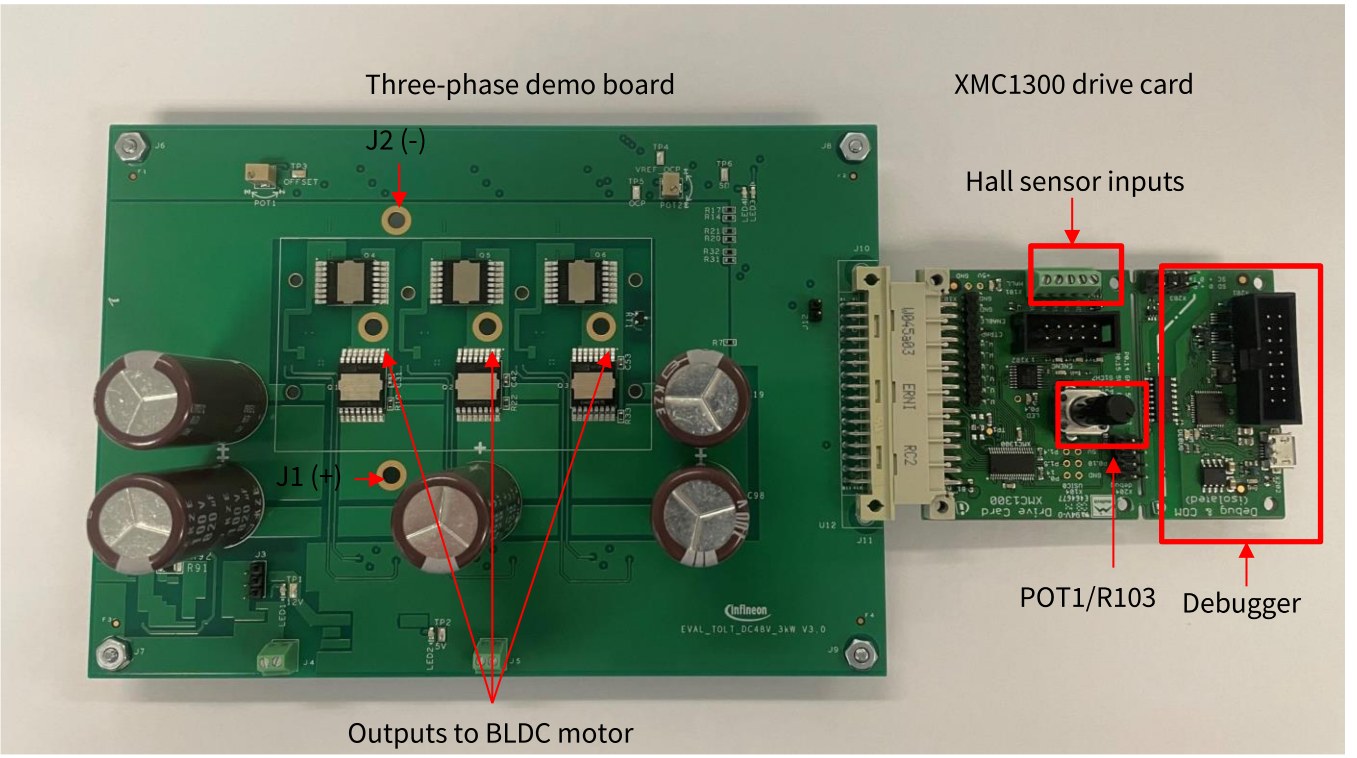


Figure 23 Three-phase power board connected to XMC1300 drive card

The following order is recommended to power up the board:

1) Output phases are connected to the BLDC motor. The order of the phases is important, as the motor will not operate correctly if the phases are incorrectly connected. **Table 4** shows the connector for each of the phases.

Table 4 Motor phase connectors

Motor phase	Connector
Phase U	U
Phase V	V
Phase W	W

2) The three Hall sensors are connected directly to the XMC1300 drive card via connector X101. **Table 5** shows the pin-out for the Hall sensor interface.

Table 5 Hall sensor interface (X101)

Pin	Description
1	GND
2	Phase U Hall sensor
3	Phase V Hall sensor

Pin	Description
4	Phase W Hall sensor
5	V_{DD} (+5 V)

3) The XMC1300 drive card is connected to the power board through the power board connector.
4) For using on-board power supplies, pin 1 and pin 2 should be shorted via J3.
5) If using external power supplies, pin 2 and pin 3 should be shorted using J3 for using external 12 V power supply, and R1 should be removed if using an external 5 V power supply.
6) The input power supply to the power board should be connected to J1 (+) and J2 (-).[1]

4.2 System performance

The three-phase inverter switching devices are **IPTC007N06NM5** (OptiMOS™ 6 60 V 0.75 mΩ TOLT) power MOSFETs optimized for battery-powered motor drive. The demo board is able to support high-side modulation with synchronous rectification PWM. In each case, the PWM operates at a fixed frequency and the duty cycle is adjusted to control the average voltage applied to each stator winding. The winding inductances remove most of the PWM frequency component, leaving a small amount of ripple. **Figure 24** shows this modulation scheme.

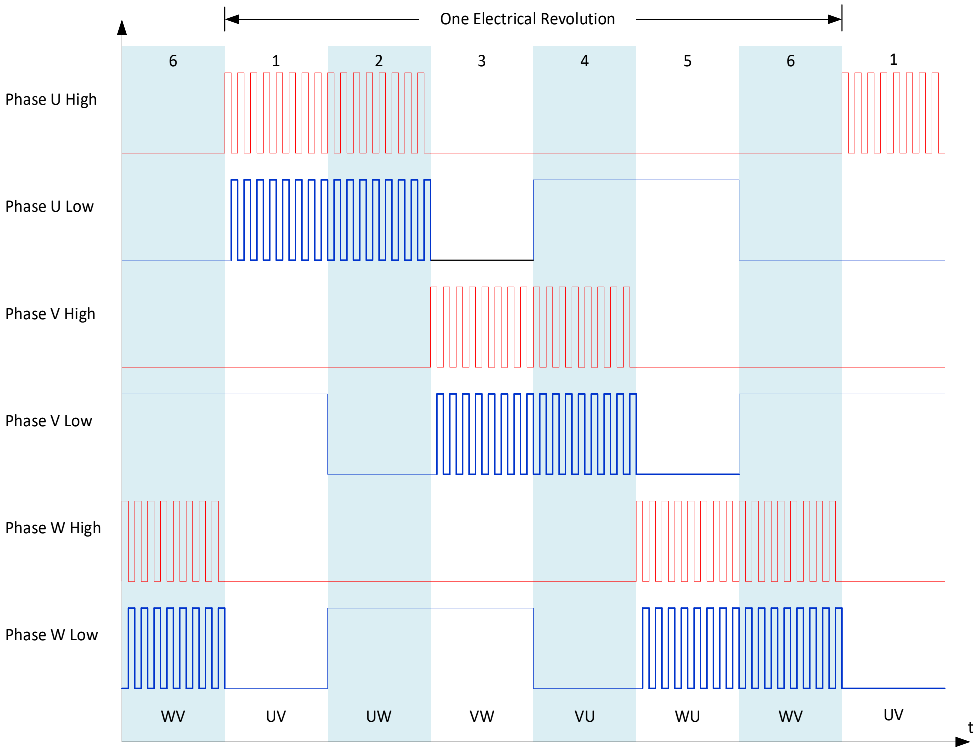


Figure 24 High-side modulation with synchronous rectification

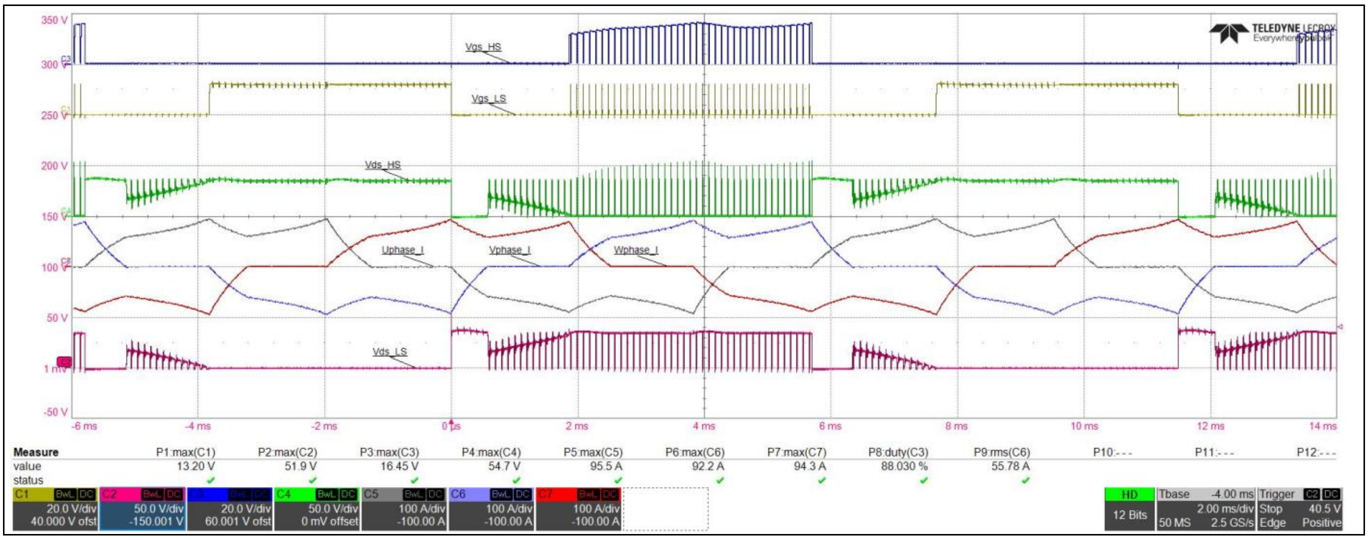
For high-side modulation with synchronous rectification, the switching dead time is inserted between the rising and falling edges of the PWM signals to prevent the high-side and low-side MOSFETs of each inverter phase from being on at the same time during switching transitions (shoot-through condition). Moreover, the main advantage of this scheme is higher efficiency due to lower body diode conduction losses in the low-side MOSFETs.

---

[1] It is recommended to use short cables for the input power supply to limit the ripple current passing through the input bulk capacitors.

4.2.1 Operating waveforms

Figure 25 and **Figure 26** show gate-source and drain-source voltages of both high-side and low-side MOSFETs for phase V, and also the phase U, V and W currents using high-side modulation with the synchronous rectification trapezoidal control method at 1300 RPM with an input power of 1.85 kW at 36 V input voltage for 2 ms/div and 1 ms/div.

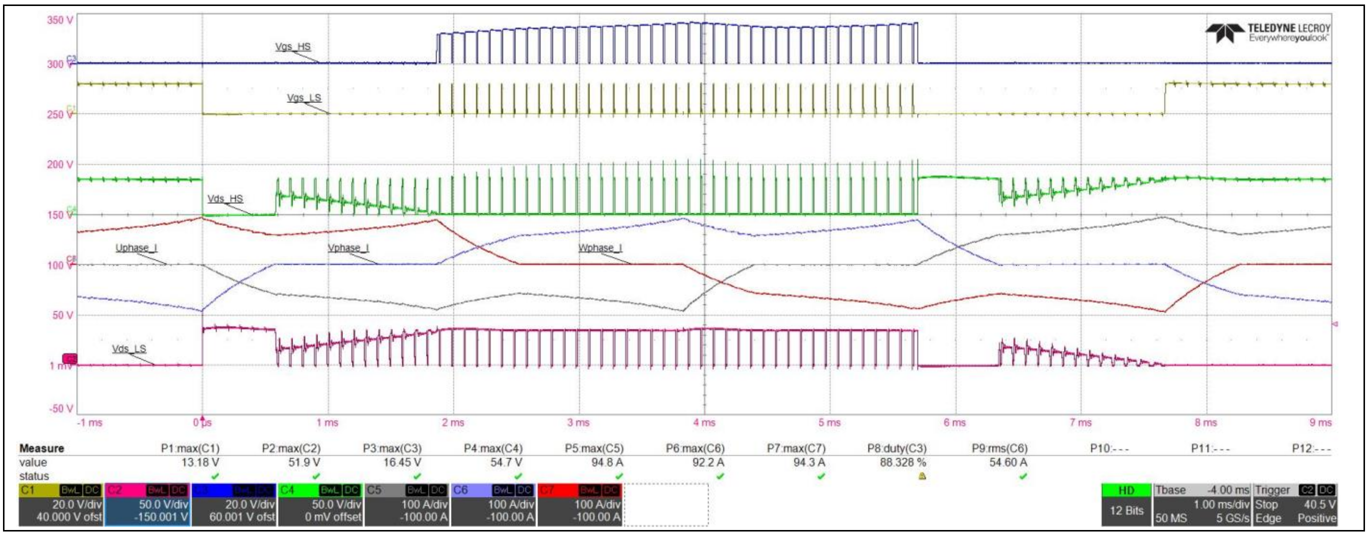


Measure	P1:max(C1)	P2:max(C2)	P3:max(C3)	P4:max(C4)	P5:max(C5)	P6:max(C6)	P7:max(C7)	P8:duty(C3)	P9:rms(C6)	P10:---	P11:---	P12:---
value	13.20 V	51.9 V	16.45 V	54.7 V	95.5 A	92.2 A	94.3 A	88.030 %	55.78 A			
status	✓	✓	✓	✓	✓	✓	✓	✓	✓			

C1 BwL DC	C2 BwL DC	C3 BwL DC	C4 BwL DC	C5 BwL DC	C6 BwL DC	C7 BwL DC
20.0 V/div 40.000 V ofst	50.0 V/div -150.001 V	20.0 V/div 60.001 V ofst	50.0 V/div 0 mV offset	100 A/div -100.00 A	100 A/div -100.00 A	100 A/div -100.00 A

HD	Tbase -4.00 ms	Trigger C2 DC
12 Bits	2.00 ms/div 50 MS 2.5 GS/s	Stop 40.5 V Edge Positive

Figure 25 **High-side and low-side MOSFET gate-source and drain-source voltages for phase V (2 ms/div); V_{GS_HS} (blue), V_{GS_LS} (yellow), V_{DS_HS} (green), V_{DS_LS} (pink), I_{PHASE_U} (gray), I_{PHASE_V} (blue), I_{PHASE_W} (red)**



Measure	P1:max(C1)	P2:max(C2)	P3:max(C3)	P4:max(C4)	P5:max(C5)	P6:max(C6)	P7:max(C7)	P8:duty(C3)	P9:rms(C6)	P10:---	P11:---	P12:---
value	13.18 V	51.9 V	16.45 V	54.7 V	94.8 A	92.2 A	94.3 A	88.328 %	54.60 A			
status	✓	✓	✓	✓	✓	✓	✓	⚠	✓			

C1 BwL DC	C2 BwL DC	C3 BwL DC	C4 BwL DC	C5 BwL DC	C6 BwL DC	C7 BwL DC
20.0 V/div 40.000 V ofst	50.0 V/div -150.001 V	20.0 V/div 60.001 V ofst	50.0 V/div 0 mV offset	100 A/div -100.00 A	100 A/div -100.00 A	100 A/div -100.00 A

HD	Tbase -4.00 ms	Trigger C2 DC
12 Bits	1.00 ms/div 50 MS 5 GS/s	Stop 40.5 V Edge Positive

Figure 26 **High-side and low-side MOSFET gate-source and drain-source voltages for phase V (1 ms/div); V_{GS_HS} (blue), V_{GS_LS} (yellow), V_{DS_HS} (green), V_{DS_LS} (pink), I_{PHASE_U} (gray), I_{PHASE_V} (blue), I_{PHASE_W} (red)**

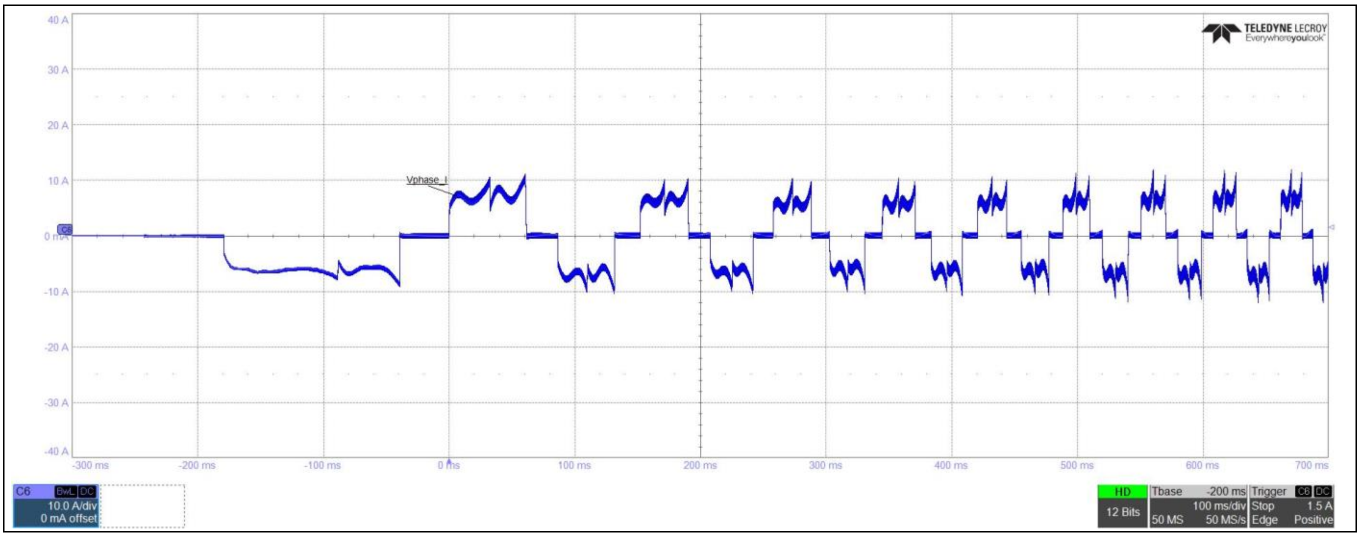
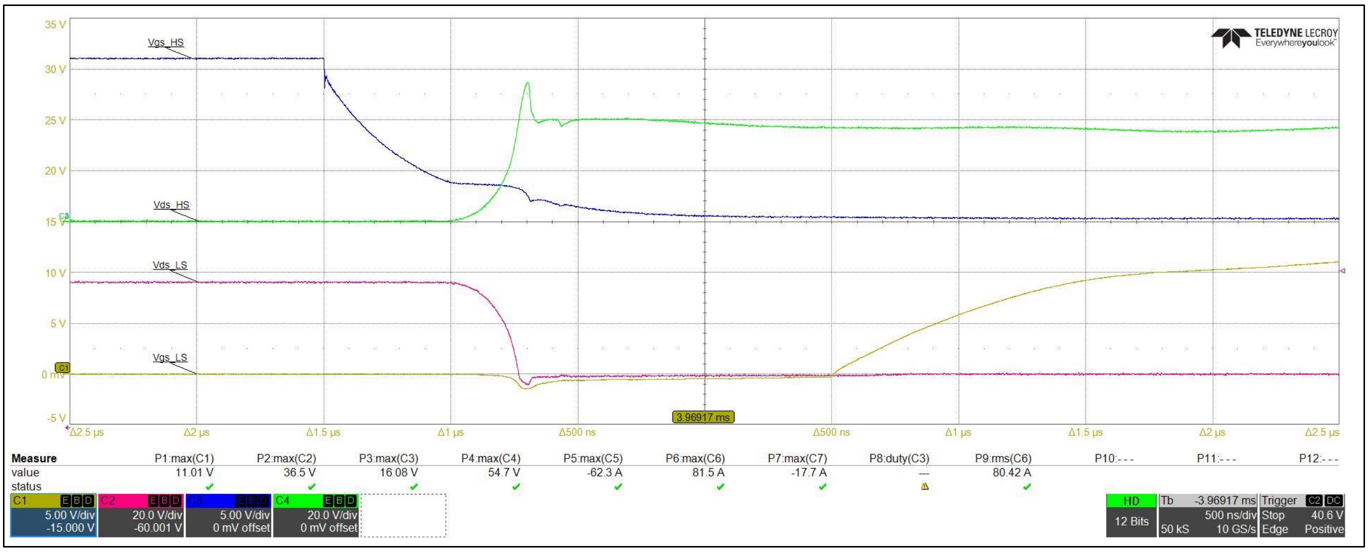


Figure 27 Phase V start-up current (100.0 ms/div); I_{PHASE_V} (blue)



Measure	P1:max(C1)	P2:max(C2)	P3:max(C3)	P4:max(C4)	P5:max(C5)	P6:max(C6)	P7:max(C7)	P8:duty(C3)	P9:rms(C6)	P10:---	P11:---	P12:---
value	11.01 V	36.5 V	16.08 V	54.7 V	-62.3 A	81.5 A	-17.7 A	---	80.42 A			
status	✓	✓	✓	✓	✓	✓	✓	⚠	✓			

Figure 28 High-side and low-side MOSFET gate-source and drain-source voltages for phase V during high-side MOSFET turn-off and low-side MOSFET turn-on (500 ns/div); V_{GS_HS} (blue), lV_{DS_LS8}(green), V_{GS_HS} (yellow), V_{DS_LS} (pink)

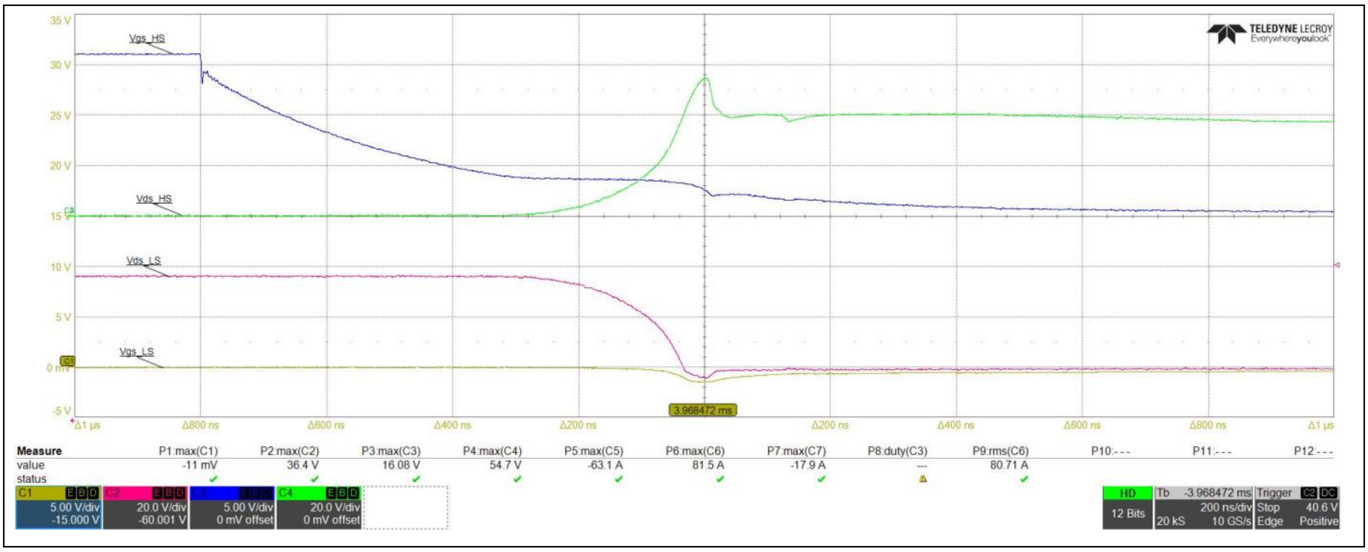


Figure 29 High-side and low-side MOSFET gate-source and drain-source voltages for phase V during high-side MOSFET turn-off and low-side MOSFET turn-on (200 ns/div); V_{GS_HS} (blue), V_{DS_LS} (green), V_{GS_HS} (yellow), V_{DS_LS} (pink)

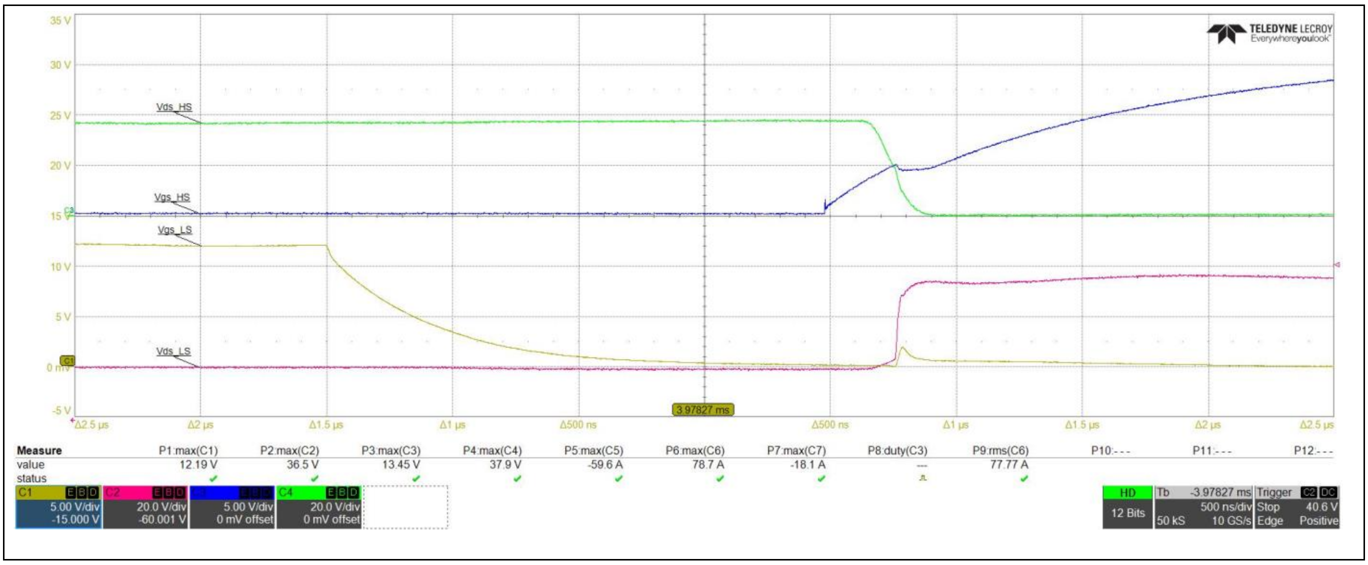
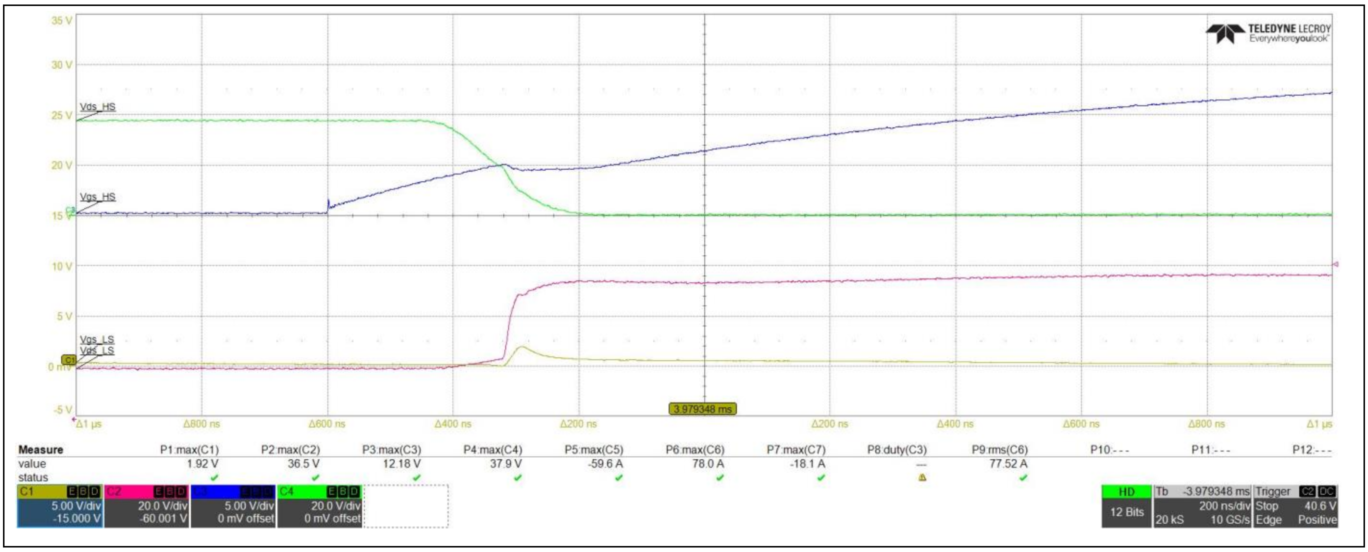


Figure 30 High-side and low-side MOSFET gate-source and drain-source voltages for phase V for high-side MOSFET turn-on and low-side MOSFET turn-off (500 ns/div); V_{GS_HS} (blue), V_{DS_LS} (green), V_{gs_HS} (yellow), V_{DS_LS} (pink)



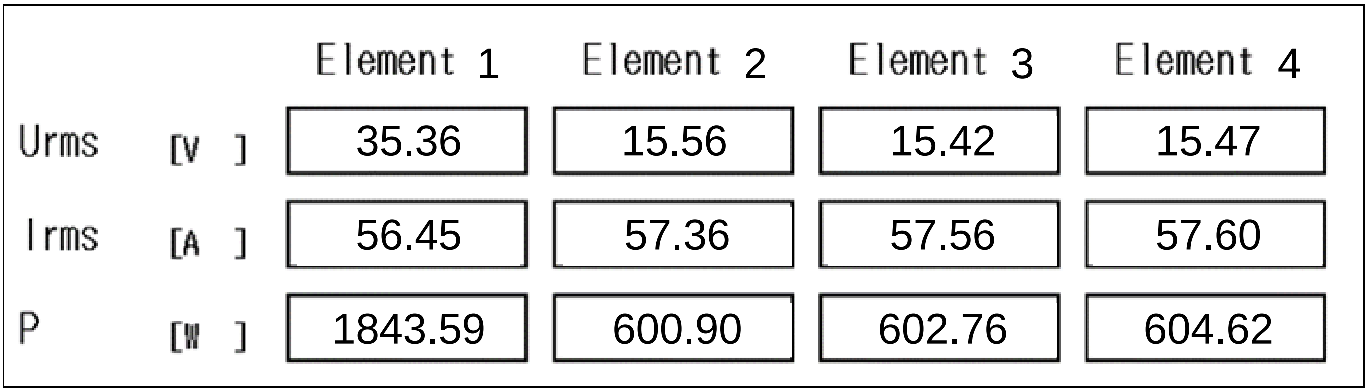
Measure	P1:max(C1)	P2:max(C2)	P3:max(C3)	P4:max(C4)	P5:max(C5)	P6:max(C6)	P7:max(C7)	P8:duty(C3)	P9:rms(C6)	P10:---	P11:---	P12:---
value	1.92 V	36.5 V	12.18 V	37.9 V	-59.6 A	78.0 A	-18.1 A	---	77.52 A			
status	✓	✓	✓	✓	✓	✓	✓	⚠	✓			

C1	C2	C3	C4
5.00 V/div -15.000 V	20.0 V/div -60.001 V	5.00 V/div 0 mV offset	20.0 V/div 0 mV offset

HD 12 Bits
Tb -3.979348 ms 200 ns/div 20 kS 10 GS/s
Trigger C2 DC Stop 40.6 V Edge Positive

Figure 31 High-side and low-side MOSFET gate-source and drain-source voltages for phase V (1 ms/div) for high-side MOSFET turn-on and low-side MOSFET turn-off (200 ns/div); V_{GS_HS} (blue), V_{GS_LS} (yellow), V_{DS_HS} (green), V_{DS_LS} (pink)

4.2.2 Power measurements



		Element 1	Element 2	Element 3	Element 4
Urms	[V]	35.36	15.56	15.42	15.47
Irms	[A]	56.45	57.36	57.56	57.60
P	[W]	1843.59	600.90	602.76	604.62

Figure 32 Input and output measurements with an input power of 2 kW at 36 V input voltage

In **Figure 32**, results element 1 represents the DC input to the inverter. Elements 2, 3, and 4 are connected to the output phases U, V and W, respectively.

The total output power is equal to 600.90 W + 602.76 W + 604.62 W = 1808.28 W for an input power of 1843.59 W.

This gives an efficiency of 1808.28/1843.59 x 100 = 98.08 percent with losses of 35.32 W.

4.2.3 Thermal measurements

Thermal images were taken after 12 minutes of operation to allow the components to rise and reach steady-state at an input power of 1850 W at 36 V input voltage as shown in **Figure 33**. No forced air cooling was used.

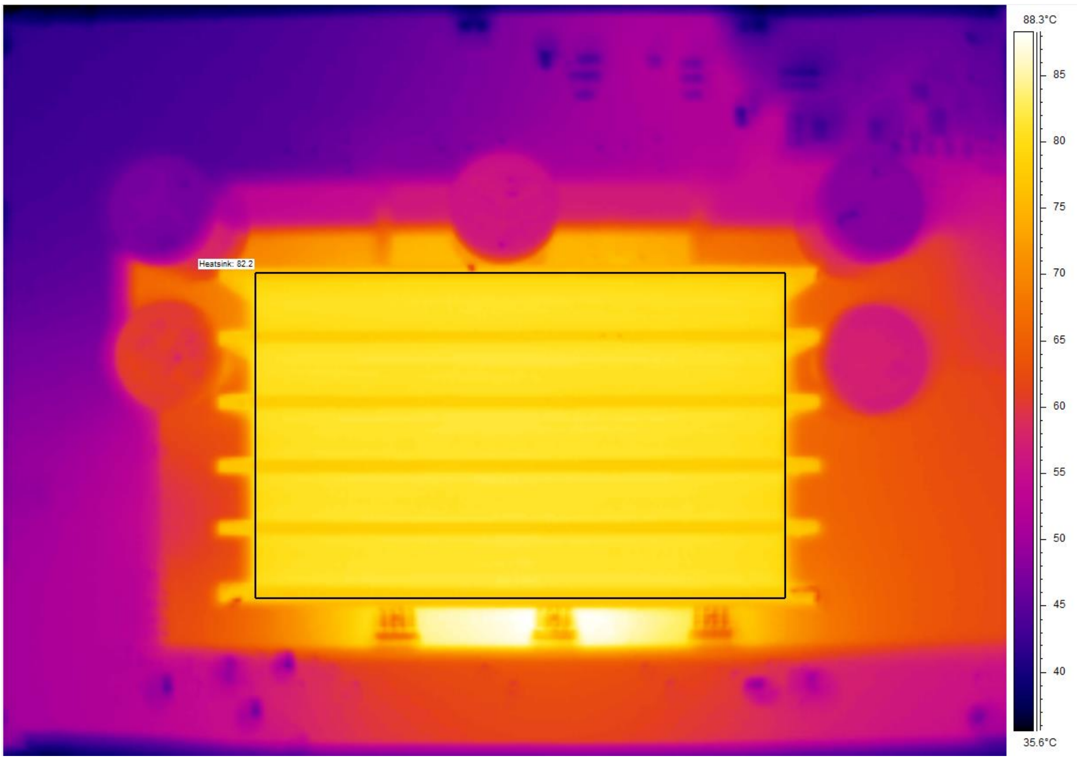


Figure 33 Thermal measurements at 36 V input and 1.85 kW load

The temperature rises at 36 V input voltage for 1.85 kW input power is only 57.2°C.

5 Schematic and PCB layout

5.1 Schematics

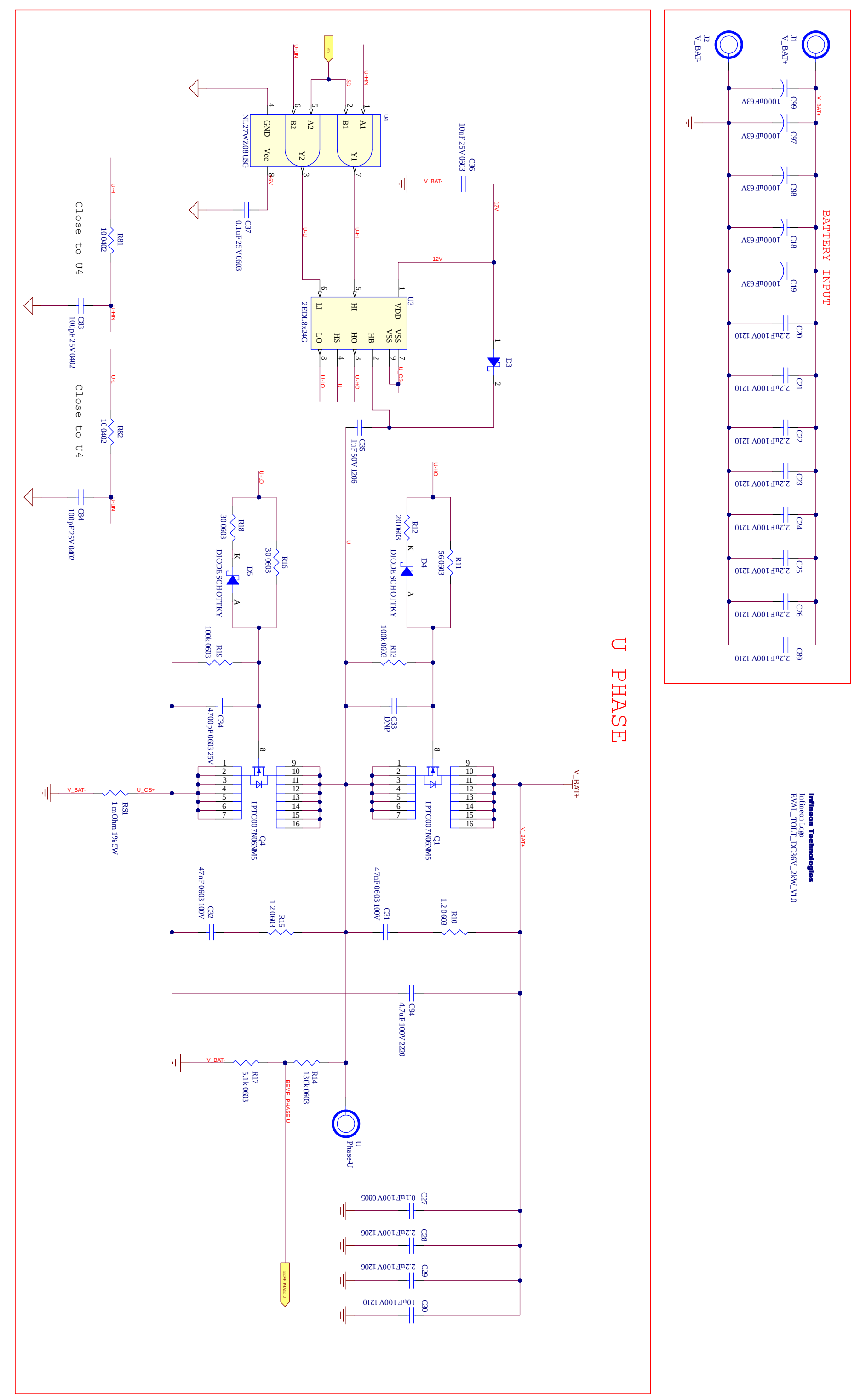


Figure 34 Input section and phase U power stage

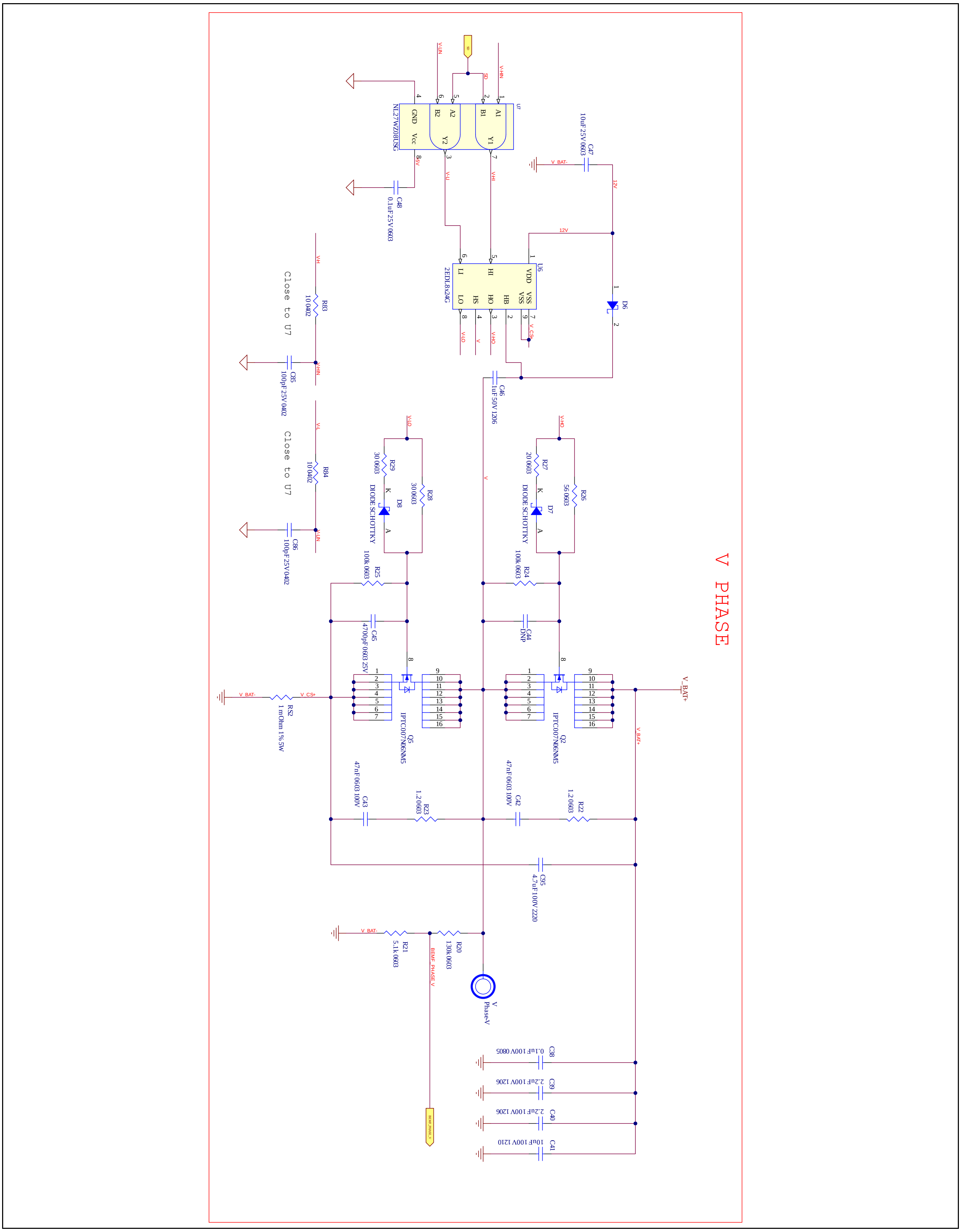


Figure 35 Phases V power stage

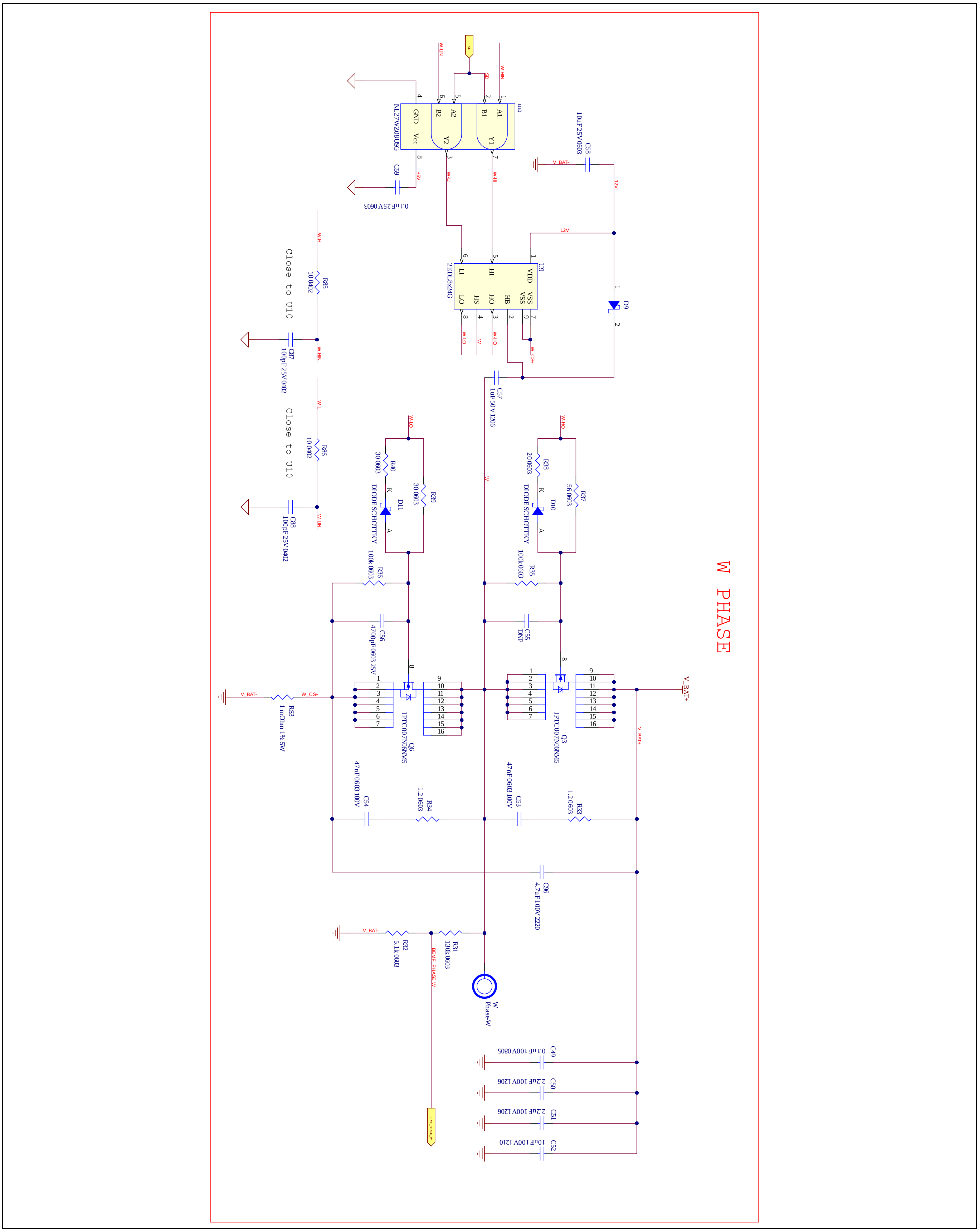


Figure 36 Phases W power stages

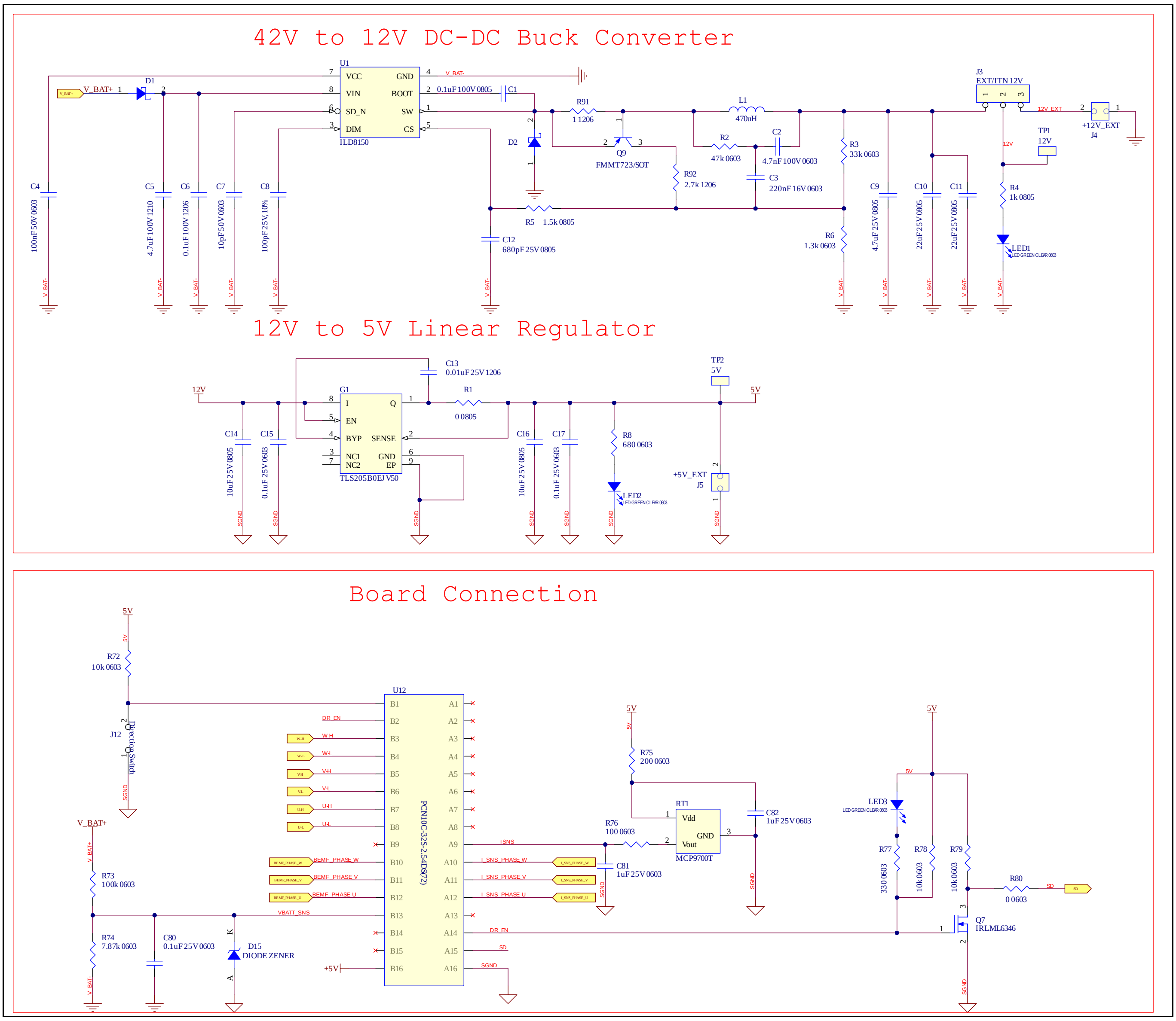


Figure 37 Board connector and voltage regulators

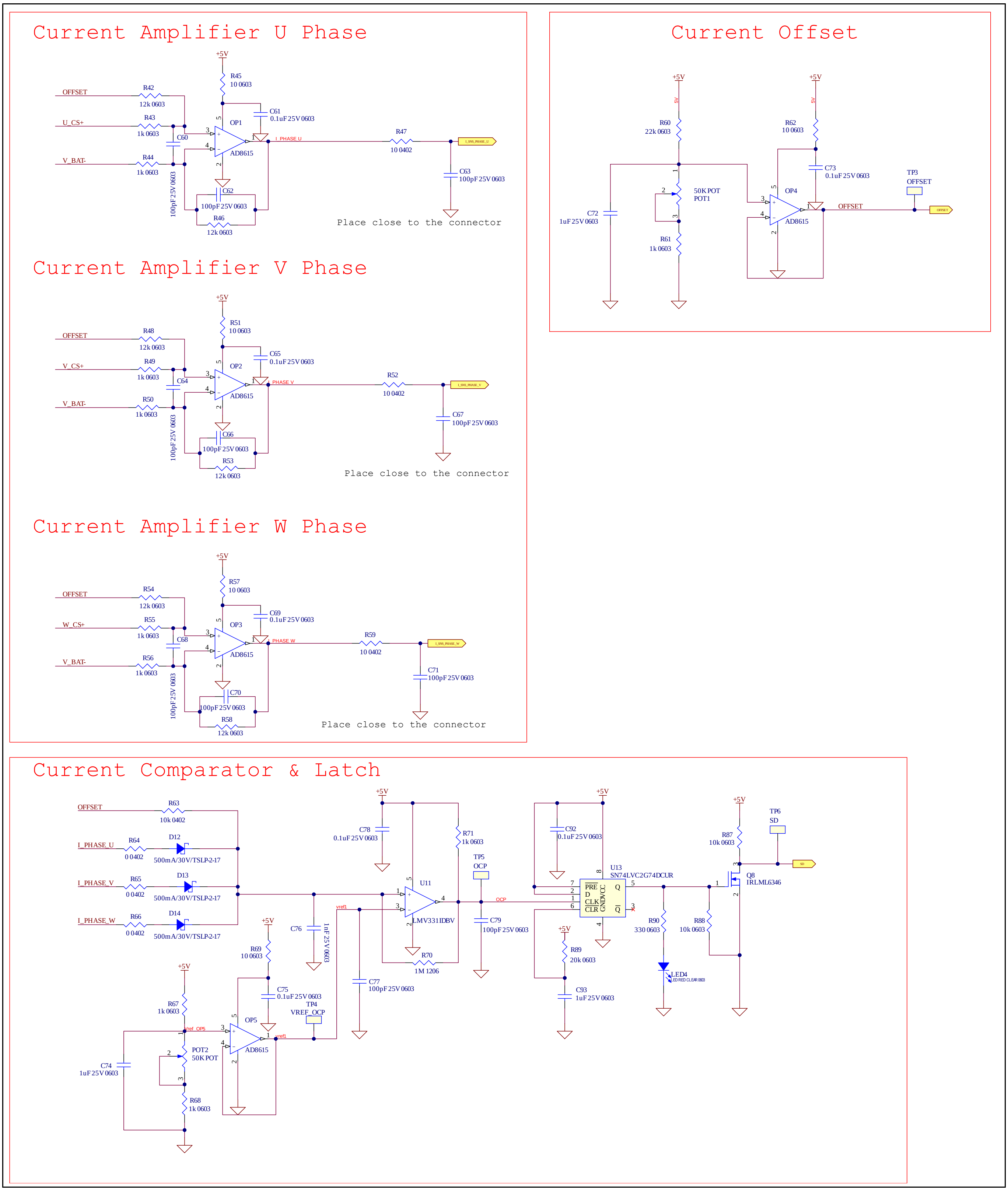


Figure 38 **Protection circuitry**

5.2 Layout

The EVAL_TOLT_DC36V_2KW board consists of six copper PCB layers. All the layers have 2 oz. copper and the board size is 170 mm x 120 mm. The board material is FR4 grade with 1.6 mm thickness. The Gerber files are available from the downloads section of the **Infineon website**. A login is required to download this material.

The top layer, mid 1 layer, mid 2 layer, mid 3 layer, mid 4 layer and bottom layer PCB layouts are shown in **Figures 35** to **40**.

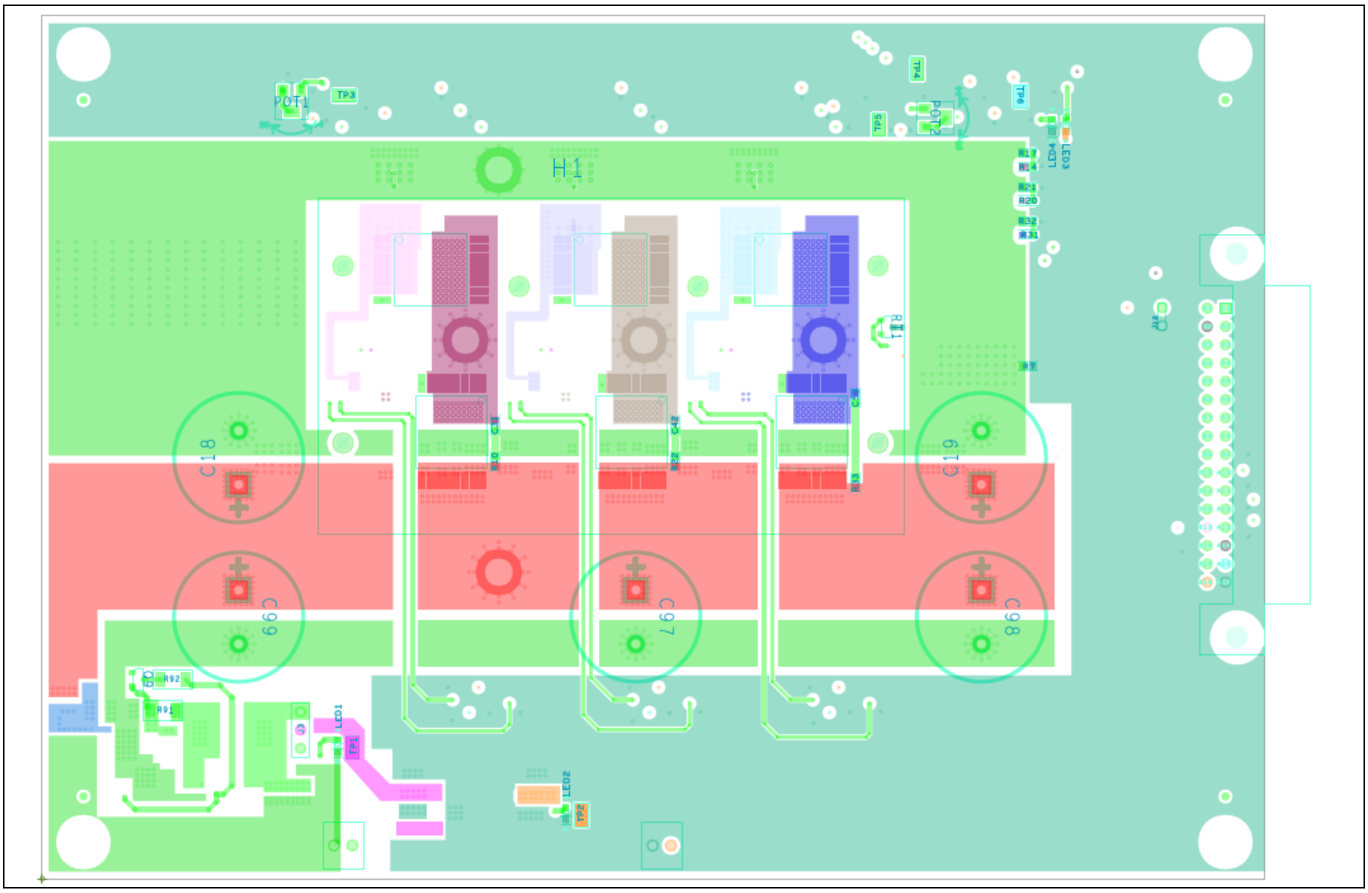


Figure 39 **Top layer**

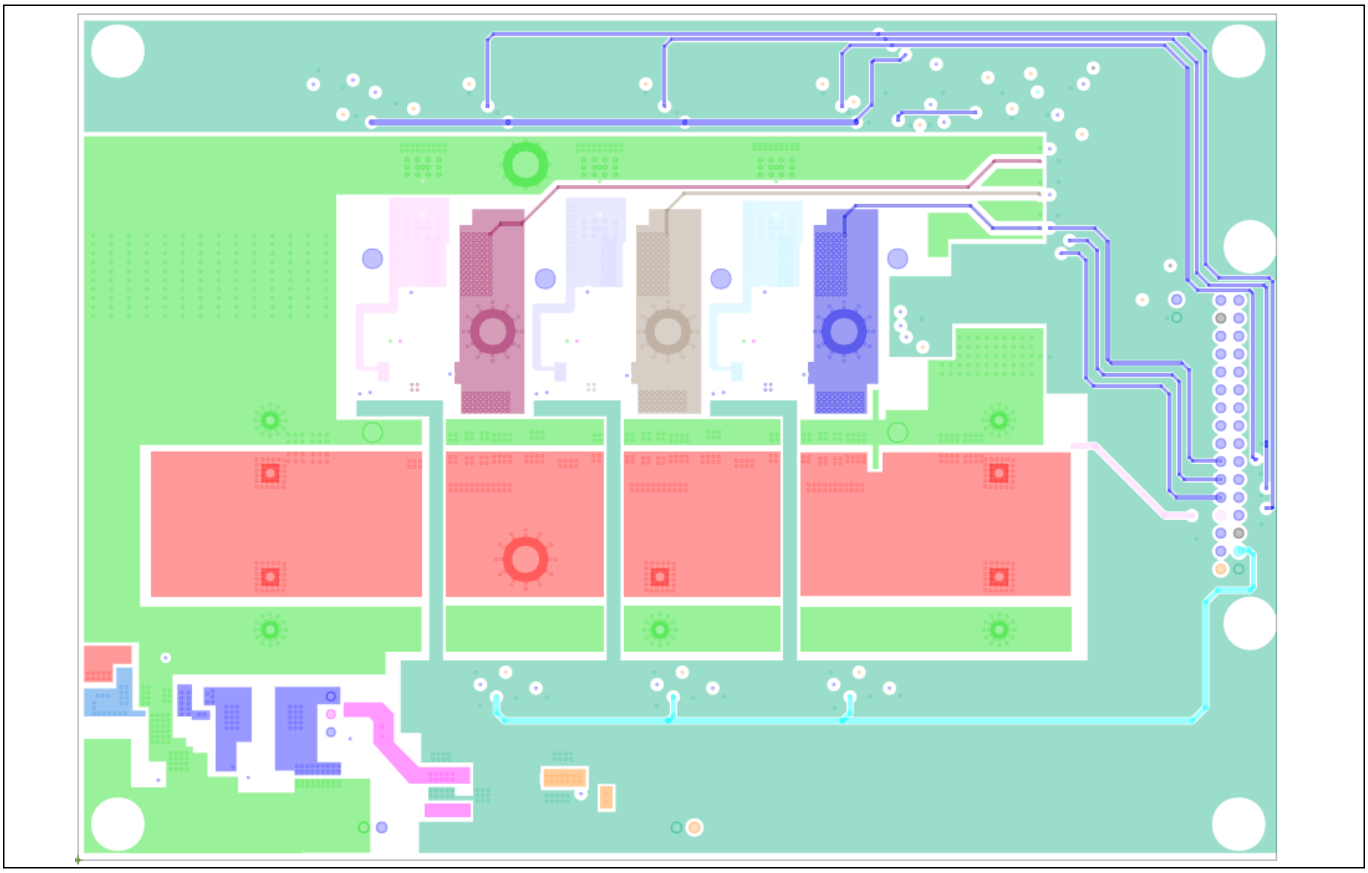


Figure 40 Mid 1 layer

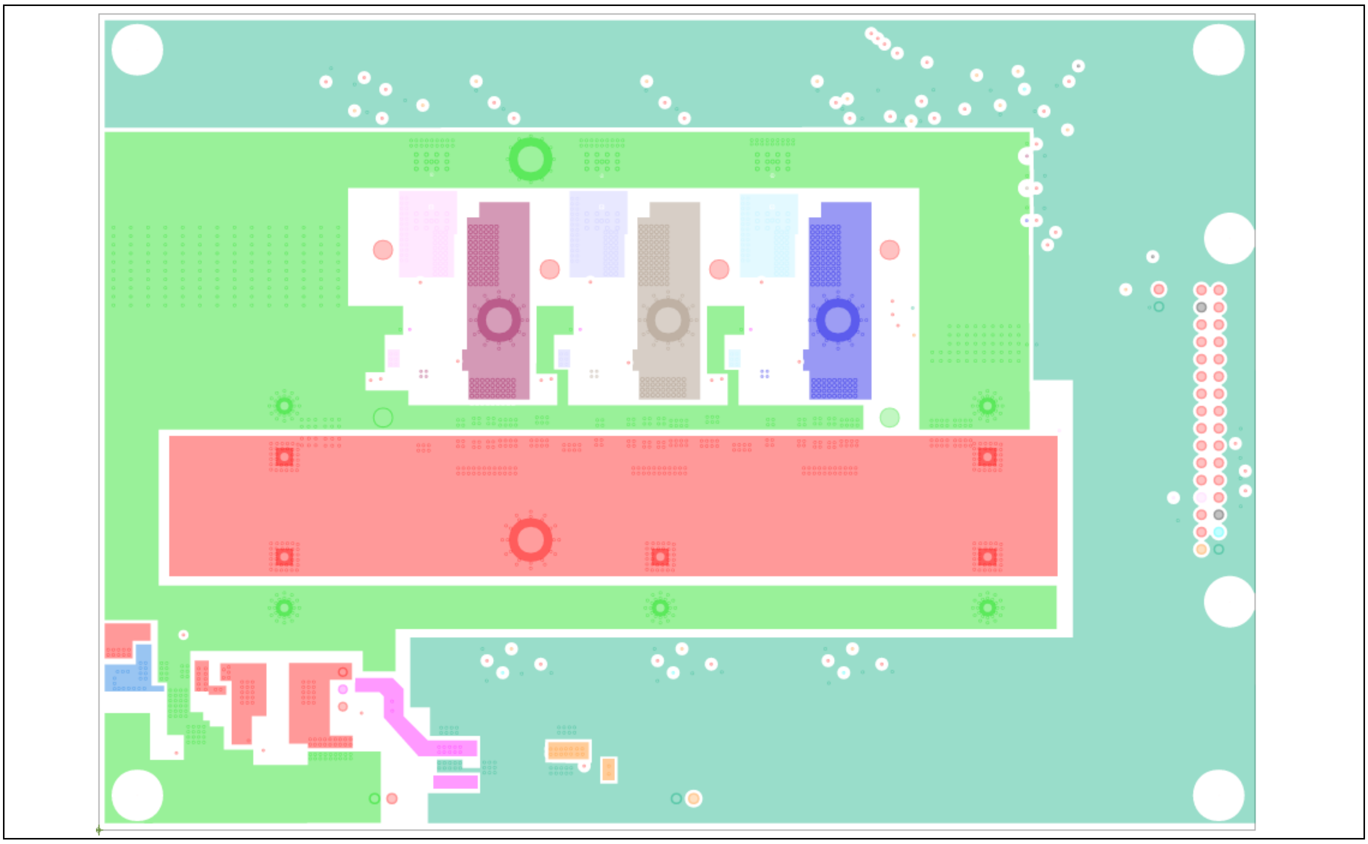


Figure 41 Mid 2 layer

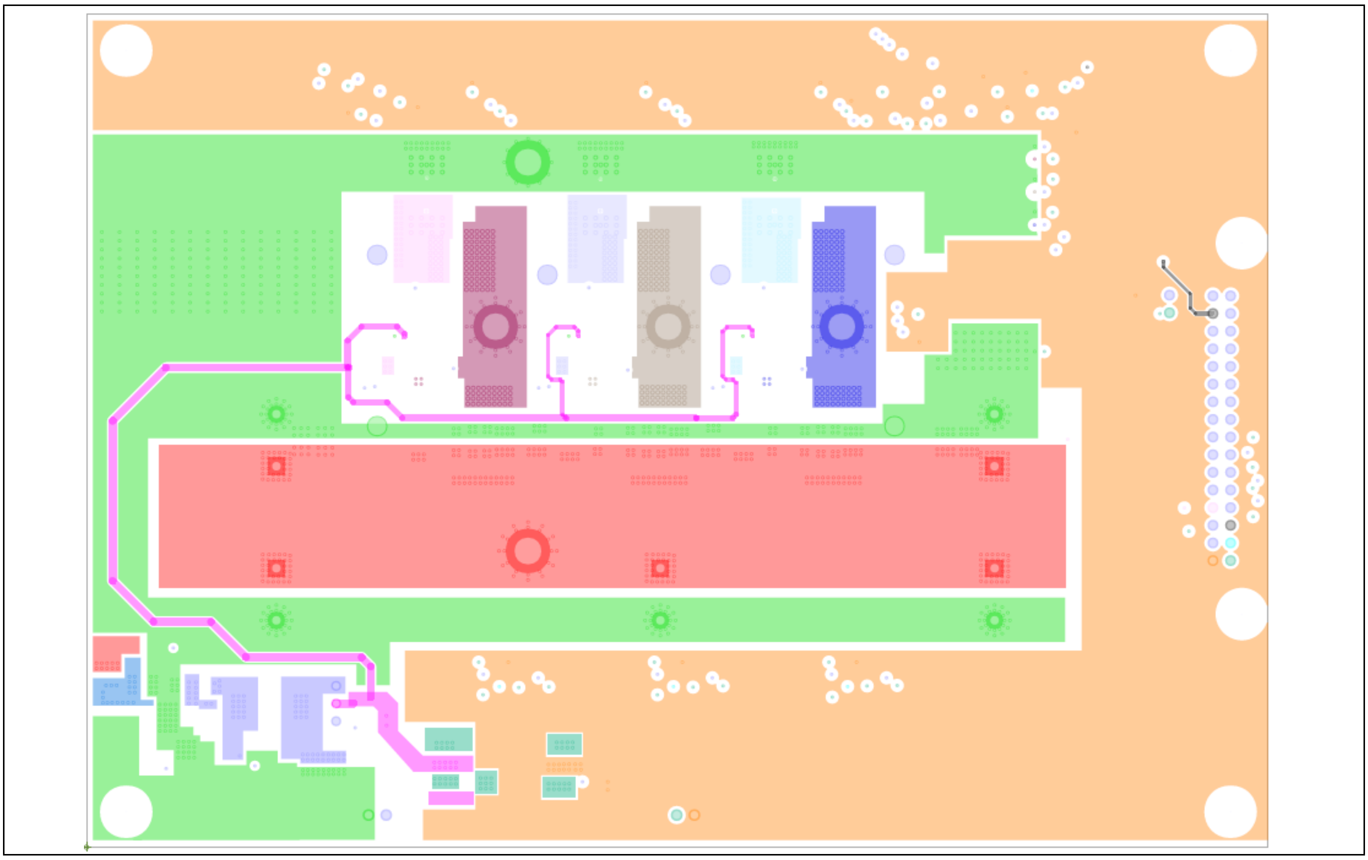


Figure 42 Mid 3 layer

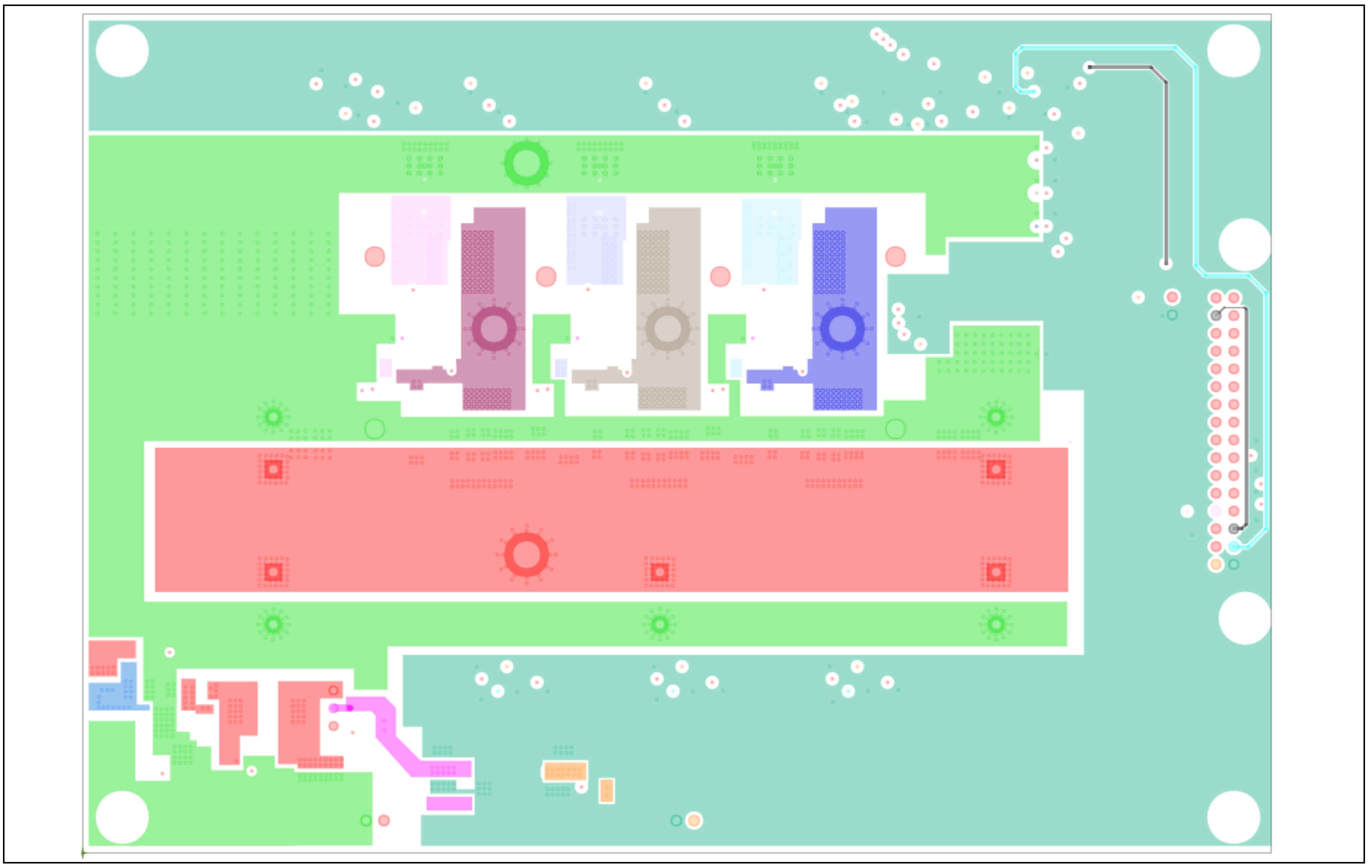


Figure 43 Mid 4 layer

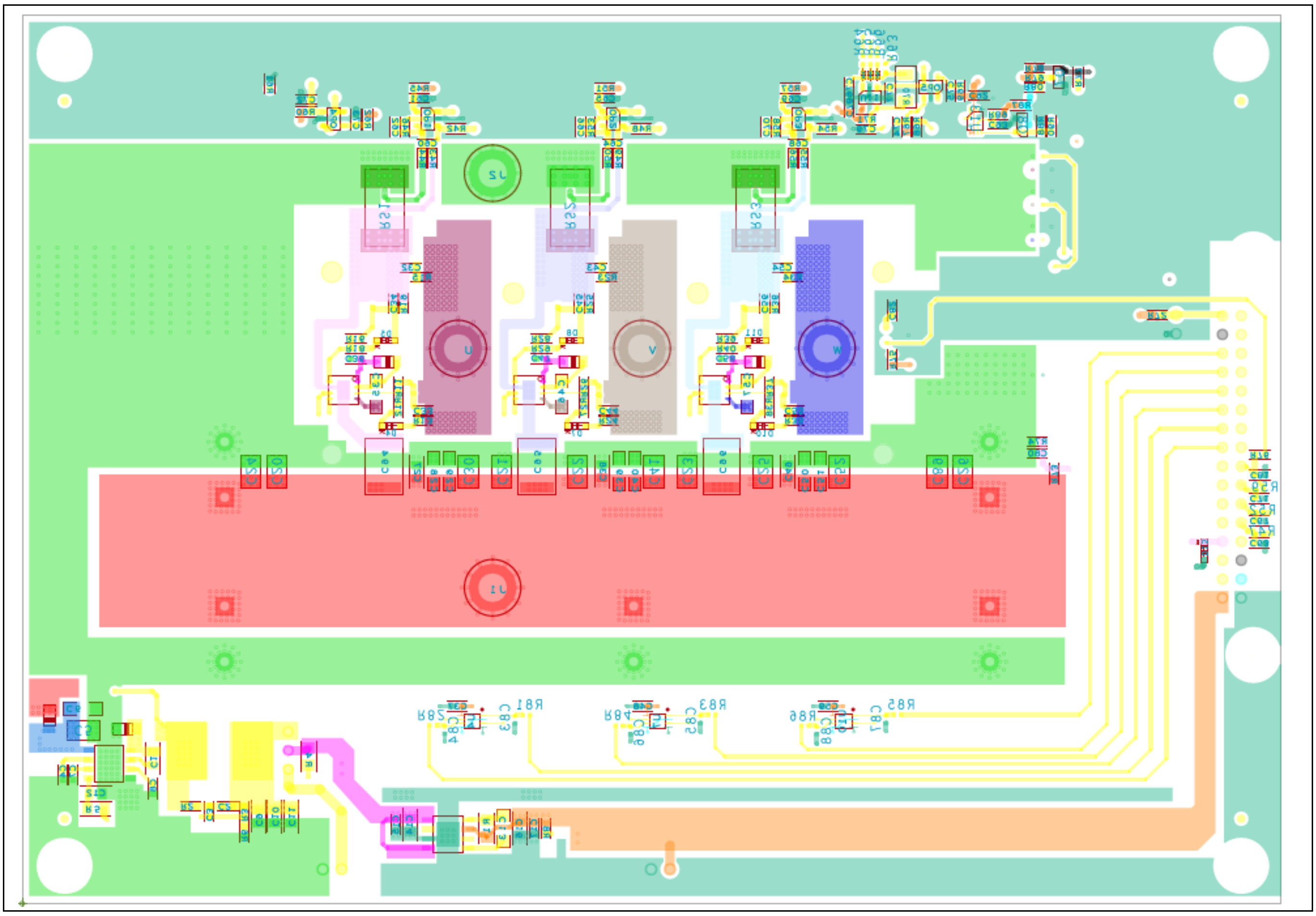


Figure 44 Bottom layer

5.3 Bill of materials

The complete bill of materials is available from the downloads section of the **Infineon website**. A login is required to download this material.

Table 6 BOM of the evaluation board EVAL_TOLT_DC36V_2KW

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
1	C1, C27, C38, C49	4	Capacitor	0.1 µF, 100 V, 10%, 0805, X7R	Kemet	C0805X104K1RAC3316
2	C2	1	Capacitor	4700 pF, 100 V, 10%, 0603, X7R	Kemet	C0603Y472K1RACAUTO
3	C3	1	Capacitor	0.22 µF, 25 V, 5%, 0603, X7R	Kemet	C0603X224J3RACAUTO
4	C4	1	Capacitor	100 nF, 50 V, 10%, 0603, X7R	Kemet	C0603C104K5RAC7082
5	C5	1	Capacitor	4.7 µF, 100 V, 10%, 1210, X7R	TDK	CNA6P1X7R2A475K250AE
6	C6	1	Capacitor	0.1 µF, 100 V, 10%, 1206, X7R	Kemet	C1206F104K1RAC3083
7	C7	1	Capacitor	10 pF, 50 V, 10%, 0603, X7R	Kemet	C0603C100K5RAC7867
8	C8, C60, C62, C63, C64, C66, C67, C68, C70, C71, C77, C79	12	Capacitor	100 pF, 25 V, 10%, 0603, X7R	Kemet	C0603C101K3RAC7867
9	C9	1	Capacitor	4.7 µF, 25 V, 10%, 0805, X7R	Kemet	C0805X475K3RAC7800
10	C10, C11	2	Capacitor	22 µF, 10 V, 20%, 0805, X7S	Kemet	C2012X7S1A226M125AC
11	C12	1	Capacitor	680 pF, 50 V, 5%, 0805, X7R	Kemet	C0805C681J5RAC7800
12	C13	1	Capacitor	0.01 µF, 25V, 5%, 1206, X7R	Kemet	C1206C103J3RACAUTO
13	C14, C16	2	Capacitor	10 µF, 25 V, 20%, 0805, X5R	Kemet	C0805C106M3PAC7800
14	C15, C17, C37, C48, C59, C61, C65, C69, C73, C75,	13	Capacitor	0.1 µF, 25 V, 20%, 0603, X7R	Kemet	C0603X104M3RAC7867

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
	C78, C80, C92					
15	C18, C19, C97, C98, C99	5	Capacitor	1000 µF, 63 V, 20%, RADIAL	United Chemi-Con	EKZE630ELL102MLP1S
16	C20, C21, C22, C23, C24, C25, C26, C89	8	Capacitor	2.2 µF, 100 V, 10%, 1210, X7R	Kemet	C1210C225K1RACAUTO
17	C28, C29, C39, C40, C50, C51	6	Capacitor	2.2 µF, 100 V, 10%, 1206, X7S	Murata	GCM31CC72A225KE02L
18	C30, C41, C52	3	Capacitor	10 µF, 100 V, 10%, 1210, X7S	Samsing Electro-Mechanics	CL32Y106KCVZNWE
19	C31, C32, C42, C43, C53, C54	6	Capacitor	0.047 µF, 100 V, 10%, 0603, X7R	Kemet	C0603X473J1REC7411
20	C34, C45, C56	3	Capacitor	4700 pF, 25 V, 10%, 0603, X7R	Kemet	C0603C472K3RAC7867
21	C35, C46, C57	3	Capacitor	1 µF, 50 V, 5%, 1206, X7R	Kemet	C1206C105J5RAC7800
22	C36, C47, C58	3	Capacitor	10 µF, 25 V, 20%, 0603, X5R	Murata	GRM188R61E106MA73J
23	C72, C74, C81, C82, C93	5	Capacitor	1 µF, 25 V, 10%, 0603, X7R	Kemet	C0603C105K3RAC7411
24	C76	1	Capacitor	1 nF, 25 V, 10%, 0603, X7R	Murata Electronics	GCJ188R71E102KA01D
25	C83, C84, C85, C86, C87, C88	6	Capacitor	100 pF, 25 V, 10%, 0402, X7R	Kemet	C0402C101K3RAC7867
26	C94, C95, C96	3	Capacitor	4.7 µF, 100 V, 10%, 2220, X7R	AVX	22201C475KAT2A
27	D1, D2	2	Diode Schottky	100 V, 2 A, SOD-123FA	onsemi	S210FA
28	D3, D6, D9	3	Diode Schottky	150 V, 2 A, SOD-123FL	Micro Commercial Co	SMD2150PL-TP
29	D4, D5, D7, D8, D10, D11	6	Diode Schottky	40 V, 750 mA, SOD-323	Infineon Technologies	BAT165E6327HTSA1
30	D12, D13, D14	3	Diode Schottky	30 V, 500 mA, SOD-882D	Nexperia USA Inc.	PMEG3005ELD,315
31	D15	1	Diode Zener	5.1 V, 300 mW, SOD-323	Nexperia USA Inc.	BZX384-B5V1,115

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
32	G1	1	IC	IC REG LIN ,5 V, 500 mA, 8DSO E-PAD	Infineon Technologies	TLS205B0EJV50XUMA1
33	H1	1	Heatsink	Heatsink 81.5 x 46.8 mm	Advanced Thermal Solutions Inc.	ATS-EXL110-300-R0
34	J3	1	Connector	CONN HEADER VERT 3POS 2.54 mm	Samtec	TSW-103-08-L-S-LA
35	J4, J5	2	Connector	TERM BLK 2P SIDE ENT 2.54 mm PCB	Phoenix Contact	1725656
36	J12	1	Connector	CONN HEADER VERT 2POS 2.54 mm	Samtec	TSW-102-08-LS
37	L1	1	Inductor	FIXED IND 470 µH 1.4 A 560 MΩ SMD	Würth Elektronik	7447709471
38	LED1, LED2, LED3	3	LED	LED GREEN CLEAR 0603	Lite-On Inc.	LTST-C190KGKT
39	LED4	1	LED	LED RED CLEAR 0603	Lite-On Inc.	LTST-C190KRKT
40	OP1, OP2, OP3, OP4, OP5	5	IC	IC OPAMP GP 10 MHz RRO SOT23-5	Analog Devices	AD8615AUJZ-REEL7
41	POT1, POT2	1	Potentiometer	TRIMMER, 50k Ω, 0.25 W, J LEAD TOP	Nidec Copal Electronics	SM42TW503
42	Q1, Q2, Q3, Q4, Q5, Q6	6	MOSFET	N-Channel, 60 V, 454 A, TOLT	Infineon Technologies	IPTC007N06NM5
43	Q7, Q8	2	MOSFET	N-Channel, 30 V, 3.4 A, SOT-23	Infineon Technologies	IRLML6346TRPBF
44	Q9	1	Transistor	PNP, 100 V, 1 A, SOT23-3	Diodes Incorporated	FMMT723QTA
45	R1	1	Resistor	0, 0.4 W, 0805	Vishay Dale	RCS08050000Z0EA
46	R2	1	Resistor	47 k, 0.25 W, 1%, 0603	Vishay Dale	RCS060347K0FKEA
47	R3	1	Resistor	33 k, 0.25 W, 1%, 0603	Panasonic Electronic Components	ERJ-PA3F3302V
48	R4	1	Resistor	1 k, 0.5 W, 1%, 0805	Vishay Dale	RCA08051K00FKEAHP
49	R5	1	Resistor	1.5 k, 0.5 W, 5%, 0805	Vishay Dale	CRCW08051K50JNEAHP
50	R6	1	Resistor	1.3 k, 0.1 W, 1%, 0603	YAGEO	RC0603JR-071K3L
51	R7, R80	2	Resistor	0, 0.25 W, 0603	Vishay Dale	RCS06030000Z0EA
52	R8	1	Resistor	680, 0.25 W, 1%, 0603	Vishay Dale	RCS0603680RFKEA

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
53	R10, R15, R22, R23, R33, R34	6	Resistor	1.2, 0.1 W, 5%, 0603	Vishay Dale	CRCW0603 1R20JNEAI F
54	R11, R26, R37	3	Resistor	56, 0.1 W, 5%, 0603	YAGEO	RC0603JR-0756RL
55	R12, R27, R38	3	Resistor	20, 0.1 W, 5%, 0603	YAGEO	RC0603JR-0720RL
56	R13, R19, R24, R25, R35, R36, R73	7	Resistor	100 k, 0.25 W, 1%, 0603	Vishay Dale	RCA060310 0KFKEAHP
57	R14, R20, R31	3	Resistor	130 k, 0.25 W, 1%, 0603	Vishay Dale	CRCW0603 130KFKEA C
58	R16, R18, R28, R29, R39, R40	6	Resistor	30, 0.1 W, 5%, 0603	YAGEO	RC0603JR-0730RL
59	R17, R21, R32	3	Resistor	5.1 k, 0.3 W, 1%, 0603	Panasonic Electronic Components	ERJ-PA3F5101V
60	R42, R46, R48, R53, R54, R58	6	Resistor	12 k, 0.125 W, 0.1%, 0603	Panasonic Electronic Components	ERA-3VEB1202V
61	R43, R44, R49, R50, R55, R56	6	Resistor	1 k, 0.125 W, 0.1%, 0603	Vishay	MCT0603M D1001BP10 0
62	R45, R51, R57, R62, R69	5	Resistor	10, 0.25 W, 5%, 0603	Panasonic Electronic Components	ERJ-PA3J100V
63	R47, R52, R59, R81, R82, R83, R84, R85, R86	9	Resistor	10, 0.125 W, 1%, 0402	TE Connectivity Passive Product	CRGP0402 F10R
64	R60	1	Resistor	22 k, 0.25 W, 1%, 0603	Panasonic Electronic Components	ERJ-PA3F2202V
65	R61, R67, R68, R71	4	Resistor	1 k, 0.25 W, 1%, 0603	Panasonic Electronic Components	ERJ-UP3F1001V
66	R63	1	Resistor	10 k, 0.063 W, 1%, 0402	Delta Electronics/Cyntec	PFR05S-103-FNH
67	R64, R65, R66	3	Resistor	0, 1/10 W, 0402	Panasonic Electronic Components	ERJ-2GE0R00X

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
68	R70	1	Resistor	1 M, 0.25 W, 0.1%, 1206	Bourns Inc.	CRT1206-BY-1004ELF
69	R72, R78, R79, R87, R88	5	Resistor	10 k, 0.25 W, 1%, 0603	Panasonic Electronic Components	ERJ-UP3F1002V
70	R74	1	Resistor	7.87 k, 0.1 W, 1%, 0603	Panasonic Electronic Components	ERJ-3EKF7871V
71	R75	1	Resistor	200, 0.3 W, 1%, 0603	Panasonic Electronic Components	ERJ-PA3F2000V
72	R76	1	Resistor	100, 0.25 W, 1%, 0603	TE Connectivity Passive Product	CRGP0603 F100R
73	R77, R90	2	Resistor	330, 0.25 W, 1%, 0603	Vishay Dale	RCS060333 0RFKEA
74	R89	1	Resistor	20 k, 0.25 W, 5%, 0603	Vishay Dale	RCS060320 K0JNEA
75	R91	1	Resistor	1, 0.75 W, 1%, 1206	YAGEO	SR1206FR-7T1RL
76	R92	1	Resistor	2.7 k, 5%, 0.75 W, 1206	Vishay Dale	CRCW1206 2K70JNEA HP
77	RS1, RS2, RS3	3	Current Sense	0.001, 5 W, 1%, 3920	Stackpole Electronics Inc	HCS3920F T1L00
78	RT1	1	Temperature Sensor	SENSOR ANALOG -40C-125C SOT23-3	Microchip	MCP9700A T-E/TT
79	U1	1	IC	LED Driver IC 1 Output DC DC Regulator Step-Down (Buck) PWM Dimming 1.5 A PG-DSO-8-27	Infineon Technologies	ILD8150EX UMA1
80	U3, U6, U9	3	IC	High-Side and Low-Side Gate Driver IC Non-Inverting PG-VDSON-8-4	Infineon Technologies	2EDL8124G XUMA1
81	U4, U7, U10	3	IC	IC GATE AND 2CH 2-INP US8	On Semiconductor	NLV27WZ0 8USG
82	U11	1	IC	IC COMPARATOR TINY LV SOT23-5	Texas Instrument	LMV331M5
83	U12	1	IC	CONN DIN RCPT 32POS PCB RA GOLD	Hirose Electric Co LTD	PCN10C-32S-2.54DS(72)
84	U13	1	IC	IC FF D-TYPE SNGL 1BIT 8VSSOP	Texas Instrument	SN74LVC2 G74MDCUT EP

Item	Part references	Quantity	Type	Value/rating/tolerance/ package/other	Manufacturer	Part number
85	-	1	Thermal Pad	Thermal Pad 457.20 mm x 457.20 mm Pink	Laird Technologies - Thermal Materials	A17536-02

References

[1] Infineon Technologies AG: *MOSFET OptiMOS™ 5 Power-Transistor,60 V (IPTC007N06NM5) datasheet*; **Available online**

[2] Infineon Technologies AG: *IRLML6346TRPBF datasheet*; **Available online**

[3] Infineon Technologies AG: *EiceDRIVER™ 2EDL8x2x datasheet*; **Available online**

[4] Infineon Technologies AG: *ILD8150/ILD8150E LED driver IC for high power LEDs with hybrid dimming down to 0.5% datasheet*; **Available online**

[5] Infineon Technologies AG: *Motor Control Application Kit For XMC1000 Family (KIT_XMC1300_DC_V1) Board User's Manual*; **Available online**

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V 1.0	2023-05-05	Initial release

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