

# EVAL\_IMD700A\_FOC\_3SH 18 V brushless DC motor drive board

## Application note

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## About this document

### Scope and purpose

This document describes the functionalities of the EVAL\_IMD700A\_FOC\_3SH 18 V motor drive board for battery-powered brushless DC (BLDC) motor drives with sensorless field-oriented control (FOC), used in applications such as cordless power tools up to 300 W. This evaluation board operates with motors that do not include integrated Hall sensors for rotor position sensing. This solution uses the XMC1400 series microcontroller (MCU) integrated into the MOTIX™ IMD700A three-phase smart driver IC and Infineon OptiMOS™ 6 3x3 source-down power MOSFETs. The MOTIX™ IMD700A reduces system component count and development time-to-market, while at the same time significantly increasing the power density, system performance and peak power pulse capabilities. The graphical user interface (GUI) software tool designed for configuring the MOTIX™ IMD700A will also be introduced.

### Intended audience

This document addresses the market for cordless power tool and other battery-powered motor drive applications, aimed at designers wishing to provide a high-performance system solution as well as reduce system costs; also design engineers, applications engineers, and students.

### Infineon components featured

- [IQE013N04LM6](#) (OptiMOS™ 6 40 V/1.5 mΩ 3x3 corner gate, source down)
- IMD701A-Q064x128 integrated XMC1400 MCU and smart three-phase half-bridge gate driver

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**Introduction**

## **1 Introduction**

### **1.1 Brushless DC motors**

BLDC motors are commutated by controlled switching of the inverter instead of using mechanical brushes. Windings are energized in a determined sequence to generate a rotating field magnetic. The rotor permanent magnet attempts to align with the stator field, producing torque and rotary motion. As with mechanical commutation, electronic commutation helps in achieving unidirectional torque similar to a conventional DC machine. In BLDC machines the rotor consists of permanent magnets, while the stator is wound with a specific number of poles. BLDC motors are often produced as outer rotor-type machines. Rotor position can be sensed using digital Hall effect sensors embedded into the stator, or sensorless control algorithms can be used to determine position and speed from the phase currents.

### **1.2 EVAL\_IMD700A\_FOC\_3SH motor drive board**

This application note describes Infineon's EVAL\_IMD700A\_FOC\_3SH motor drive evaluation board optimized for 18 V battery-powered tools operating with sensorless field-oriented or vector control. The current design considers the electrical driving capabilities for BLDC machines without requiring sensors to determine rotor position and speed. This evaluation board (with alternative firmware) also supports operation with Hall sensors.

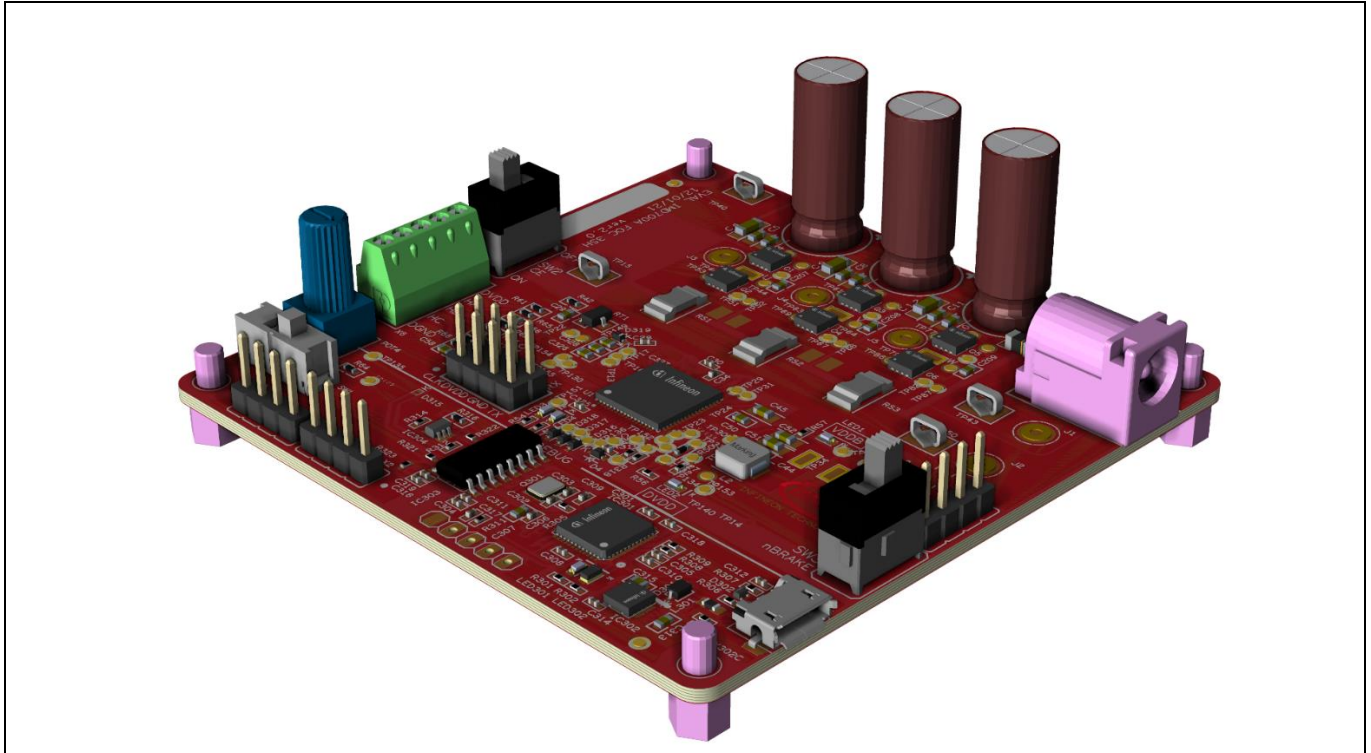
An onboard isolated debugger is included, ready for direct connection to a PC via a USB type A port. The source code is completely implemented using the Infineon Eclipse-based IDE, DAVE™ (development platform for XMC™ MCU, [www.infineon.com/DAVE](http://www.infineon.com/DAVE)). The control method implements a vector speed-control algorithm based on the BLDC motor using pulse-width modulation (PWM) and three current shunts for phase current measurement.

The firmware is developed using the XMC1400 family MCU, which is integrated into the MOTIX™ IMD700A ([www.infineon.com/XMC](http://www.infineon.com/XMC)).

With this kit, users can evaluate the MOTIX™ IMD700A-based motor drive system using the control capabilities of the XMC1400 by means of the implemented control algorithm. The board includes a switch for changing the motor direction and a speed control. Configuration and control are also possible through the dedicated motor control graphical user interface (MCGUI), which connects to the demo board through a USB cable interfacing with an onboard programmer/debugger.

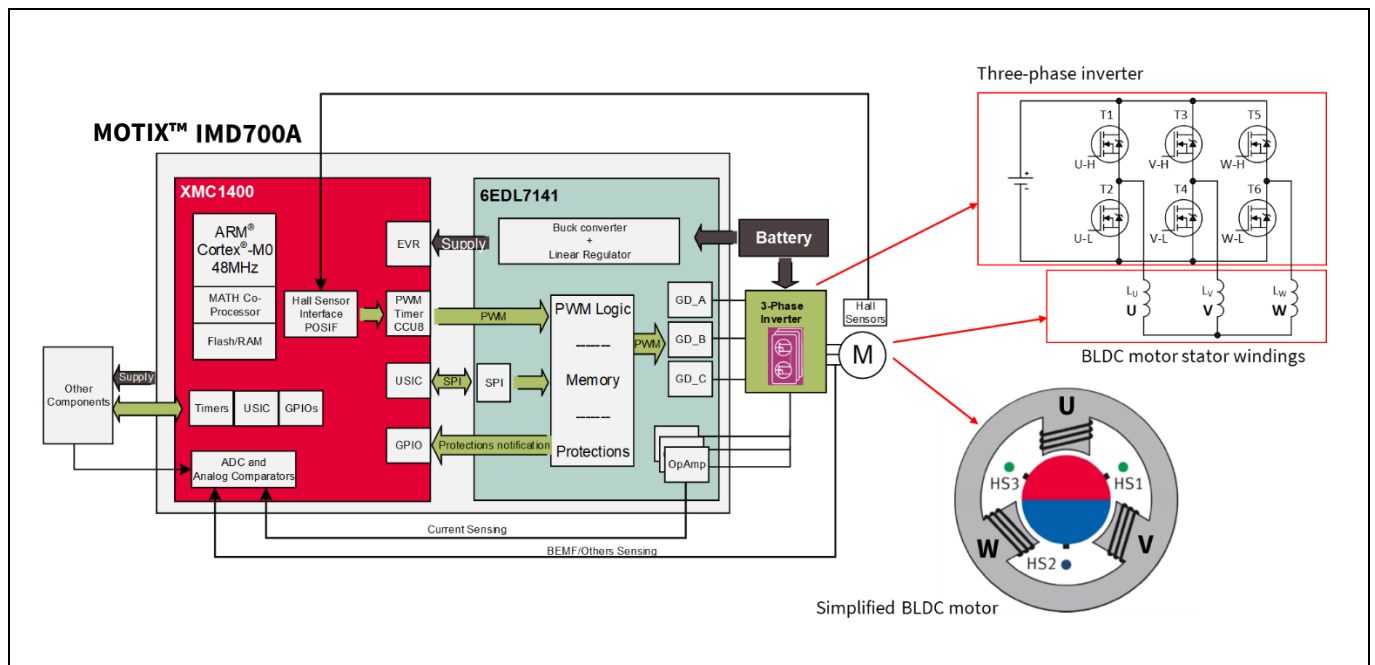
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**Figure 1** EVAL\_IMD700A\_FOC\_3SH demo board

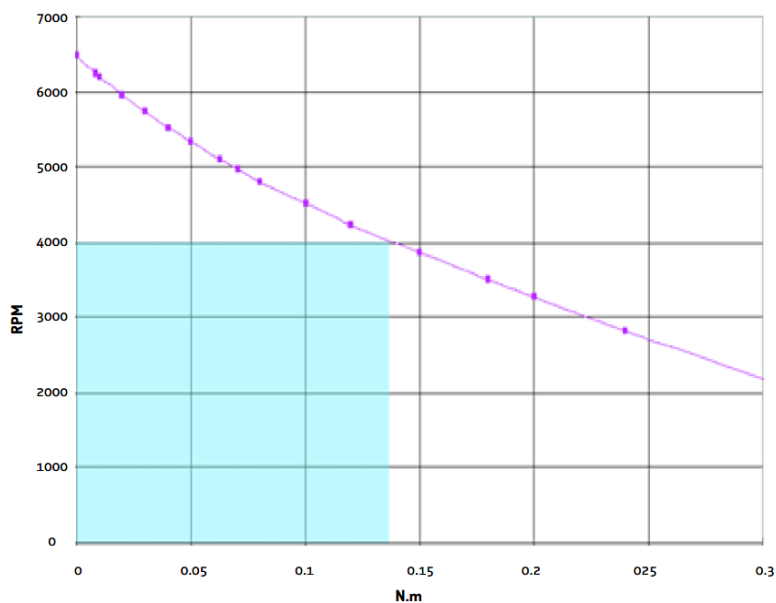
The EVAL\_IMD700A\_FOC\_3SH board system block diagram of the main system elements excluding the onboard debugger is as follows:



**Figure 2** Simplified system block diagram

Rotary velocity is plotted against torque measured with 24 V supply voltage for the example motor datasheet, shown below. The blue area represents the region where the motor may be safely used without overheating the stator coils.

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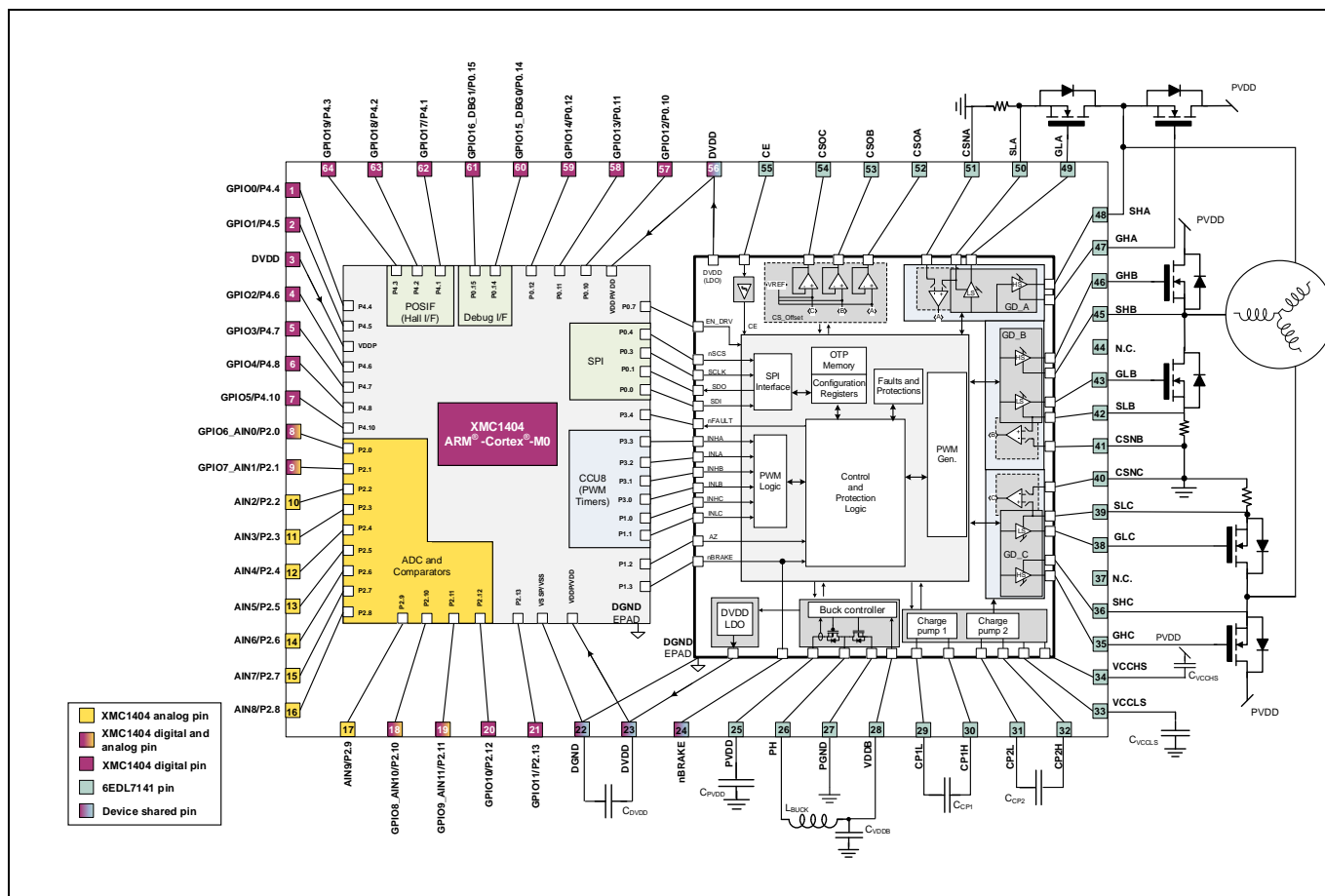


**Figure 3** Rotary velocity vs. torque curve for example BLDC motor

## Introduction

### 1.3 MOTIX™ IMD700A functional overview

The MOTIX™ IMD700A is a three-phase smart gate driver in a 64-pin VQFN package for BLDC or permanent magnet synchronous motor drive systems. It consists of an MCU (XMC1400) connected to a configurable three-phase half-bridge gate driver (MOTIX™ 6EDL7141) able to operate in multiple PWM modes with an integrated DC-DC synchronous buck converter, low dropout linear voltage regulator, and configurable precision current sense (CS) amplifiers. There are many configuration options, which can be set via an advanced MCU interface in conjunction with a PC-based GUI. Configuration settings can be made permanent by storing them in the built-in one-time programmable (OTP) memory.



**Figure 4** MOTIX™ IMD700A internal block diagram

The MCU communicates with the MOTIX™ IMD700A via an internal SPI to enable configuration. PWM signals from the MCU provide the gate drive control pulses, which can be decoded in several different ways. The MOTIX™ IMD700A provides gate drive pulses to the three-phase inverter low- and high-side MOSFETs. The gate drive output voltages can be selected to several different levels between 7 V and 15 V, and the switch-on and switch-off profiles can be optimized to minimize EMI and switch-off transients by configuration of gate drive current during several time intervals of the switching process. This also eliminates the need for resistor-diode gate drive networks. Protection signals and phase current measurements are available from the MOTIX™ IMD700A to connect to digital and analog MCU inputs.

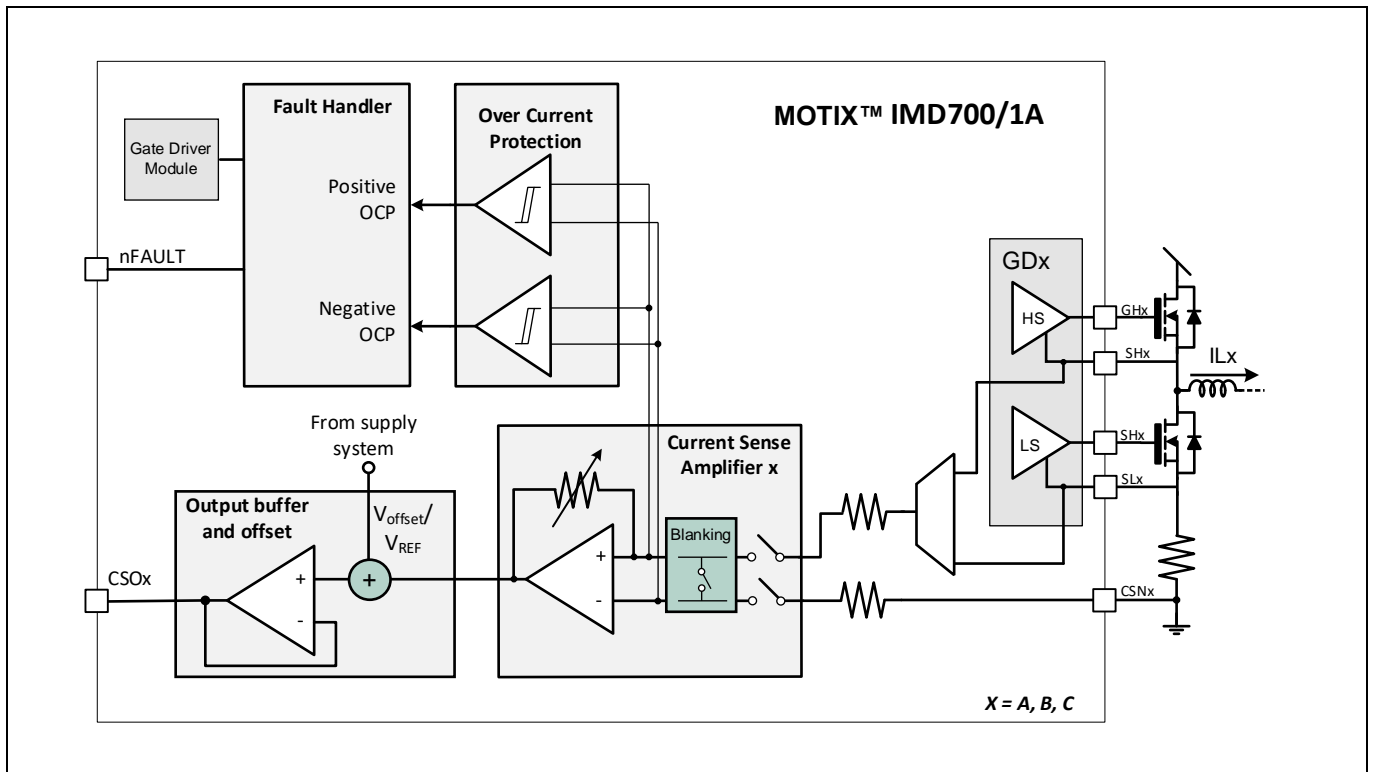
The MOTIX™ IMD700A integrates three precision CS amplifiers, which can be used to measure the current in the inverter via shunt resistors. Single, double, or triple shunt measurements are supported. Each CS amplifier can be enabled individually. The gain and offset are configured internally and can be set via the user interface. An additional output buffer enables adding a variable offset voltage to the sense amplifier output, which can be

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### Introduction

set to four different values either by programming the internally generated level or by applying an external voltage at the  $V_{REF}$  input pin so that negative current in current shunts can also be measured.

A positive overcurrent comparator detects an overcurrent condition on a motor winding for a positive shunt voltage. This comparator can be used to apply PWM cycle-by-cycle pulse truncation, terminating the gate drive to limit the maximum motor current. An additional negative overcurrent comparator is also used for detecting the overcurrent condition on motor winding for negative shunt currents. A built-in digital-to-analog converter (DAC) is used for programming the thresholds of the overcurrent comparators.



**Figure 5** MOTIX™ IMD700A CS amplifiers and comparators

The MOTIX™ IMD700A also includes a complete power system infrastructure based on the synchronous buck regulator, which efficiently converts the battery voltage to an internal supply voltage able to provide up to 300 mA. The output voltage  $V_{DDB}$  is set to 6.5 V, 7 V or 8 V, depending on the gate drive voltage setting  $PVCC$ , which can be 7 V, 10 V, 12 V or 15 V. The only external components required are the inductor and capacitor. The buck regulator supplies the linear regulator, which can provide a noise-free 3.3 V (MOTIX™ IMD700A) or 5 V (MOTIX™ IMD701A) supply for the digital circuitry and MCU.

Integrated low-side and high-side charge pumps supplied from the buck regulator provide the gate driver supply voltages, which enable duty cycles up to 100 percent. Each charge pump uses an external switched capacitor (CP1 for the low-side and CP2 for the high-side) to transfer charge from the buck converter output to the gate driver bias supplies:  $VCCLS$  and  $VCCHS$ .  $VCCLS$  is referenced to the system zero volt rail, and  $VCCHS$  is referenced to the system positive supply rail. Unlike conventional half-bridge drivers, the MOTIX™ IMD700A includes an advanced high-side driver scheme that enables  $VCCHS$  to supply the switch-on voltage and current to the high-side gate drivers for all three phases without the need for separate floating supplies for each phase. The values of the switched capacitors and bias supply capacitors,  $CVCCLS$  and  $CVCCHS$ , need to be selected according to the datasheet instructions for the charge pumps to operate correctly. The charge pump clock frequency is configurable from 166 kHz and 1800 kHz, with an additional frequency modulation to reduce EMI.

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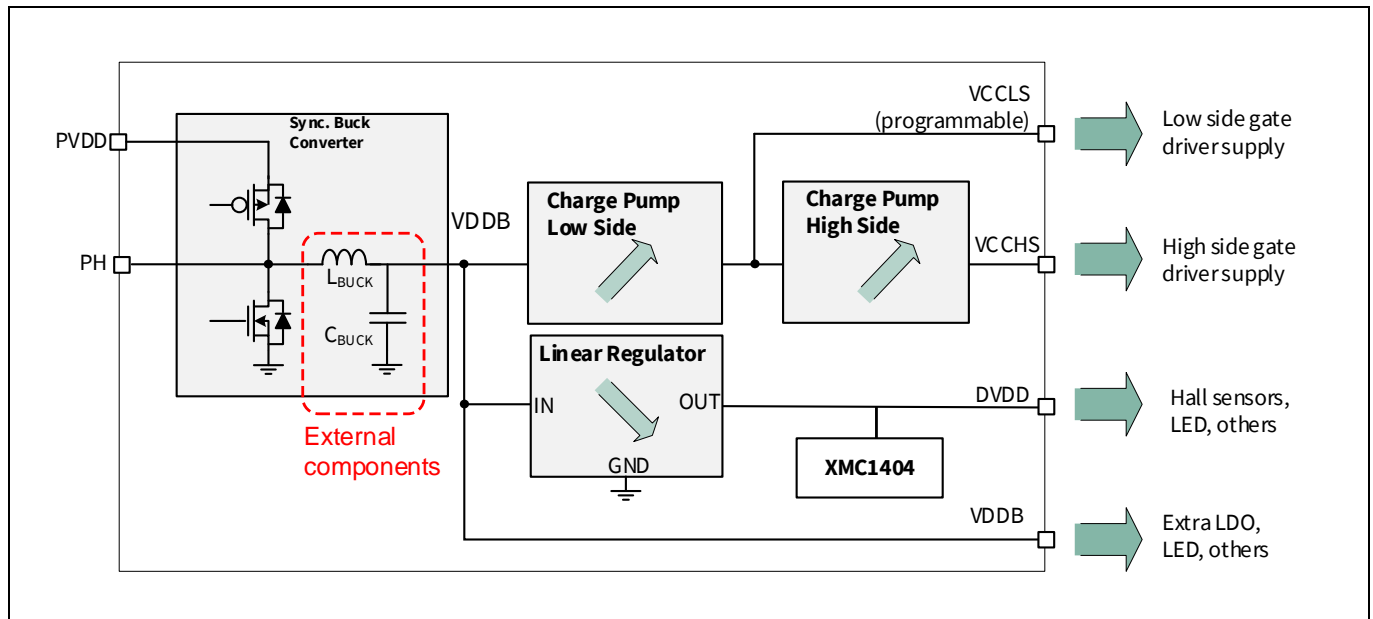


Figure 6 MOTIX™ IMD700A integrated power supplies

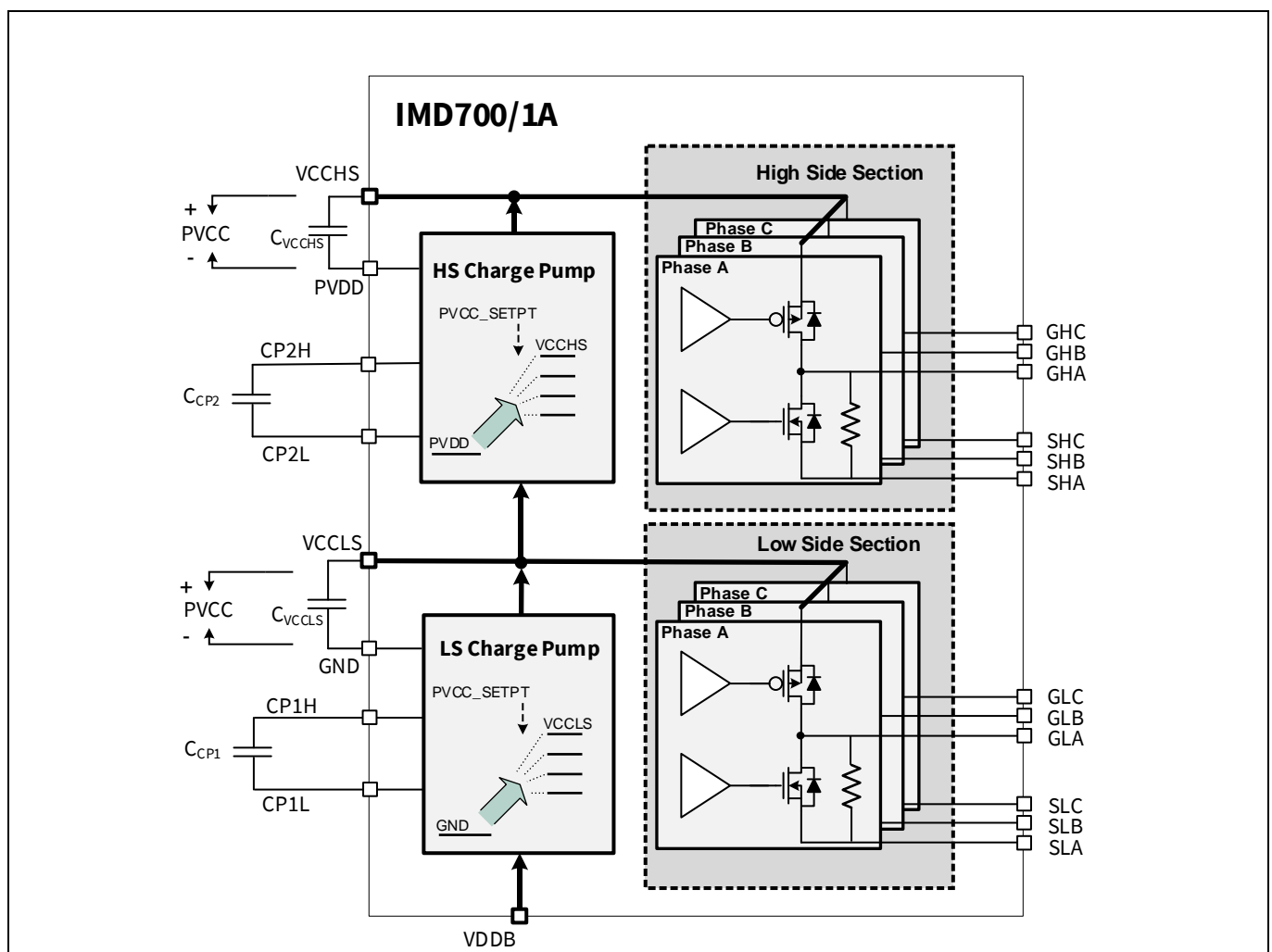


Figure 7 MOTIX™ IMD700A integrated charge pumps and gate drivers



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The EVAL\_IMD700A\_FOC\_3SH evaluation board operates using the 6PWM mode with the firmware supplied.

The MOTIX™ IMD700A also incorporates several protection functions, including:

- Overcurrent protection (OCP) for the internal power supplies and inverter phases
- Undervoltage lockout (UVLO) for the input bus voltage and digital supply voltage
- Overtemperature detection, warning, and shutdown
- A configurable watchdog timer
- Memory fault detection

Locked rotor detection is also available in designs using Hall sensors.

## 2 Specifications

### Input and output at normal operation

- DC input voltage 12 to 24 V, nominal 18 V
- Maximum input current 20 A
- Output voltage three-phase FOC
- Maximum output current per phase 15 A<sub>RMS</sub>
- Maximum output continuous power 300 W

### Control scheme

- Sensorless FOC
- Switching frequency 20 kHz
- Three current shunts

### Protection features

- Input fuse
- Input reverse polarity
- Output overcurrent
- Thermal shutdown

### Maximum component temperature

In an ambient temperature of 30°C, the maximum allowed component temperatures are as follows:

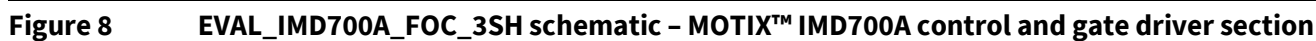
- Resistors less than 100°C
- Ceramic capacitors, film capacitors, and electrolytic capacitors less than 100°C
- MOSFET transistors and diodes less than 100°C
- ICs less than 100°C

### Dimensions of the evaluation board

Maximum width 3.0 in./76.2 mm, maximum length 3.0 in./76.2 mm.

**Note:** *In order for this board to operate, the firmware must be configured correctly for the specific motor being driven. This requires motor parameters such as phase-winding inductance and resistance to be entered into the motor control GUI before flashing the firmware to the target board.*

**Attention:** *The board should be tested only by qualified engineers and technicians.*



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## Schematics

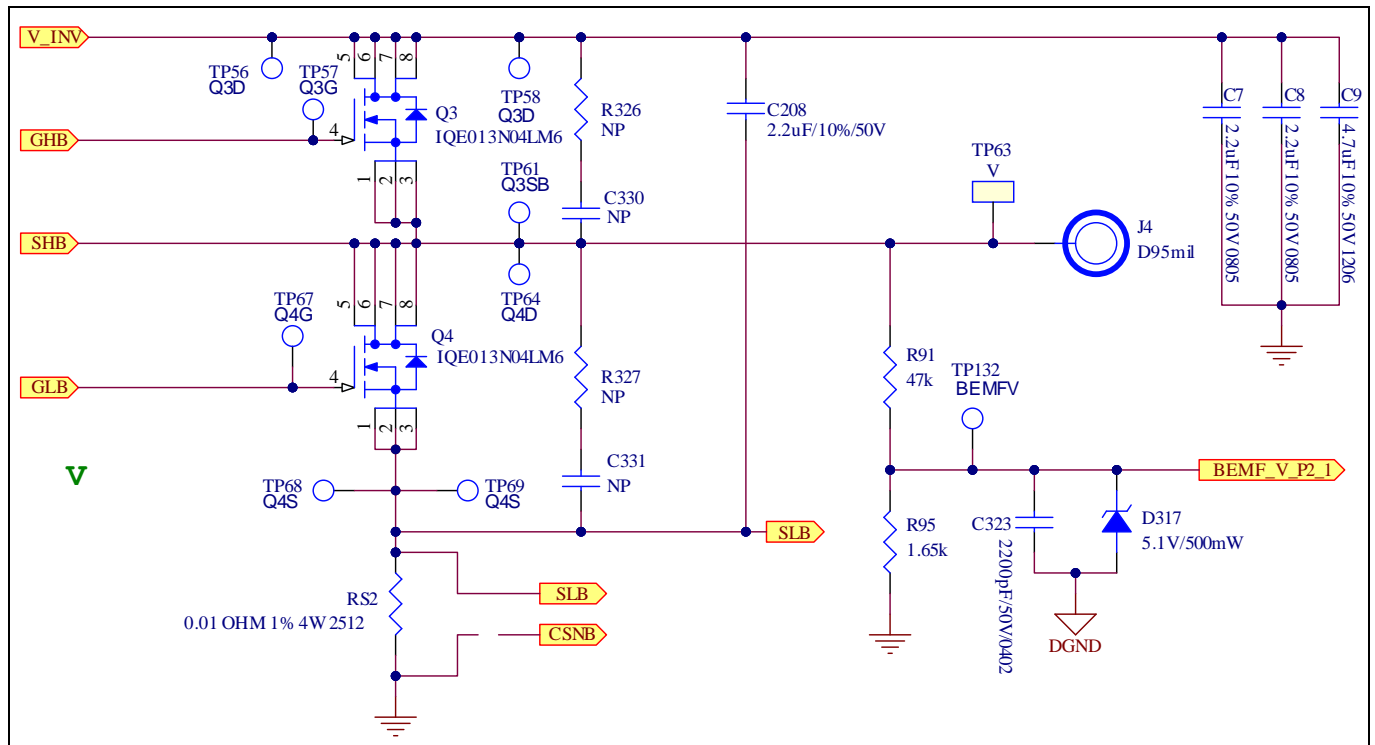


Figure 9 EVAL\_IMD700A\_FOC\_3SH schematic – power stage, phase “U”

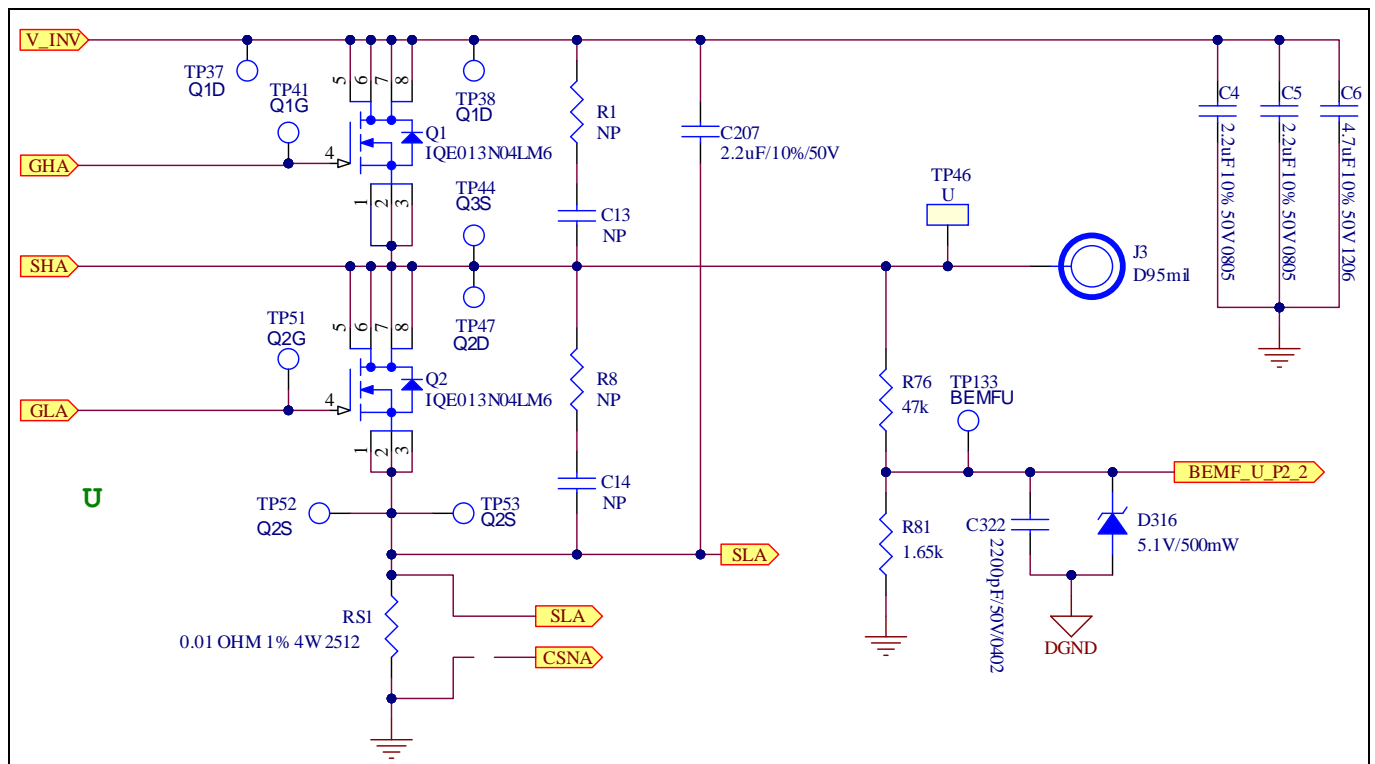


Figure 10 EVAL\_IMD700A\_FOC\_3SH schematic – power stage, phase “V”

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## Schematics

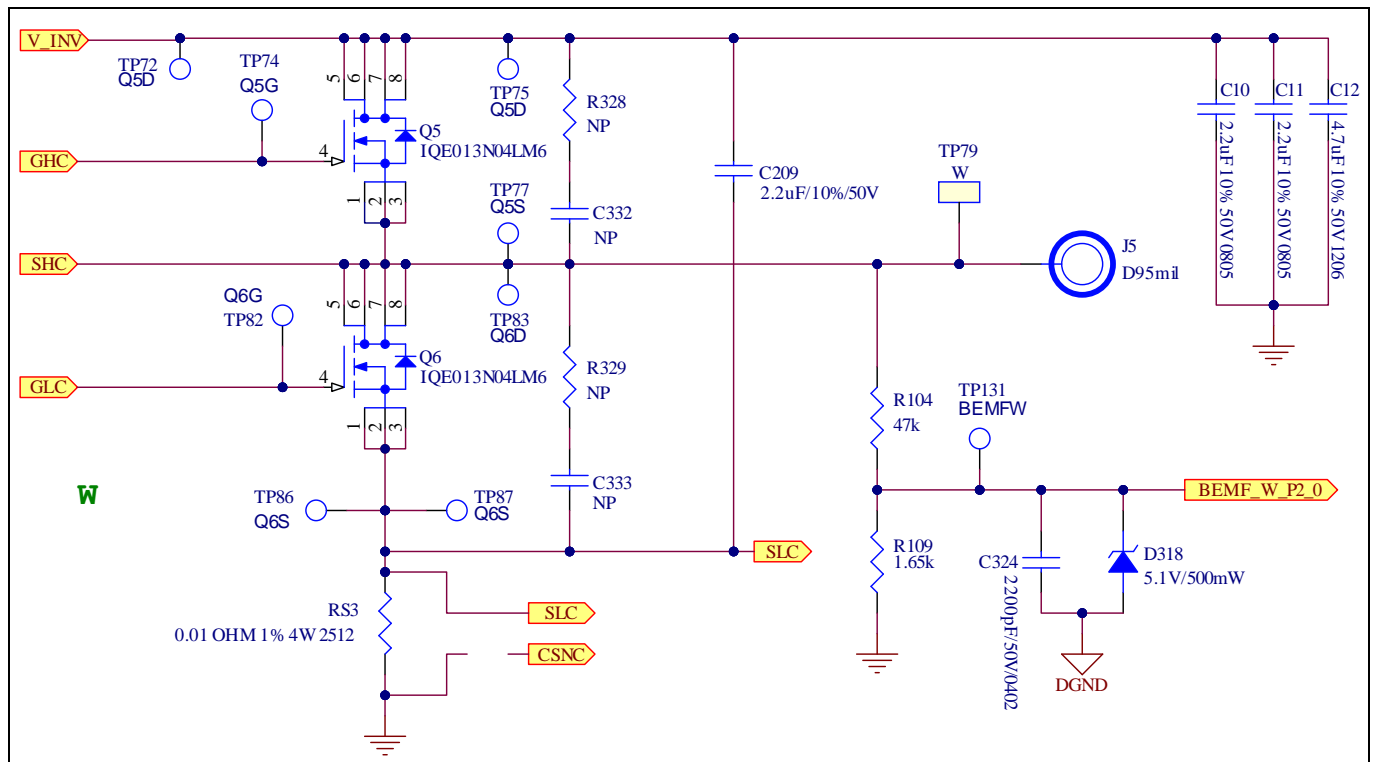


Figure 11 EVAL\_IMD700A\_FOC\_3SH schematic – power stage, phase “W”

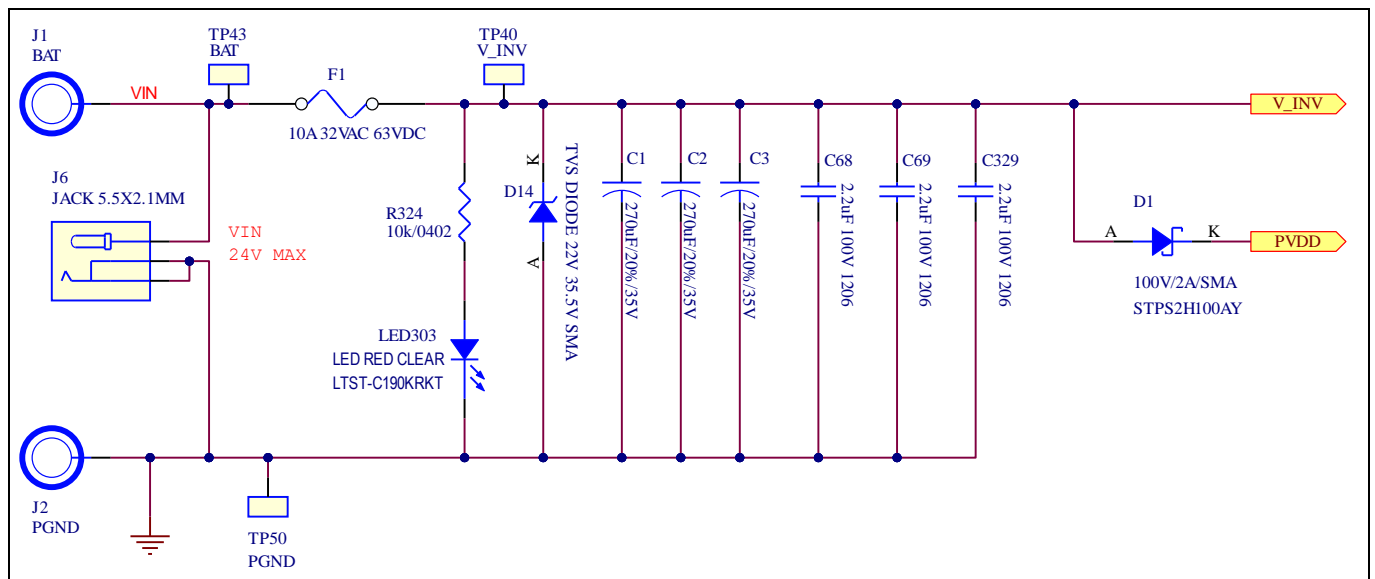


Figure 12 EVAL\_IMD700A\_FOC\_3SH schematic – DC input

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## Schematics

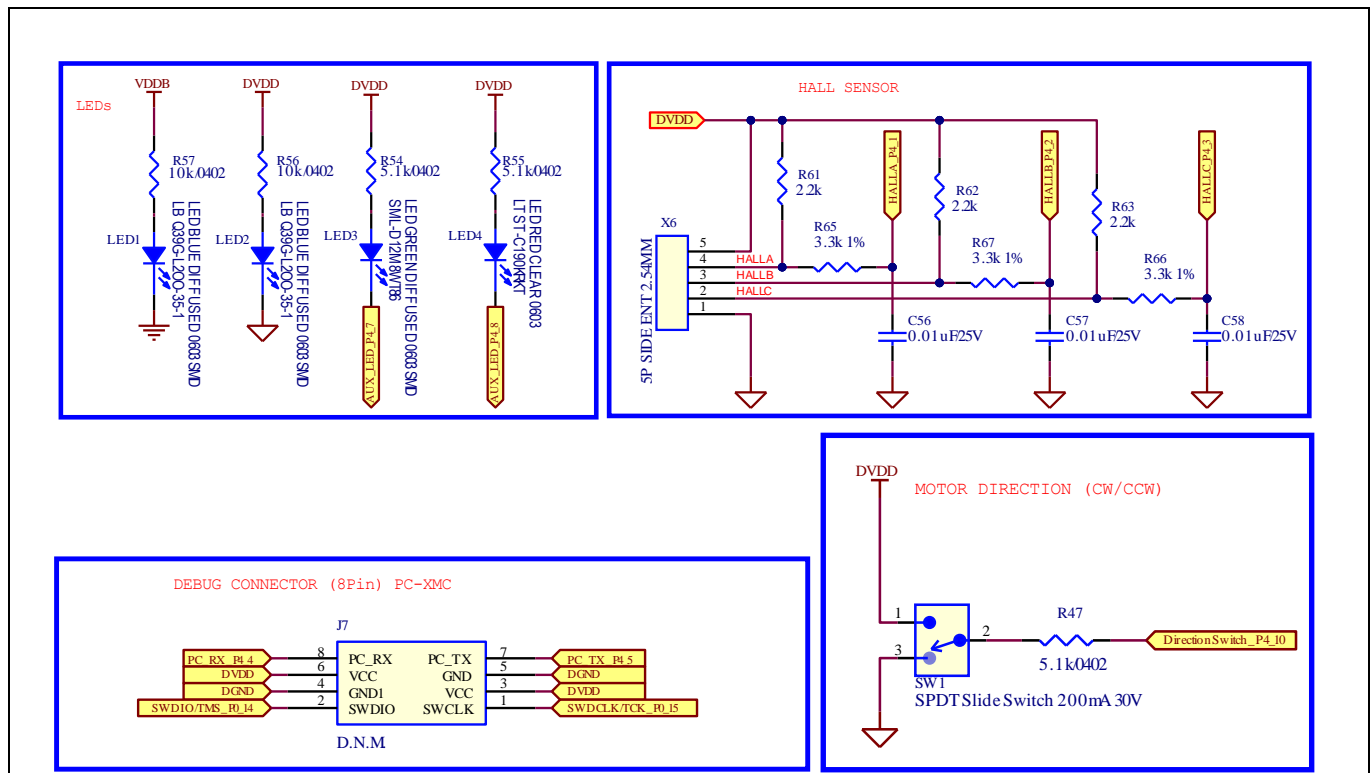


Figure 13 EVAL\_IMD700A\_FOC\_3SH schematic – power LED indicators and connections

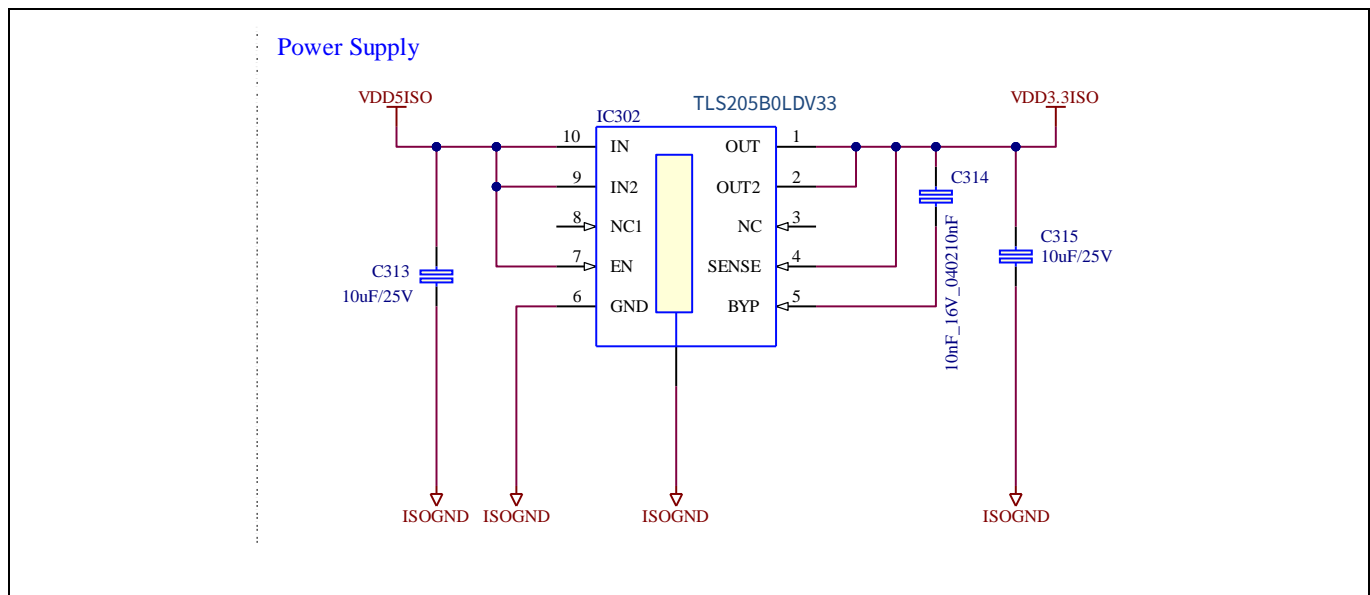
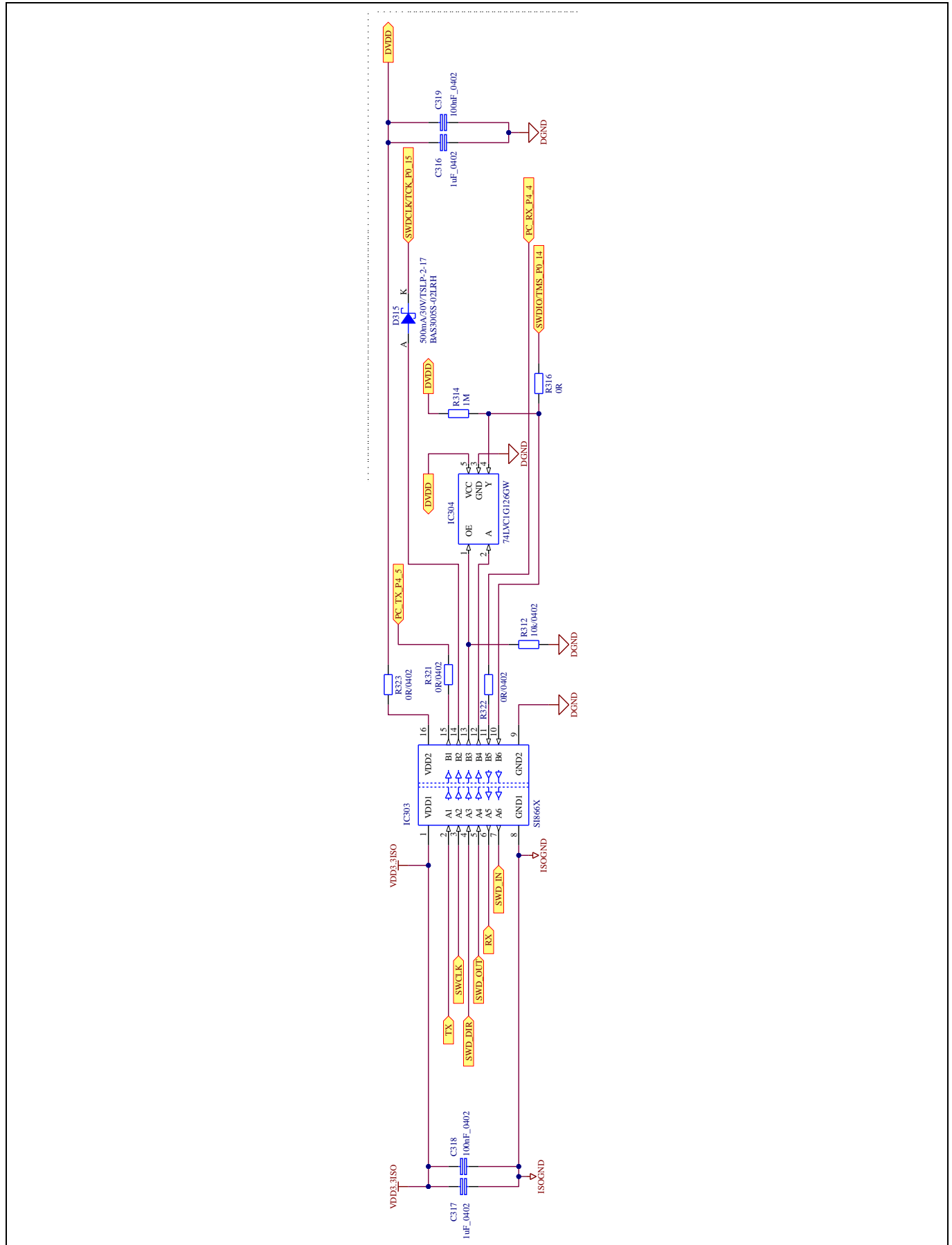


Figure 14 EVAL\_IMD700A\_FOC\_3SH schematic – linear regulator





**Figure 16** EVAL\_IMD700A\_FOC\_3SH schematic – debugger power supply and isolators



## 4 Hardware functional description

The main hardware elements for sensorless FOC are the three-phase inverter power stage, the MOTIX™ IMD700A combined three-phase smart gate driver and XMC1400 series 32-bit MCU with Arm® Cortex®-M0 and CORDIC MATH coprocessor, which provides hardware acceleration of trigonometric functions used in motor control to speed up these calculation functions compared to a software implementation.

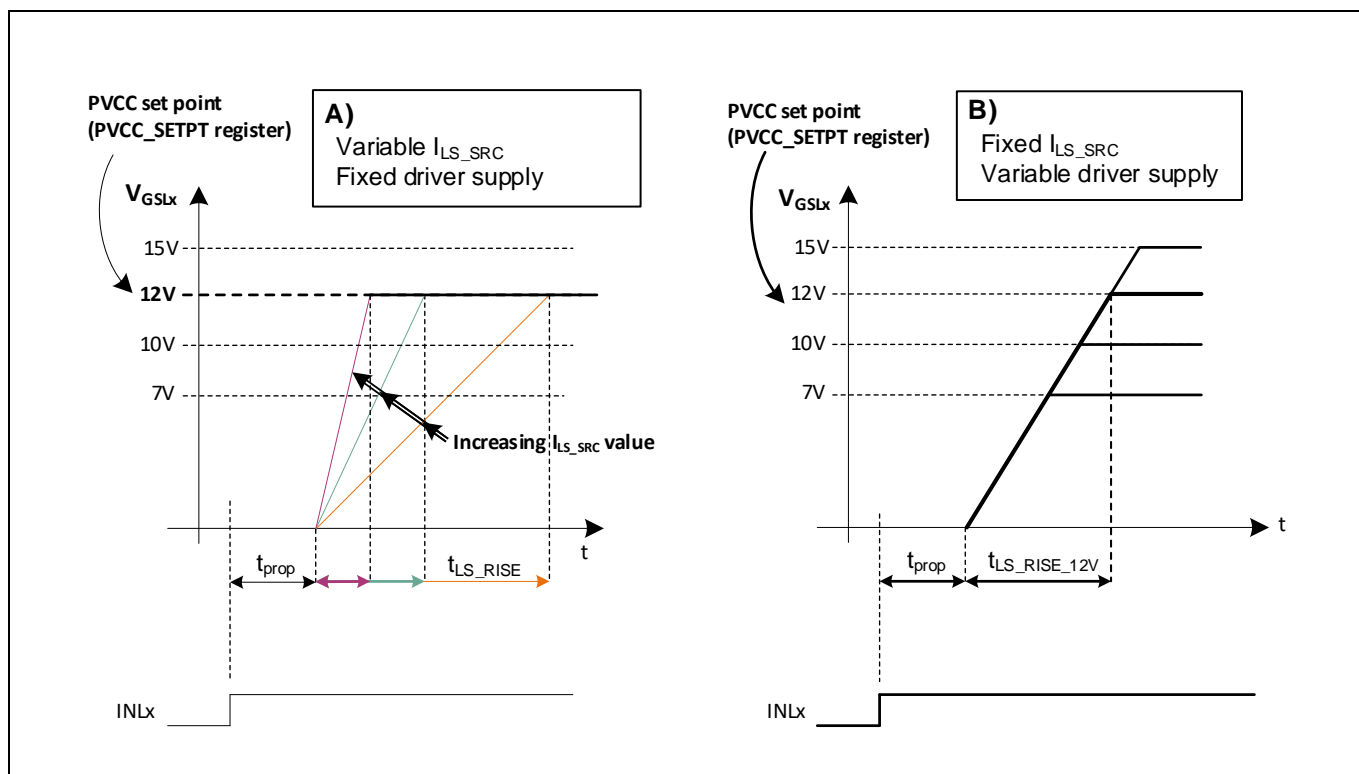
The three-phase inverter switching devices are IQE013N04LM6 (OptiMOS™ 6 40 V/1.5 mΩ 3x3 corner gate, source-down PQFN) power MOSFETs optimized for battery-powered power tool applications.

Dead time is inserted between the rising and falling edges of the PWM signals to prevent the high-side and low-side MOSFETs of each inverter phase from being on at the same time during switching transitions (shoot-through condition). The body diode of each MOSFET conducts current when the MOSFET is off.

Sensorless FOC requires three shunt resistors (RS1, 2, and 3 in this case) to sense the lower MOSFET current in each phase.

### 4.1 MOTIX™ IMD700A integrated smart gate driver MOTIX™ 6EDL7141

Optimized gate drive pulses to the high- and low-side MOSFETs in each phase are provided by the MOTIX™ IMD700A smart gate driver. Logic-level switching PWM pulses are supplied to the 6EDL7141 section from the XMC1404 MCU section. The high- and low-side gate drivers allow operation over the full duty cycle range up to 100 percent. The gate drive voltages can be set to different levels, including 7 V, 10 V, 12 V and 15 V. One benefit of the charge pumps is that voltage levels can be maintained even if the battery voltage drops to a lower level, allowing standard gate-level MOSFETs to be used.



**Figure 17** MOTIX™ IMD700A gate drive control

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### Hardware functional description

Control of the drain-source rise and fall times is one of the most important parameters for optimizing drive systems, affecting critical factors such as switching losses, dead time optimization, and drain voltage ringing that can lead to possible MOSFET avalanching. Correct configuration of the gate drive also helps to minimize EMI emissions. The MOTIX™ IMD700A can control the slew rate of the driving signal to control the rise and fall slew rates of the drain-to-source voltage by adjusting the gate drive sink and source currents during different time segments during the switch-on and switch-off processes. This permits the designer to eliminate diode resistor networks commonly used in gate drive circuits. In most cases gate resistors can be removed altogether, reducing component count and at the same time simplifying and allowing further optimization of the circuit layout.

### 4.1.1 Configuration of the gate driver

#### 4.1.1.1 Gate drive current and timing

Using the motor control GUI tool, the designer can configure the gate driver current and timings with the following parameters via SPI accessible registers:

**Table 1** Gate drive parameters<sup>1</sup>

Parameter	Description	Minimum	Maximum
I <sub>HS_SRC</sub>	Source current value for switching ON high-side MOSFETs	10 mA	500 mA
I <sub>HS_SINK</sub>	Sink current value for switching OFF high-side MOSFETs	10 mA	500 mA
I <sub>LS_SRC</sub>	Current value for switching ON low-side MOSFETs	10 mA	500 mA
I <sub>LS_SINK</sub>	Current value for switching OFF low-side MOSFETs	10 mA	500 mA
I <sub>PRE_SRC</sub>	Pre-charge current value for switching ON both high-side and low-side	10 mA	1.5 A
I <sub>PRE_SINK</sub>	Pre-charge current value for switching OFF both high-side and low-side	10 mA	1.5 A
T <sub>DRIVE1</sub>	Amount of time that I <sub>PRE_SRC</sub> is applied. Shared configuration between high and low	0 ns	2.59 μs
T <sub>DRIVE2</sub>	Amount of time that I <sub>HS_SRC</sub> and I <sub>LS_SRC</sub> are applied. Shared configuration between high-side and low-side drivers	0 ns	2.55 μs
T <sub>DRIVE3</sub>	Amount of time that I <sub>PRE_SINK</sub> is applied. Shared configuration between high-side and low-side drivers	0 ns	2.59 μs
T <sub>DRIVE4</sub>	Amount of time that I <sub>HS_SINK</sub> and I <sub>LS_SINK</sub> are applied. Shared configuration between high-side and low-side drivers	0 ns	2.55 μs

The gate driver implementation is illustrated in the figure below. The EVAL\_IMD700A\_FOC\_3SH evaluation board operates in 6PWM mode, in which the integrated MCU inserts a specific dead time between the INHx and INLx signals generated by its PWM modules. This driving scheme is also applicable to other PWM modes. Propagation delays are not shown for simplification of the diagram.

When the input signal from the MCU transitions from low to high, the gate driver switch-on sequence is triggered. If required, the gate drive output first applies a constant current defined by the user-programmable value I<sub>PRE\_SRC</sub> for a time defined by T<sub>DRIVE1</sub>, at the end of which the MOSFET gate voltage should have reached the threshold voltage V<sub>GS(TH)</sub>. In designs where the MOSFET gate charges are small, as in this example, the pre-charge should be disabled since it is intended for high gate charge devices only. *It should be noted that if attempting to use pre-charge with low Q<sub>G</sub> devices, the gate drive may not function correctly.*

The period of the gate switch-on sequence is defined by the parameter T<sub>DRIVE2</sub>, which begins immediately after the completion of T<sub>DRIVE1</sub>.<sup>2</sup> The current applied during T<sub>DRIVE2</sub> determines both di<sub>D</sub>/dt and dV<sub>DS</sub>/dt of the MOSFETs, as it will supply the current to charge the Q<sub>SW</sub> of the MOSFET being driven. Pre-charge may be disabled by setting T<sub>DRIVE1</sub> to zero.

In the three-phase motor drive configuration, each half-bridge operates in continuous mode with hard switch-on of the high-side. Hard switch-on of the low-side may also occur if the dead time is not long enough for the snubber capacitor to charge due to the phase current. Once the T<sub>DRIVE2</sub> period has elapsed, the gate driver applies full current (1.5 A) to ensure fastest full turn-on of the MOSFET by supplying the remaining charge required to raise V<sub>GS</sub> to the programmed PVCC value (Q<sub>OD</sub> = Q<sub>G</sub> – Q<sub>SW</sub> – Q<sub>G(TH)</sub>).

<sup>1</sup> Available current and time delay values are listed in section 8 “Register Map” of the IMD700A datasheet [1].

<sup>2</sup> In this example T<sub>DRIVE1</sub> is set to zero to disable pre-charging.



**Application note****Hardware functional description**

A similar process takes place during the switch-off of the MOSFET, in which the parameters  $T_{DRIVE3}$  and  $T_{DRIVE4}$  determine the periods for which the programmed discharge currents are applied.

When adjusting the slew rate to a desired value by means of setting the gate drive parameters, it is important to set the dead time to a suitable value greater than the sum of  $T_{DRIVE1}$  and  $T_{DRIVE2}$  for the low-to-high transition and  $T_{DRIVE3}$  and  $T_{DRIVE4}$  for the high-to-low transition, or whichever is greater if both dead times are equal.

The above figure shows in detail the  $V_{GS}$  charging and discharging transitions for a high-side MOSFET in one of the inverter phases during a typical hard-switched transition. The different charging and discharging phases of the MOSFET switch-on and -off are illustrated above. Thanks to the flexible timing structure provided by the MOTIX™ IMD700A gate driver with its many available  $T_{DRIVE(X)}$  settings, the current can be set during each interval. This enables the designer to configure and optimize the switch-on and switch-off operations without the need for any external gate drive components.

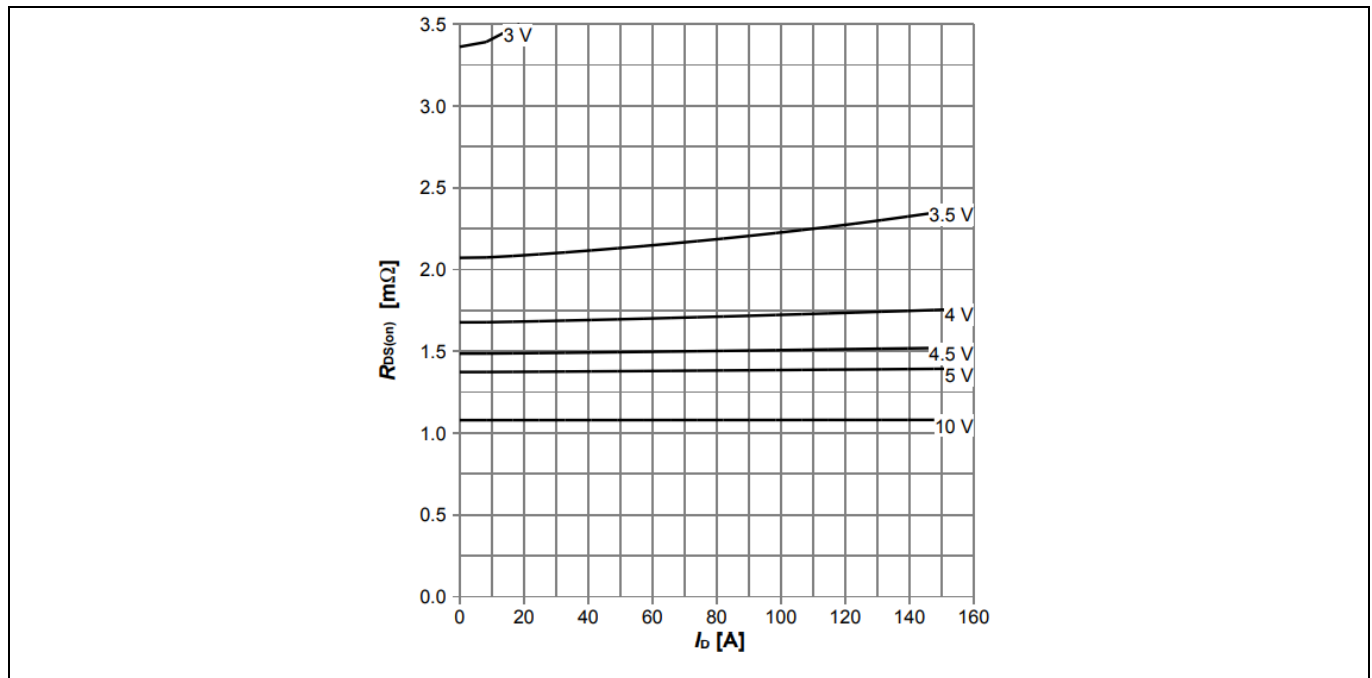
During hard switching, the controlled gate drive currents enable adjustment of the slew rate  $dV_{DS}/dt$ , by controlling the gate drive current during the periods  $T_{DRIVE2}$  and  $T_{DRIVE4}$ , during which the charge  $Q_{SW}$  is injected or extracted from the gate as  $V_{DS}$  transitions. Higher currents can be used for fast charging and discharging of  $Q_{GS(TH)}$  and  $Q_{OD}$ , since neither  $dI_D/dt$  nor  $dV_{DS}/dt$  are affected during these periods.

If required, the pre-charge current can be selected from 17 available values. Sixteen of these are defined by  $I_{PRE\_SRC/SNK}$  with an additional 1.5 A option, which is the maximum current capability of the gate driver. In cases where larger MOSFETs with high gate charge are used,  $Q_{G(TH)}$  during turn-on or  $Q_{OD}$  during turn-off may benefit from using the full gate driver capability. Full strength during the pre-charge may be selected via the GUI.

In the EVAL\_IMD700A\_FOC\_3SH evaluation board, because  $Q_{G(TH)}$  is small,  $T_{DRIVE3}$  is also set to zero. For small MOSFETs it is not necessary to discharge the  $V_{GS}$  to the plateau voltage at a faster rate.

#### **4.1.1.2 Gate drive voltage**

As mentioned, motor drive systems utilize a range of different MOSFET sizes and technologies. Additionally, the MOSFETs may have standard or logic-level gate thresholds, where  $V_{GS(TH)}$  for logic-level devices such as the IQE013N04LM6 used in the EVAL\_IMD700A\_FOC\_3SH evaluation board is significantly lower than for standard-level parts. As a consequence, for a given gate-to-source voltage, a logic-level MOSFET would produce a lower  $R_{DS(on)}$  than a normal-level MOSFET. Increasing the gate drive voltage reduces the  $R_{DS(on)}$  of the MOSFET channel during conduction and as a result the conduction losses of the system, as shown in the figure below. However, increasing the driving voltage also increases the switching rise and fall times, leading to higher switching losses.



**Figure 20** IQE013N04LM6  $R_{DS(on)}$  vs.  $V_{GS}$  characteristic

The MOTIX™ IMD700A offers the designer several driving voltage options to select from, depending on the system requirements, allowing designers to adjust the MOSFET driving voltage (PVCC voltage) via SPI registers. The same value PVCC applies to both high- and low-side charge pumps, with four possible values: 7 V, 10 V, 12 V and 15 V. This is done by setting bitfield PVCC\_SETPT via the GUI, where the default value is 12 V. Gate drive outputs include UVLO.

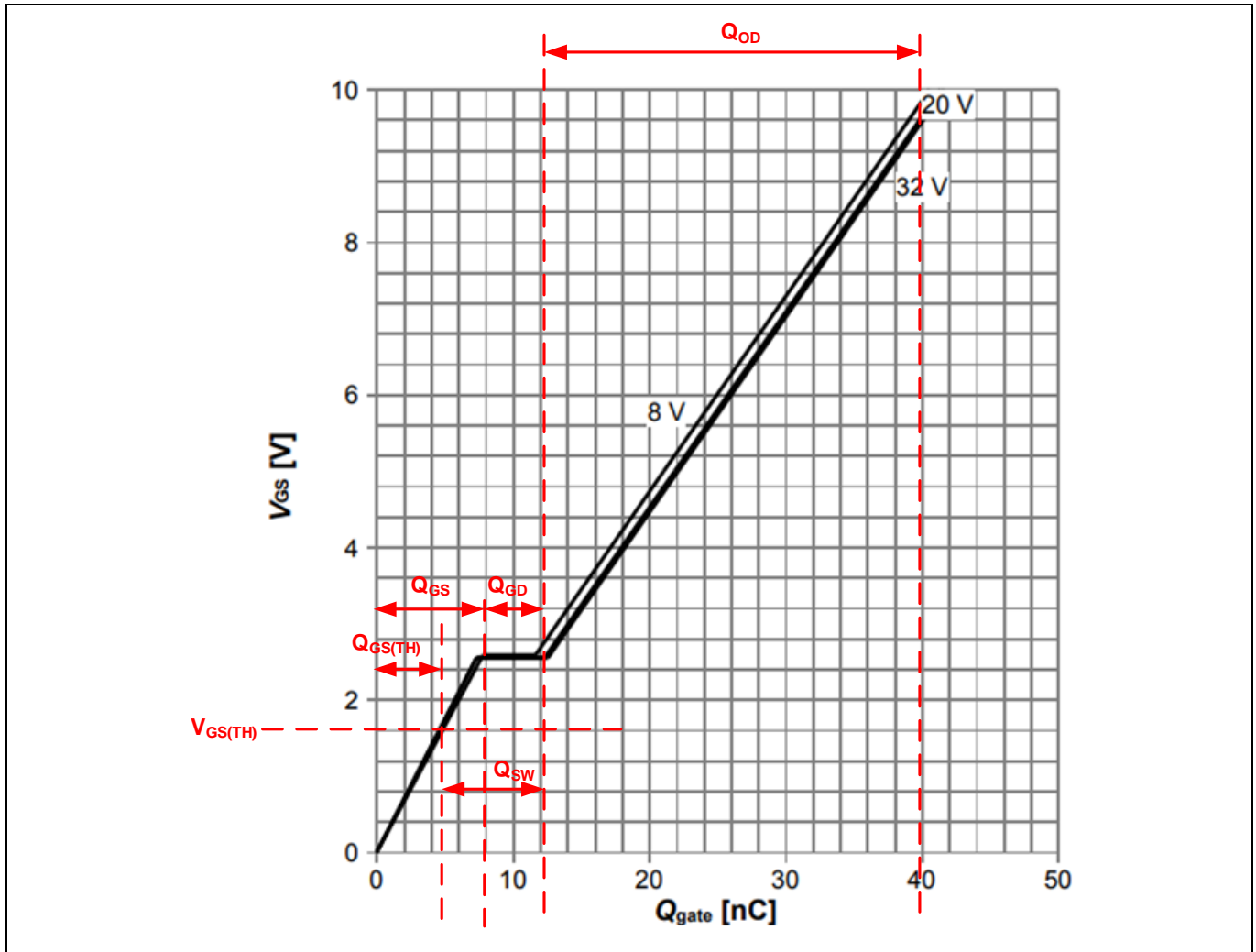
MOSFETs in an inverter can be exposed to non-zero gate-source voltage levels when gate drivers are not activated. In some cases, such voltages can be high enough to pass the MOSFET gate turn-on threshold, partially switching on the device. If a high- and low-side MOSFET in an inverter phase were to switch on at the same time, the resulting high current could destroy the devices. In order to prevent this, it is common to add weak pull-down resistors between the gates and sources of each MOSFET. The MOTIX™ IMD700A avoids the need for these resistors by integrating the following functions into its gate driver outputs:

- **Weak pull-down:** a weak pull-down (RGS\_PD\_WEAK) is always connected between the gate and source of each gate driver output. This ensures a weak pull-down during states where the gate driver is off, either because EN\_RV is turned off or because the device is fully off (CE off). This mechanism is similar to the ones described above.
- **Strong pull-down:** during gate driver off periods, if the external gate-to-source voltage increases for any reason, a strong pull-down (RGD\_PD\_STRONG) is activated, ensuring a tight pull-down to prevent any partial turn-on.

#### 4.1.1.3 Determining the values for EVAL\_IMD700A\_FOC\_3SH

This system is designed for an 18 V battery with IQE013N04LM6 MOSFETs switching at 20 kHz with a dead time of 400 ns. From [Figure 20](#) it can be seen that a gate drive  $V_{DR}$  of 10 V will produce a low  $R_{DS(on)}$ .

The following graph outlines the charging phases of the IQE013N04LM6 during the switch-on process, which are in reverse during switch-off.



**Figure 21** IQE013N04LM6 gate charge graph

It is important to consider that the  $V_{DS}$  transient produced at switch-off should be limited to a peak below the MOSFET  $BV_{DSS}$  rating under the worst-case condition of a stalled motor to prevent avalanching. The transient peak value is controlled by limiting the switch-off speed. The switch-off transient peak value is determined by:

$$V_{DS(PK)} = L_P \cdot \frac{di_D}{dt} \quad [1]$$

Where  $L_P$  represents the inductance in the circuit carrying the drain current, which is composed of PCB trace and package inductances.  $di_D/dt$  is determined by the selected gate current during  $T_{DRIVE4}$ .

#### 4.1.1.3.1 Gate switch-on configuration procedure

1. Determine the gate drive voltage setting.

It can be seen from the  $R_{DS(on)}$  vs.  $V_{GS}$  characteristic that the IQE013N04LM6 fully reaches sufficiently low  $R_{DS(on)}$  with 10 V gate drive voltage. Therefore, PVCC is set to 10 V.

2. In this design pre-charge is not required, because  $Q_{GS(TH)}$  is only 4.6 nC and so the gate drive configuration can be simplified by setting  $T_{DRIVE1}$  to zero. A simplified calculation method is therefore used.

Calculate the minimum value of  $T_{DRIVE2}$  based on a selected value of  $I_{HS,LS\_SRC}$ , in this case 200 mA and the charge required to switch on the MOSFET.

$$t_{DRIVE2} > \frac{Q_{GS(TH)} + Q_{SW}}{I_{HS,LS\_SRC}} \quad [2]$$

$$t_{DRIVE2} > \frac{4.6 \text{ nC} + 8 \text{ ns}}{200 \text{ mA}} = 63 \text{ ns}$$

In this case 100 ns is chosen to ensure the switching plateau has been passed before the strong pull-up is applied, with maximum gate drive source current of 1.5 A applied after  $T_{DRIVE2}$  has elapsed. It should be noted that as  $V_{GS}$  charges to the full voltage the gate driver can no longer sustain 1.5 A source current though the gate remains pulled up to the full drive voltage.

#### 4.1.1.3.2 Gate switch-off configuration procedure

1. Because pre-charge (or discharge in this case) is not used  $T_{DRIVE3}$  is set to zero.
2. A simplified calculation can be used to obtain the value of  $T_{DRIVE4}$  based on a selected value of  $I_{HS,LS\_SRC}$ , in this case 200 mA and the charge required to switch on the MOSFET.

$$t_{DRIVE4} > \frac{Q_G}{I_{HS,LS\_SRC}} \quad [3]$$

$$t_{DRIVE4} > \frac{41 \text{ nC}}{200 \text{ mA}} = 205 \text{ ns}$$

In this case 400 ns is chosen to ensure the device will always be fully switched on before the strong pull-up is applied, with maximum gate drive source current of 1.5 A applied after  $T_{DRIVE4}$  has elapsed. This ensures that the switch-off transient will be limited by the switch-off speed of the MOSFET determined by  $I_{HS,LS\_SRC}$ . It should be noted that as  $V_{GS}$  charges to the full voltage the gate driver can no longer sustain 1.5 A source current though the gate remains pulled up to the full drive voltage.

#### 4.1.1.3.3 Setting the dead time

1. Calculate the total switch-off time as follows:

$$T_{DRIVE(OFF)} = T_{DRIVE3} + T_{DRIVE4} + T_{TH} + t_{rr} \quad [4]$$

$$T_{DRIVE(OFF)} = 0 \text{ ns} + 400 \text{ ns} + 3.1 \text{ ns} + 25 \text{ ns} = 428.1 \text{ ns}$$

The MOSFET body diode recovery time  $t_{rr}$  should also be added. To avoid the possibility of shoot-through and/or avalanching of the MOSFETs due to part variations and also temperature variations, it is recommended to add at least 20 percent to the calculated value:

As a general rule, the dead time  $T_{DT}$  should be set to be greater than  $T_{DRIVE(OFF)} + 20$  percent.



## Application note

## Hardware functional description

In the EVAL\_IMD700A\_FOC\_3SH evaluation board the dead time is set in the MCU, not in the MOTIX™ IMD700A, because the system operates in 6PWM mode.

$$T_{DT} \geq T_{DRIVE(ON)} \times 1.2 \quad [5]$$

$$T_{DT} \geq 428.1 \text{ ns} \times 1.2 = 513.1 \text{ ns}$$

A value of 400 ns was found to be sufficient in this case, which was determined by lab measurements of the board (refer to [section 10.3](#)). The rising and falling dead times ( $T_{DT+}$  and  $T_{DT-}$ ) are both set to this value.

The designer should also be aware that if drain-to-source snubber networks are connected to each MOSFET to reduce EMI and switch-off transients (not necessary in the EVAL\_IMD700A\_FOC\_3SH board), then hard-switching may occur in the low-side unless the dead time is further increased to allow the snubber capacitors to charge. Furthermore, if the gate drive during switch-off produces a slower turn-off, then the switching transition ( $dV_{DS}/dt$ ) will also be delayed, which may also produce hard-switching in the low-side unless the dead time is increased. In this design the switching losses are acceptably low, with hard-switching of both high- and low-sides.

**Table 2** List of calculated gate drive parameters

Parameter	Description	Value
$I_{HS\_SRC}$	Source current value for switching on high-side MOSFETs	200 mA
$I_{HS\_SNK}$	Sink current value for switching off high-side MOSFETs	200 mA
$I_{LS\_SRC}$	Current value for switching on low-side MOSFETs	200 mA
$I_{LS\_SNK}$	Current value for switching off low-side MOSFETs	200 mA
$I_{PRE\_SRC}$	Pre-charge current value for switching on both high-side and low-side	125 mA (not used)
$I_{PRE\_SNK}$	Pre-charge current value for switching off both high-side and low-side	125 mA (not used)
$T_{DRIVE1}$	Amount of time that $I_{PRE\_SRC}$ is applied. Shared configuration between high and low	0 ns
$T_{DRIVE2}$	Amount of time that $I_{HS\_SRC}$ and $I_{LS\_SRC}$ are applied. Shared configuration between high-side and low-side drivers	100 ns
$T_{DRIVE3}$	Amount of time that $I_{PRE\_SNK}$ is applied. Shared configuration between high-side and low-side drivers	0 ns
$T_{DRIVE4}$	Amount of time that $I_{HS\_SNK}$ and $I_{LS\_SNK}$ are applied. Shared configuration between high-side and low-side drivers	400 ns
$T_{DT}$	Dead time for positive and negative transitions	400 ns

#### 4.1.1.3.4 Procedure for tuning the gate drive on the bench

Please note that the following is a general procedure, not specific to the EVAL\_IMD700A\_FOC\_3SH board:

1. Ensure that RC snubbers are fitted across the drain and source of each MOSFET Q1 to Q6 if needed.
2. *Do not use the 120 ns default values for the rising and falling dead times!*  
Set a longer dead time initially (such as 1  $\mu$ s) than the calculated value to ensure that shoot-through will not occur. Then reduce the dead time to a suitable value once the  $T_{\text{DRIVE}}$  and gate drive current settings have been determined.
3. Create a project in the GUI for an FOC three shunt design and enter the values of:  $T_{\text{DRIVE1}}$ ,  $T_{\text{DRIVE2}}$ ,  $T_{\text{DRIVE3}}$ ,  $T_{\text{DRIVE4}}$ ,  $I_{\text{PRE\_SRC}}$ ,  $I_{\text{PRE\_SINK}}$ ,  $I_{\text{HS,LS\_SINK}}$ ,  $I_{\text{HS,LS\_SRC}}$ , calculated using the procedure above.
4. Save the project.
5. Use the “write device” command to configure the MOTIX™ IMD700A with the values in the project.
6. Operate the board at maximum battery voltage and monitor the high-side and low-side  $V_{\text{GS}}$  and  $V_{\text{DS}}$  waveforms using differential probes for the high-side.
7. Increase to maximum load<sup>1</sup> and check the  $V_{\text{DS}}$  transient peak values to ensure that avalanching is not taking place and that there is sufficient headroom between the peak voltage and the MOSFET  $BV_{\text{DSS}}$  rating.
8. Check that the waveforms appear correct. If not, make the necessary adjustments to the gate drive parameters listed in (3).
9. Determine whether the slew rates are acceptably close to the target value. If not, adjust gate drive source and sink currents via the GUI as necessary to ensure correct switching transitions.
10. If carrying out EMI measurements, to reduce EMI the slew rate may be reduced. However, when doing this keep in mind that switching losses will be increased.
11. Reduce the dead time values to the desired values. Ensure the dead times are recalculated and adjusted to accommodate the slower slew rates if the slew rates have been altered. Also allow additional time for operation at the maximum input voltage.
12. Save the project each time a value is changed.<sup>2</sup>
13. When the final values have been decided, use the “burn OTP” function to permanently set these values in the MOTIX™ IMD700A.

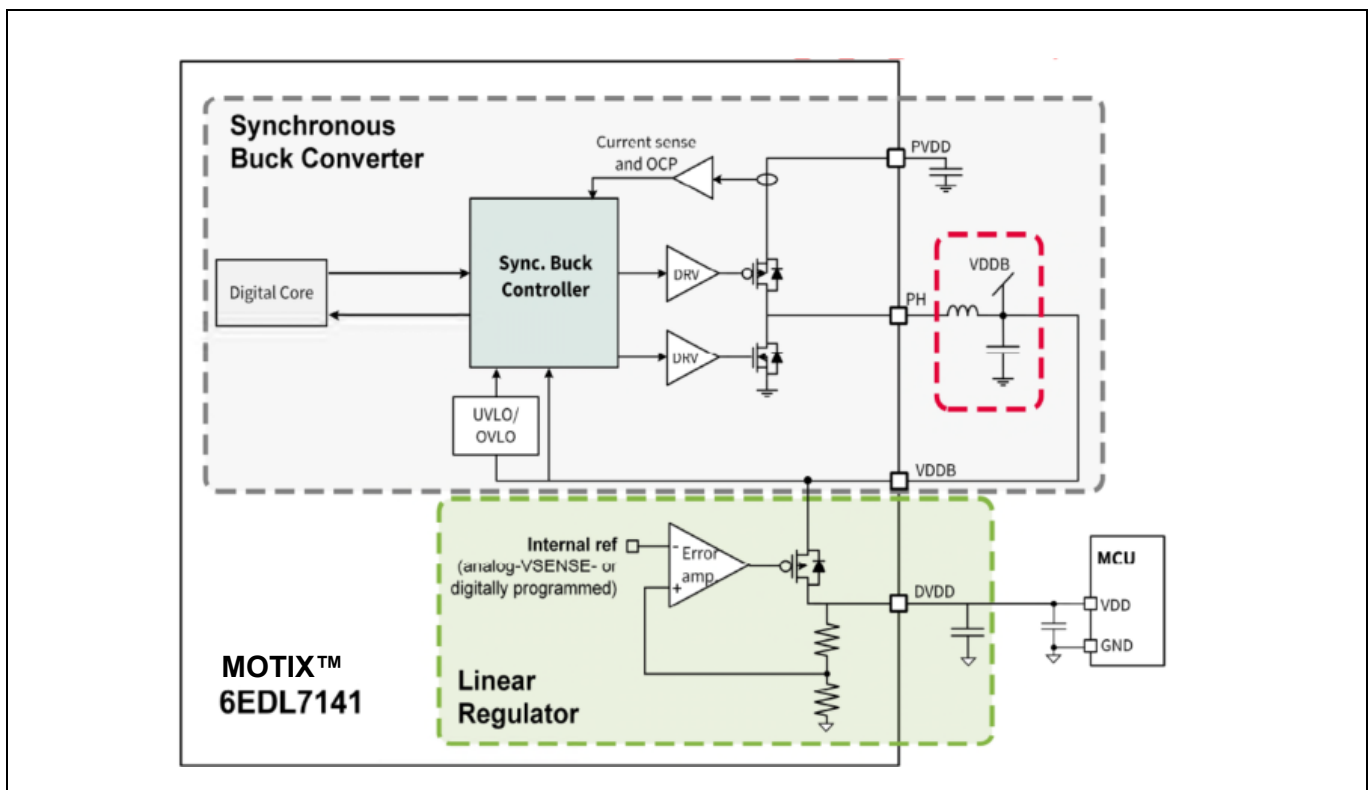
<sup>1</sup> If the load is a BLDC motor, increase the torque and speed to fully load the system.

<sup>2</sup> It is advisable to change the filename each time.

#### 4.1.2 Configuration of the buck and linear regulators

The VDDB output can be used to supply external components as long as the current limits of the buck converter, charge pumps, and linear regulator are not exceeded. The voltage is set to 6.5 V if PVCC is 7 V, 7 V if PVCC is 10 V and 8 V if PVCC is 12 V or 15 V. Intelligent OCPs are also implemented for both the buck converter and the linear regulator to prevent any damage to the device if the VDDB output becomes overloaded. Additional overtemperature protections (OTS, OTW) are integrated to ensure that the device operates within correct thermal limits.

Two different switching frequencies, 500 kHz (default value) or 1 MHz, can be selected via the GUI. The buck inductor L1 value is 22  $\mu$ H for 500 kHz switching and 10  $\mu$ H for 1 MHz. The values for the buck output capacitors C40 and C41 are 22  $\mu$ F with an additional 0.22  $\mu$ F ceramic capacitor C320 added to reduce high-frequency (HF) noise. A detailed figure of both the synchronous buck converter and linear voltage regulator circuits is depicted in the following figure:



**Figure 22** Detail of integrated synchronous buck converter and linear regulator

The following protections are implemented to ensure correct operation of the buck converter:

- Output undervoltage lockout (UVLO)
- Output overvoltage lockout (OVLO)
- OCP, cycle by cycle

In a situation in which the current exceeds the OCP level, the buck converter controller terminates the high-side gate drive pulse until the start of the next PWM period. The low-side operates accordingly after insertion of the dead time.

Once the OCP event takes place, a counter increments each consecutive period that the peak current is reached. After 16 switching cycles, the buck OCP fault is triggered and the nFAULT pin is set low to signal the MCU. The buck converter will continue operation in current limitation to ensure the MCU remains powered. If the OCP is not triggered for three consecutive PWM periods, the counter resets.

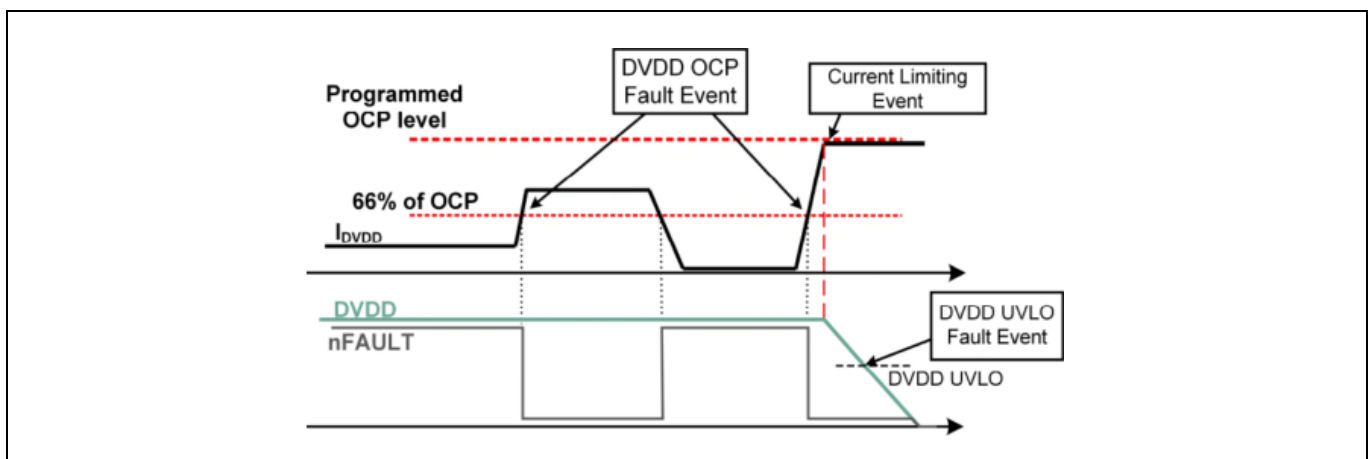
## Application note

### Hardware functional description

The integrated linear regulator output DVDD can be set to either 3.3 V or 5 V by means of an external resistor R44, which is set to 10 k $\Omega$  on this evaluation board to set DVDD to 5 V. It is possible to override this hardware setting through the GUI, which can also read back the value set by hardware. The linear regulator can also be used to provide an offset to the CS amplifiers to allow negative current measurements.

DVDD OCP can be configured between four different levels, 50 mA, 150 mA, 300 mA or 450 mA, with 450 mA being the default value. If the OCP level is reached a fault is reported through the nFAULT pin. The DVDD OCP works in two different stages:

1. Pre-warning mode at 66 percent of selected OCP level:  
The nFAULT pin is pulled down to signal the controller that an OCP warning has occurred. If the current level reduces before reaching the 100 percent level, the operation will continue normally, releasing the nFAULT pin. The pre-warning allows some extra time for the MCU to decide how to react to the possible OCP event.
2. Current limiting mode at 100 percent of selected OCP level:  
If current increases beyond the configured OCP level, the DVDD regulator limits its output current. This causes the DVDD voltage to drop, eventually resulting in a DVDD UVLO fault if the UVLO threshold is crossed. This protects DVDD against a short-circuit condition.  
Exposure to absolute maximum rating conditions for extended periods may affect device reliability. The device should be operated only under recommended operating conditions as specified in the datasheet [\[1\]](#).



**Figure 23** DVDD OCP behavior including pre-warning and current-limiting modes

### 4.1.3 Configuration of the charge pumps

The high- and low-side gate driver charge pumps are based on switched capacitor circuits that operate at a determined switching frequency. Selection from one of four frequencies, 781.3 kHz, 390.6 kHz, 195.3 kHz or 1.56 MHz, allows flexibility for EMC optimization, with 781.3 kHz being the default setting. Another useful feature in reducing the EMI impact of the charge pump is the spread spectrum feature, which can also be enabled and disabled via the GUI. This function is enabled by default to provide a frequency variation in the charge pump clock signal to distribute emissions over a wider frequency range, thereby reducing peaks.

The charge pump flying capacitors C33 and C39 are set to 0.22  $\mu$ F and the tank capacitors C30 and C32 are set to 2.2  $\mu$ F. The MOTIX™ IMD700A provides pre-charging of the charge pump output capacitors (C30 and C32) to a voltage just below the buck converter output voltage (VDDDB) before the EN\_DRV pin is activated. In this way, the charge pump start-up time and therefore the system start-up time are reduced. In this case, when EN\_DRV is activated by the MCU to enable the gate driver stage, the charge pumps need only ramp up the voltage from

## Application note

### Hardware functional description

the existing pre-charge voltage to the selected target value. Pre-charge is disabled by default and can be enabled via the GUI.

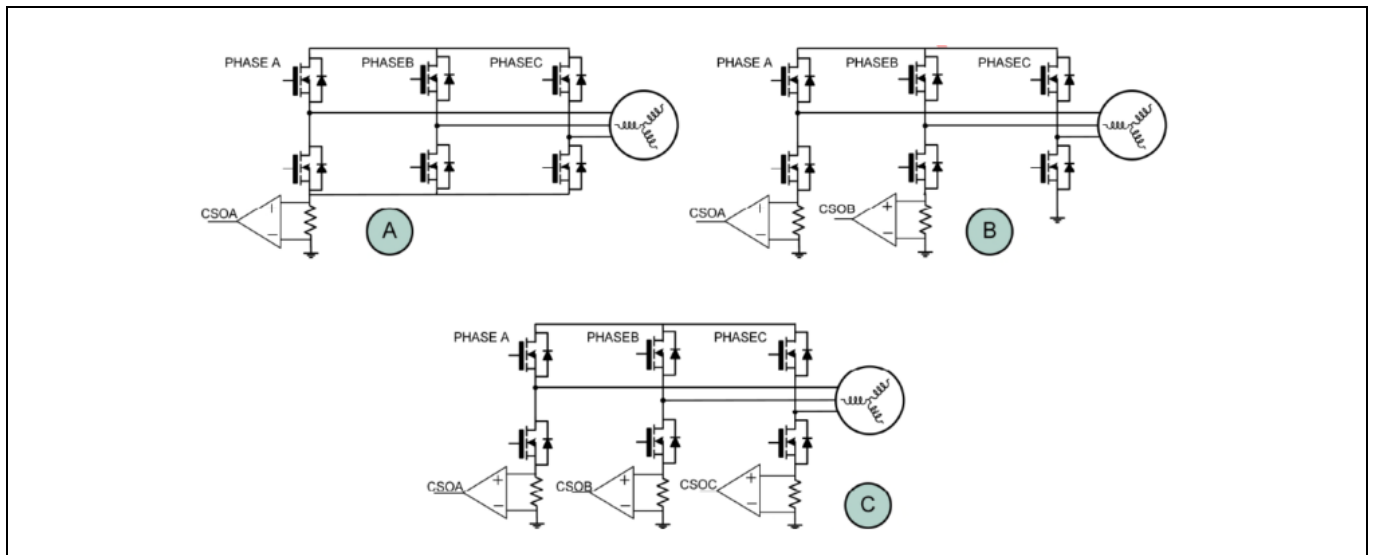
The start-up time for the charge pumps, defined as the time that the gate drive supply voltages require to reach the target programmed voltage, depends on several factors:

- Target voltage: the higher it is, the longer the start-up time for the gate drivers.
- Charge pump clock frequency: higher clock frequency results in faster start-up time.
- Charge pump tank capacitor values: a smaller value results in faster ramp-up time but higher ripple.
- Charge pump flying capacitors: smaller capacitors lead to a slower start-up time.

#### 4.1.4 Configuration of the current sense amplifiers

The device integrates three CS amplifiers that can be used to measure the current in the inverter via shunt resistors. Single, double, or triple shunt measurements are supported, as shown below.

Each CS amplifier can be enabled individually. Gain and offset are generated internally and are programmable.



**Figure 24** Single (A), dual (B), and triple (C) shunt CS configurations

The CS amplifier block contains the following sub-blocks, explained in detail in this section:

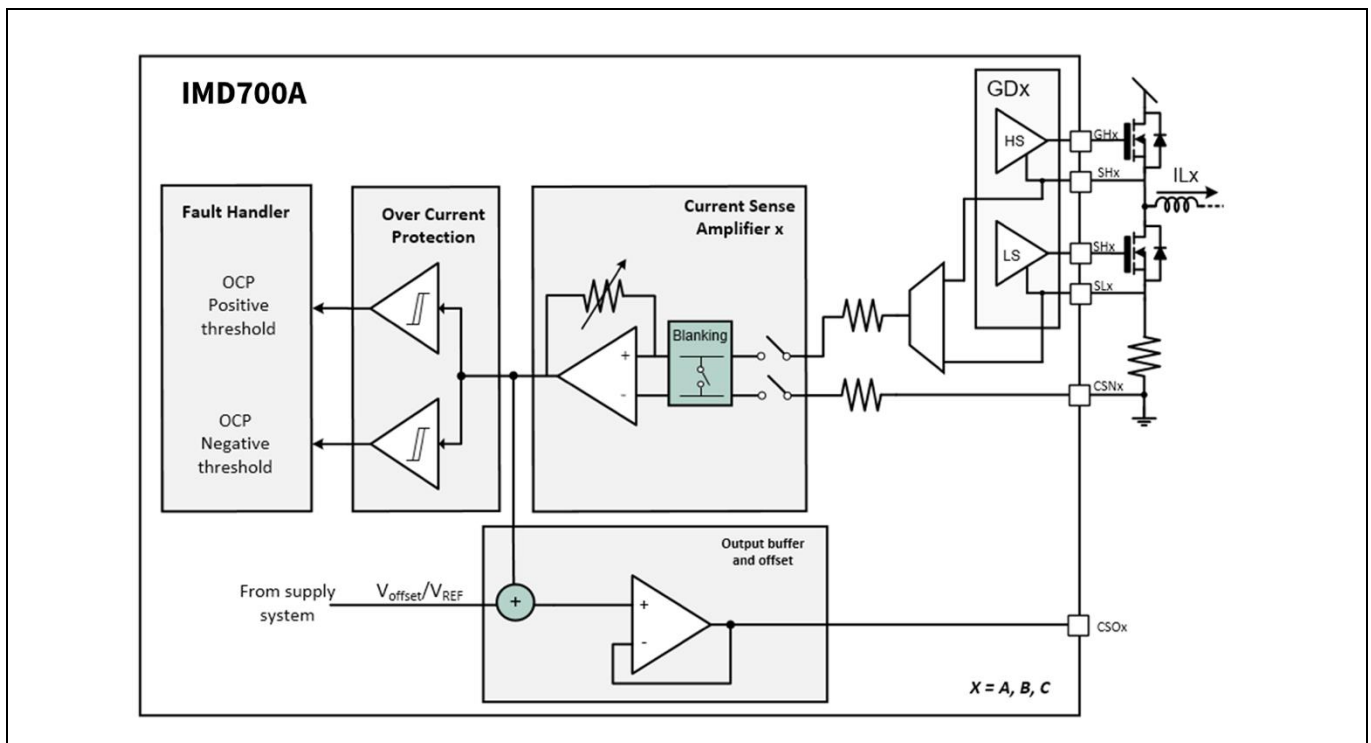
- CS amplifier: connected to external shunt resistor or internally to an SHx pin for  $R_{DS(on)}$  sensing. This module amplifies the shunt voltage or  $V_{DS(on)}$  voltage to a level suitable for a MCU ADC input. It includes leading-edge blanking (LEB) of the signal synchronized to the gate drive, which is active during periods to eliminate noise.
- Output buffer: allows adding a variable offset voltage to the sense amplifier output. The offset amount can be set to one of four different values, either by programming the internally generated level or by applying an external voltage at the  $V_{REF}$  input pin. With this implementation, negative shunt currents can also be measured.
- Positive overcurrent comparator: used for detecting the overcurrent conditions on motor windings for positive shunt voltage. This comparator causes the gate drive pulse to be terminated, thus limiting the motor current.

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### Hardware functional description

- Negative overcurrent comparator: used for detecting the overcurrent condition on motor windings for negative shunt currents.
- OCP DAC: used for programming the overcurrent comparator thresholds. One sets the positive level and a second sets the negative level, and these are shared among the different OCP comparators.

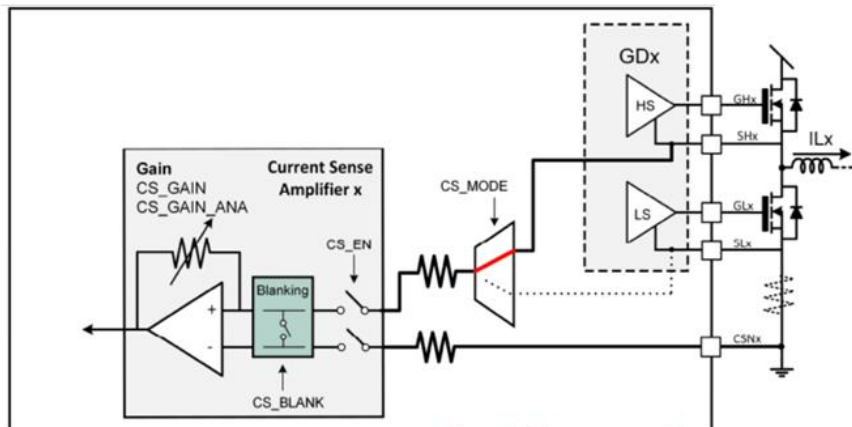
The CS amplifier architecture includes an “auto-zero” function. This takes place during MOTIX™ IMD700A start-up and operation to maintain accuracy of measurements during the lifetime of the device. If no GHx rising edge happens for a given time ( $t_{\text{AUTO\_ZERO\_CYCLE}}$ ), i.e., if the low-side is fully turned on for a long period in a six-step commutation, then an internal watchdog timer triggers an auto-zero compensation – auto-zero continuous during STANDBY state. The auto-zero feature can be disabled via the GUI. In addition, the MOTIX™ IMD700A includes a CS amplifier user calibration mode that can be used to measure and compensate for offset at a time when the shunt current is known to be zero, i.e., when all of the gate drives are low.



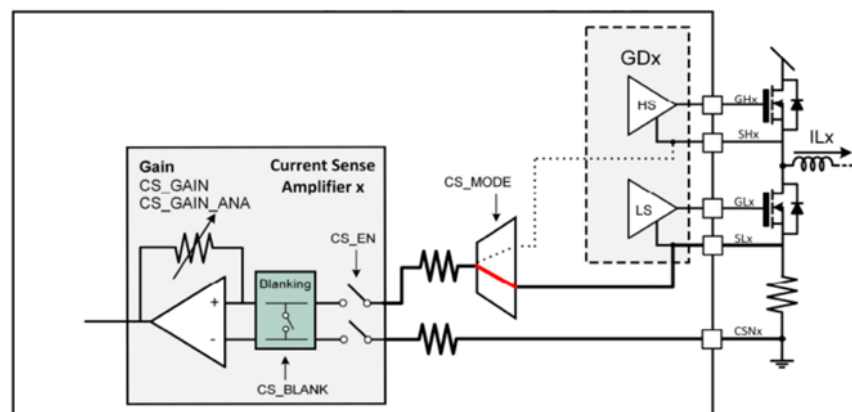
**Figure 25 CS amplifier simplified block diagram**

The CS amplifiers in MOTIX™ IMD700A can be configured for RDS(on) sensing to avoid the use of shunt resistors; however, this function is not used in the EVAL\_IMD700A\_FOC\_3SH board, which uses three shunt resistors; RS1, RS2, and RS3. In this implementation all three CS amplifiers are required.

The CS amplifiers have a default voltage gain of 4. This can be changed via the GUI to any of the following values: 8, 12, 14, 20, 24, 32 or 64. Alternatively, the gain can be selected by connecting an external resistor from pin CS\_GAIN to ground. In order to enable analog programming of the CS amplifier via an external resistor, the user must ensure that bitfield CS\_GAIN\_ANA is set accordingly. The value of RGAIN is read during the start-up sequence of the MOTIX™ IMD700A. Table 15 in the datasheet [\[1\]](#) provides the resistor values and register settings for gain selection in both analog and digital modes.



**Figure 26** System diagram of a low-side  $R_{DS(on)}$  CS configuration (not used here)



**Figure 27** System diagram of an external shunt CS configuration

In many motor drive inverters such as this evaluation board, the current is sensed via shunt resistors. In this case, the voltage across the shunt needs to be amplified only when the low-side MOSFET is switched on. In other cases, it might be useful to monitor the signal continuously. The MOTIX™ IMD700A supports four different modes of operation of the CS amplifiers regarding when the output is connected to the amplifier, which can be selected through the GUI.

These four modes are as follows:

- Always off: CS amplifier output disabled. This is achieved by disabling the amplifier in register CSAMP\_CFG via bitfield CS\_EN.
- GL on (default mode): in this mode, the CSOx pin is connected to the amplifier only when the corresponding GLx signal is active. In single shunt mode CSOx is connected according to the OR'ing of all two or three GLx signals. If two or three amplifiers are enabled then the signals for enabling CSOx come from the corresponding GLx signal. This mode is mandatory if  $R_{DS(on)}$  sensing is selected to avoid overvoltage damage to the internal circuitry.
- GH off: similar to GL on, this mode exposes the output to the GL on period but extends the sensing period to the dead times, both rising and falling.

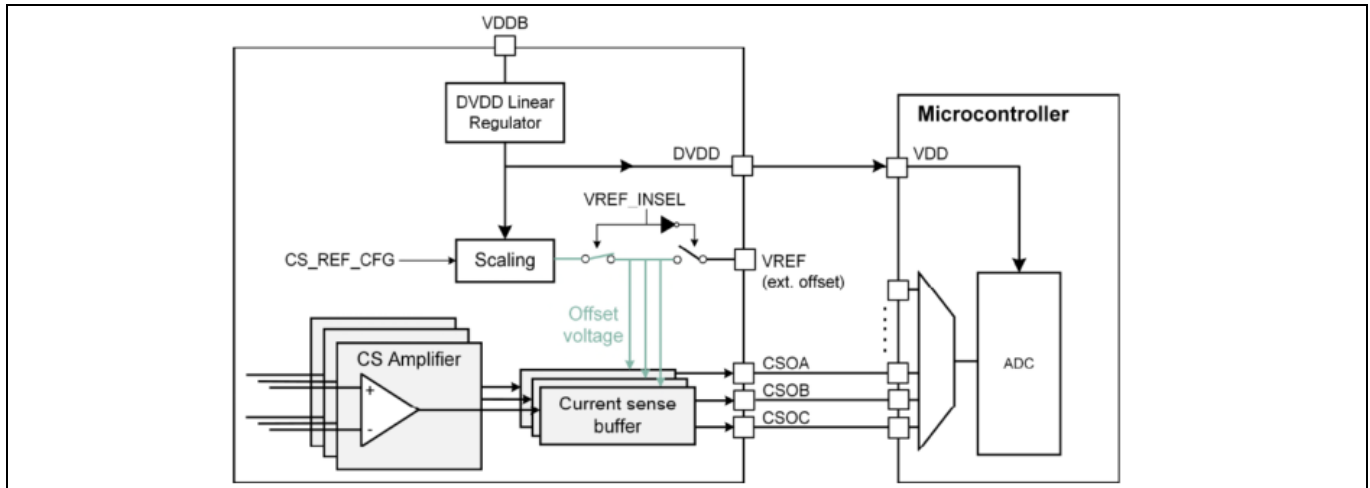


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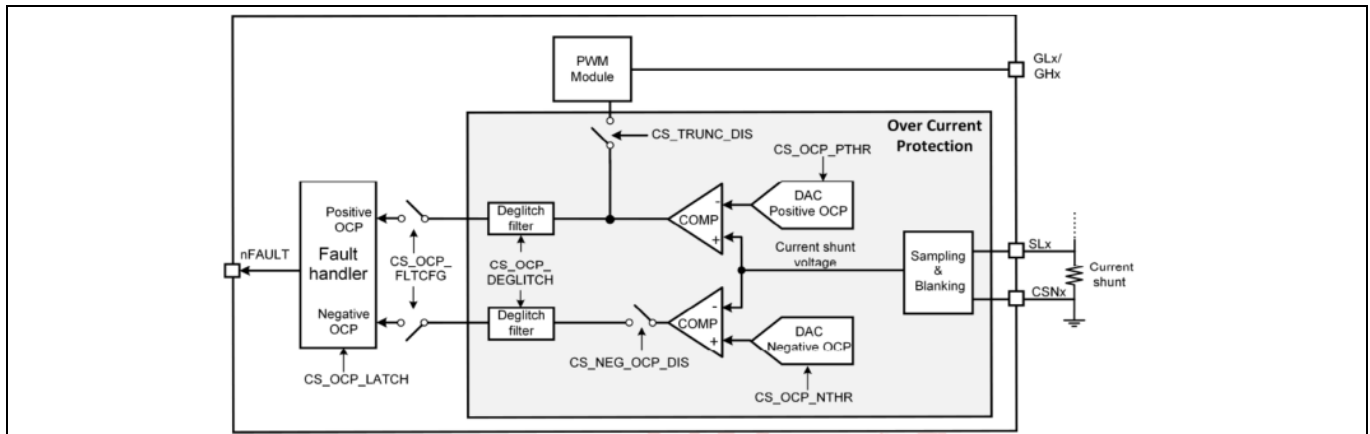
### Hardware functional description

- Always on: this mode connects the activated amplifier CSOx signals continuously to the amplifier independently of PWM signals.

The programmable LEB function can be configured in the CS amplifiers. Since both phase node voltage SHx and SLx pins (CSNy) are subject to ringing due to the switching activity, the blanking module disconnects the inputs for a configurable time (CS\_BLANK). The default blanking time is zero, and values between 50 ns and 8  $\mu$ s can be selected via the GUI. The MOTIX™ IMD700A internal linear voltage regulator (DVDD) can be used for offset generation for CS amplifiers. The default value is 1/2DVDD, and values of: 5/12, 1/3 and 1/4DVDD are also available.



**Figure 28** CS amplifier offset generation block diagram



**Figure 29** CS amplifier architecture

How the MOTIX™ IMD700A reacts to an OCP event is programmable via the GUI. The following scenarios can be useful for different applications:

- Apply PWM truncation immediately after OCP event and report on the nFAULT pin after OCP event-deglitching is disabled if truncation is enabled.
- Disable reporting but keep truncation of PWM.
- Trigger a configurable brake action upon OCP event. If truncation is not desired, a brake event can be configured using one of the available braking modes.
- Disable OCP protection, both nFAULT reporting and truncation of PWM. In such cases, OCP is ignored.



## Application note

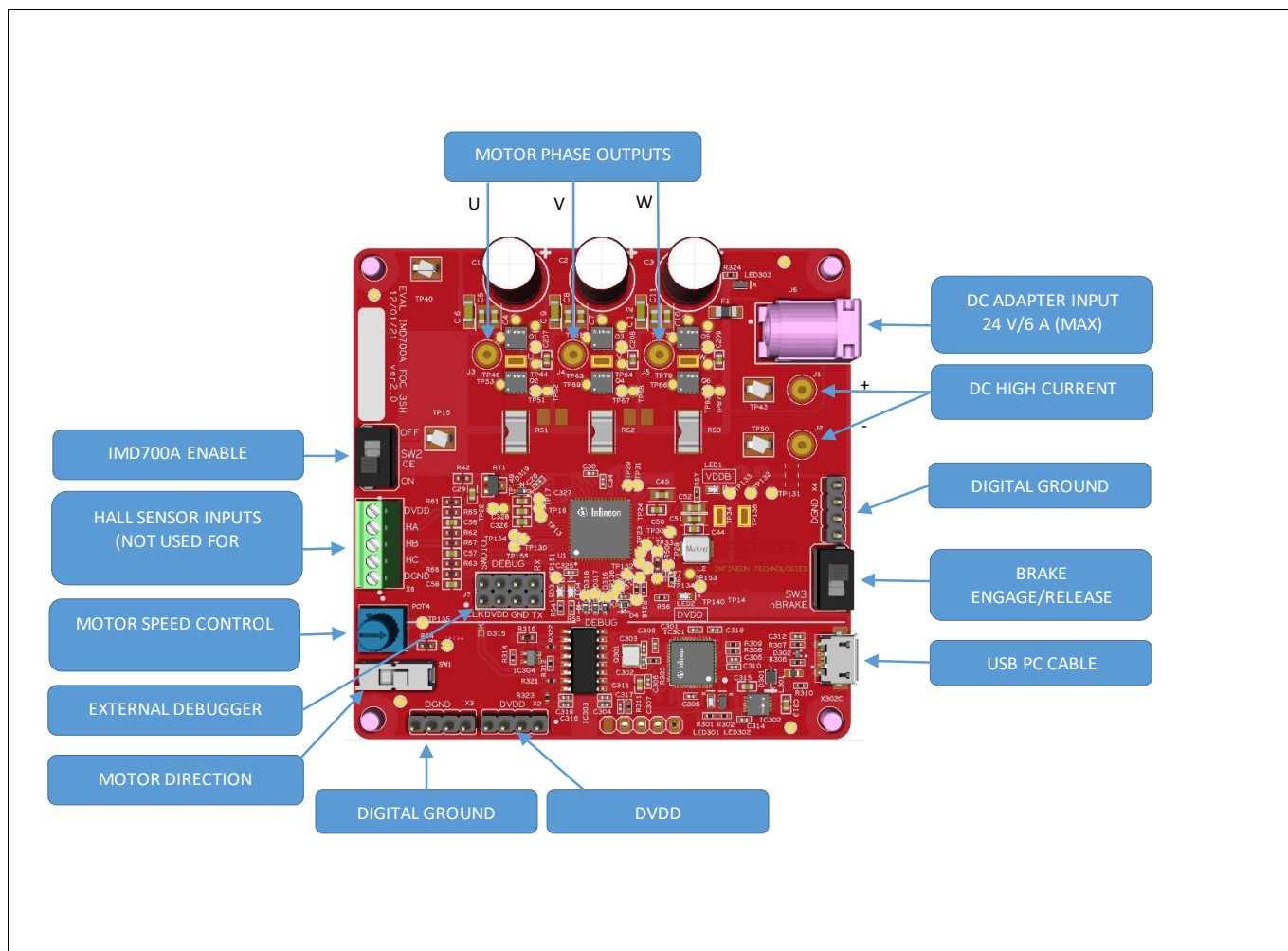
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### Hardware functional description

It is also possible to select whether the OCP fault is latched or not via the GUI. In a latch configuration, the nFAULT pin is held low until the fault is cleared via an SPI command or after a power cycle. If the OCP fault is configured as non-latched, the nFAULT pin remains low while the fault is being detected but will pull up again when the OCP condition is no longer present. Configuration allows the user to set a target number of consecutive events (PWM cycles) required to activate the nFAULT fault signaling.

If a positive OCP event occurs, the high-side PWM is truncated. The result is that the high-side MOSFETs are all switched off, and the current flowing in the motor windings therefore recirculates through the low-side MOSFET body diodes.

## 4.2 Board connections and controls



**Figure 30** EVAL\_IMD700A\_FOC\_3SH external connections and controls

## 4.3 Onboard programmer/debugger

The EVAL\_IMD700A\_FOC\_3SH board includes an onboard debugger, which is located below the white line shown on the top-side component legend. This is connected to a PC through a USB cable to enable control, programming and debugging via a dedicated GUI or firmware development tool such as DAVE™.

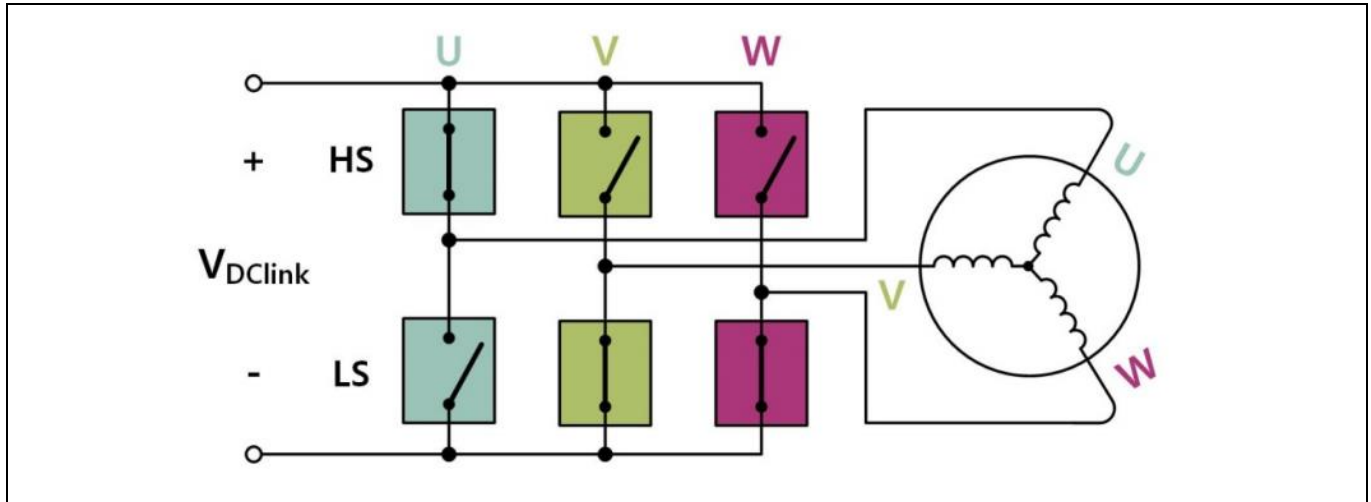
## 4.4 External programmer/debugger

If for any reason the user wishes to use an external debugger such as the XMC™ Link, this can be connected to via the 4x2-way header indicated.

## 5 Control and firmware

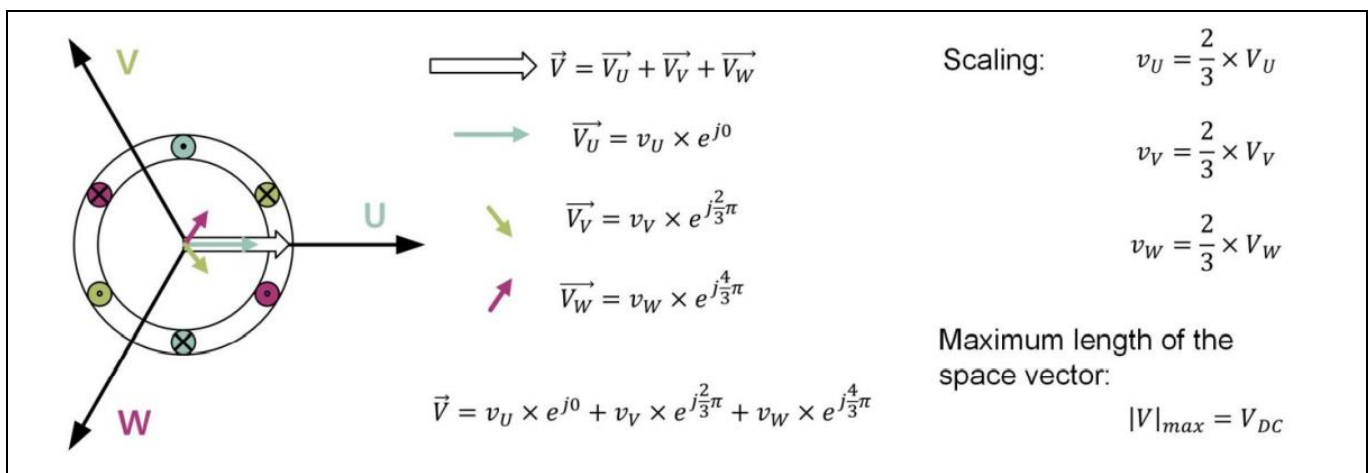
### 5.1 Space vector modulation

The power stage of the EVAL\_IMD700A\_FOC\_3SH motor drive inverter consists of three half-bridge switching stages supplying the phase windings denoted: U, V, and W.



**Figure 31** Three-phase voltage source inverter

Excluding the states in which the high and low switches of the same leg are turned on at the same time, there are six active states possible, each with a different combination of high- and low-side switches active. In each of these states the magnetic fields produced in the phase windings are differently affected. These magnetic fields can be visualized as vectors. The combined effect of these fields can be represented as the sum of the vectors in the form of complex numbers, as follows:<sup>1</sup>



**Figure 32** Complex number representation of space vector

The voltage applied to the energized winding with respect to the neutral point ( $v_{v,v,w}$ ) is 2/3 of the DC-link voltage if both non-energized windings are connected to the zero-volt return. Since these are connected in parallel, the impedance is half that of the energized winding.

<sup>1</sup> Euler's formula:  $e^{j\theta} = \cos \theta + j \sin \theta$

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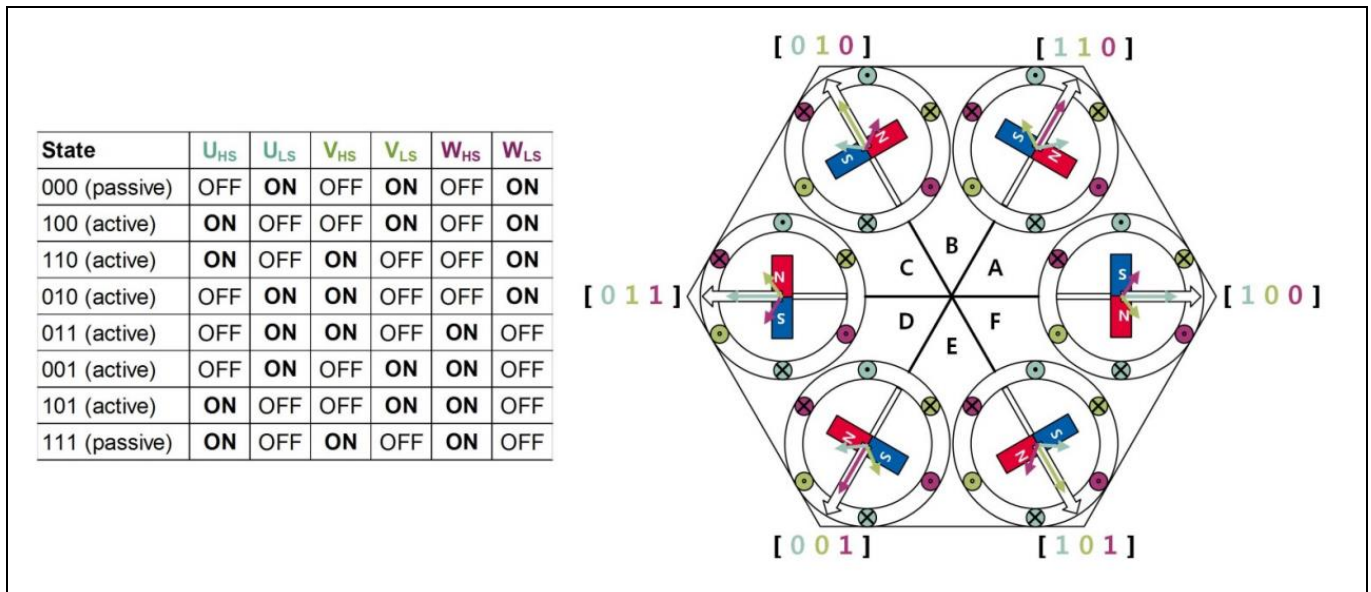
## Control and firmware

This can be expressed as follows:

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \frac{V_{DClink}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad [6]$$

Where the switch states are 1 = ON, 0 = OFF and only one switch is on at any one time.

The switching states can be mapped to a resulting magnetic field expressed as a vector in the space vector diagram of the coordinates U, V, and W. There are two passive states leading to two null vectors, which do not cause a magnetic field, and six active states represented by non-null vectors. These active vectors divide the space vector diagram of a U-V-W system into six sectors, named A, B, C, D, E and F.



**Figure 33** Space vector diagram of a three-phase U-V-W motor

Despite the fact that the stator coils are fixed in their positions, the magnetic dipole rotates depending on the currents present in each phase, which are proportional to field strength. Considering any combination of voltages on the phases, their resulting magnetic stator field (flux) may be expressed by a reference vector  $\vec{V}_{ref}$  defined as:

$$\vec{V}_{ref} = V_{ref} \times e^{-j\varphi} \quad [7]$$

It is rotating in space at speed  $\omega$  expressed in radians per second, where  $\omega = 2\pi f$  and  $f$  is the rotation frequency. This reference vector may be located in between any pair of the adjacent six active states, referred to as sectors. Any position of the reference vector in a sector may be produced by a linear combination of the two active vectors which define the sector (e.g.,  $\vec{V}_1$  and  $\vec{V}_2$ ) and one zero vector ( $\vec{V}_0$ ). The attenuation factor needed for the two active vectors depends on the relative angle  $\gamma_{rel}$ , which is the absolute angle  $\theta$  minus the angle of the first active vector in the sector (according to a clockwise rotation convention). This may be implemented physically by electrically adjusting the phase status significantly faster than  $V_{REF}$  changes. This means within a switching period  $T_s$ , each of the three active vectors must be applied for a certain duration so that the resulting average vector voltage is equal to  $V_{REF}$ . Average phase voltage is determined by the PWM duty cycle of each phase.

## Application note

## Control and firmware

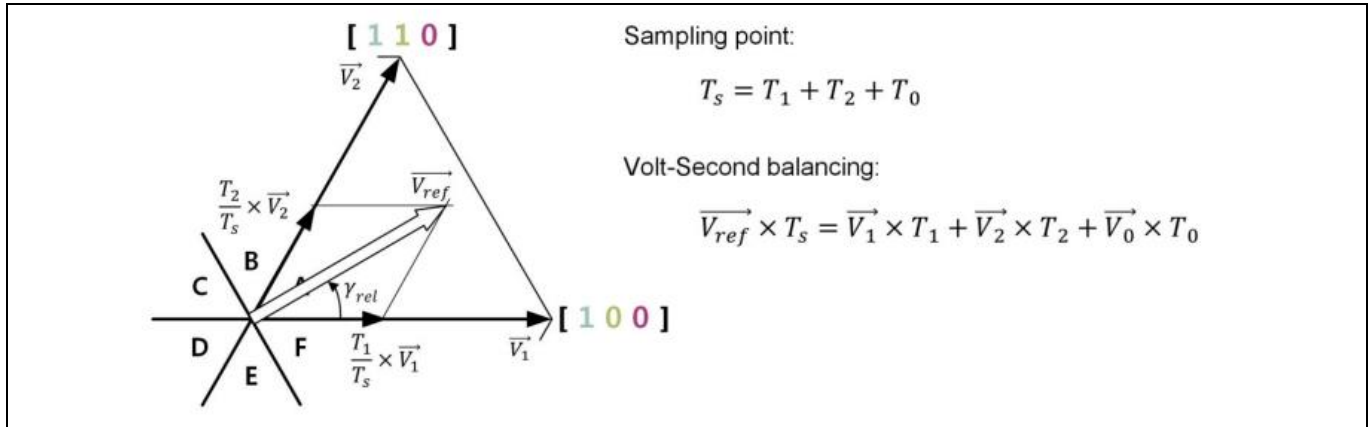


Figure 34 Reference vector approximation

Considering the scaling of the reference vector and expressing the vector voltages as complex numbers, the following equations are valid for the PWM on-time (time during which the high-side switches are on) for space vector modulation:

$$\vec{V}_{ref} = \frac{T_0}{T_s} \vec{V}_0 + \frac{T_1}{T_s} \vec{V}_1 + \frac{T_2}{T_s} \vec{V}_2 \quad [8]$$

$$T_1 = T_s \frac{V_{ref}}{V_{DC}} \sin\left(\frac{\pi}{3} - \gamma_{rel}\right) \quad [9]$$

$$T_2 = T_s \frac{V_{ref}}{V_{DC}} \sin(\gamma_{rel}) \quad [10]$$

$$T_0 = T_s - T_1 - T_2 \quad [11]$$

The aim of the control is to calculate the duty cycle for each bridge phase that makes the  $V_{REF}$  rotate with the desired electrical rotation.

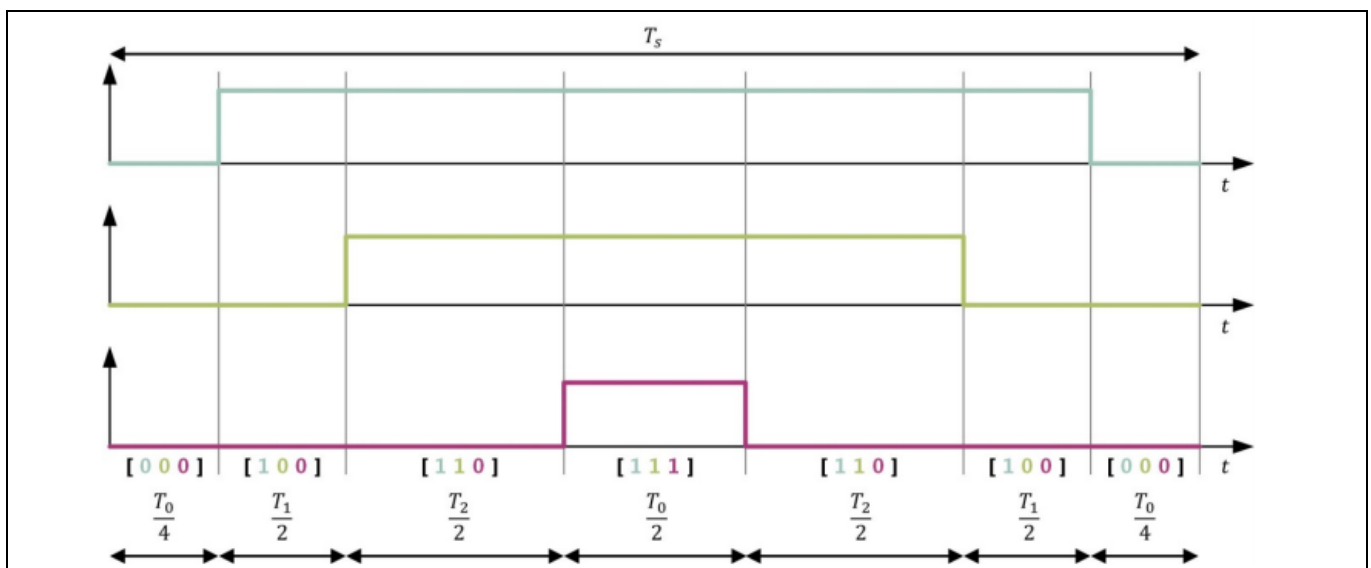
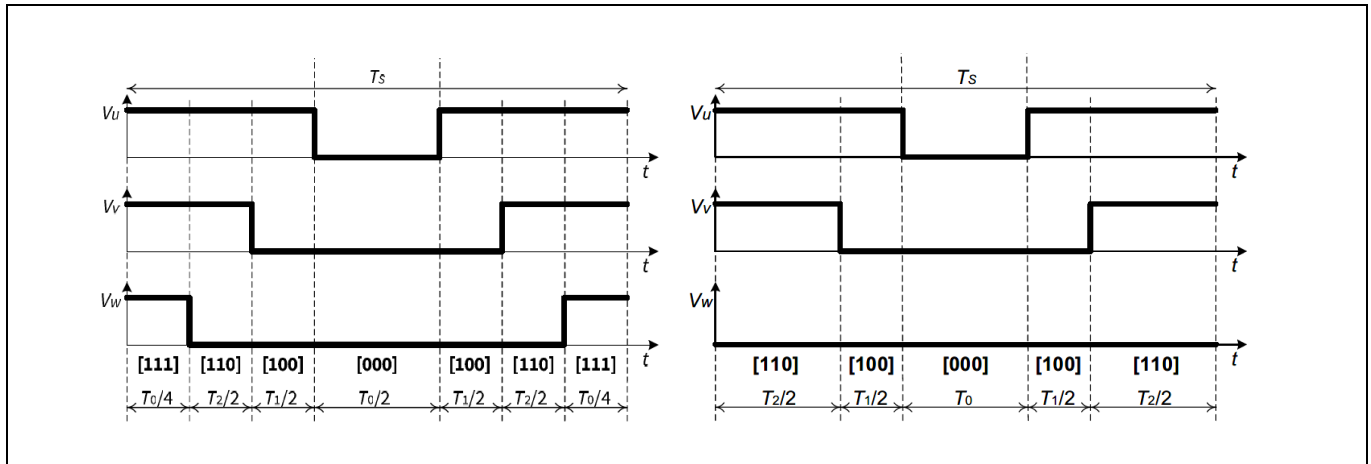


Figure 35 An example switching cycle pattern for one cycle of PWM

## Application note

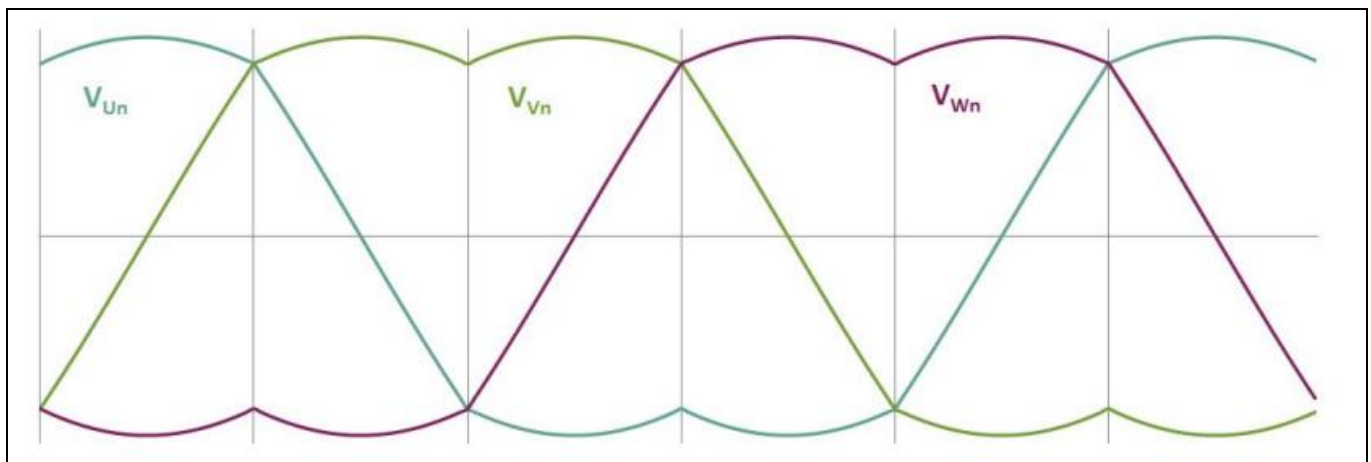
### Control and firmware

The firmware supports seven-segment SVM as shown above, and also five-segment SVM, which can be selected in the GUI tool. The five-segment SVM uses the same equations as in the seven-segment SVM to calculate the  $T_0$ ,  $T_1$ , and  $T_2$  timing. In the five-segment SVM, the zero vector is only  $[000]$ . Unlike in the seven-segment SVM, the zero vectors are  $[000]$  and  $[111]$ , which reduces the number of switching transitions required, thereby lowering switching losses.



**Figure 36** Seven-segment and five-segment SVM

The output voltage of each motor phase voltage vs. neutral through the complete electrical rotation is shown below. The resulting voltages  $V_{UV}$ ,  $V_{UW}$  and  $V_{VW}$  at the motor are sinusoidal.



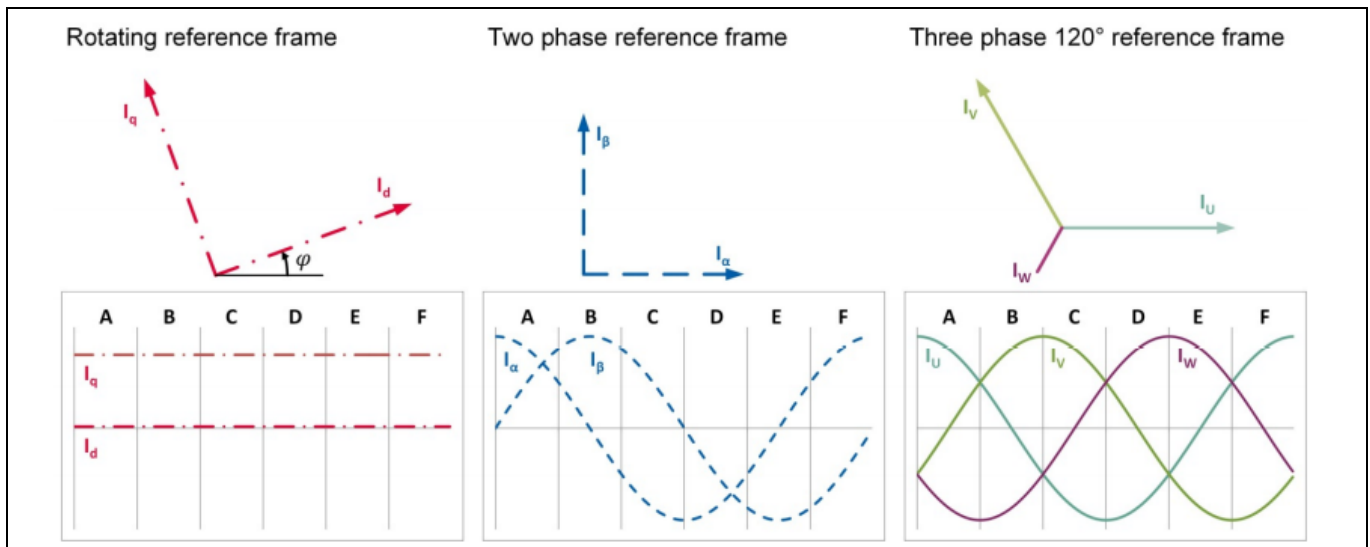
**Figure 37** Output voltages of space vector modulation

## 5.2 Field-oriented control

The EVAL\_IMD700A\_FOC\_3SH control firmware is based on a sensorless FOC system. In contrast to trapezoidal commutation, FOC uses vector control in place of scalar control. A variable-frequency drive control method is used in which the stator phase currents of the BLDC motor are identified as two orthogonal components. These are described by perpendicular vectors defining magnetic flux and torque, from which the control firmware calculates the corresponding current component references.

FOC is a method that generates a three-phase sinusoidal modulation, which can easily be controlled in frequency and amplitude to minimize the currents and therefore maximize the efficiency. The essential idea is the transformation of three-phase sampled current signals into two rotor-fixed signals and vice versa. In the rotor-fixed reference frame, the currents can be treated as stationary values and are relatively easy to control. Using the inverse vector rotation, the controller generated reference voltages can be returned to a rotating vector in the stator reference frame.

### 5.2.1 Stationary and rotating reference frames



**Figure 38** Stationary and rotating reference frames

The mathematical transformation from the three-phase system to the two-phase system is called the Clarke transform, represented by the following equations:

$$i_{\alpha} = i_U \quad [12]$$

$$i_{\beta} = \frac{1}{\sqrt{3}}(i_U + 2i_V) \quad [13]$$

If the phase currents are balanced, then:

$$i_U + i_V + i_W = 0 \quad [14]$$



## Application note

### Control and firmware

The transformation from a stationary to a rotating reference frame is called the Park transform, expressed by the following equations:

$$i_d = i_\alpha \cos(\varphi) + i_\beta \sin(\varphi) \quad [15]$$

$$i_q = i_\alpha \sin(\varphi) + i_\beta \cos(\varphi) \quad [16]$$

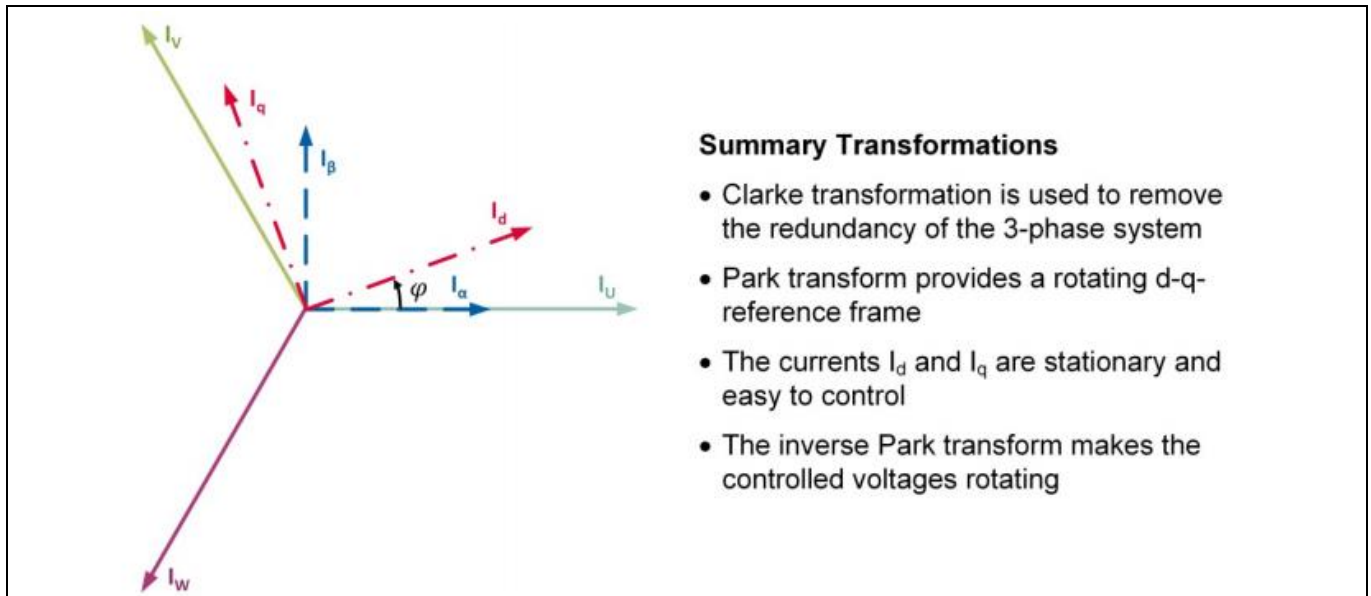
Where  $\varphi$  is the instantaneous angle of the sinusoidal current with frequency  $\omega$ .

The inverse Park transformation is given by:

$$i_\alpha = i_d \cos(\varphi) - i_q \sin(\varphi) \quad [17]$$

$$i_\beta = -i_d \sin(\varphi) + i_q \cos(\varphi) \quad [18]$$

The values of  $i_\alpha$  and  $i_\beta$  can be used directly to calculate the required PWM duty cycles using an SVM generator algorithm, and therefore the inverse Clarke transform is not required.



**Figure 39** Summary of transformations

The stationary currents  $i_d$  and  $i_q$  can also be converted to polar coordinates of angle and magnitude to provide input to the SVM generator.



## Application note

## Control and firmware

## 5.2.2 Sensorless FOC

Sensorless operation offers the advantage of saving the cost of an encoder or other position sensor. In order to achieve this, the motor's rotor flux is utilized to calculate the rotation angle and thus estimate rotor position and speed. The rotor flux itself is calculated in the flux estimator, which extracts the back electromotive force (BEMF) from the applied phase voltage by subtracting the voltage drops not associated with the BEMF. The rotor flux is then computed by integration of the estimated BEMF, which cannot be measured directly. Sensorless algorithms are less reliable when the applied phase voltage or measured current is inexact during low-speed operation.

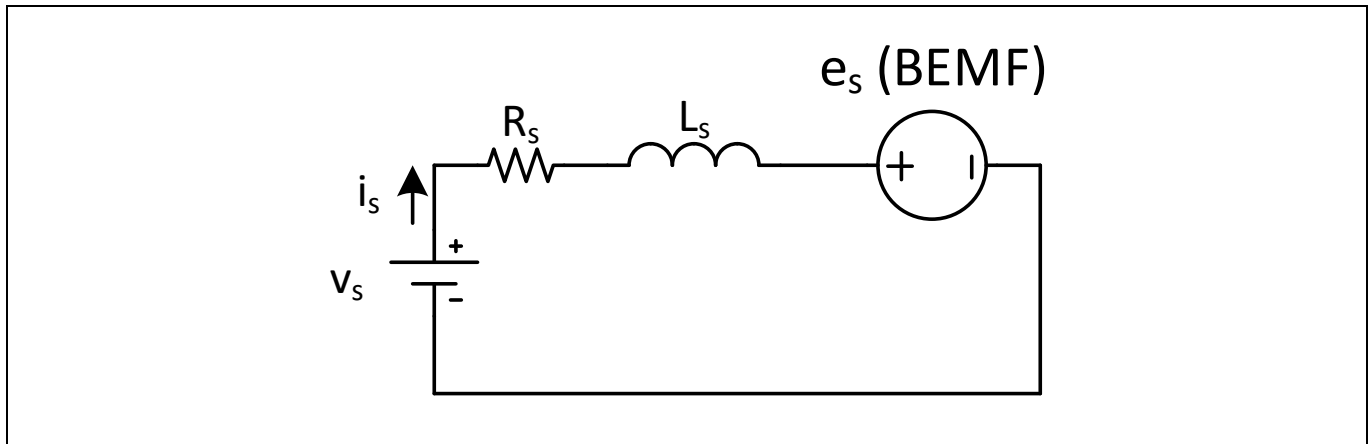


Figure 40 Back EMF estimation

$$v_s = R i_s + L \frac{di_s}{dt} + e_s \quad [19]$$

Where  $v_s$  represents the voltage applied to the stator winding,  $R_s$  the winding resistance,  $L_s$  the winding inductance and  $e_s$  is the BEMF generated by the motor rotation.  $v_s$  is calculated from the sensed DC supply voltage, and values of  $R_s$  and  $L_s$  for the motor must be entered as parameters for the firmware.

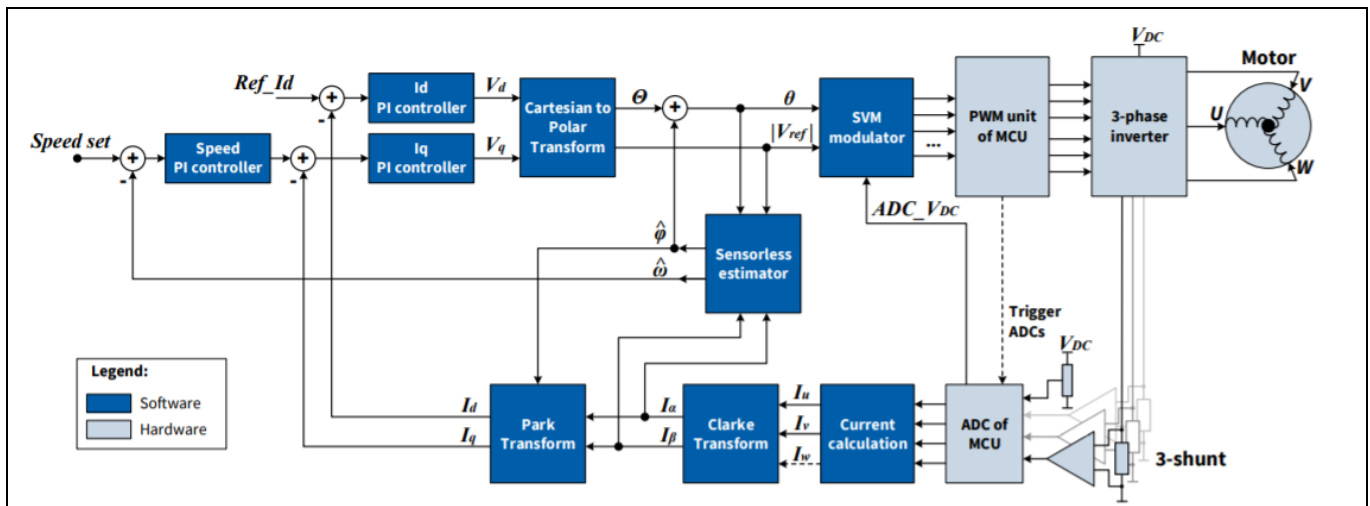


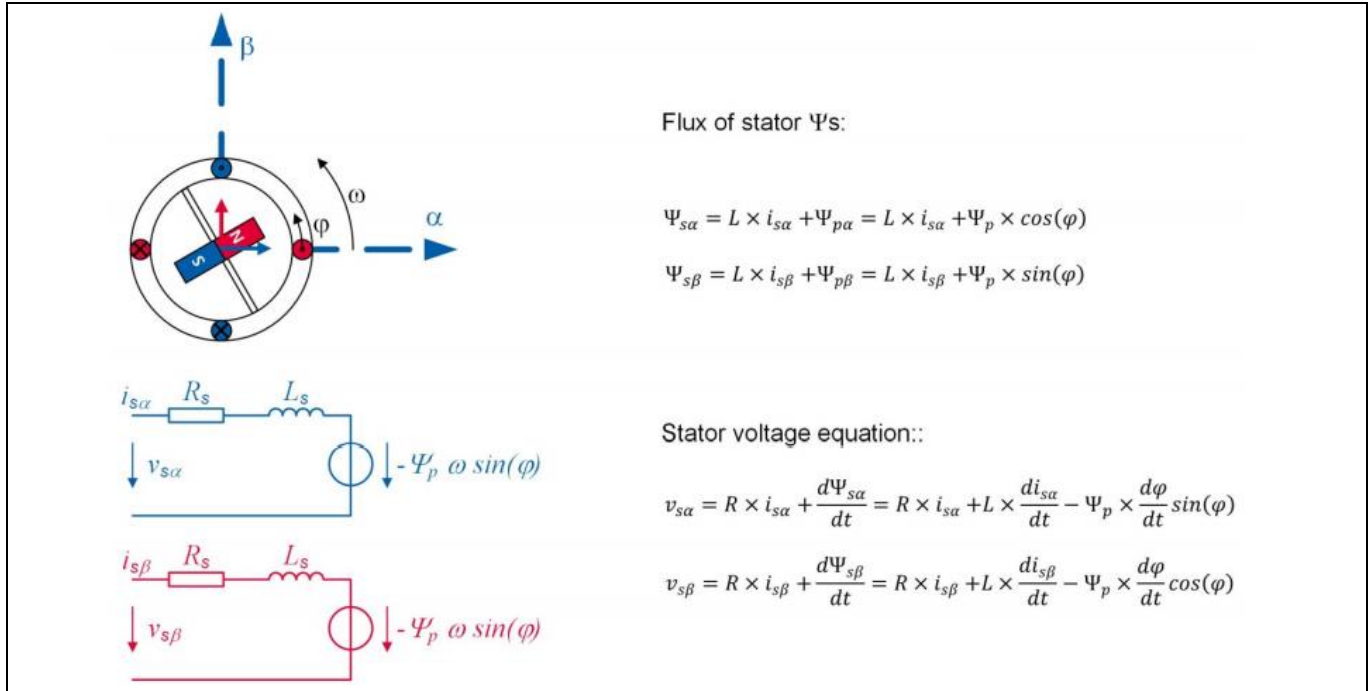
Figure 41 Block diagram of FOC system with speed control

The above figure shows the block diagram of the sensorless FOC algorithm. The flux estimator's input signals are taken from the orthogonal two-phase stator system with the index  $\alpha$  and  $\beta$ . The estimator output signal represents the rotor angle  $\varphi$ . The motor signals in the two-phase ( $\alpha\beta$ ) stator system are equivalent to the

## Application note

### Control and firmware

three-phase ( $uvw$ ) system. As a result, an ideal two-phase motor can be assumed in the  $\alpha$ - $\beta$  system with only two equations to calculate. The figure below shows the voltage equations of the motor in the  $\alpha$ - $\beta$  system:



**Figure 42** Block diagram of FOC system

The stator fluxes  $\Psi_{s\alpha}$  and  $\Psi_{s\beta}$  contain the mutual inductance  $L \times \vec{i}_s$  and the flux of the rotor  $\vec{\Psi}_p$  generated by its permanent magnet. The stator voltage equations ( $v_{s\alpha}$  and  $v_{s\beta}$ ) contain the resistance of the coil  $R \times \vec{i}_s$  and the derivative of the stator flux according to Faraday's law. Integrating the voltage equations, the stator flux is calculated as:

$$\Psi_{s\alpha} = \int v_{s\alpha} - Ri_{s\alpha} . dt \quad [20]$$

$$\Psi_{s\beta} = \int v_{s\beta} - Ri_{s\beta} . dt \quad [21]$$

The flux of the motor and therefore the rotor permanent magnet orientation angle is given by:

$$\Psi_{p\alpha} = \Psi_{s\alpha} - Li_{s\alpha} = \int v_{s\alpha} - Ri_{s\alpha} . dt - Li_{s\alpha} \quad [22]$$

$$\Psi_{p\beta} = \Psi_{s\beta} - Li_{s\beta} = \int v_{s\beta} - Ri_{s\beta} . dt - Li_{s\beta} \quad [23]$$

$$\phi = \tan^{-1} \left( \frac{\Psi_{p\beta}}{\Psi_{p\alpha}} \right) \quad [24]$$

The position of the rotor can therefore be calculated by knowing the resistance  $R$  and inductance  $L$  of the motor windings. The stator voltage  $v_s$  is derived from the algorithm and the current  $i_s$  is measured in real time.

### 5.3 Motor parameters

As mentioned in the previous section, it is necessary for the FOC algorithm to be provided with the values of stator winding inductance and resistance. These values may be obtained from the motor manufacturer's datasheet or measured directly from the motor using an LCR meter. If the inductance between two phases with the third phase left unconnected is measured, the result can be divided by 2 to obtain the value for one phase winding:

$$L_U = \frac{L_{UV}}{2} \quad [25]$$

The same applies for the resistance:

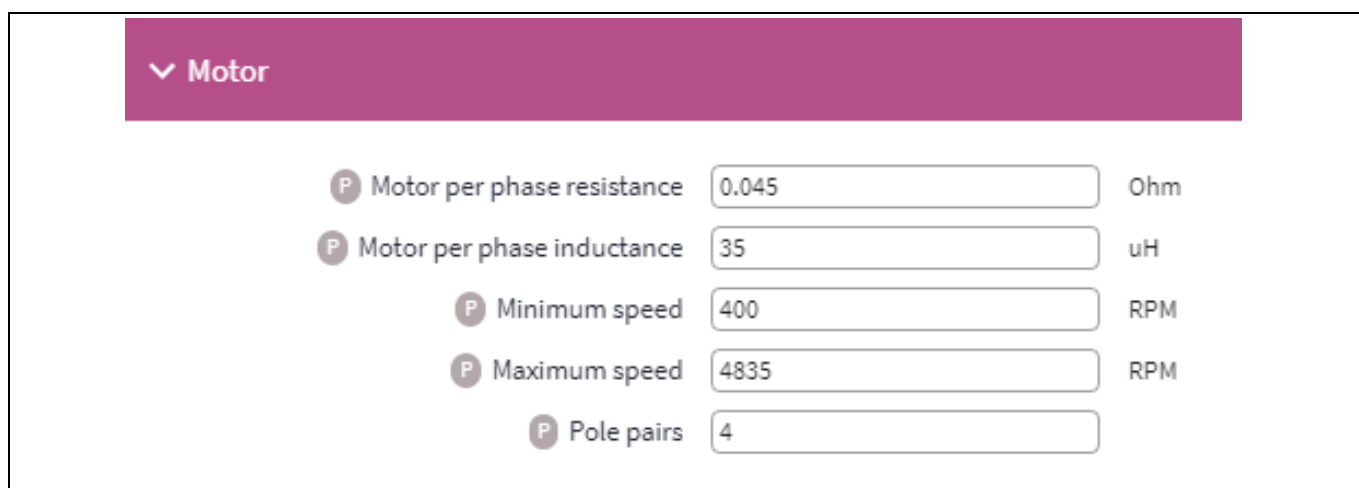
$$R_U = \frac{R_{UV}}{2} \quad [26]$$

Note that it is normal to see some tolerance in these values, so it is recommended to use the typical values from the datasheet or, if using measured values, to measure all three values and work out the average.

$$L_{U,V,W} = \frac{L_{UV} + L_{UW} + L_{VW}}{6} \quad [27]$$

$$R_{U,V,W} = \frac{R_{UV} + R_{UW} + R_{VW}}{6} \quad [28]$$

These values may then be entered into the MOTIX™ IMD700A Flash memory via the GUI.



The screenshot shows a GUI window titled "Motor" with a dropdown arrow. Below the title, there are five parameter entries, each with a "P" icon in a circle, a text label, a numeric input field, and a unit label:

- Motor per phase resistance: 0.045 Ohm
- Motor per phase inductance: 35 uH
- Minimum speed: 400 RPM
- Maximum speed: 4835 RPM
- Pole pairs: 4

**Figure 43** Entering the stator winding parameters

## 5.4 Firmware implementation

The EVAL\_IMD700A\_FOC\_3SH firmware is pre-installed and may be updated through the BPA motor control GUI, which may be downloaded from the Infineon Toolbox desktop app for installing and launching Infineon software tools. It also enables the user to keep track of installed Infineon software tools and updates.

Using the GUI, the user must enter the values of the motor phase resistance and inductance, the number of pole pairs, and the minimum and maximum speed limits so that the sensorless FOC algorithm in the firmware can be configured to the correct values.

The GUI also offers the following control scheme options:

1. **Open-loop V/f voltage control:** used for start-up open-loop operation.
2.  **$V_q$  voltage control:** used when fast response is more important than speed regulation.
3. **Speed control through inner current loop regulation:** used when tight speed regulation is required and a slower response is acceptable.

The major components of the FOC  $V_q$  and speed control algorithms are as follows:

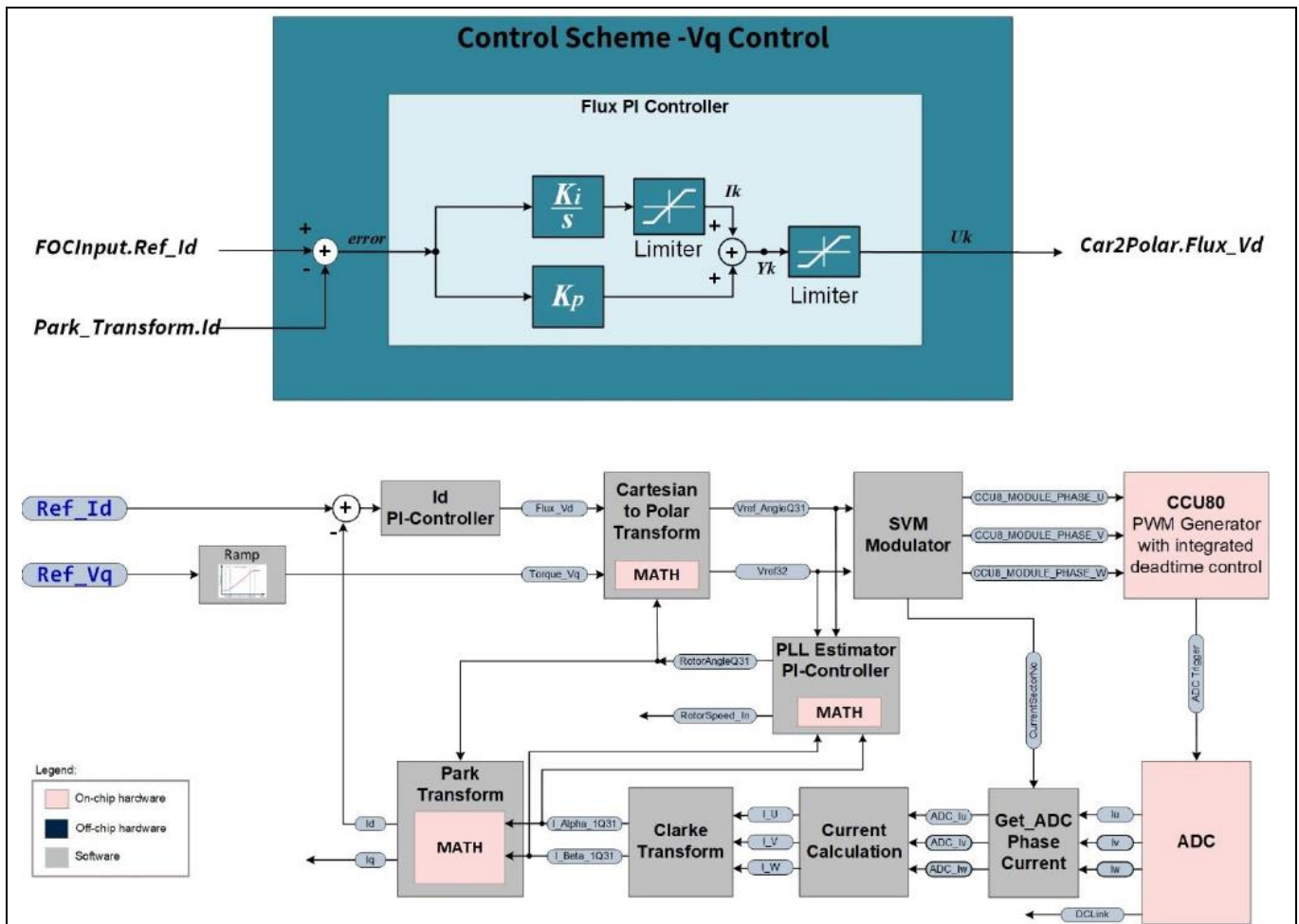


Figure 44 Block diagram of FOC  $V_q$  control scheme



The operations motor's start, stop and speed adjustment are controlled by applying an analog voltage signal to an ADC port of the MOTIX™ IMD700A. The relationship between the ADC data and the motor target speed for speed control scheme is shown in the figure below.



## Application note

### Control and firmware

1. TH\_POT\_ADC: threshold for motor stop. If ADC data is below this threshold, the motor will stop. Above this threshold, the motor will start with the minimum speed RPM setting.
2. Maximum value of 12-bit ADC, 4096: maximum target speed of the motor, according to the maximum RPM setting.

#### 5.4.1 Motor start-up

It is not possible to apply FOC immediately at motor start-up, because there is no phase current or BEMF information available from which to determine the initial rotor position. Without this information the desired stator field vector cannot be computed to determine the PWM outputs for the phases. To overcome this, the system incorporates an initial position detection (IPD) and rotor pre-alignment scheme to move the rotor from an unknown to a known position before ramping up the speed. The GUI tool allows pre-alignment to be enabled or disabled in the firmware. If it is disabled, a PLL estimator algorithm developed by Infineon is used to estimate the initial rotor position.

Two different start-up schemes are available: V/f open loop and direct FOC. In the first (default) case the system operates in open-loop voltage/frequency (V/f) control, which is a motor control method that maintains the output voltages proportional with the frequency to maintain a constant motor flux, preventing weak magnetic fields or saturation. V/f voltage control is used to start the motor and provide the initial speed ramp-up. Because the initial position is not known, an IPD scheme has been employed to enable rotor pre-alignment. The firmware switches from V/f control to FOC when the speed reaches a set RPM, which can be set via the GUI. In the second case FOC is implemented as soon as the initial alignment has taken place.

#### 5.4.2 Speed control

In order to estimate the position of the rotor, the BEMF of the motor is calculated by the flux estimator. This is based on the RL motor circuit, whose behavior is described in equations 25 to 28. The current values are the estimated currents in the stator coordinate system ( $\alpha\beta$ ) and the motor parameters as defined, which can be set through the GUI. The rotor speed and position feedback of the motor are then determined by a phase-locked loop (PLL) estimator.

During FOC operation a closed-loop speed control scheme is implemented based on a cascaded speed and current control structure of PI controllers. To maintain a 90-degree difference between the flux and torque vectors the reference for the direct component  $I_d$  is set to zero. The  $I_q$  component reference is given by the difference between the commanded speed and the estimated speed. The error between this and the computed  $I_q$  from the sensed phase currents provides the input to the torque PI controller. The outputs  $V_d$  and  $V_q$  are then used to determine the magnitude and angle of the desired PWM vector to be supplied to the SVM modulator.

The control of  $I_d$  and  $I_q$  currents are not independent from one another. The  $I_d$  current affects the  $I_q$  current and vice-versa.

This coupling effect acts as a disturbance, which becomes prominent during transient conditions at high speed. To correct for this coupling effect, feed-forward decoupling is applied to each axis to remove the disturbance.

$$\text{Torque voltage, } V_q = V_q - \omega L_q I_q \quad [29]$$

$$\text{Flux voltage, } V_d = V_d + \omega L_d I_d \quad [30]$$

Assuming the torque inductance and the flux inductance are equal,  $\omega$  represents the estimated speed from the PLL estimator output.

#### 5.4.3 Motor stop

For motor stop operations, two types of motor stop mechanisms are provided:

- Ramp down and braking
- Immediate motor stop

The motor will ramp down to a predefined speed of three times the defined low RPM limit, and then the motor brake is applied. This mechanism can be used in motor control applications which allow the motor to ramp down and stop, e.g., washing machines, ceiling fans.

If the motor brake is applied immediately this will result in a surge in motor phase current during the brake operation. This mechanism is useful for motor control applications where the motor needs to be stopped very rapidly for safety reasons, e.g., in power tool applications. In this case the MOTIX™ IMD700A braking function can be operated according to the braking mode selected through the GUI.



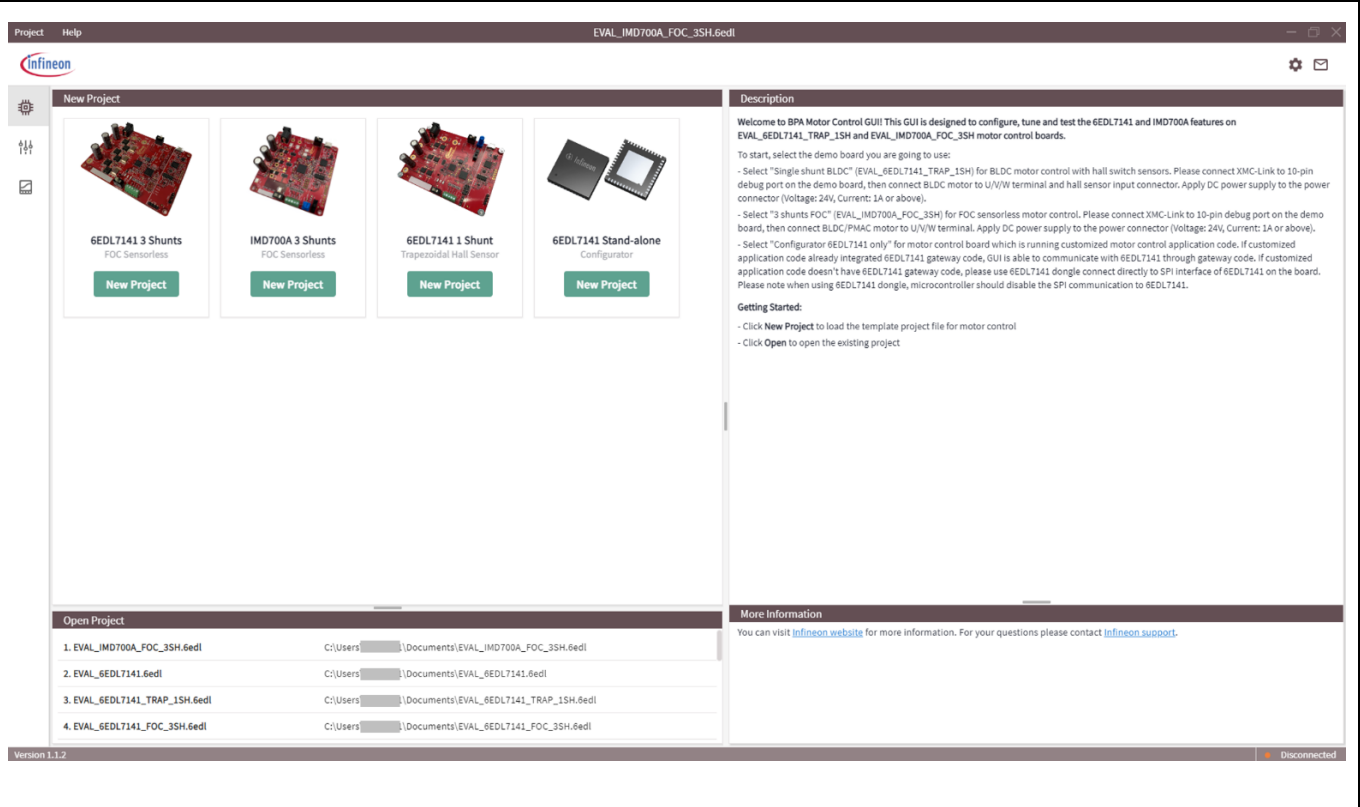
# EVAL\_IMD700A\_FOC\_3SH 18 V brushless DC motor drive board

## Application note

### Motor control GUI

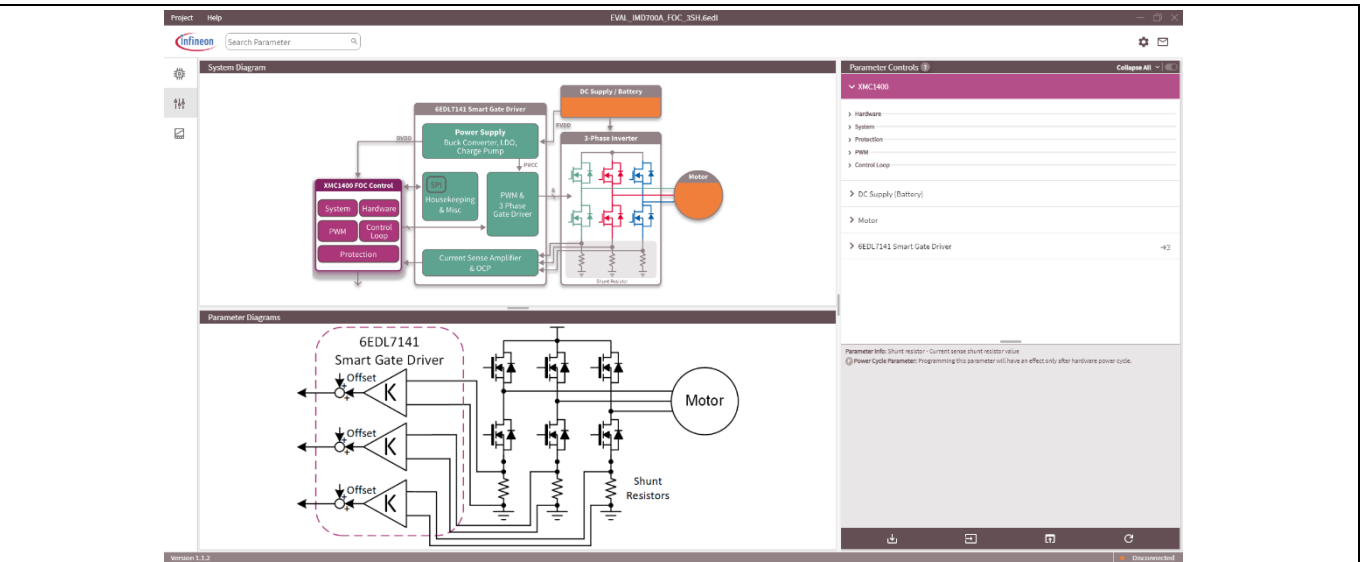
## 6 Motor control GUI

The 6EDL motor control GUI downloads control firmware and configuration settings for the MOTIX™ IMD700A on motor control boards operating with trapezoidal or FOC with one or three shunts. Once the parameters for a particular project have been selected, the configuration can be saved. The launch screen appears as follows:



**Figure 47** 6EDL motor control GUI (v.1.1.2) launch screen

To start a new project first select the required configuration from the three available options. The EVAL\_IMD700A\_FOC\_3SH evaluation board is a three-shunt design for FOC, which when selected brings the GUI to the next screen. The next step is to expand the dropdown menu from the “XMC1400” option in the Parameter Controls panel.



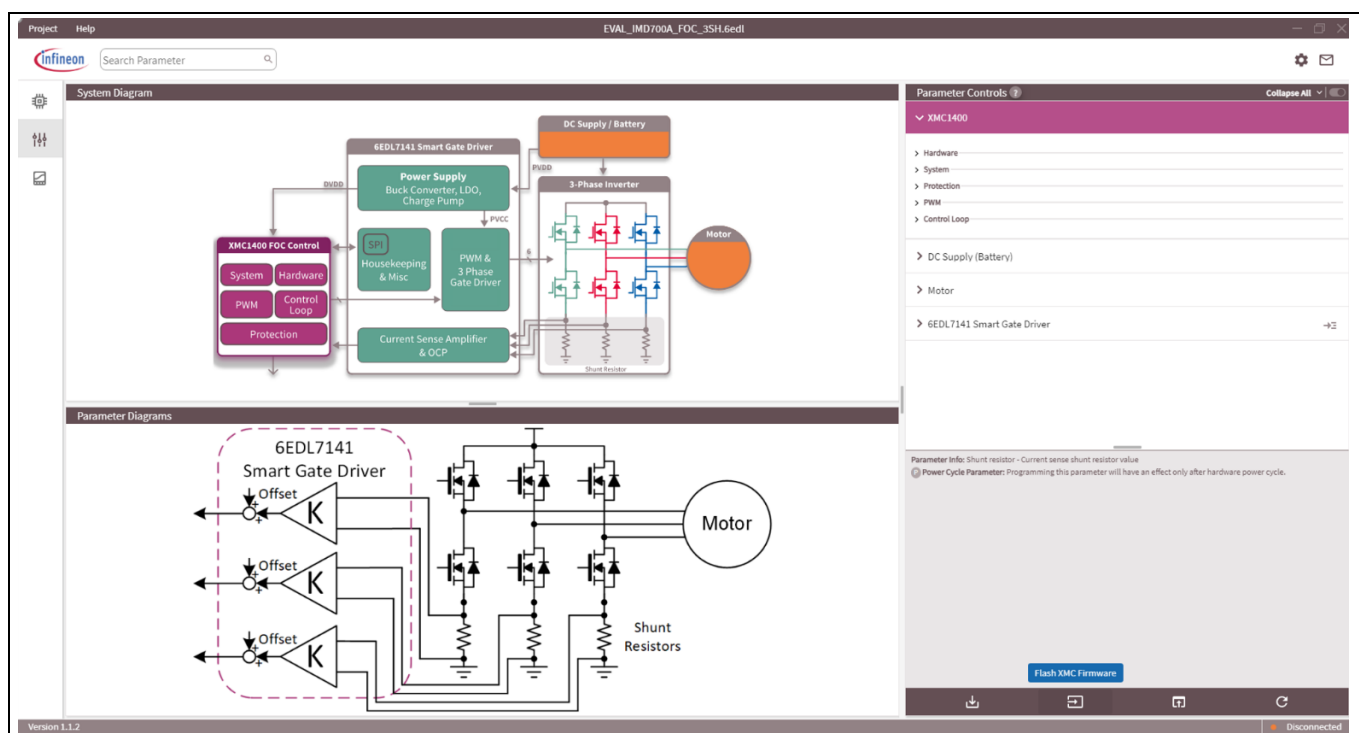
**Figure 48** FOC with three-shunt firmware configuration menu



## 6.1 Installing the firmware from the GUI

To support transfer of MOTIX™ IMD700A parameters from the GUI, the firmware must include the functions that support this. The EVAL\_IMD700A\_FOC\_3SH board is pre-installed with the correct firmware and parameters.

The GUI includes a suite of firmware options that can be downloaded to any compatible motor drive board that uses the XMC1400 MCU with the MOTIX™ 6EDL7141 or the integrated MOTIX™ IMD700/1A. In the figure above, on the right-hand side the XMC1400 is expanded to show the firmware options available. The figure below displays some of the firmware options that are available, such as the PWM frequency and dead time.<sup>1</sup>



**Figure 49 Firmware options and download**

There are various important firmware parameters to be selected before downloading, which are listed in the table below. When the firmware parameters have been selected in the GUI, the firmware may be downloaded to the board via the USB cable by clicking the “Flash XMC Firmware” button, as shown above. A message will appear to inform the user that the firmware was successfully programmed onto the MCU. It is necessary to cycle the power to the target board after updating the firmware to update all of the parameters.

**Table 3 List of firmware parameters**

Parameter	Description	Value	Unit
<i>Hardware</i>			
ADC reference voltage	VADC reference voltage, same as DVDD	5	V
Shunt resistor	BOM RS1, RS2, RS3	10 <sup>2</sup>	mΩ
<i>System</i>			
Potentiometer control	Enable hardware potentiometer	By pot only	
Control scheme	Select command parameter	Speed inner current control	

<sup>1</sup> 6PWM mode is used in FOC where the dead time is set by the MCU of the IMD700A.

<sup>2</sup> Alternate shunt values may be used depending on the motor type being driven.

## Application note

## Motor control GUI

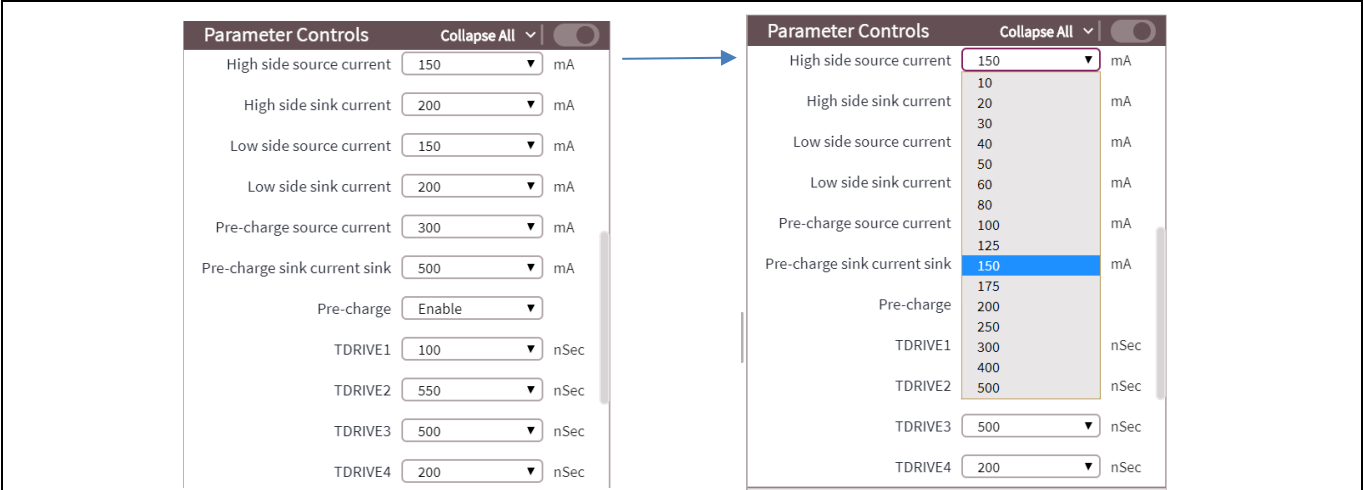
<i>Protection</i>			
Overvoltage threshold (18 V and 24 V settings)	Maximum DC input voltage	21.6/28.8	V
Undervoltage threshold (18 V and 24 V settings)	Minimum DC input voltage	14.4/19.2	V
DC-link over/undervoltage	Input voltage under/overvoltage	Enable	
<i>PWM</i>			
PWM frequency	PWM switching frequency	20	kHz
Dead time	PWM dead time for rising edge	0.4	μs
DC bus compensation	Enable/disable DC bus compensation	Disable	
DQ decoupling		Disable	
<i>Control loop</i>			
Rotor initial position detection		Rotor IPD pre-alignment	
IPD pre-alignment ramp rate		100	V/s
IPD pre-alignment voltage		0.8	V
IPD pre-alignment time		100	ms
Direct FOC start-up $V_q$ voltage		0.8	V
Open-loop V/f start-up offset voltage		0.5	V
Open-loop start-up V/f constant		0.08	V/Hz
Motor start-up method		Motor start V/f open loop	
Transition speed from V/f to closed loop		500	RPM
V/f speed ramp-up rate		100	RPM/s
Speed control ramp-up rate		50	RPM/s
Speed control ramp-down rate		50	RPM/s
SVM switching scheme	Select five- or seven-segment SVM	Standard SVM five-segment	
<i>DC supply</i>			
Nominal DC-link voltage <sup>1</sup>	Nominal input/battery voltage	18/24	V
Voltage divider R-high	Input voltage divider high resistance	75	kΩ
Voltage divider R-low	Input voltage divider low resistance	7.87	kΩ
<i>Motor</i>			
Motor per phase resistance	Phase winding resistance to neutral point	0.36	Ω
Motor per phase inductance	Phase winding inductance to neutral point	600	μH
Minimum speed	Low speed limit	200	RPM
Maximum speed	High speed limit	4000	RPM

<sup>1</sup> This needs to be changed for different input voltages. In this case the nominal voltage is 18 V and the maximum is 24 V.

Pole pairs	Number of rotor pole pairs	4	
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## 6.2 Configuring the MOTIX™ IMD700A parameters

The PWM configuration and gate driver parameters can be selected by expanding the “PWM and Three Phase Gate Driver” menu and selecting each parameter from the options available.



**Figure 50** Selecting the gate drive parameters

The GUI enables configuration of all of the MOTIX™ IMD700A selectable parameters, including the onboard power supply and charge pump settings and the CS amplifiers and OCP thresholds as discussed in previous sections.

Once all of the firmware options and MOTIX™ IMD700A parameters have been selected for a design, the project should be saved via the Project menu at the top of the screen. The project file has a .6EDL extension.

The target board containing the MOTIX™ IMD700A can be connected to the PC via an XMC™ LINK debugger; however, this is not necessary for the EVAL\_IMD700A\_FOC\_3SH evaluation board, which has its own onboard debugger and can be connected directly to a USB port on the PC. The MOTIX™ IMD700A can be programmed with the selected values using the following options:



**Figure 51** Transferring the settings to the MOTIX™ IMD700A

The “Write Parameters” option transfers the configuration to volatile memory, which will remain only while the MOTIX™ IMD700A is powered. This option should be used during bench testing and optimization until the designer is completely satisfied that all of the correct values have been selected. If values are changed during bench evaluation, the project should be saved again. When the designer is sure that the final values have been obtained, the “Burn 6EDL7141 OTP” option may be used to permanently set the configuration of the MOTIX™ 6EDL7141 parameters within the MOTIX™ IMD700A in OTP memory.

## Application note

## Motor control GUI

Table 4 List of additional MOTIX™ IMD700A parameters

Parameter	Value	Unit
<b>Power supply</b>		
PVCC setpoint	12	V
Charge pump clock frequency	781.25	kHz
Charge pump spread spectrum	Enable	
Charge pump pre-charge	Disable	
Buck converter frequency	500	kHz
DVDD setpoint	V_SENSE pin	
DVDD soft-start time	100	μs
DVDD turn-on delay	200	μs
DVDD OCP threshold	450	mV
<b>PWM and three-phase gate driver<sup>1</sup></b>		
PWM mode	6 PWM	
PWM freewheeling mode	Active FW	
Brake configuration	Low-side	
Alternate recirculation	Disable	
Pre-charge	Enable	
<b>CS and OCP</b>		
Amplifier A	Enable	
Amplifier B	Enable	
Amplifier C	Enable	
Amplifier gain <sup>2</sup>	8x	
Amplifier gain analog select	Disable	
Amplifier mode	Shunt resistor	
Internal offset selection	¼ DVDD	
Use external offset	Disable	
Amplifier timing mode	GLx high	
Amplifier blanking time	1000	ns
Amplifier auto-zero	Internal trigger	
OCP positive threshold	300	mV
OCP negative threshold	-300	mV
PWM truncation	Enable	
OCP deglitch time	8	μs
OCP fault trigger	8 events	
OCP fault latching	Disable	
Brake on OCP	Enable	
Negative OCP	Enable	

<sup>1</sup> Refer to Table 3 for parameters not listed here<sup>2</sup> Different gain values may be required depending on the motor being driven and the values of RS1, RS2, and RS3.

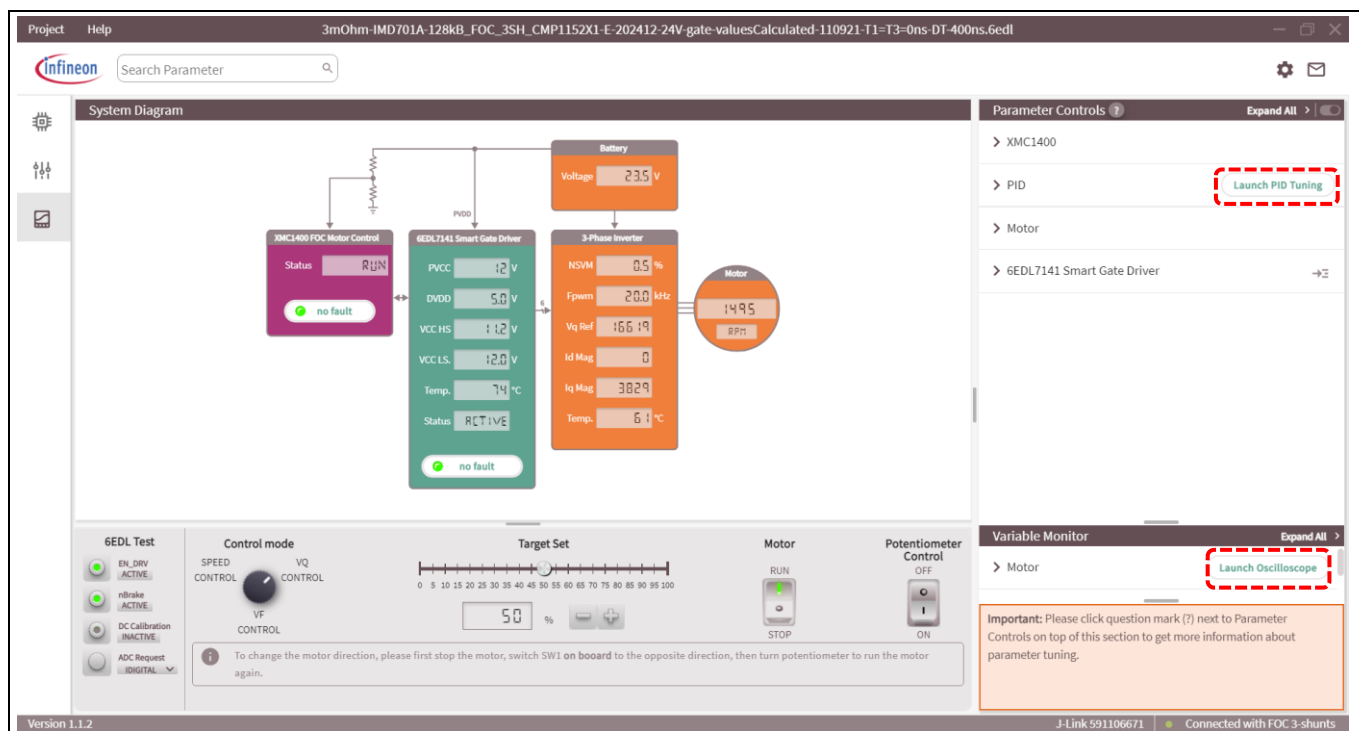
## Application note

## Motor control GUI

Housekeeping		
Hall sensor deglitch time	640	ns
Overtemperature shutdown	Enable	
ADC measurement filter	8	
APC PVDD measurement filter	32	
Watchdog (WD) timer	Disable	
WD input selection	EN_DRV	
WD fault report	Status reg. only	
WD period time	100	μs
Buck converter WD	Enable	
Rotor lock detection time	1	s
Rotor lock detection	Disable	
WD fault latching	Disable	
Brake on WD timer overflow	Disable	
WD DVDD restart delay	0.5	ms
WD DVDD restart attempts	0	
User ID	0	

### 6.3 Using the GUI to control the board

The BPA motor control GUI also has the ability to control and monitor the operation of a MOTIX™ IMD700A-based motor drive inverter such as the EVAL\_IMD700A\_FOC\_3SH. This is done through the test bench screen, which allows control of the control mode and motor speed.



**Figure 52 GUI test bench screen**

The test bench screen provides a real-time display of the system parameters such as the power supply, internal regulator and charge pump voltages as well as the battery input voltage. It also indicates the rotor revolutions per minute (RPM), the motor current, the PWM switching frequency and duty cycle, and also the MOTIX™ IMD700A temperature from its integrated sensor. Fault status is also indicated.

In addition to monitoring the system, the motor control mode, direction and speed can be commanded from this GUI screen using the control mode knob and target set slider controls in the lower area of the screen. The motor can be started or stopped via the motor switch, and the board-mounted speed control potentiometer can also be enabled and disabled. In order to control the speed through the GUI, the potentiometer control switch on the right must be in the “off” position.

If required, the control loop parameters may also be monitored and adjusted through the PID tuning screen, which can be launched from the test bench screen as indicated above. Output waveforms can be observed with the oscilloscope screen. Both of these can be launched from the above test bench screen by clicking on the highlighted buttons.

Application note

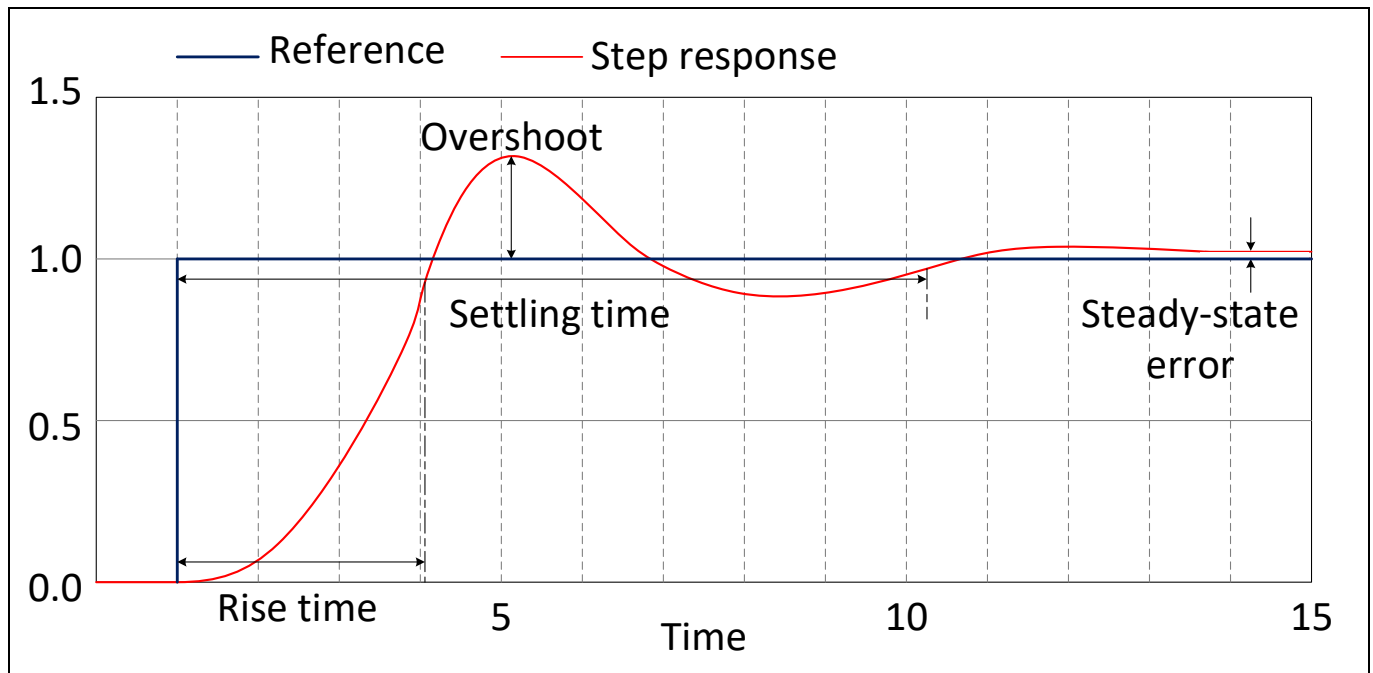
Motor control GUI



Figure 53 Oscilloscope view showing the phase currents;  $I_u$  (green),  $I_v$  (red),  $I_w$  (blue)

## 6.4 PID tuning

During operation the graphs display the input and output values of the different PI controllers, which indicate the stability of each loop in the system. Tuning of the  $K_p$ ,  $K_i$  and scale parameters for flux, PLL, speed and torque can be carried out by adjusting the values in the PID tuning screen to optimize the system response, as illustrated here:



**Figure 54** Step response of a control loop

Adjustment is done by clicking inside the box and changing the value according to the instructions displayed on the right-hand panel. Once the values are changed, clicking on the Save button will download the new values to the MOTIX™ IMD700/1A.



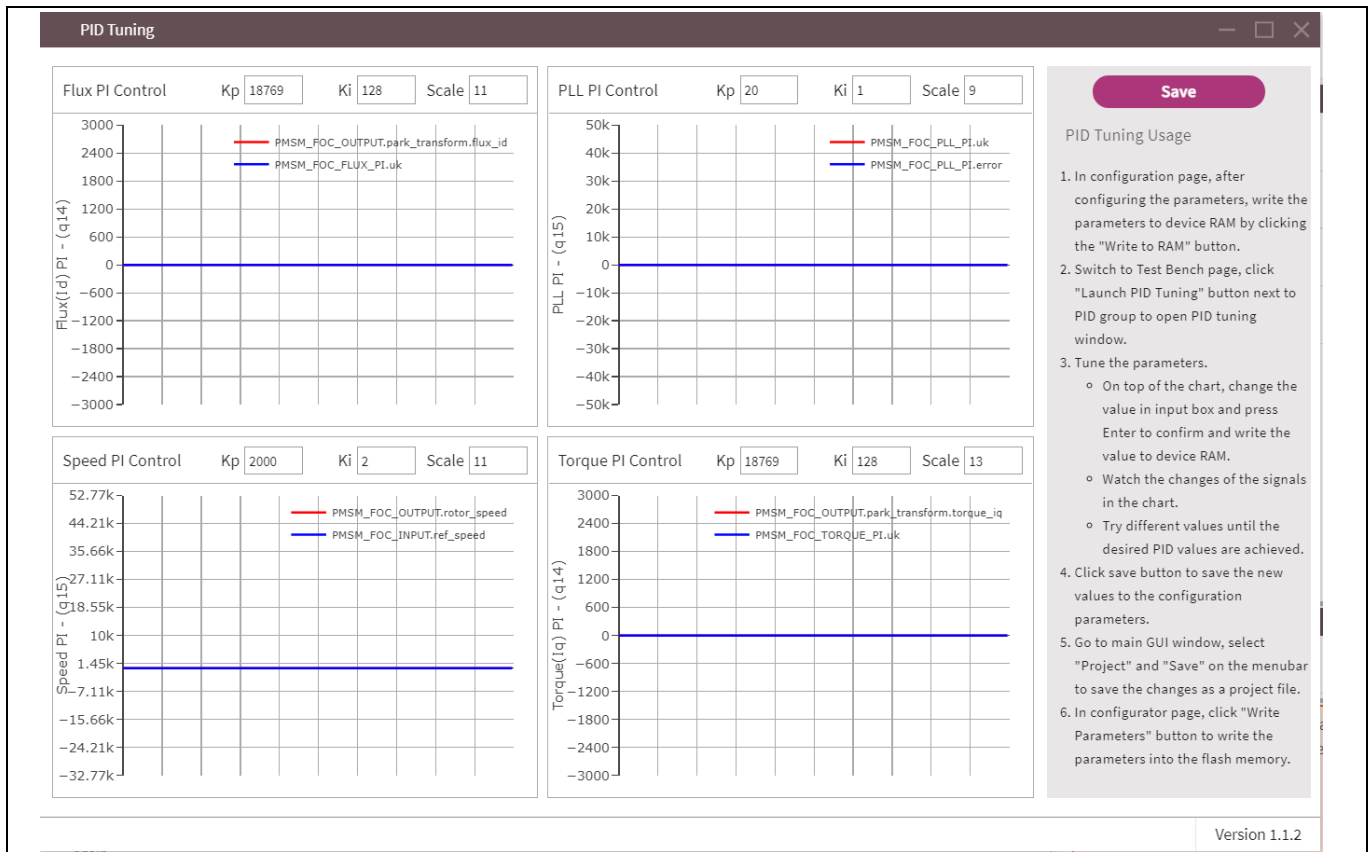


Figure 55 PID tuning screen

### 6.4.1 $V_q$ control loop tuning

Only  $I_d$  or flux PI control and PLL PI control (for the PLL estimator) need to be tuned for  $V_q$  control. The purpose of tuning the control loop is to enable smooth running of the motor, producing sinusoidal phase current waveforms and compensating for motor load changes.

For each control loop, there are  $K_p$ ,  $K_i$  and scale parameters. By adjusting these values, the output response to the error detected at the input of the control loop will be altered. Their relationships are as follows:

$$K_{\text{proportional gain}} = K_p / 2^{\text{Scale}} \text{ and } K_{\text{integral gain}} = K_i / 2^{\text{Scale}} \quad [31]$$

where  $K_p$  or  $K_i$  are integer values stored in the source code for proportional gain and integral gain, respectively. To increase the value of  $K_p$  and  $K_i$  at the same time, reduce the scale value by one. To reduce both  $K_p$  and  $K_i$  by a factor of two, increase the scale value by one. The first step in tuning is to increase or decrease the value of the scale to make the current waveform of  $I_u$ ,  $I_v$ , and  $I_w$  as sinusoidal as possible. The current waveforms can be monitored by using the BPA motor to control the GUI's oscilloscope function. The current shape can be fine-tuned by individually adjusting the values of  $K_p$  and  $K_i$  for the relevant control loop. The effects of increasing the proportional gain  $K_p$  or integral gain  $K_i$  of the PI controller independently are illustrated in the table below:

Table 5 Effects of  $K_p$  and  $K_i$  adjustment

Gain adjustment		Effect on loop response to input step change			
$K_p$	$K_i$	Rise time	Overshoot	Settling time	Steady-state error
Increase	No change	Reduced	Increased	Minor change	Reduced
No change	Increase	Reduced	Increased	Increased	Reduced/removed

When tuning the PLL PI control loop and flux PI control loop, ensure that the PMSM\_FOC\_PLL\_Pi.uk (red line of PLL PI control) and PMSM\_FOC\_FLUX\_Pi.uk (blue line of flux PI control) are not saturated to a fixed value. These two values represent the output of the control loop, and their saturation would indicate that the control loop is outputting its maximum value to reduce the error, but is unable to do so and is therefore unstable.

### **6.4.2 Speed control loop tuning**

There are four control loops, namely PLL PI control, flux PI control, torque PI control and speed PI control. The default  $K_p$ ,  $K_i$  and scale values for the PLL PI control, flux PI control and torque PI control can be used as a starting point for tuning the speed PI control to obtain sinusoidal phase current waveforms under different load conditions and reach a steady speed.

As with  $V_q$  control-loop tuning, the PID tuning and oscilloscope tools are used. If by adjusting the scale value of the speed PI control, the phase current waveform becomes distorted, then it will be necessary to adjust the scale value of the flux and torque PI control to improve the shape of the phase currents to make them more sinusoidal. One thing to note is that the  $K_p$ ,  $K_i$  and scale value for both flux and torque PI control should be the same when tuning the speed control of the motor.

## 7 Bill of materials

Reference	Qty	Type	Value/Rating	Manufacturer	Part number
C1, C2, C3	3	Capacitor	270 $\mu$ F, 35 V, Radial	United Chemi-Con	EKZE350ELL271MH20D
C4, C5, C7, C8, C10, C11	6	Capacitor	2.2 $\mu$ F, 50 V, 20%, 0805, X5R	TDK	C2012X5R1H225M085AB
C6, C9, C12	3	Capacitor	4.7 $\mu$ F, 50 V, 10%, 1206, X5R	Murata Electronics	GRM319R61H475KA12D
C13, C14, C330, C331, C332, C333	6	Capacitor	Not fitted	Würth Elektronik	885012207125
C23, C25, C27	3	Capacitor	330 pF, 25 V, 10%, 0603, X7R	Würth Elektronik	885012206056
C24	1	Capacitor	0.01 $\mu$ F, 25 V, 10%, 0402, X7R	AVX	04023C103KAT4A
C26, C41, C44, C326	4	Capacitor	0.1 $\mu$ F, 25 V, 20%, 0603, X7R	KEMET	C0603X104M3RAC7867
C28, C30, C34	3	Capacitor	100 pF, 25 V, 5%, 0402, COG/NPO	KEMET	C0402C101J3GAC7867
C29, C31	2	Capacitor	1 $\mu$ F, 25 V, 10%, 0603, X5R	Samsung Electro- Mechanics	CL10A105KA8NNNC
C33, C325	2	Capacitor	0.1 $\mu$ F, 25 V, 10%, 0402, X5R	Samsung Electro- Mechanics	CL05A104KA5NNNC
C35	1	Capacitor	1 $\mu$ F, 100 V, 10%, 0805, X7S	TDK	C2012X7S2A105K125AB
C37, C38	2	Capacitor	4.7 $\mu$ F, 100 V, 10%, 1210, X7S	TDK	CGA6M3X7S2A475K200AB
C40	1	Capacitor	4.7 $\mu$ F, 25 V, 10%, 0805, X5R	Samsung Electro- Mechanics	CL21A475KAQNNNG
C43, C48, C327	3	Capacitor	10 $\mu$ F, 16 V, 10%, 0603, X5R	Murata Electronics	GRM188R61C106KAALD
C45	1	Capacitor	0.47 $\mu$ F, 100 V, 20%, 0805, X7S	TDK	C2012X7S2A474M125AE
C49, C328	2	Capacitor	0.22 $\mu$ F, 16 V, 10%, 0603, X7R	TDK	CL10B224KO8NNNC
C50	1	Capacitor	0.47 $\mu$ F, 25 V, 10%, 0603, X7R	Murata Electronics	GRM188R71E474KA12D
C51, C52	2	Capacitor	22 $\mu$ F, 16 V, 20%, 0805, X5R	Samsung Electro- Mechanics	CL21A226MOCLRNC
C56, C57, C58	3	Capacitor	0.01 $\mu$ F, 25 V, 10%, 0603, X5R	AVX	06033D103KAT2A
C68, C69, C329	3	Capacitor	2.2 $\mu$ F, 100 V, 10%, 1206, X7S	TDK	CGA5L3X7S2A225K160AB
C181	1	Capacitor	0.1 $\mu$ F, 100 V, 10%, 0603, X7R	Yageo	CC0603KRX7R0BB104

## Application note

## Bill of materials

C207, C208, C209	3	Capacitor	2.2 $\mu$ F, 50 V, 10%, 0603, X5R	Murata Electronics	GRM188R61H225KE11D
C301, C305, C306, C308, C309, C310, C311, C312, C318, C319	10	Capacitor	0.1 $\mu$ F, 25 V, 10%, 0402, X7R	Vishay Vitramon	VJ0402Y104KXXCW1BC
C302, C303	2	Capacitor	15 pF, 25 V, 5%, 0402, COG/NPO	Walsin Technology	0402N150J250CT
C304, C314	2	Capacitor	10000 pF, 25 V, 5%, 0402, X7R	KEMET	C0402C103J3RACAUTO
C307	1	Capacitor	4.7 $\mu$ F, 25 V, 20%, 0603, X5R	Taiyo Yuden	TMK107BBJ475MA-T
C313, C315	2	Capacitor	10 $\mu$ F, 25 V, 20%, 0603, X5R	Murata Electronics	GRM188R61E106MA73J
C316, C317	2	Capacitor	1 $\mu$ F, 6.3 V, 10%, 0402, X5R	Taiyo Yuden	JMK105BJ105KV-F
C322, C323, C324	3	Capacitor	2200 pF, 50 V, 10%, 0402, X5R	TDK	C1005X5R1H222K050BA
D1	1	Diode	Schottky, 100 V, 2A, SMA	STMicroelectronics	STPS2H100AY
D4, D5, D8, D316, D317, D318, D319	7	Diode	Zener, 5.1 V, 500 mW, SOD523	On-Semi	MM5Z5V1T1G
D14	1	Diode	TVS, 22 V, 35.5 V, SMA	Diodes Incorporated	SMAJ22A-FDICT-ND
D301	1	Diode	Schottky, 30 V, 1 A, SOD323	Infineon	BAS3010A-03W
D302	1	Diode	TVS DIODE 5.3VWM 15VC TSFP-3	Infineon	ESD5V3U2U03FH6327XTS A1
D315	1	Diode	Schottky, 500 mA, 30 V, TSLP-2-17	Infineon	BAS3005S-02LRH
F1	1	Fuse	10 A, 32 VAC, 63 VDC, 1206	Littelfuse Inc.	0458010.DR
IC301	1	IC	MCU, 32BIT, 256 KB FLASH, 48VQFN	Infineon	XMC4200Q48K256BAXUM A1
IC302	1	IC	Regulator, linear, 3.3 V, 300 mA, TSON- 10	Infineon	TLS205B0LDV33XUMA1
IC303	1	IC	DGTL ISO 2500VRMS 6CH GP 16SOIC	Silicon Labs	634-SI8662BB-B-IS1
IC304	1	IC	Buffer, 5.5 V, 5TSSOP	Nexperia	74LVC1G126GW,125
J1, J2, J3, J4, J5	5	Connector	Not fitted	Keystone Electronics	476-4

## Application note

## Bill of materials

J6	1	Connector	Jack 2.10 mm ID (0.083"), 5.50 mm OD (0.217") Through Hole, Right Angle	Tensility International Corp	54-00129
J7	1	Connector	Header, 8pos, 1.27v mm	Sullins Connector Solutions	GRPB042VWVN-RC
JP301	1	Connector	Not fitted	Molex	22032051
L2	1	Inductor	22 µH, 1A, 4020	Würth Elektronik	74437324220
L301	1	Inductor	Ferrite Bead, 60 Ω, 500 mA, 0603	Würth Elektronik	74279267
LED1, LED2	2	LED	BLUE, 2.85 V, 0603	OSRAM	LB Q39G-L200-35-1
LED3, LED301	2	LED	GREEN, 2.2 V, 0603	Rohm Semiconductor	SML-D12M8WT86
LED4, LED302, LED303	3	LED	RED, 2 V, 0603	Lite-On Inc.	LTST-C190KRKT
POT4	1	Potentiometer	Trimmer, 10 k, 0.5 W	Bourns Inc.	3362P-1-103TLF
Q1, Q2, Q3, Q4, Q5, Q6	6	MOSFET	N-Channel, 40 V, 31 A, 1.35 mΩ PG-TSON-8-4	INFINEON	IQE013N04LM6
Q301	1	Crystal	12 MHz, 8 pF, 200 Ω, 2-SMD	Kyocera International Inc.	CX3225GA12000D0PTVCC
R1, R8, R326, R327, R328, R329	6	Resistor	Not fitted	Yageo	AC0805FR-071RL
R35, R38, R40	3	Resistor	470, 0.0625 W, 1%, 0402	Yageo	RC0402FR-07470RL
R36	1	Resistor	75 k, 0.1 W, 1%, 0603	Panasonic	ERJ-3EKF7502V
R37	1	Resistor	100 k, 0.1 W, 1%, 0603	Yageo	RC0603FR-07100KL
R39	1	Resistor	7.87 k, 0.1 W, 1%, 0603	Yageo	RC0603FR-077K87L
R41	1	Resistor	22 k, 0.1 W, 1%, 0603	Stackpole Electronics Inc	RMCF0603FG22K0
R42	1	Resistor	200, 0.1 W, 1%, 0603	Panasonic	ERJ-3EKF2000V
R43	1	Resistor	100, 0.0625 W, 1%, 0402	Yageo	RC0402FR-07100RL
R45, R47, R54, R55, R325	5	Resistor	5.1 k, 0.1 W, 5%, 0402	Panasonic	ERJ-2GEJ512X
R50	1	Resistor	0.1, 0.2 W, 1%, 0603	Yageo	PT0603FR-7W0R1L
R56, R324	2	Resistor	10 k, 0.1 W, 1%, 0402	KOA Speer Electronics, Inc.	RK73H1ETTP1002F

## Application note

## Bill of materials

R57, R309, R311, R312	4	Resistor	10 k, 0.0625 W, 5%, 0402	Yageo	RC0402JR-0710KL
R61, R62, R63	3	Resistor	2.2 k, 0.1 W, 1%, 0603	Yageo	RC0603FR-072K2L
R64	1	Resistor	1 k, 0.1 W, 0603, 5%	Yageo	RT0603DRD071KL
R65, R66, R67	3	Resistor	3.3 k, 0.1 W, 1%, 0603	Yageo	RT0603FRE073K3L
R76, R91, R104	3	Resistor	47 k, 0.1 W, 1%, 0603	Yageo	RC0603FR-0747KL
R81, R95, R109	3	Resistor	1.65 k, 0.1 W, 1%, 0603	Panasonic	ERJ-3EKF1651V
R301, R302	2	Resistor	680, 0.0625 W, 1%, 0402	Vishay Dale	CRCW0402680RFKEDC
R305	1	Resistor	510, 0.1 W, 1%, 0402	Panasonic	ERJ-U02F5100X
R306, R307	2	Resistor	22, 0.1 W, 5%, 0402	Panasonic	ERJ-2GEJ220X
R308	1	Resistor	4.7 k, 0.1 W, 1%, 0402	Panasonic	ERJ-2RKF4701X
R310, R314	2	Resistor	1 M, 0.0625 W, 1%, 0402	Yageo	RC0402FR-071ML
R316	1	Resistor	0 $\Omega$ , JUMPER, 0603	KOA Speer Electronics	RK73Z1JTDD
R318	1	Resistor	32.4 k, 0.0625 W, 1%, 0402	Bourns Inc.	CR0402-FX-3242GLFCT-ND
R319	1	Resistor	3.3 k, 0.0625 W, 5%, 0402	Yageo	RC0402JR-073K3L
R321, R322, R323	3	Resistor	0, 0.1 W, 0402	Panasonic	ERJ-2GE0R00X
RS1, RS2, RS3	3	Resistor	10 m $\Omega$ , 5 W, 1%, 2512	KOA Speer Electronics, Inc.	TLRH3APTTE10LOF
RT1	1	IC	Sensor, - 40 to 150°C, SOT23-3	Microchip Technology	MCP9700T-E/TT
ST1, ST2, ST3, ST4	4	Standoff	Hex, #4-40, Aluminum, 1/4"	Keystone Electronics	8714
SW1	1	Switch	Slide, SPDT, 200 mA, 30 V	E-Switch	EG1218
SW2, SW3	2	Switch	Slide, SPST, 0.4 VA, 28 V	NKK Switches	AS11CP
U1	1	IC	Gate driver, 3-Phase, Motor drive, PG-VQFN-64-8	Infineon	IMD701AQ064X128AAXU MA1
X2, X3, X4	3	Connector	Header, vertical, 4x1, through hole, 0.025, SQ, 100mil, SP	Molex	22284045

**Application note****Bill of materials**

X6	1	Connector	5-pin, side entry, 2.54 mm	PHOENIX CONTACT	1725685
X302C	1	Connector	USB-mini	Würth Elektronik	629105150921
NT1, NT2, NT3, NT4	4	Fastner	Nut, 0.250 4-40 Steel Hex	Keystone Electronics	9600

## **8 Motor specifications**

The motor used for obtaining the results presented here is a CMP1152X1E-202412 BLDC motor with three Hall sensors positioned at 120-degree relative angles (not used with sensorless FOC driver), manufactured by Parker Hannifin Corp. The specifications are as follows:

- Rated voltage: 18 to 36 V DC
- Maximum RMS continuous phase current: 59.9 A
- Maximum rated power: 1.4 kW at 18 V DC, 1.6 kW at 36 V DC
- Maximum rated speed: 2682 RPM at 18 V DC, 4068 RPM at 36 V DC
- Inertia: 2712 g.cm<sup>2</sup>, 6436 lb-ft<sup>2</sup>
- Stall torque: 5.71 Nm, 50.5 inch-lb
- KE: 5.79 V/kRPM
- Insulation class: H (180°C)

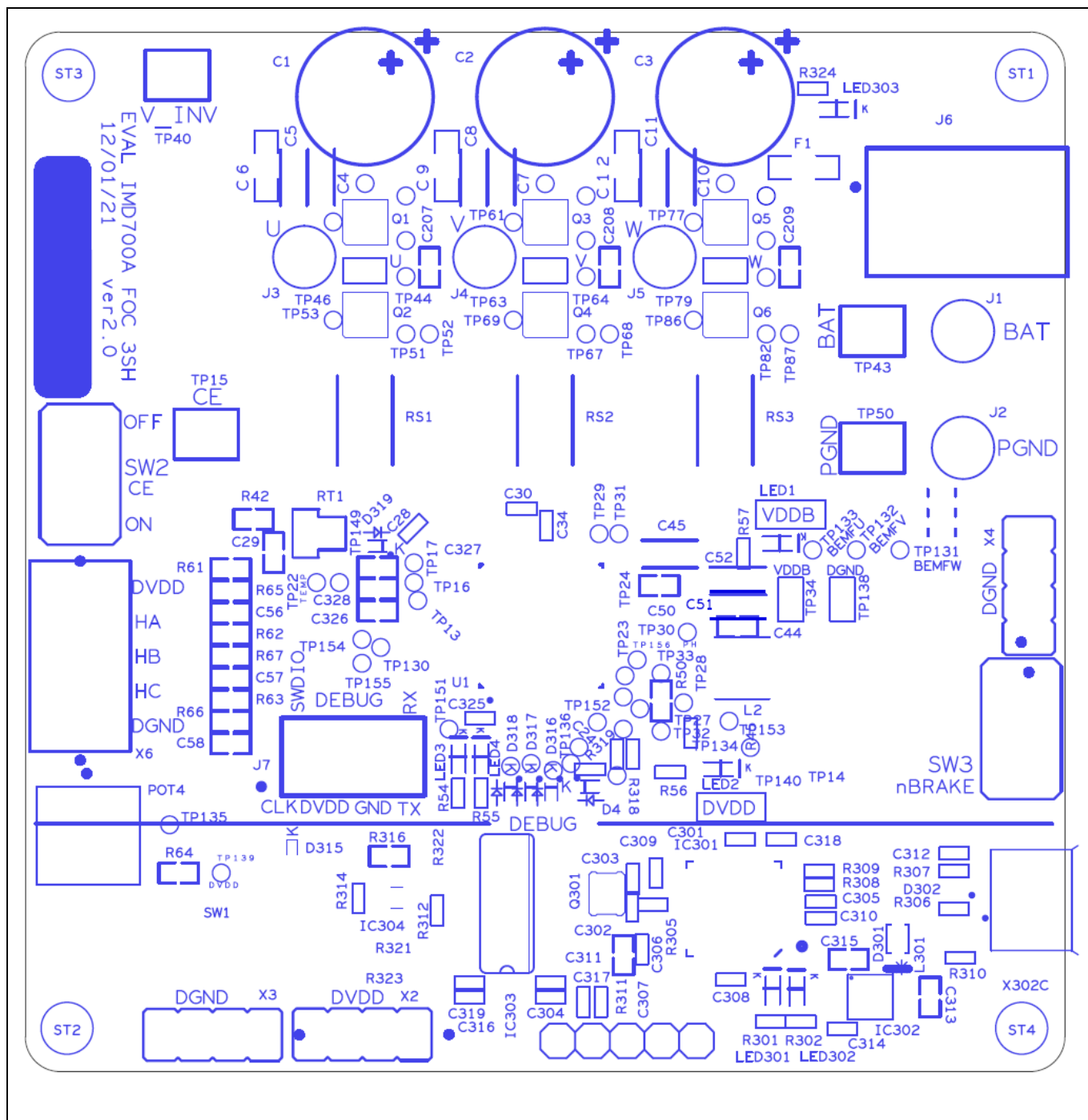


## Application note

## PCB layout

## 9 PCB layout

The EVAL\_IMD700A\_FOC\_3SH evaluation board utilizes a six-layer PCB with 2 oz. copper on the top and bottom layers and 1 oz. copper on the internal layers. Components are mounted on the top and bottom sides. The width is 3.0 inches/76.2 mm and the length is 3.0 inches/76.2 mm.



**Figure 56** EVAL\_IMD700A\_FOC\_3SH PCB top silkscreen

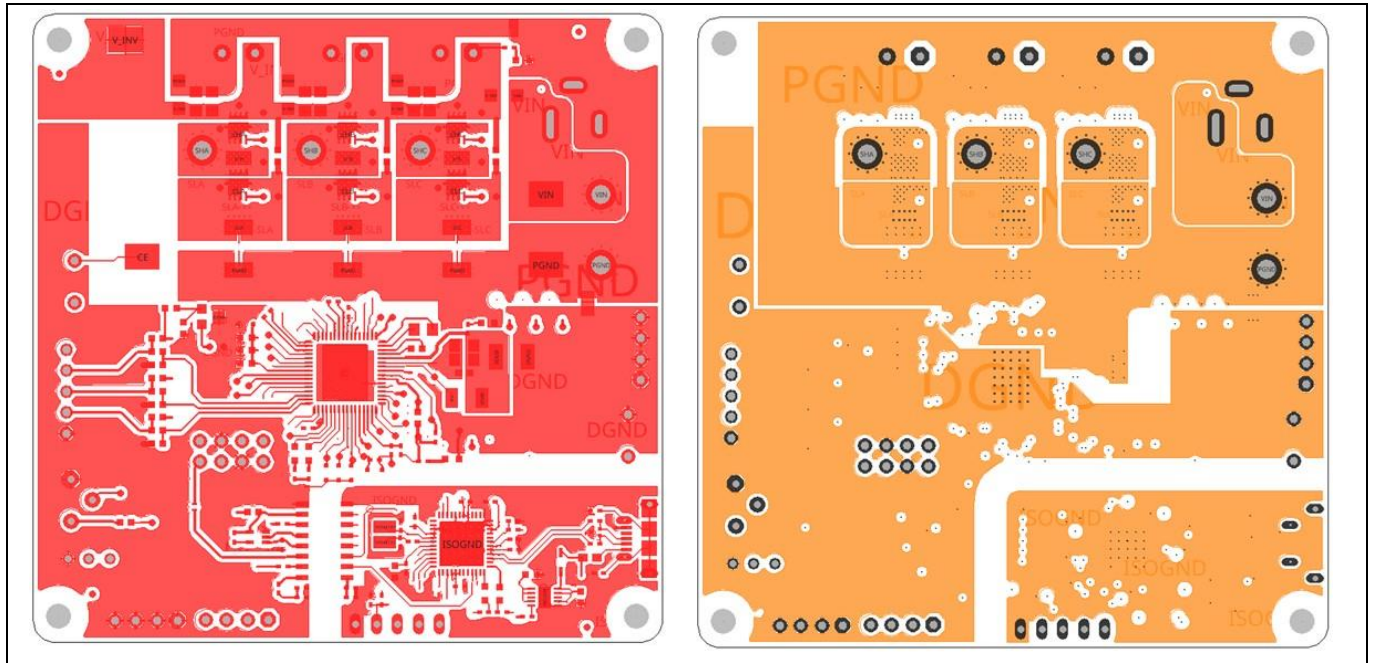


Figure 57 EVAL\_IMD700A\_FOC\_3SH PCB top layer (left) and inner layer 1 (right)

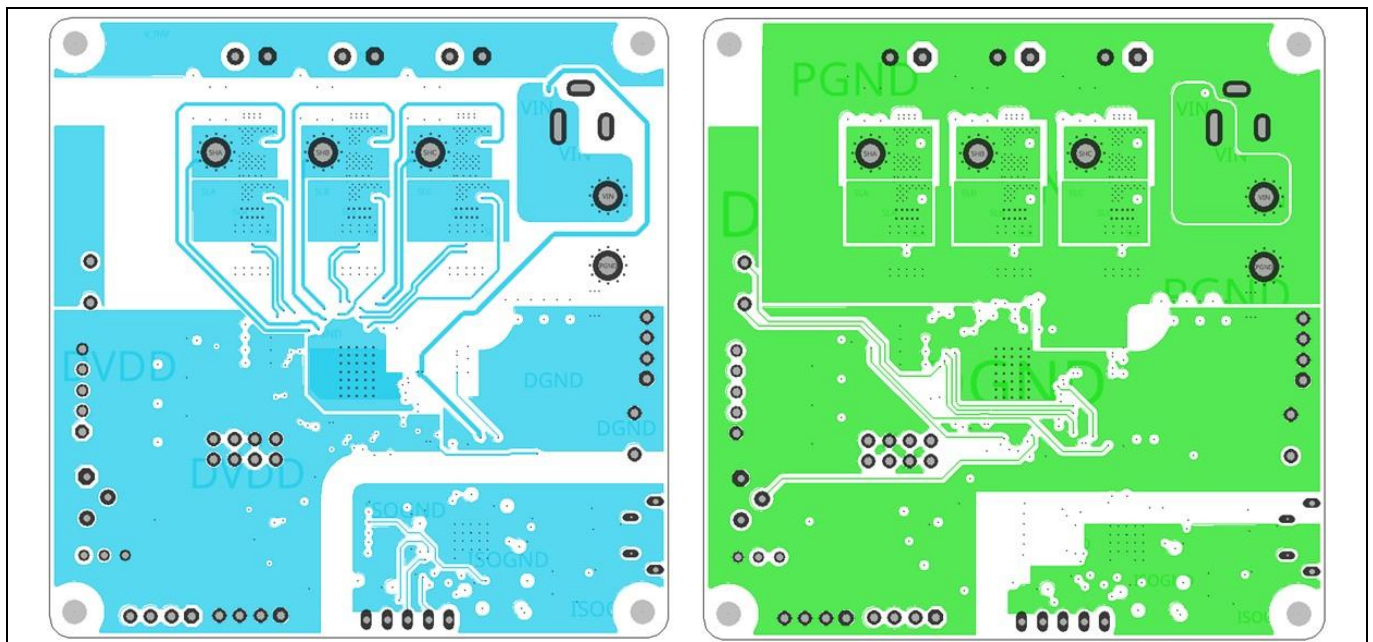


Figure 58 EVAL\_IMD700A\_FOC\_3SH PCB internal layers 2 (left) and 3 (right) GND

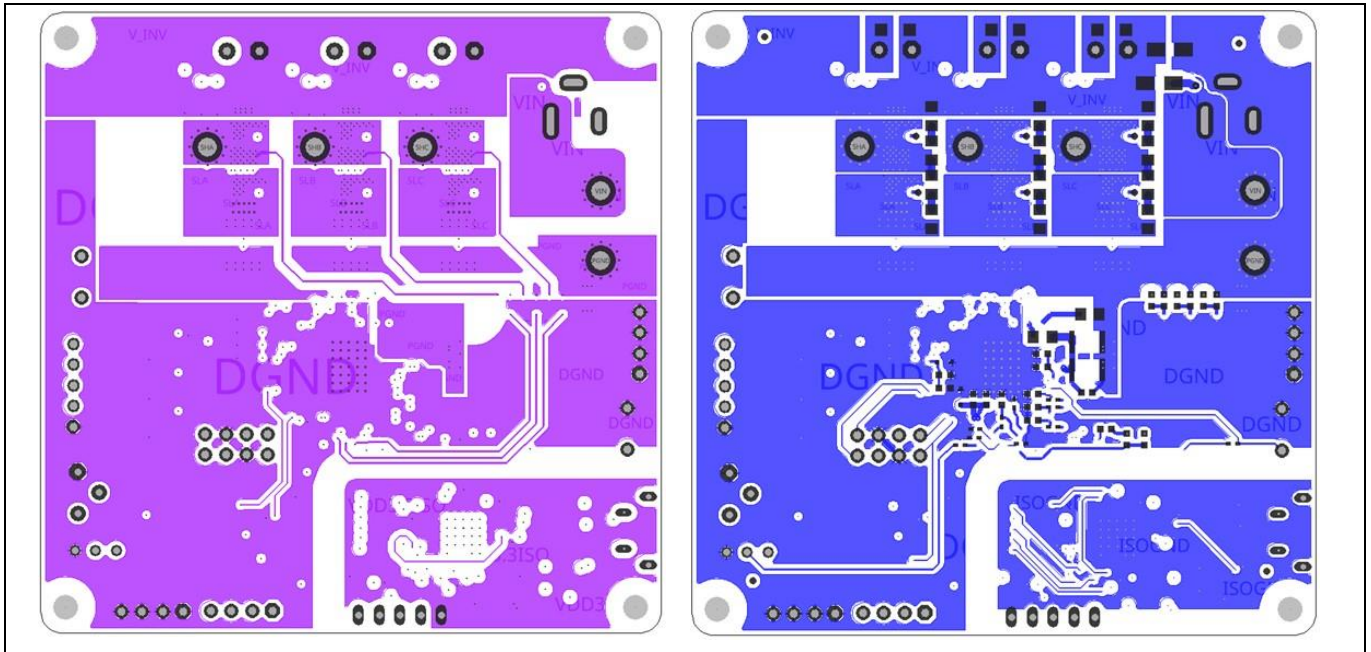
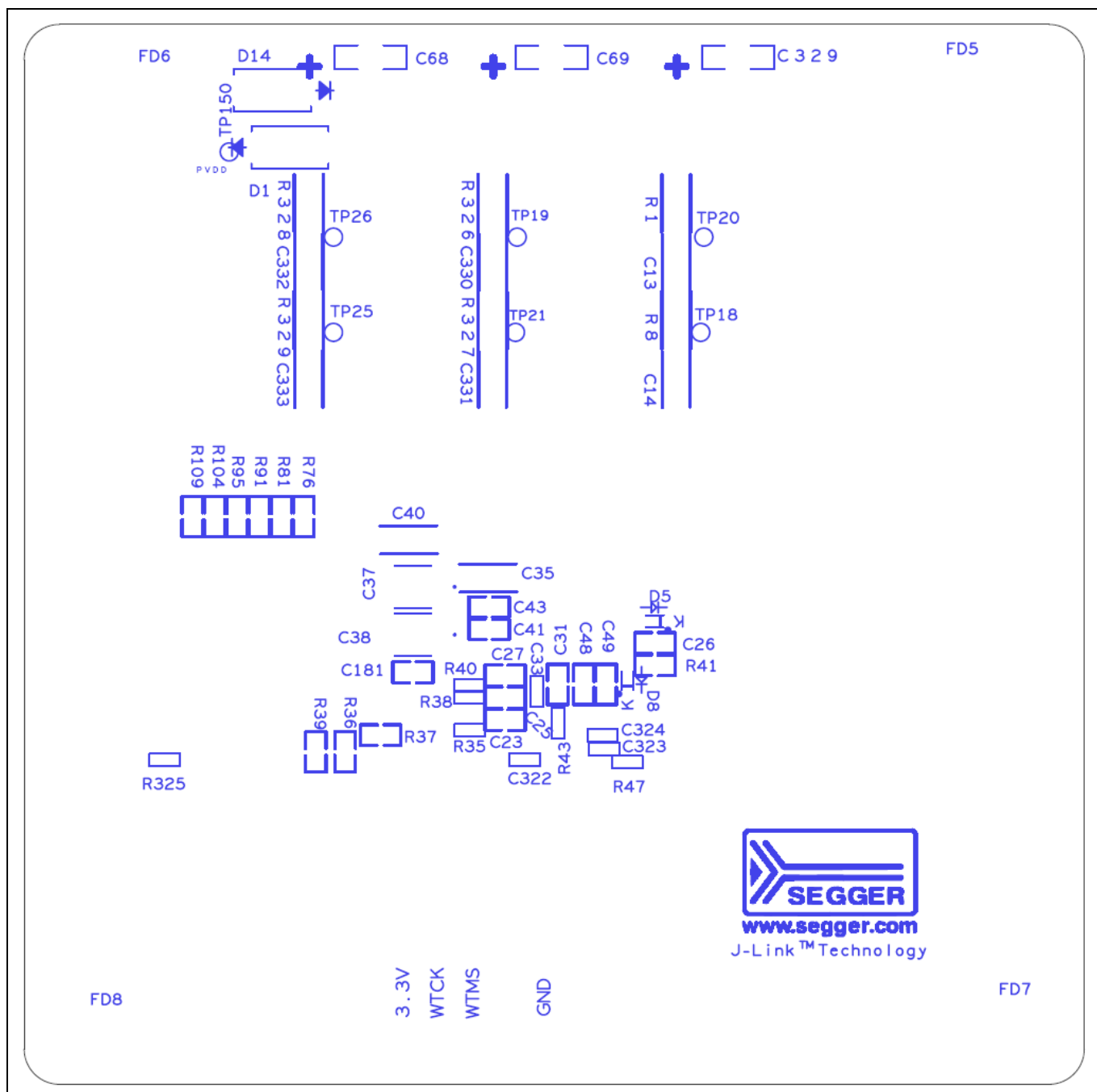
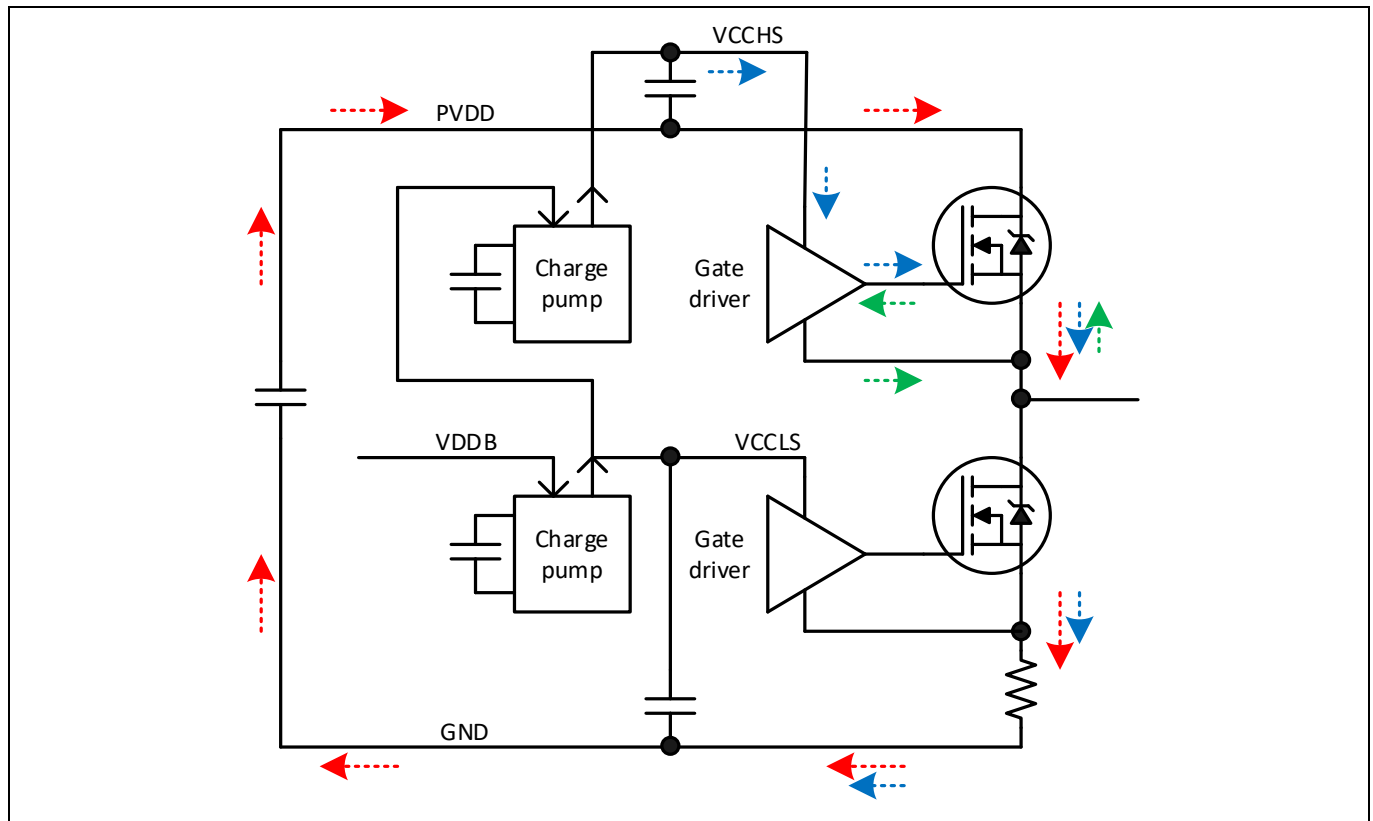


Figure 59 EVAL\_IMD700A\_FOC\_3SH PCB internal layers 4 (left) bottom (right)



**Figure 60** EVAL IMD700A FOC 3SH PCB bottom silkscreen

The PCB layout is optimized to minimize radiated EMI. This is done by keeping the loops carrying the switching currents as small as possible. The HF switching current loops are illustrated in the figure below. It should be noted that during the switching transition, the high-side gate drive loop current returns to the main ground rather than back to the gate driver as in a conventional high-side driver. Because this is the case, the high-side gate drive loop should also be kept as tight as possible. The top layer connects the DC bus to the top-side MOSFET drains, and the first internal layer returns the MOSFET current via the CS shunt. The switching loop for each phase begins and ends at the electrolytic capacitor and HF decoupling capacitors. The return traces on the first internal layer pass underneath the power traces, thus creating very tight HF switching loops.

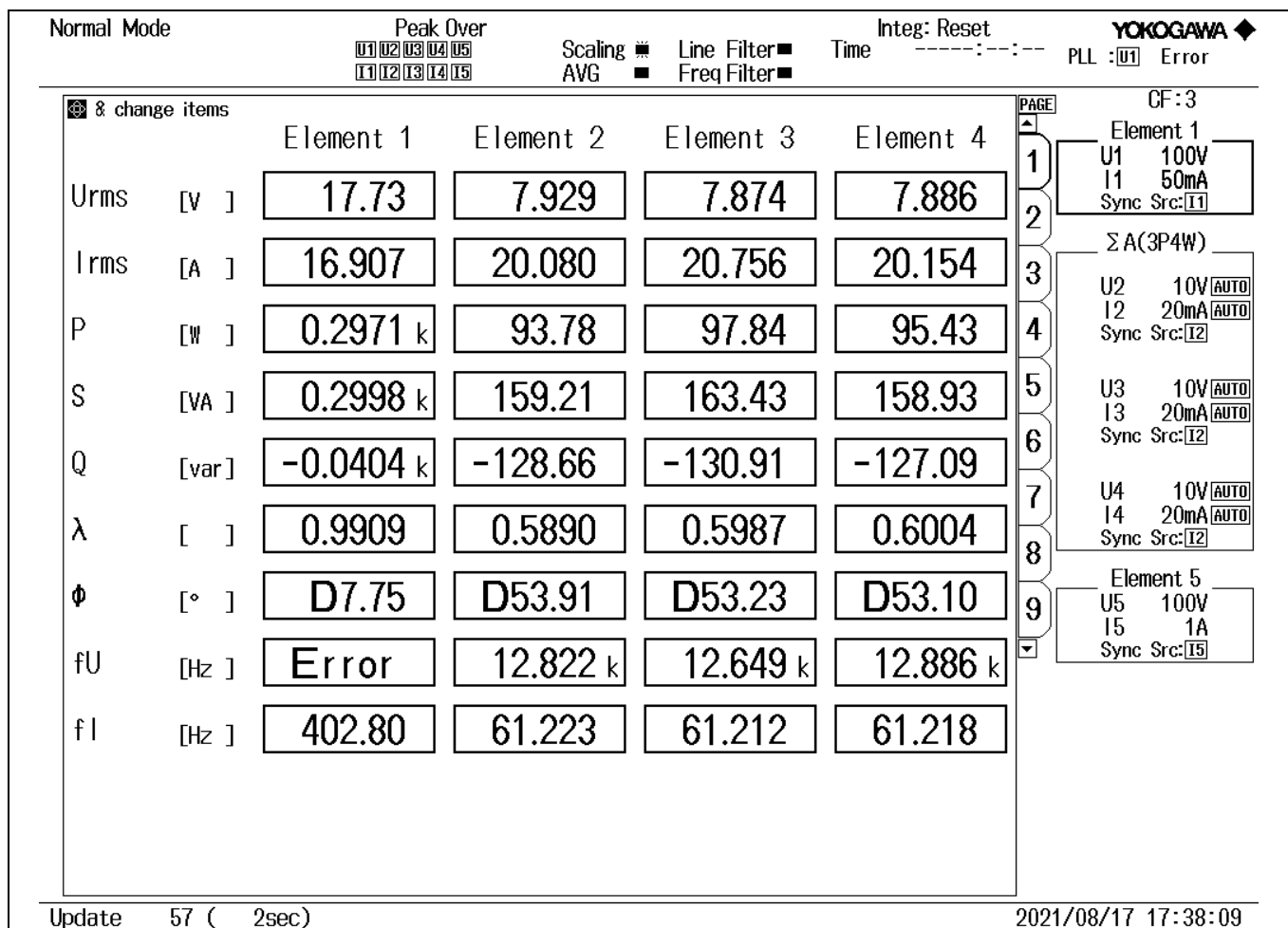


**Figure 61** HF current loop for one phase.

Red: main HF switching loop; blue: high-side gate drive switch-on current loop;  
Green: high-side gate drive switch-off current loop.

## 10 Test results

### 10.1 Power measurements



**Figure 62 Input and output measurements at nominal input voltage 18 V and 300 W input power**

In the above results<sup>1</sup>, element 3 represents the DC input to the inverter. Elements 4, 5, and 6 are connected to the output phases U, V, and W respectively.

The total output power is equal to 93.78 W + 97.84 W + 95.43 W = 287.05 W for an input power of 297.1 W.

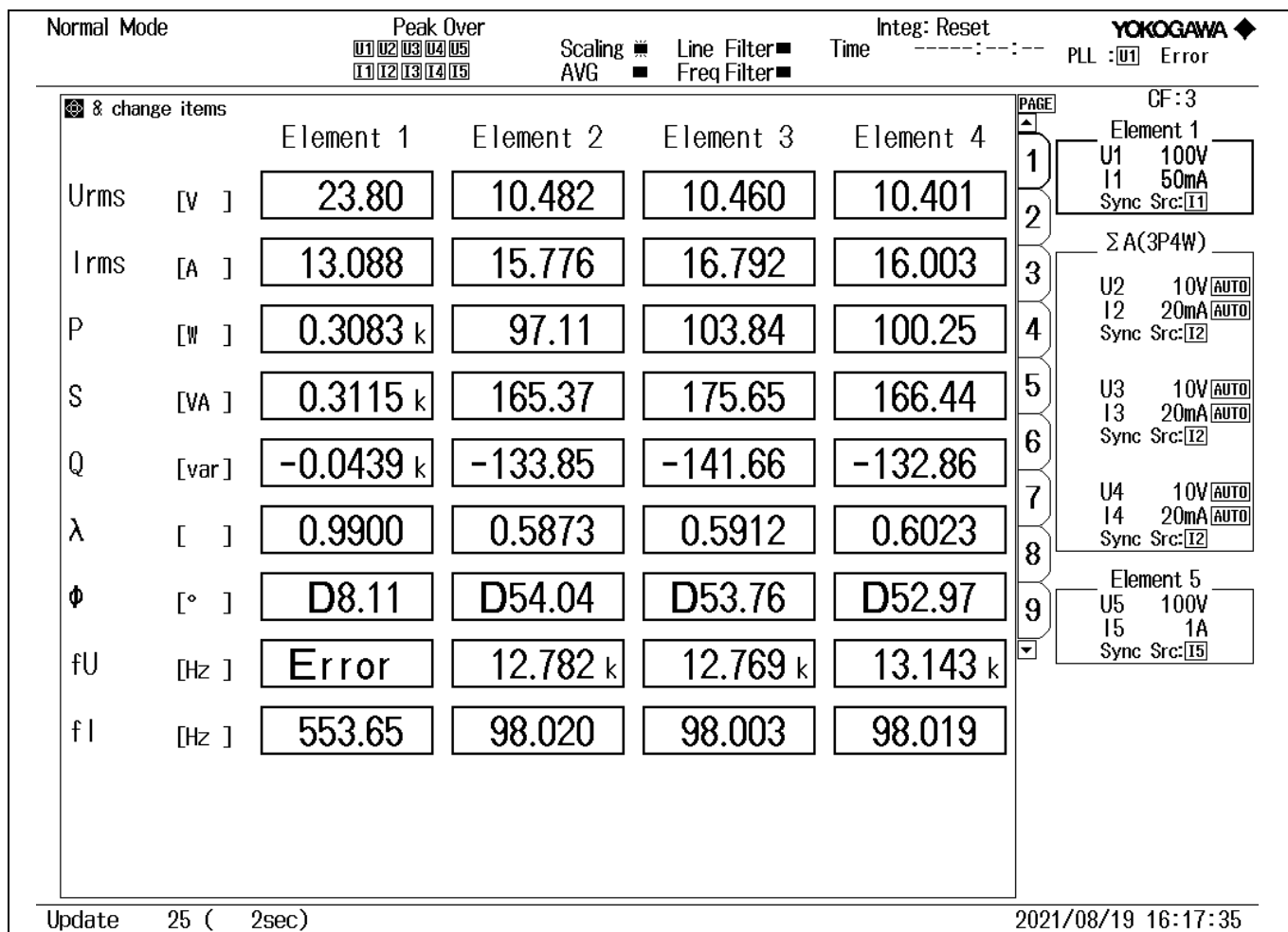
This gives an efficiency of  $287.05/297.1 = 96.6$  percent with losses of 10.05 W.

<sup>1</sup> The shunt values RS1, RS2, and RS3 were changed to 3 mΩ during this test to minimize power losses.



## Application note

## Test results



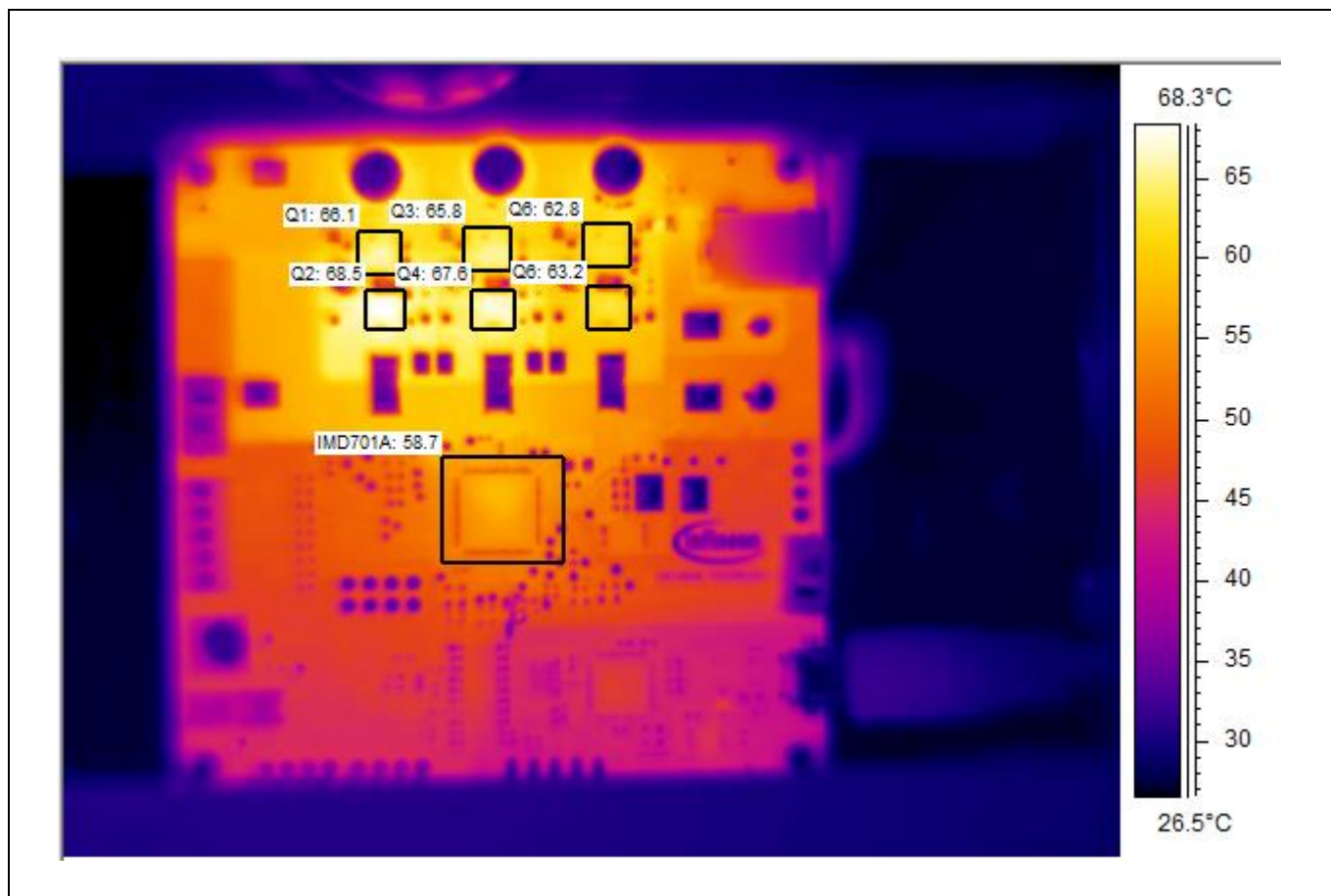
**Figure 63** Input and output measurements at nominal input voltage 24 V and 300 W input power

The total output power is equal to  $97.11 \text{ W} + 103.84 \text{ W} + 100.25 \text{ W} = 301.2 \text{ W}$  for an input power of 308.3 W.

This gives an efficiency of  $301.2/308.3 = 97.7$  percent with losses of 7.1 W.

## 10.2 Thermal measurements

Thermal images were taken after 15 minutes of operation to allow the component temperatures to rise and reach steady-state. No heatsinking or forced air-cooling was used.



**Figure 64 Thermal measurement summary at 18 V input and 300 W load**

Analysis	Position	$\epsilon_T$	Obj. Par	Image	Text comment				
Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev	Result	Expression	
Image		26.4	68.5	42.1					
Q1		54.3	66.1	11.8	63.5	2.0			
IMD701A		35.7	58.7	23.0	53.8	3.1			
Q2		49.3	68.5	19.2	65.1	4.2			
Q3		54.0	65.8	11.7	63.7	1.7			
Q4		52.3	67.6	15.3	64.9	2.8			
Q6		49.4	62.8	13.4	61.1	2.0			
Q6		43.6	63.2	19.6	59.8	4.4			

**Figure 65 Thermal measurement summary at 18 V input and 300 W load**

With the maximum rated phase current of 20 A<sub>RMS</sub> the highest MOSFET temperature rise is 43.5°C considering an ambient temperature of 25°C.

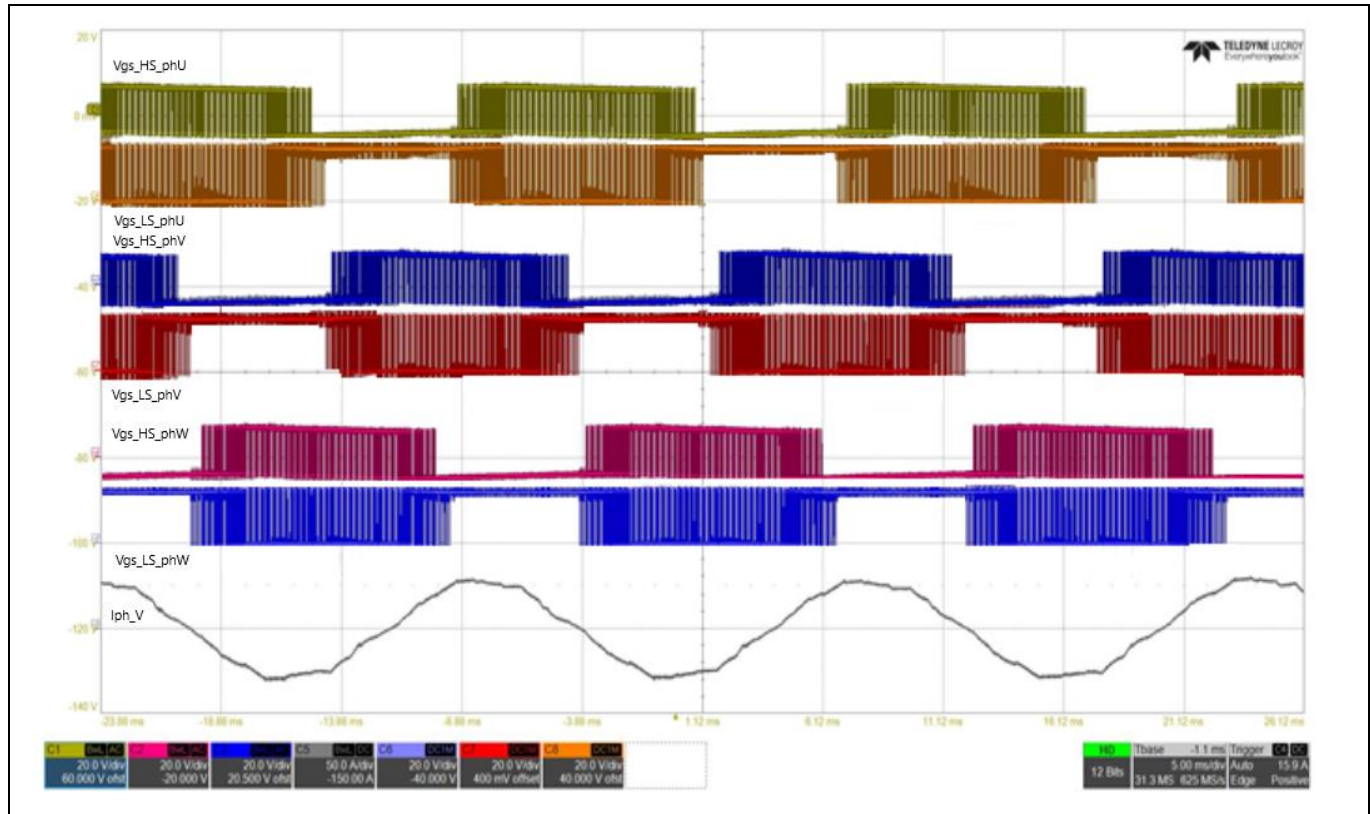


## Application note

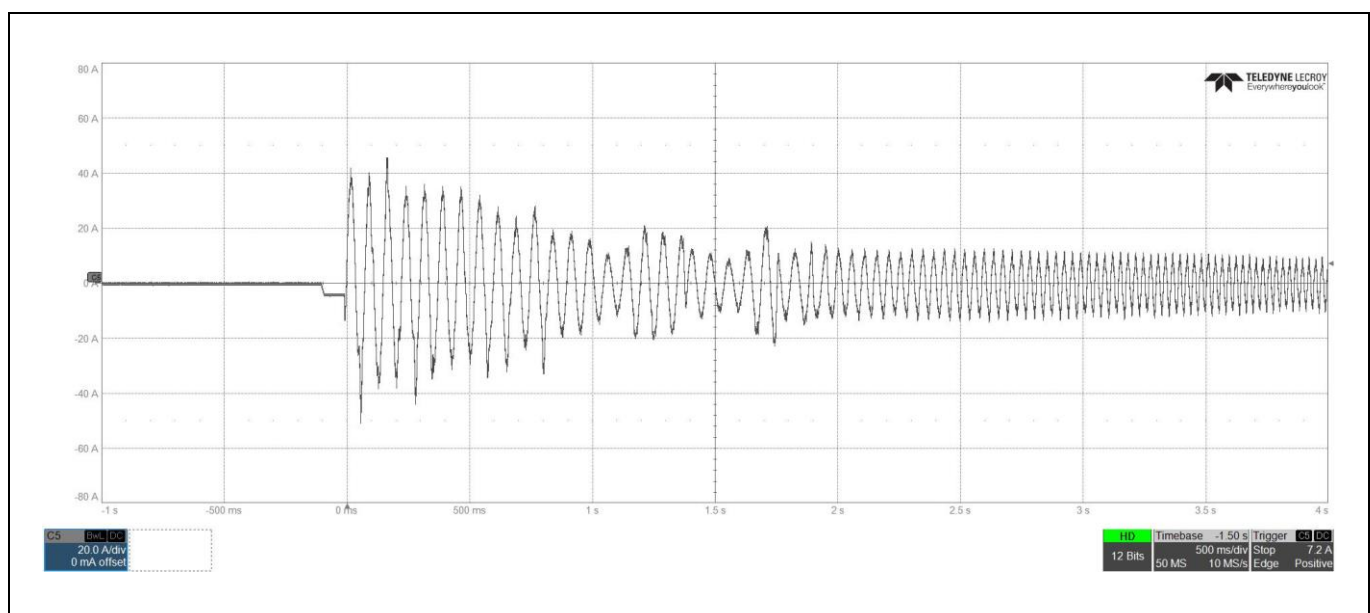
## Test results

## 10.3 Operating waveforms

The following waveforms were captured with the EVAL\_IMD700A\_FOC\_3SH board driving a motor at 1400 RPM with an output power of 300 W at 18 V and 24 V inputs.



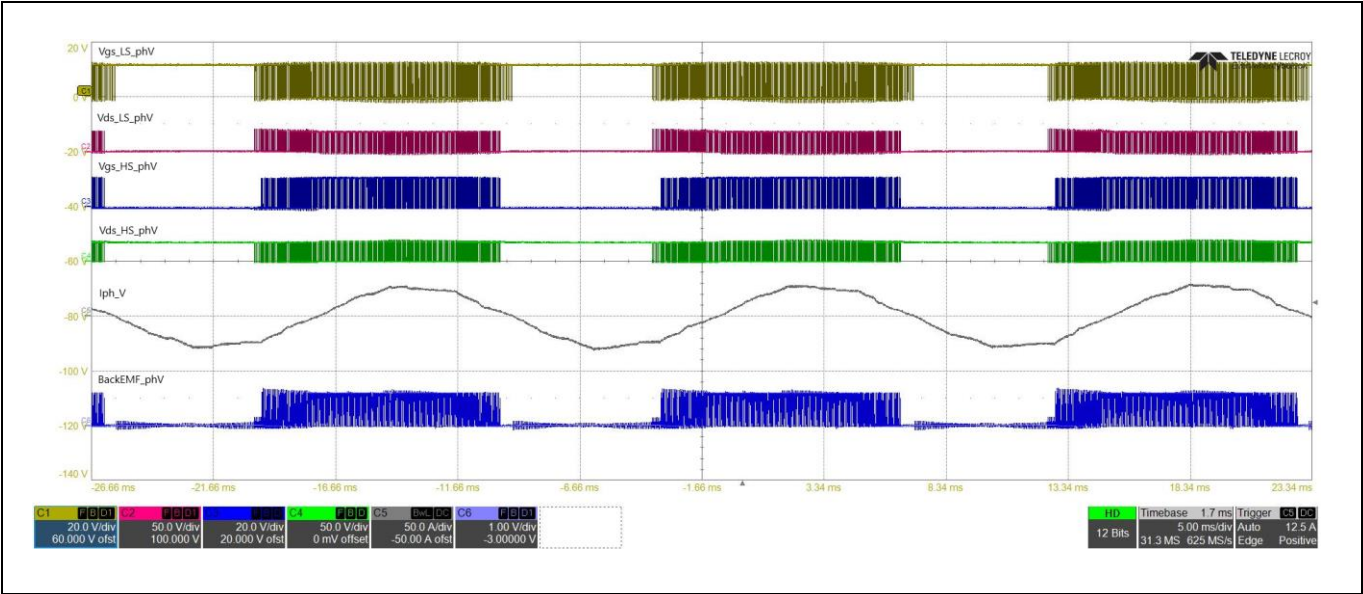
**Figure 66** High- and low-side gate drive pulses, 18 V input (5 ms/div)  
 $V_{GS\_HS\_phU}$  (yellow),  $V_{GS\_LS\_phU}$  (orange),  $V_{GS\_HS\_phV}$  (blue),  $V_{GS\_LS\_phV}$  (red),  $V_{GS\_HS\_phW}$  (pink),  
 $V_{GS\_LS\_phW}$  (purple),  $I_{PHASE\_phV}$  (gray)



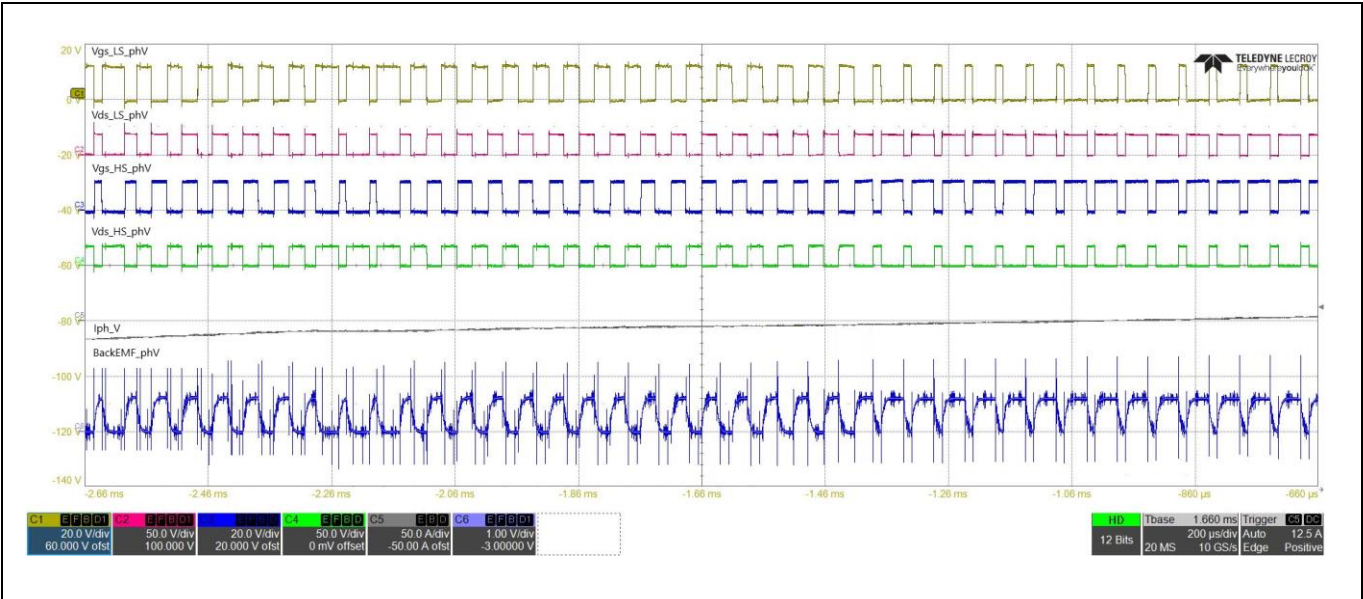
**Figure 67** Phase "V" start current, 18 V input (500 ms/div)  
 $I_{PHASE}$  (gray)

Application note

Test results



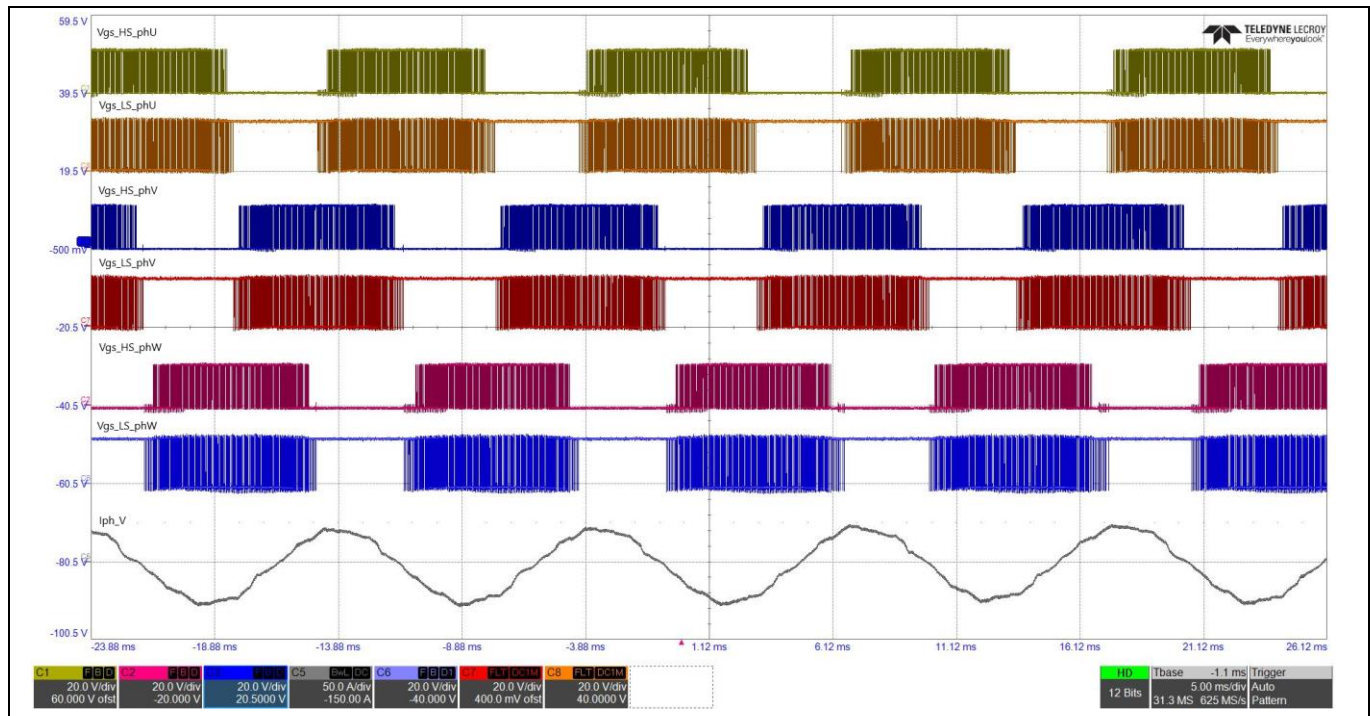
**Figure 68** Phase "V" waveforms, 18 V input (5 ms/div)  
V<sub>GS\_LS</sub> (yellow), V<sub>DS\_LS</sub> (red), V<sub>GS\_HS</sub> (blue) V<sub>DS\_HS</sub> (green), I<sub>PHASE</sub> (gray), BEMF (blue)



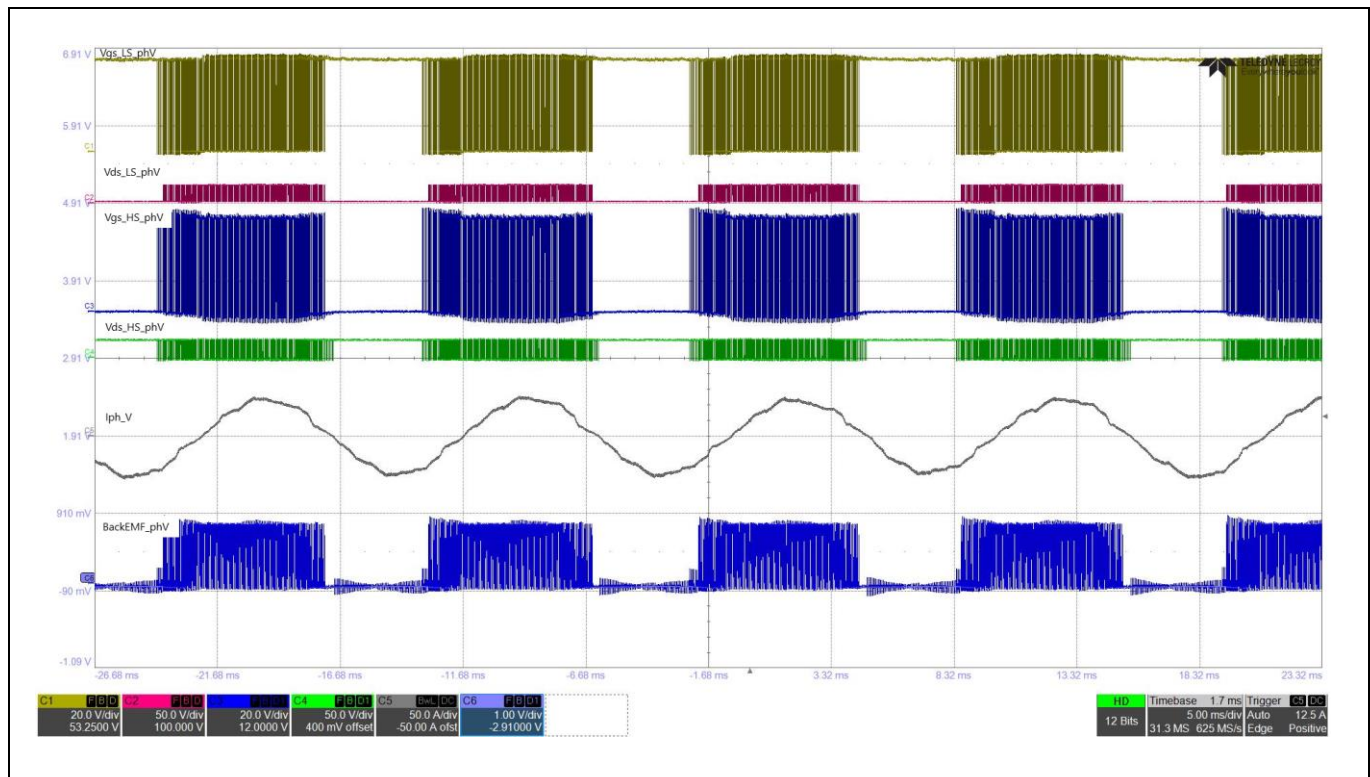
**Figure 69** Phase "V" waveforms, 18 V input (200 μs/div)  
V<sub>GS\_LS</sub> (yellow), V<sub>DS\_LS</sub> (red), V<sub>GS\_HS</sub> (blue) V<sub>DS\_HS</sub> (green), I<sub>PHASE</sub> (gray), BEMF (blue)

## Application note

## Test results



**Figure 70** High- and low-side gate drive pulses, 24 V input (5 ms/div)  
V<sub>GS\_HS\_phU</sub> (yellow), V<sub>GS\_LS\_phU</sub> (orange), V<sub>GS\_HS\_phV</sub> (blue) V<sub>GS\_LS\_phV</sub> (red), V<sub>GS\_HS\_phW</sub> (pink),  
V<sub>GS\_LS\_phW</sub> (purple), I<sub>PHASE\_phV</sub> (gray)

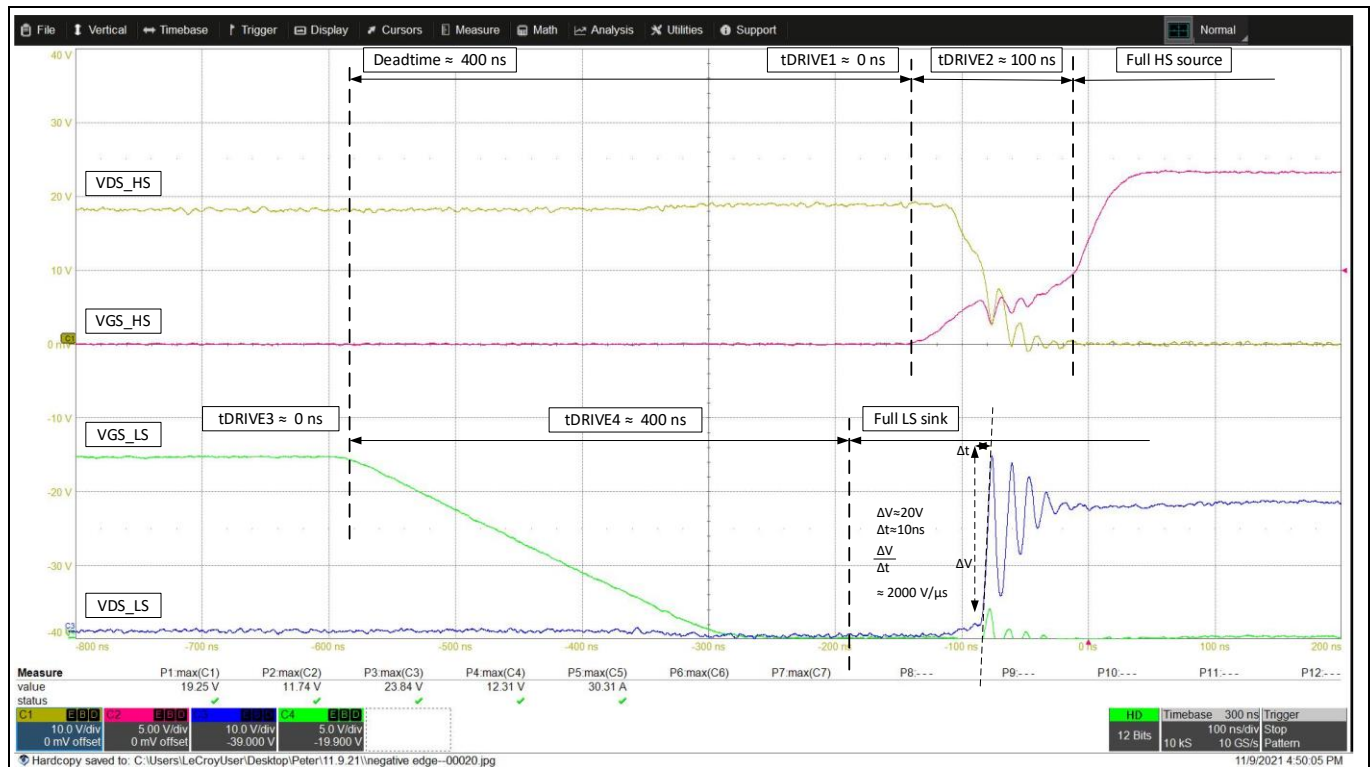


**Figure 71** Phase "V" waveforms, 24 V input (5 ms/div)  
V<sub>GS\_LS</sub> (yellow), V<sub>DS\_LS</sub> (red), V<sub>GS\_HS</sub> (blue) V<sub>DS\_HS</sub> (green), I<sub>PHASE</sub> (gray), BEMF (blue)



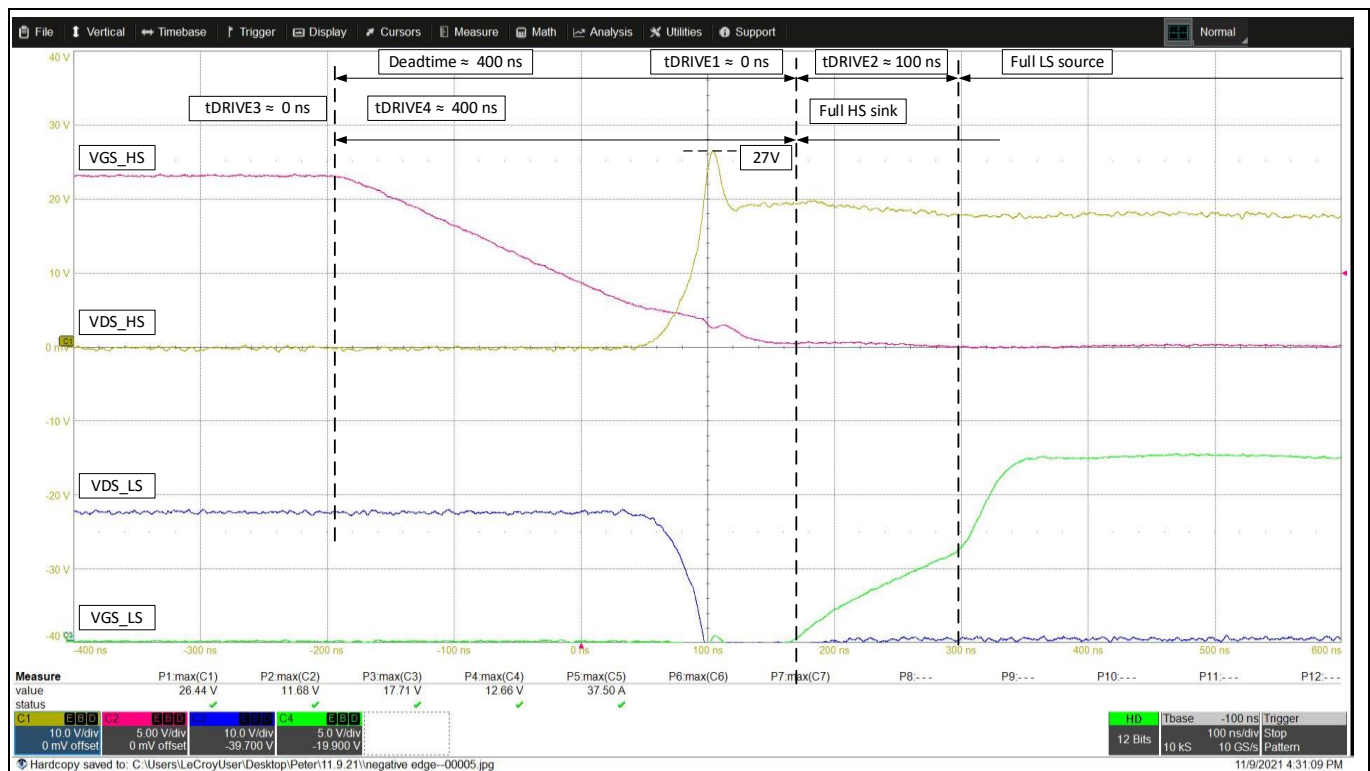
## Application note

## Test results



**Figure 72** Phase “V” node positive transition for 18 V input at 300 W (100 ns/div)

$V_{GS\_LS}$  (green),  $V_{DS\_LS}$  (blue),  $V_{GS\_HS}$  (red),  $V_{DS\_HS}$  (yellow)



**Figure 73** Phase “V” node negative transition for 18 V input at 300 W (100 ns/div)

$V_{GS\_LS}$  (green),  $V_{DS\_LS}$  (blue),  $V_{GS\_HS}$  (red),  $V_{DS\_HS}$  (yellow)

## Application note

## Test results

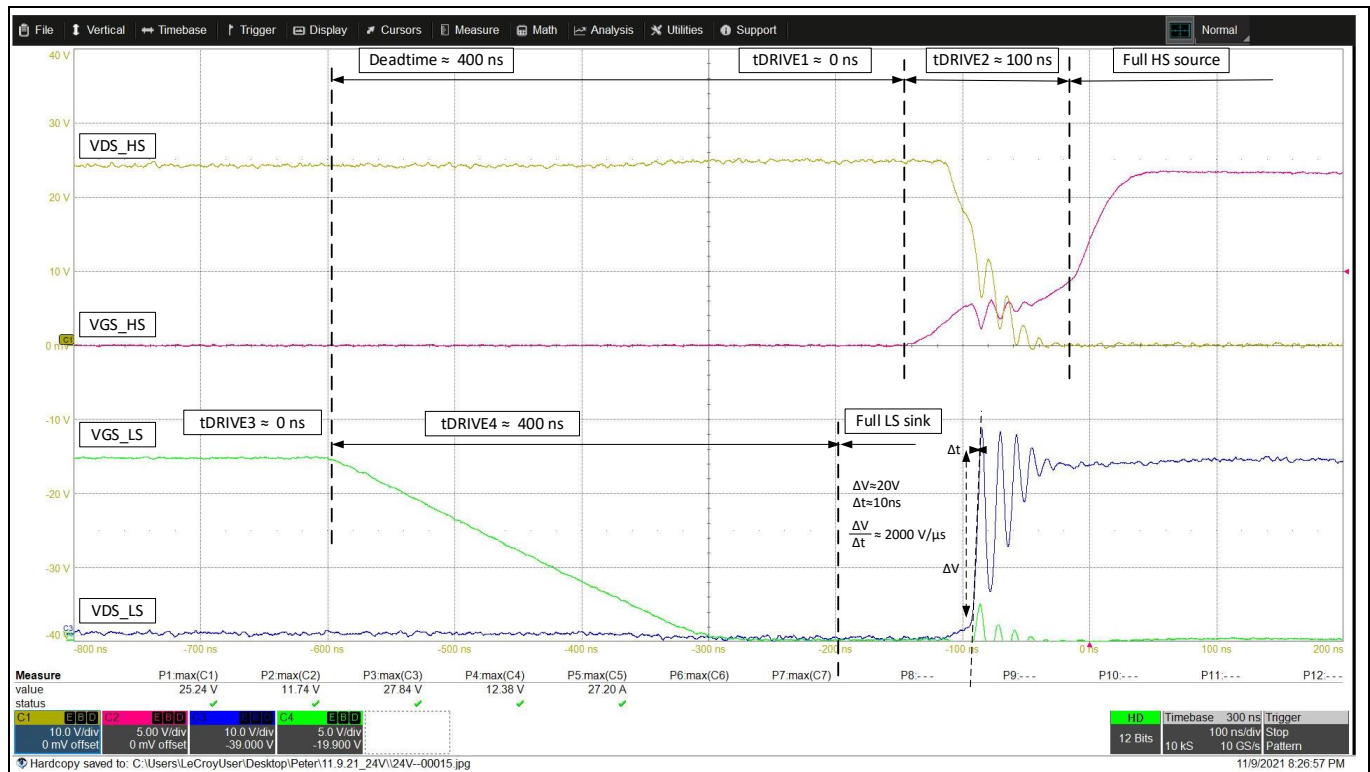


Figure 74 Phase "V" node positive transition for 24 V input at 300 W (100 ns/div)

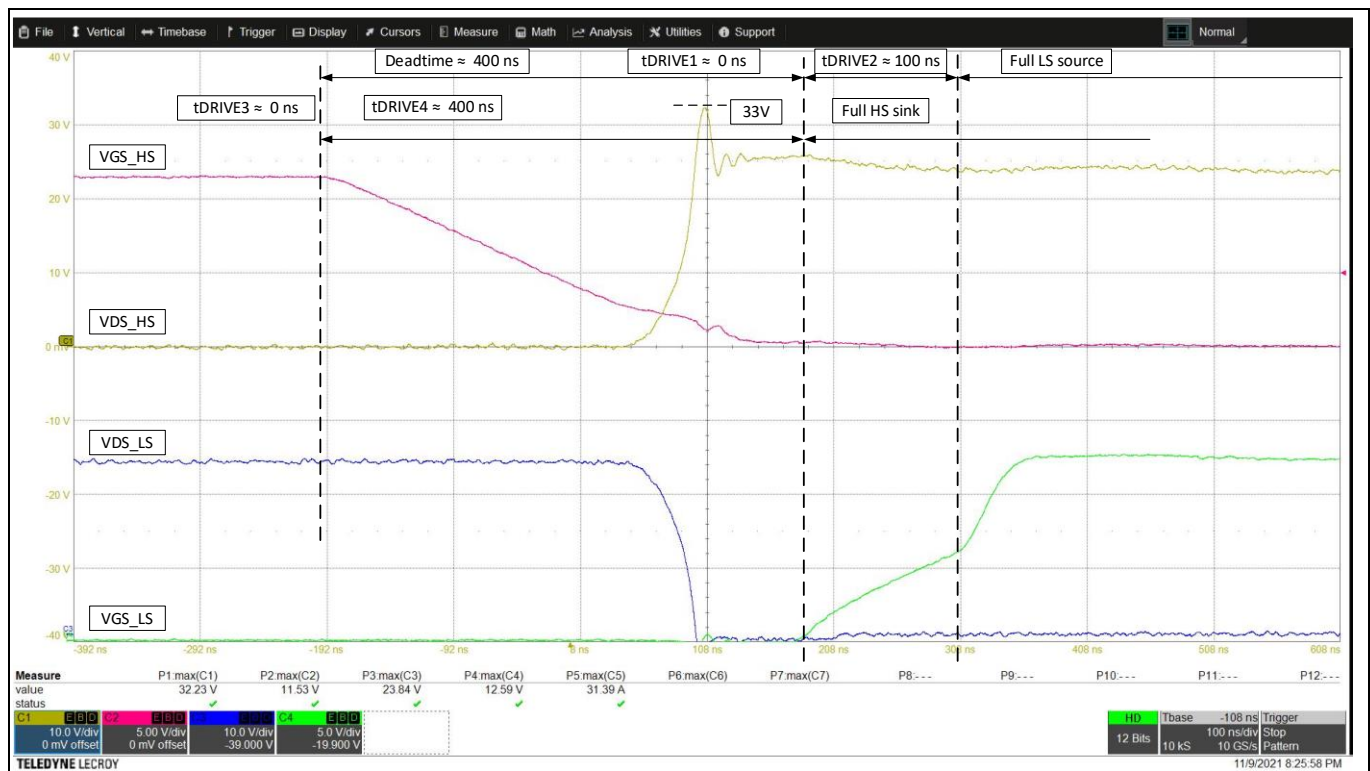
V<sub>GS\_LS</sub> (green), V<sub>DS\_LS</sub> (blue), V<sub>GS\_HS</sub> (red), V<sub>DS\_HS</sub> (yellow)

Figure 75 Phase "V" node negative transition for 24 V input at 300 W (100 ns/div)

V<sub>GS\_LS</sub> (green), V<sub>DS\_LS</sub> (blue), V<sub>GS\_HS</sub> (red), V<sub>DS\_HS</sub> (yellow)

## 11 Conclusion

The EVAL\_IMD700A\_FOC\_3SH evaluation board meets specifications, and the features and versatility of the MOTIX™ IMD700A are demonstrated. The principle of operation, design of the circuitry, control scheme, and PCB layout have all been discussed. The motor speed, direction and braking may be controlled locally with switches and a potentiometer located on the board, or may be controlled by the GUI tool. The extensive capabilities of the GUI tool have been explained. A simplified calculation method for the gate drive parameters for small MOSFETs with low gate charge has been shown and the results verified in the test waveforms. The ability to install customized firmware and configuration parameters to the system greatly simplifies the design process, eliminates unnecessary components and is thereby able to simplify product development and reduce time-to-market.

In addition, the FOC control algorithm has been described and the methods for entering the motor parameters and tuning the control loops using the motor control GIU have been explained.

Test results show that the EVAL\_IMD700A\_FOC\_3SH evaluation board operates with better than 95 percent efficiency when driving a 300 W load with a temperature rise of less than 45°C on the power device packages in the open air with convection cooling.

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**Revision history**

Document version	Date of release	Description of changes
V 1.0	2022-02-10	First release
V 1.1	2022-05-19	Updated Figure 8 to include op-amp filters
V 1.2	2023-04-26	Updated figures 9, 10, and 11 Updated BOM to current version Added clarification on shunt resistor values IC302 part number updated Corrections in section 4.1.1.3.4 and section 6

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