EVAL_DRIVE_3PH_PFD7

3-PH motor drive evaluation board with FOC sensorless control

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About this document

This application note provides an overview of the evaluation board EVAL_DRIVE_3PH_PFD7, including its main features, key data, pin assignments, schematics and layout. It also describes how to quickly get started with this kit and take advantage of Infineon's CoolMOS™ PFD7 superjunction (SJ) MOSFETs, 2ED gate-driver IC and microcontroller iMOTION™ IMC100 series.

Scope and purpose

EVAL_DRIVE_3PH_PFD7 is a three-phase motor drive evaluation board with sensorless Field Oriented Control (FOC), which demonstrates Infineon's latest SJ technology tuned specially for motor drives by introducing a complete system-level solution using discrete inverters to control and drive three-phase motors.

The evaluation board EVAL_DRIVE_3PH_PFD7 was developed to support customers in the first steps of designing a three-phase inverter stage for the target applications.

The Infineon components used in the motor drive evaluation board are:

- IPN60R1K5PFD7S 600 V CoolMOS™ PFD7 MOSFET

- 2ED28073J06F 600 V half-bridge gate-driver IC (EiceDRIVER™)

- IMC101T-T038 iMOTION™ microcontroller

- BAT54-03W silicon Schottky diode

- IFX1117ME V33 3.3 V low drop-out voltage regulator

Intended audience

This application note is intended for all technical specialists who aim to reduce system cost and improve light-load efficiency, which in turn will enable longer run-time and reduce time-to-market.

Table of contents

1 Safety precautions

In addition to the precautions listed throughout this manual, please read and understand the following statements regarding hazards associated with development systems.

Table 1 **Precautions**

⚠	**Attention:** The ground potential of the EVAL_DRIVE_3PH_PFD7 system is biased to a negative DC bus voltage potential. When measuring voltage waveform by oscilloscope, the scope's ground needs to be isolated. Failure to do so may result in personal injury or death.
⚠	**Attention:** Only personnel familiar with the drive and associated machinery should plan or implement the installation, start-up and subsequent maintenance of the system. Failure to comply with this may result in personal injury and/or equipment damage.
⚠	**Attention:** The surfaces of the drive may become hot, which may cause injury.
⚠	**Attention:** The EVAL_DRIVE_3PH_PFD7 system contains parts and assemblies sensitive to Electrostatic Discharge (ESD). Electrostatic control precautions are required when installing, testing, servicing or repairing this assembly. Component damage may result if ESD control procedures are not followed. If you are not familiar with electrostatic control procedures, refer to applicable ESD protection handbooks and guidelines.
⚠	**Attention:** An incorrectly applied or installed drive can result in component damage or reduction in product lifetime. Wiring or application errors such as under-sizing the motor, supplying an incorrect or inadequate AC supply, or excessive ambient temperatures may result in system malfunction.
⚠	**Attention:** Remove and lock out power from the drive before you disconnect or reconnect wires or perform a service. Wait 3 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.
⚠	**Attention:** The EVAL_DRIVE_3PH_PFD7 system contains DC bus capacitors which take time to discharge after removal of the mains supply. Before working on the drive system, wait 3 minutes for capacitors to discharge to safe voltage levels. Failure to do so may result in personal injury or death.

2 Introduction

Motors are a key part of many appliances. So far, the traditional approach has been based on (on/off) control with no speed control techniques. This leads to a much higher power consumption.

On the other hand, inverterization is the technique commonly used today, where an inverter converts power from DC to AC. This means the end application not only runs much more quietly and smoothly, but also the inverterized solution helps to reduce average power consumption in comparison to the traditional on/off control.

Infineon aims to make the world an easier and greener place by delivering highly energy-efficient semiconductor solutions at its best performance. In this application note we focus on developing a complete system design to help customers reduce time-to-market. Infineon offers a range of products dedicated to motor applications such as iMOTION™ controllers, CoolMOS™ discrete SJ MOSFETs and EiceDRIVER™ gate-driver ICs. This covers complete solutions including applications for BLDC fans, refrigerators, pumps and low-power appliances.

The EVAL_DRIVE_3PH_PFD7 evaluation board is designed to make inverter power stage design easy by using discrete components based on Infineon's CoolMOS PFD7™ SJ MOSFETs, 2ED gate-driver IC and microcontroller iMOTION™ IMC100. This application note also provides information to enable customers to copy, modify and qualify the design for production according to their own specific requirements.
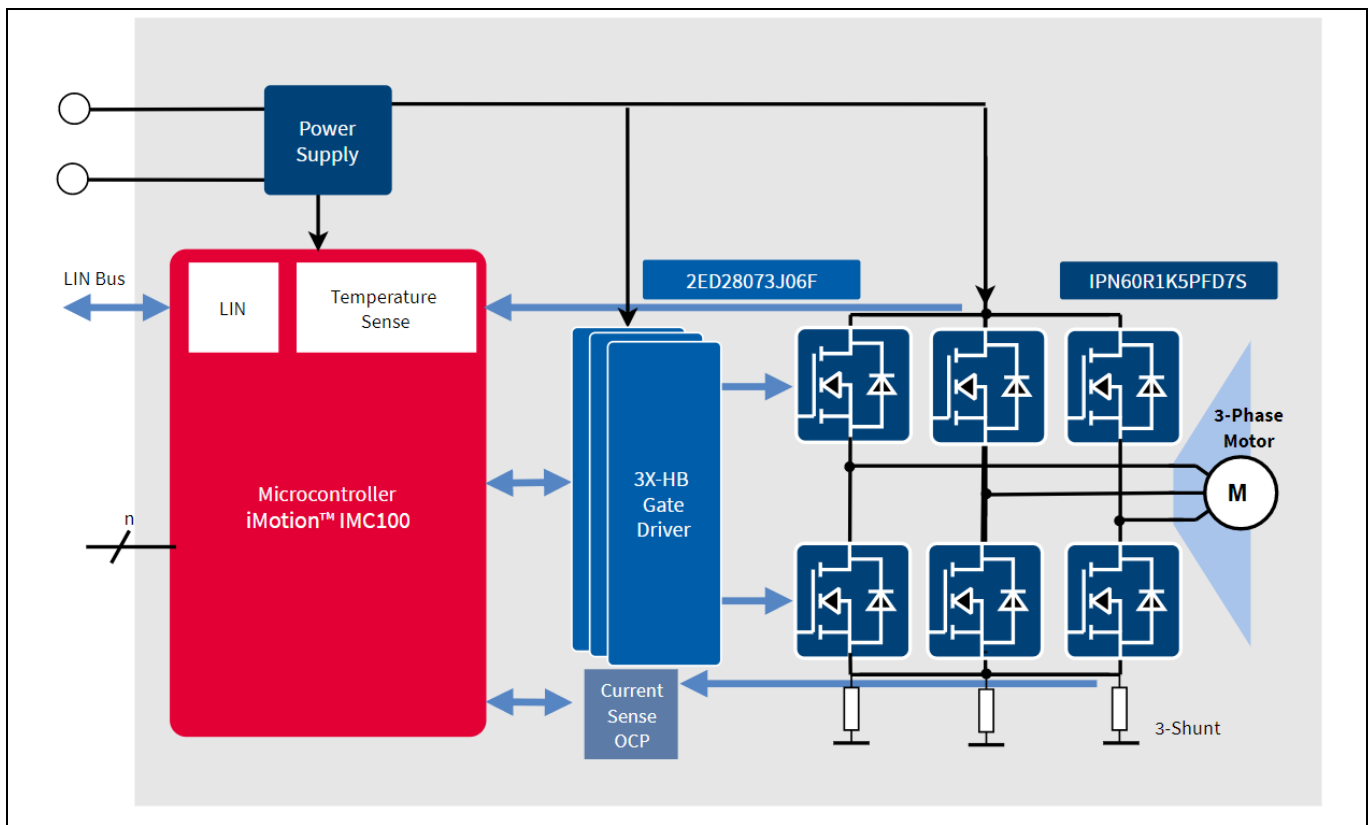
Figure 1   EVAL_DRIVE_3PH_PFD7 block diagram

The board is equipped with all assembly circuits to enable sensorless FOC, as described on the block diagram of the EVAL_DRIVE_3PH_PFD7 in Figure 1. This evaluation board includes a voltage divider for DC-link voltage measurement, EMI filter and eight-pin iMOTION™ interface connector, auxiliary power supply to provide +13 V and +3.3 V, with a single-phase AC input, rectifier and three-phase output for connecting the motor. The power stage contains three shunts for current sensing that can be easily modified for a single shunt configuration.

Introduction

The EVAL_DRIVE_3PH_PFD7 evaluation board uses the iMOTION™ platform, MCEDesigner™, which is a Windows-based application that allows you to read and write the memory of the iMOTION™ microcontrollers during run-time. It can be easily interfaced through iMOTION™ Link. This tool is designed to program and debug IMC100 and all future series of iMOTION™ motor control ICs. It is essential for tuning your motor control system.

Important note: *The* iMOTION™ Link *does not come in the box with the evaluation board – the kit must be ordered separately.*

2.1   Summary of features

- Low Bill of Materials (BOM) reducing the overall solution blueprint
- Smooth start-up using inductive sensing
- Best light-load efficiency solution
- Sensorless FOC
- Ease of use with Graphical User Interface (GUI)

2.2   Benefits

- Highly efficient
- Cost-effective
- Simplified design
- Accelerated time-to-market

2.3   Target applications

- Fans
- Fridges
- Pumps
- Small appliances

3 Design specification and features
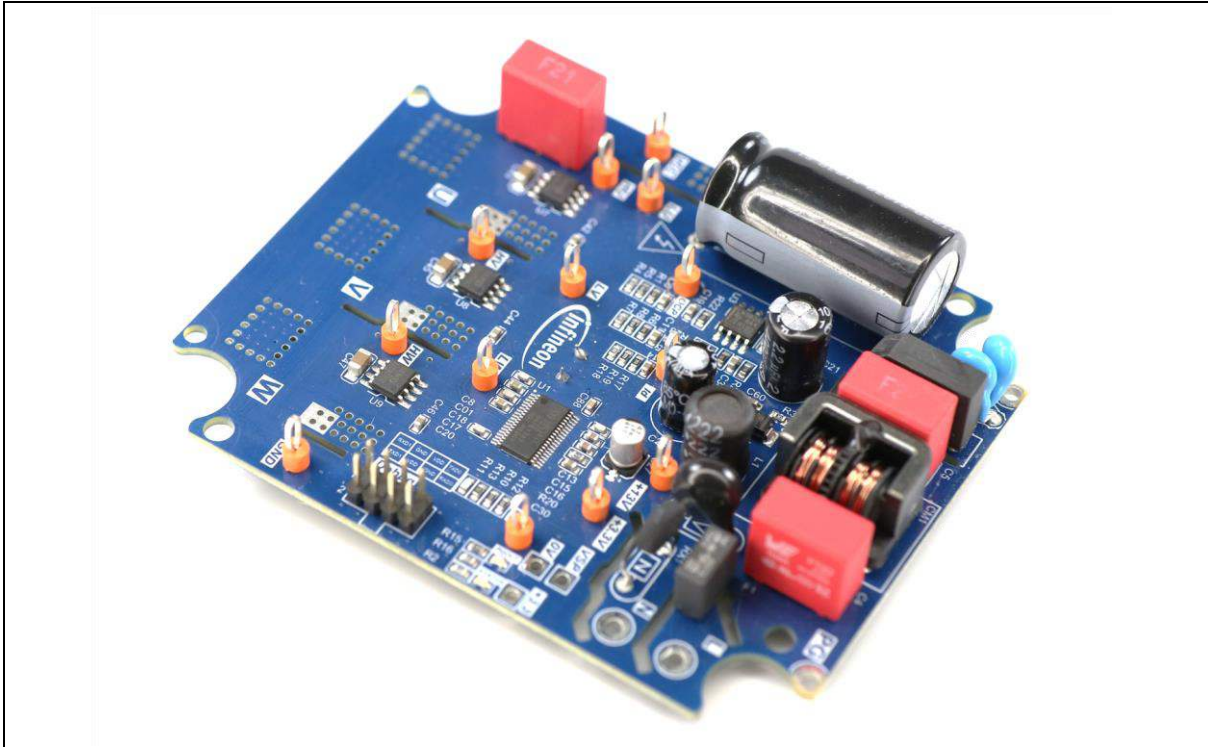
The EVAL_DRIVE_3PH_PFD7 is a complete evaluation board for motor drive applications. The kit demonstrates Infineon's latest discrete power SJ MOSFET CoolMOS™ PFD7 technology for motor drive applications.

Main features:

- Onboard EMI filter
- Current sensing for each phase configured by default
- Sensing of DC-link voltage
- +13 V, +3.3 V auxiliary power supply based on simple buck converter
- Compact design using 600 V CoolMOS™ PFD7 in SOT-223 package
- Integrated op-amp for current sensing and comparator within the iMOTION controller
- Onboard de-modulator for speed and on/off control using potentiometer
- Hardware and software Over Current Protection (OCP)
- Over Voltage (OV) and Under Voltage (UV) detection
- Fully customized for fridge compressor, air-conditioning outdoor fan and ceiling fan applications
- FOC sensorless algorithm-enabled smooth start-up using inductive sensing
- PCB dimensions: 93 x 74.5 x 18 mm

3.1 Key data

CoolMOS™ PFD7 is Infineon's latest series of SJ MOSFETs with an integrated fast body diode. It is the ideal choice for motor drive applications such as in-home appliances, in which there is a need for high efficiency under light-load conditions.

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Design specification and features

The fast reverse-recovery of CoolMOS™ PFD7 offers designers the benefits of reduced stress on the device while the body diode is not fully recovered, and an extra safety margin for repetitive hard-commutation topologies, which translates to reduced design-in effort and ease of use.

- 600 V technology with integrated fast body diode
- Low switching losses due to low Q_{rr} at repetitive commutation on the body diode
- Controllable di/dt and dV/dt
- Low Q_{oss}
- On-chip ESD protection according to HBM class 2
- $R_{DS(on)}$ up to 360 mΩ in SOT-223 package and 210 mΩ in D-PAK
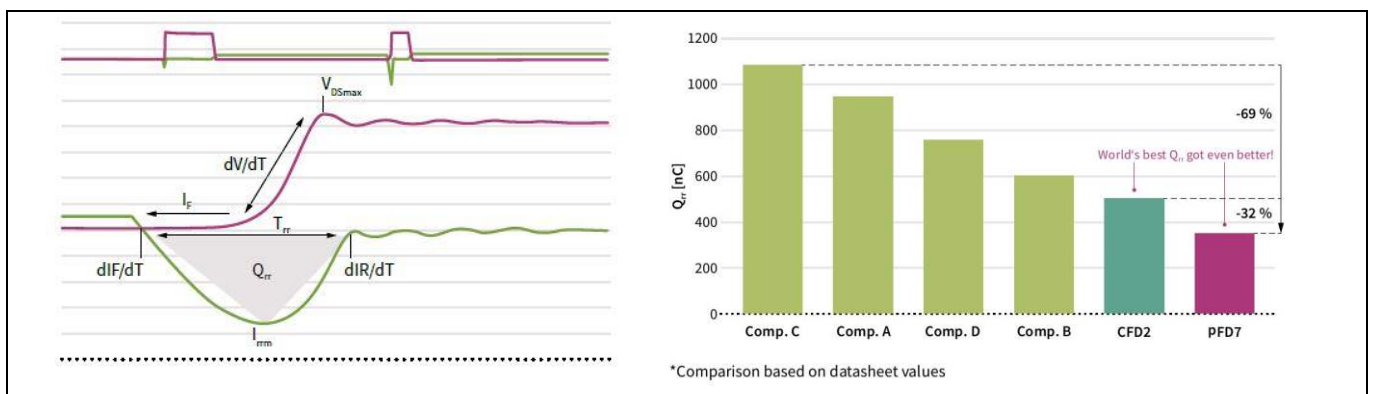
Figure 2   Highest reliability from lowest reverse-recovery charge and reverse-recovery time

For further information regarding CoolMOS™ PFD7, such as static and dynamic electrical behavior, as well as thermal and mechanical characteristics, please refer to the datasheet of IPN60R1K5PFD7S. Table 2 provides the absolute maximum ratings of the IPN60R1K5PFD7S.

Table 2   Absolute maximum ratings of CoolMOS™ IPN60R1K5PFD7S

Symbol	Description	Min.	Max.	Unit
V_{DSS}	MOSFET blocking voltage	–	600	V
I_d at T = 25°C	Countinous current per MOSFET	–	3.6	A
P_d at TC = 25°C	Maximum power dissipation per MOSFET	–	6	W
T_j	Operating junction temperature	-55	150	°C
T_C	Operating case temperature	-55	150	°C
V_{SD}	Diode forward voltage	1.0		V
t_{rr}	Reverse-recovery time	40		ns
Q_{rr}	Reverse-recovery charge	0.06		μC

3.1.1   Comparing CoolMOS™ PFD7 to previous-generation CFD2

Compared to Infineon's previous HV SJ MOSFET with integrated fast body diode, CFD2, the 600 V CoolMOS™ PFD7 offers technical as well as commercial advantages.

Design specification and features

The 600 V CoolMOS™ PFD7 offers best-in-class Q_{rr} and reverse recovery time (t_{rr}) levels, as debated on Figure 3 PFD7 shows a 30% reduced Q_{rr} compared to the previous generation CFD2. PFD7 also shows a significantly reduced gate charge (Q_g) and competitive charge stored in the output capacitance (Q_{oss}). All these technological benefits can be translated to lower switching losses, which ultimately benefits the target application. The graph in Figure 4 highlights the total E_{on} losses compared to previous technology, CFD2. The measurements were done on a hard-switched half-bridge designed to simulate the real application using the same gate resistor, with a bus voltage of 320 V DC and gate-driver voltage of 15 V with switching current from 0.1 to 3 A.

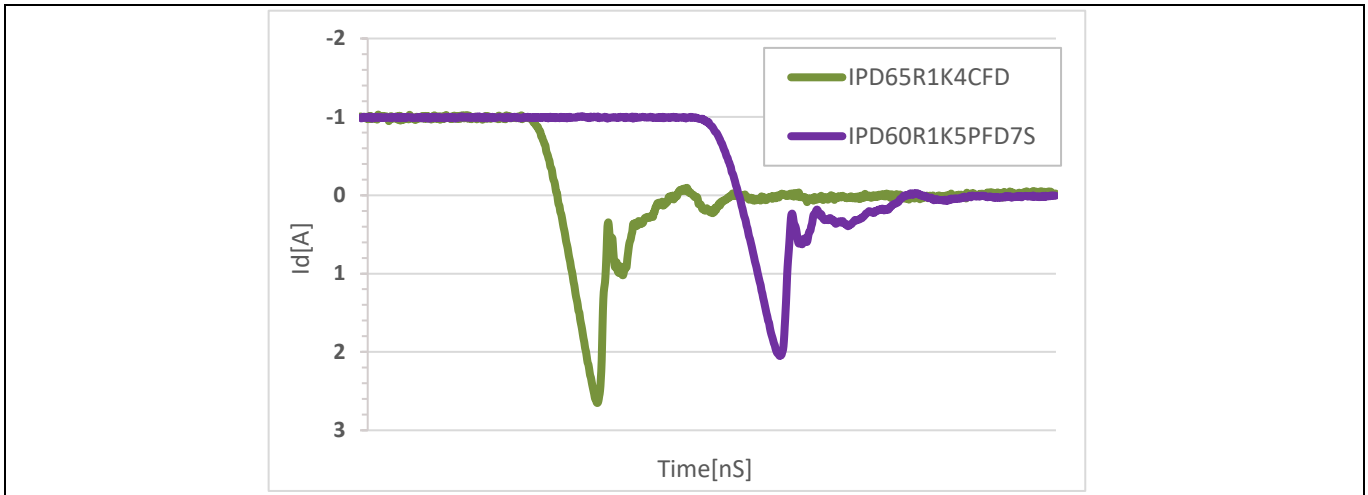**Figure 3   Reverse recovery charge Qrr comparison for different CoolMOS™ fast body diode technologies at 1A freewheeling current, dV/dt less than 5 V/ns ,T_{amb} = 25°C**
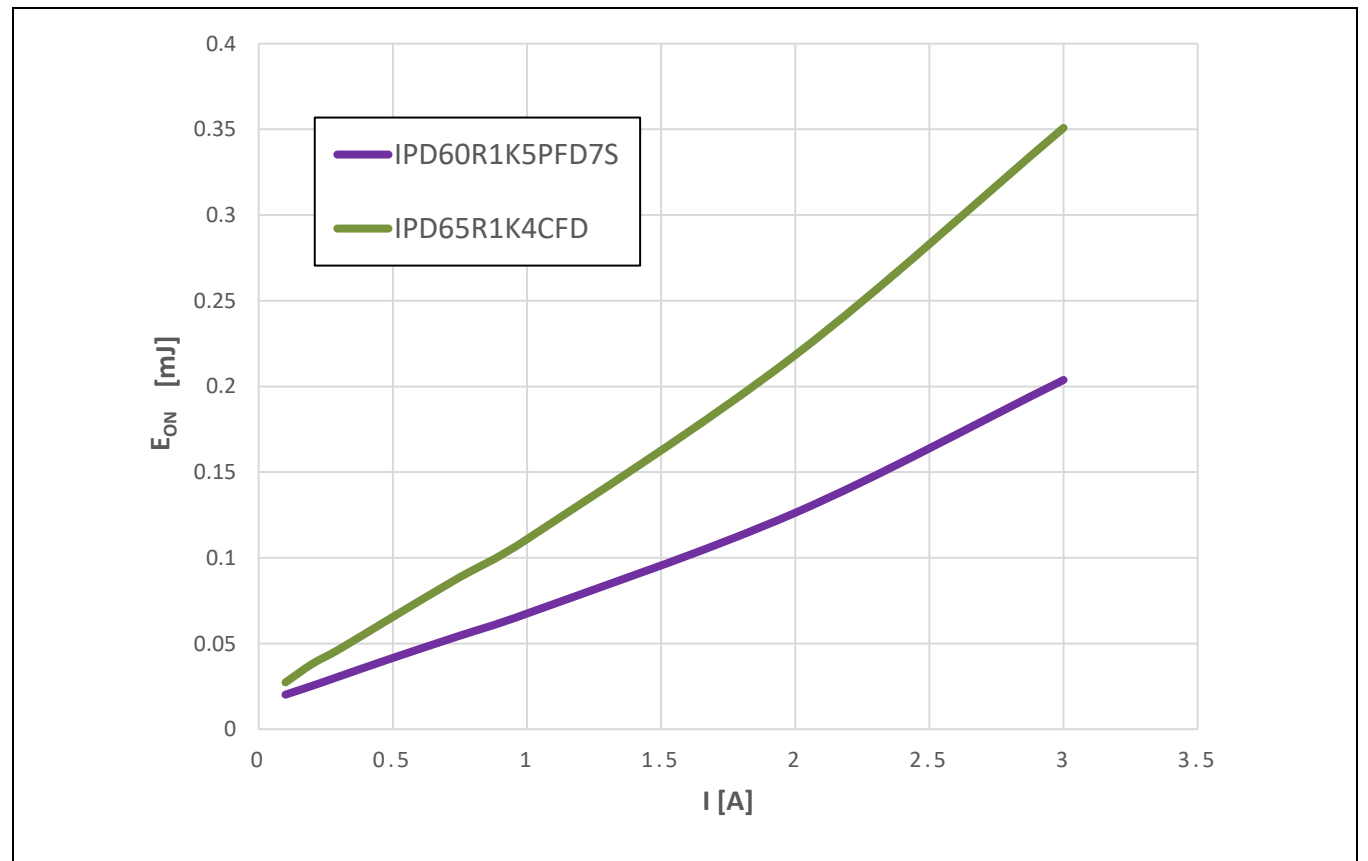

Figure 4   Turn-on loss comparison with different CoolMOS™ fast body diode technologies at 320 V DC, gate voltage 15 V, dV/dt less than 5 V/ns ,T_{amb} = 25°C (at the same R_g)

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Design specification and features

Furthermore, an additional benefit of the technology is the lower temperature dependency of the $R_{DS(on)}$. The following diagram shows this behavior. The structure of the CoolMOS™ PFD7 offers the lowest $R_{DS(on)}$ change driven by increasing junction temperature. All these technology parameters result in the highest efficiency in target applications.
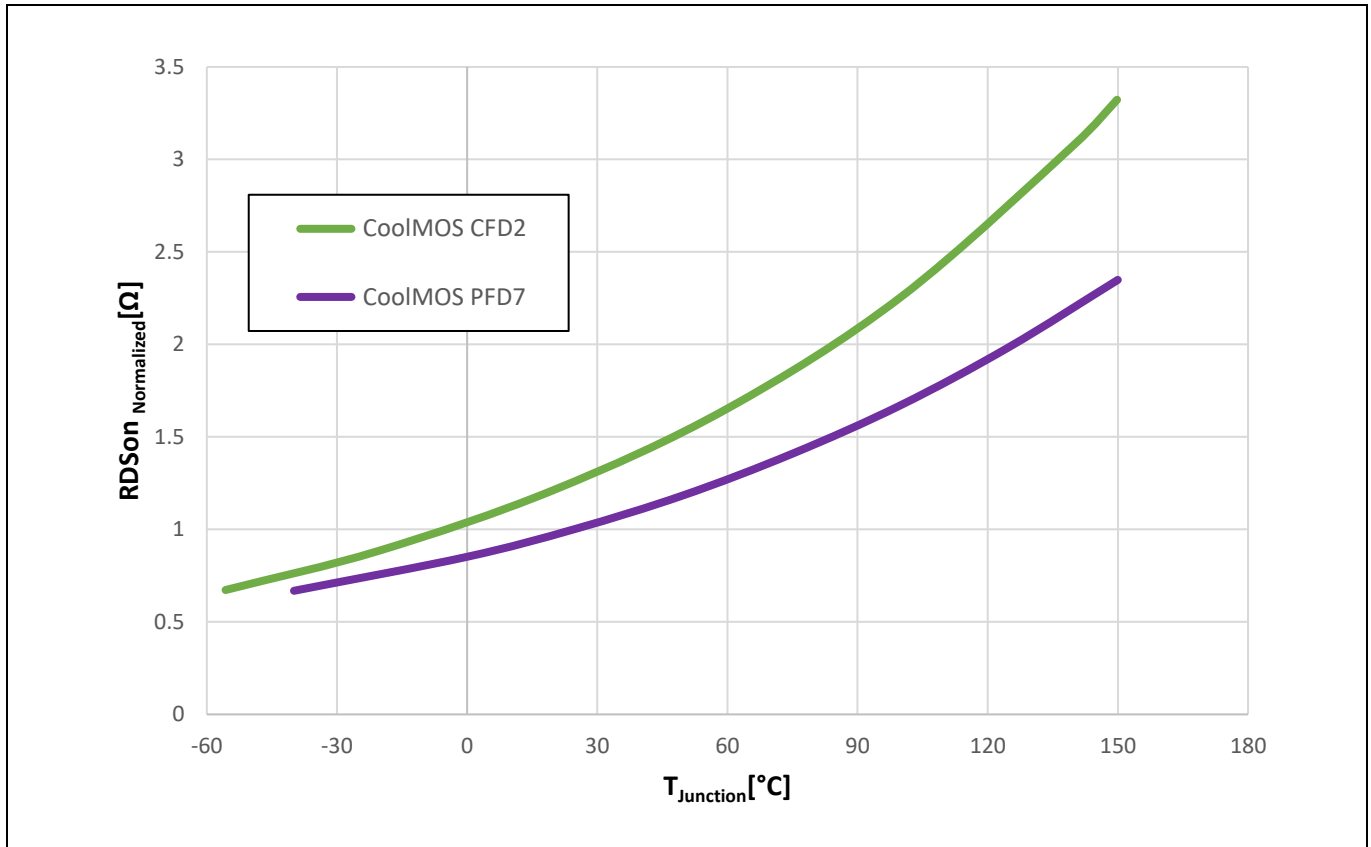
Figure 5 **Temperature dependency of the $R_{DS(on)}$ CoolMOS™ CFD2 vs. PFD7**

To understand the technology benefits, a one-to-one comparison based on the motor drive application requirement was done, taking into account tuning the switching dV/dt to below 5 V/ns as a base of comparison.

For a fair comparison between technologies we compare IPD60R1K5PFD7S with a maximum $R_{DS(on)}$ of 1.5 Ω against IPD65R1K4CFD with a maximum $R_{DS(on)}$ of 1.4 Ω.

IPD60R1K5PFD7S stands for the 1.5 Ω 600 V CoolMOS™ PFD7 in D-PAK package, the latest and best-performing fast body diode device from Infineon designed for motor drive applications.

Figure 6 shows the distribution of losses per switch for an inverter stage, where the simulation was done at 100°C T_j, switching a load current of I_d = 0.5 A. The IPD60R1K5PFD7S has a low loss contribution and exhibits a good balance of conduction and switching losses at 15 kHz switching frequency. Thanks to this, the inverter stage performs better in all load ranges when comparing PFD7 against CFD2 devices in a real application mesuerment shown in Figure 7.

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Design specification and features
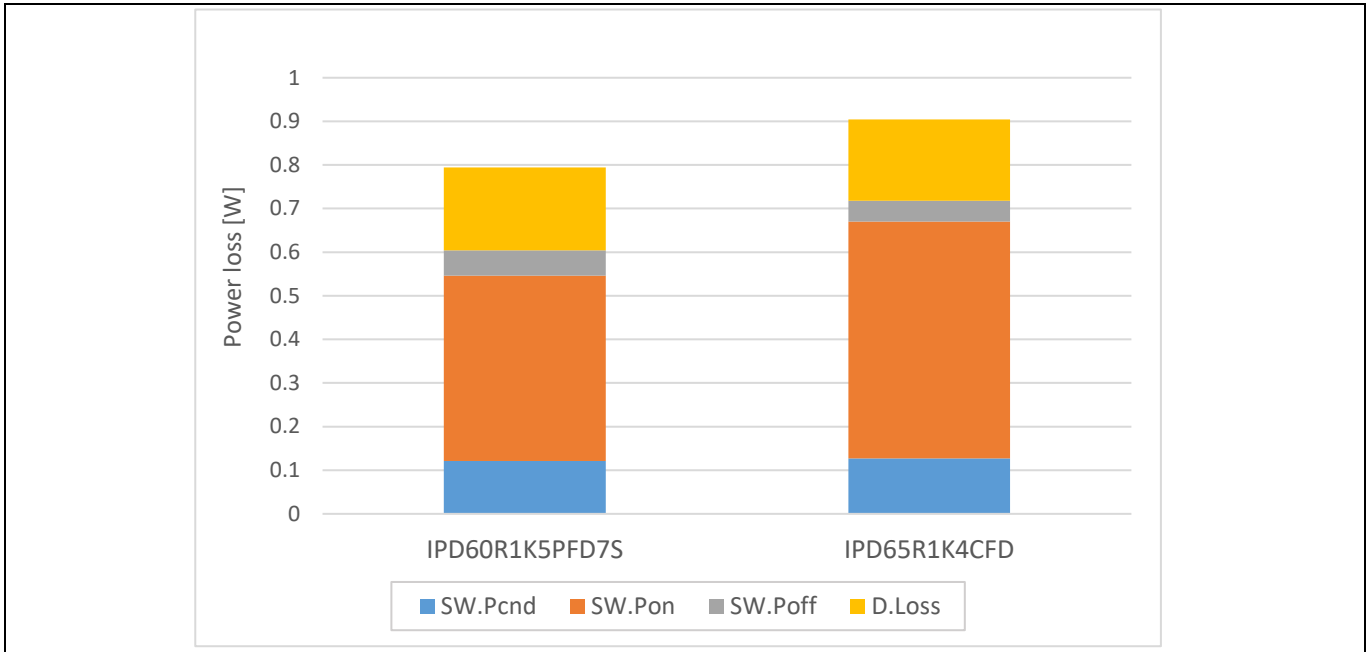
Figure 6   **Estimated distribution of losses for different CoolMOS™ fast body diode technologies: 320 V input at 20 kHz, T$_j$ = 100°C, switching current = 0.5 A (same dV/dt less than 5 V/ns)**
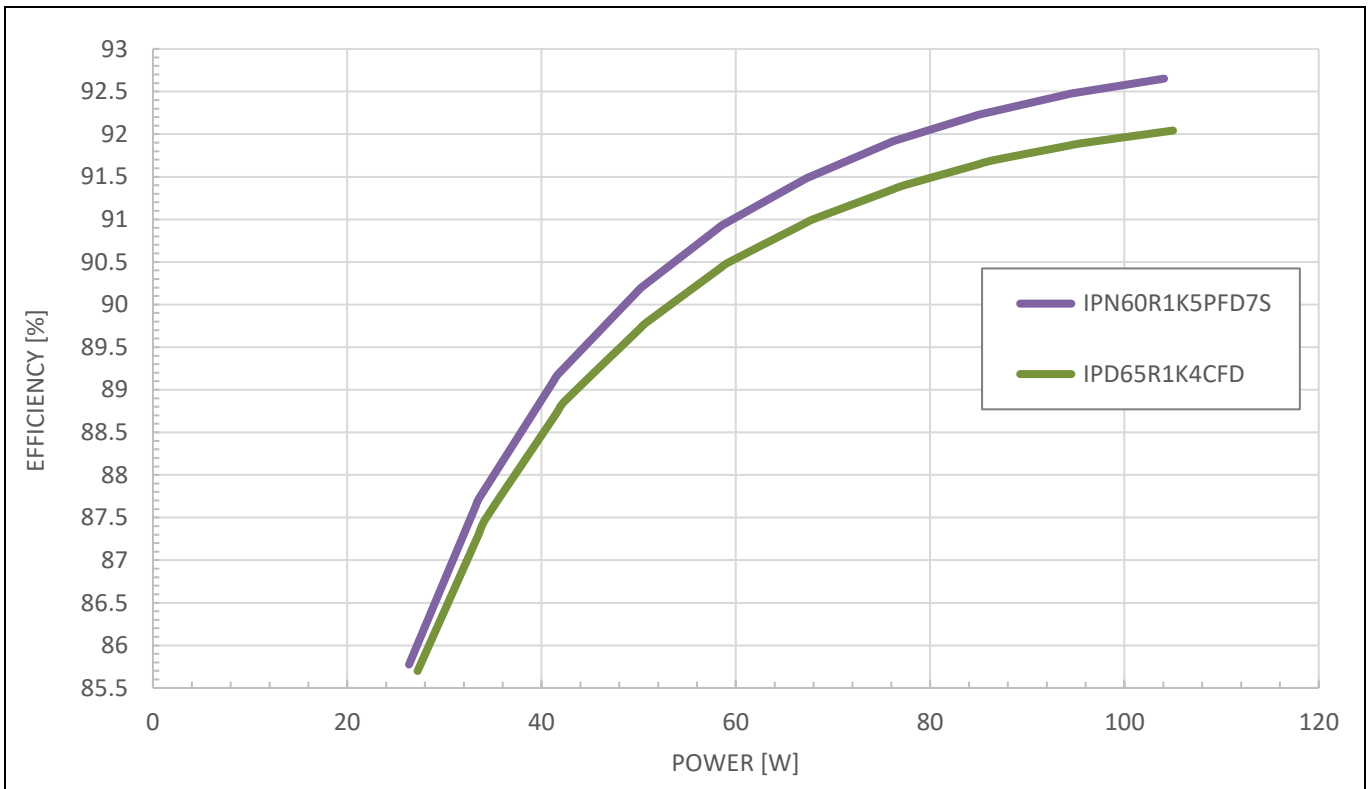
Figure 7   **Measured efficiency up to 100 W at 320 V DC bus input and 15 kHz switching frequency with different CoolMOS™ fast body diode technologies**

The 600 V CoolMOS™ PFD7 portfolio in D-PAK and SOT-223 package (Figure 8) ranges from 2 Ω (maximum) to 210 mΩ (minimum).

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Design specification and features

600 V CoolMOS™ PFD7		
$R_{DS(ON)}$ [mΩ]	DPAK PG-TO252-3-344	SOT-223 PG-SOT223-3-1
2000	IPD60R2K0PFD7S	IPN60R2K0PFD7S
1500	IPD60R1K5PFD7S	IPN60R1K5PFD7S
1000	IPD60R1K0PFD7S	IPN60R1K0PFD7S
600	IPD60R600PFD7S	IPN60R600PFD7S
360	IPD60R360PFD7S	IPN60R360PFD7S
280	IPD60R280PFD7S	
210	IPD60R210PFD7S	

Figure 8 **$R_{DS(on)}$ portfolio for 600 V CoolMOS™ PFD7 in D-PAK and SOT-223**

3.2 Design thermal simulation limits

In order to define the thermal capabilities of the EVAL_DRIVE_3PH_PFD7 design, a thermal characterization test was performed. The test was performed under the following conditions:

Room temperature T_{amb} = 25°C, different phase current values until the case temperature reaches 120°C, two PWM frequencies (5 and 16 kHz) under three-phase SVM modulation. The board is a FR4 PCB material with two layers of 2 oz. copper thickness. This has been considered as well as the PCB layout, and the results are shown in Figure 9.

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Design specification and features

Figure 9   **Thermal characterization, at 5 to 20 kHz**

3.3   Variable inductance sensing

One of the main concerns of running a BLDC motor with a sensorless control is its start-up operation. The initial rotor position should be known so that the corresponding motor phases are energized. If the energized phases are incorrect, the rotor will not be able to rotate.
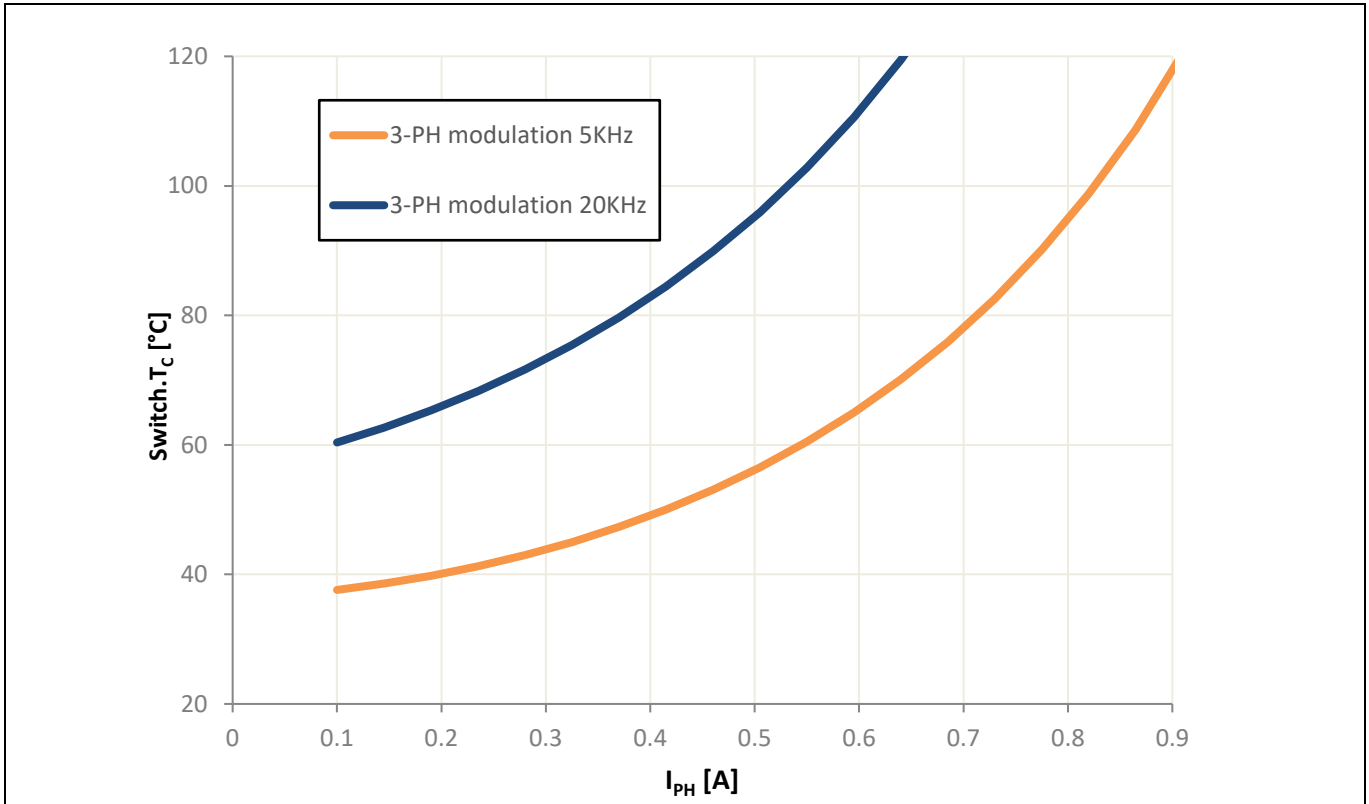
An effective method is using variable inductance to detect the initial rotor position. This feature is enabled by the iMOTION™ control IC. It does not depend on any motor specific characteristics, which allows it to work on any motor. This method relies on the fact that if voltage is applied across an inductor in the presence of a permanent magnet, the resulting current will either add or subtract from the external field created by the permanent magnet, which leads to a further decrease or increase in the inductance. In the case of a BLDC motor, the inductor is the stator while the permanent magnet is the rotor.

The implementation of this method requires that a voltage is applied for a fixed time such that it creates a magnetic field in the direction of only one winding. In order to do this, two phases are held to ground and one is switched to high, creating the forward magnetic field. Then two are switched to high and one is held to ground, creating the opposing magnetic field.

The two peak currents created from the two opposing magnetic fields are then measured and compared. The larger peak will indicate the current that is in the same direction as the magnetic field caused by the permanent magnet (rotor). Therefore, the polarity of the permanent magnet can be obtained, i.e. the rotor position is found within 180 degrees.

By repeating the entire procedure for the other two phases, the rotor position can be narrowed down to within 60 degrees, which is sufficient for proper commutation.

3.4 Critical Over Voltage Protection (OVP)

Critical Over Voltage (OV) is a condition in which the motor BEMF builds up and charges the DC bus capacitor to an exceedingly high voltage.

This could be due to regenerative braking, which is a reverse torque used to slow the rotor. In normal operation, a current is applied to the motor winding. During active braking, the phase of the current is inverted, so that current is now removed from the motor windings. The rotor experiences a torque, proportional to the current, opposite the direction of motion, and the DC bus becomes charged from the motor current.

In the iMOTION™ control IC, the critical OVP is implemented in the MCE firmware. The critical OV condition is detected by comparing the DC bus voltage feedback to a configurable voltage level. When a critical OV is detected, a zero vector (low-side device turn-on) PWM state is entered, independent of any condition (including faults). The use of a zero vector forces short-circuit to the motor terminal and hence prohibits charging of DC bus capacitors. On application of the zero vector, the motor current will circulate within the motor windings and the rotational energy of the motor will be dissipated inside the motor (copper and core losses). The inverter is held in the zero vector state until the critical OV fault is cleared. This feature would help keep the bus capacitor small, which in turn benefits the design by reducing the Bill of Materials (BOM) and total design cost.

3.5 Specifications of the evaluation board EVAL_DRIVE_3PH_PFD7

Table 3 shows the important specifications of the evaluation board EVAL_DRIVE_3PH_PFD7.

Table 3   EVAL_DRIVE_3PH_PFD7 board specifications

Parameters	Value	Conditions
Input		
Voltage	85 to 265 V AC	
Input current	1.1 A$_{rms}$	Limited by line filter and rectifier bridge
Output		
Current per leg	825 mA	T$_{amb}$ = 25°C, Tc$_{hotspot}$ = 110°C, V DC$_{bus}$ = 300 V, three-phase modulation, 5 kHz PWM
DC bus		
Maximum DC bus voltage	370 V	
Minimum DC bus voltage	120 V	
Current FB		
Current Sensing (CS) resistors R61, R62, R63	0.25 Ω	The default configuration uses three shunts sensing in the emitter paths – IU+, IV+, IW+
Protections		
Output current trip level	2.4 A	Configured by either changing shunt resistors or adapting comparator threshold

Design specification and features

Parameters	Value	Conditions
Onboard power supply		
13 V	+13 V ±5 percent, max. 250 mA	Supply for inverter gate driver input power
3.3 V	+3.3 V ±5 percent, max. 50 mA	Supply for microcontroller, CS and OCP circuit
PCB characteristics		
Material	FR4, two layers, 2 oz. copper	
Dimensions	93 x 74.5 x 18 mm	

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Board functional groups and connectors

4 Board functional groups and connectors

4.1 Functional groups

Figure 10 and Figure 11 show the functional groups of the EVAL_DRIVE_3PH_PFD7 evaluation board.

1. Inverter gate drivers
2. Three-phase motor phase connector
3. EMI filter and rectifier group
4. Auxiliary power circuit
5. Over-current comparator
6. Microcontroller iMOTION™
7. AC-line input connector
8. Debug connector
9. Speed control connector
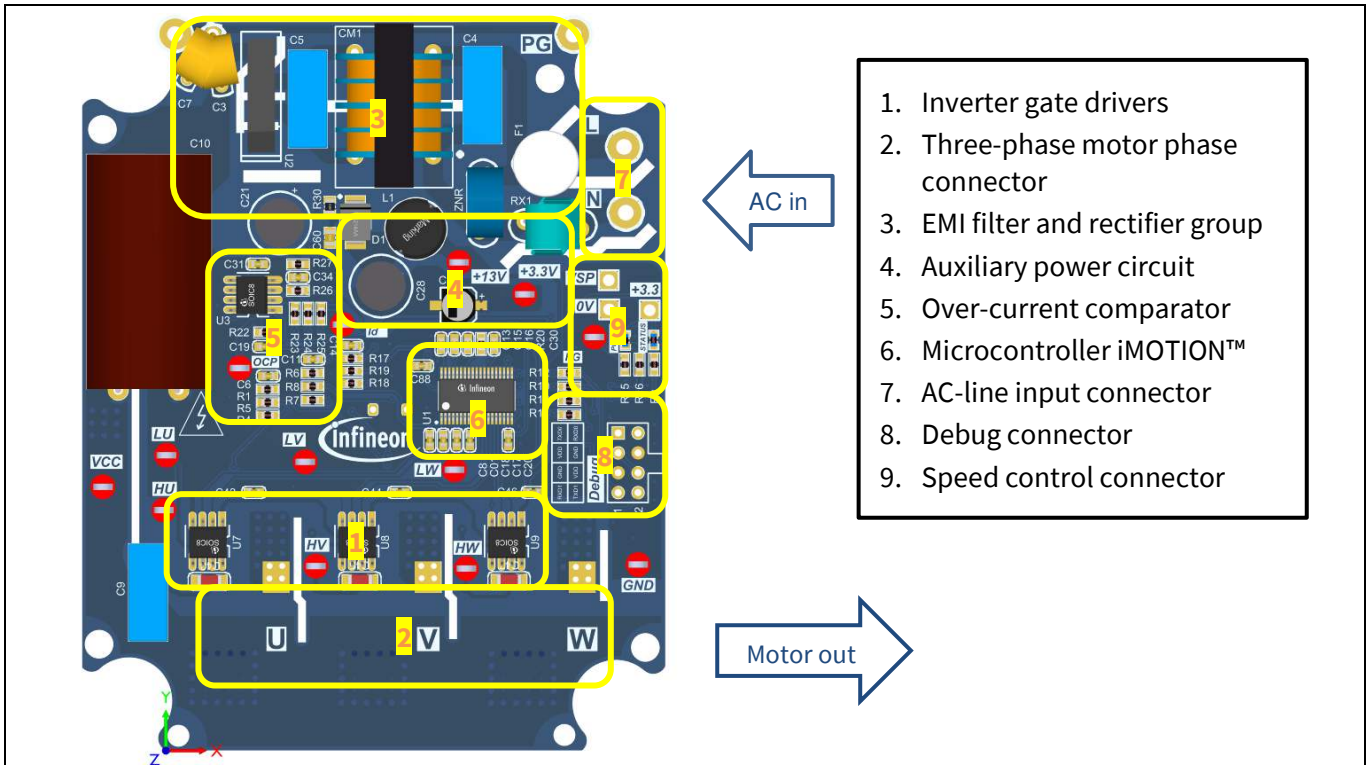
Figure 10   Functional groups of the EVAL_DRIVE_3PH_PFD7 evaluation board's top side

10. Inverter stage CoolMOS™ PFD7
11. Shunt resistors
12. Onboard power supply 13 V and 3.3 V generation
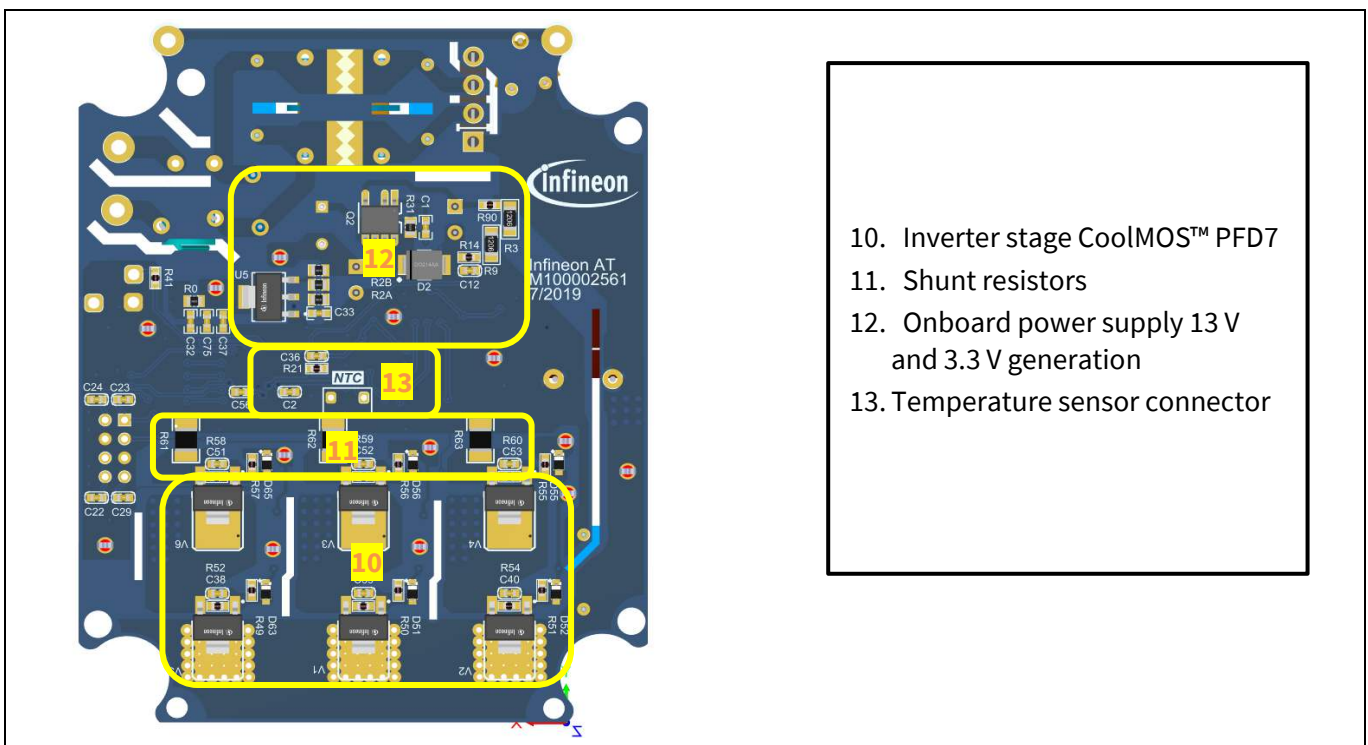13. Temperature sensor connector

Figure 11   Functional groups of the EVAL_DRIVE_3PH_PFD7 evaluation board's bottom side

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Board functional groups and connectors

4.2 AC-line connector

This section gives general information on the input/output connectors on the EVAL_DRIVE_3PH_PFD7 evaluation board. Figure 12 indicates the details of the line connector. It is possible to connect DC voltage to the AC-line connector, and in this case a permanent DC current will be conducted through the rectifier bridge. Maximum ratings on the rectifier must be checked for this condition as well as the DC supply's polarity at the connector. The evaluation board is protected by an onboard fuse rated at 3.15 A.
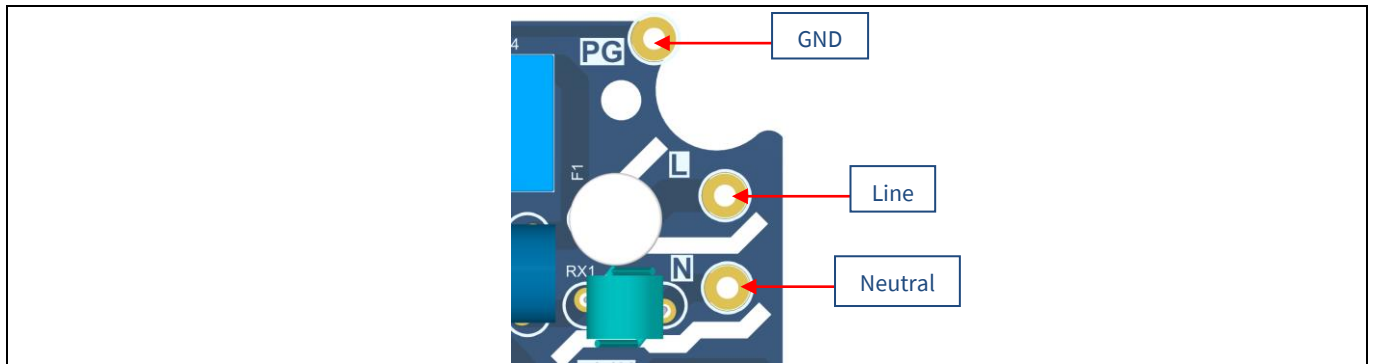

Figure 12 AC-line connector

4.3 Motor-side connector

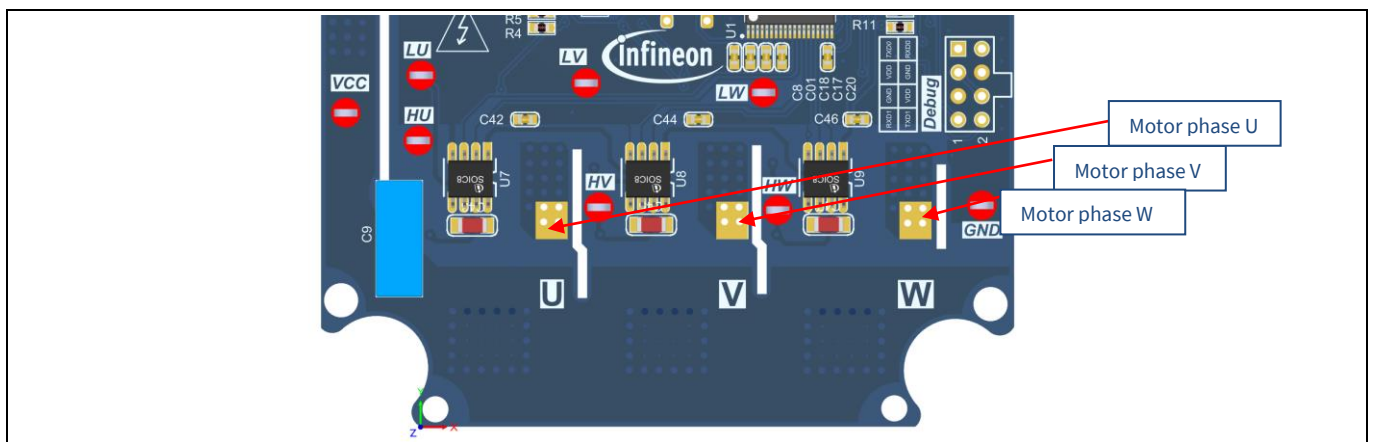Figure 13 shows details of the three-phase motor-side connection.

Figure 13 Motor-side connector

4.4 Speed control potentiometer

Figure 14 shows details of the motor speed control potentiometer connection.

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Board functional groups and connectors
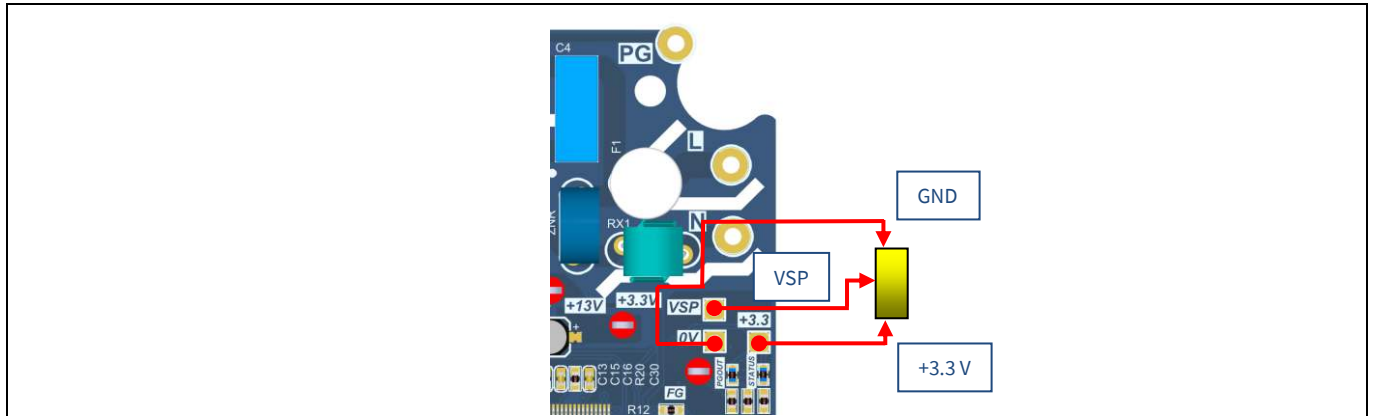
Figure 14   Speed control potentiometer connector

4.5   Eight-pin debug connector

The EVAL_DRIVE_3PH_PFD7 supports debugging via Serial Wire Debug (SWD) and Serial Port Debug (SPD).
Figure 15 shows details of the pin assignment.
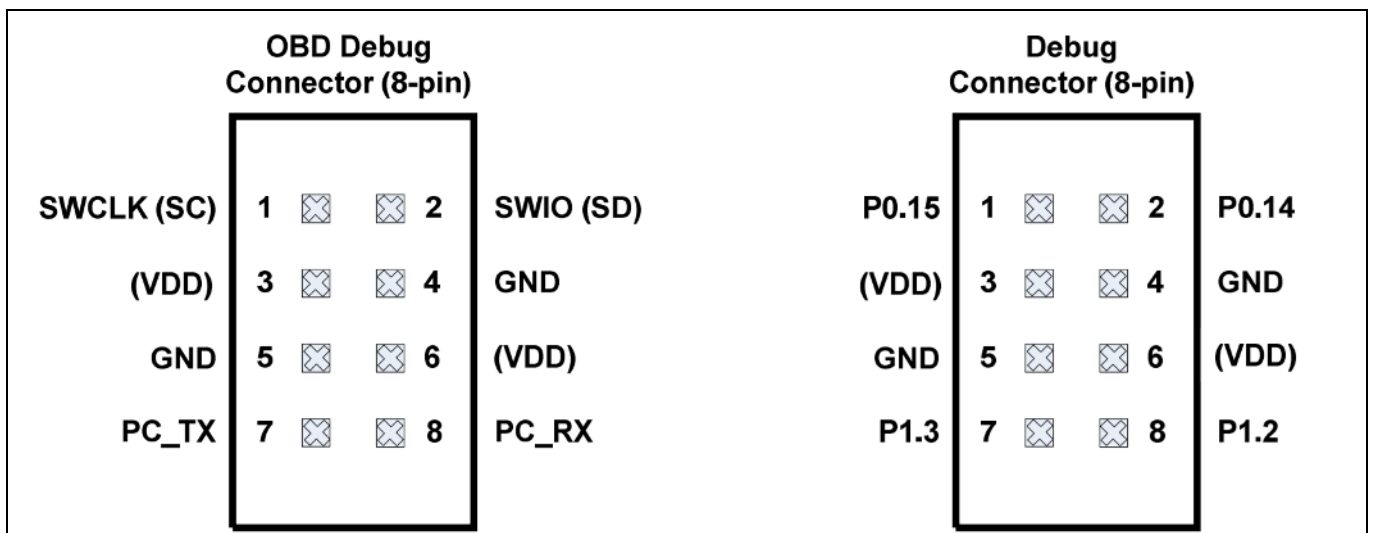
Figure 15   Pin assignment of the eight-pin debug connector

The default debug connections used in the EVAL_DRIVE_3PH_PFD7 are as follows:

- SWD:
    - SWIO/SPD – P0.14 (SWD0)
    - SWCLK – P0.15 (SWD0)
- Full duplex UART communication via a virtual COM port:
    - PC_RXD – P1.2 USIC0CH1.DOUT0
    - PC_TXD – P1.3 USIC0CH1.DX0A

4.6 Test points

Figure 16 describes the test points available on the EVAL_DRIVE_3PH_PFD7.

Test point	Item	Description
+13 V, +3.3 V, 0 V	1	Bias output
Id, OCP	2	Motor current
LU, HU, LV, HV, LW, HW	3	3PH-PWM
V_{CC}	4	+BUS voltage

Figure 16   Board test point locations

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
iMOTION™ development tools and software
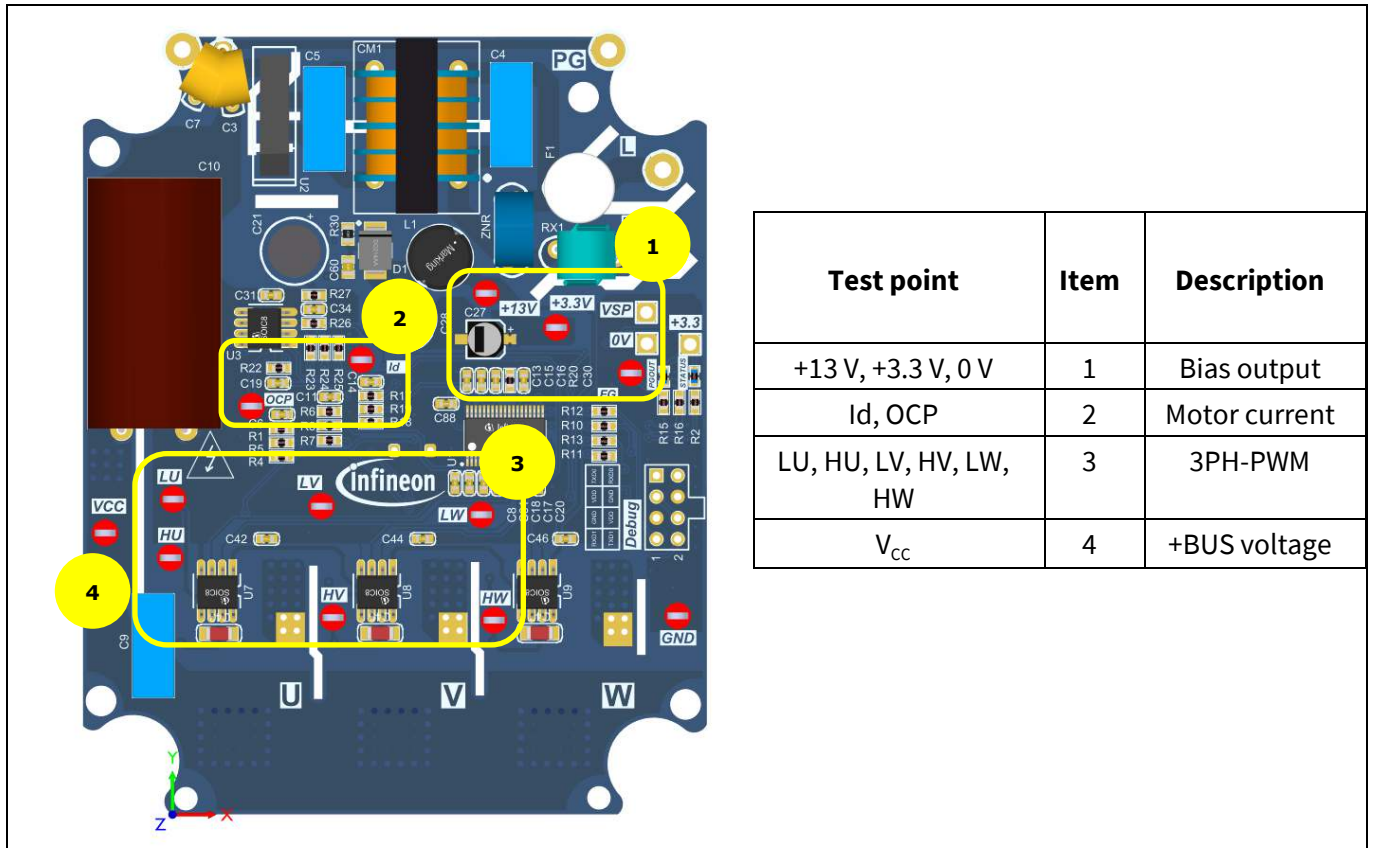
5 iMOTION™ development tools and software

The iMOTION™ development tool installers for MCEDesigner and MCEWizard are available for download via the Infineon iMOTION™ website. All the available tools and software variants are listed there. The evaluation board must be connected with the debugger iMOTION™ Link, and the debugger uses the SEGGER J-Link's driver for UART communication with EVAL_DRIVE_3PH_PFD7. The J-Link driver will be installed during the MCEDesigner installation. If the driver is not installed properly, please go to the SEGGER J-Link website to download and install the latest J-Link "Software and Documentation pack for Windows".

Please note that the debugger iMOTION™ Link *must be ordered separately.*

5.1 MCEWizard set-up overview

After installing the MCEWizard, a short-cut for the MCEWizard appears on the Windows desktop. Double-click the short-cut to open the MCEWizard and configure the parameters for the evaluation boards and motor. Please follow the instructions in the "Get Started" document.

Figure 17 shows the "Welcome Page" for MCEWizard, where the control board can be selected through the pull-down list. For EVAL_DRIVE_3PH_PFD7 please select Eval-M1-101T (as control board). Ensure both the "I have modified the circuit board" and "Enable advanced question" check marks are not selected. After selecting the control board, start the MCEWizard system set-up procedure by clicking the "Next" button in the bottom-right corner, as shown in Figure 16. Please follow the MCEWizard set-up steps by entering the parameter values specified in the "Get Started" document.

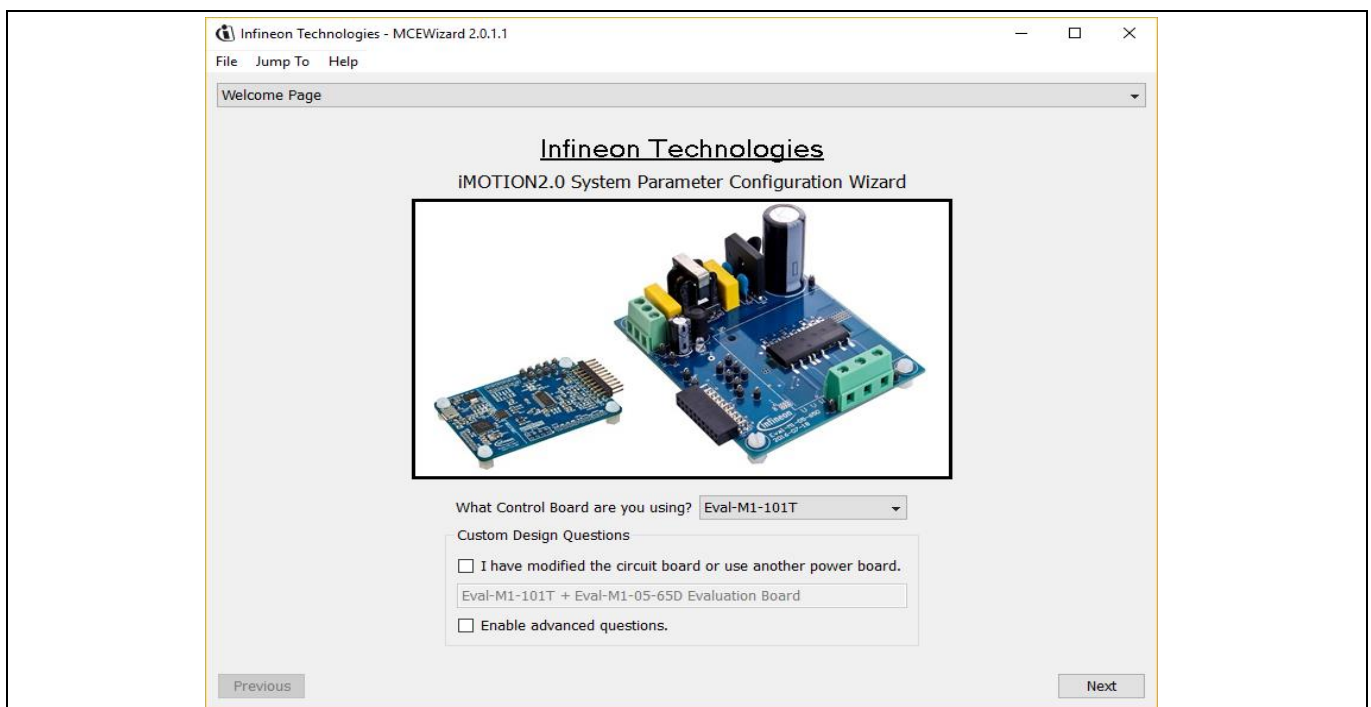**Figure 17** **Welcome page of MCEWizard**

After all the MCEWizard questions are answered, the "Verify & Save Page" will be shown, as in Figure 18. Click "Calculate" and "Export to Designer File (.txt)" to save the parameter file, which will be used by the MCEDesigner in the next steps. If some error is detected, double-click on the error message (highlighted in red) and adjust the related parameter.
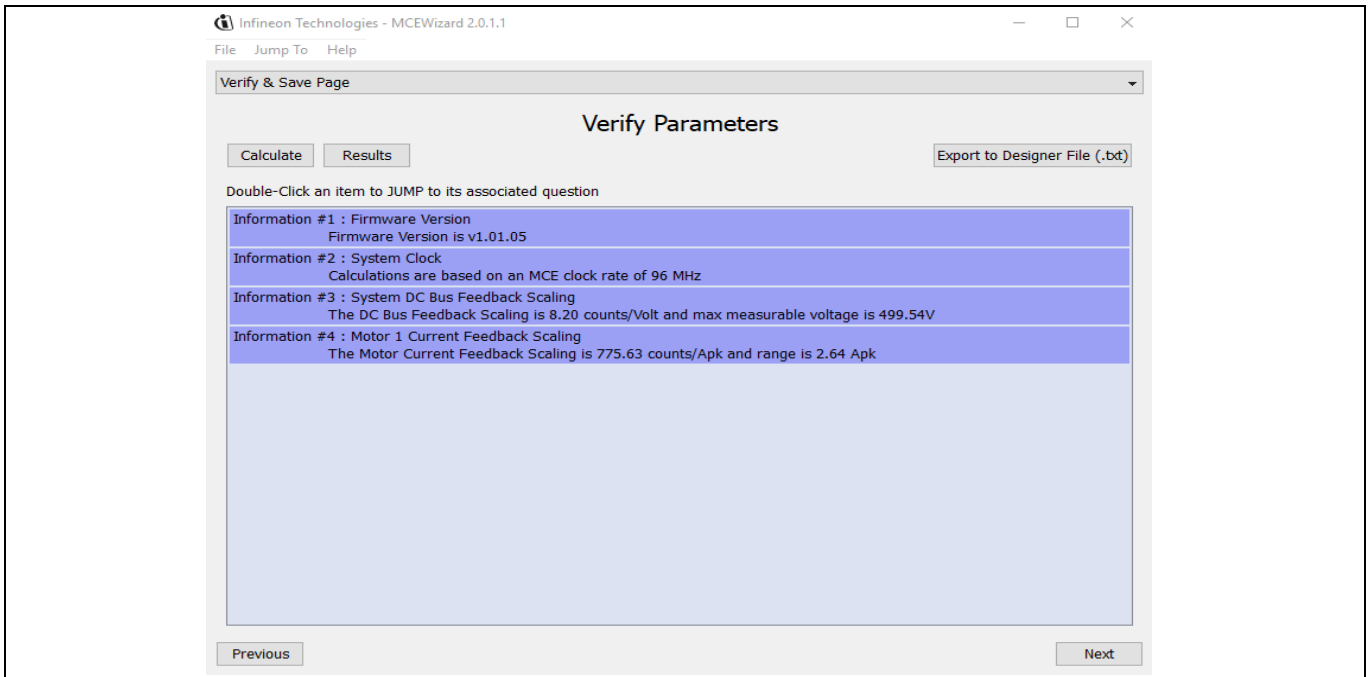
Figure 18   Verify & Save Page for MCEWizard

5.2   MCEDesigner set-up overview

After installing MCEDesigner installer, there should be a short-cut for MCEDesigner on the Windows desktop. Double-click the short-cut to open MCEDesigner and then open the "IMC101T_xx.irc" file (Figure 19).

Figure 19   MCEDesigner's main display

Connect the iMOTION™ Link as well as the AC power to the power input connector and power on the system to give the 3.3 V supply to the controller (the communication is isolated).

EVAL_DRIVE_3PH_PFD7
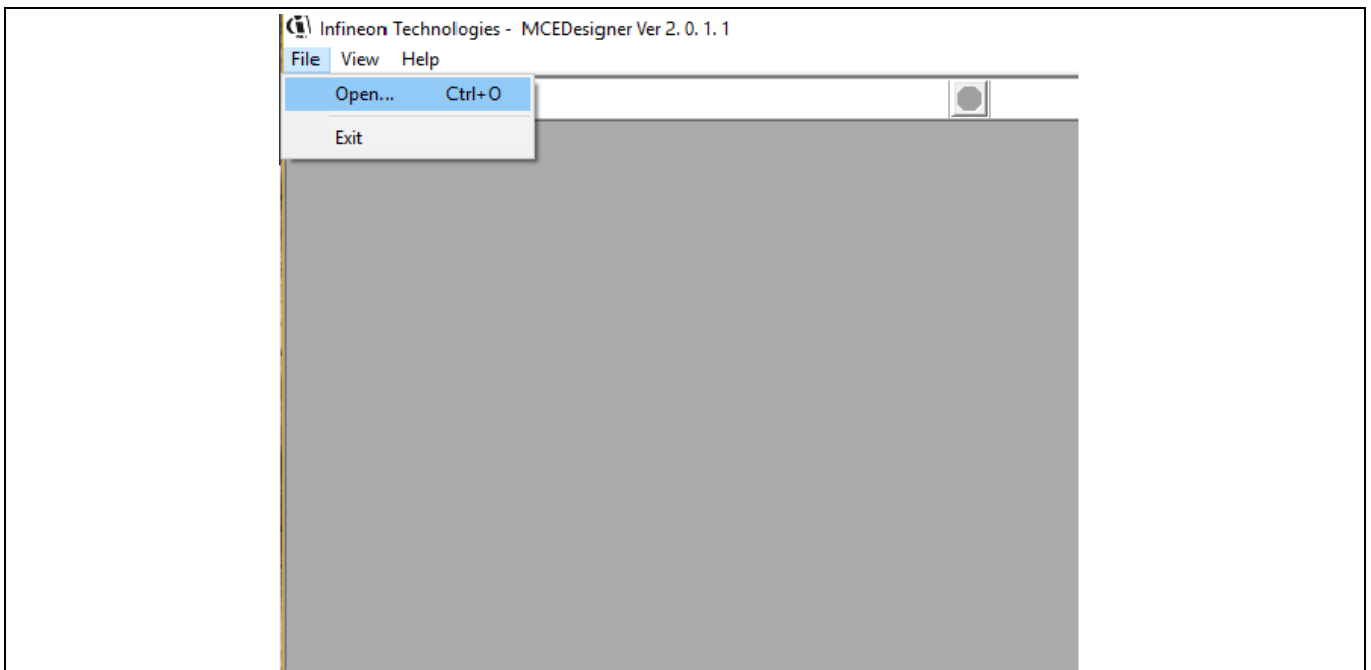## 3-PH motor drive evaluation board with FOC sensorless control
iMOTION™ development tools and software

MCEDesigner should automatically connect to the EVAL_DRIVE_3PH_PFD7 evaluation board using the default COM port (indicated by a green circle next to the "COMx Up" status in the bottom frame of the MCEDesigner GUI). If it cannot establish the connection, change the COM port with the following steps: click on the "System" window and then click on Preferences > Connection > Connect using, and chose one of the other available COM ports from the drop-down list

Use the following steps to program the firmware and the parameters file into the internal Flash memory of the iMOTION™ control IC: click on the system page, click Tools > Programmer, and select "Program Firmware and Parameters" (Figure 20). The encrypted firmware is available in "IMM101T MCE Software Package" downloaded as an .ldf file. Regarding the parameters file, browse and select the .txt file created from the MCEWizard.

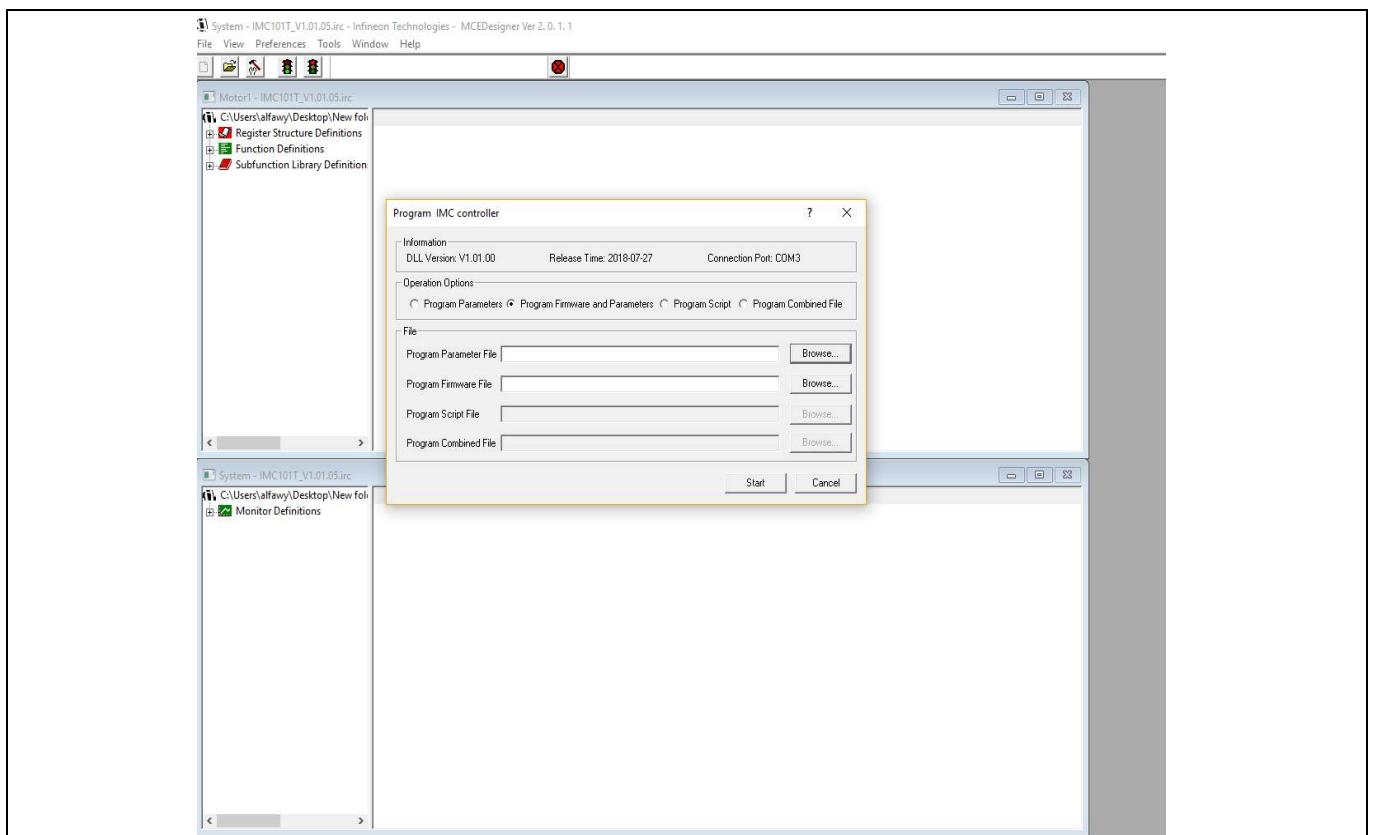**Figure 20**   **"Program IMC Controller" pop-up window**

After the "Drive System Parameter" file has been programmed into the IMC101 controller, and the motor drive system is powered, the MCEDesigner can be used to start/stop the motor, display motor current traces, change the motor speeds, and modify drive parameters and many other functions. Please refer to the MCEDesigner documentation for more details.

6 Schematics and layout

To meet individual customer requirements and make the EVAL_DRIVE_3PH_PFD7 evaluation board a basis for development or modification, all necessary technical data such as schematics, layout and components are included in this chapter.

6.1 EMI input filter and rectifier circuit

Figure 21 depicts the schematic from the AC-line input connector to the rectified DC bus voltage. This circuitry includes a passive EMI filter consisting of elements C4, C5, CM1, C3 and C7, a 2 A/600 V rectifier block U2, and an NTC inrush current limiter as well as ZNR for surge current protection. An electrolytic capacitor C10 and foil capacitor C9 are used for buffering the rectified DC bus voltage DC+. The design is protected by a 3.15 A fuse F1 on the line input terminal L.
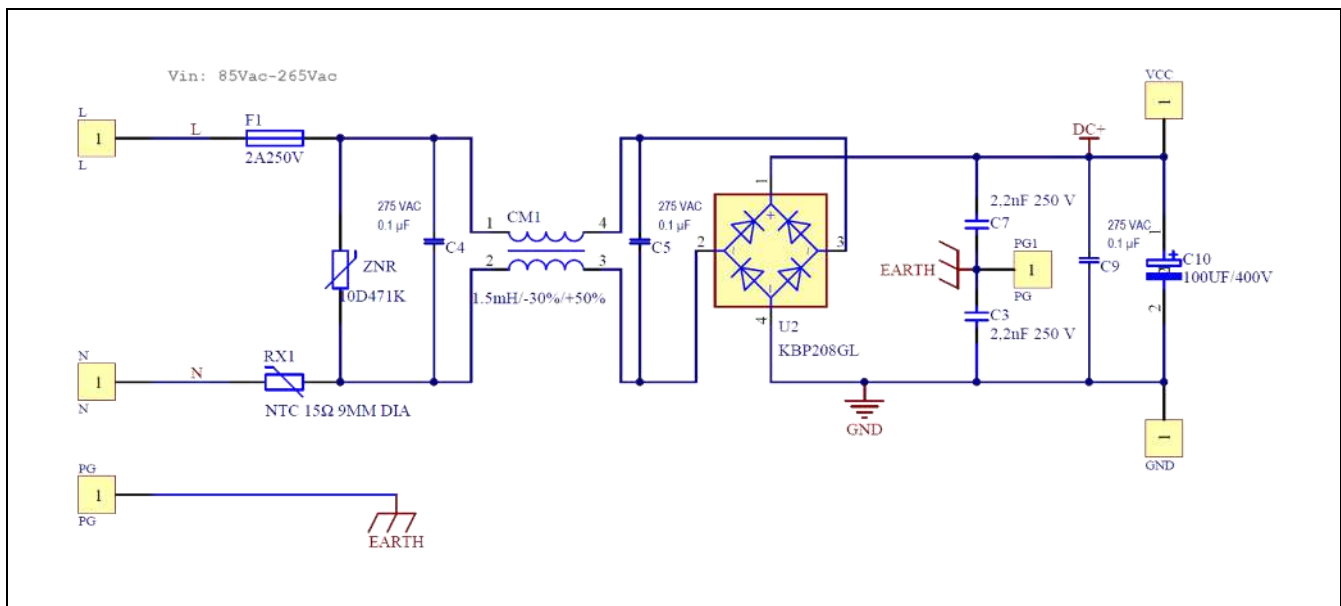

Figure 21   Schematic for EMI input filter and AC-DC section of the EVAL_DRIVE_3PH_PFD7

6.2 Three-phase inverter using CoolMOS™ PFD7

The control of power MOSFETs with respect to turn-on is a matter of the gate resistance value; a different method of controlling the turn-on could be by using a constant current source, which results in an easy-to-use solution, improved controllability and reduced turn-on propagation delay.

High switching rates of the MOSFET drain-source voltage during PWM operation in motor drive inverters cause displacement currents over the parasitic capacitance of the motor to the protected earth. These currents flow dominantly through the bearings, which leads to an accelerated aging of the bearings. This is a well-known failure mechanism and can be explained by the function of the switching frequency of the inverter as well as the switching speed of the inverter's MOSFET.

The slower the turn-on and turn-off, the less current flows through the bearings, and so switching slowly is always correlated with increased switching losses. The aim is to tune the switching processes toward low switching speed for motor control applications where little maintenance is desirable.

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
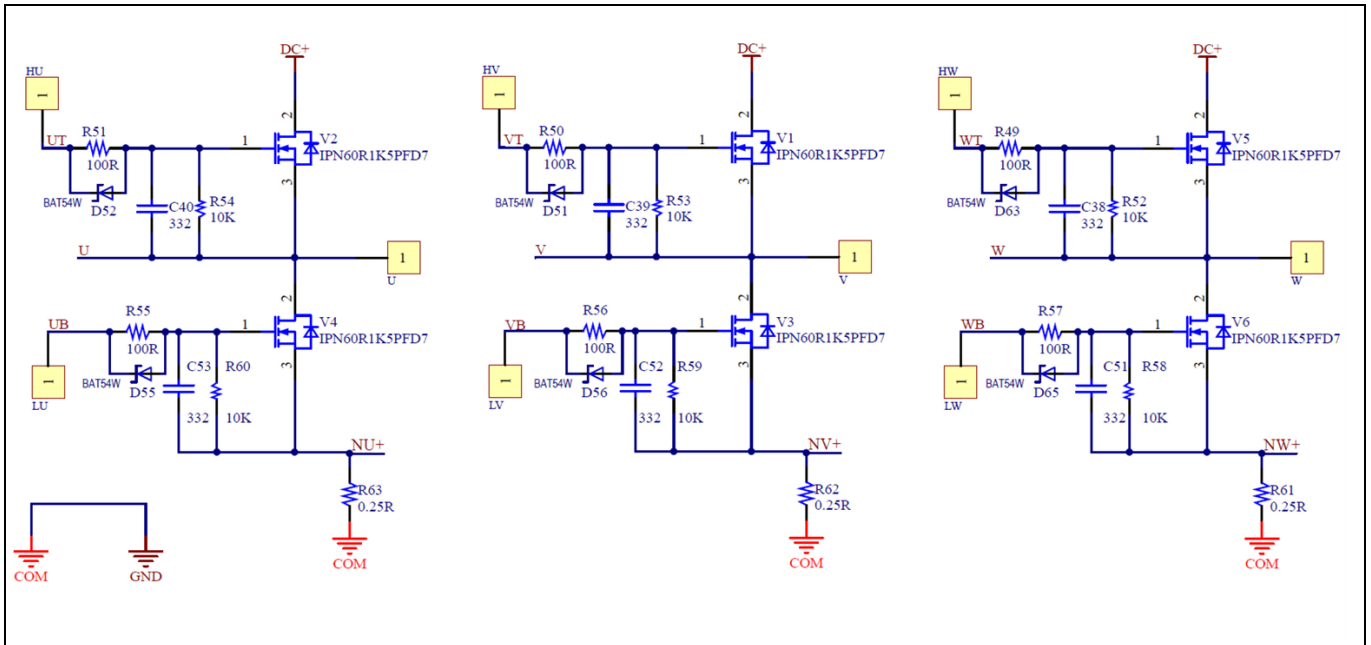Schematics and layout

Figure 22   Schematic of the three-phase inverter on the EVAL_DRIVE_3PH_PFD7 evaluation board

The three-phase power inverter is implemented using six CoolMOS™ PFD7s (IPN60R1K5PFD7S). Each inverter leg has its own shunt in the low-side path for phase current measurement. The inverter section is implemented as shown in Figure 22. The design includes the same gate circuit for the high-side and low-side MOSFETs. The gate of the MOSFET is driven using the 2ED28073J06F level-shift gate driver with a IO+ of 20 mA, and the gate resistance selected is R_{gon} = 100 Ω, which is enough to reduce turn-on dV/dt to less than 5 V/ns.

A higher R_g value not only degrades the MOSFET's working conditions by increasing the temperature and switching losses, but also degrades application efficiency and working conditions by fully modifying the switching behavior of the device. A higher R_g affects the driver/PWM controller heavily, requiring it to sustain a higher temperature, as well as dissipating more power to charge the MOSFET input capacitance. It also potentially produces cross-conduction that may cause system disruption due to static dV/dt.
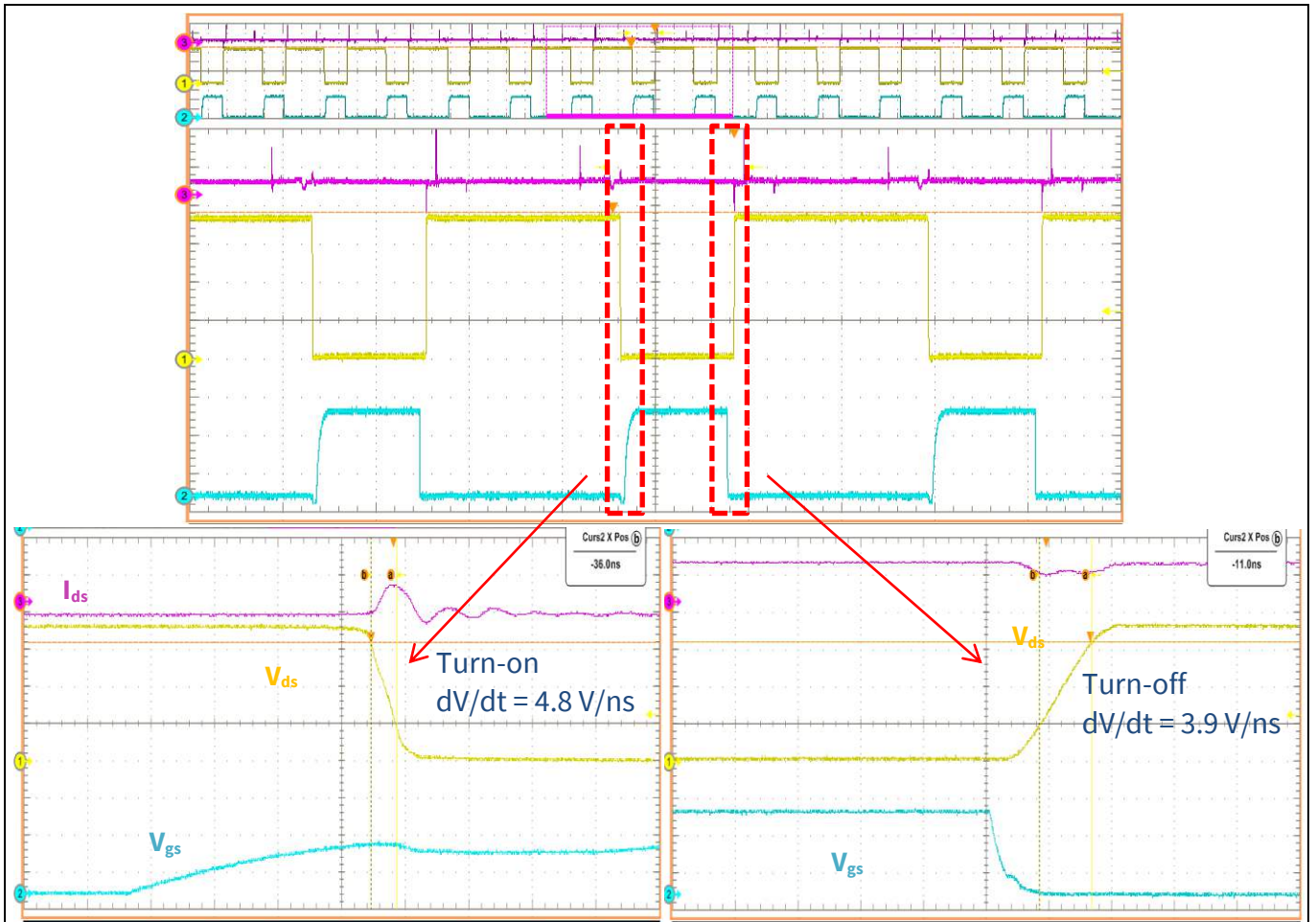
Figure 23   Controlled dV/dt

6.3   Power supply

Figure 24 depicts the schematic of the power supply available on the EVAL_DRIVE_3PH_PFD7 board. The bias supply is designed with a buck converter using the LNK304. It operates on a wide AC input voltage from 85 V AC to 265 V AC to generate a non-isolated +13 V output to supply the MOSFET's gate-driver circuit. The linear regulator (IFX1117ME V33) generates +3.3 V from the +13 V provided by the buck circuit. The +3.3 V power supply is used to supply the over-current comparator circuit and the iMOTION™ microcontroller.
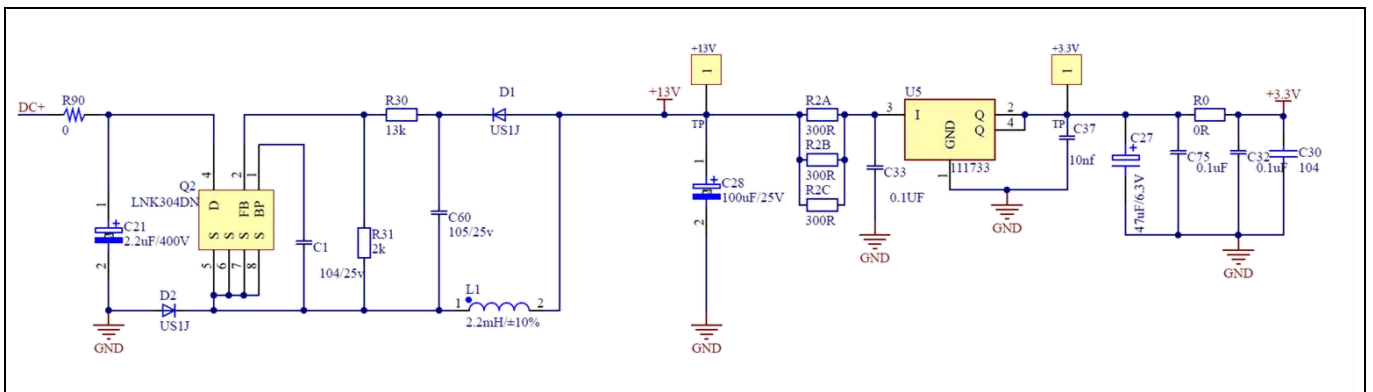

Figure 24   Power supply section of the EVAL_DRIVE_3PH_PFD7 evaluation board

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Schematics and layout

6.4 Current Sense (CS) and Over Current Protection (OCP) circuit

Figure 25 shows the motor phase OCP circuitry. The design offers hardware and software current detection. The three-phase motor currents are sensed and sent back to the microcontroller through IU, IV and IW. In addition, the sensed three-phase currents of the motor are feed to the comparator, and in case of over-current detection, the comparator sends a fault signal to the microcontroller to interrupt the PWM modulation and immediately stop all output to the motor. The comparator threshold can be set through the voltage divider provided by resistors R26 and R27. By default for the emitter shunt trip, R27 is 1 kΩ. The reference voltage is 206 mA.
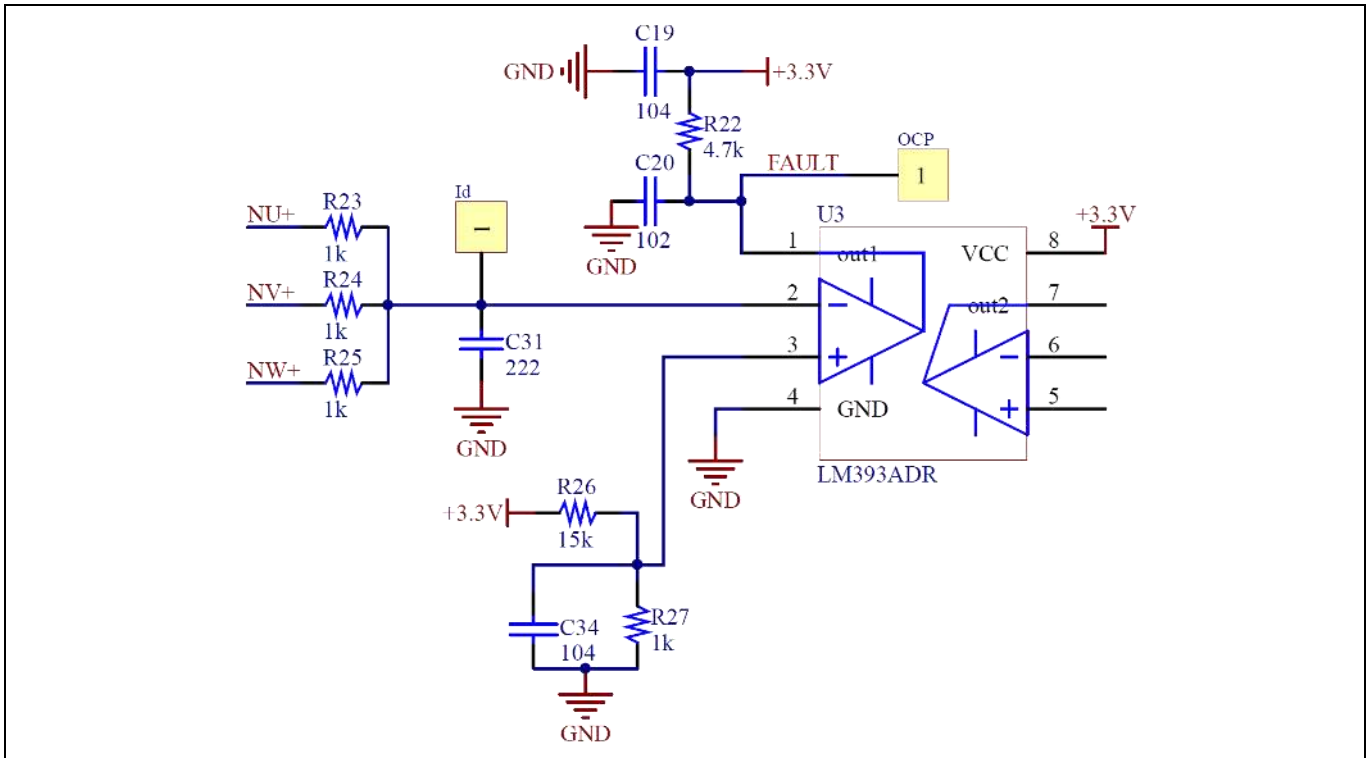

Figure 25   **OCP circuit**

6.5 DC-link voltage measurement

Pin 2 (V DC) of the microcontroller provides access to the DC-link voltage. Figure 26 provides the DC bus sense resistor details.
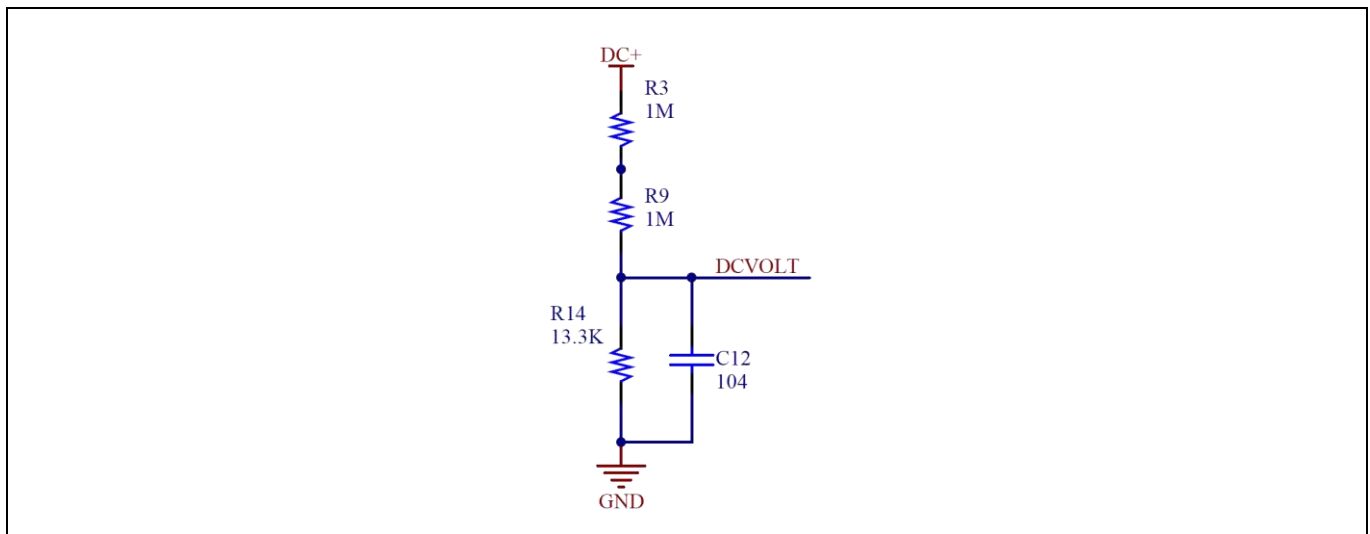
Figure 26   The DC bus sense resistor on the EVAL_DRIVE_3PH_PFD7 evaluation board

The DC$_{VOLT}$ provides input to the microcontroller with a voltage range of 0 to 3.3 V on controller pin 2 (V DC), reflecting a DC bus voltage range of 0 to 400 V.

6.6   EiceDRIVER™ 2EDN non-isolated gate driver for MOSFETs

The 2ED28073J06F is a high voltage, high-speed power MOSFET and IGBT drivers with dependent high and low side referenced output channels. Proprietary HVIC and latch immune CMOS technologies enable ruggedized monolithic construction. The logic input is compatible with standard CMOS or LSTTL output, down to 3.3V logic. The output drivers feature a high-pulse current buffer stage designed for minimum driver cross-conduction. The floating channel drives N-channel power MOSFETs or IGBTs in the high side configuration that operates up to 600V. The product features useful for motor control applications are as listed below:

- Negative VS transient immunity of 70 V, dV/dt immune
- Lower di/dt gate driver for better noise immunity
- Floating channel designed for bootstrap operation
- Operating voltages (VS node) upto + 600 V
- Maximum bootstrap voltage (VB node) of + 625 V
- Integrated bootstrap diode
- Integrated shoot-through protection with built-in dead time
- Integrated short pulse / noise rejection filter on input
- Independent under voltage lockout for both high and low side
- Schmitt trigger inputs with hysteresis
- 3.3 V, 5 V and 15 V input logic compatible
- Maximum supply voltage of 25 V
- Outputs in phase with inputs
- Suitable for both trapezoidal and sinusoidal motor control
- Available in small footprint DSO-8

The 2ED28073J06F comes with an advanced input filter that allows an improvement in the input / output pulse symmetry of the gate driver and helps to reject noise spikes and short pulses. This input filter is there for both the HIN and LIN inputs. Figures 27 and 28 show the working principle of the new filter.
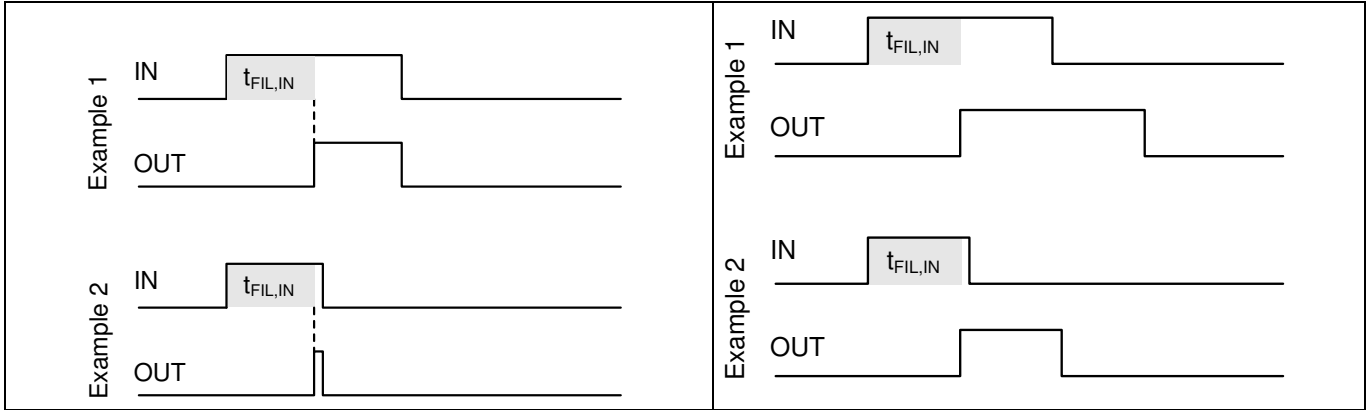

Figure 27   Typical input filter   **Figure 28   Advanced input filter**

Figure 27 shows a typical input filter and the asymmetry of the input and output. The upper pair of waveforms (Example 1) show an input signal with a duration much longer then $t_{FIL,IN}$; the resulting output is approximately the difference between the input signal and $t_{FIL,IN}$. The lower pair of waveforms (Example 2) show an input signal with a duration slightly longer then $t_{FIL,IN}$; the resulting output is approximately the difference between the input signal and $t_{FIL,IN}$.

Figure 28 shows the advanced input filter and the symmetry between the input and output. The upper pair of waveforms (Example 1) show an input signal with a duration much longer then $t_{FIL,IN}$; the resulting output is approximately the same duration as the input signal. The lower pair of waveforms (Example 2) show an input signal with a duration slightly longer then $t_{FIL,IN}$; the resulting output is approximately the same duration as the input signal.

2ED28073J06F has input filter-providing protection against short-pulses (e.g., noise) on the input lines. If the duration of the input signal is less than $t_{FIL,IN}$, the output will not change states. Example 1 of Figure 29 shows the input and output in the low state with positive noise spikes of durations less than $t_{FIL,IN}$; the output does not change states. Example 2 of Figure 29 shows the input and output in the high state with negative noise spikes of durations less than $t_{FIL,IN}$; the output does not change states.
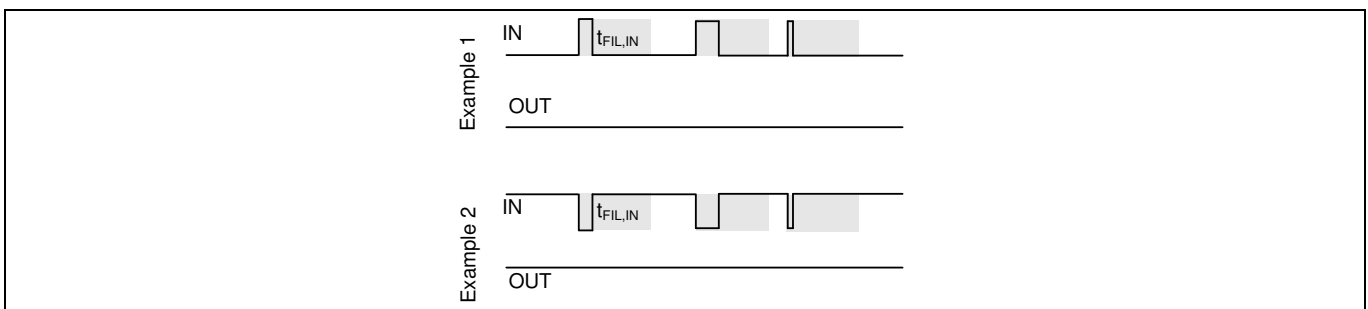

Figure 29   Noise rejecting input filters

In a typical motor drive system, dV/dt is in the range of 3 V / ns to 5 V / ns. The negative VS transient voltage can exceed this range during some events such as short circuit and over-current shutdown, when di/dt is greater than in normal operation. An indication of the 2ED28073J06F's robustness can be seen in Figure 30, where the

EVAL_DRIVE_3PH_PFD7
3-PH motor drive evaluation board with FOC sensorless control
Schematics and layout

2ED28073J06F's Safe Operating Area is shown at V_{BS}=15 V based on repetitive negative VS spikes. A negative VS transient voltage falling in the grey area (outside SOA) may lead to IC permanent damage; vice versa unwanted functional anomalies or permanent damage to the IC do not appear if negative Vs transients fall inside the SOA.
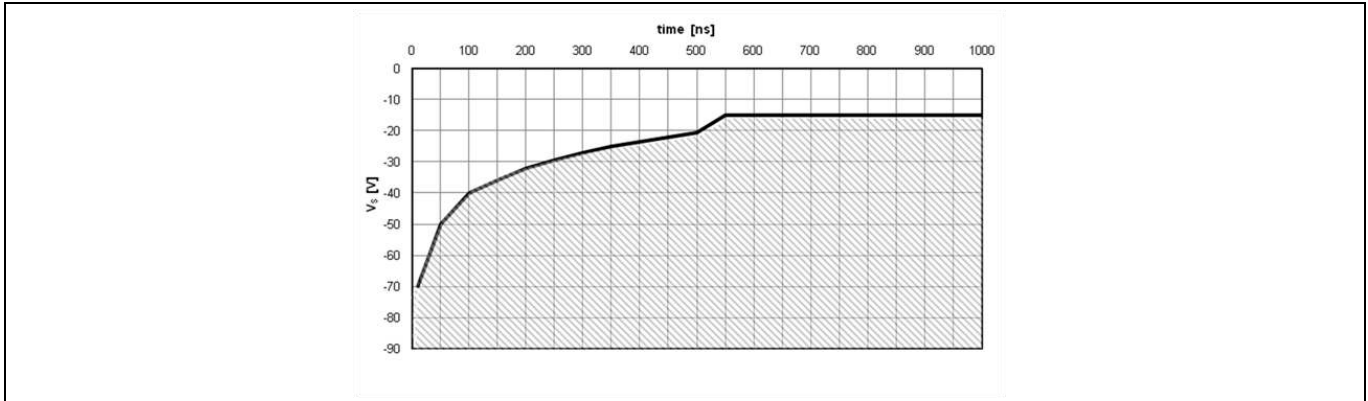

Figure 30   Negative VS transient SOA for 2ED28073J06F @ VBS=15 V

Additionally, the 2ED28073J06F has been tested to successfully drive CoolMOS™ PFD7 variants such as IPS60R1K0PFD7S, IPD60R1K5PFD7S and IPD60R2K0PFD7S with a dv/dt in the range of 3 V /ns to 5 V/ ns with very low turn on resistor of 100 Ω. Along with an external gate to source capacitance of 3.3 nF, the Miller capacitance induced voltages as seen in half-bridge circuits is also well within the gate threshold of CoolMOS™ PFD7.
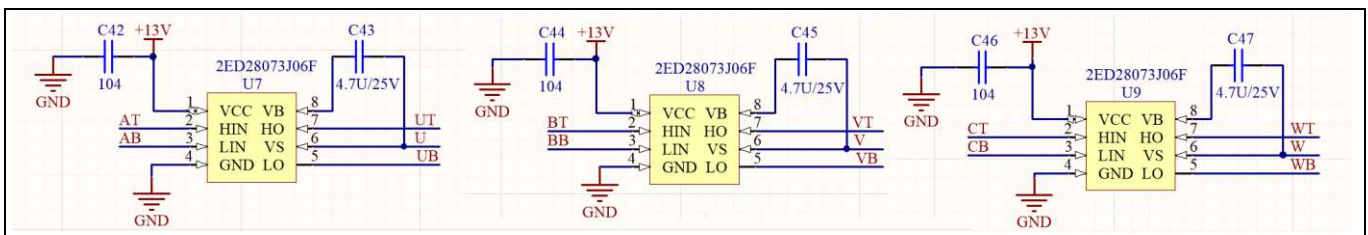

Figure 31   Power inverter – gate driver

The +13 V supply V_{CC} is monitored by the 2ED28073J06F. In case of UV the driver output is switched off. The thresholds are typically V_{CCUV+} = 8.9 V (positive going) and V_{CCUV-} = 7.7 V (negative going).

The three capacitors C43, C45 and C47 are used as bootstrap capacitors to provide the necessary floating supply voltages U, V and W respectively.

With the method of injecting enough current to the gate of the CoolMOS™ IO+ = 20 mA the switching dV/dt can be kept low at the inverter output, and the system can remove the external components that are typically used for this. These components usually include several resistors and high-voltage capacitors for each of the power MOSFETs. This reduces BOM and assembly costs, in addition to reducing the overall solution blueprint.

6.7   Temperature sensor characteristics

The EVAL_DRIVE_3PH_PFD7 has an onboard temperature sensor that is used by the MCE to linearly derate the power consumption and protect the inverter section. The linear power derating function with temperature shutdown is defined by parameters programmed by the user. The power dissipation must be limited so that the average MOSFET case temperature does not exceed 120°C.

The NTC is effectively a resistor whose value decreases as the temperature rises. The NTC is connected between GND and the VTH pin (see schematics). An external resistor network is connected to the NTC, the simplest of which is one resistor R21 pulled up to V_{CC}.

The NTC resistance can be calculated at any temperature as follows:

$$Rth = \text{R25}. \, e^{\text{B}\left(\frac{1}{Tth} - \frac{1}{T25}\right)}, \text{ where } R_{25} \text{ is } 47k\Omega \text{ and } B \text{ is } 4050 \, k$$

Table 4   NTC thermistor characteristics

Symbol	Description	Typ	Units	Conditions
R_{NTC}	NTC	47	kΩ	TC = 25°C, ±1 percent tolerance
R21	Pull-up	5.5	kΩ	
B	0.21	4050	k	±1 percent tolerance
Temperature range		-40 to 125	°C	

$$Vshut \, down = \frac{\text{Rth@}max \, temperature}{\text{Rth@}max \, temperature + \text{R} \, pullup} * 3.3V$$
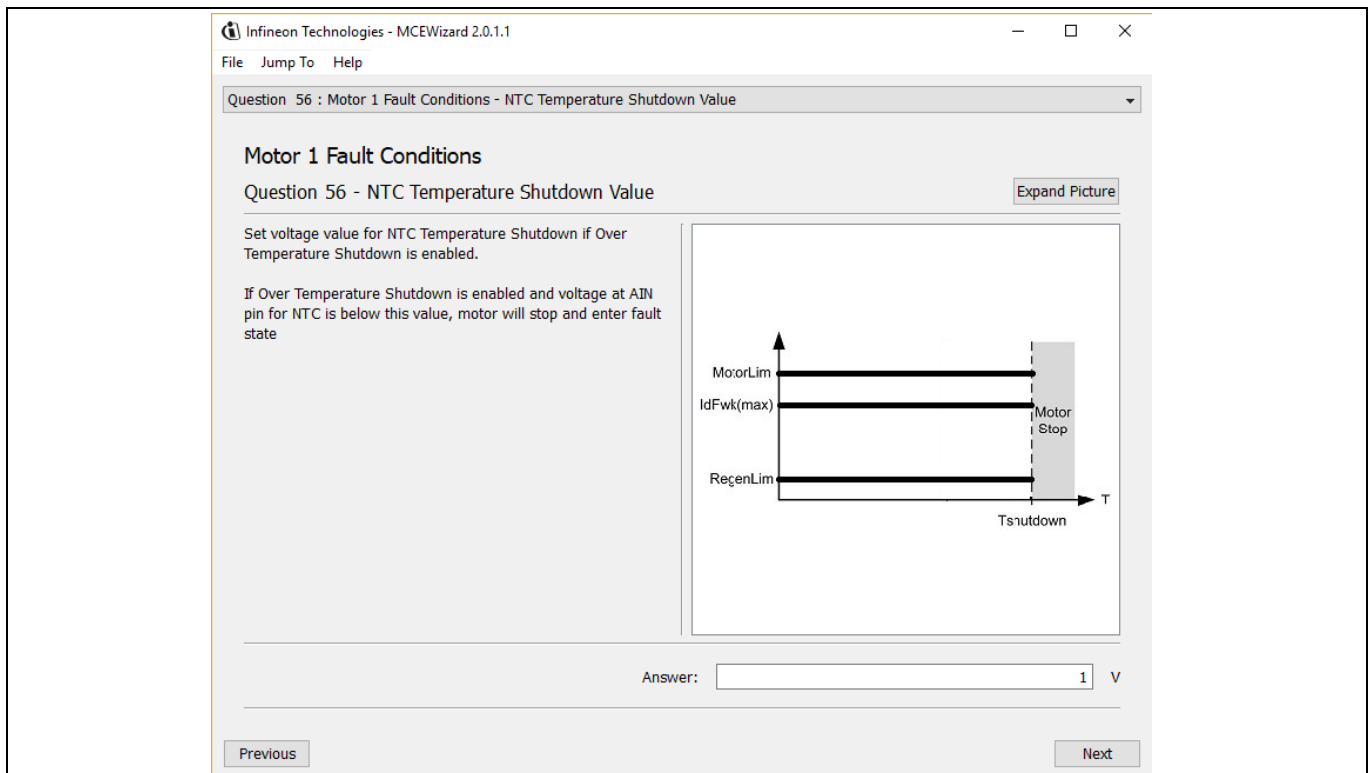

Figure 32   External temperature sense input configuration in MCEWizard

6.8 Analog VSP control and PG~out~ configuration

For analog VSP control input mode, a variable resistance can be used to control the motor speed "4.3 Speed control potentiometer", and the speed can be calculated by measuring the frequency of Pulse Generation (PG) signal output of the controller. The PG number per revolution for the motor can be configured in MCEWizard, as shown in Figure 33.

Motor speed can be calculated as shown below:

$$Motor\ speed(RPM)\ = \frac{PGOUT\ Freuqency(Hz)\ *\ 60s}{Pulse\ Per\ Revolutio}$$
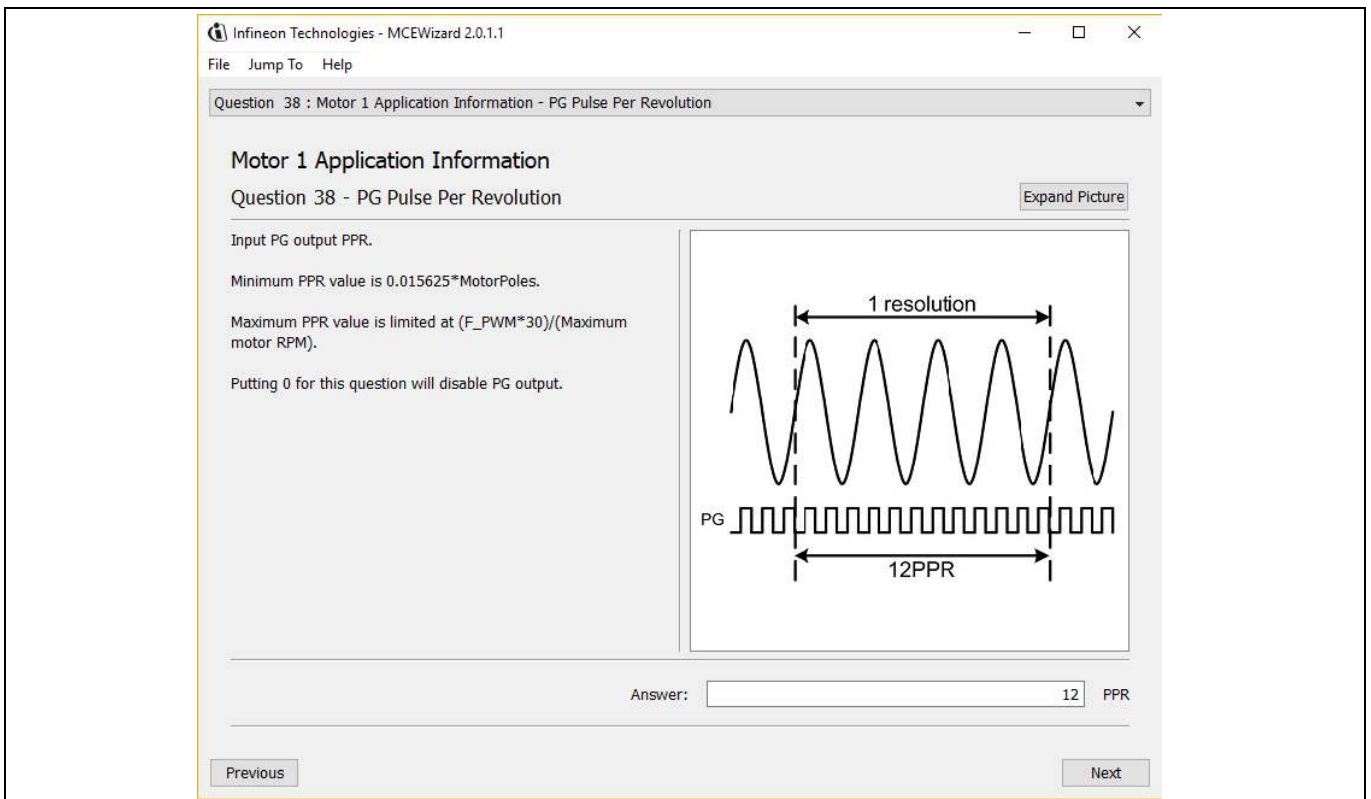

Figure 33   PG pulse per revolution configuration

7 Measurements

The EVAL_DRIVE_3PH_PFD7 was tested driving a three-phase fan motor using FOC. The inverter stage temperature was monitored during the test, and care was taken to make sure the steady-state was reached on each load point before recording the efficiency and temperature on the CoolMOS™devices. After the measurement was recorded the load was increased gradually untill reaching full load, 75 W. For details of the measurement equipment, see Table 5.

Table 5   Equipment list measurement parameters

Name	Comment
3-PH fan motor	
Axial fan type	A2D200-AA02-01
Power	75 W
Power factor	0.8
Number of poles	Four pole pairs
Phase resistance	150 Ω
Phase inductance	300 mH
Maximum speed	3000 RPM
Phase connections (U, V, W, N)	Delta connection
Yokogawa WT3000 power analyzer	
Voltage range	300 V
Current range	1 A
Line filter	50 Hz
Output three-phase wirings	3P4W
Input one-phase wirings	1P1W
Temperature measuring equipment	
Thermocouples	J-type GG-JI-36-SLE
Temperature measuring unit	A55003830
Thermal camera	FLIR

7.1 Test set-up

In order to test the performance of the EVAL_DRIVE_3PH_PFD7, the board was tested on a test bench developed by Infineon and used to simulate a real cooling fan application. The three-phase fan is a 75 W high-speed fan used for industrial cooling applications. The efficiency was monitored by a Yokogawa WT3000 power meter and the case temperature was measured and monitored by an infrared camera.

7.2 Short-circuit test

During a short-circuit event, the instantaneous power is very high, which will heat up the powered device very quickly. The MOSFET must be turned off before thermal failure.

The power dissipation during a short-circuit event can be calculated by doing an integral over-drain source voltage and drain current through the short-circuit event. This energy must be less than the critical energy, which can cause the device to fail.

$$\mathrm{E}(CS) = \int_{t1}^{t3} Vds.Id.dt$$

Figure 34 shows a short-circuit test performed on the IPN60R1K5PFD7S for a pulse of 3 µS at 400 V bus voltage and T_{case} = 25°C ,the total energy was calculated using the equation above, E(sc) = 22 µJ. The IPN60R1K5PFD7S passed the short-circuit test, the short-circuit energy E(sc) = 22 µJ is too low to cause a failure to the part.
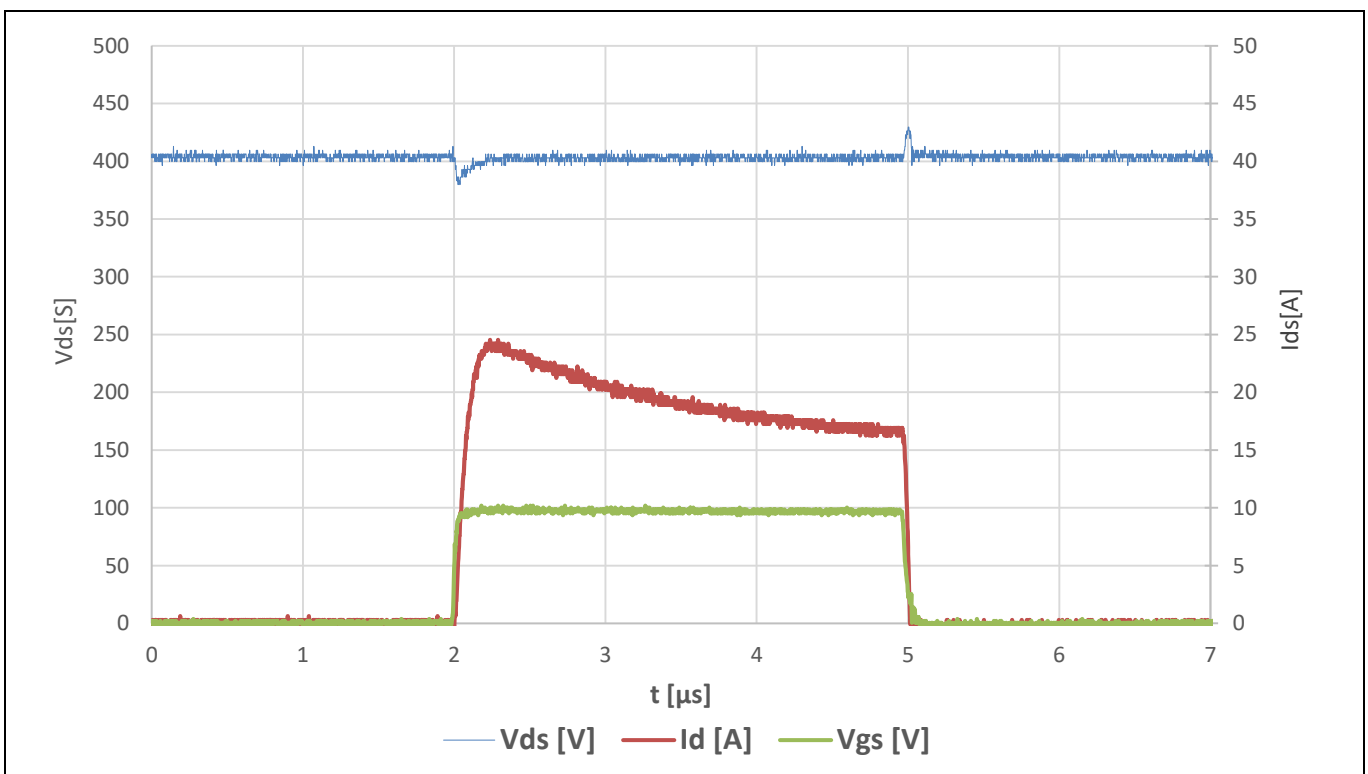

Figure 34   **Short-circuit test**

7.3   Thermal behavior

The temperature distribution is uniform at the inverter stage due to the symatric modulation scheme, as demonstrated by detailed analysis of the thermal images:
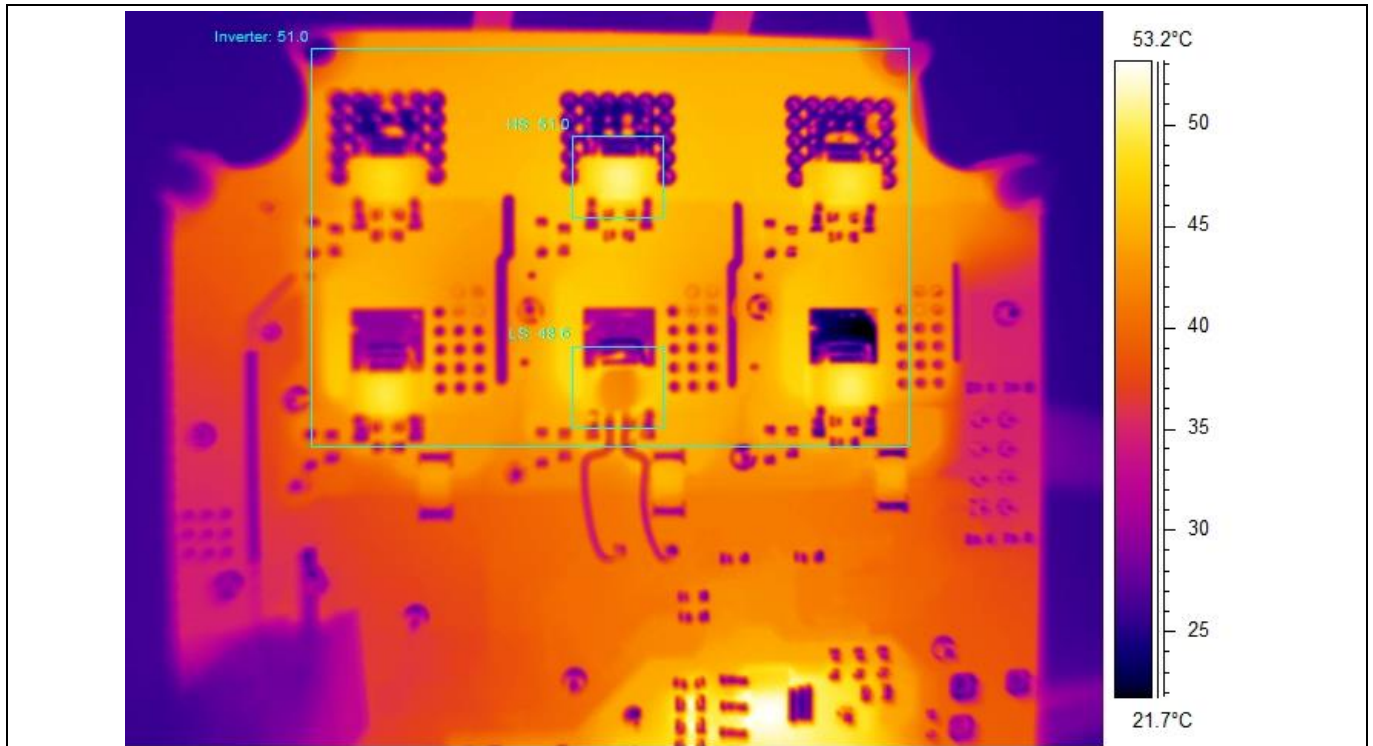
Figure 35 Thermal images at P_{in} = 75 W, $f_{\_sw}$ = 10 kHz, T_{max} = 53°C

7.4 Efficiency

The test was performed with 230 V AC up to 75 W load, with an ambient temperature of 25°C and switching frequency at 10 kHz. Besides the losses of the power switching efficiency, there were also rectification, driving and power supply losses. The complete board efficiency results are shown in Table 6 and plotted in Figure 36.

Table 6 Efficiency measurement, f_{sw} = 10 kHz, IPN60R1k5PFD7S

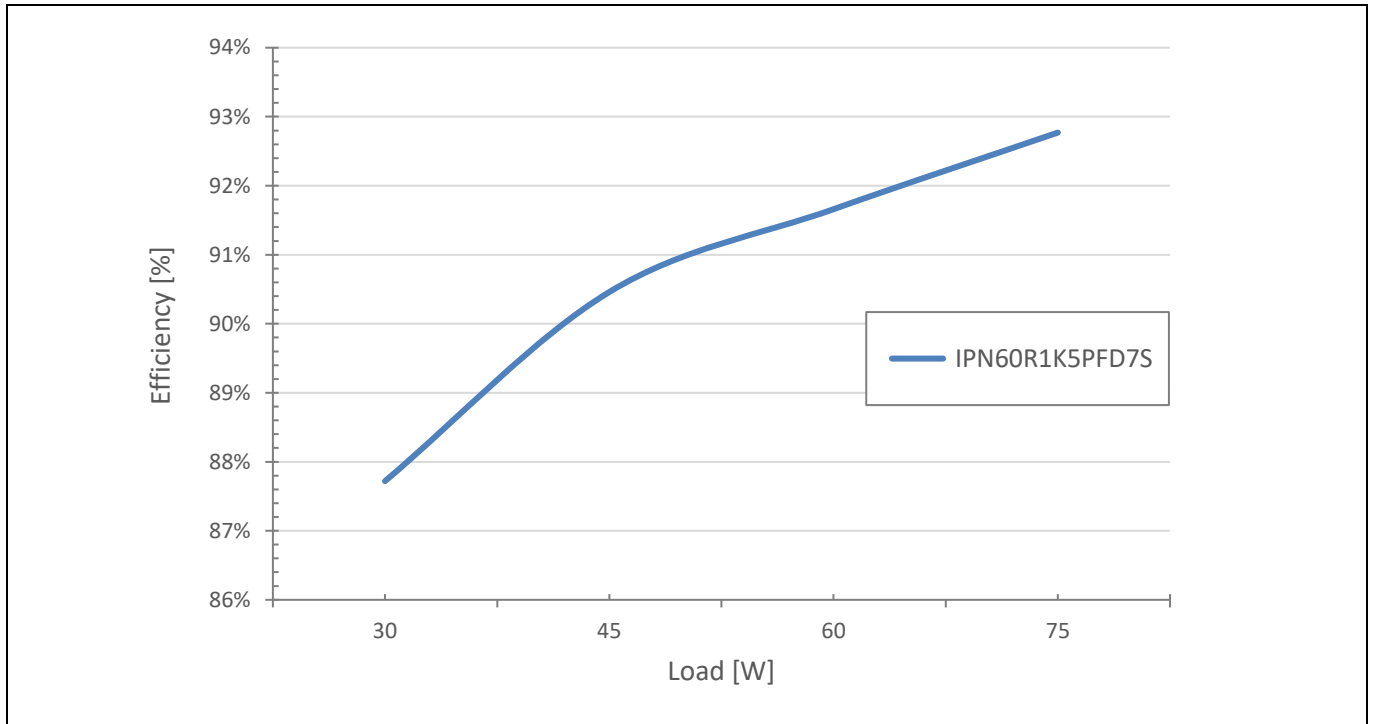| P_{DC} [W]	Phase I_{DC} [mArms]	I_{AC} [mArms]	Efficiency [%]
30	197.4	263	87.72
45	241	393	90.46
60	271	496	91.66
75	311	652	92.77

Figure 36   **Efficiency measurement curve f$_{sw}$ = 10 kHz, IPN60R1K5PFD7S**

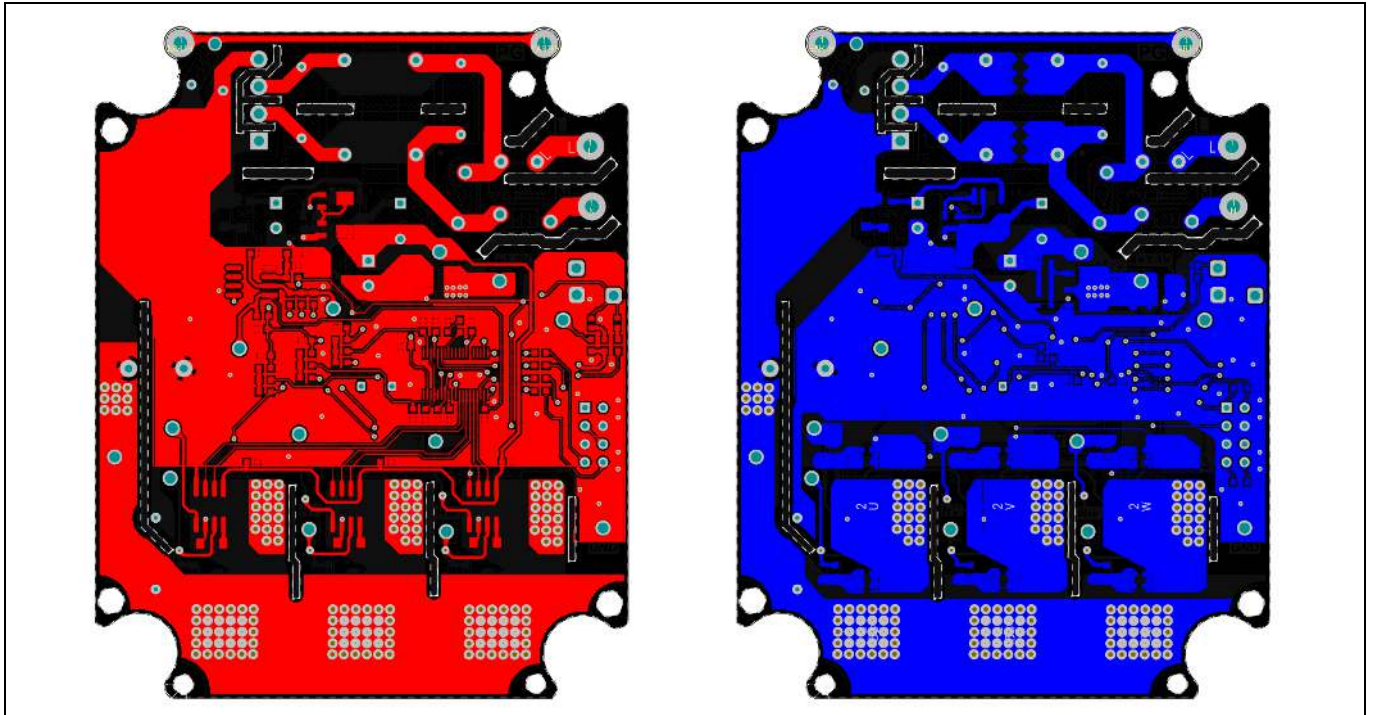# 8 Board information

8.1 Board layout

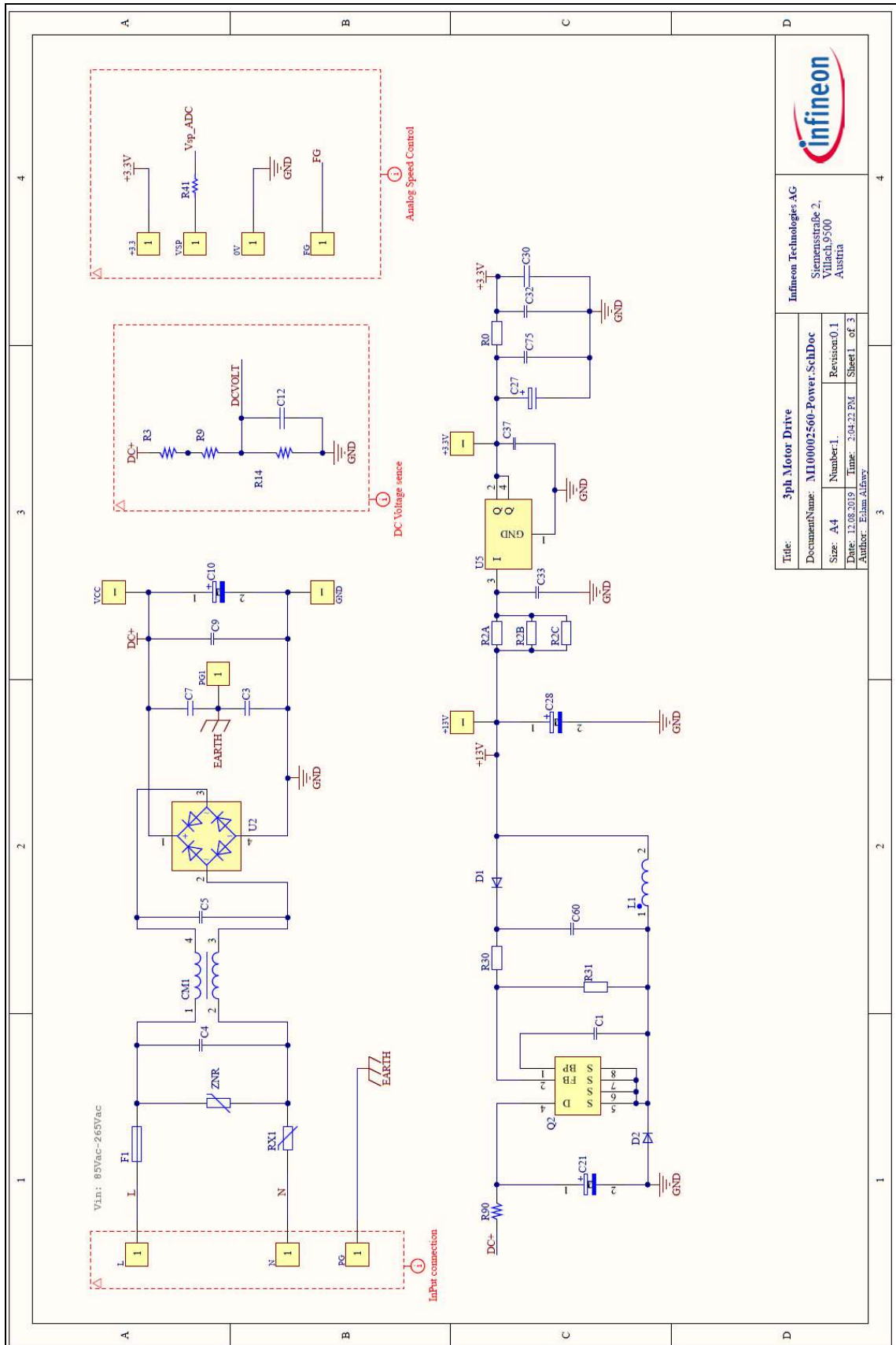**Figure 37**   **Board layout top view (left) and bottom view (right)**

9 Board schematics

Figure 38   Microcontroller

Figure 39 **Power section**

Figure 40   Inverter section
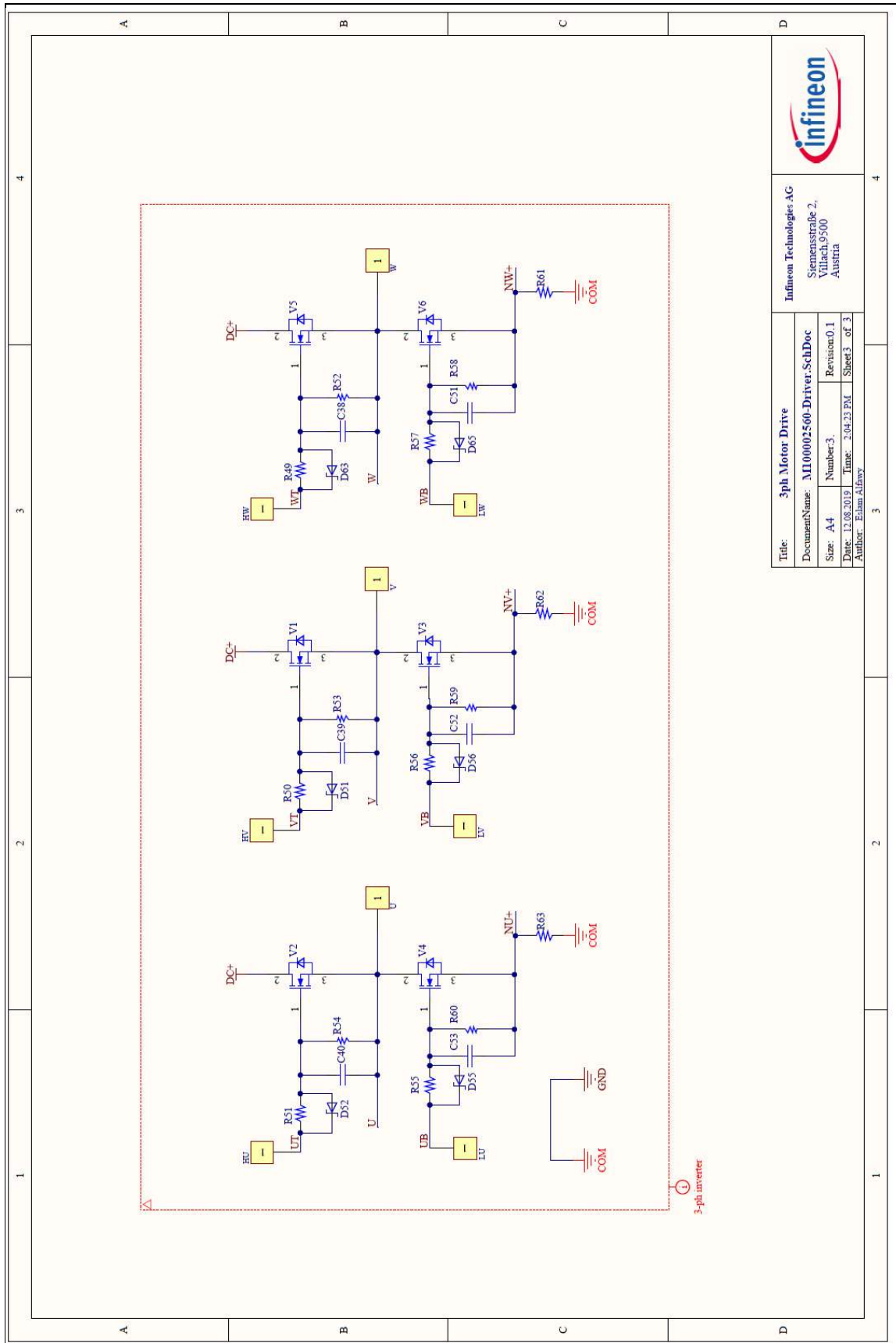
10 Bill of Materials (BOM)

No.	Ref.	Description	Package	Manufacturer
1	**V1, V2, V3, V4, V5, V6**	**IPN60R1K5PFD7**	**TO-252AA**	**Infineon**
2	**U5**	**IFX1117ME V33**		**Infineon**
3	**U1**	**IMC101T-T038**	**TSSOP38**	**Infineon**
4	**D52, D55, D51, D56, D63, D65**	**BAT54W**	**SOD323**	**Infineon**
5	**U7, U8, U9**	**2ED28073J06F**	**SO-8**	**Infineon**
6	ZNR	Varistor	MOV-10D471KTR	Bourns
7	F1	3.1 A/250 V	0034.6019	Schurter
8	CM1	2.3 mH/1.7 A	SSRH7HS-M17023	Kemet
9	RX1	NTC/15 Ω/9 mm dia.	B57153S0150M000	Epcos
10	U2	KBP208GL	800 V, 2 A KBP, 4-pin	Diode Bridge
11	U3	LM393ADGKR	SO-8	Texas Instruments
12	Q2	LNK304DN	SOIC-8	Power Integrations
13	PG$_{OUT}$, STATUS	LED, 3.3 V	SMD 0603	Any
14	NTC1	Thermistor, 47 kΩ	NXRT15WB473FA3A016	Murata
15	+3.3 V, +13 V, GND, HU, HV, HW, I$_d$, LU, LV, LW, OCP, V$_{CC}$, FG	5013 – test point, PCB, through-hole	5013	Any
16	Debug	Male header 8	Harwin M20	Any
17	D1, D2	600 V/1 A standard diode	US1J R2	Taiwan Semiconductor
18	R61, R62, R63	R$_{sense}$ 0.25 Ω/2010/ 500 mW, ± 1 percent	WSL2010R2500FEA	Vishay
19	C21	2.2 µF/400 V	MCKSK400M2R2F12S	Multicomp Pro
20	C3, C7	2.2 nF/250 V	Ceramic capacitor	Any
21	C4, C5, C9	0.1 µF/275 V AC	890324023023	Würth Elektronik
22	C2, C8, C13	220 pPF/25 V ±1 percent	SMD 0603	Any
23	C10	100 µF/400 V	400KXW68MEFC12.5X40	Rubycon
24	C1, C6, C11, C12, C14, C19, C30, C34, C36, C42, C44, C46, C56,C32, C33, C75, C01, C17	0.1 µf/25 V	SMD 0603	Any
25	C22, C23, C24, C29	15 pF/25 V	SMD 0603	Any
26	C27	47 µF/6.3 V	EEEFK0J470UR	Panasonic

27	C28	100 µF/25 V	MCGPR25V107M6.3X11	Panasonic
28	C15, C16, C31	222/25 V ±1 percent	SMD 0603	Any
29	C37	10 nF/25 V	SMD 0603	Any
30	C88	472/25 V	SMD 0603	Any
31	C43, C45, C47	4.7 µF/25 V	SMD 1206	Any
32	C38, C39, C40, C51, C52, C53	332/25 V	SMD 0603	Any
33	C60	102/25 V	SMD 0603	Any
34	C18, C20	220 µF/25 V ±1 percent	SMD 0603	Any
35	L1	Inductivity/radial/2.2 mH/360 mA/5.9 Ω ±10 percent	RLB9012-222KL	Bourns
36	R2, R4, R7, R16, R18, R31	2 k	SMD 0603	Any
37	R5, R8, R15, R19, R49, R50, R51, R55, R56, R57	100 R ±1 percent	SMD 0603	Any
38	R14	13.3 k	SMD 0603	Any
39	R23, R24, R25, R27	1 k ±1 percent	SMD 0603	Any
40	R10, R11, R12, R13	510 R	SMD 0603	Any
41	R1, R6, R17, R41, R52, R53, R54, R58, R59, R60	10 k ±1 percent	SMD 0603	Any
42	R2A, R2B, R2C	300 R	SMD 0603	Any
43	R90, R0	0 R	SMD 0603	Any
44	R20	47 R	SMD 0603	Any
45	R3, R9	1 M	SMD 1206	Any
46	R21	5.5 k	SMD 0603	Any
47	R22	4.7 k	SMD 0603	Any
48	R30	13 k	SMD 0603	Any
49	R26	15 k	SMD 0603	Any

Revision history

Document version	Date of release	Description of changes

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