Power Tools

ME/MF DirectFET™ Kit

About this document

This application note presents the description of the Infineon's demo board for cordless power tools. The current design considers the electrical driving capabilities for brushless DC (BLDC) machines with three hall sensors used for rotor position detection and speed measurement. This board utilises the ME/MF DirectFET^{TM} power devices (IRF7480/IRF7483) and the firmware is developed using the XMC^{TM}1300 family (www.infineon.com/XMC).

The source code, available in the package, is completely implemented using the Infineon Eclipse-based IDE, DAVE^{TM} (Development Platform for XMC^{TM} Microcontroller) (www.infineon.com/DAVE). The control method implements a scalar speed control algorithm based on the brushless DC motor (BLDC) using pulse-width modulation (PWM) and three hall sensors.

With this kit, users can evaluate the properties of the low $R_{DS(ON)}$ low voltage Infineon DirectFET^{TM} using the control capabilities of the XMC^{TM}1300 by means of the implemented control algorithm BLDC_SCALAR_HALL_XMC13 with customised features for power tools application.

Scope and purpose

This document intends to describe the functionalities of the Power Tools DirectFET^{TM} ME/MF Kit for motor control applications, more specifically for cordless BLDC drives in battery powered power tools when three hall sensors are available for speed and rotor position sensing. Together with the Infineon DirectFET^{TM} low $R_{DS(ON)}$ low voltage MOSFETs, such solution can help reduce system cost and time to market while at the same time significantly increase the power density, system performance and peak power pulse capabilities.

Intended audience

This document addresses the market for cordless power tool manufactures who intend to provide to a high performance system solution as well as reduce the system costs.

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1 Power Tools ME/MF [1] DirectFET^{TM} Kit

1.1 Overview

The "Power Tools ME/MF DirectFET™ Kit" is a complete solution from Infineon for the battery powered low voltage BLDC power tools motor drives. The digital controller of the power drive is based on the Infineon XMCTM1300 family (Infineon Technologies AG, 2014) (Infineon Technologies AG, 2014) and is implemented in the Infineon motor control drive kit KIT_XMC1300_DC_V1 (Infineon Technologies AG, 2013). Standard power board connector is used to plug in the XMCTM1300 Drive Card controller board as the platform to run the control software. Both, power board and controller board (drive card) are necessary for the application. The power board and drive card are interfaced using a single connector (PCN10C-32S-2) as depicted in Figure 1.
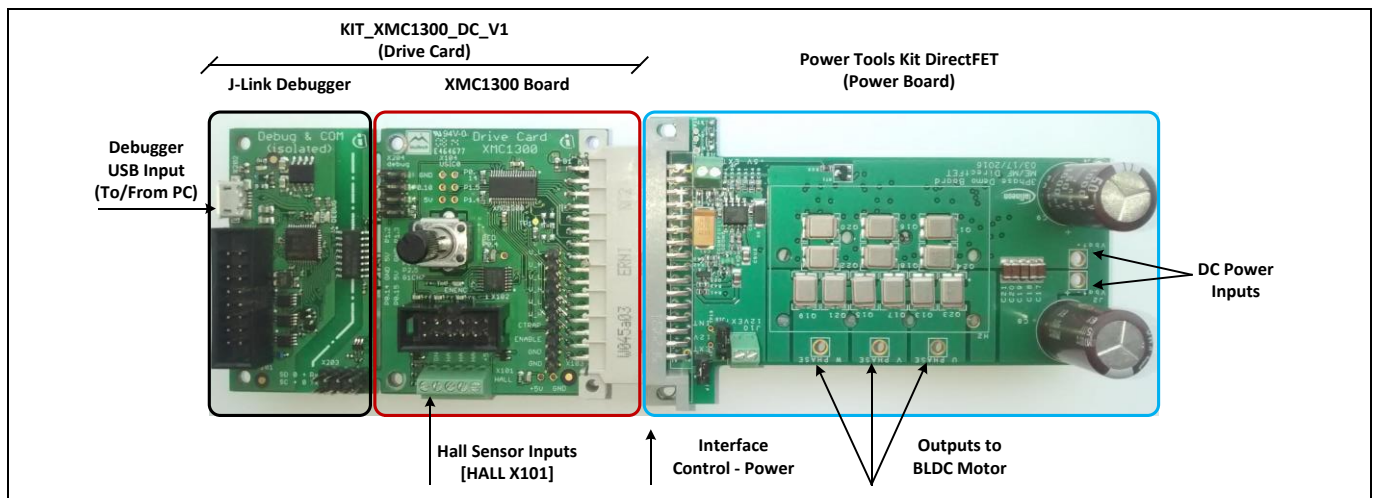

Figure 1 Power board (Power Tools Kit DirectFET™) and control board (KIT_XMC1300_DC_V1) system interface

The power board provides on board 5.0 V and 12.0 V power supplies for microcontroller and gate driver ICs, respectively. However, the option of using external power supplies is also considered. It also provides overcurrent and over-temperature protections. A single shunt is used to measure the current in the path of three legs of the inverter going to ground. Overcurrent threshold level can be changed through hardware by changing the values of some resistors. However, over-temperature threshold level can be changed only through software.The hall sensors are connected directly to the XMCTM microcontroller board via connector X101, as shown in Figure 1. The pin-out description of this connector is described in Table 1.

Table 1 HALL sensor interface [HALL X101]

Pin	Port	Peripheral
1	GND	VSS, VSSP
2	P1.0	POSIF0.IN2A
3	P1.1	POSIF0.IN1B
4	P0.13	POSIF0.IN0B
5	VDD (+5V)	HALL sensor power supply

The interface between the XMC control board and the power board is performed via connector MAB32B2 from the XMC control board side, and the connector U9 from the inverter power board side. The pin-out is provided in Table 2.

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[1] ME refers to Medium size can (MCAN) DirectFET^{TM}, E-Designation with 5 Source pads while MF refers to MCAN DirectFET^{TM}, F-Designation with 3 Source pads.

Table 2 Power board connector pin-map

X302 MAB32B2[1]	U9 FAB32Q2[1]	Function on Power Inverter	Port	Peripherals	
A1	A16	GND	VSS, VSSP		
A2	A15	SD (Shutdown)	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	-	P2.9	VADC0.G0CH2	VADC0.G1CH4
A6	A11	SD (Shutdown)	P2.10	VADC0.G0CH3	VADC0.G1CH2
A7	A10	$\overline{DR-EN}$	P2.11	VADC0.G0CH4	VADC0.G1CH3
A8	A9	T-Sense	P2.1	VADC0.G0CH6	
A9	A8	-	-		
A10	A7	-	-		
A11	A6	-	-		
A12	A5	-	-		
A13	A4	-	-		
A14	A3	-	-		
A15	A2	-	-		
A16	A1	-	-		
B1	B16	VDD (+5V)	VDD, VDDP		
B2	B15	-	-		
B3	B14	-	-		
B4	B13	V-BAT	P2.3		VADC0.G1CH5
B5	B12	V_{EMF_U}	P2.6	VADC0.G0CH0	
B6	B11	V_{EMF_V}	P2.8	VADC0.G0CH1	VADC0.G1CH0
B7	B10	V_{EMF_W}	P2.0	VADC0.G0CH5	
B8	B9	Current_Amp_OUT	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 & P0.3	CCU80.OUT21	CCU80.OUT03
B14	B3	W-H	P0.8 & P0.2	CCU80.OUT20	CCU80.OUT02
B15	B2	-	P0.12	CCU80.IN0A, IN1A, IN2A, IN3A	
B16	B1	Direction Switch	P0.11		

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[1] The numbering of pins in the power board connector is reversed with respect to the numbering in the control board.

1.1.1 Key Features

The capabilities of the "Power Tools ME/MF DirectFET^{TM} Kit" for cordless battery powered application are as follows:

- ME/MF layouts for MCAN DirectFET^{TM}, two MOSFETs in parallel at each leg of the inverter
- Standard power board connector to plug in the XMC^{TM}1300
- 20.0 V nominal input voltage
- 6.0 V to 40.0 V input voltage range
- 50.0 A_{Peak} and 35 A_{RMS} phase current for continuous operation
- 200.0 A_{Peak} current for 100.0 ms
- Latched shut down overcurrent protection through one shunt amplifier
- Over-temperature protection with programmable threshold level
- 5.0 V and 12.0 V on board power supplies for microcontroller and gate drivers, respectively
- External power supply options for microcontroller and power MOSFETs gate drivers
- Die temperature measurement through openings on bottom side of the PCB
- Block commutation modulation method with three hall sensors or back EMF
- Scalar BLDC motor speed control with three hall sensors for speed monitoring based on the BLDC_SCALAR_HALL_XMC13 with improved features for the specific application in cordless power tools
- Configurable modulation schemes (high-side modulation with or without synchronous rectification) for efficiency improvement evaluation
- Flexible user configuration capabilities by means of DAVE^{TM} (Version 4)
- Hall pattern learning by detecting the hall and phase excitation patterns during start-up
- Overcurrent protection (adjustable by hardware)
- Over-temperature protection (adjustable by software)
- Wrong hall pattern protection
- Serial interface via USB connection for monitoring of motor variables and parameters using Infineon µCProbe

1.2 System Block Diagram

Block diagram of the three-phase demo board is shown in Figure 2. In the demo board, at each leg, two MCAN (Medium Size Can) DirectFET^{TM}s with ME package (IRF7480) are used in parallel. However, for less power usage, single MOSFET can be populated at each leg or MF package DirectFET^{TM}s (IRF7483) with lower number of source pads can be used.

A buck converter is used to create a 5.0 V supply for analogue and digital circuits on the board and also for powering the XMC drive card via the power board connector. However, by changing the position of jumper J13 to "Ext.", an external 5.0 V power supply can be used, instead. A boost converter is used to create a 12.0 V supply for the gate drivers. An external gate driver voltage can be used if the position of J15 is changed to "Ext." (Figure 2).
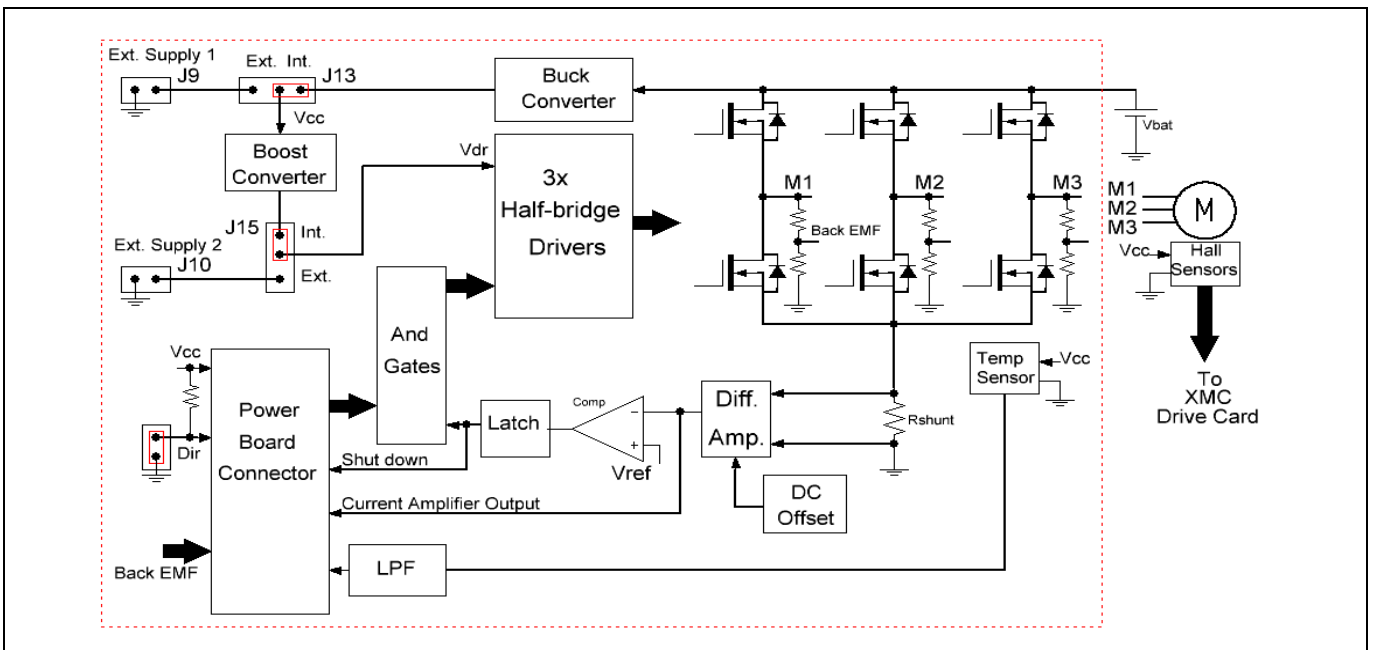

Figure 2   Block diagram of the 3 phase demo board

Overcurrent protection is achieved by using a shunt in the ground path for the low-side FETs. The output of the current amplifier is also supplied to the XMC drive card. Over-temperature protection is provided by a sensor on the PCB. Temperature voltage is provided to the XMC drive card after passing through a low-pass RC filter.

Back EMF signals are provided to the XMC drive card through voltage dividers. The hall sensor signals are connected directly to the XMC drive card.

1.3 Hardware Description

Different circuit sections on the demo board (power board side) are shown in Figure 3 and Figure 4. An aluminium heatsink is attached on top of the DirectFET^{TM}s. Sil-Pad, a thermally conductive insulator is used between the heatsink and DirectFET^{TM}s. Some openings are made on the PCB to facilitate the measurement of the die temperature of DirectFET^{TM}s using an infrared thermal camera.
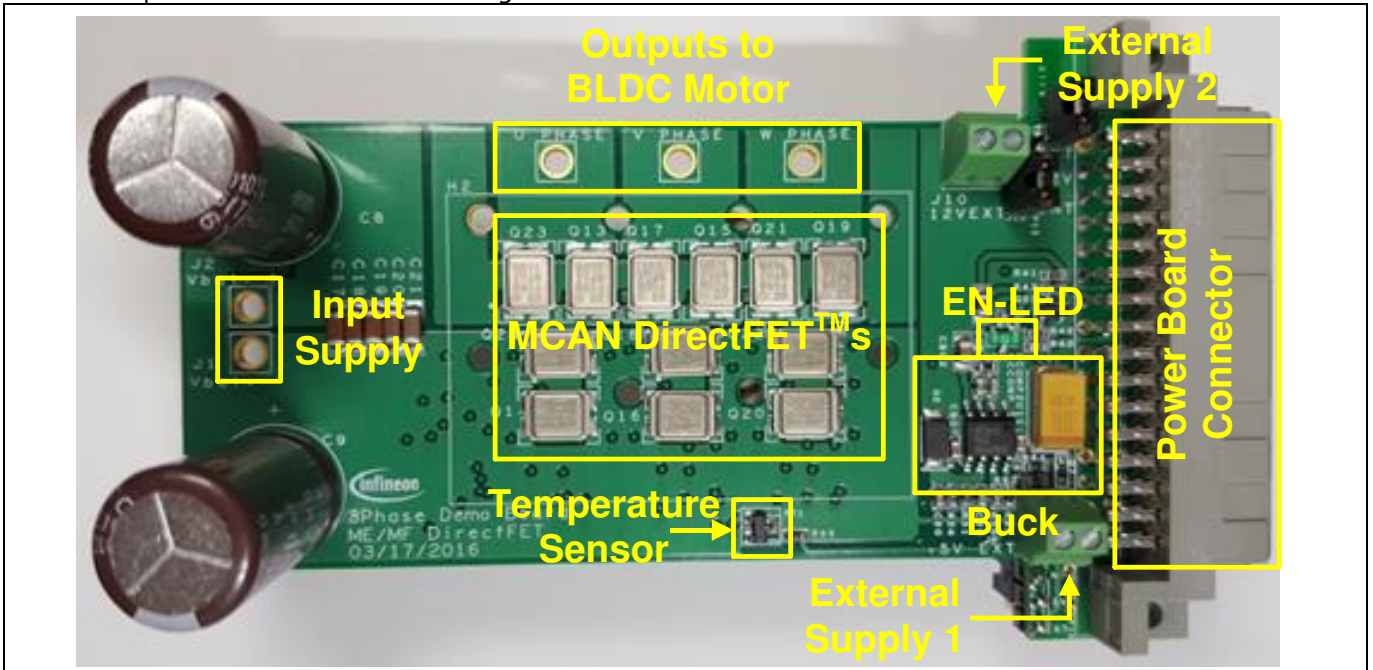

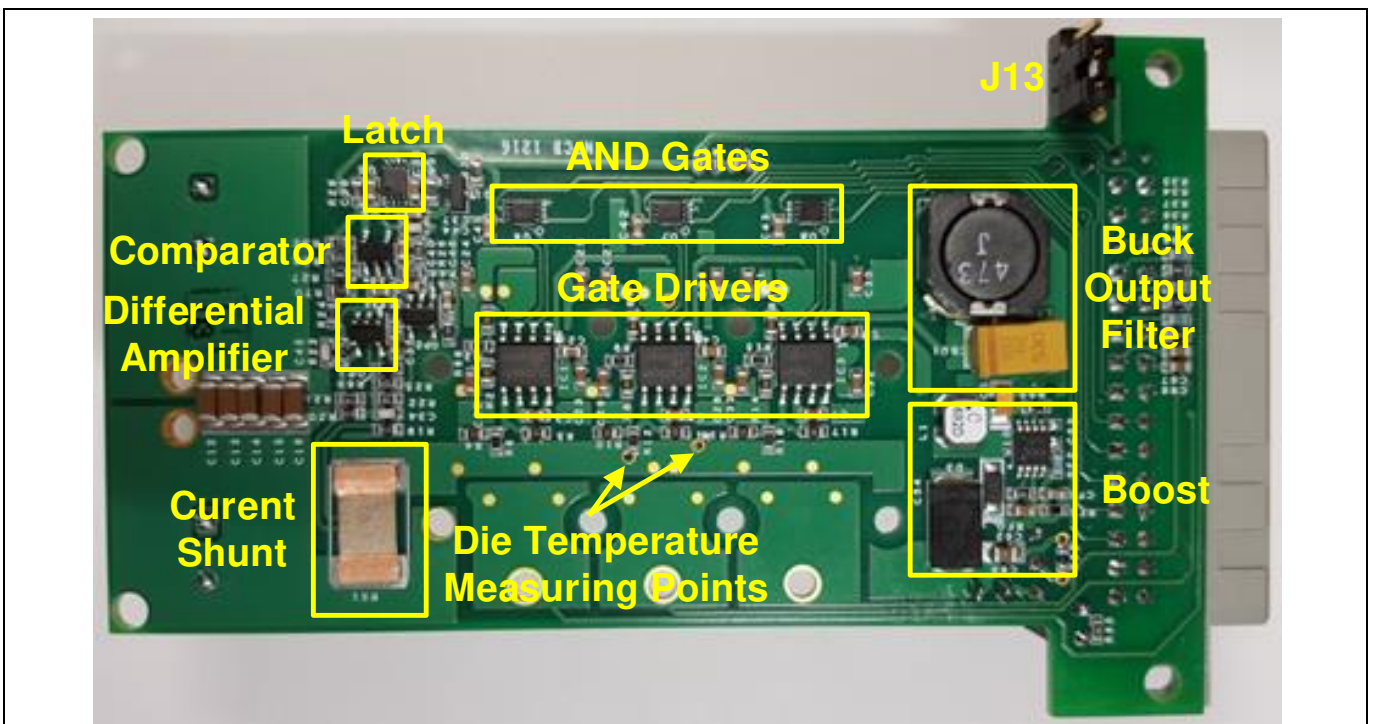Figure 3   Different hardware sections shown on the demo board (top side)

Figure 4   Different hardware sections shown on the demo board (bottom side)

1.3.1 Power Supplies

In cordless power tool applications, battery voltage can drop to half of its nominal value under load. For nominal battery voltages higher than 18.0 V, using a linear voltage regulator to provide the microcontroller voltage would create considerable losses. This is why two DC-DC converters are needed: a buck converter to provide a 3.3 V or 5.0 V for microcontroller and a boost converter to provide the gate driver voltage (12.0 V). These converters are shown in Figure 5.
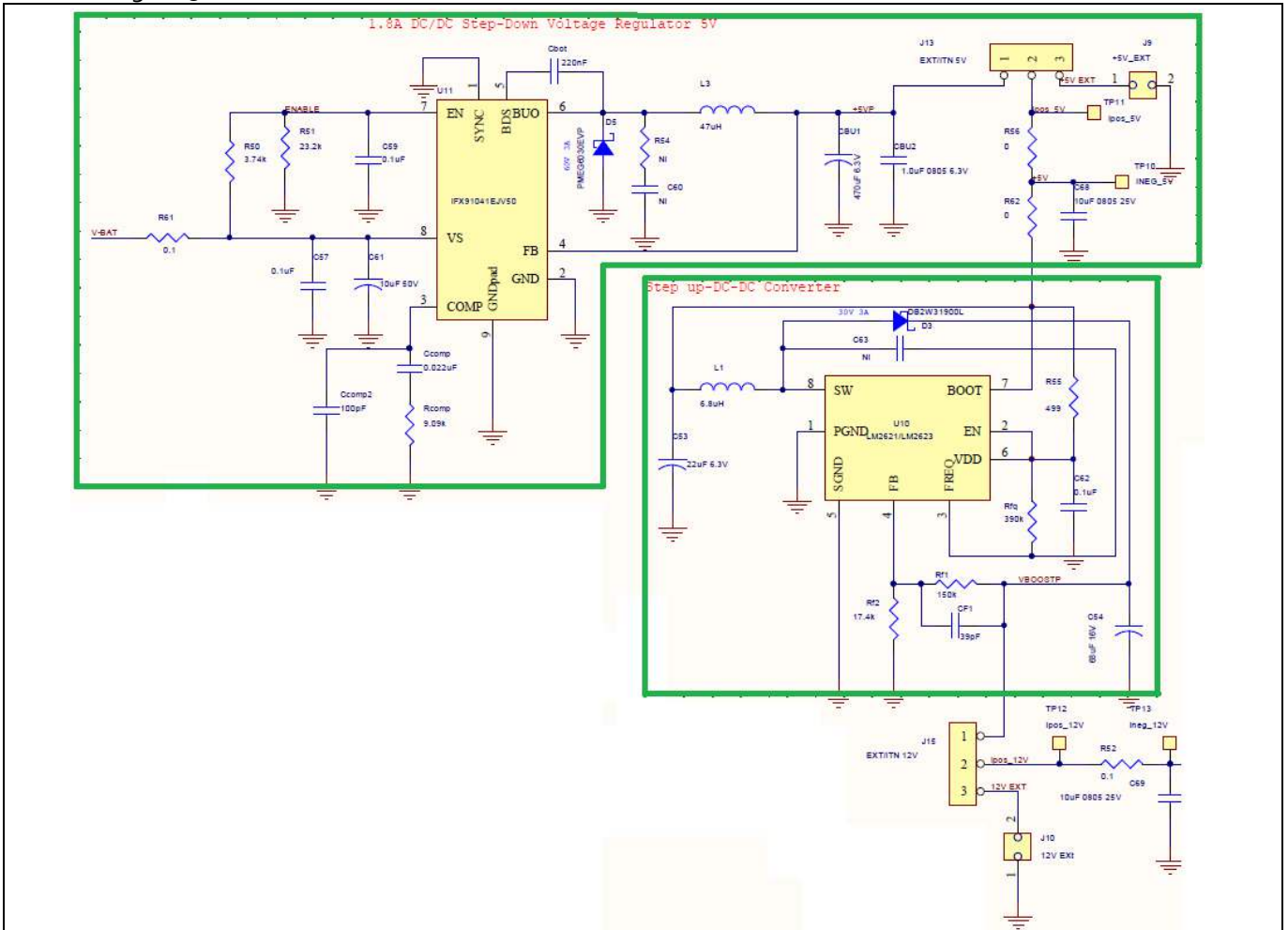

Figure 5   Buck and boost converters used in the demo board

Infineon's IFX91041 series buck converters are capable of driving up to 1.8 A load current. There are fixed 5.0 V, 3.3 V and also an adjustable output voltage version for this family of devices. The fixed 5.0 V output version (IFX91041EJV50) has been used in this demo board. However, the 3.3 V version is pin compatible and can easily be used instead to provide 3.3 V in case it is needed.

An external power supply can be used instead of the buck converter to provide the voltage for the microcontroller. As shown in Figure 5, a jumper in J13 is used to choose between internal or external options. J9 is the connector bringing the external power supply to the demo board.

There is a boost converter (LM2621) on the board to provide the 12.0 V required for the MOSFET gate driver ICs. Boost switching frequency is set at 1.0 MHz, in a hysteresis mode, which allows using a 6.8μH inductor in the circuit. However, the option of using an external power supply instead of the boost converter is also considered in this demo board. The jumper in J15 should be changed to "EXT" position to short pins 2 and 3 in order to use the external power supply. In this case, the external power supply should be connected to J10 as the gate driver voltage.

All possible combinations are shown in Table 3. The "EXT" and "INT" positions for J13 and J15 are shown by labels on the board. V_J9 and V_J10 are the external supply voltages provided by connectors J9 and J10, respectively.

Table 3   Different Combinations for J13 and J15

J13	J15	V_{CC}	V_{DR}
INT (Default)	INT (Default)	5.0 V	12.0 V
INT	EXT	5.0 V	V_J10
EXT	INT	V_J9	12.0 V
EXT	EXT	V_J9	V_J10

Test points TP10 and TP11 are considered for measuring current drawn from the 5.0 V (internal or external) power supply. TP12 and TP13 are for the same purpose for the 12.0 V supply.

1.3.2   Overcurrent Protection

Overcurrent protection circuit is shown in Figure 6 and Figure 7. CS+ and CS- are the Kelvin points from the 1.0 mΩ shunt in the ground path for the low-side MOSFETs as shown in Figure 2. OP1 is a differential amplifier with the gain set at about 10.0. OP2 is a buffer used to apply a DC offset of 1.0 V to the amplifier to consider the negative currents. Output of the differential amplifier OP1, after passing through a low-pass filter, is sent to the power board connector so that the microcontroller can have the current data. This data can be used for field oriented control (FOC) technique or digital protection purposes. However, on board overcurrent protection is realized by comparing the current signal with a reference voltage in U4. With the component values shown in Figure 7, V_{REF} is set at 1.8 V and considering the 1.0 V DC voltage offset and the gain of 10.0 for the amplifier the overcurrent trip level is set at 80.0 A.
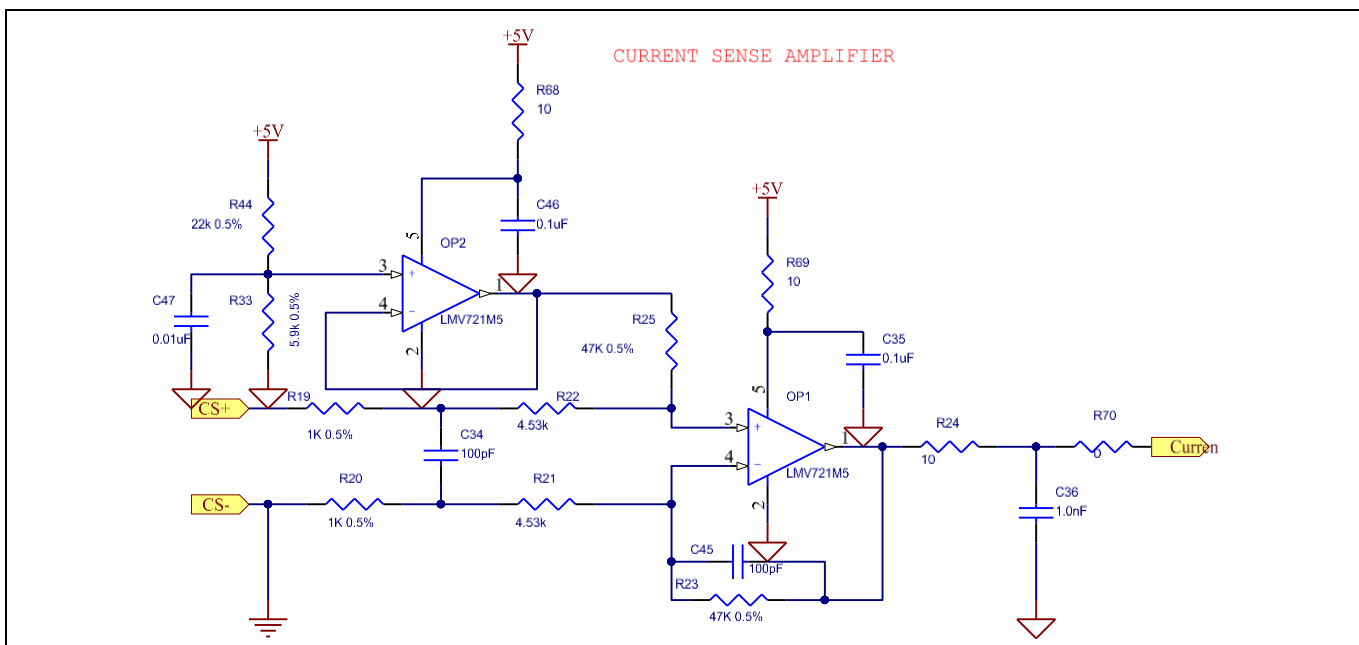
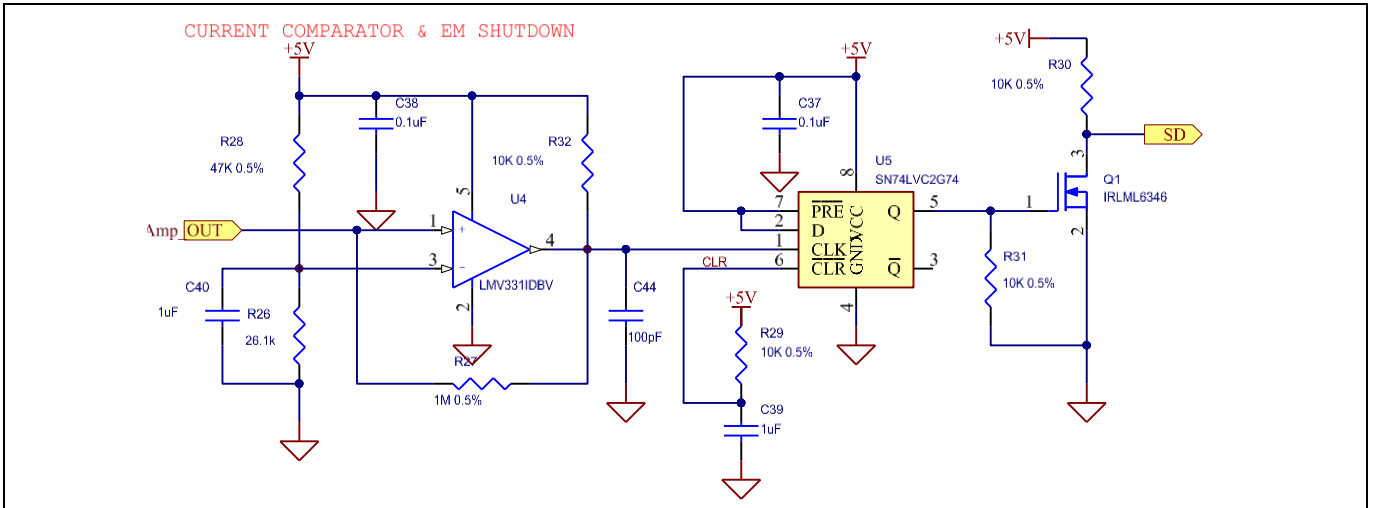Figure 6   Current sense operational amplifier

Figure 7   Current shutdown circuitry (SD)

In order to prevent from false tripping, C45 is added in parallel with R23 to introduce integration in the transfer function of the differential amplifier OP1. The gain of this amplifier is adjusted to be slightly higher than 10.0 so that the attenuation caused by the low-pass filter in the output (R24, C36 and R70) is compensated.

Output of the current amplifier is passed to the microcontroller via pin B9 of the power board connector, as shown in Figure 8.
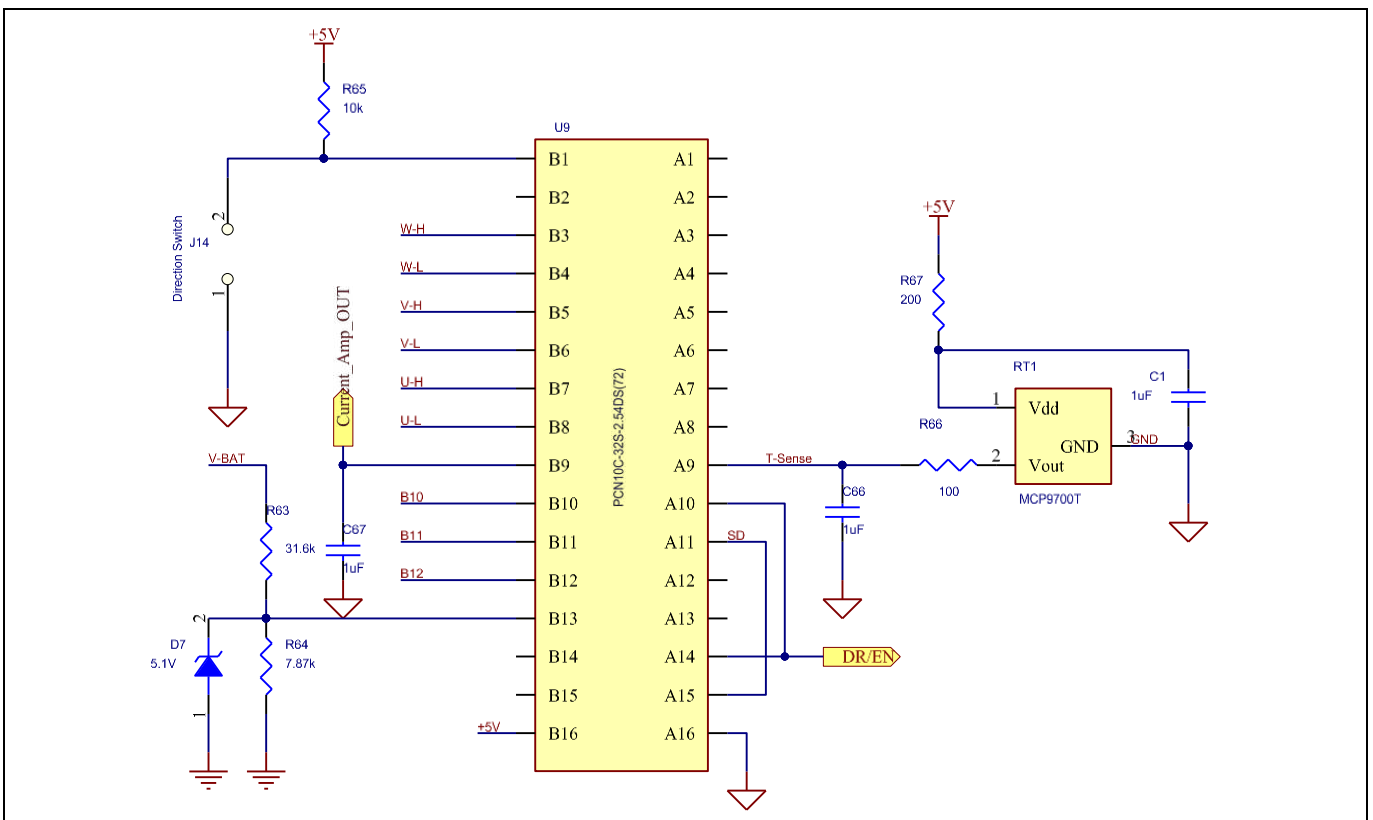

Figure 8   Power board connector

Overcurrent trip signal from comparator U4 is latched by a DFF (U5). This latched signal is inverted by Q1 to create the SD shutdown signal which is also passed to the microcontroller via pins A11 and A15, as shown in Figures 7 and 8. The reason

why 2 pins have been used for this signal is so that both XMC^{TM}1300 and XMC^{TM}4400 Drive Cards could be used with this demo board.

1.3.3 Over-Temperature Protection

MCP9700, an analogue temperature sensor, in an SOT-23 package is soldered on the PCB close to the heatsink to measure the temperature of the board as shown in Figure 3.

This sensor converts temperature to voltage with a 0.5 V offset at 0.0 °C and a 10.0 mV/°C temperature coefficient, as shown in Figure 9. In order to suppress the switching noise at the output of the sensor due to BLDC motor operation, low pass filters are used both in the V_{DD} and in the output path. Output voltage is connected to the microcontroller via pin A9 of the power board connector as shown in Figure 8.
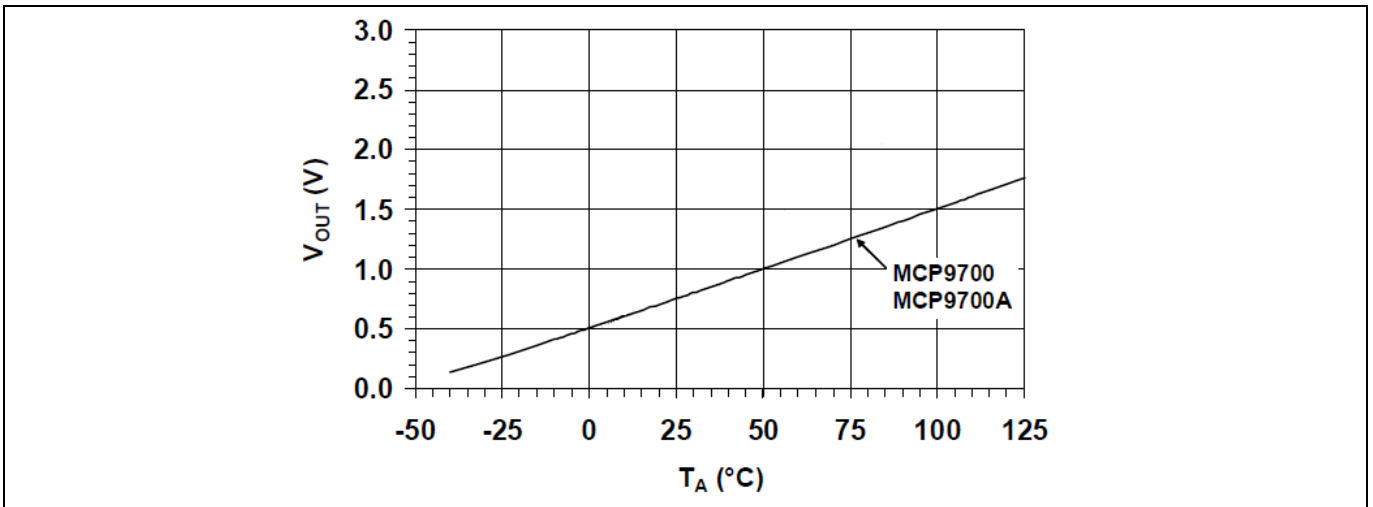

Figure 9   Output voltage vs. temperature for MCP9700

1.3.4 Gate Drivers

Infineon's 2EDL05N06PF half-bridge MOSFET gate driver IC has been used for each phase in this demo board. Gate driver circuit for phase U is shown in Figure 10. U-H and U-L are PWM control signals from the microcontroller for phase U high-side and low-side MOSFETs, respectively.
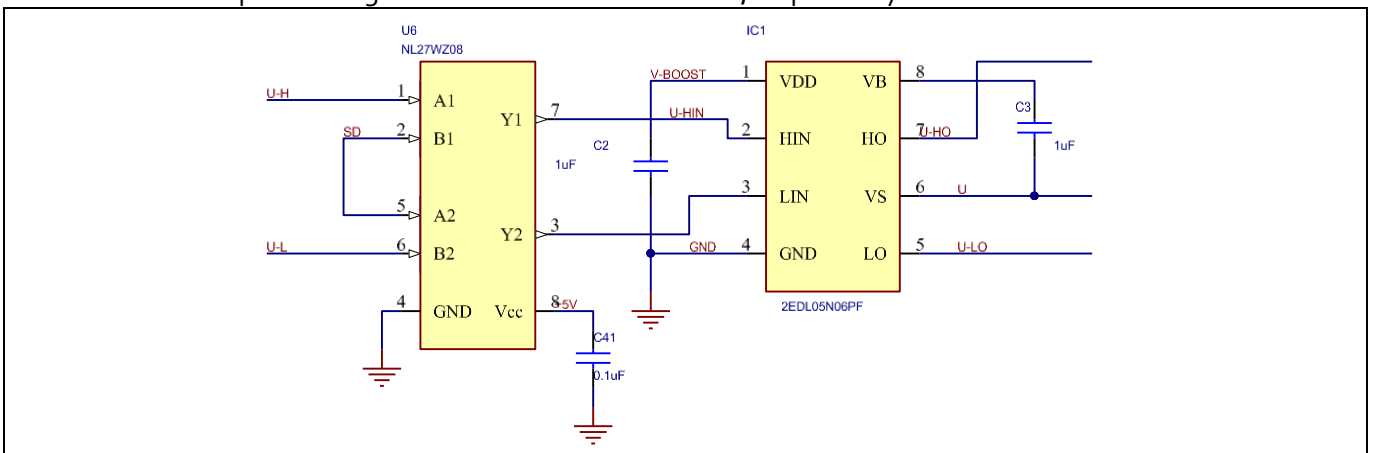

Figure 10   Gate driver circuit for each phase

During normal operation of the circuit, SD is high which allows the PWM signals (U-H and U-L for phase U) to pass through the gate driver. U-HO and U-LO are the outputs of the gate driver which are connected to gate resistors of high-side and low-side MOSFETs in phase U, respectively. SD signal is created in overcurrent protection circuit explained previously and shown in Figure 6 and Figure 7. However, the microcontroller also has control of this signal. There is a driver enable signal ($\overline{DR - EN}$) coming from the microcontroller via pin A10 (Figure 8) that can override the logic of SD signal to disable the gate drivers. In normal operation of the circuit, ($\overline{DR - EN}$) is low which turns on EN-LED D1 shown in Figure 11. The position of this LED is shown in Figure 3. So, in normal conditions, Q25 is off and SD signal is pulled up by R41, as shown in Figure 11.
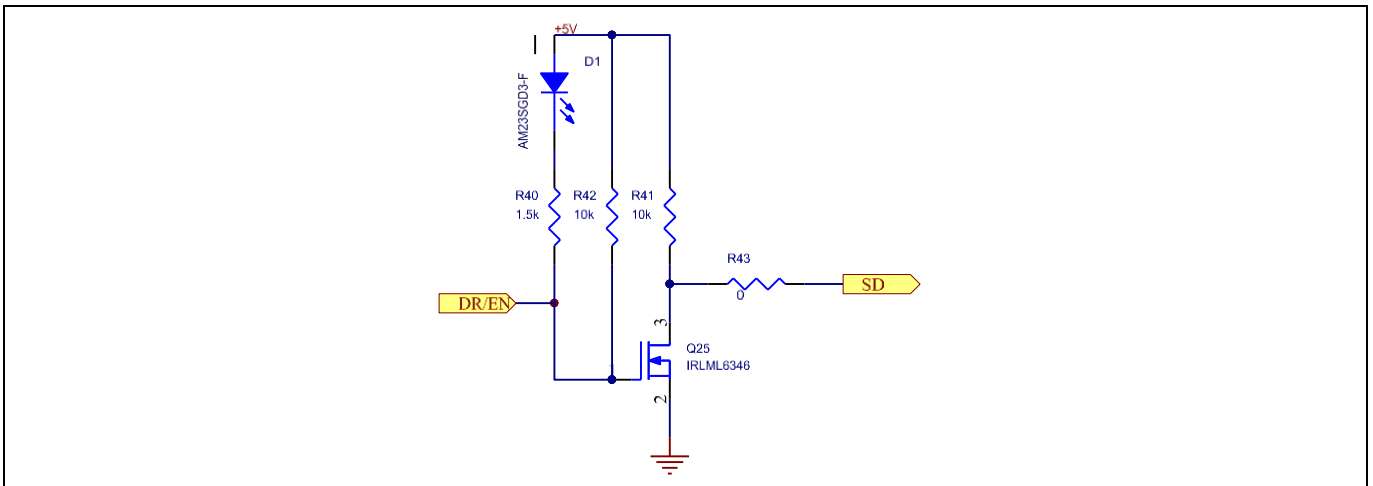

Figure 11   Drive-enable circuit

Whenever an overcurrent trip occurs or ($\overline{DR - EN}$) is set high by microcontroller, the shut-down signal SD goes low which turns off all the MOSFETs in the three phase inverter.

1.3.5   Heatsink and Gap Pad

One important advantage of DirectFET™s is the capability of top-side cooling using a heatsink. An aluminium heatsink from Alpha (UB45) has been customized for our power board. As shown in Figure 12, this heatsink can be ordered with different base thicknesses and fin heights.
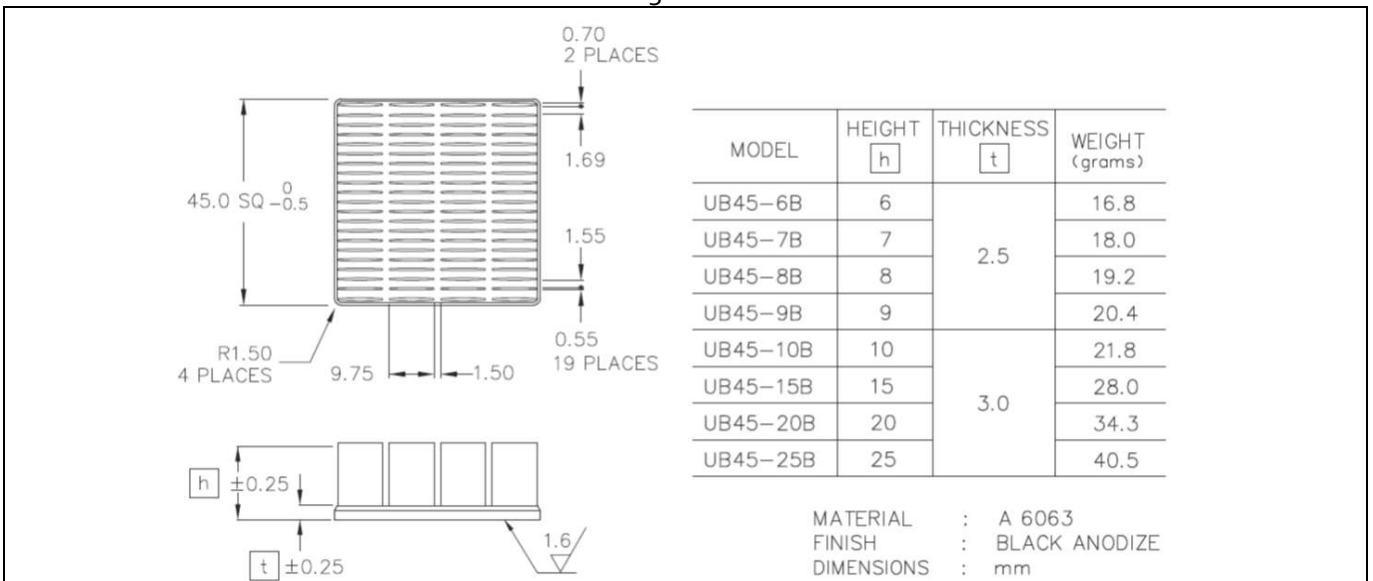

Figure 12   UB45 Aluminium heatsink series

Thermal resistance for UB45 series is shown in Figure 13 as a function of air flow.
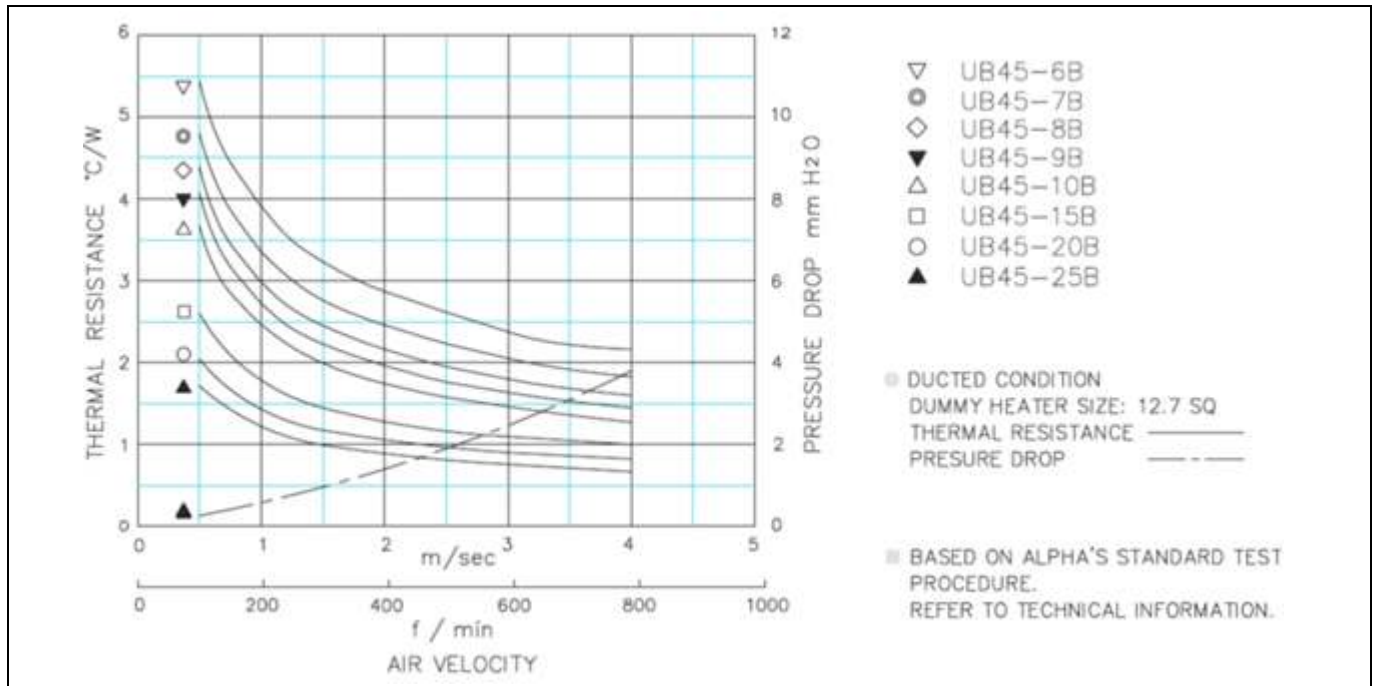

Figure 13   Thermal resistance for UB45 series heatsinks

The heatsink was with 3mm base thickness, 7mm height, 30mm width and added tapped holes, as shown in Figure 14.
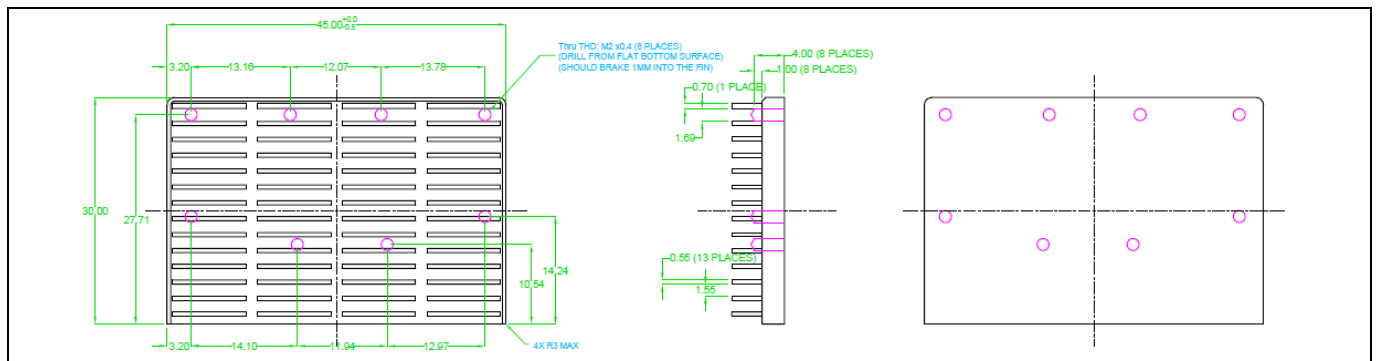

Figure 14   Customized UB45 aluminium heatsink

For electrical isolation between DirectFET™s and the heatsink, a Gap Pad (5000S35) with 0.5 mm (20.0 mils) thickness is used. Typical properties of this Gap Pad are shown in Figure 15.

TYPICAL PROPERTIES OF GAP PAD 5000S35

PROPERTY	IMPERIAL VALUE	METRIC VALUE	TEST METHOD
Color	Light Green	Light Green	Visual
Reinforcement Carrier	Fiberglass	Fiberglass	—
Thickness (inch) / (mm)	0.020 to 0.125	0.508 to 3.175	ASTM D374
Inherent Surface Tack (1 side)	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)	>5000	>5000	ASTM D149
Dielectric Constant (1000 Hz)	7.5	7.5	ASTM D150
Volume Resistivity (Ohm-meter)	10^9	10^9	ASTM D257
Flame Rating	V-O	V-O	U.L. 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-in²/W) 0.040" (3)	0.41	0.34	0.30

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 inch². 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 15   Typical Properties for Gap Pad 5000S35

The available thicknesses for Gap Pad 5000S35 are shown in Figure 16 as a function of thermal resistance.
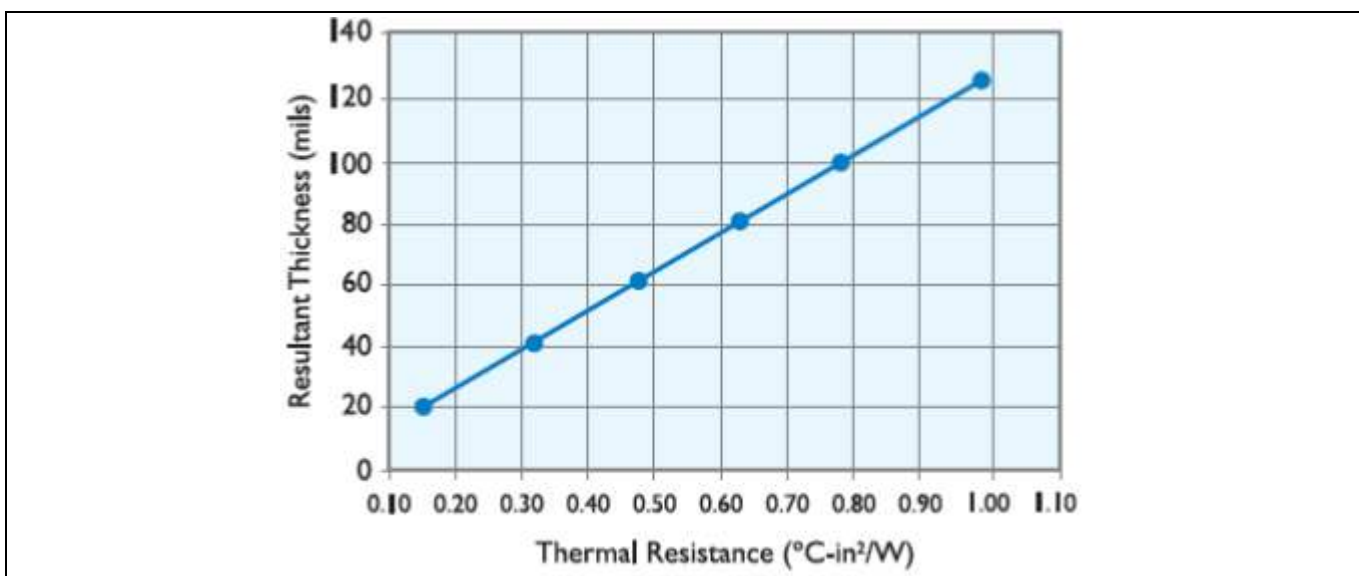

Figure 16   Available Thicknesses for Gap Pad 5000S5 as a function of thermal resistance

In order to make sure that the Gap Pad is not mechanically overstressed, the torque level of 0.9 Nm to 1.1 Nm should be applied to tighten the screws of the heatsink. The drawing for the Gap Pad is shown in Figure 17.
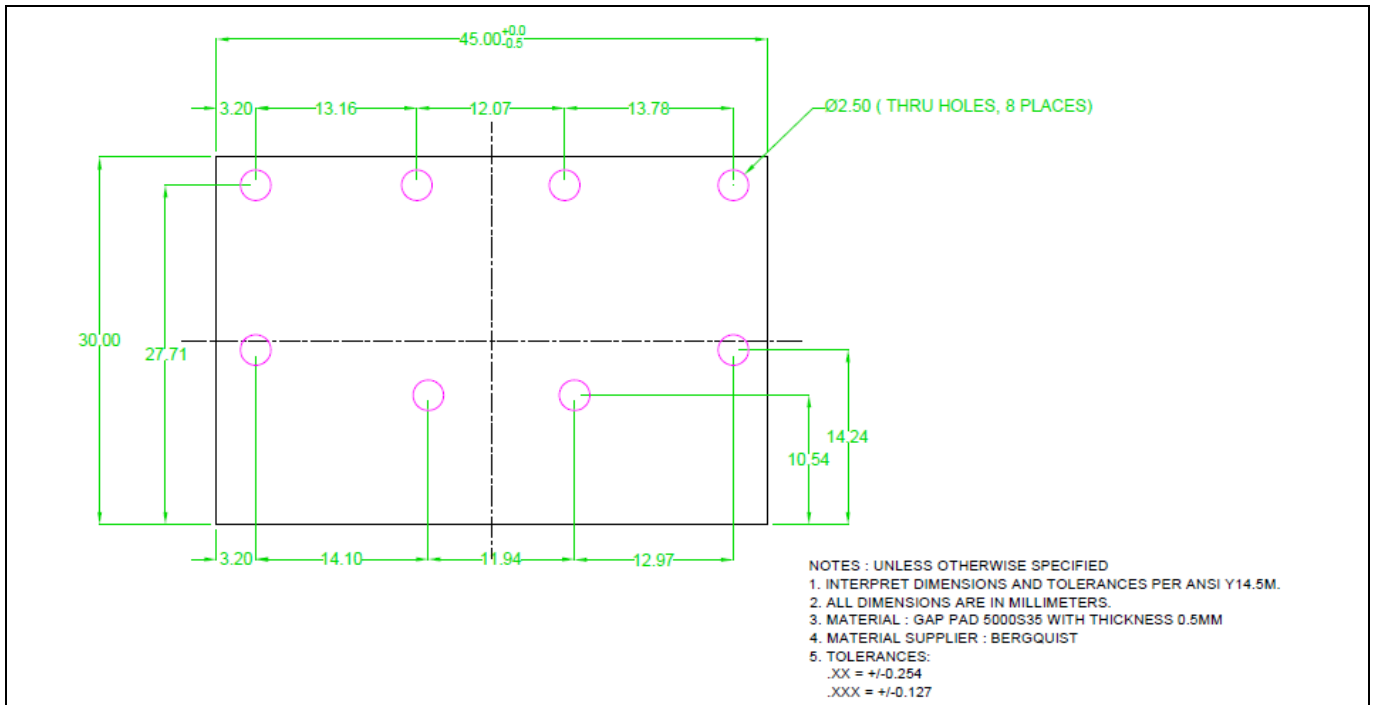

Figure 17   Drawing for the customized Gap Pad 5000S5

1.4 System Power Up

It should be noted that this three phase demo board is not a stand-alone solution to run a BLDC motor. It requires an XMC™1300 (or an XMC™4400) Drive Card as the controller board. Figure 18 shows the three-phase demo board (right-side) connected to an XMC™1300 Drive Card (left-side).
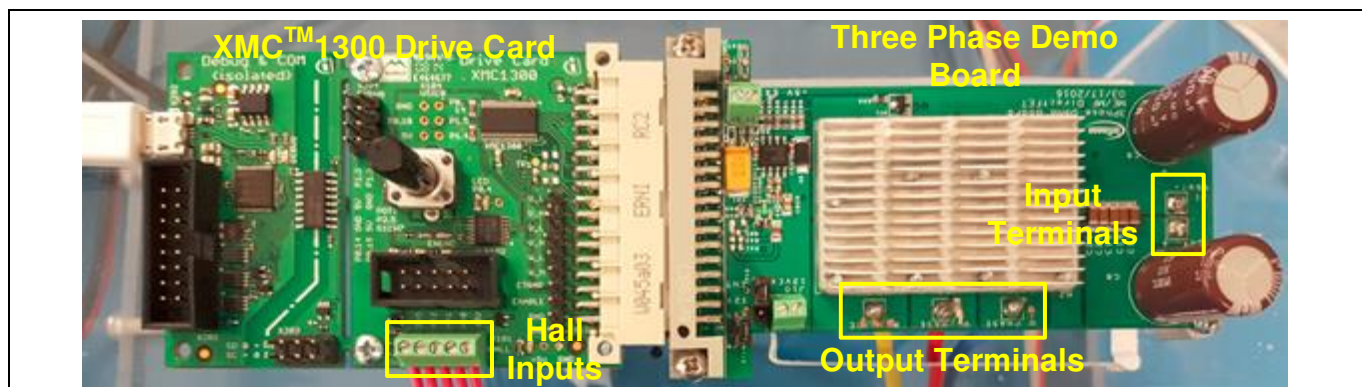

Figure 18   Three-Phase Demo Board Connected to XMCTM1300 Drive Card

The software description will be provided in a separate section but for now it is assumed that the XMC™ Drive Card is already loaded with the required code and ready to be used.

Note: The controller board In this Kit is being delivered with the software loaded in "Hall learning mode" and default parameters. For full motor control, new Hall parameters need to be added in the code, the Learning Mode disabled, and the controller re-programmed with this modified code. Please see sections 1.5.4 and 2 for insertion of new Hall parameters in code and subsequent re-programming instructions.

The following order is recommended to run the board:

1. Output phases are connected to the BLDC motor. Order is not important when in Hall Learning Mode.

2. BLDC Hall sensors are directly connected to the Hall X101 connector in the XMC™1300 Drive Card. Order of Hall sensor inputs (pins 2, 3,and 4 only) is not important when in Hall Learning Mode. However, as shown in Table 1.1, pin1 is GND and pin5 is VDD (+5V).

3. XMC™ Drive Card is connected to the demo board through the power board connector;

4. For using the on-board power supplies, jumpers of J13 and J15 should be on "INT" positions.

5. In case of using external power supplies, they should be connected to J9 and J10 and make sure that jumpers of J13 and J15 are on "EXT" positions;

6. Input power supply (20.0 V typical) or 18.0 V battery should be connected to J1 (+) and J2 (-). It is recommended to use short cables for the input power supply to limit the ripple current passing through the input bulk capacitors. Additional input capacitors could be used close to the board, if long cables are used.

7. If programming or in "Hall Learning Mode" a USB to micro USB cable <u>has</u> to be connected from computer to connector X202 on the controller board.

Please refer to Figure 3 and Figure 4 for the position of the connectors and jumpers in the demo board.

1.5 Getting Started with the Infineon Power Tools DirectFET™ Kit

1.5.1 Getting Started with DAVE™ (Version 4)

DAVE™ is an Infineon free of charge Eclipse based IDE using a GNU C-compiler providing extensive, configurable, and reusable code repository for XMC™ industrial microcontroller powered by ARM® Cortex®-M processors.

DAVE™ installation package is provided in www.infineon.com/DAVE and all the documentation necessary for installation and quick start can be downloaded from the same webpage. As reference guides, the user is advised to refer to the documents (Infineon Technologies AG, 2016) and (Infineon Technologies AG, 2015)

1.5.1.1 Importing Application into a New Workspace

The first time an application is loaded into the DAVE™ workspace, the user should define the desired storage folder and import the application from the provided package. The workspace storage folder is selected just after DAVE™ is launched in the "Workspace Launcher" window (Figure 19).
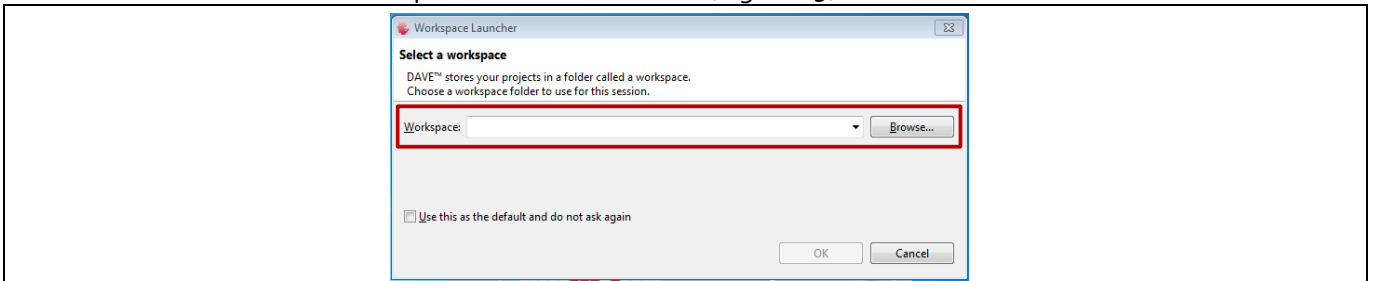

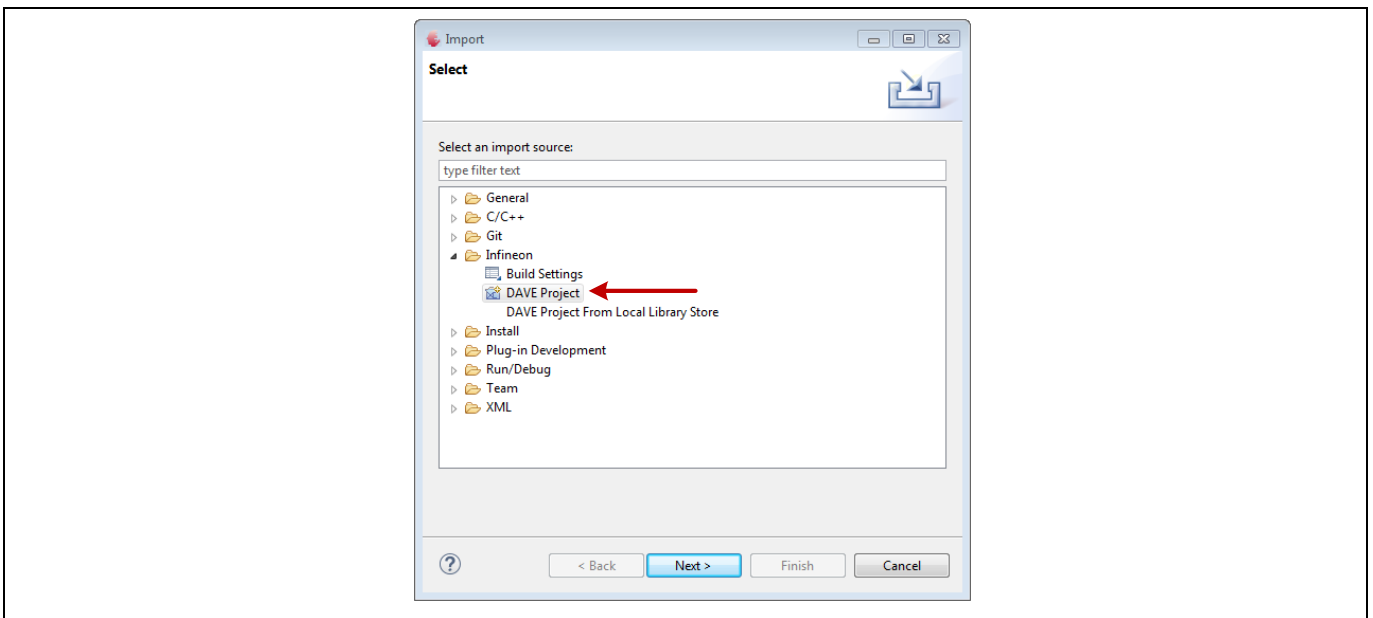**Figure 19   Workspace Launcher window from DAVETM start-up**

Figure 20   Import source selection options from DAVETMTM

After properly launched, the application files from the kit must be imported into the user workspace. To do so, one should choose the "File" tab and select the "Import" option. The "Import" window is opened and the option "Infineon/DAVE Project" must be selected. Figure 20 shows the "Import" window as it appears in DAVE™.

Selection of the source directory, in the "Select Root Directory" in the "Import Dave Projects" window is performed in the following sequence. The folder "BLDC_SCALAR_HALL_XMC13_Power_Tool", in the kit package, is then selected. The check-box "Copy Projects into Workspace" must be activated, otherwise, DAVE™

will use the source files in the kit package and all the modifications will overwrite the original files. Figure 21 illustrates the "Import Dave Projects" window for source file directory selection.
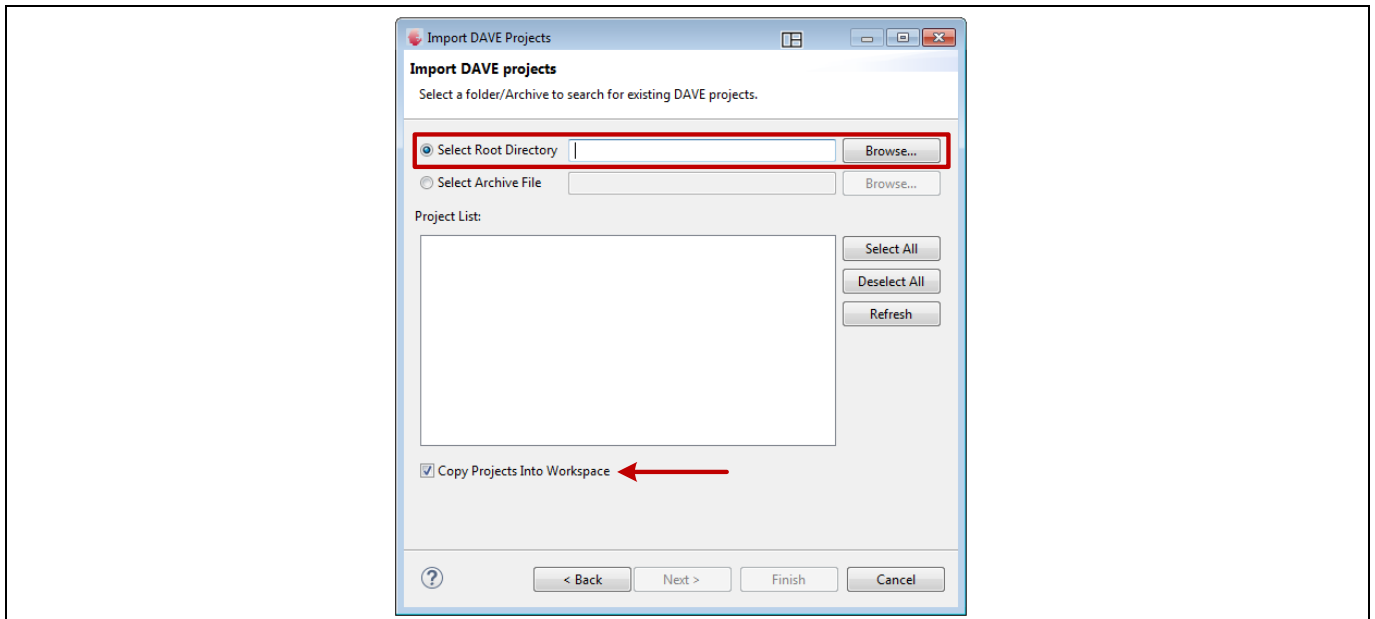
Figure 21   Import DAVETM Projects window for source files selection

1.5.1.2   DAVE^TM IDE Perspective

As soon as the application is properly loaded in DAVE^TM, user is able to access all the configuration files, routines and interrupt service routines (which are part of the BLDC drive for power tools applications) via DAVE^TM main window (Figure 22). Basically, the digital control method is developed most completely in C-Language and uses GNU C-Compiler for creating the executable file to be loaded into the microcontroller flash memory.
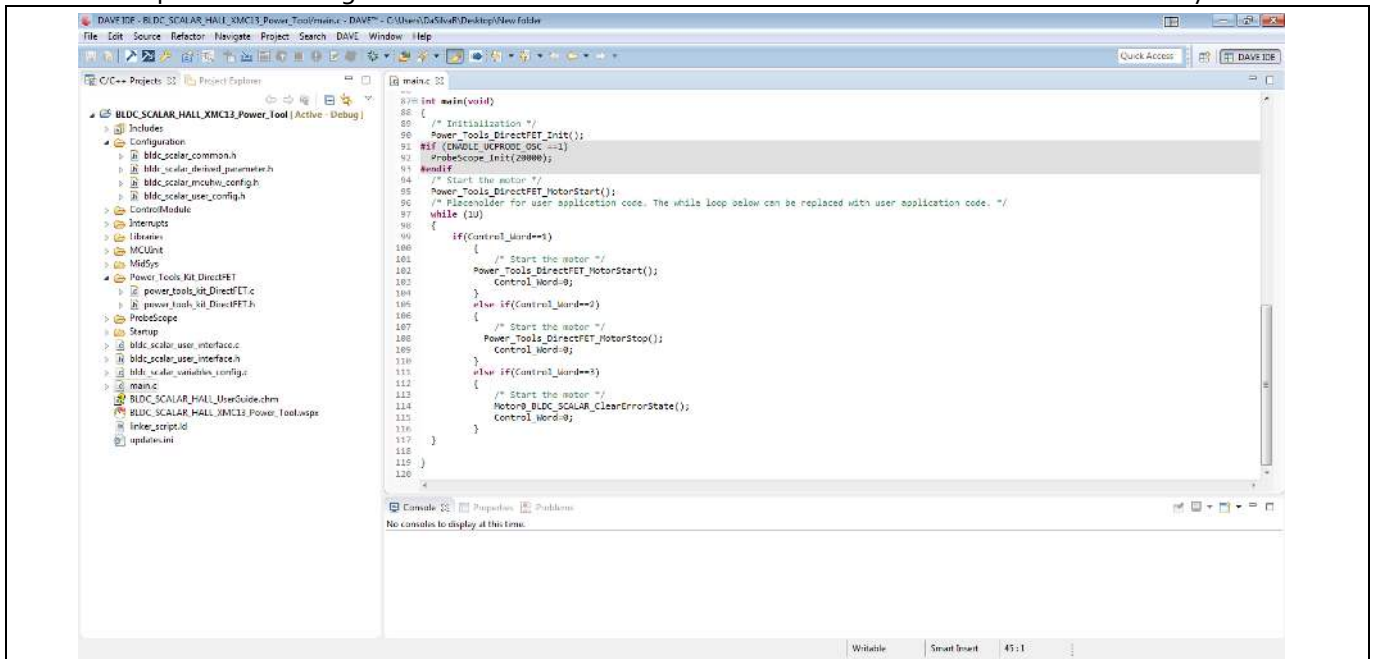
Figure 22   DAVETM main window

In the project explorer window, the user has access to the BLDC_SCALAR_HALL_XMC13 application description. The full documentation about the general algorithm which implements the scalar speed control for a block

commutated BLDC motor drive is available. Figure 23 illustrates the main window view for the BLDC_SCALAR_HALL_UserGuide.chm application description file.
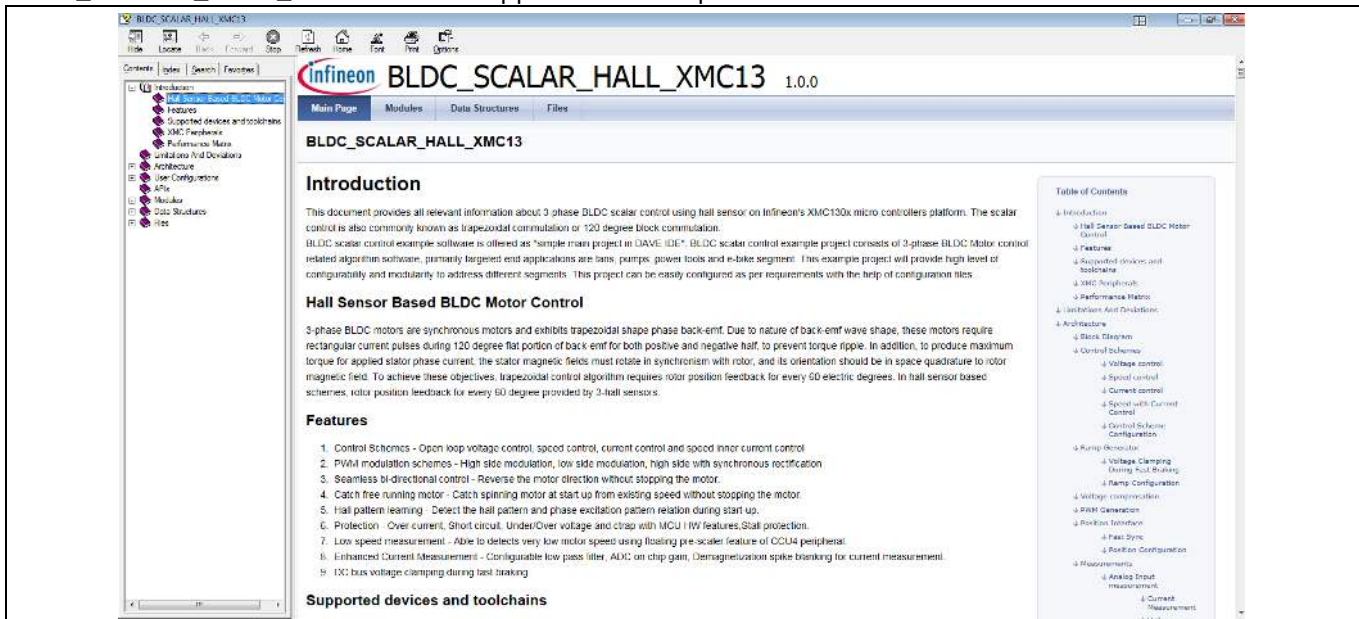

Figure 23 BLDC_SCALAR_HALL_XMC13 motor control application user's manual main window

1.5.2 Parameters Selection and Settings

BLDC_SCALAR_HALL_XMC13 has a set of parameters for configuration with a reasonable number of definitions. Moreover, for this specific application, the code for the power tools kit introduces a few more parameters for more user flexibility during field implementation. The user is again advised to refer to BLDC_SCALAR_HALL_UserGuide.chm file as main reference. The following description provides the most relevant parameters and default settings for faster and easier starting with the kit.

"power_tools_kit_DirectFET.h" contains the global definitions of the BLDC scalar motor drive control with three hall sensors. Table 4 shows the most relevant parameters to be adjusted by the user for the kit configuration.

Table 4 List of the main configurable parameters for the power tools application case

File	#	Parameter Name	Default Value
power_tools_kit_DirectFET.h	1	MOTOR_NO_LOAD_SPEED (RPM)	20000
	2	MOTOR_POLE_PAIRS	2
	3	MODULATION	BLDC_SCALAR_PWM_HIGHSIDE_SYNCHRECTI
	4	PWM_FREQ (Hz)	10000.0
	5	SYSTICK_PERIOD (µs)	1000.0
	6	ENABLE_RAMP	0
	7	RAMP_UP_RATE (RPM/s)	1000.0
	8	RAMP_DOWN_RATE (RPM/s)	1000.0
	9	SPEED_KP	20972
	10	SPEED_KI	2
	11	ENABLE_STALL_DETECTION	1
	12	STALL_DETECTION_TIME (ms)	1000.0
	13	NOMINAL_DC_LINK_VOLT (V)	20
	14	RISING_DEAD_TIME (µs)	2.0
	15	FALLING_DEAD_TIME (µs)	2.0
	16	CURRENT_AMPLIFIER_OFFSET (V)	1.0
	17	CURRENT_RSHUNT (mΩ)	1.0
	18	CURRENT_AMPLIFIER_GAIN	10.37

Table 4 (Continued)

File	#	Parameter Name	Default Value
power_tools_kit_DirectFET.h	19	VOLTAGE_DIVIDER_RATIO	24.9
	20	AMPLITUDE_HIGH_THRESHOLD (%)	95.0
	21	HALL_POSITIVE_DIR_SEQ	BLDC_SCALAR_HALL_SEQ_1
	22	HALL_PAT_A, B, C, D, E and F	See code

23	MC_PAT_A, B, C, D, E and F	See Code
24	BLANKING_TIME (µs)	0.5
25	PH_DELAY_TIME	1.0
26	MIN_ANALOG_INPUT_LOW_LIMIT	10.0
27	POTENTIOMETER_PT1_FILTER_ENABLE	0
28	POTENTIOMETER_FILTER_TIMECONST	0.001
29	ENABLE_HALL_LEARNING	0
30	OPEN_LOOP_VOLTAGE	8.0
31	OPEN_LOOP_SPEED	1000.0

1.5.2.1 Parameters Description

1. MOTOR_NO_LOAD_SPEED:

   This is the parameter which defines directly the maximum no-load speed presented by the BLDC rotor. It is an unsigned integer type variable and it is defined in RPM values. The default value is set to be 20000.0 RPM.

2. MOTOR_POLE_PAIRS:

   It defines the number of pole-pairs of the machine rotor. It is a unsigned integer number and presents 2 as default value.

3. MODULATION:

   It selects the type of modulation used for the generation of the BLDC block commutation pulses. For the power tools application, the user has only two configurations: BLDC_SCALAR_PWM_HIGHSIDE for standard PWM block commutation and BLDC_SCALAR_PWM_HIGHSIDE_SYNCHRECTI for BLDC block commutation with synchronous rectification.

4. PWM_FREQ:

   This parameter defines the switching frequency in Hz to be applied in the PWM block commutation of the BLDC machine. For this case, the user can have as an input a single precision float input. The range of operation of the switching is not allowed to be outside the interval between 1.0 kHz and 100.0 kHz. As a default value, 10.0 kHz is used.

5. SYSTICK_PERIOD:

   SYSTICK defines the period in which the system state machine runs inside the microcontroller. It is also defined in a single precision floating point type value and its range can be set from 1000.0 µs to 10000.0 µs. 1.0 ms is the default value for the state machine call function.

6. ENABLE_RAMP:

   It defines the enable signal for the ramp-up of the motor speed. Enabling the ramp-up option, a linear function is defined to increase the speed reference from 0 RPM to a value set by the speed reference potentiometer. By default, the ramp-up function is disabled.

7. RAMP_UP_RATE:

   This value defines the ramp-up rate from an increase in the speed reference defined by the speed reference potentiometer. Due to the fact the ramp function is not enabled by default, this parameter is not considered.

8. RAMP_DOWN_RATE:

   This value defines the ramp-down rate from a decrease in the speed reference defined by the speed reference potentiometer. Due to the fact the ramp function is not enabled by default, this parameter is not considered.

9. SPEED_KP:

The Proportional-Integral (PI) controller has the proportional gain defined by this parameter. As the calculation of the PI is performed using fixed-point operation, this parameter is defined in Q15 base.

10. SPEED_KI:

The Proportional-Integral (PI) controller has the integration gain defined by this parameter. As the calculation of the PI is performed using fixed-point operation, this parameter is defined in Q15 base.

11. ENABLE_STALL_DETECTION:

The stall detection is enabled by ENABLE_STALL_DETECTION. In case the stall detection is enabled, the rotor is going to be allowed to operate, for a certain period of a time, with its rotor locked. By default, this functionality is enabled.

12. STALL_DETECTION_TIME:

It defines the period of time that the rotor is allowed to operate in stall operation, meaning the amount of time that the motor, even with its rotor locked, is still operating. This value is set by a single precision float type value in milliseconds. By default, its value is set to be 1000.0 ms (1.0 s).

13. NOMINAL_DC_LINK_VOLT:

This parameter is used to define the nominal input voltage of the inverter 6-switches inverter bridge. It is defined using a single precision float value and has a default value equal to 20.0 V. The "Power Tools DirectFET^{TM} Kit" is equipped with Infineon IRF7480 which is a 40.0 V device. The user must be aware of the input voltage selection for possible protection of the switching devices in the board.

14. RISING_DEAD_TIME:

This parameter defines the dead-time for the rising edge of the PWM pulse. It is also a single precision float value and has a default value of 2.0 μs.

15. FALLING_DEAD_TIME:

This parameter defines the dead-time for the falling edge of PWM pulse. It is also a single precision float value and has a default value of 2.0 μs.

16. CURRENT_AMPLIFIER_OFFSET:

The current measurement is performed via a single-shunt configuration connected to the DC input of the 6-switches inverter bridge. In order to avoid negative voltage levels at the input of the microcontroller analogue to digital converter (ADC), a level shift is applied to the resistor shunt differential output signal via operational amplifier circuitry. CURRENT_AMPLIFIER_OFFSET defines the hardware DC level shift applied on the DC current measurement. It is a single precision float value and has default value approximately equals to 1.0 V.

17. CURRENT_RSHUNT:

This parameter defines the shunt value, in mΩ, of the DC current measurement circuitry (R_{S1}). It is a single precision float value and has a default value of 1.0 mΩ as it is presented by the power board circuitry.

18. CURRENT_AMPLIFIER_GAIN:

The DC current amplifier gain is defined by the hardware. For the microcontroller internal measurement and proper scaling factor, this parameter has to be defined, otherwise, the interface with μCProbe will present mismatches in the streamed variables. This parameter has a default value of approximately 10.37 and it is calculated by the ration between the resistors R_{23} and R_{21} or R_{22}. This parameter also requires a single precision floating point type value.

19. VOLTAGE_DIVIDER_RATIO:

The input voltage is monitored by the microcontroller and streamed via serial connection using the μCProbe. This voltage value, most likely with a larger value than the microcontroller ADC reference (5.0 V) (20.0 V as default value), is stepped-down, by a simple voltage divider (R_{63} and R_{64}). As default value, this ratio is set to be approximately 4.02. This parameter also requires a single precision float point type value.

20. AMPLITUDE_HIGH_THRESHOLD:

This parameter, defined as a single precision value in the range of 0.0% and 100.0%, when reached its threshold, applies a 100.0% duty-cycle in the PWM modulation of the BLDC block commutation. This value is set to be 95.0% by default.

21. HALL_POSITIVE_DIR_SEQ:

This parameter defines the positive sequence of the hall pattern for the motor rotation direction. By default, it is set equals to HALL_SEQ_1. This sequence is a dummy definition for the values in the parameters HALL_PAT_A, B, C, D, E and F.

22. HALL_PAT_A, B, C, D, E and F:

These values define the sequence of hall pattern rotor positions. By default, the positive sequence is 1, 3, 2, 6, 4 and 5. In the following chapters, there is a brief description of hall pattern and PWM pattern definitions are presented.

23. MC_PAT_A, B, C, D, E and F:

These values define the sequence of the PWM pattern applied to the terminals of the BLDC motor according to the sequence of hall pattern from HALL_PAT_A, B, C, D, E and F. In the following chapters, there is a brief description of hall pattern and PWM pattern definitions.

24. BLANKING_TIME:

The blanking time for the hall pattern event detection is defined by this parameter. It has a range from 0.5 µs to 5.0 µs. By default, this single precision float value is set to be 0.5 µs.

25. PH_DELAY_TIME:

This is the definition of the phase delay time. It is a single precision float value and has a default value of 1.0 µs. It can be defined in the range between 0.6 µs and 5.1 µs.

26. MIN_ANALOG_INPUT_LOW_LIMIT:

This parameter is related to the minimum speed of the BLDC motor. It corresponds with the percentage of the maximum speed in relation to the reference potentiometer value. As default, it is defined to be 5.0% which is equivalent to the 5.0% of the maximum speed of 20000 RPM. The minimum speed is then calculated internally by the microcontroller and for this case, it is set to be 1000 RPM. This is a single precision floating number.

27. POTENTIOMETER_PT1_FILTER_ENABLE:

This parameter enables or disables the use of a reference filter for the speed reference potentiometer. This functionality is used in case of noise in the reference potentiometer. This functionality is disabled by default.

28. POTENTIOMETER_FILTER_TIMECONST:

This parameter defines the time constant for the first order low pass filter applied on the speed reference potentiometer. By default, the value is not considered in the motor drive algorithm; however, it can be defined as a single precision float value. It is considered to be defined in seconds.

29. ENABLE_HALL_LEARNING:

This function is used for the detection of the hall pattern and its correspondence to the multichannel PWM pattern applied to the three phase bridge. In the following chapters, we will present a brief description of hall pattern and PWM pattern definitions. If the user is already aware of these values, this function must be disabled.

30. OPEN_LOOP_VOLTAGE:

This parameter defines the input voltage value for the hall pattern recognition function (ENABLE_HALL_LEARNING). It is a single precision float value and is set to be 8.0 V by default. This value for the input voltage is set to be between 5.0 V and the nominal input voltage (20.0 V by default). During

this operation, the motor is controlled in open loop condition. By then, the user is advised to define a lower value for the input for avoiding large values for phase currents.

31. OPEN_LOOP_SPEED:

This parameter represents a fraction of the no-load maximum speed for operation of the BLDC motor drive during open loop condition for hall pattern identification mode.). It is a single precision float value and is set to be 5.0% by default, which represents a fraction of 5.0% (1000 RPM) of the maximum set no-load speed (20000 RPM).

32. TEMEPRATURE_SHUTDOWN_THRESHOLD:

This is the threshold level for the power board temperature, in °C, above which the inverter stops operating. It is an integer value and used as a reference to compare with the board temperature measured by the MCP9700T sensor. This parameter has a default value of 80°C.

33. TEMPERATURE_HYSTERESIS:

This is the value for the power board temperature, in °C, above which the inverter will not start. This is an additional temperature protection to force the user not to start the power tool at an already high temperature condition. It is an integer number with a default value of 50°C.

1.5.3   Compilation and Debug Session

After configuring the parameters in Table 4, when required, the code must be compiled and loaded into the XMC^{TM}1302 flash memory via the Segger J-Link Programmer/Debbuger. This device is already present in the KIT_XMC1300_DC_V1 Infineon Kit.

For compiling the code, the user must access the "Project" instance from the main tab menu and click on the "Build Project" option, as it is illustrated in Figure 24 "Build All" and "Clean" options can also be used. For more details on the compilation option of DAVE^{TM}, the user is advised to refer to (Infineon Technologies AG, 2016) and (Infineon Technologies AG, 2015).
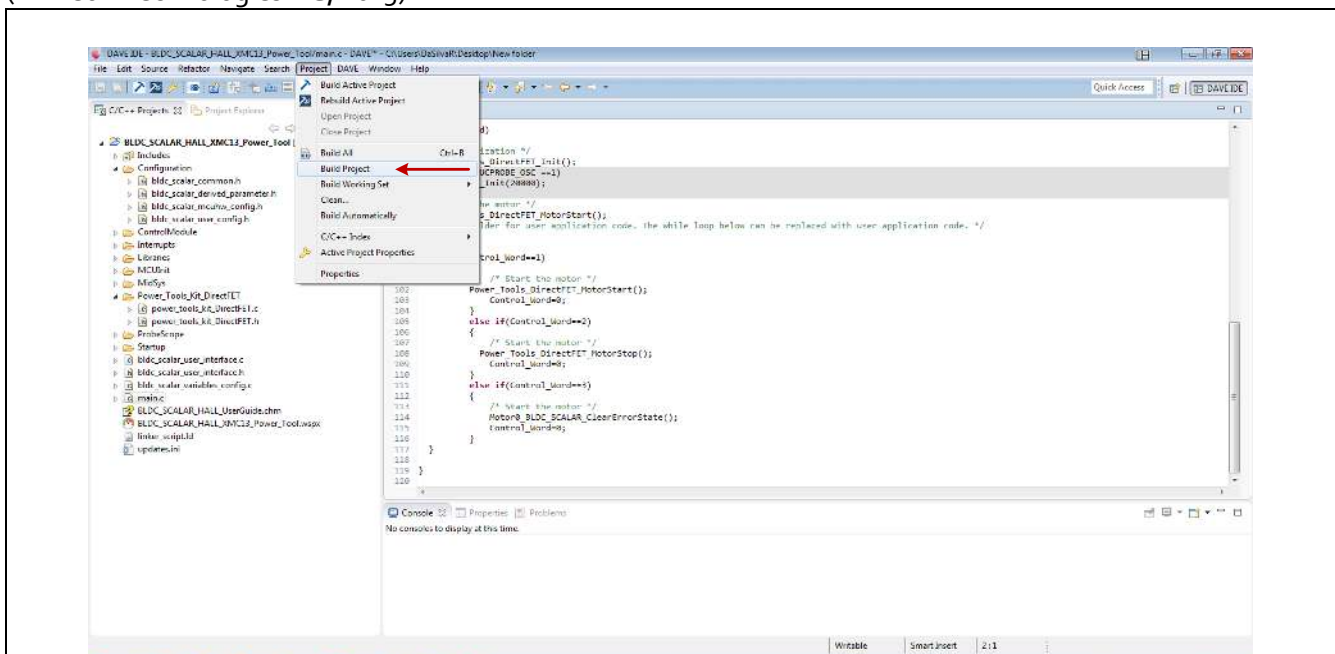
Figure 24   "Build Project" (code compilation) functionality of DAVE™

For loading the code into the device internal flash, the Segger J-Link Programmer/Debbuger is used. The debugger must be connected to the computer via USB cable. The power board should properly be powered. When the ENABLE_HALL_LEARNING is enabled, it is advised to apply 18.0 V or 20.0V and limit the input current from the external supply to 1A, since the BLDC motor drive during Learning operates in open loop.

The connection with debugger and the starting of the debug session is initiated by hitting the shortcut button indicated by the "bug" image in DAVE^{TM} as shown in Figure 25.

Figure 25   Debug mode shortcut button from DAVETM

The debug session is followed by the "Debug Configurations". The first time the debugger is initialized, the main window from Figure 26 is activated. Then, the user must select the Segger J-Link by double clicking on the option "GDB SEGGER J-Link Debugging". After that, the "Debug" button is activated and the debug session is started automatically Figure 27.
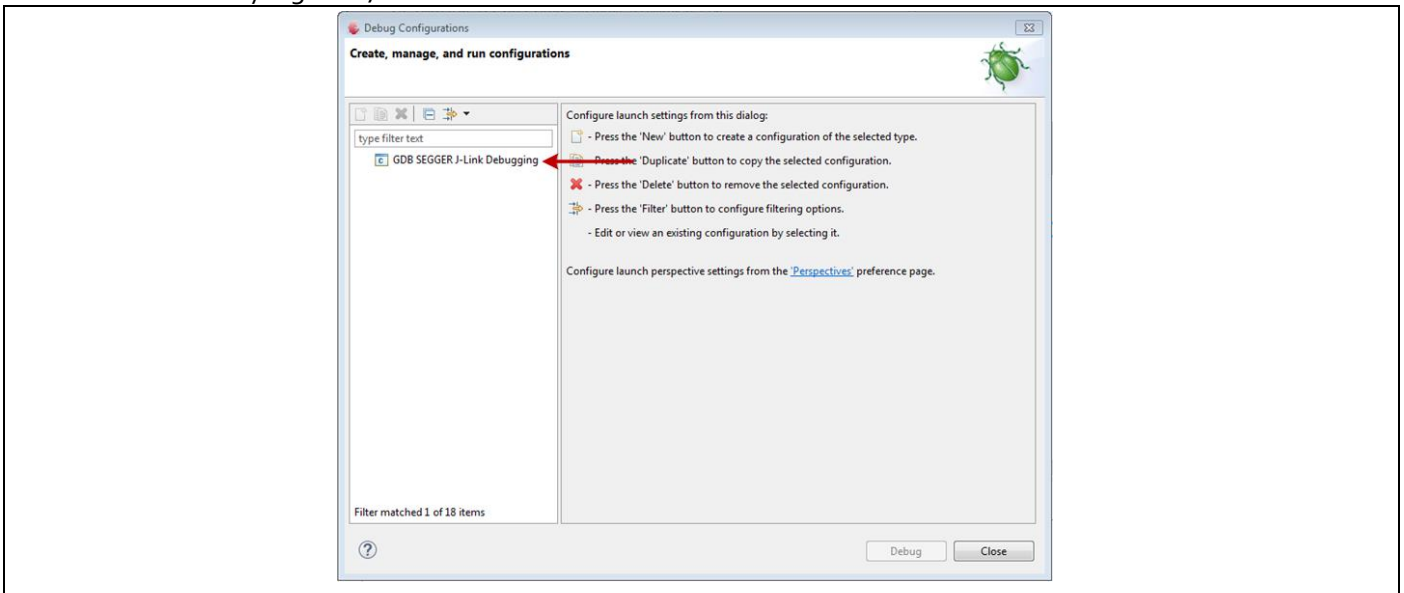
Figure 26   Debug Configurations main window
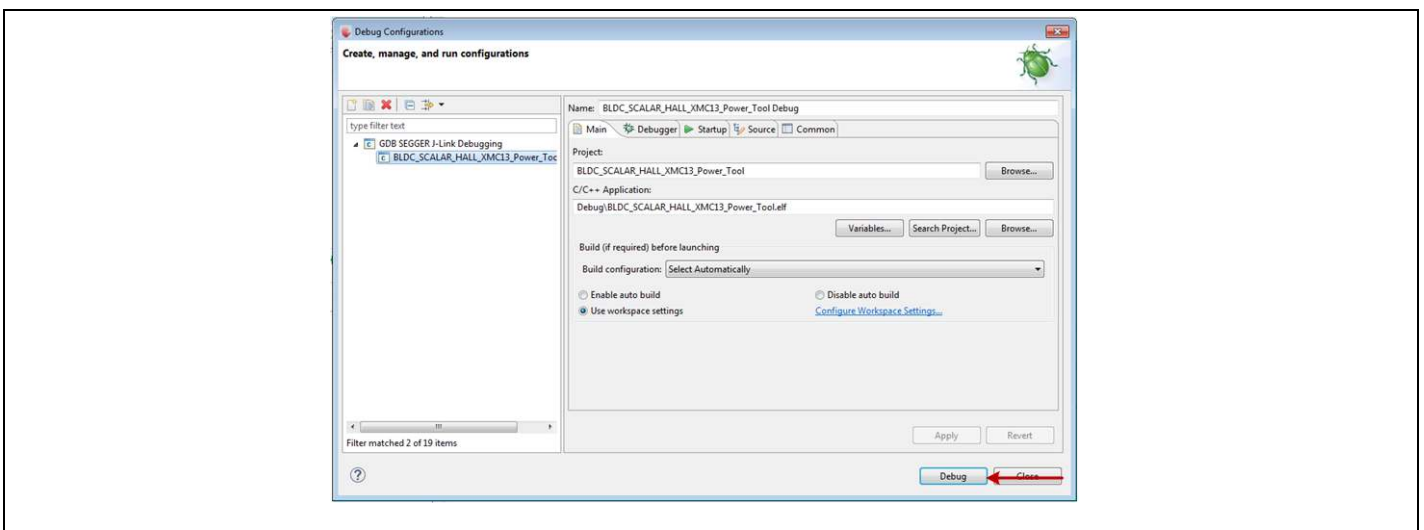
Figure 27   Debug Configurations session initialized

1.5.4 Acquisition of Hall and Multichannel PWM Patterns

Initially, the sequence and relationship of the Hall sensors position with respect to the motor windings positons (Phases) is not known. Therefore it is necessary to run the motor with the loaded code as it comes pre-programmed in "Hall learning mode" as part of the kit.

The macros represented by HALL_PAT_A, B, C, D, E and F are acquired directly from the hall sensors outputs at the connector X101. (as an alternative, one can manually rotate the rotor and measure the pattern with either an oscilloscope, or a simple multimeter). After the hall sequence is acquired, the macros HALL_PAT_A, B, C, D, E and F can be updated in the "power_tools_kit_DirectFET.h" file.

For the acquisition of the multichannel PWM pattern, the system is configured to operate in open loop condition. Both duty-cycle and speed are predefined. The hall learning pattern recognition is enabled using the macro ENABLE_HALL_LEARNING from Table 4. DC voltage value and open-loop speed settings are defined in the definitions labelled as OPEN_LOOP_VOLTAGE and OPEN_LOOP_SPEED, respectively.

After starting the debugging mode perspective, as described previously, the system can be resumed (play button) and, with the adaptive multichannel PWM pattern learning function enabled, the BLDC motor performs a few rotations and stops. After the rotor has stopped, the suspend mode can be triggered (pause button). Figure 28 shows the results for the multichannel PWM acquisition during motor start-up.
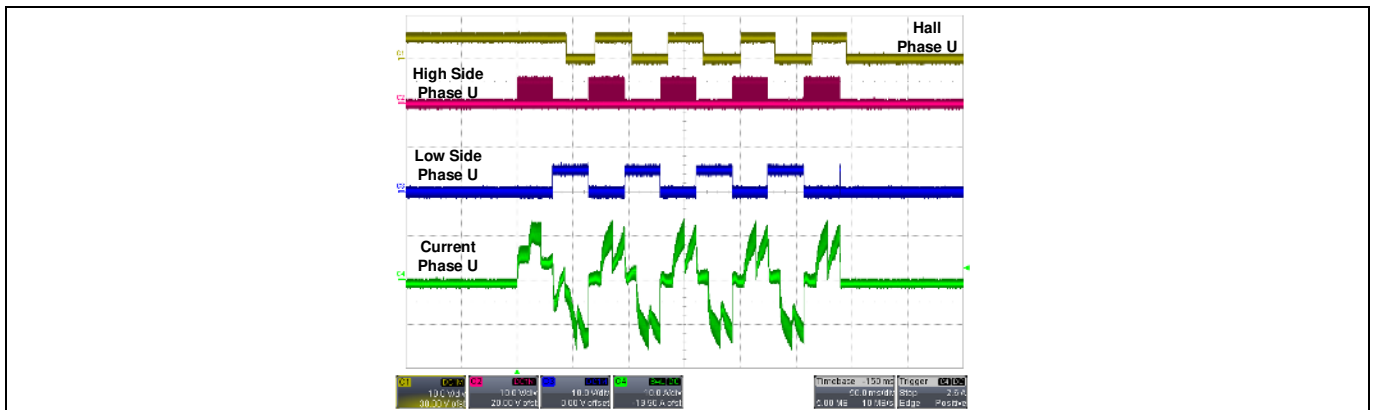
Figure 28   System waveforms for multichannel PWM pattern detection

With the system paused, the multichannel PWM pattern can be displayed in the "Expression" window. By selecting the "Expression" view in the "Show View" option of the "Window" tab, one can add any system variable. Figure 29 illustrates a screenshot of the debugging window perspective and activation of the "Expression" window.
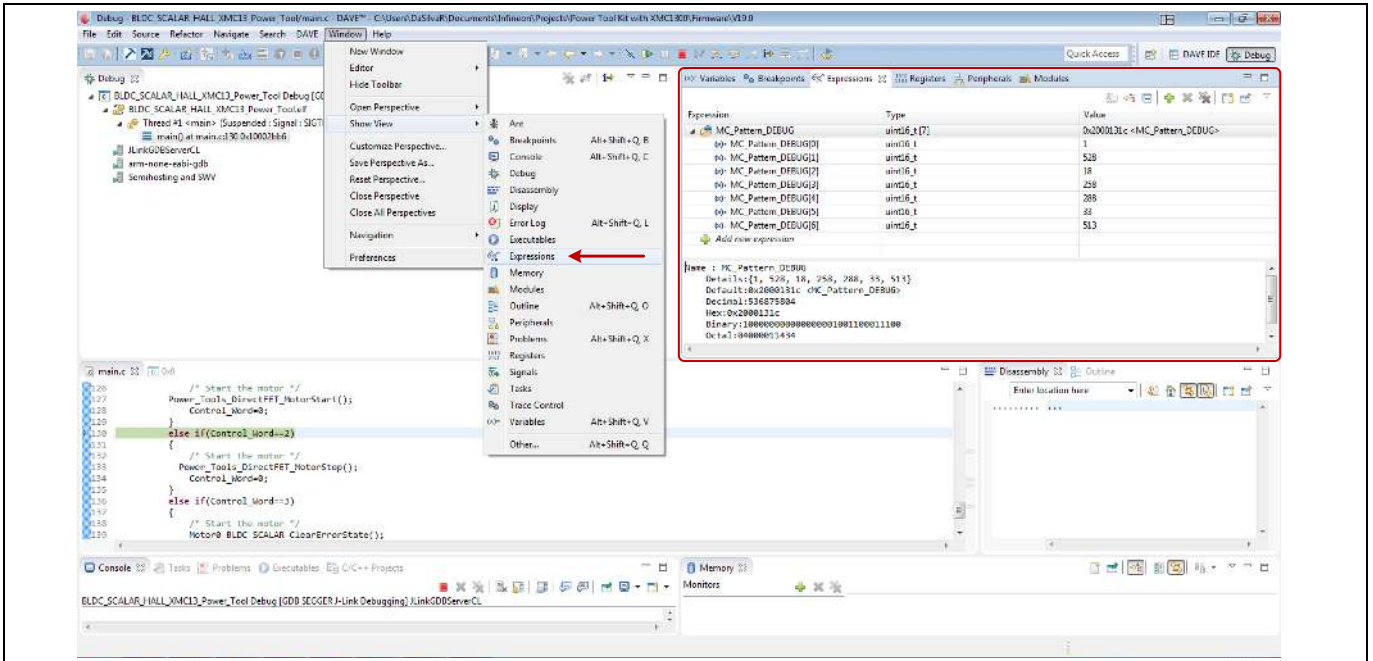
Figure 29   Debugging mode view and "Expression" selection window

By adding the variable name MC_Pattern_DEBUG in the "Expression" window (Add new expression), the 6 multichannel PWM pattern states can be recognized directly from DAVE™. The first element must be disregarded, meaning that only the last six elements of the string MC_Pattern_DEBUG are necessary for the pattern recognition. The values of the MC_Pattern_DEBUG string are basically the values for the position interface (POSIF.MCM). For detailed description of operating modes of this peripheral, (Infineon Technologies AG, 2014) must be referenced.

Converting MC_Pattern_DEBUG to hexadecimal and using the macros from the Table 5 and Table 6, the MC_PAT_A, B, C, D, E and F can be completed following the same sequence for the HALL_PAT_A, B, C, D, E and F. Hall learning procedure is explained in details in section 2.

1.6 System Operation

After the initialisation procedure, the control algorithm makes use of the hall sensor signals for measuring the rotor speed, and in case of deviation, it makes the proper adjustment in the duty-cycles of the PWM signals. Later chapters briefly describe the implementation of the speed control in the XMC^{TM}1300 family.

Motor is operated in a closed loop speed control method. For this mode, the speed level is selected via potentiometer POTI/R103. This potentiometer is easily identified in the XMC control board (Figure 30)
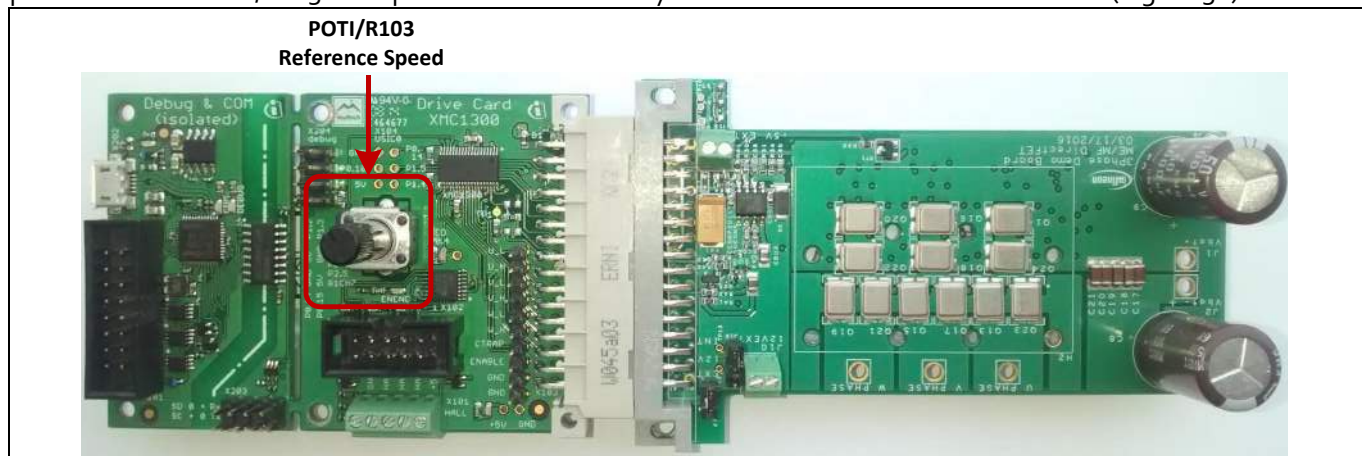
Figure 30   Location of the speed reference control potentiometer POTI/R103

Many different configurations can be achieved by changing the settings in the file "power_tools_kit_DirectFET.h".The user can customize the operation of the "Power Tools DirectFET^{TM} Kit", including input voltage level, protection threshold values, operating motor speed and high frequency modulation parameters.

Two cases are available for user selection: BLDC_SCALAR_PWM_HIGHSIDE and BLDC_SCALAR_PWM_HIGHSIDE_SYNCHRECTI. However, the operating principle in both cases remains the same, since the algorithm behind the control strategy does not change. The major distinction in these operating modes is related to the modulation.

The first case is the standard BLDC PWM block commutation method and the second one is BLDC PWM block commutation with synchronous rectification. Advantage of the standard one is appreciated in the simplicity of the modulation signal generation as well as for the total gate losses in the system. The synchronous case, though, presents higher efficiency due to the avoidance of diode conduction during the high side modulation, but it requires a more precise and complex modulation scheme.

The following sections show an initial comparison between these two modes of modulation. However, the steady-state performance analysis is presented only for the synchronous rectification case.

1.6.1 Modulation Signals and Main Waveforms

For both modulation cases, the PWM pattern changes according to the hall sensors outputs in each 60° rotor angular displacement. The outputs of the hall sensors are shown in Figure 31 for a 2 pole-pair BLDC motor at 6000 RPM rotor speed. With the frequency of these signals, which is approximately 200.0 Hz based on the oscilloscope measurement, and knowing the number of pole pairs of the BLDC motor (2), one can derive approximately the 6000 RPM rotor speed.
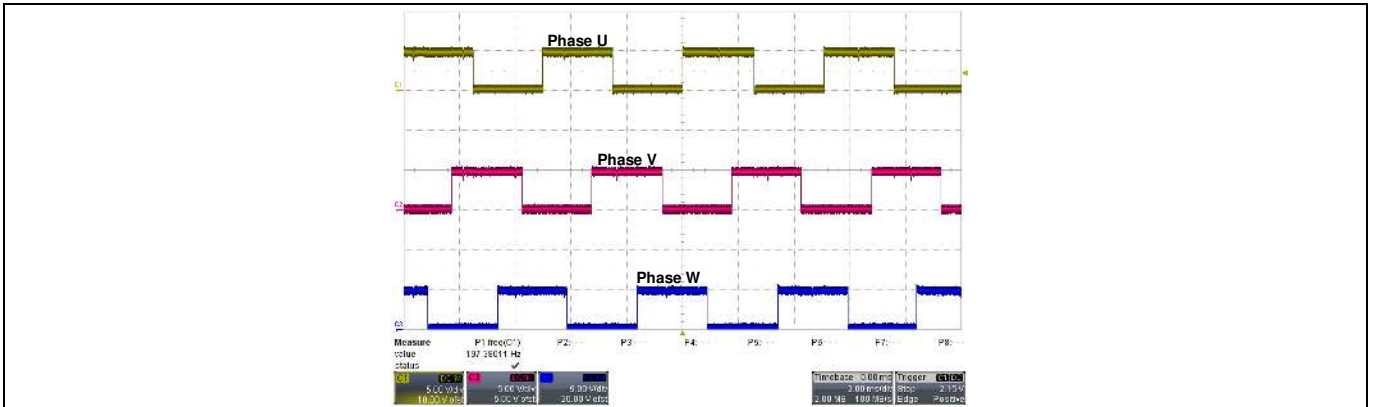
Figure 31   Hall sensors output pattern at 6000 RPM rotor speed
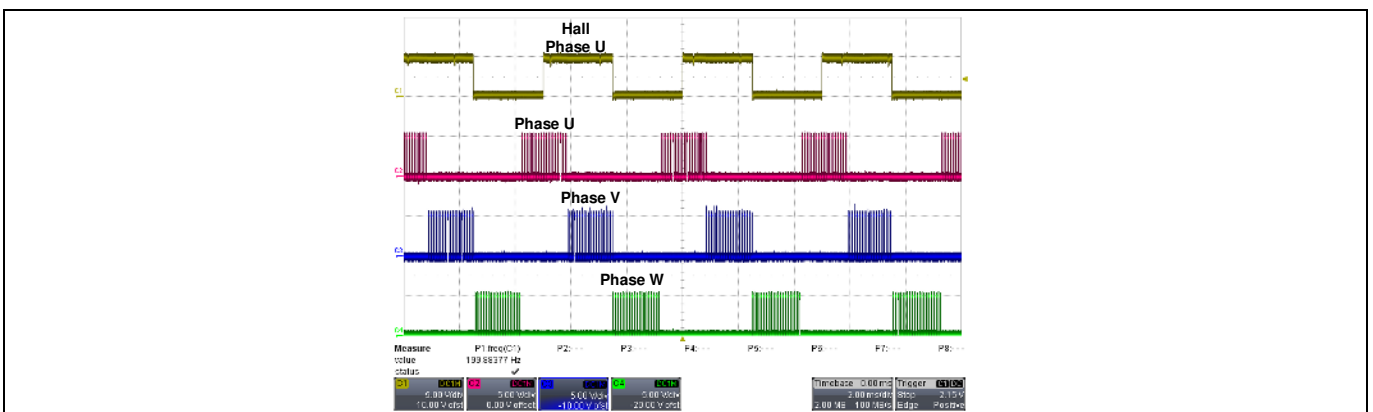

Figure 32   High side PWM pulses from the XMCTM at 6000 RPM rotor speed

The high side gate PWM signals are theoretically identical, with or without synchronous rectification. As an experimental result for an in-house test setup, the PWM signals from the microcontrollers to the high side switches are shown in Figure 32 considering the phase displacement from the hall sensor output of the U phase.
For the low side switches, Figure 33 and Figure 34 illustrate the PWM signals from the XMC™1302 outputs for non-synchronous and synchronous rectification modes, respectively. From such waveforms one can notice the major differences between the two different modes of modulations.
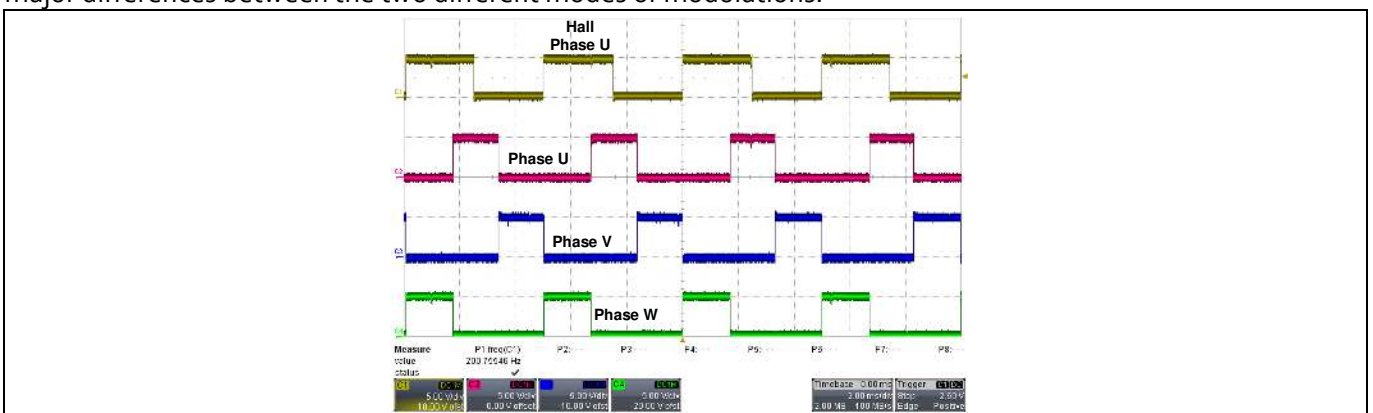
Figure 33   Low side PWM signals for non-synchronous rectification mode at 6000 RPM rotor speed
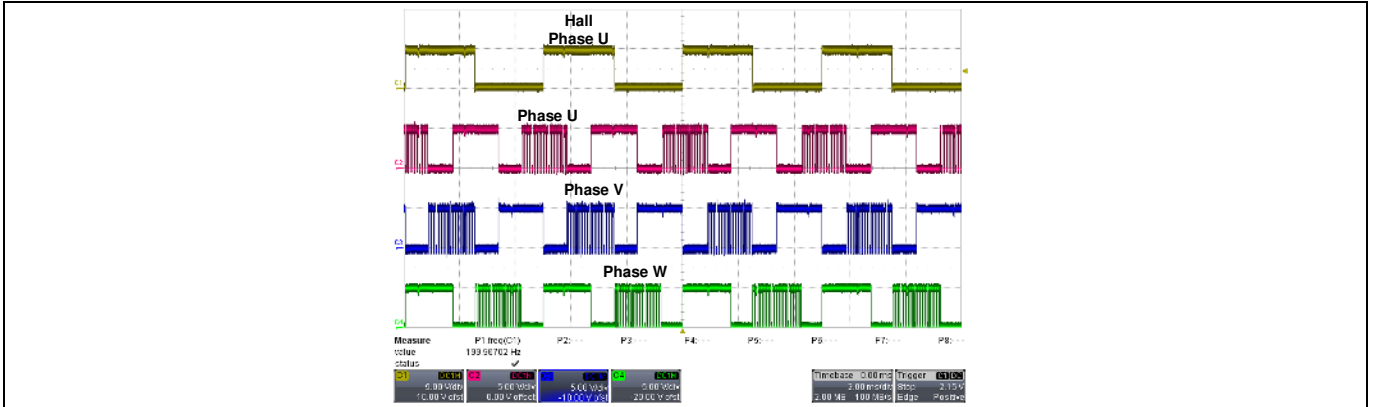
Figure 34   Low side PWM signals for synchronous rectification at 6000 RPM rotor speed

For a 20 V input voltage, 6000 RPM speed reference and approximately 3.25 Nm torque in the motor shaft, the main waveforms of the BLDC motor are illustrated in Figure 35 (unipolar block commutation mode without synchronous rectification) and in Figure 36 (unipolar block commutation mode with synchronous rectification on the low side switch).
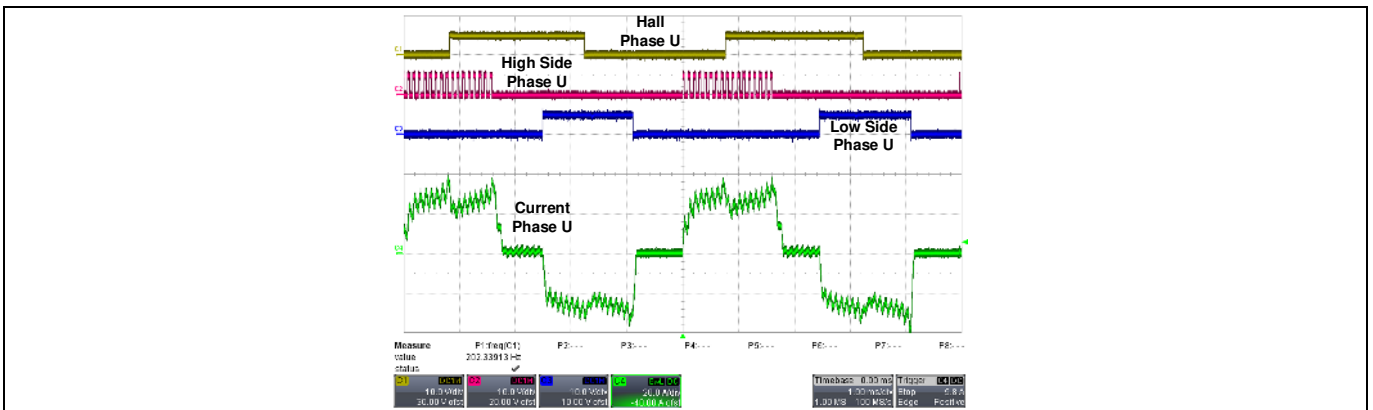
Figure 35   Phase U signals and output current waveform for non-synchronous rectification mode at 6000 RPM rotor speed
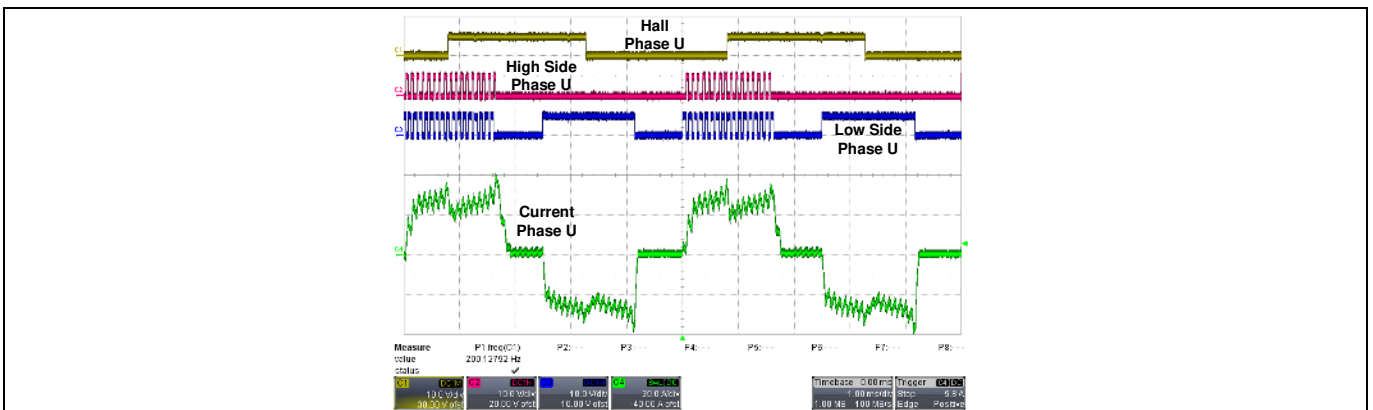
Figure 36   Phase U signals and output current waveform for synchronous rectification mode at 6000 RPM rotor speed

In Figure 35 andFigure 36, the yellow trace shows the hall sensor output of U phase, magenta and blue traces represent the gate signals from the controller for the high side and low side switches of U phase, respectively and the green trace shows the phase current for U phase.

Waveforms shown in Figure 35 and Figure 36 are considerably similar. The main difference between them is that in Figure 36, there is simultaneous modulation of high and low side FETs during the phase activation in the synchronous rectification. The advantage of the synchronous rectification is an improvement of the system efficiency due to the decrease in the low side body diode conduction time.

The motor back-EMF is also measured with respect to the power supply ground. The waveforms related to the back-EMF measurements are illustrated in Figure 37 for unipolar block commutation scheme and in Figure 38 for the synchronous rectification method made possible by the modulation of the low side FETs. The phase U, V and W are labelled in the oscilloscope captures.
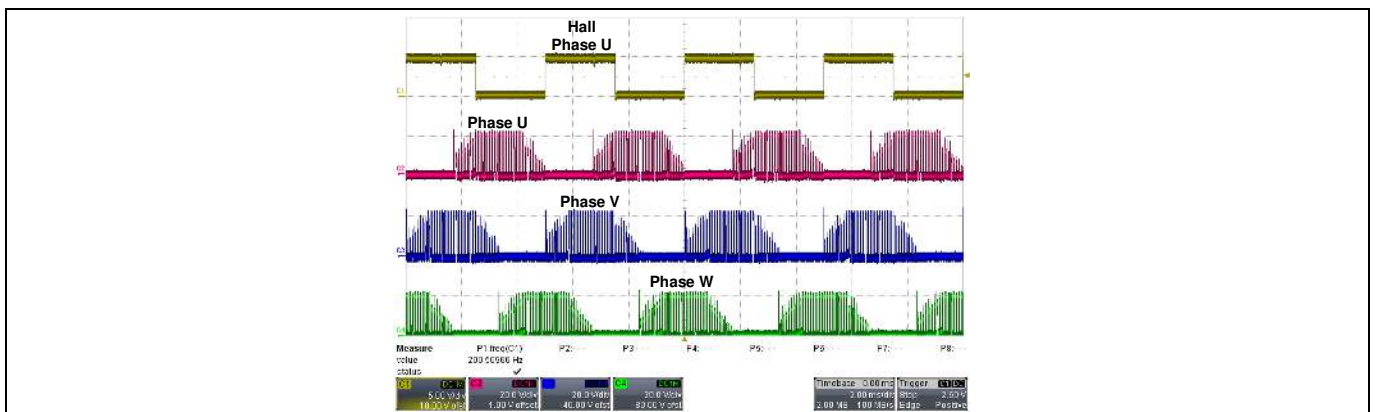
Figure 37   System back-EMF waveforms for unipolar block commutation at 6000 RPM rotor speed
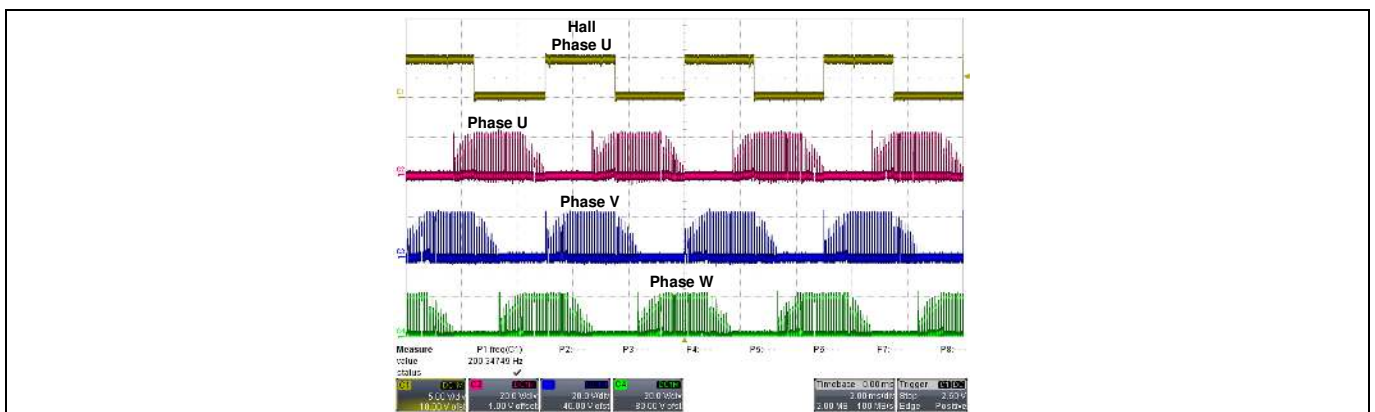
Figure 38   System back-EMF waveforms for unipolar block commutation with synchronous rectification at 6000 RPM rotor speed

The system waveforms do not show major differences when considering block commutation modulation with or without synchronous rectification. Therefore, all the waveforms considered from now on are considered as block commutation with synchronous rectification, unless otherwise specified.

For two different rotor speeds, 10000 RPM and 20000 RPM, both measured at no load, and approximately 25A$_{RMS}$ flowing through the inverter output terminal, Figure 39 and Figure 40 illustrate the in-house setup test results. The hall sensor output of the phase U is illustrated in the first oscilloscope channel (yellow trace), high side and low side gate signals in the second and third channels (magenta and blue traces), respectively. Output current for the same phase (U) is depicted in the last channel (green trace). Frequency and RMS current measurements are also included in the waveforms.
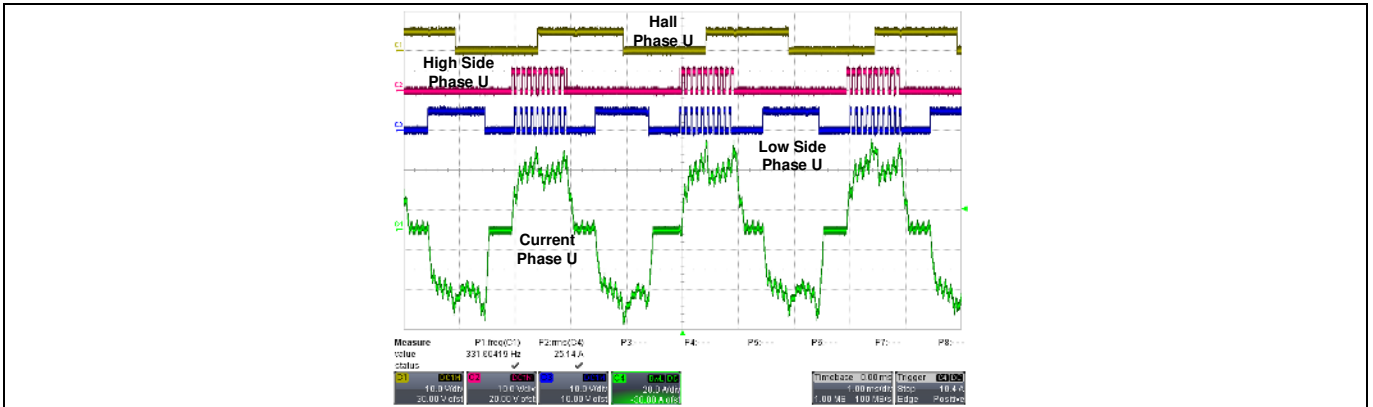
Figure 39   Phase U signals and output current waveform for synchronous rectification mode at 10000 RPM rotor speed and 25ARMS output current (5.0 Nm)
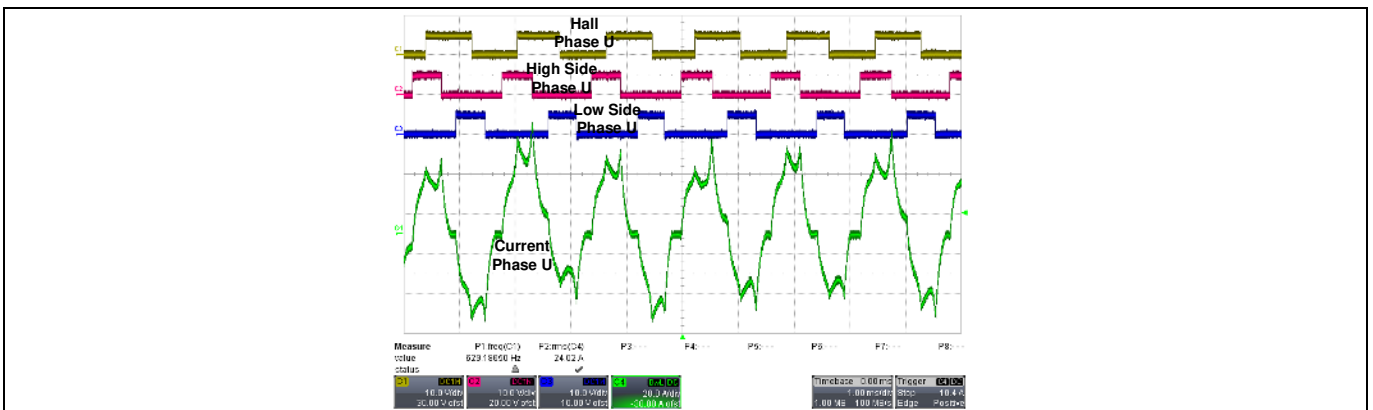

Figure 40   Phase U signals and output current waveform for synchronous rectification mode at 20000 RPM rotor speed and 25ARMS output current (3.5 Nm)

At 10000 RPM, the duty-cycle is approximately 50.0% and the rotor frequency approximately matches the reference value set on the speed reference potentiometer. At 20000 RPM, due to saturation of the duty-cycle (100.0%), the rotor speed decreases to approximately 18500 RPM.

1.6.2   Overcurrent Protection

The "Power Tools DirectFET™ Kit" is equipped with a built-in hardware current protection circuitry formed by a DC shunt current measurement shutdown system. The trigger is selected via the analogue comparator and once latched, the gate signals are automatically disabled via digital AND gates. The microcontroller, as soon as the shutdown signal is identified, stops the motor operation. The current shutdown level is set to switch the system off by a current approximately equal to 90.0 A peak. Changes in the current level require hardware modification. Two tests are illustrated in Figure 41 and Figure 42. In both cases the phase currents are illustrated together with the shutdown signal (active low).
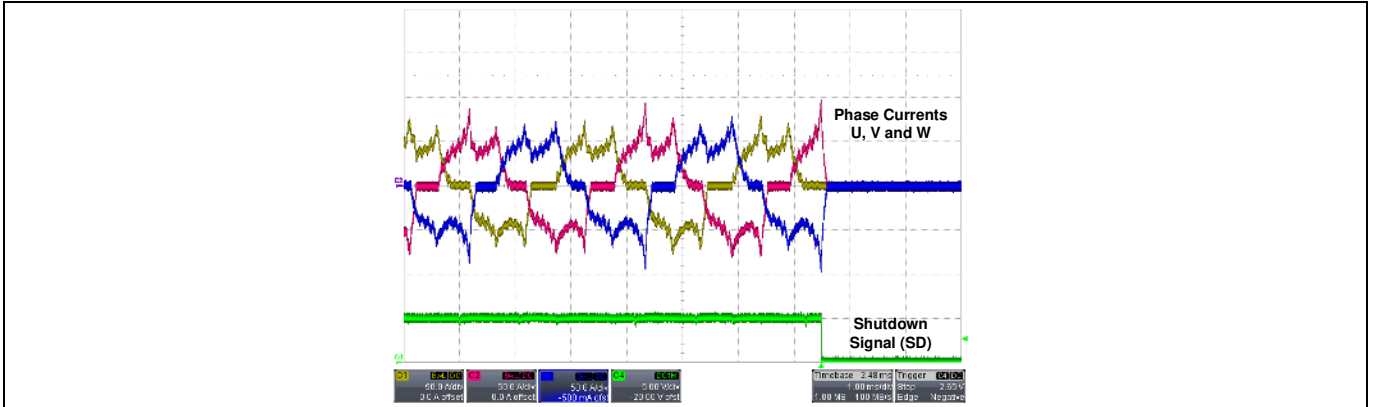
Figure 41   Current shutdown protection operation at 10000RPM rotor speed (50% Duty-Cycle)
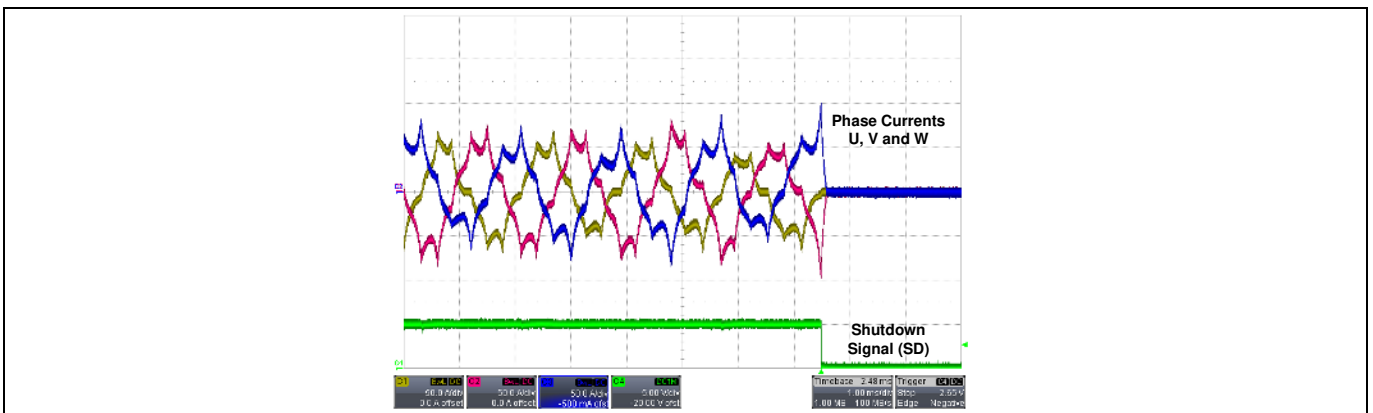

Figure 42   Current shutdown protection operation at 20000RPM rotor speed (100% Duty-Cycle)

1.6.3   Temperature Protection

When the system reaches a defined temperature set by "TEMPERATURE_SHUTDOWN_THRESHOLD" from the file "power_tools_kit_DirectFET.h", the gate pulses are automatically disabled. Such protection system is derived from an analogue-to-digital conversion of a voltage reading from the temperature sensor MCP9700T. Two tests have been performed: for rotor speed equal to 10000 RPM and 25.0 A_{RMS} of load (5.0 Nm torque) and 10000 RPM and 25.0 A_{RMS} of load (3.25 Nm torque). The monitored region is illustrated in the Figure 43.
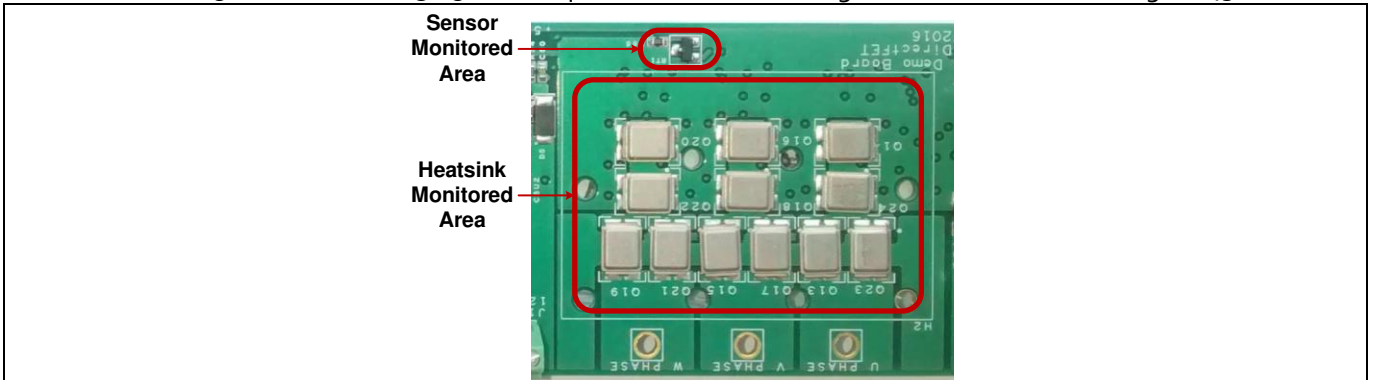
Figure 43   Monitored region for the heatsink temperature and sensor temperature data acquisition via a thermal camera

The two tests are illustrated in Figure 44 andFigure 45. For these waveforms, the yellow trace (channel 1) represents the hall sensor output from phase U, the blue trace (channel 3) represents the shutdown signal from the microcontroller, the magenta trace (channel 2) represents sensor output and green trace (channel 4) illustrates the phase current. For both cases, the phase current was set to be approximately 25.0 A$_{RMS}$.
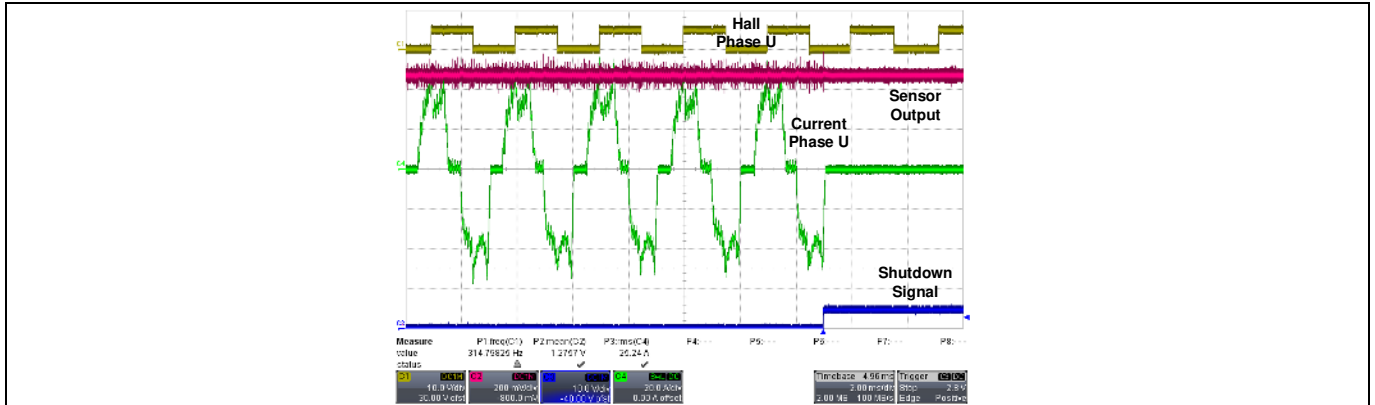

Figure 44   Temperature shutdown protection operation at 10000RPM rotor speed (50.0% Duty-Cycle/25.0 ARMS)
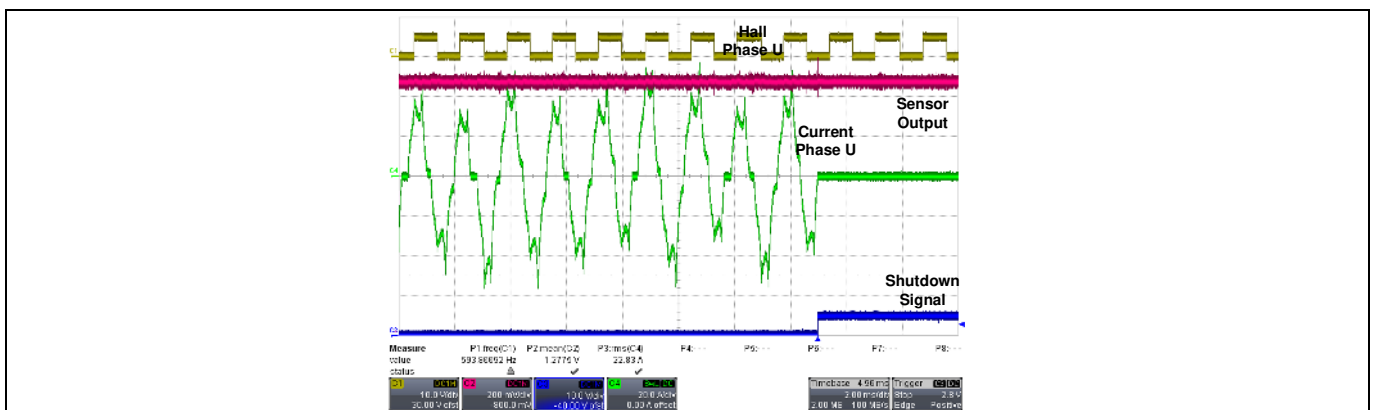
Figure 45   Temperature shutdown protection operation at 20000RPM rotor speed (100.0% Duty-Cycle/25.0 ARMS)

Considering the total time for temperature shutdown, the temperature data is recorded and illustrated in Figure 46 and Figure 47. For both cases, as seen in the recorded data, the shutdown acts when the sensor temperature is approximately 80°C. The time for system shutdown is about 4.5 minutes for 10000.0 RPM and about 4.0 minutes for 20000.0 RPM.
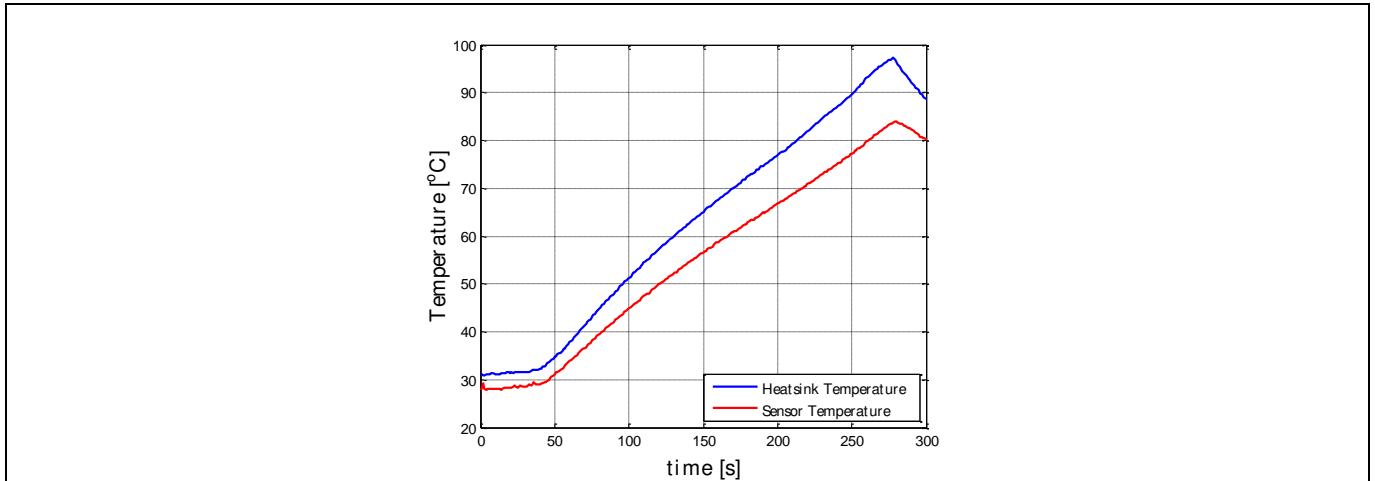
Figure 46 Temperature shutdown protection operation at 10000RPM rotor speed (50% Duty-Cycle/25.0 ARMS)
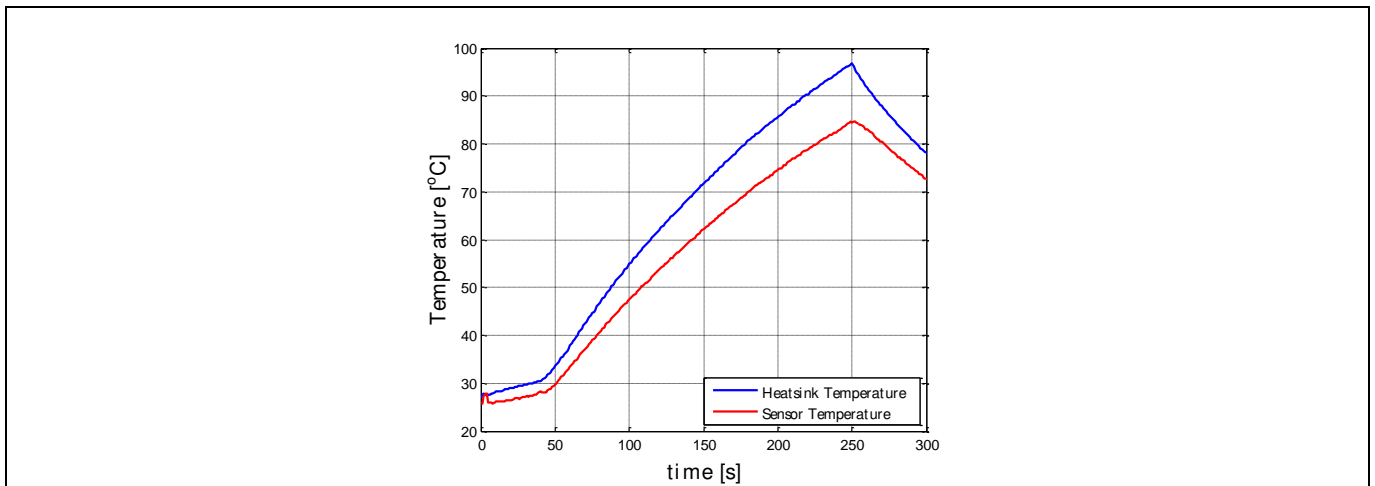

Figure 47 Temperature shutdown protection operation at 20000RPM rotor speed (100% Duty-Cycle/25.0 ARMS)

1.7   Operating Principle

The motor control algorithm implemented in the XMC[TM]1300 family is based on a speed control block commutation algorithm of the BLDC motor. The microcontroller has access to the terminal of three hall sensors, and according to the pattern generated from the combined output states, the proper switching sequence of the PWM signals are generated. In addition, input voltage, input current and temperature are digitized in order to provide protection means for safe operation of the motor.

A simplified diagram of a two poles BLDC motor is illustrated in Figure 48 where the coils are displaced by 120°. No brushes are necessary, since the commutator is replaced by a six-switch bridge inverter (Figure 49)
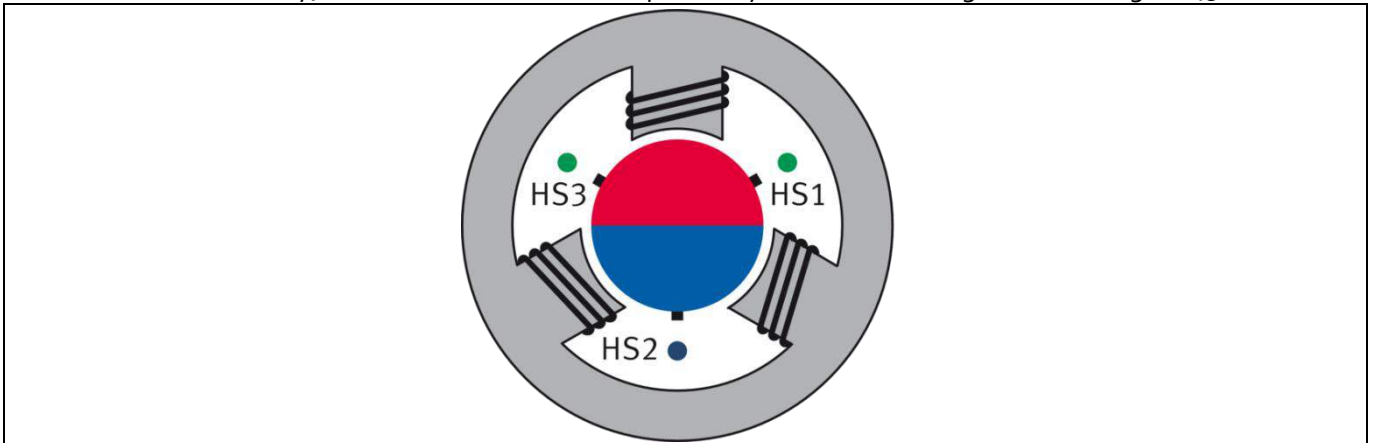

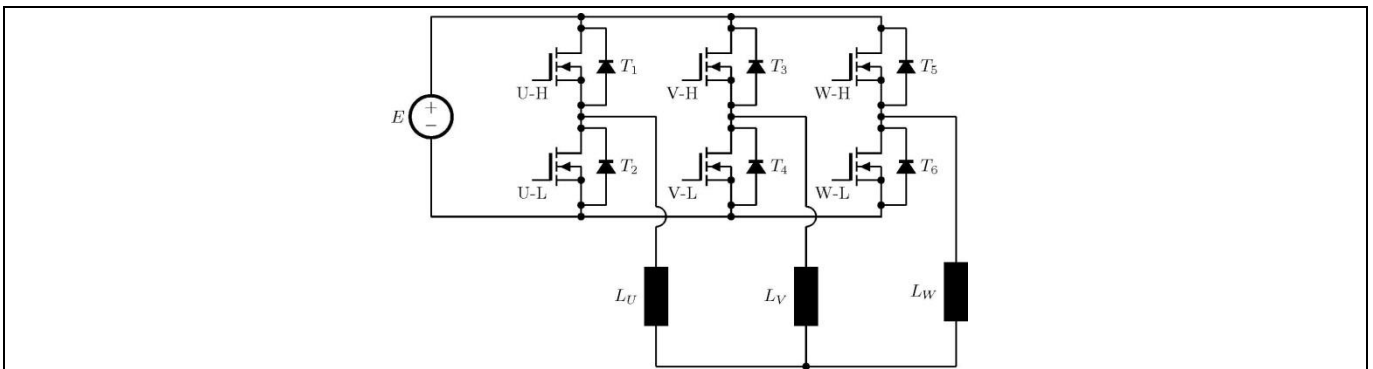**Figure 48   Simplified diagram of a 2 poles BLDC motor**

Figure 49   Simplified diagram of a 6-switch inverter bridge

By properly controlling the states of the MOSFETs in the inverter circuitry of Figure 49, one can precisely control the magnetic flux on the coils of the motor stator. Moreover, the speed of the rotor can be regulated by adjusting the PWM duty cycle.

The speed is directly measured using thee hall sensors. With the pattern created by the output of this rotor positioning method, the control system is able to identify the proper PWM pattern which must be applied to the inverter switches.

Depending on the hall pattern presented by the current position of the motor, the high side and low side of all phases are modulated. Considering the pattern shown in Figure 50, the output of the hall sensors (red traces and considering the phase U the LSB and phase W the MSB) can present the set {6, 4, 5, 1, 3, 2}. POSIF0 and CCU8 of the XMC[TM]1300 family is going to create the PWM pattern (blue traces) using the multi-channel patterns {0x120, 0x 021, 0x201, 0,210, 0x012, 0x102, 0x120} for unipolar block commutation and {0x320, 0x 023, 0x203, 0,230, 0x032, 0x102, 0x320} for the case with synchronous rectification.
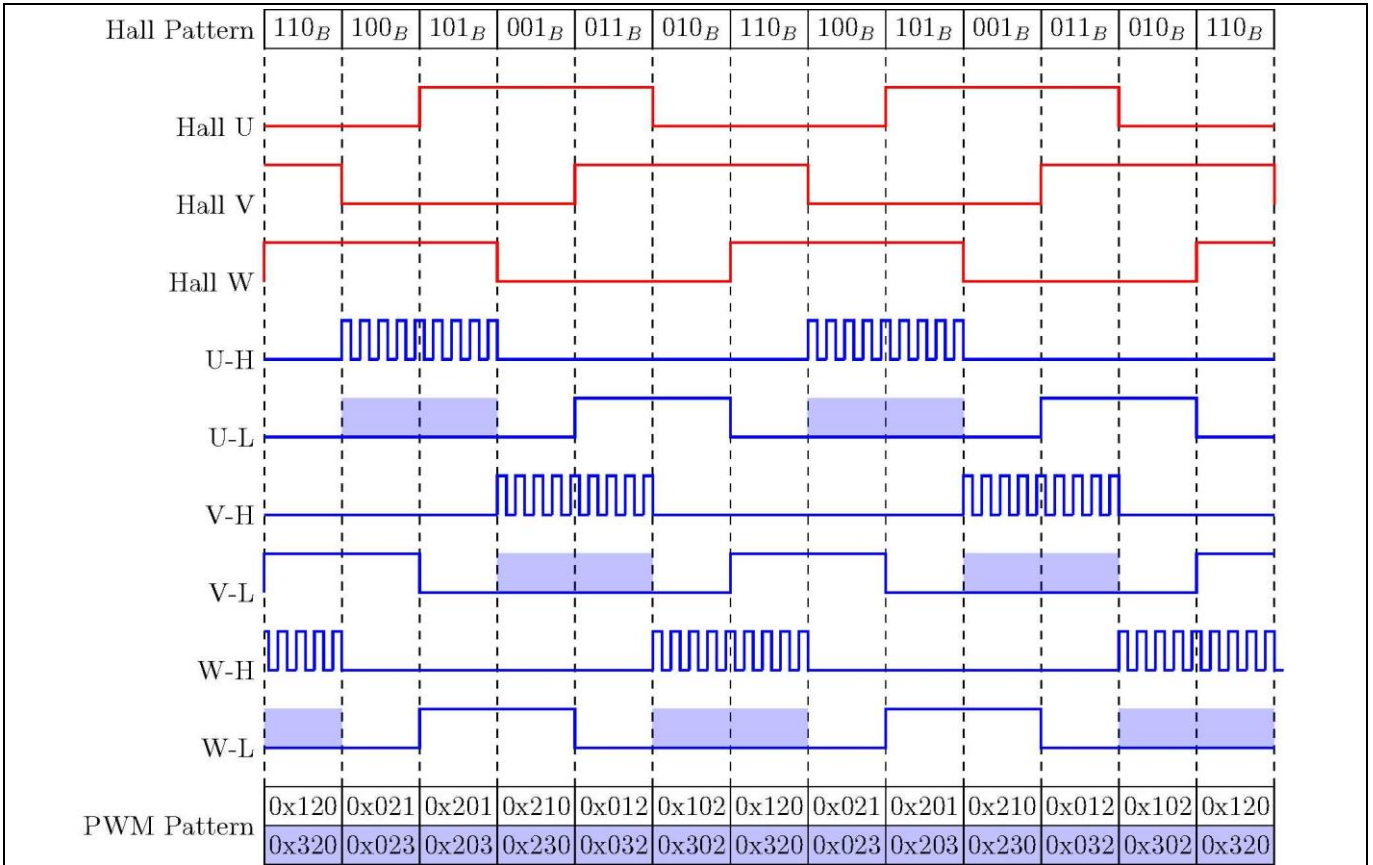
Figure 50   Hall and PWM patterns and switching states for a BLDC motor drive

The numbers presented in the PWM pattern set are related to the combined states of the high side and low side switches. For instance, for the first element of the set {0x120}, the phase W is addressed with the number "1" (MSB), phase V with "2" and phase U with "0" (LSB). For each of the three cases, "0", "1", "2" or "3" the PWM signals of the respective phase are selected to be all off, only high side switch modulating, only low side switch modulating or both switches modulating in a complementary manner and with a selected dead-time, respectively. For more details in the generation of the multi-channel pattern, the XMC documentation is available in (Infineon Technologies AG, 2014).

From the parameters of Table 4, MODULATION (3), HALL_PAT_A, B, C, D, E and F (22) and MC_PAT_A, B, C, D, E and F (23) indirectly combine the hall pattern and Multichannel PWM patterns required by the BLDC modulation. Selection of MODULATION using BLDC_SCALAR_PWM_HIGHSIDE or BLDC_SCALAR_PWM_HIGHSIDE_SYNCHRECTI selects the non-synchronous or synchronous rectification cases. For the Multichannel PWM pattern, the phase labels and (W,V and U) and the switches states (High (H), Low (L) and Off (OFF)) are grouped into a single string with phase W as MSB and phase U as the LSB. Figure 51 illustrates the multichannel PWM string structure for definition of the modulation patterns for the BLDC drive code.

Phase W	State	Phase V	State	Phase U	State
W	H (High), L (L), OFF	V	H (High), L (L), OFF	U	H (High), L (L), OFF

Figure 51   Sequence of phases in the Multichannel PWM string structure

For the unipolar block commutation modulation, for each of the patterns from theFigure 50, the circuit will present two switching states.

The active phase is selected when one of the high side switches of one of the phases is going to be activated. From the other two phases in the sequence, a low side switch is also kept in the active state. This stage represents the phase where the input supply is directly connected to the load.

The freewheeling stage happens after the high side switch is turned off by grounding the respective gate signal. The body of the low side MOSFET of the same phase conducts the inductor current.

All the switching states for the unipolar block commutation and the respective PWM pattern number are represented in Table 5.

Table 5   **Switching states for a unipolar block commutation considering the positive half-cycle of the motor currents.**

Table 5   **(Continued)**

	Active Phase	Freewheeling Phase
(0x102) WH_VOFF_UL		
(0x120) WH_VL_UOFF		
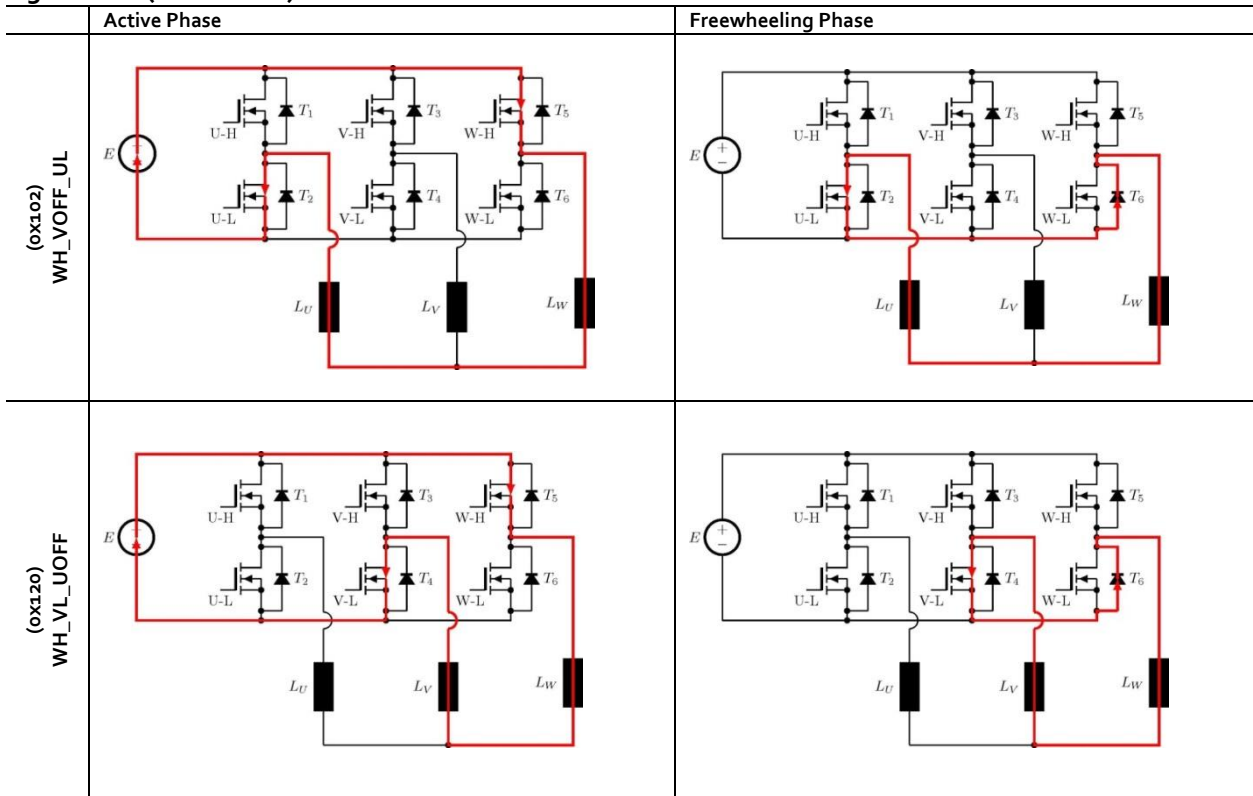
For the unipolar block commutation with synchronous rectification, not only the active and freewheeling stages are present, but a third phase is also generated in order to minimise the conduction time of the body diode of the low side MOSFET. Therefore, this technique aims to improve the total losses in the system.

Active phase and freewheeling phase are represented by the same switching topological states from Table 5. However, due to the synchronous rectification, the low side MOSFET channel operates in the complementary mode with the high side switch and the freewheeling stage present only during the dead-time operation. Table 6 contains all the three switching states for the synchronous rectification cases as well as the respective PWM patterns.

Table 6   **Switching states for a unipolar block commutation with synchronous rectification considering the positive half-cycle of the motor currents.**
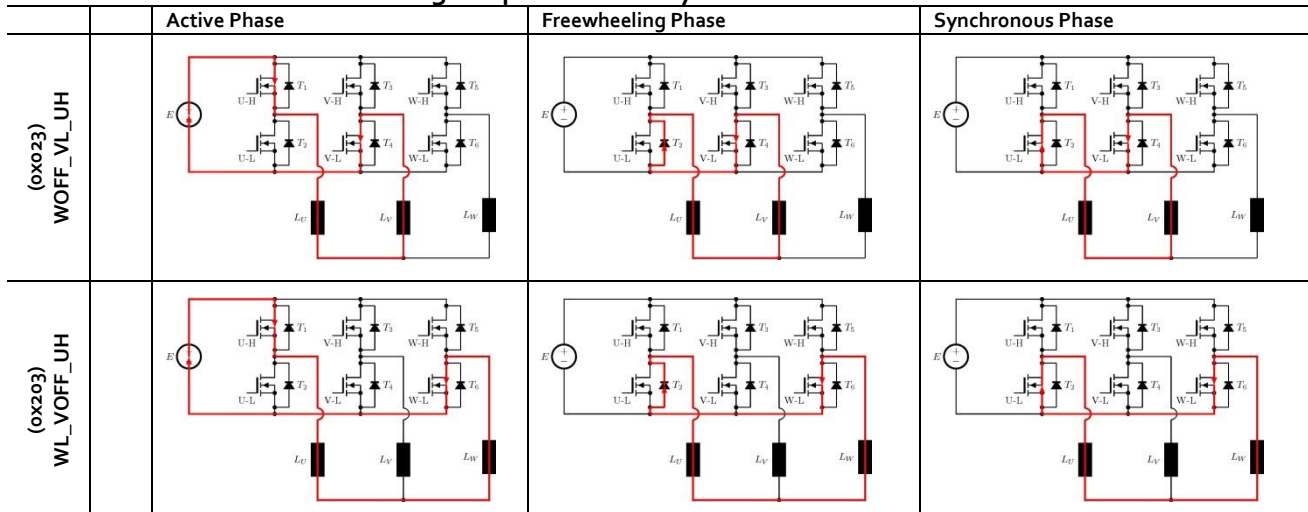
	Active Phase	Freewheeling Phase	Synchronous Phase
(0x023) WOFF_VL_UH			
(0x203) WL_VOFF_UH			

Table 6　　　**(Continued)**

		Active Phase	Freewheeling Phase	Synchronous Phase
(0x230) WL_VH_UOFF				
(0x032) WOFF_VH_UL				
(0x302) WH_VOFF_UL				
(0x320) WH_VL_UOFF				

1.8 Schematic and PCB layout:

In this section the schematic and PCB layout for our demo board are provided. Figure 52 shows the schematic of the demo board. The PCB has 4 layers. The outer layers are 2 oz. copper and inner layers 1 oz. All layers are shown in Figure 53 to Figure 58, including silk screen for top and bottom layers.
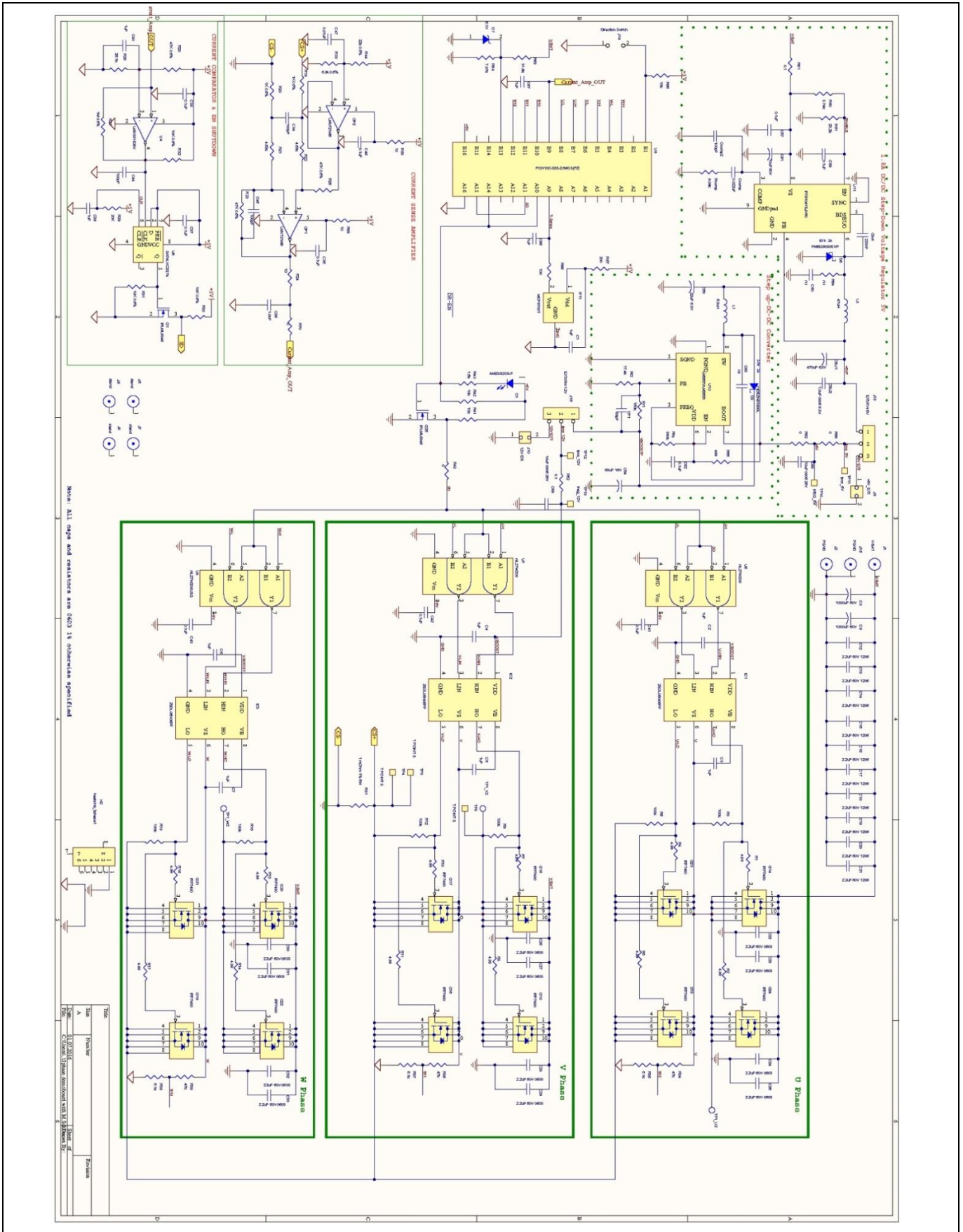
Figure 52   Schematic of the demo board
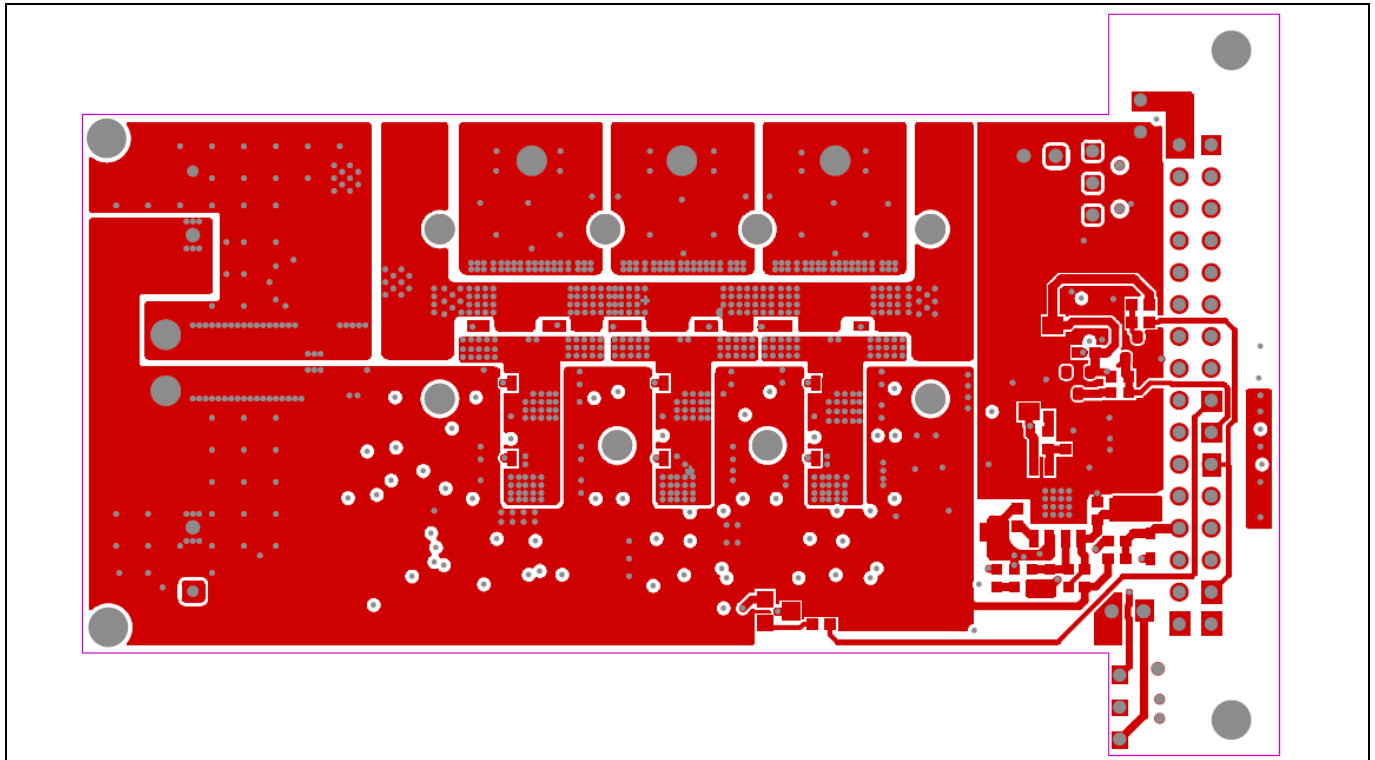
Figure 53   Top layer copper
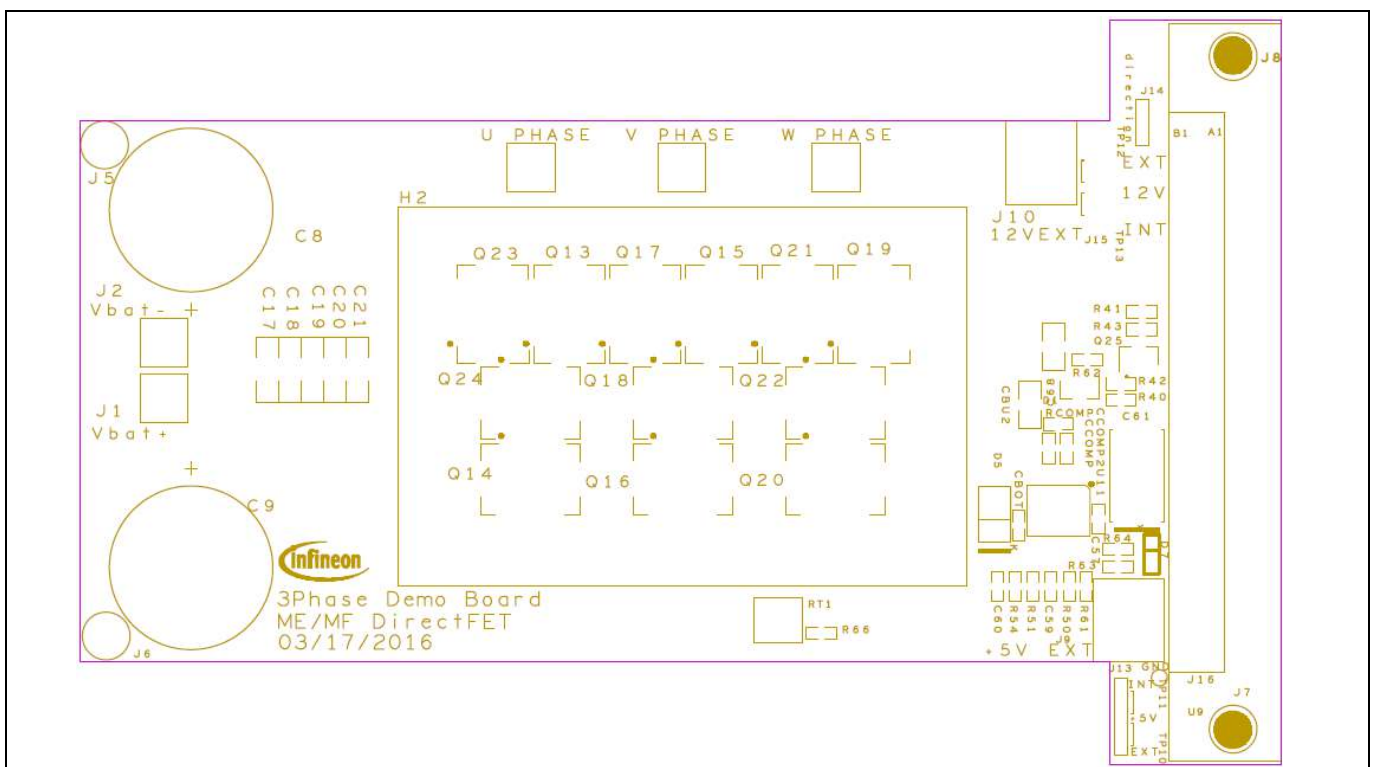
Figure 54   Top layer silk screen
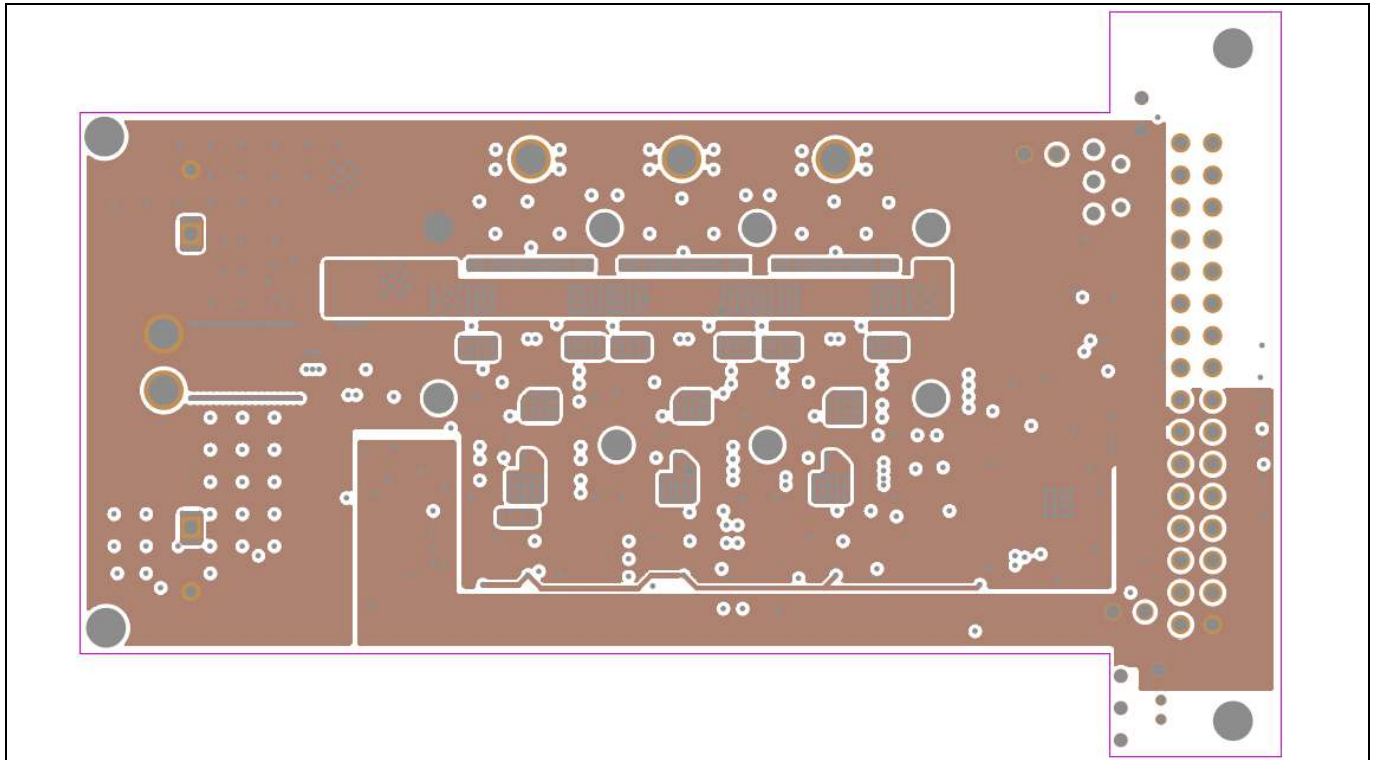
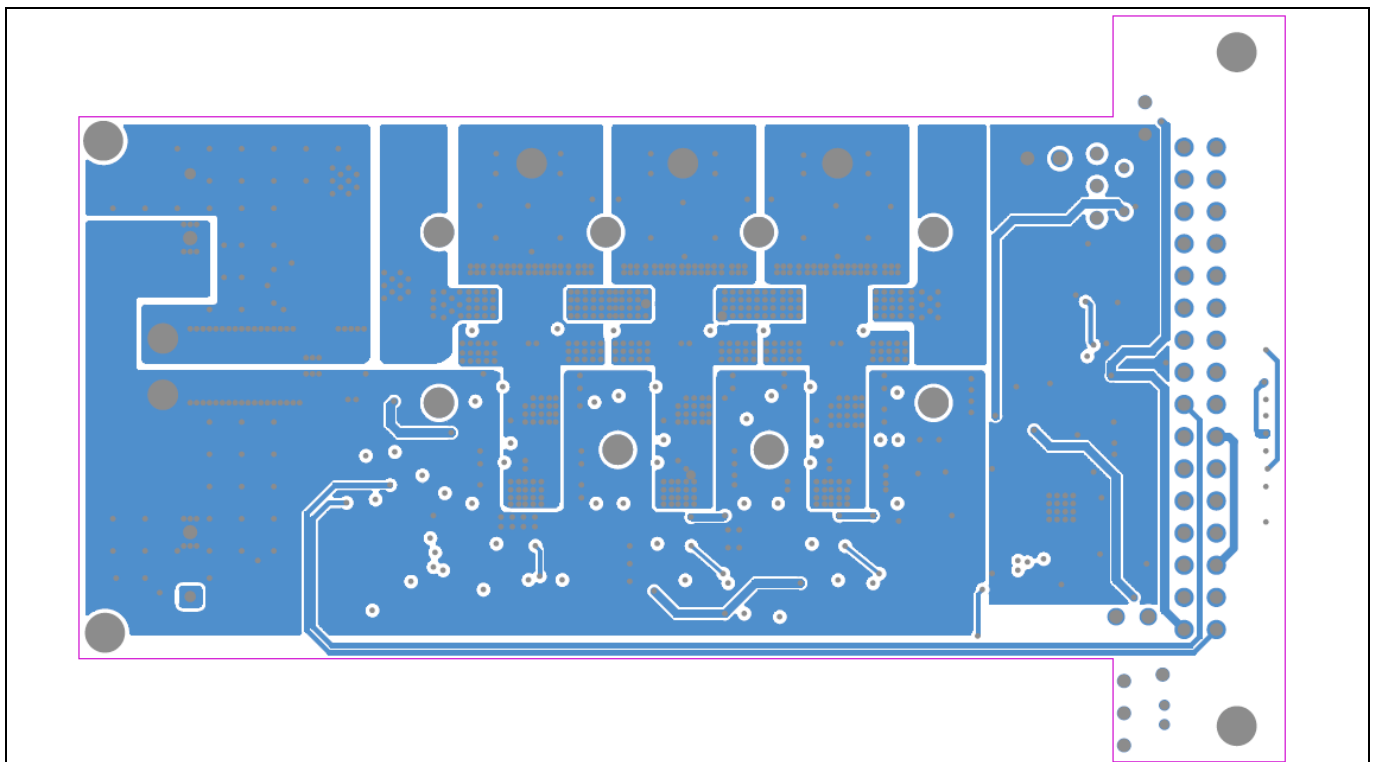**Figure 55   Middle layer 1 copper**

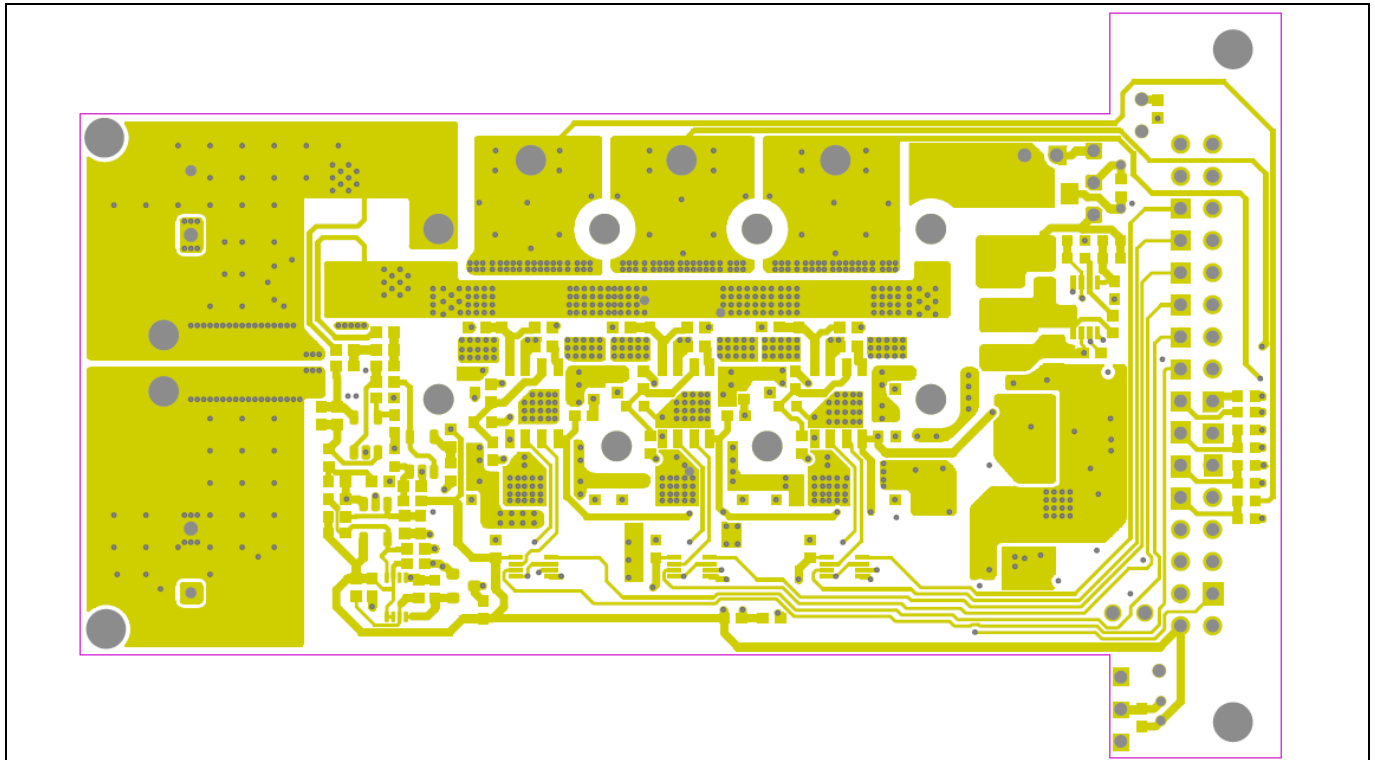**Figure 56   Middle layer 2 copper**
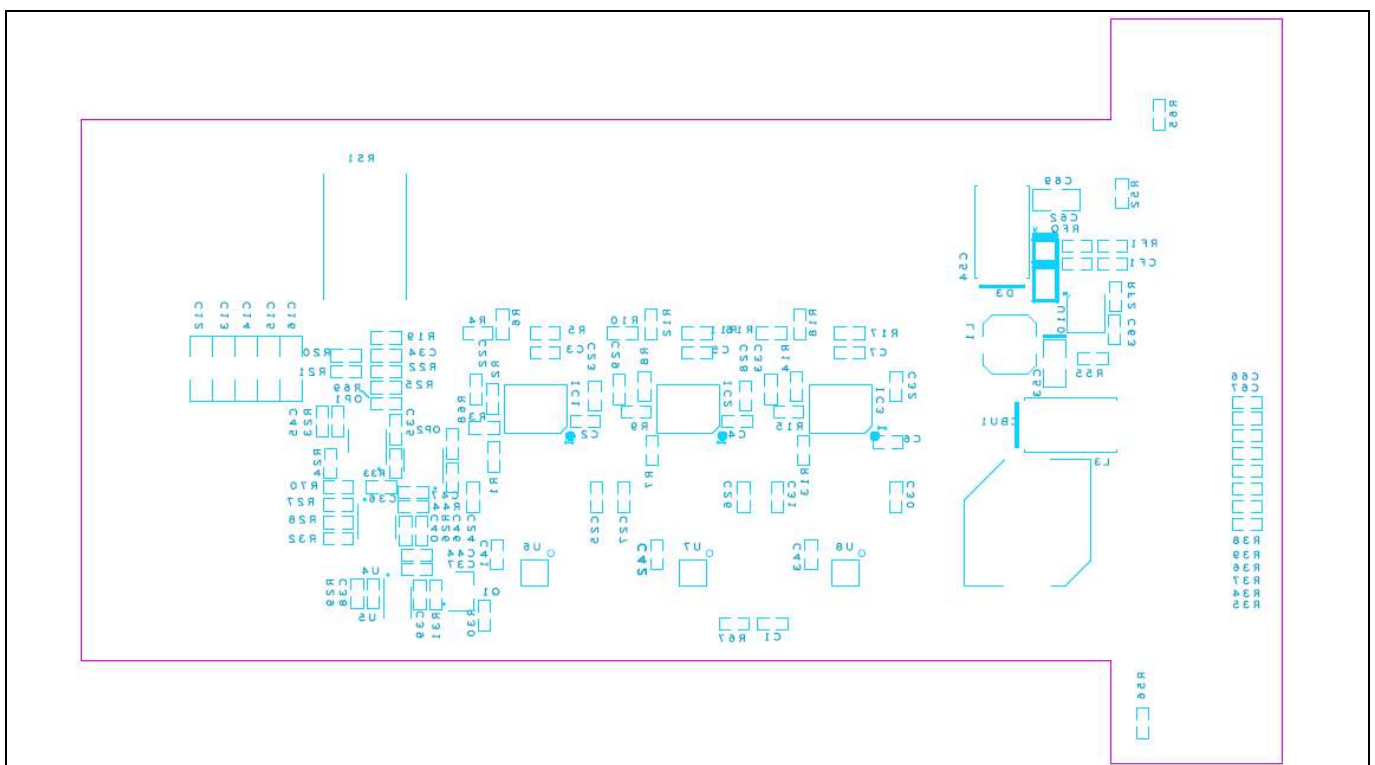
Figure 57   Bottom layer copper

Figure 58   Bottom layer silk screen

1.9 Bill of Materials

Bill of Material is shown in Table 7.

Table 7   Bill of Materials

Item Number	Quantity	Part Reference	Part Description	Value	PCB Footprint	Part Number
1	11	C1,C2,C3,C4,C5,C6,C7, C39,C40,C66,C67	Cap Cer. 1uF 25V 20% 0603 X7R	1uF	C0603	C1608X7R1E105M
2	2	C8,C9	Cap 1000uF 50V Electrolytic Capacitor	1000uF 50V	cap16x25mm	EKZE500ELL102ML2
3	10	C12,C13,C14,C15, C16,C17,C18,C19,C20,C21	Cap Cer.2.2uF 50V X7R 1206	2.2uF 50V 1206	C1206	C3216X7R1H225K160AB
4	12	C22,C23,C24,C25,C26,C27, C28,C29,C30,C31,C32,C33	Cap Cer.2.2uF 50V X7R 0603	2.2uF 50V 0603	C0603	GRM188R61H225kE11D
5	4	C34,C44,C45,CCOMP2	Cap Cer. 100pF 50V 5% 0603 NPO	100pF	C0603	C0603C101J3GACTU
6	10	C35,C37,C38,C41,C42, C43,C46,C57,C59,C62	Cap Cer. 0.1uF 50V 10% 0603 X7R	0.1uF	C0603	C1608X5R1H104M
7	1	C36	Cap Cer. 1.0nF 50V 20% 0603 X7R	1.0nF	C0603	C1608X7R1H102M080AE
8	1	C47	Cap Cer. 0.01uF 50V 10% 0603 X7R	0.01uF	C0603	C1608X5R1E103M
9	1	C53	Cap Tant Poly 22UF 6.3V 0805	22uF 6.3V	C0805	TCJR226M006R0500
10	1	C54	Tantalum Capacitors - Polymer SMD 16volts 68uF 20% ESR=50mohms	68uF 16V	7343	T521V686M016ATE050
11	20	C60,C63,J1,J2,J5,J6,J7 ,J8,J16,R54,TP3,TP4,TP8,TP10, TP11,TP12,TP13, TP1_U2,TP1_V2,TP1_W2		NI	-	open
12	1	C61	CAP TANT 10UF 50V 10% 2917	10uF 50V	7343	T491D106K050AT
13	2	C68,C69	Cap Cer. 10uF 25V 10% 0805 X5R	10uF 0805 25V	C0805	C2012X5R1E106K085AC
14	1	CBU1	CAP TANT 470UF 6.3V 10% 2917	470uF 6.3V	7343	T491D477K006AT
15	1	CBU2	Cap Cer. 1.0uF 6.3V 10% 0805 X7R	1.0uF 0805 6.3V	C0805	CGJ4J2X7R0J105K125AA
16	1	CF1	Cap Cer. 39PF 50V CoG 0603	39pF	C0603	C1608C0G1H390J080AA
17	1	CBOT	Cap Cer. 220nF 50V 10% 0603 X7R	220nF	C0603	C1608X7R1H224K080AB
18	1	CCOMP	Cap Cer. 0.022uF 50V 10% 0603 X7R	0.022uF	C0603	C1608X7R1H223M080AA
19	1	D1	LED GREEN DIFFUSED TO236-3 SMD	AM23SGD3-F	sot95p233p	AM23SGD3-F
20	1	D3	Diode Schottky 30V 3A	DB2W31900L	SOD123	DB2W31900L
21	1	D5	Diode Schottky 60V 3A	PMEG6030EVP	SOD128	PMEG6030EVP
22	1	D7	Zener Voltage 500mW SOD-523 SMD	5.1V	sod523	MM5Z5V1T1G
23	1	H2	Heat Sink	heatsink_3phase1	heatsink_3phase_2	S08CDY04
24	3	IC1,IC2,IC3	600V half bridge gate drive IC	2EDL05N06PF	pg-dso-8-51	2EDL05N06PF
25	2	J9,J10	Terminal block 2P 2.54mm 90DEG	+5V_EXT	6Aterminal	1725656
26	2	J13,J15	Test point,233mil,40mils,3 pin	EXT/ITN 5V	jumper3	TSW-103-08-LS
27	1	J14	Test point,233mil,40mils,2 pin	Direction Switch	jumper	TSW-102-08-LS
28	1	L1	Inductor 6.8uH DCR=0.150Ohm 1.2A	6.8uH	LPS4018	LPS4018-682MR
29	1	L3	inductor 47uH DCR=120Ohm	47uH	MSS1048T	MSS1048T-473ML
30	2	OP1,OP2	IC OPAMP GP 10MHZ RRO SOT23-5	LMV721M5	sot95p235p	LMV721M5
31	2	Q1,Q25	30V Single N-Channel Power MOSFET in a Micro 3 63mOHM	IRLML6346	sot95p233p	IRLML6346
32	12	Q13,Q14,Q15,Q16,Q17,Q18, Q19,Q20,Q21,Q22,Q23,Q24	Direct FET N Channel 40V	IRF7480	ir_dirfet_me	IRF7480M
33	12	R1,R2,R4,R5,R7,R8,R10, R11,R13,R14,R16,R17	Res.4.99 Ohm 1% 0603	4.99	R0603	RC0603FR-074R99L
34	6	R3,R6,R9,R12,R15,R18	Res. 100k 1% 0603	100k	R0603	ERJ-3EKF1003V
35	3	R19,R20,R24	Res.1K 0.5% 0603	1K 0.5%	R0603	RT0603DRD071KL

Table 7   **(Continued)**

Item Number	Quantity	Part Reference	Part Description	Value	PCB Footprint	Part Number
36	2	R21,R22	Res.4.53K 1% 0603	4.53k	R0603	ERJ-3EKF4531V
37	3	R23,R25,R28	Res.47K 0.5% 0603	47K 0.5%	R0603	RT0603DRD0747KL
38	1	R26	Res.26.1K 1% 0603	26.1k	R0603	ERJ-3EkF2612V
39	1	R27	Res.1M 0.5% 0603	1M 0.5%	R0603	CRCW06031M00DHEAP
40	1	R29	Res.20K 1% 0603	20K	R0603	ERJ-3EKF2002V
41	3	R30,R31,R32	Res.10K 0.5% 0603	10K 0.5%	R0603	RR0816P-103-D
42	1	R33	Res.5.9K 0.5% 0603	5.9k 0.5%	r0603	RT0603DRD075K9L
43	3	R34,R36,R38	RES SMD 47K OHM 1% 1/16W 0603	47k	R0603	ERJ-3EKF4702V
44	3	R35,R37,R39	Res.5.1K 1% 0603	5.1k	R0603	ERJ-3EKF5101V
45	1	R40	Res.1.5K 1% 0603	1.5k	R0603	ERJ-3EKF1501V
46	3	R41,R42,R65	Res.10K 1% 0603	10k	R0603	ERJ-3EKF1002V
47	4	R43,R56,R62,R70	Res.0OHM 1% 0603	0	R0603	ERJ-3GEY0R00V
48	1	R44	Res.22K 0.5% 0603	22k 0.5%	R0603	RR0816P-223-D
49	1	R50	Res.3.74K 1% 0603	3.74k	R0603	CRCW06033K74FKEA
50	1	R51	Res.23.2K 1% 0603	23.2k	R0603	ERJ-3EKF2322V
51	2	R52,R61	Res. 0.1Ohm 1% 0603	0.1	R0603	WSL0603R1000FEA
52	1	R55	Res.499Ohm 1% 0603	499	R0603	ERJ-3EKF4990V
53	1	R63	Res.31.6K 1% 0603	31.6k	R0603	RK73H1JLTD3162F
54	1	R64	Res.7.87K 1% 0603	7.87k	R0603	ERJ-3EKF7871V
55	1	R66	Res.100 Ohm 1% 0603	100	R0603	ERJ-3EKF1000V
56	1	R67	Res.200 Ohm1% 0603	200	R0603	RK73H1J2000F
57	2	R68,R69	Res.10 Ohm 1% 0603	10	R0603	RK73H1JLTD10R0F
58	1	RS1	Res.1 mOhm 1% 5W	1 mOhm 1% 5W	hcs3920ft1l00	HCS3920FT1L00
59	1	RT1	Sensor Temp Radiometric	MCP9700T	sot23	MCP9700T
60	1	RCOMP	Res 9.09K 1% 0603	9.09k	R0603	RK73H1JTTD9091F
61	1	RF1	Res.150K 1% 0603	150k	R0603	ERJ-3EKF1503V
62	1	RF2	Res.17.4K 1% 0603	17.4k	R0603	ERJ-3EKF1742V
63	1	RFQ	Res.390K 1% 0603	390k	R0603	ERJ-3EKF3903V
64	1	U4	IC OPAMP GP 10MHZ RRO SOT23-5	LMV331IDBV	sot95p235p	LMV331DBV
65	1	U5	Single Positive-Edge-Triggered D-Type Flip-Flop	SN74LVC2G74	sop50p310x90-8l15n	SN74LVC2G74
66	3	U6,U7,U8	Dual2-Input AND gate	NL27WZ08	NL27WZ08	NL27WZ08USG
67	1	U9	DIN 41612 Connectors 32P R/A RECEPT T/H PCN 10 SERIES	PCN10C-32S-2.54DS(72)	con32pinfemale	PCN10C-32S-2.54DS(72)
68	1	U10	Low Input Voltage, Step-Up DC-DC Converter	LM2621/LM2623	LM2621	LM2621
69	1	U11	600V half bridge gate drive IC	IFX91041EJV50	IFX91041	IFX91041
70	8	Heatsink screw	type M2x6 7985-A4	-	M2x6 7985-A4	MPPXX02006-100M1
71	1	Gap pad	Gap pad 5000 S35	-	-	-
72	3	Shunt	CONN SHUNT 2POS	-	-	SNT-100-BK-T

2 Hall Learning Procedure

1) Download and install Dave V4.2.6

2) Import project according to instructions in section 1.5

3) Connect USB cable to connector X202, Hall sensors connections to connector X203 (to pins 2, 3, 4 order not important). Connect Motor wires (phase wires, order not important) and Power wires from external Supply (Set for 20V, 1A. Current can later be increased for normal operation).

4) Under C/C++ Projects, click on the file: BLDC_SCALAR_HALL_XMC13_Power_Tool. This file contains the actual code to be compiled after any changes. The changes to the different parameters are made in a separate file: **power_tools_kit_DirectFET.h** which is called by reference. To view or to make changes to the contents of this file double click on it. The path is: (BLDC_SCALAR_HALL_XMC13_Power_Tool **>>** Power_Tools_Kit_DirectFET **>> power_tools_kit_DirectFET.h**)

5) From the Menu bar, select Project **>>** Build Project

6) Press the "Debug" icon on the toolbar

7) The "Perspective" window opens, press "yes" (if additional window opens, press "yes" as well)

8) On the toolbar, Press the "play" Icon. This initiates the Hall Learning. Now the correct sequence of Hall sensors and Phase motor windings has been stored in the program

9) **On the toolbar Press "Pause"**

10) The window "expressions" opens. (If it does not, go to Window >> Show View >>Expressions)

11) In the "Expressions" window click on the"Add new expression" and type: MC_Pattern_DEBUG, then click on the expand arrow on the upper left of this window. A list of 7 lines of numbers appears. **Write down** the six last numbers(ignore the first line number) **keeping the same order** as in the expressions window. You will be referring to the Table 8.

Table 8   Strings vs. Decimal Numbers for MC_Pattern_DEBUG

Decimal Numbers from Expression Window	String to be Inserted in Code	Hexadecimal form (for information only)
528	**WL_VH_UOFF**	0X210
18	**WL_VOFF_UH**	0X201
258	**WOFF_VL_UH**	0X021
288	**WOFF_VH_UL**	0X012
33	**WH_VOFF_UL**	0X102
513	**WH_VL_UOFF**	0X120

12) Exit the program. Then Start the program again. Open the file containing the code: "**power_tools_kit_DirectFET.h**". The path is:(BLDC_SCALAR_HALL_XMC13_Power_Tool **>>** Power_Tools_Kit_DirectFET **>> power_tools_kit_DirectFET.h**)

13) Insert each one of the Strings (Macros) in lines 98 through 103 in parenthesis in the same order they appeared when you copied them from the expressions window and converted to the string using table

14) On line 111 Disable learning by typing 0U (that's zero followed by letter "U") between parenthesis (it was 1U before)

15) Project >> Build Project

16) Press the "Debug" Icon

17) Press "Yes" on the perspective window that just opened

18) Right click on the Highlighted file (mailo at mail.c....) and choose "Terminate and remove"

19) Disconnect the USB cable, power down the external supply

20) Motor should be ready to run. Make sure to turn the speed pot on the control card to the minimum position before the next power-up.

3   Bibliography

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Attention:

Revision History

Major changes since the last revision

Page or Reference	Description of change