REF_IMD701A_720W_DC24 motor driver board for battery-powered applications

About this document

Scope and purpose

This document describes the functionalities of the REF_IMD701A_720W_DC24 motor driver board for battery-powered BLDC/PMSM motor drives with sensorless field-oriented control (FOC), used in applications such as cordless power tools up to 720 W. This reference 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™ IMD701A three-phase smart driver IC and OptiMOS™ 6 40 V power MOSFETs. IMD701A reduces the system component count and development time-to-market, while significantly increasing the power density, system performance, and peak power pulse capabilities. The MOTIX™ BPA Motor Control Workbench for configuring MOTIX™ IMD701A 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 who want to provide a high-performance system solution while reducing the system costs, application engineers, and students.

Infineon components featured

- OptiMOS™ 6 BSC007N04LS6 40 V/0.7 mΩ 5x6 MOSFET
- MOTIX™ IMD701A-Q064x128 integrated XMC1400 MCU and smart three-phase half-bridge gate driver

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Table 1 Safety precautions

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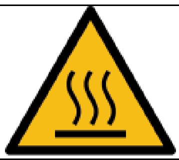	**Caution:** *The heat sink and device surfaces of the evaluation or reference board may become hot during testing. Hence, necessary precautions are required while handling the board. Failure to comply may cause injury.*
	**Caution:** *Only personnel familiar with the drive, power electronics and associated machinery should plan, install, commission and subsequently service the system. Failure to comply may result in personal injury and/or equipment damage.*
	**Caution:** *The evaluation or reference board contains parts and assemblies sensitive to electrostatic discharge (ESD). Electrostatic control precautions are required when installing, testing, servicing or repairing the assembly. Component damage may result if ESD control procedures are not followed. If you are not familiar with electrostatic control procedures, refer to the applicable ESD protection handbooks and guidelines.*

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1 Introduction

1.1 REF_IMD701A_720W_DC24 motor drive board

This user manual describes Infineon's REF_IMD701A_720W_DC24 motor drive reference board optimized for 18 V battery-powered tools operating with sensorless field-oriented control. The current design considers the electrical driving capabilities for BLDC/PMSM machines without requiring sensors to determine the rotor position and speed. This reference board (with an 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 implemented using the Infineon Eclipse-based IDE, ModusToolbox™ (a modern, extensible development ecosystem supporting a wide range of Infineon microcontroller devices). The control method implements a vector speed-control algorithm based on the BLDC/PMSM motor using pulse-width modulation (PWM) and three current shunts for phase current measurement.

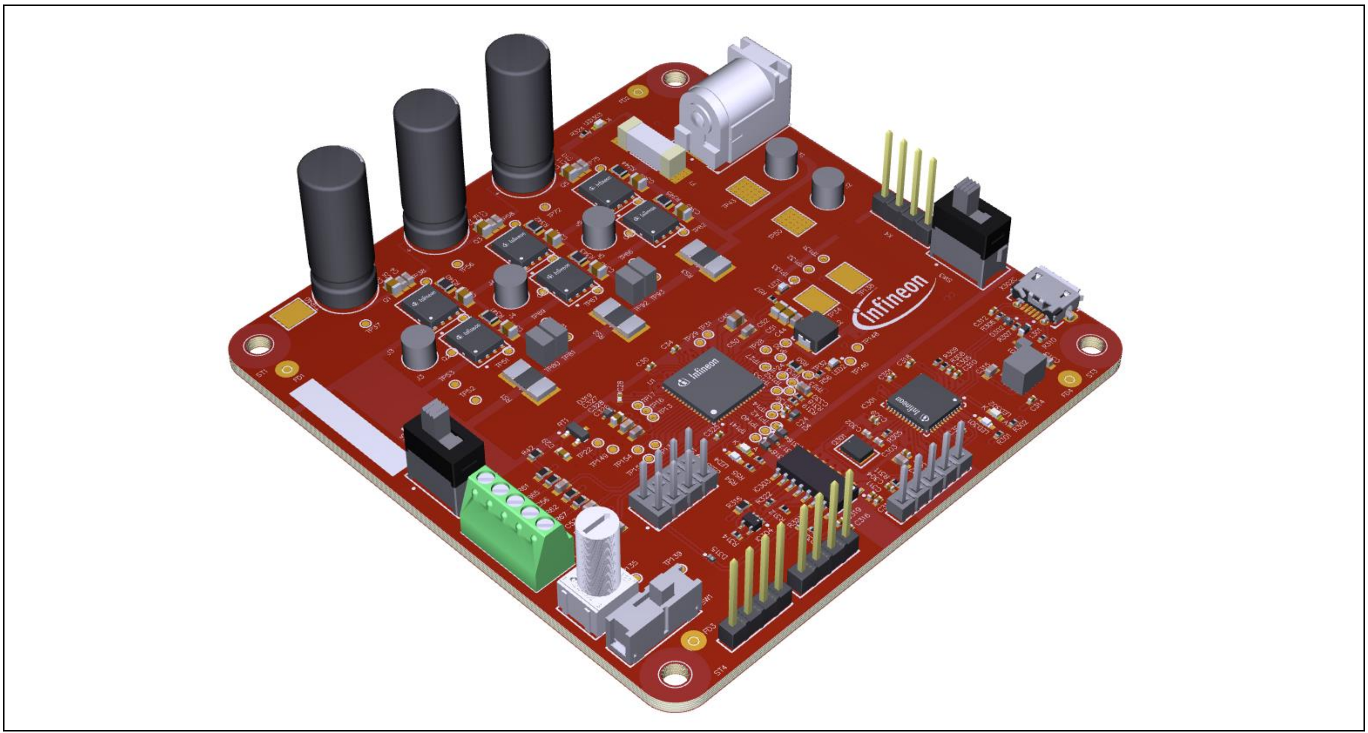


Figure 1 REF_IMD701A_720W_DC24 reference board

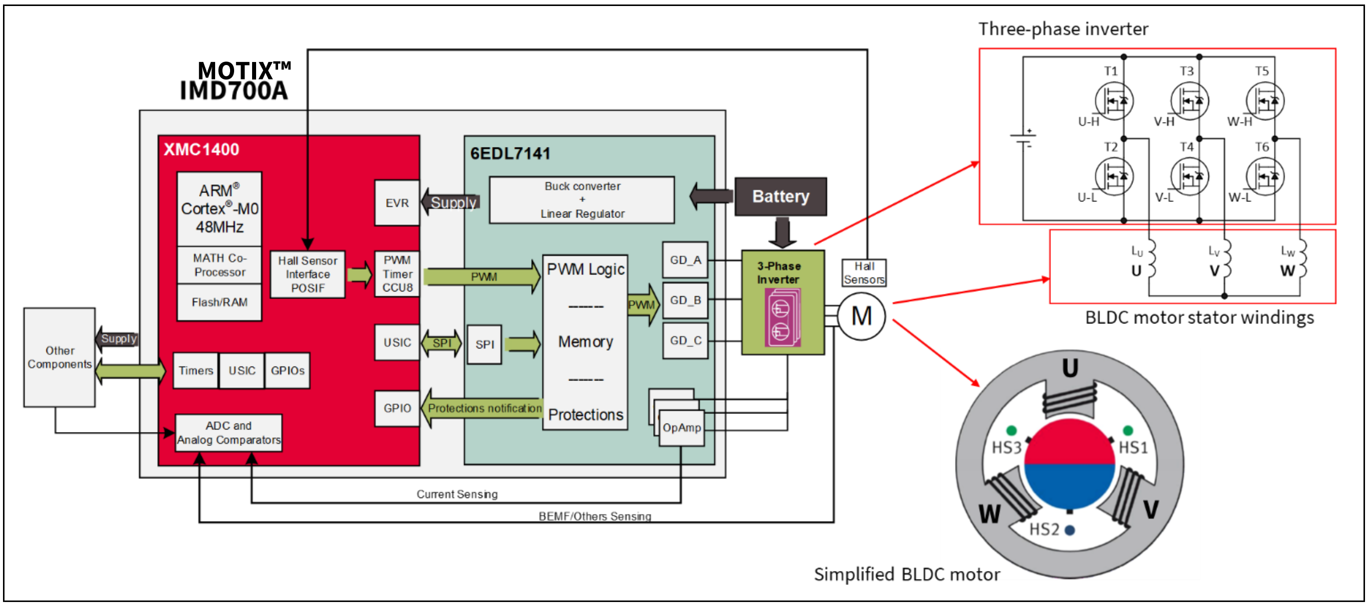


Figure 2 **Simplified system block diagram excluding the onboard debugger**

1.2 MOTIX™ IMD701A functional overview

MOTIX™ IMD701A is a three-phase smart gate driver in a 64-pin VQFN package for BLDC or PMSM drive systems. It consists the XMC1400 MCU connected to a configurable three-phase half-bridge gate driver (MOTIX™ 6EDL7141). This configuration can 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 MOTIX™ BPA Motor Control Workbench. Configuration settings can be made permanent by storing them in the built-in one-time programmable (OTP) memory.

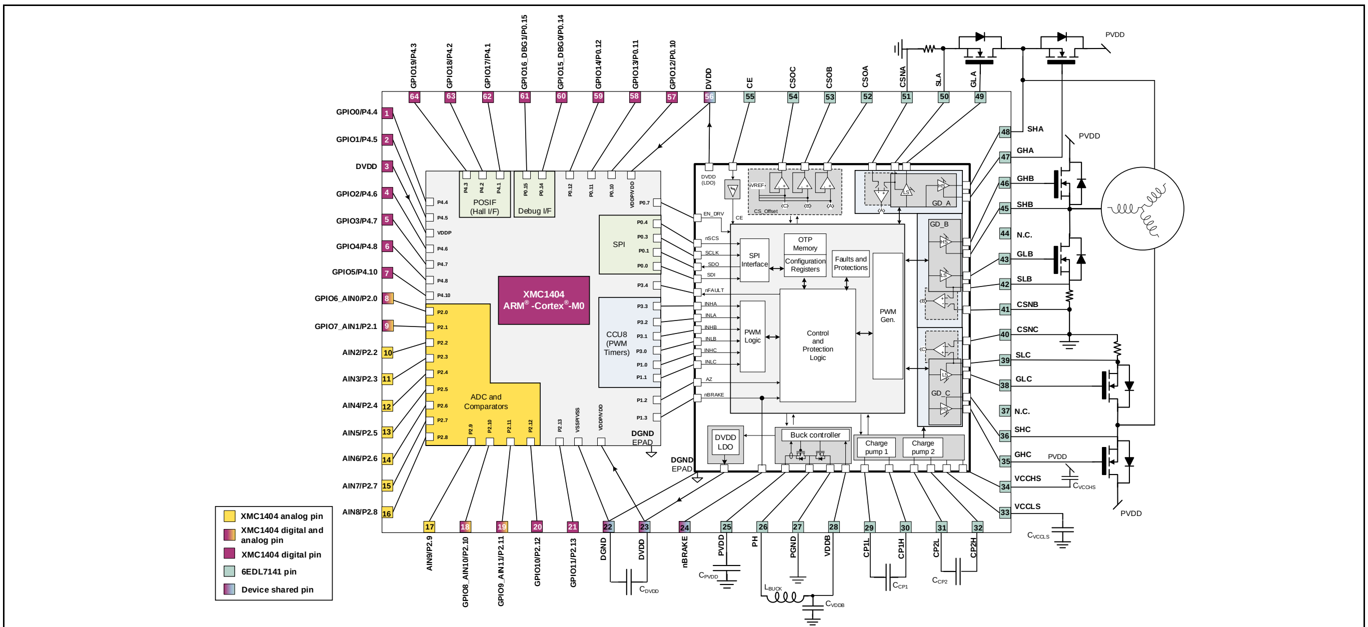


Figure 3 **MOTIX™ IMD701A internal block diagram**

The MCU communicates with the smart gate driver via the internal SPI interface for configuration. PWM signals from the MCU provide the gate-drive control pulses, which can be decoded in several different ways for 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. In addition, the switch-on and switch-off profiles can be optimized to minimize EMI and switch-off transients by configuring the 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 smart gate driver to connect to digital and analog MCU inputs.

MOTIX™ IMD701A 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.

A positive overcurrent comparator detects an overcurrent condition present in a motor winding from 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 negative overcurrent in a motor winding that produce negative shunt currents. A built-in DAC is used for programming the thresholds of the overcurrent comparators.

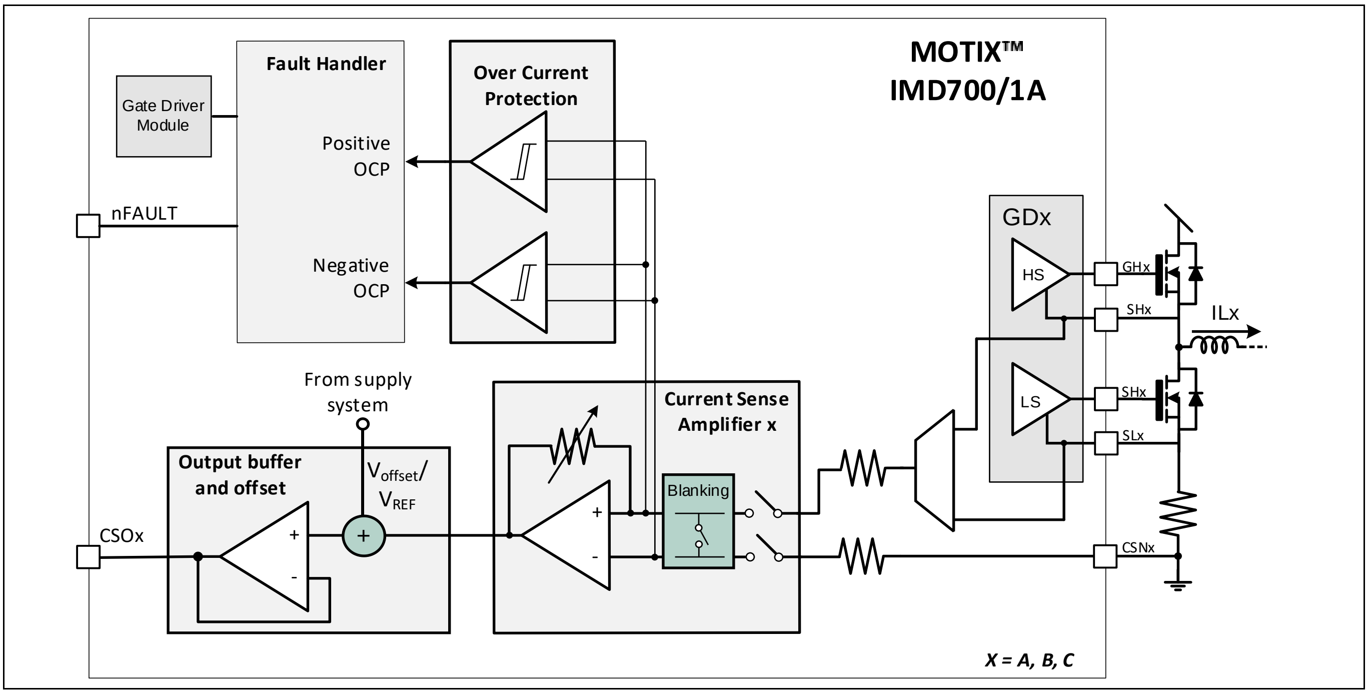


Figure 4 **MOTIX™ IMD701A CS amplifiers and comparators**

1.3 MOTIX™ BPA Motor Control Workbench

You can use MOTIX™ BPA Motor Control Workbench to download the control firmware and configuration settings for MOTIX™ IMD701A on motor control boards operating with trapezoidal or FOC motor control with one or three shunts. You can use the workbench to select the parameters for a project and then save the configuration.

Note: *REF_IMD701A_720W_DC24 uses the same project option with EVAL_IMD700A_FOC_3SH, as REF_IMD701A_720W_DC24 has similar functionalities with it. After configuring the parameters in Workbench, you need to modify some default parameters to fit the design.*

Install MOTIX™ BPA Motor Control Workbench.

2 Specifications

2.1 Input and output at normal operation

- 12 V to 24 V DC input voltage; 18 V nominal
- 40 A maximum input current
- Output voltage three-phase FOC
- 720 W peak output power

2.2 Control schemes

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

2.3 Protection features

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

Note: *You must configure the firmware correctly for the specific motor being driven before operation. Use MOTIX™ BPA Motor Control Workbench to enter parameters such as phase-winding inductance and resistance before flashing the firmware to the target board.*

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

3 Hardware functional description

The main hardware elements for sensorless FOC are the following:

- Three-phase inverter power stages
- MOTIX™ IMD701A combined three-phase smart gate driver
- XMC1400 series 32-bit MCU with Arm® Cortex®-M0. The CORDIC MATH coprocessor included with the MCU 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 OptiMOS™ 6 BSC007N04LS6 40 V/0.7 mΩ 5x6) 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 is realized with three leg shunt resistors (RS1, 2, and 3 in this case) to sense the lower MOSFET current in each phase.

3.1 MOTIX™ IMD701A integrated smart gate driver

MOTIX™ IMD701A is a controller integrated with the XMC1404 MCU and three-phase smart gate driver specifically designed for three-phase BLDC or PMSM drive applications.

3.1.1 Gate drive current and timing

Using MOTIX™ BPA Motor Control Workbench, you can configure the gate driver current and timings to optimize the switching profile for enhanced EMI performance. See Figure 5 for the gate driver implementation. The REF_IMD701A_720W_DC24 reference board operates in 6 PWM mode, in which the integrated MCU inserts a specific dead-time between the INHx and INLx signals generated by its PWM modules. For the sake of simplicity, propagation delays are not shown.

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_{PRE_SRC} for a time defined by T_{DRIVE1}, at the end of which the MOSFET gate voltage should have reached the threshold voltage $V_{GS(TH)}$. The period of the gate switch-on sequence is defined by the T_{DRIVE2} parameter, which begins immediately after the completion of T_{DRIVE1}. The current applied during T_{DRIVE2} determines both dI_D/dt and dV_{DS}/dt of the MOSFETs, because it supplies the current to charge the Q_{SW} of the MOSFET being driven.

In designs where the MOSFET gate charges are small, as in this example, T_{DRIVE2} is set to zero. This will result in the driver charging the MOSFETs during T_{DRIVE1}; and after T_{DRIVE1} elapses, 1.5 A will be applied ignoring the T_{DRIVE2} configuration.

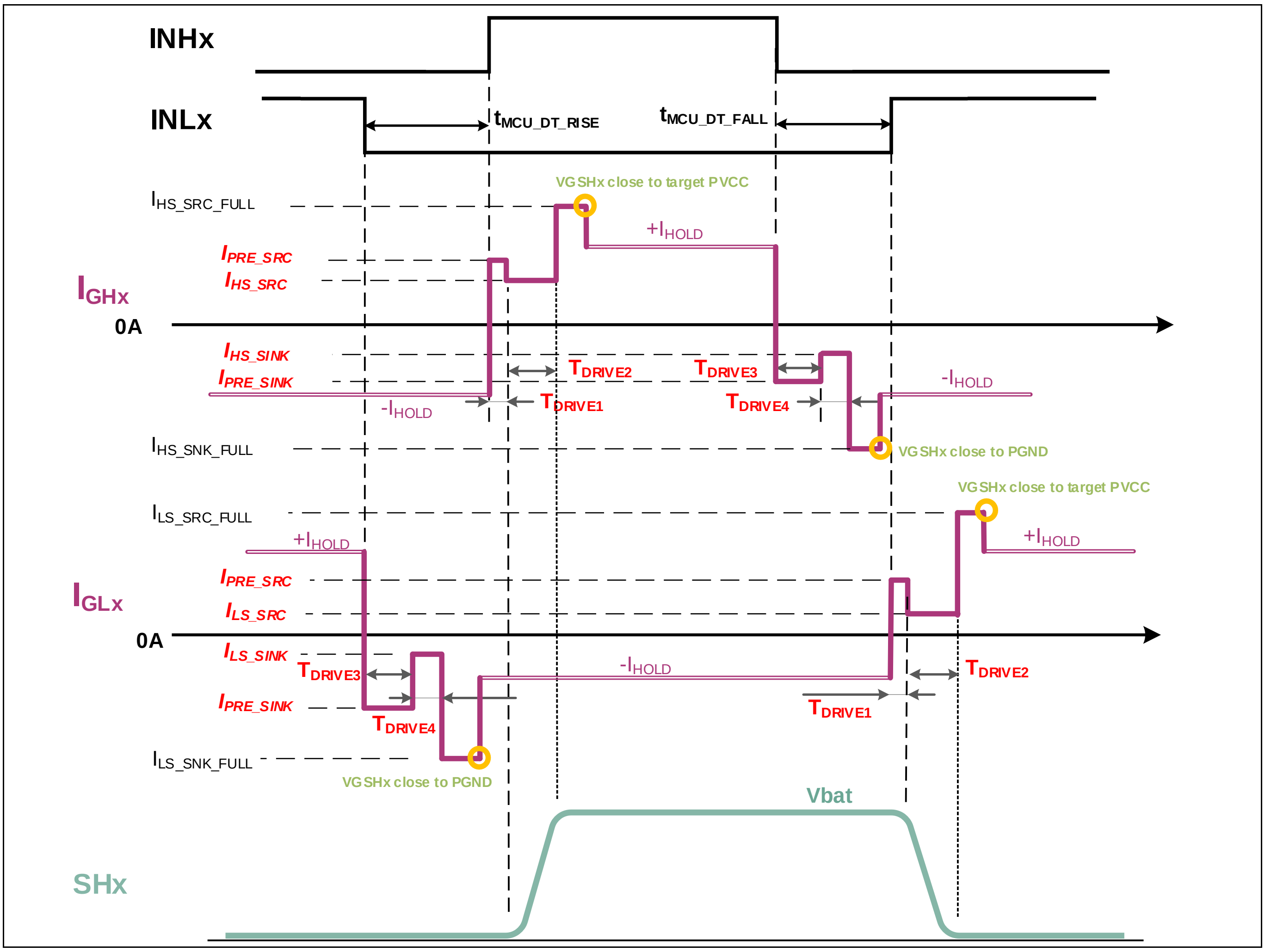


Figure 5 **MOTIX™ IMD701A slew rate control for half-bridge**

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.

3.1.2 Gate drive voltage

A range of different MOSFET sizes and technologies are used in motor drive systems. Additionally, the MOSFETs may have standard or logic-level gate thresholds. For example, $V_{GS(TH)}$ for logic-level devices such as the OptiMOS™ 6 BSC007N04LS6 40 V MOSFETs used in REF_IMD701A_720W_DC24 is significantly lower than standard-level parts. As a result, 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, which results in lower conduction losses of the system—see Figure 13. However, increasing the driving voltage also increases the switching rise and fall times, leading to higher switching losses.

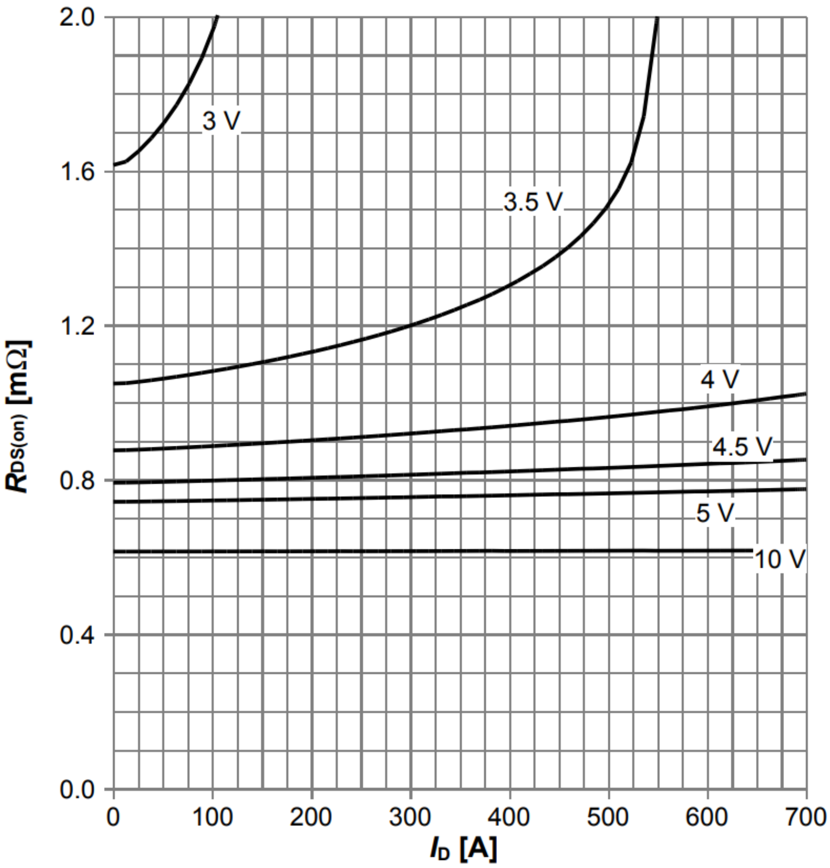


Figure 6 **BSC007N04LS6 $R_{DS(on)}$ vs V_{GS} characteristic**

MOTIX™ IMD701A offers several driving voltage options to select from depending on the system requirements, allowing you to adjust the MOSFET driving voltage (PVCC voltage) via SPI registers. The same PVCC value 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 the PVCC_SETPT bitfield via MOTIX™ BPA Motor Control Workbench, where the default value is 12 V.

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 device. In order to prevent this, it is common to add weak pull-down resistors between the gates and sources of each MOSFET. MOTIX™ IMD701A avoids the need for these resistors by integrating the following functions into its gate driver outputs.

3.1.3 Calculating the MOSFET slew rate relative parameter

It is convenient to get the slew rate relative parameter from the **6EDL71x1 MOSFET Slew Rate Configurator**.

1. Open MOTIX™ BPA Motor Control Workbench and click **6EDL71x1 MOSFET Slew Rate** to build a new project.

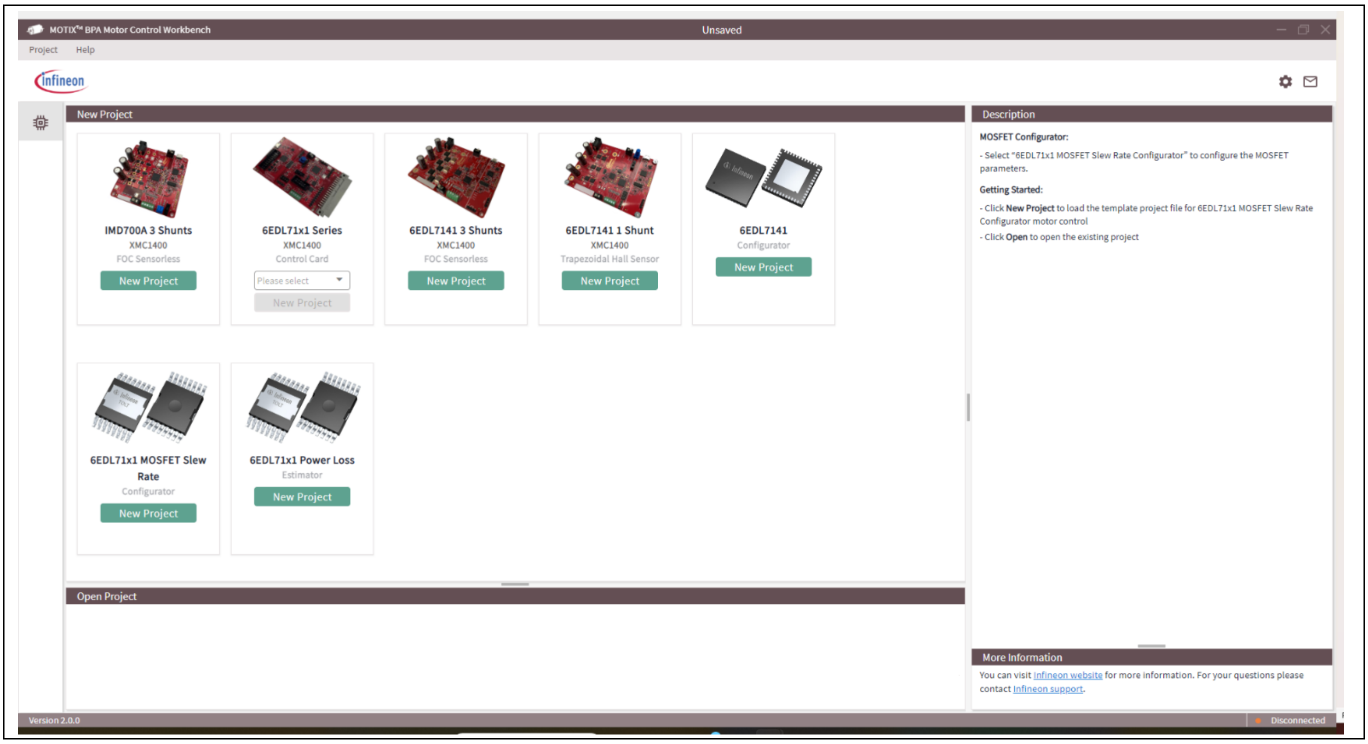


Figure 7 MOTIX™ BPA Motor Control Workbench

2. Enter the basic information of the system operating conditions (see Figure 8). After adding the necessary data, click **Update MOSFET Parameters**.

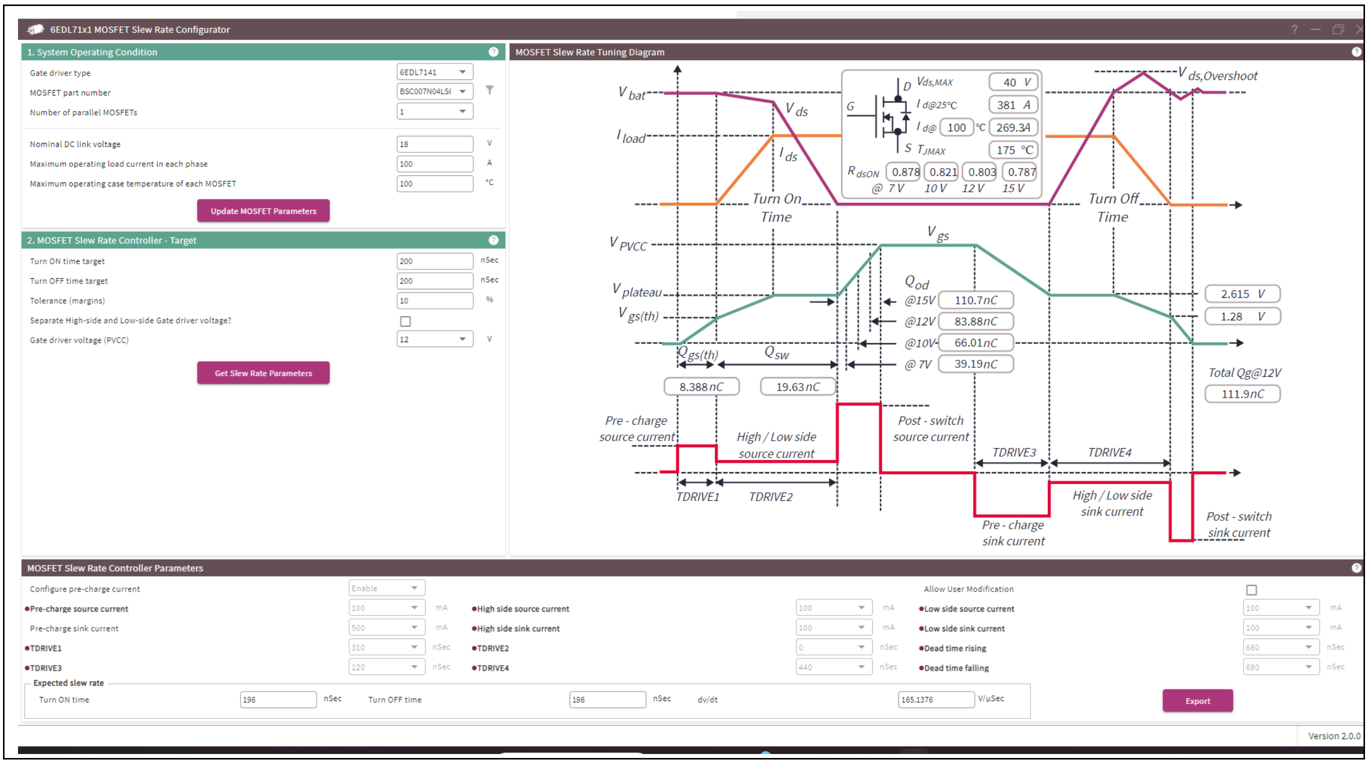


Figure 8 6EDL71x1 MOSFET Slew Rate Configurator

3. Go to **MOSFET Slew Rate Controller-Target** and enter the parameters for the target performance that you would like to achieve in the solution.

4. Click **Get Slew Rate Parameter**.

All 6EDL71x1 parameters that are required to be set are shown in the **MOSFET Slew Rate Controller Parameters** section. This shows the simulation result based on the MOSFETs simulated model.

Note: The lab measurements might require some adjustment.

In this reference board, the slew rate parameters are listed in the following table as an example.

Table 2 Calculated gate drive parameters

Parameter	Description	Value
I_{HS_SRC}	Source current for switching on high-side MOSFETs	100 mA
I_{HS_SINK}	Sink current for switching off high-side MOSFETs	100 mA
I_{LS_SRC}	Current for switching on low-side MOSFETs	100 mA
I_{LS_SINK}	Current for switching off low-side MOSFETs	100 mA
I_{PRE_SRC}	Pre-charge current for switching on both high-side and low-side	100 mA
I_{PRE_SINK}	Pre-charge current for switching off both high-side and low-side	500 mA
T_{DRIVE1}	Duration that I_{PRE_SRC} is applied. Shared configuration between high-side and low-side drivers	310 ns
T_{DRIVE2}	Duration that I_{HS_SRC} and I_{LS_SRC} are applied. Shared configuration between high-side and low-side drivers	0 ns
T_{DRIVE3}	Duration that I_{PRE_SINK} is applied. Shared configuration between high-side and low-side drivers	120 ns
T_{DRIVE4}	Duration that I_{HS_SINK} and I_{LS_SINK} are applied. Shared configuration between high-side and low-side drivers	440 ns
T_{DT}	Dead-time for positive and negative transitions	750 ns

3.1.4 Configuring the synchronous buck converter

MOTIX™ 6EDL7141 integrates a synchronous buck converter, linear voltage regulator, and charge pumps for both high- and low-side gate drivers. The synchronous buck converter requires minimum external components—the diodes, voltage dividers, and bootstrap capacitors used in a normal buck converter are not required in this solution. The 6EDL7141 gate driver supplies both (high side and low side) charge pumps and the integrated DVDD voltage regulator with the help of an external filter (LC).

Two different switching frequencies, 500 kHz (default value) or 1 MHz, can be selected via MOTIX™ BPA Motor Control Workbench. The buck inductor L2 value is 22 µH for 500 kHz switching and 10 µH for 1 MHz. The values for the buck output capacitors C51 and C52 are 22 µF with an additional 0.1 µF ceramic capacitor (C44) added to reduce the high-frequency (HF) noise. See Figure 9for details of both the synchronous buck converter and linear voltage regulator circuits:

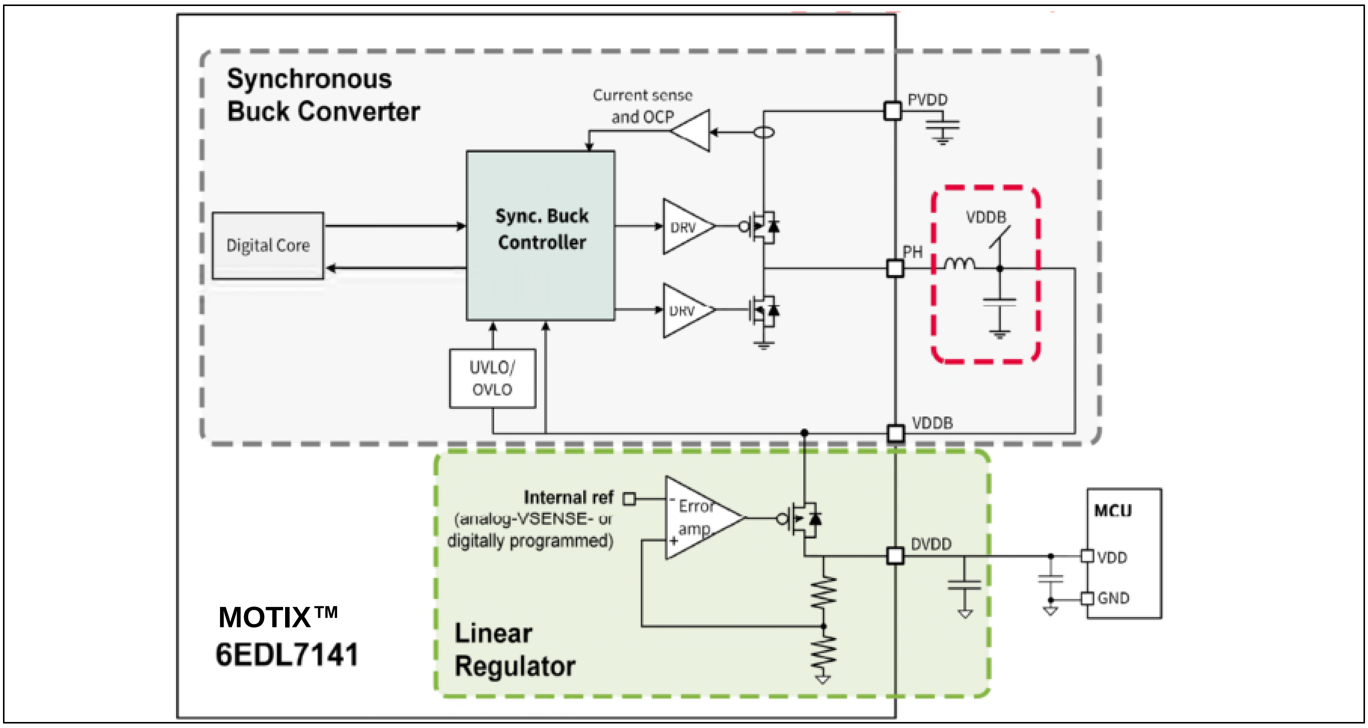


Figure 9 Integrated synchronous buck converter and linear regulator

3.1.5 Configuring the DVDD linear regulator

The integrated linear regulator generates the DVDD voltage rail that can supply the XMC1404 MCU and additional elements in the circuit like Hall sensors, LEDs, and temperature sensor. DVDD OCP can be configured between four different levels: 50 mA, 150 mA, 300 mA, or 450 mA (default). If the OCP level is reached, a fault is reported through the nFAULT pin. The DVDD OCP works in two different stages:

- **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.
- **Current limiting mode at 100 percent of selected OCP level:** If the 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.

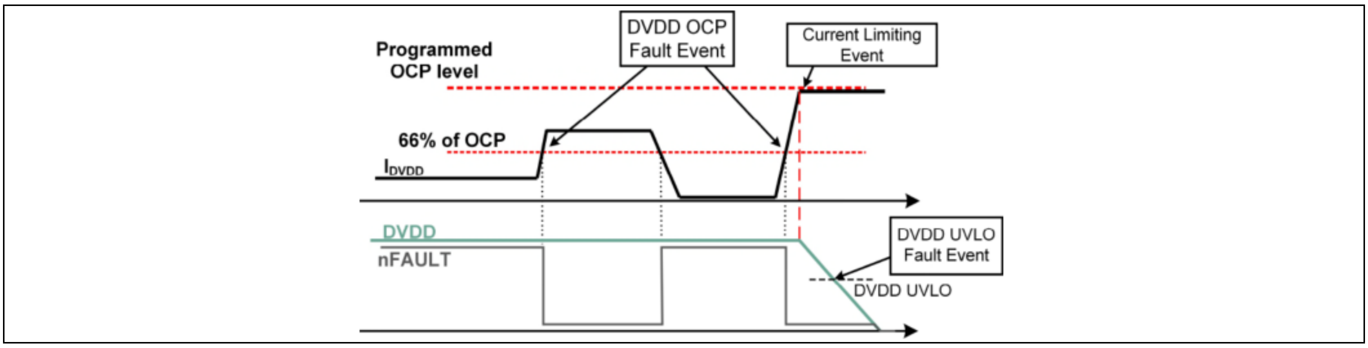


Figure 10 DVDD OCP behavior including pre-warning and current-limiting modes

3.1.6 Configuring charge pumps

The charge pump works at a determined switching frequency based on switched capacitor. 6EDL7141 provides four different clock frequencies by configuring the CP_CLK bitfield in the CP_CFG register through the SPI interface. The charge pump capacitors (both flying and tank capacitors) must be chosen according to this configuration; both affect the startup time of VCCLS and VCCHS rails and potentially affect the voltage ripple in those pins.

In this design, the charge pump flying capacitors (C45 and C50) are set to 0.47 µF, while the tank capacitor C35 is set to 1 µF and C40 is set to 4.7 µF. MOTIX™ IMD701A provides pre-charging of the charge pump output capacitors (C35 and C40) to a voltage just below the buck converter output voltage (VDDB) before the EN_DRV pin is activated. In this case, to shorten the system startup time, when the MCU activates EN_DRV to enable the gate driver stage, charge pumps need only ramp up the voltage from the existing pre-charge voltage to the selected target value. Pre-charge is disabled by default and can be enabled via MOTIX™ BPA Motor Control Workbench.

The startup time for the charge pumps (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 startup time for the gate drivers.
- **Charge pump clock frequency:** A higher clock frequency results in a faster startup time.
- **Charge pump tank capacitor values:** A smaller value results in a faster ramp-up time but causes higher ripple.
- **Charge pump flying capacitors:** Smaller capacitors lead to a slower startup time.

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

The CS amplifier block contains the following sub-blocks:

- **CS amplifier:** This is connected to an 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 an 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:** This 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:** This is used for detecting overcurrent conditions on motor windings for a positive shunt voltage. This comparator causes the gate drive pulse to be terminated, thus limiting the motor current.
- **Negative overcurrent comparator:** This is used for detecting the overcurrent condition on motor windings for negative shunt currents.
- **OCP DAC:** This is used for programming the overcurrent comparator thresholds. One sets the positive level and the second sets the negative level; these are shared among different OCP comparators.

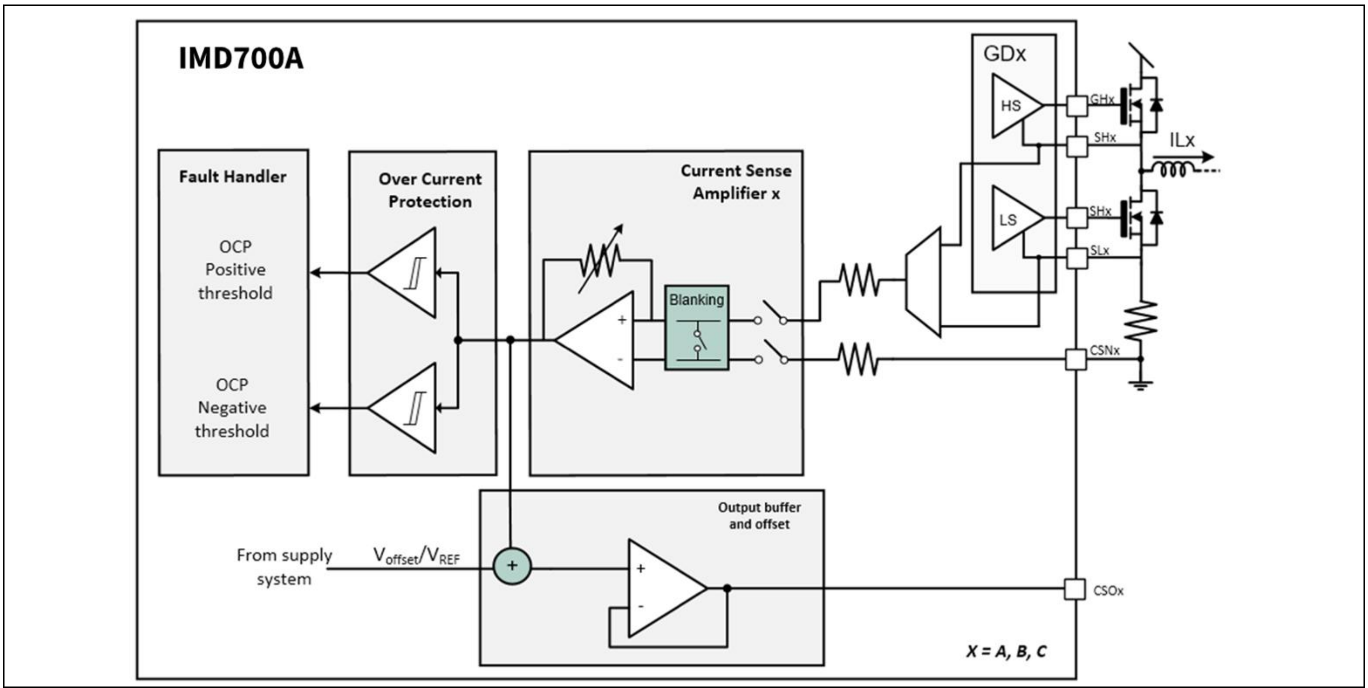


Figure 11 CS amplifier simplified block diagram

REF_IMD701A_720W_DC24 uses three 1 mΩ shunt resistors for sensing the phase current. The CS amplifiers have a default voltage gain of 4. This can be changed via MOTIX™ BPA Motor Control Workbench 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 the CS_GAIN pin to ground. To enable analog programming of the CS amplifier via an external resistor, you must ensure that the CS_GAIN_ANA bitfield in the CSAMP_CFG register is set accordingly. The value of RGAIN is read during the startup sequence of MOTIX™ IMD701A.

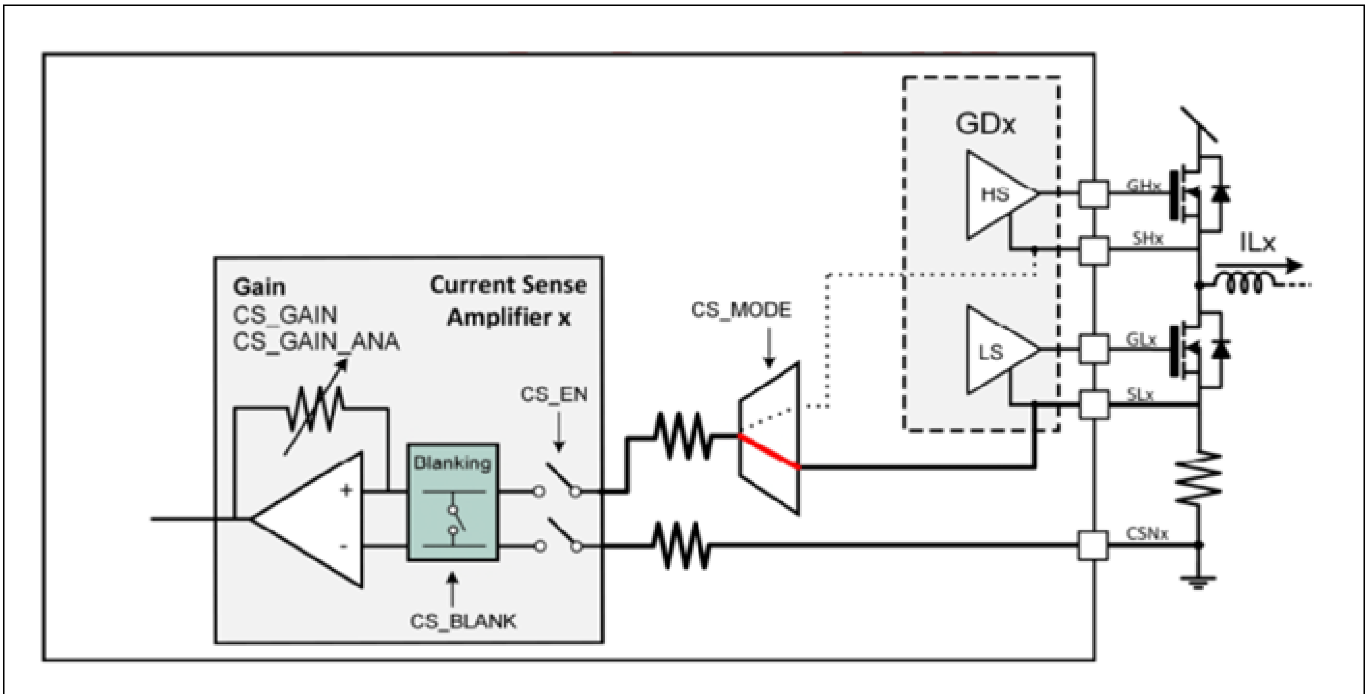


Figure 12 System diagram of an external shunt CS configuration

In many motor drive inverters such as this reference board, the current is sensed via shunt resistors. In this case, the voltage across the shunt must be amplified only when the low-side MOSFET is switched on.

The programmable LEB function can be configured in the CS amplifiers. Because 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 µs can be selected via MOTIX™ BPA Motor Control Workbench. The MOTIX™ IMD701A 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.

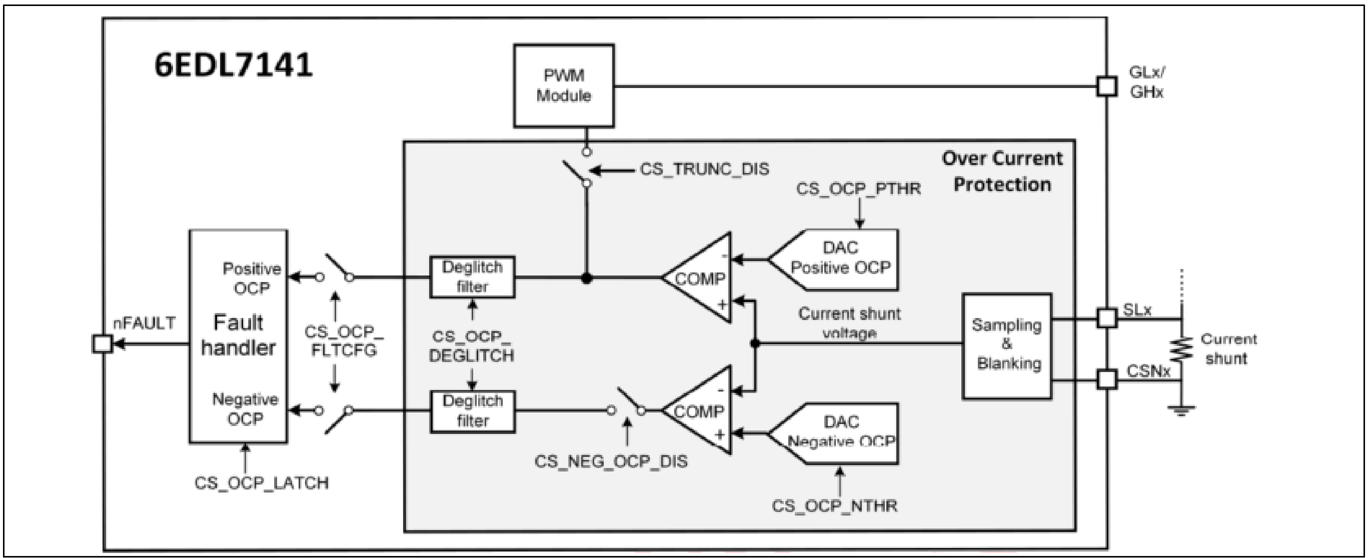


Figure 13 **CS amplifier architecture**

You can configure how MOTIX™ IMD701A reacts to an OCP event using MOTIX™ BPA Motor Control Workbench. The following scenarios can be useful for different applications:

- Apply PWM truncation immediately after the OCP event and report on the nFAULT pin after the OCP event. Deglitching is disabled if truncation is enabled.
- Disable reporting but keep PWM truncation.
- Trigger a configurable brake action upon the 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 PWM truncation. In such cases, OCP is ignored.

It is also possible to select whether the OCP fault is latched via MOTIX™ BPA Motor Control Workbench. 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 removed. You can 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.

3.2 Board connections and controls

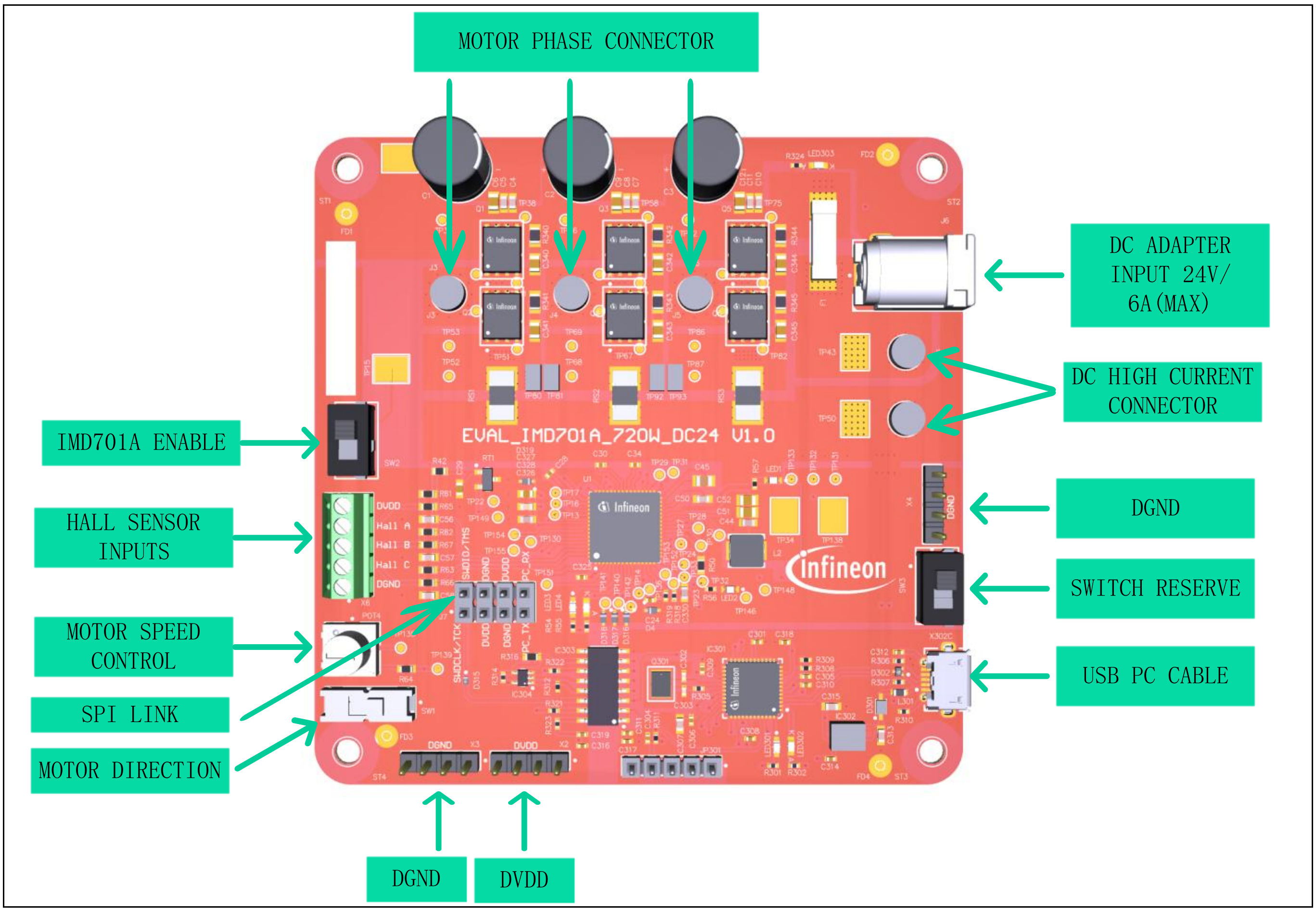


Figure 14 REF_IMD701A_720W_DC24 external connections and controls

3.3 Onboard programmer/debugger

The REF_IMD701A_720W_DC24 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 ModusToolbox™.

3.4 External programmer/debugger

You can connect an external debugger such as the XMC™ Link via the 4x2-way header indicated.

4 Firmware

4.1 Firmware structure

The PMSM FOC motor control firmware is developed based on a well-defined layered approach.

The layered architecture is designed in such a way as to separate the modules into groups. This allows different modules in a given layer to be easily replaced without affecting the performance in other modules and the structure of the complete system.

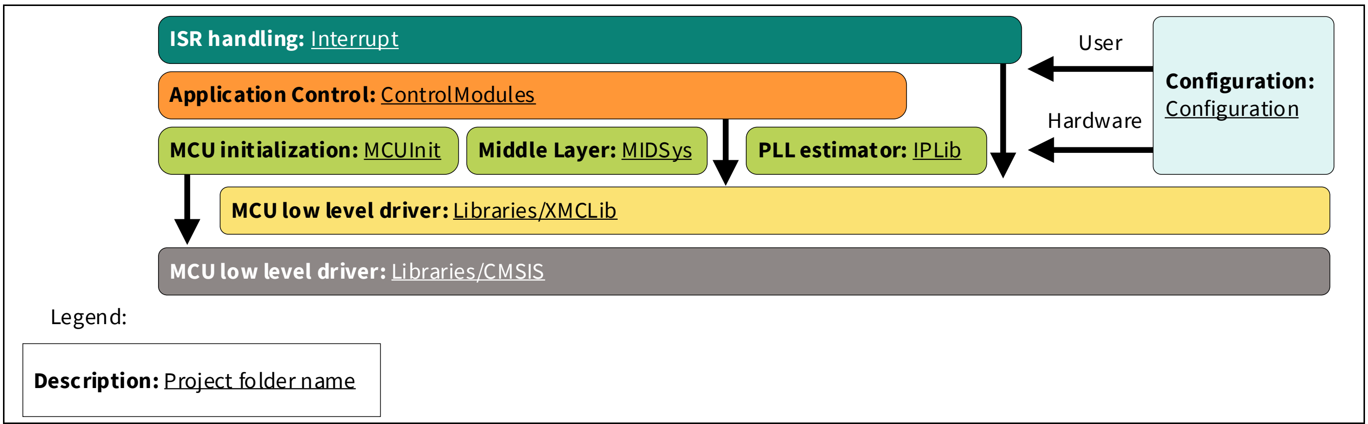


Figure 15 PMSM FOC firmware overview - layered structure

The project folder structure is well-organized based on the layered approach.

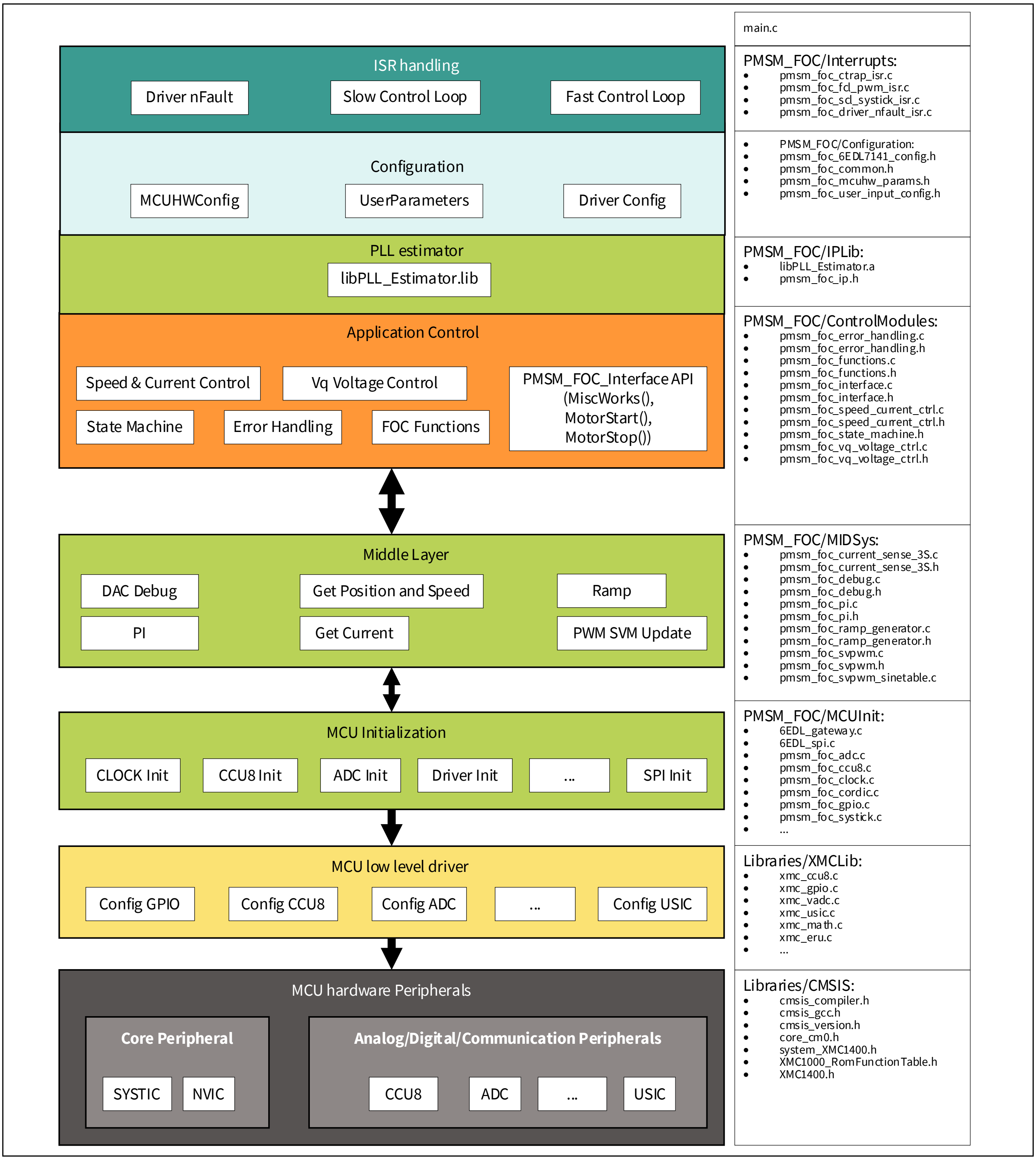


Figure 16 Project folder structure

4.2 Firmware block diagram

Figure 17 shows the firmware block diagram of this reference design.

Speed reference or the V_q voltage reference can be the control target, depending on the application. A ramp function is called to achieve the required slope of the speed or the V_q voltage.

The FOC control method is based on the 'd-q' model of the PMSM. The three-phase currents are measured and transformed into currents of the 'd' and 'q' axes, which are used to control the flux and torque of the motor.

The firmware involves an outer speed control loop and two inner current control loops. The outputs of the two current control loops are transformed into a three-phase voltage by the space vector modulator (SVM). The three phase voltages are then applied to the motor by the inverter.

The firmware uses a sensorless PLL estimator for the rotor position and the speed, which means that position sensors are not required to estimate the rotor position, but uses the measured currents and voltage.

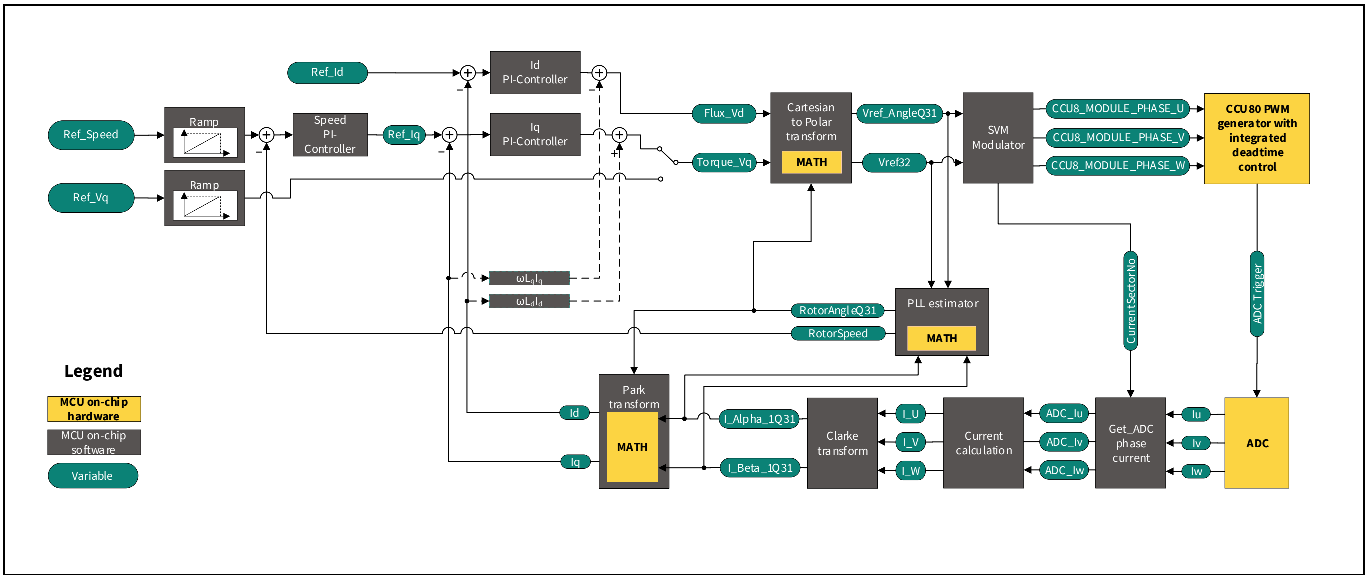


Figure 17 Firmware block diagram

4.3 Control schemes

In this software block, the control scheme for the three-phase PMSM FOC motor can be:

- Open-loop voltage control
- V_q voltage control
- Speed control

4.3.1 Open-loop voltage control

In an open-loop voltage control, a reference voltage (V_{ref}) is used to cause the power inverter to generate a given voltage at the motor. The mechanical load influences the speed and the current of the PMSM motor.

This control scheme is usually used at the development stage. It provides a less accurate control over the output voltage than a closed-loop system. However, it is an easy way to generate waveforms when you want to validate specific features of the board. For example, you can use this approach to validate the switching performance of the MOSFETs before the closed-loop control scheme is fine-tuned.

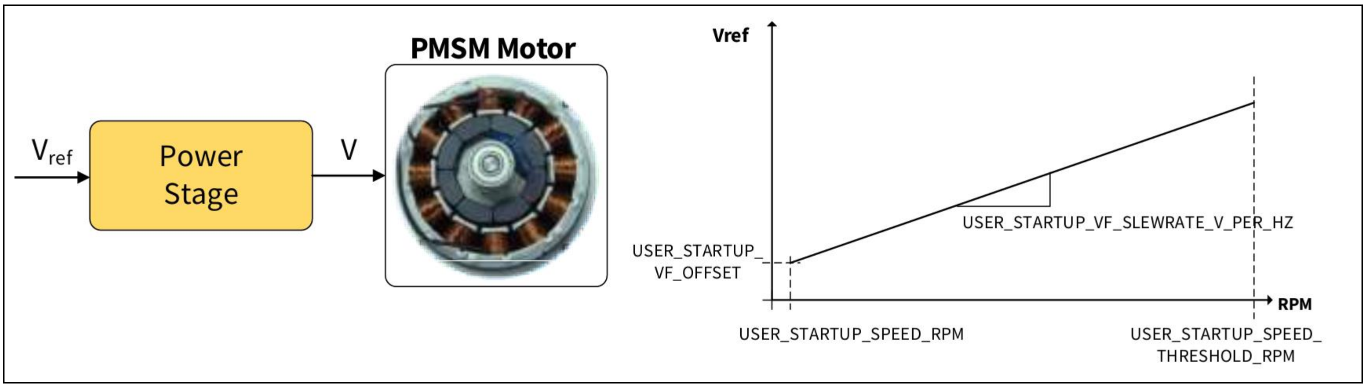


Figure 18 Open-loop voltage control

4.3.2 V_q voltage control

The V_q voltage control method is used when a fast response is required and varying speed is not a concern. This control scheme can be used for power drill applications. The speed PI control loop and torque PI control loop are disabled.

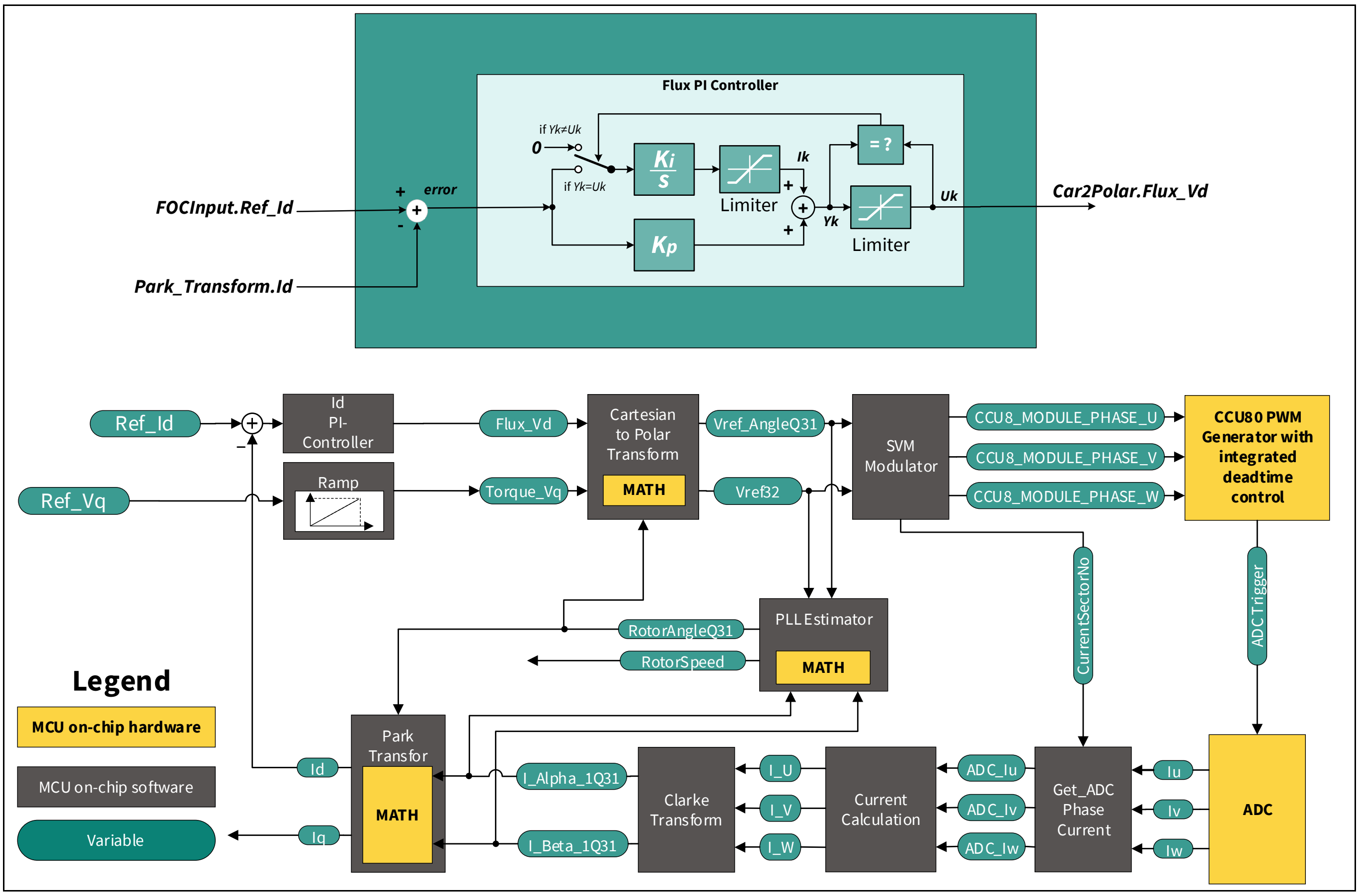


Figure 19 V_q voltage control scheme

4.3.3 Speed control

The speed control scheme is closed-loop control. This scheme uses a cascaded speed and current control structure because the change response for a speed control loop is much slower than the one for the current loop.

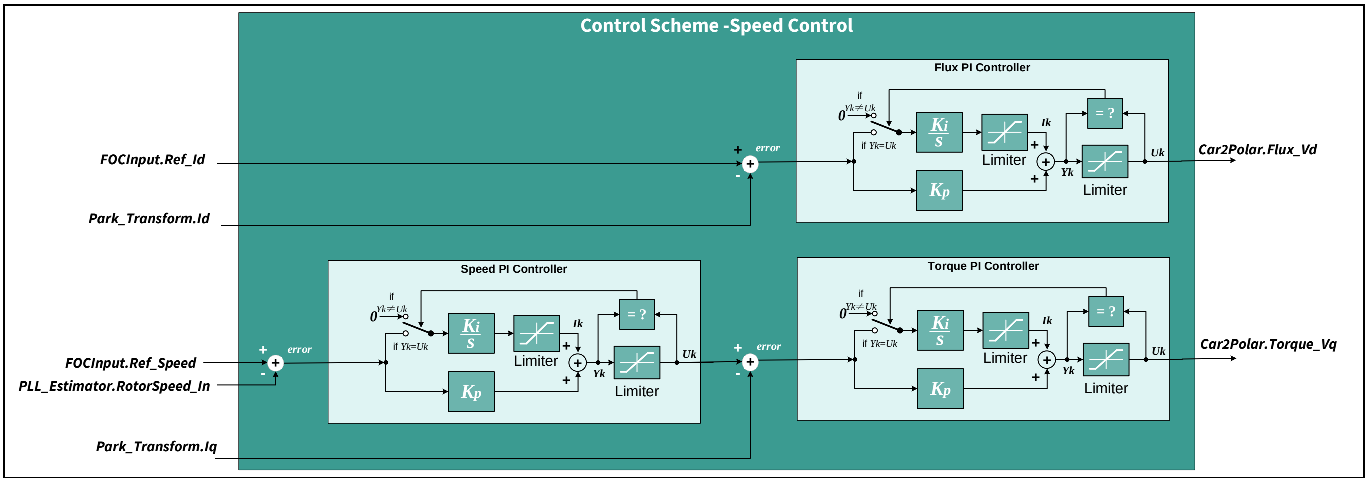


Figure 20 Speed control scheme

The speed PI controller supports integral anti-windup. The integral output is held stable when either PI output or integral output reaches its limit. The output of the speed controller PI is used as the reference for the torque PI controller. Direct FOC startup and transition startup (open-loop to closed-loop) modes are supported in the speed control scheme.

4.3.3.1 Transition startup mode: Three-step startup

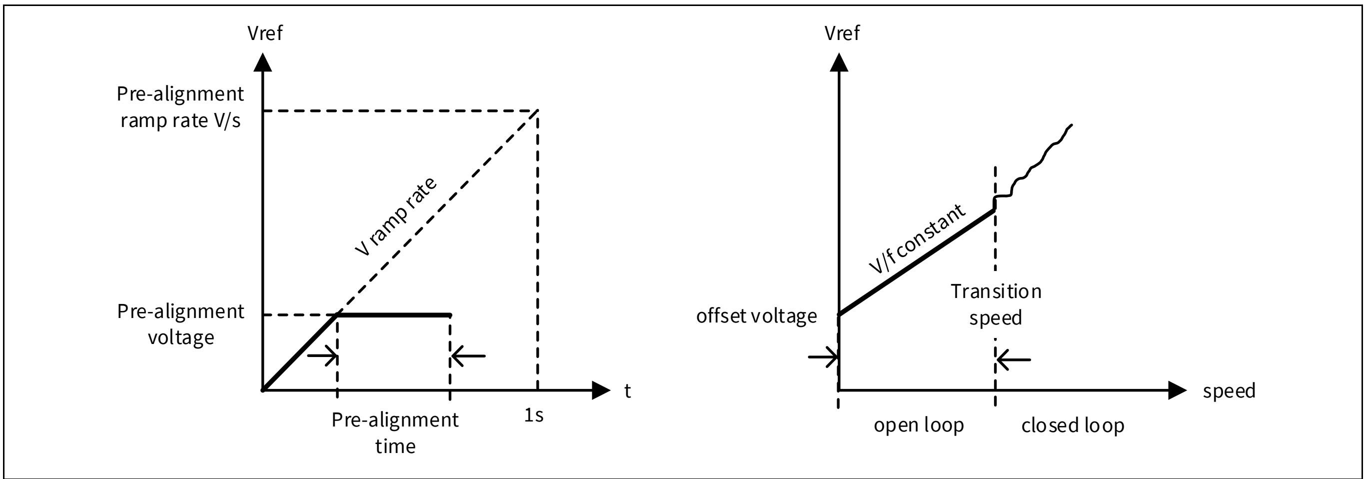


Figure 21 Three-step motor startup mechanism

This mode involves the following three steps:

1. After the pre-alignment implementation (optional), the motor starts in the V/f open-loop control state and ramps up to a user-defined startup speed.
2. The PI controllers' integral terms are initialized at the end of an open loop for a smooth transition to a closed loop.

3. The state machine switches to the `FOC_CLOSED_LOOP` state and ramps up the motor speed to the user-defined target speed.

4.4 Protection schemes

This firmware supports the following protection schemes:

- Gate driver fault reporting pin
- Overvoltage protection (OVP)/undervoltage protection (UVP)

The corresponding error status is set when either fault occurs; it changes the motor state machine to `PMSM_FOC_MSM_ERROR`.

4.4.1 Gate driver fault reporting pin

The MOTIX™ 6EDL7141 smart gate driver contains many protection features such as follows:

- Overcurrent protection (OCP) for:
  - DVDD linear regulator
  - Buck converter
  - Motor leg shunt OCP
- Undervoltage lockout (UVLO) protection for:
  - Gate driver supply voltage, both high-side and low-side drivers
  - Supply voltage PVDD
  - DVDD linear regulator output voltage
  - Buck converter output voltage
- DVDD linear regulator overvoltage lockout (OVLO) protections
- Rotor locked detection based on Hall sensor inputs
- Configurable watchdog
- Overtemperature shutdown (OTS) and warning (OTW)
- OTP memory fault

When an event occurs, the fault is asserted and the nFAULT pin is pulled LOW, reporting the fault to the XMC1404 MCU via a GPIO interrupt. In the ISR, the error status is set to PMSM_FOC_EID_NFAULT_FAULT and the nBRAKE pin of the gate driver is activated.

The following registers of 6EDL7141 provide information on the status of the device faults:

- **FAULT_ST**: Holds most of the functional related faults. A fault can be triggered only after a number of events of a malfunction. Status will immediately record the event information.
- **TEMP_ST**: Provides the status on the temperature warning and temperature reading itself
- **SUPPLY_ST**: Reports on the status of all supplies UVLO/OVLO and OCPs
- **FUNC_ST**: Status of OCP faults for all current sense amplifier, Hall sensors, and incorrect Hall sensor pattern
- **OTP_ST**: Programming and reading of overtemperature protection (OTP) related faults

See the MOTIX™ IMD701A datasheet [1] for more details on protections and fault handling.

4.4.2 Overvoltage/undervoltage protection

The DC-link voltage is read in the `PMSM_FOC_SysMonitoring()` function in the *PMSM_FOC\ControlModules\pmsm_foc_interface.h* file every PWM period match interrupt. An error is generated if the DC-link voltage is higher than the overvoltage threshold or lower than the undervoltage threshold. The error status is set as PMSM_FOC_EID_OVER_VOLT or PMSM_FOC_EID_UNDER_VOLT accordingly.

4.5 Firmware configuration

This section describes the general configuration such as control scheme, hardware board parameters, and the motor parameters. The configuration options are available in the *PMSM_FOC\Configuration\pmsm_foc_user_input_config.h* file.

4.5.1 Motor group

- `#define USER_MOTOR_R_PER_PHASE_OHM (0.0075f)`

  Defines the motor phase to neutral resistance in Ω.

- `#define USER_MOTOR_LS_PER_PHASE_uH (20.0f)`

  Defines the motor phase to neutral stator inductance in µH. For interior permanent magnet synchronous motor (IPMSM) brushless DC motors, q-axis inductance (Lq) is used.

- `#define USER_MOTOR_POLE_PAIR (1.0f)`

  Number of pole pairs in the motor is used to calculate the electrical RPM of the rotor.

- `#define USER_SPEED_HIGH_LIMIT_RPM (120000U)`

  Maximum allowed target speed. Additional control parameters are calculated from this value.

- `#define USER_SPEED_LOW_LIMIT_RPM (1000U)`

  Minimum allowed target speed. In sensorless motor control, it is important to have the speed high enough to measure and estimate module parameters. The minimum speed depends on the application and motor.

4.5.2 Board group

- `#define USER_VDC_LINK_V (18.0f)`

  Defines the inverter DC-link voltage in V. This is the nominal voltage of the inverter.

- `#define USER_CURRENT_AMPLIFIER_GAIN (32.0f)`

  Defines the current sensing amplifier gain. The gain must be the same as the configuration for 6EDL7141, which is configured in the *MCUInit\6EDL_gateway.c* file.

- `#define USER_MAX_ADC_VDD_V (5.0f)`

  Defines the maximum voltage at the ADC.

- `#define USER_R_SHUNT_OHM (0.001f)`

  Defines the phase current-sensing shunt resistor in Ω.

4.5.3 System group

- `#define USER_SLOW_CTRL_LOOP_PERIOD_uS          (1000.0F)`

  Slow control loop scheduler interrupt period.

- `#define VOLTAGE_DIVIDER_R_HIGH                 (75.0f)`
- `#define VOLTAGE_DIVIDER_R_LOW                  (7.87f)`
- `#define USER_VDC_LINK_DIVIDER_RATIO (VOLTAGE_DIVIDER_R_LOW/(VOLTAGE_DIVIDER_R_HIGH+VOLTAGE_DIVIDER_R_LOW))`

  DC-link voltage sensing resistor-divider ratio for high-side and low-side; depends on the actual value on the predefined board. Do not change the calculation of the ratio for DC-link voltage divider; it is fixed as R2/(R2+R1).

- `#define USER_DRIVERIC_DELAY_US                 (0.2f)`

  Configuration for the driver IC propagation delay. It affects the ADC trigger point.

- `#define USER_BOOTSTRAP_PRECHARGE_TIME_MS       (100U)`

  Initial bootstrap pre-charging time.

- `#define USER_ROTOR_PRE_ALIGN_METHOD            (ROTOR_PRE_ALIGNMENT)`

  Options:

  - ROTOR _PRE_ALIGNMENT
  - ROTOR_PRE_ALIGN_NONE

- `#define USER_MOTOR_STARTUP_METHOD              (MOTOR_STARTUP_DIRECT_FOC)`

  See Section 4.3 for more information on the startup method.

  Options:

  - MOTOR_STARTUP_DIRECT_FOC
  - MOTOR_STARTUP_VF_OPEN_LOOP

- `#define USER_ROTOR_PRE_ALIGNMENT_V_RAMP_RATE (10.0F)`

  Defines the pre-alignment voltage ramp rate in V/s.

- `#define USER_ROTOR_PRE_ALIGNMENT_VOLTAGE_V    (0.2F)`

  Defines the pre-alignment voltage in volts. It should be less than `USER_VDC_LINK_V`.

- `#define USER_ROTOR_PRE_ALIGNMENT_TIME_MS      (500.0F)`

  Defines the rotor startup alignment time in ms. Minimum range is the PWM period.

- `#define USER_VQ_INITIAL_VALUE_V               (0.2F)`

  V_q value initial value based on load and maximum current.

- `#define USER_FOC_CTRL_SCHEME (SPEED_INNER_CURRENT_CTRL)`

  Defines the control scheme. SPEED_INNER_CURRENT_CTRL must be enabled for speed control scheme.

  Options:

  – SPEED_INNER_CURRENT_CTRL
  – VQ_VOLTAGE_CTRL
  – VF_OPEN_LOOP_CTRL

- `#define USER_MOTOR_BI_DIRECTION_CTRL (DISABLED)`

  If enabled, the motor can run with the rotor angle increasing or decreasing.

  Options:

  – ENABLED
  – DISABLED

- `#define USER_REF_SETTING (DISABLED)`

  Defines the reference setting method of using the board's potentiometer for speed or V_q voltage.

  Options:

  – ENABLED
  – DISABLED

- `#define USER_TH_POT_ADC (120U)`

  Threshold POT ADC in which the motor can enter or exit motor idle state. The range of the ADC results is from 0 to 4095. It can be configured according to the application.

- `#define USER_POT_ADC_LPF (3U)`

  POT ADC filter coefficient configuration.

4.5.4 Protection group

- `#define USER_VDC_UV_OV_PROTECTION (ENABLED)`

  Options:

  – ENABLED
  – DISABLED

- `#define USER_OVERCURRENT_PROTECTION (DISABLED)`

  Options:

  – ENABLED
  – DISABLED

- `#define USER_WATCH_DOG_TIMER (DISABLED)`

  Options:

- ENABLED
- DISABLED

- `#define USER_VDC_OVER_LIMIT ((uint16_t)(((USER_VDC_LINK_V * USER_VDC_LINK_DIVIDER_RATIO)/USER_MAX_ADC_VDD_V) * (1<<12) * 140.0 / 100.0))`
- `#define USER_VDC_MIN_LIMIT ((uint16_t)(((USER_VDC_LINK_V * USER_VDC_LINK_DIVIDER_RATIO)/USER_MAX_ADC_VDD_V) * (1<<12) * 60.0 / 100.0))`

  Defines the threshold for OVP and UVP. Default value is ± 40% of `USER_VDC_LINK_V`.

4.5.5 PWM group

- `#define USER_CCU8_PWM_FREQ_HZ (20000U)`

  Defines the PWM frequency in Hz. This is the fastest loop in this code example. The main tasks of the FOC are done in this loop or fractions of it.

- `#define USER_DEAD_TIME_US (0.75f)`

  Defines the dead-time in µs. This value must be defined according to the switches and bridge drivers. If the dead-time value is set too small, it will lead to a short from high-side MOSFET to low-side MOSFET. A high dead-time value reduces the maximum voltage that can be applied. In default settings, the same dead-time is applied to the rising and falling edge. If not compensated for, the dead-time adds a constant error.

- `#define USER_CCU8_PASSIVE_LEVEL_OUT0 CCU8_PASSIVE_LOW`

  PWM output passive level required for driver IC for high-side.

- `#define USER_CCU8_PASSIVE_LEVEL_OUT1 CCU8_PASSIVE_LOW`

  PWM output passive level required for driver IC for low-side.

- `#define USER_CCU8_INPUT_TRAP_LEVEL XMC_CCU8_SLICE_EVENT_LEVEL_SENSITIVITY_ACTIVE_LOW`

  Traps the signal input level selection for CTrap, which can be used for handling critical hardware errors (such as an overcurrent condition).

4.5.6 Control loop group

4.5.6.1 Transition startup (open-loop to closed-loop) mode parameters

- `#define USER_VF_OFFSET_V (0.3f)`

  Offsets the voltage for the transition startup mode. The initial torque is applied with this configuration.

- `#define USER_VF_V_PER_HZ (0.04f)`

  V/f open-loop control startup slew rate in V/Hz.

- `#define USER_VF_TRANSITION_SPEED_RPM (3500)`

  Defines the threshold speed to transition from open-loop control to closed-loop control.

- `#define USER_VF_SPEED_RAMPUP_RATE_RPM_PER_S  (3500U)`

  V/f open-loop control startup ramp-up rate in RPM per second.

4.5.6.2 V_q voltage control scheme configuration

- `#define USER_VQ_REF_HIGH_LIMIT_V (USER_VDC_LINK_V / USER_SQRT_3_CONSTANT)*1.15`

  Defines the limit of the reference torque voltage. The maximum voltage reference is defined as the DC-link voltage divided by the square root of 3, multiplied by 1.15 to cater for overmodulation.

- `#define USER_VQ_REF_LOW_LIMIT_V          (0.2f)`

  Sets the minimum V_q reference voltage required for the motor to operate in a closed loop.

- `#define USER_VQ_RAMPUP_STEP              (1U)`

  V_q voltage increment step in the target count.

- `#define USER_VQ_RAMPDOWN_STEP            (1U)`

  V_q voltage decrement step in the target count.

- `#define USER_VQ_RAMP_SLEWRATE            (10U)`

  The V_q voltage ramping cycle time is (USER_VQ_RAMP_SLEWRATE * PWM period). The V_q voltage increases (USER_VQ_RAMPUP_STEP) or decreases (USER_VQ_RAMPDOWN_STEP) every cycle.

4.5.6.3 Speed inner current control scheme configuration

- `#define USER_SPEED_REF_HIGH_LIMIT_RPM    (USER_SPEED_HIGH_LIMIT_RPM)`

  Defines the upper limit of the user speed reference.

- `#define USER_SPEED_REF_LOW_LIMIT_RPM     (USER_SPEED_LOW_LIMIT_RPM)`

  Defines the lower limit of the user speed reference.

- `#define USER_SPEED_RAMPUP_RPM_PER_S      (25U)`
- `#define USER_SPEED_RAMPDOWN_RPM_PER_S    (25U)`
- `#define USER_SPEED_RAMP_SLEWRATE         (2)`

  The V_q voltage ramping cycle time is (USER_SPEED_RAMP_SLEWRATE * PWM period). The speed increases (USER_SPEED_RAMPUP_RPM_PER_S) or deceases (USER_SPEED_RAMPDOWN_RPM_PER_S) every cycle.

4.5.6.4 SVM switching sequences

- `#define USER_SVM_SWITCHING_SCHEME        (STANDARD_SVM_7_SEGMENT)`

  Options:

  – STANDARD_SVM_7_SEGMENT

- STANDARD_SVM_5_SEGMENT

- `#define USER_SVM_SINE_LUT_SIZE (1024U)`

  Defines the lookup table (LUT) array size.

  Options:

  - 256U
  - 1024U

- `#define USER_SCALE_UP_SINE_LUT (10U)`
  - Scales up the LUT by 10 to increase the resolution.

- `#define USER_VDC_VOLT_COMPENSATION (ENABLED)`

  DC bus voltage compensation. The DC bus voltage change is compensated if it is enabled.

  Options:

  - ENABLED
  - DISABLED

4.5.6.5 ADC and motor phase current offset calibration

- `#define USER_ADC_CALIBRATION (ENABLED)`

  ADC startup calibration.

  Options:

  - ENABLED
  - DISABLED

- `#define USER_MOTOR_PH_OFFSET_CALIBRATION (ENABLED)`

  Motor phase current offset calibration.

  Options:

  - ENABLED
  - DISABLED

4.5.6.6 d-q voltage decoupling components

- `#define USER_DQ_DECOUPLING (DISABLED)`

  Options:

  - ENABLED
  - DISABLED

4.5.6.7 PLL observer setting

- `#define USER_PLL_LPF (2)`

PLL estimator filter coefficient.

Options:

- 0: Filter disabled
- >0: Filter enabled

- `#define USER_PLL_SPEED_LPF (2)`

  PLL estimator speed filter coefficient.

  Options:

  - 0: Filter disabled
  - >0: Filter enabled

4.5.6.8 Braking configuration

- `#define USER_MOTOR_BRAKE_DUTY (20U)`

  Defines the brake duty percentage. For example, set '100' for strong brake and '10' for weak brake.

- `#define USER_BRAKING_VDC_MAX_LIMIT (115U)`

  Defines the percentage of the DC link voltage for voltage clamping during the brake.

4.5.6.9 Configuration to enable or disable Micrium/MicroInspector

- `#define USER_UCPROBE_GUI (ENABLED)`

  Options:

  - ENABLED
  - DISABLED

- `#define USER_UCPROBE_OSCILLOSCOPE (DISABLED)`

  Options:

  - ENABLED
  - DISABLED

4.5.6.10 Configuration of GUI 6EDL_SPI_LINK code

- `#define GUI_6EDL7141_INTEGRATION (SWD_MODE)`

  Options:

  - DISABLED
  - SWD_MODE

4.5.6.11 PI controller parameters

- `#define USER_PI_SPEED_KPP (8000)`

Defines the proportional gain K_p of the speed controller.

- `#define USER_PI_SPEED_KII                    (1)`

  Defines the integral gain K_i of the speed controller.

- `#define USER_PI_SPEED_SCALE_KPKII            (9+USER_RES_INC)`

  Defines the K_p and K_i scale of the speed controller.

- `#define USER_PI_PLL_KP                       (20)`

  Defines the proportional gain K_p of the PLL observer.

- `#define USER_PI_PLL_KI                       (1)`

  Defines the integral gain K_i of the PLL observer.

- `#define USER_PI_PLL_SCALE_KPKI               (9)`

  Defines the K_p and K_i scale of the PLL observer.

- `#define USER_PI_SPEED_UK_LIMIT_MIN           (0)`

  Defines the minimum output of the speed controller.

- `#define USER_PI_SPEED_UK_LIMIT_MAX           (32767)`

  Defines the maximum output of the speed controller.

- `#define USER_PI_TORQUE_UK_LIMIT_MIN          (-32768)`

  Defines the minimum output of the torque controller.

- `#define USER_PI_TORQUE_UK_LIMIT_MAX          (38000)`

  Defines the maximum output of the torque controller.

- `#define USER_PI_FLUX_UK_LIMIT_MIN            (-32768)`

  Defines the minimum output of the flux controller.

- `#define USER_PI_FLUX_UK_LIMIT_MAX            (5000)`

  Defines the maximum output of the flux controller.

4.5.6.12 PMSM FOC variables scaling

- `#define USER_RES_INC                         (2U)`

  This definition increases the calculation resolution for the angle and speed.

- `#define SCALEUP_MPS_K                        (8U)`

Defines the CORDIC scaling.

- `#define SPEED_TO_RPM_SCALE                    (11U)`

  Defines the scaling for converting the speed value in software to RPM engineering units.

5 Configuring the board parameters

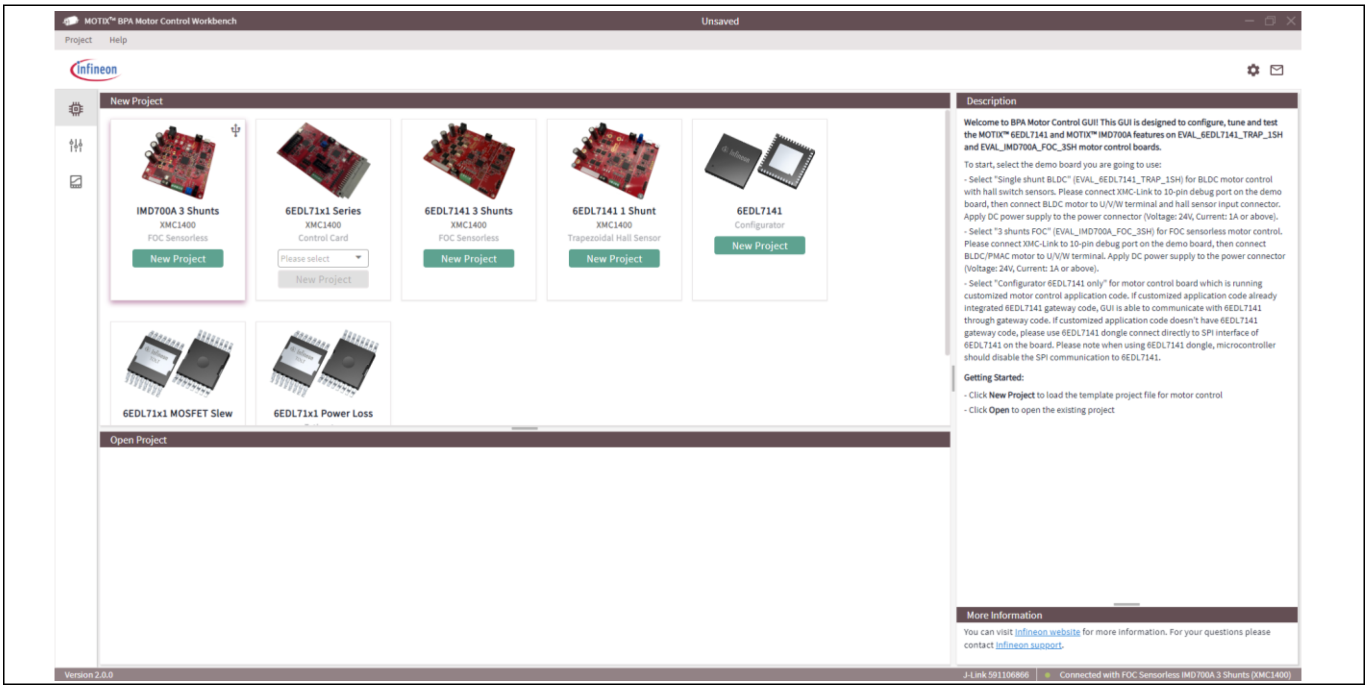


Figure 22 MOTIX™ BPA Motor Control Workbench v2.0.0 launch screen

To start a new project:

1. Start MOTIX™ BPA Motor Control Workbench.
2. On the launch screen, in the **New Project** area, select the required configuration.
3. Select the REF_IMD701A_720W_DC24 reference board, which is a three-shunt design for PMSM.
4. Expand the drop-down menu from the **IMD700A 3 Shunts** option in the **Parameter Controls** panel.
5. Set the details of parameters based on the system setup and solution required.

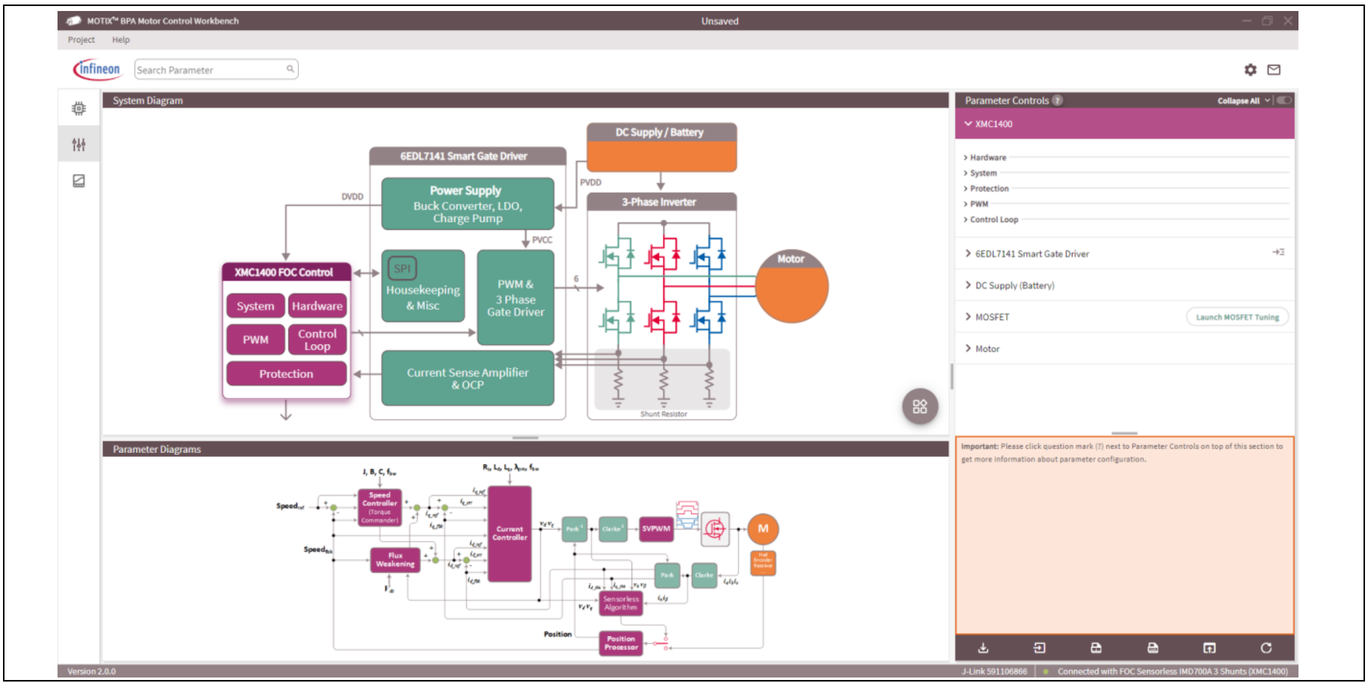


Figure 23 IMD700A 3 Shunts firmware configuration menu

5.1 Installing the firmware from Workbench

To support the transfer of MOTIX™ IMD701A parameters from MOTIX™ BPA Motor Control Workbench, the firmware must include the functions that support this. The REF_IMD701A_720W_DC24 board is pre-installed with the correct firmware and parameters.

MOTIX™ BPA Motor Control Workbench includes a suite of firmware options that can be downloaded to any compatible motor drive board that uses the XMC1400 MCU with MOTIX™ 6EDL7141 or the integrated MOTIX™ IMD700/1A gate drivers. In Figure 23, the right-hand side shows the XMC1400 group expanded to show the firmware options available. Figure 24 shows some of the firmware options that are available such as the PWM frequency and dead-time.

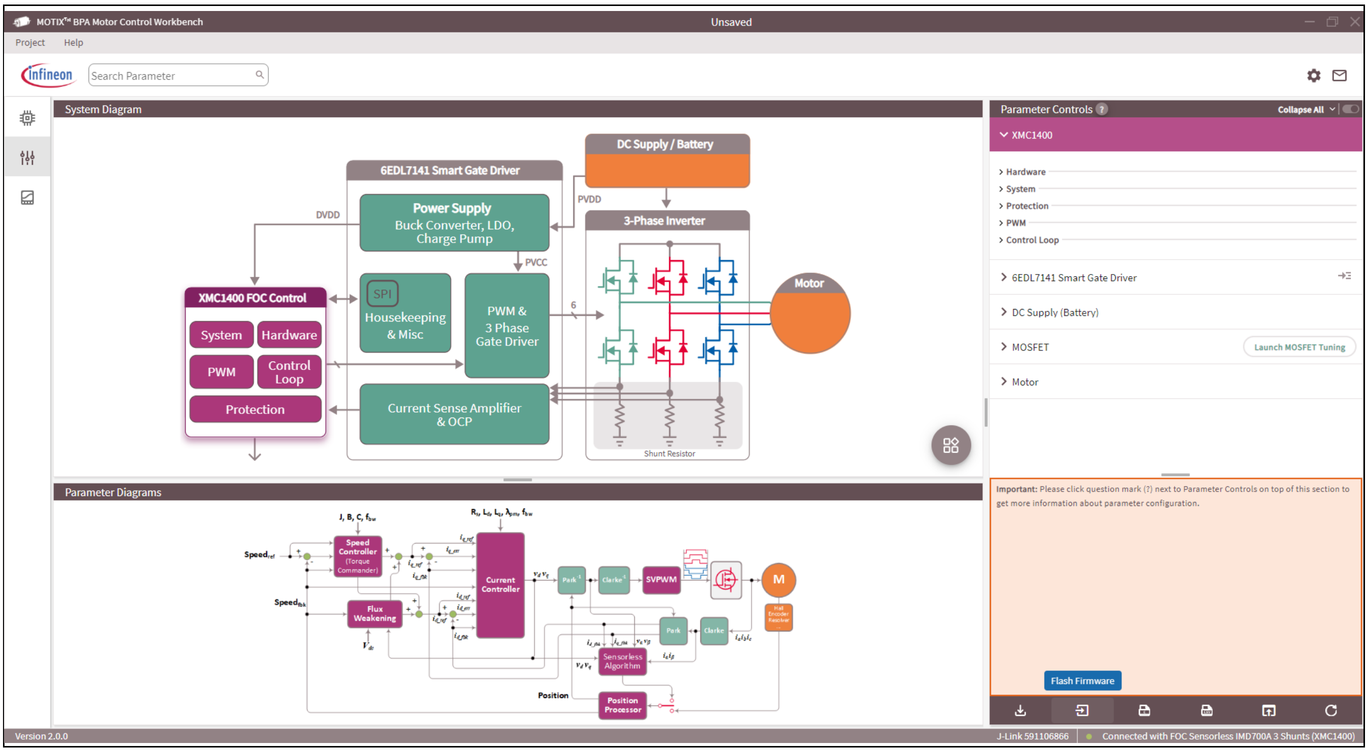


Figure 24 Firmware options and download

1. On the **Parameter Controls** panel on the right, select and configure the parameters as listed in the following table.

   You need to select the firmware parameters listed in Table 3 before downloading. These parameters depend on the components on the board, motor specification, and application, and need to be changed according to the actual situation.

Table 3 Firmware parameters

Parameter	Description	Value	Unit
Hardware			
ADC reference voltage	VADC reference voltage, same as DVDD	5	V
Shunt resistor	BOM RS1, RS2, RS3	1	mΩ
System			
Potentiometer control	Enable hardware potentiometer	Enable	–

Parameter	Description	Value	Unit
Control scheme	Select command parameter	Speed inner current control	–
Protection			
Overvoltage threshold (18 V and 24 V settings)	Maximum DC input voltage	25.2/33.6	V
Undervoltage threshold (18 V and 24 V settings)	Minimum DC input voltage	10.8/14.4	V
DC-link over/undervoltage	Input voltage under/overvoltage	Enable	–
PWM			
PWM frequency	PWM switching frequency	20	kHz
Dead time	PWM dead-time for rising edge	0.75	µs
DC bus compensation	Enable/disable DC bus compensation	Enable	–
DQ decoupling	-	Disable	–
Control loop			
Rotor initial position detection	-	Rotor IPD pre-alignment	-
Pre-alignment ramp rate	–	100	V/s
Pre-alignment voltage	–	0.8	V
Pre-alignment time	–	100	ms
Direct FOC startup Vq voltage	–	0.8	V
Open-loop V/f startup offset voltage	–	0.5	V
Open-loop startup V/f constant	–	0.08	V/Hz
Motor startup method	–	MOTOR_STARTRUP_DIRECT_FOC	-
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	-
DC supply			
Nominal DC-link voltage[1]	Nominal input/battery voltage	18/24	V
Voltage divider R-high	Input voltage divider high resistance	75	kΩ

[1] This needs to be changed for different input voltages. In this case the nominal voltage is 18 V and the maximum is 24 V.

Parameter	Description	Value	Unit
Voltage divider R-low	Input voltage divider low resistance	7.87	kΩ
Motor			
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
Pole pairs	Number of rotor pole pairs	4	–

2. Click the **Flash XMC Firmware** button on the bottom right to download the firmware to the board via the USB cable.
   A message will appear that the firmware was successfully programmed onto the MCU.
3. Click **Write Parameters** to write the updated parameters to IMD700A.
4. Power cycle the target board after updating the firmware to update all the parameters.

5.2 Configuring MOTIX™ 6EDL7141 parameters

Using the Workbench, you can select and update the PWM configuration and gate driver parameters for MOTIX™ 6EDL7141. These parameters include the onboard power supply and charge pump settings, CS amplifiers, and OCP thresholds.

1. On the panel on the right, under **6EDL7141 Smart Gate Driver**, expand the **PWM & 3 Phase Gate Driver** group on the panel on the left.
2. Select each parameter from the options available.

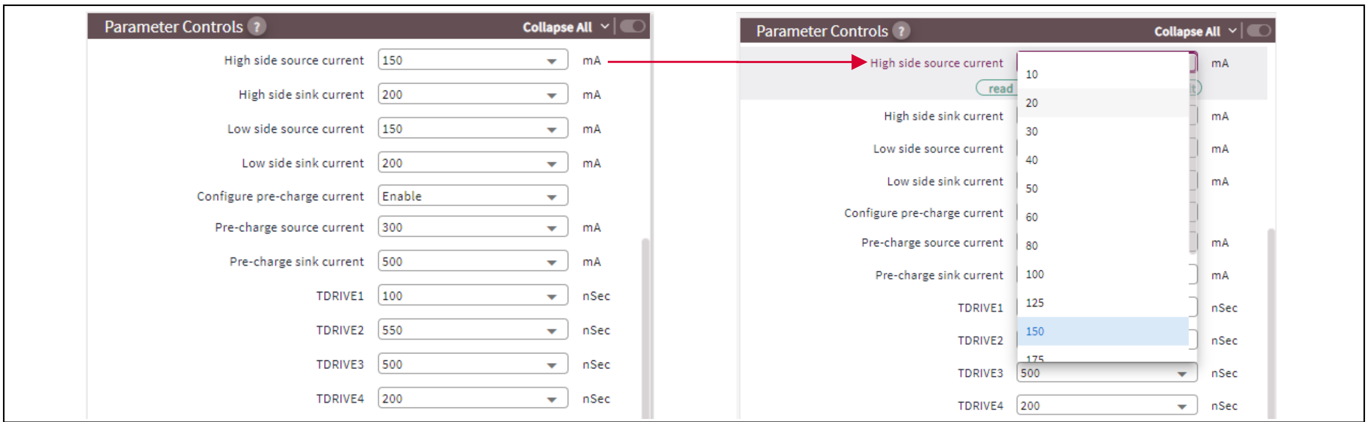


Figure 25 Selecting the gate drive parameters

3. Select **Project** > **Save** at the top left of the screen to save the project. The project file has a *.6EDL* extension.
4. Connect the target board directly to a USB port on the PC.

Note: The target board containing MOTIX™ IMD701A can be connected to the PC via an XMC™ LINK debugger; however, this is not necessary for the REF_IMD701A_720W_DC24 reference board because it has its own onboard debugger.

5. Program MOTIX™ 6EDL7141 using one of the following options:

Figure 26 Transferring the settings to MOTIX™ IMD701A

- Use the **Write Parameters** option to transfer the configuration to the volatile memory on the board. This configuration will remain only while MOTIX™ 6EDL7141 is powered. Use this option during bench testing and optimization until the you have verified that correct values have been selected. If values are changed during bench evaluation, the project should be saved again.
- Use the **Burn 6EDL7141 OTP** option to permanently set the configuration of MOTIX™ 6EDL7141 parameters within MOTIX™ IMD701A in the OTP memory. Use this option when after validating the final values that match your performance requirements.

Table 4 Additional MOTIX™ 6EDL7141 parameters

Parameter	Value	Unit
Power supply		
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 soft-start time	100	µs
DVDD turn-on delay	800	µs
DVDD OCP threshold	450	mV
PWM and three-phase gate driver[2]		
PWM mode	6 PWM	–
PWM freewheeling mode	Diode FW	–
Brake configuration	Low-side	–
Alternate recirculation	Disable	–
Pre-charge	Enable	–
CS and OCP		
Amplifier A	Enable	–
Amplifier B	Enable	–
Amplifier C	Enable	–
Amplifier gain	12x	–
Amplifier mode	Shunt resistor	–
Internal offset selection	1/2 DVDD	–
Use external offset	Disable	–
Amplifier timing mode	GLx high	–

[2] See Table 3 for parameters not listed here.

Parameter	Value	Unit
Power supply		
Amplifier blanking time	0	ns
Amplifier auto-zero	Internal trigger	–
OCP positive threshold	70	mV
OCP negative threshold	-70	mV
PWM truncation	Disable	–
OCP deglitch time	8	µs
OCP fault trigger	Always trigger	–
OCP fault latching	Enable	–
Brake on OCP	Enable	–
Negative OCP	Enable	–
Housekeeping		
Hall sensor deglitch time	0	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	–

5.3 Using the Workbench to control the board

You can use MOTIX™ BPA Motor Control Workbench to control and monitor the operation of a MOTIX™ IMD701A-based motor drive inverter such as the REF_IMD701A_720W_DC24.

- Click the **Test Bench** icon on the left panel to start the Test Bench.

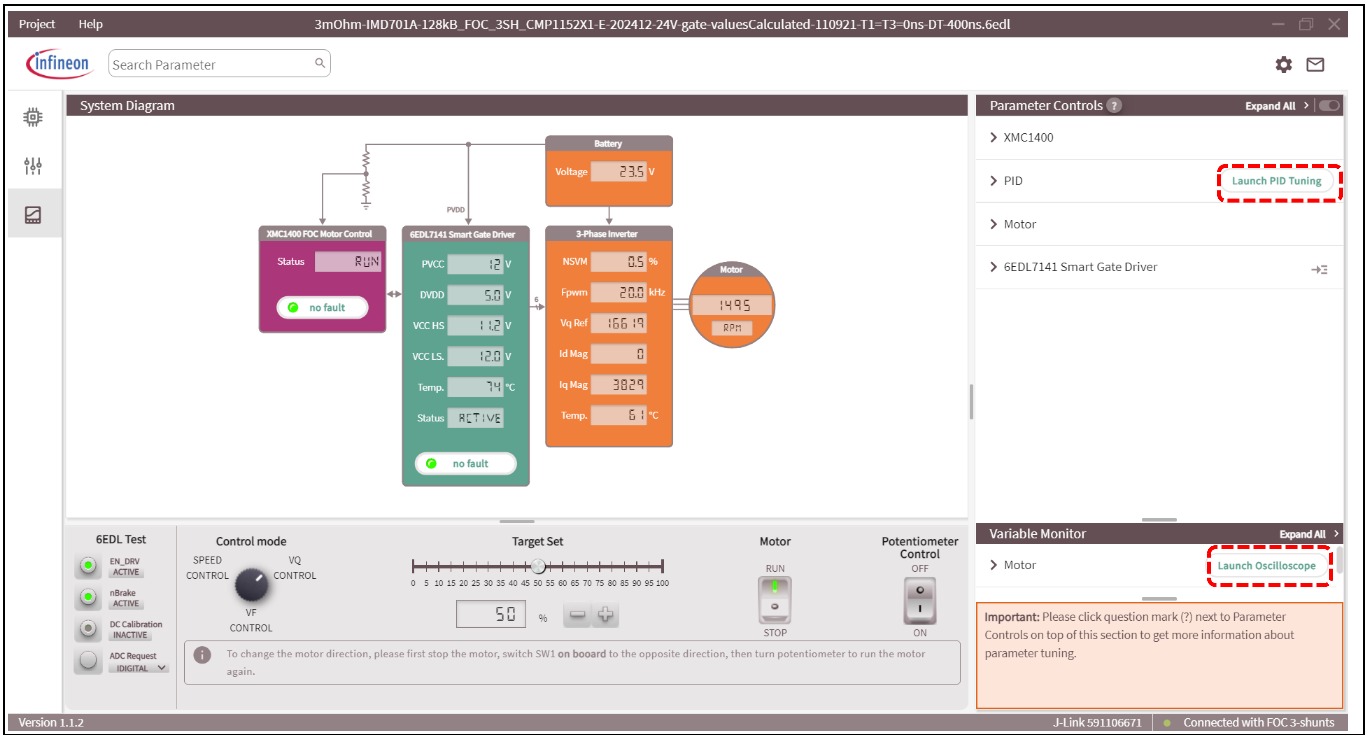


Figure 27 **Workbench Test Bench screen**

5.3.1 Monitor parameters on Test Bench

The Test Bench screen provides a real-time display of the parameters such as the following:

- Power supply
- Internal regulator
- Charge pump voltages
- Battery input voltage
- Rotor RPM
- Motor current
- PWM switching frequency and duty cycle
- MOTIX™ IMD701A temperature from its integrated sensor
- Fault status

5.3.2 Control operations

In addition to monitoring the system, you can control the following operations:

- Change the motor control mode
- Change the direction and speed using the control mode knob and target set slider controls
- Start/stop the motor via the motor switch
- Enable/disable the board-mounted speed control potentiometer.

Note: *To control the speed through Workbench, the potentiometer control switch on the right must be in the "OFF" position.*

5.3.3 Monitor and change control loop parameters

You can monitor and change the control loop parameters through the PID tuning screen.

1. Click **PID Tuning** to launch the screen from the Test Bench screen.
2. Click **Launch Oscilloscope**. You can view the output waveforms in the oscilloscope screen.

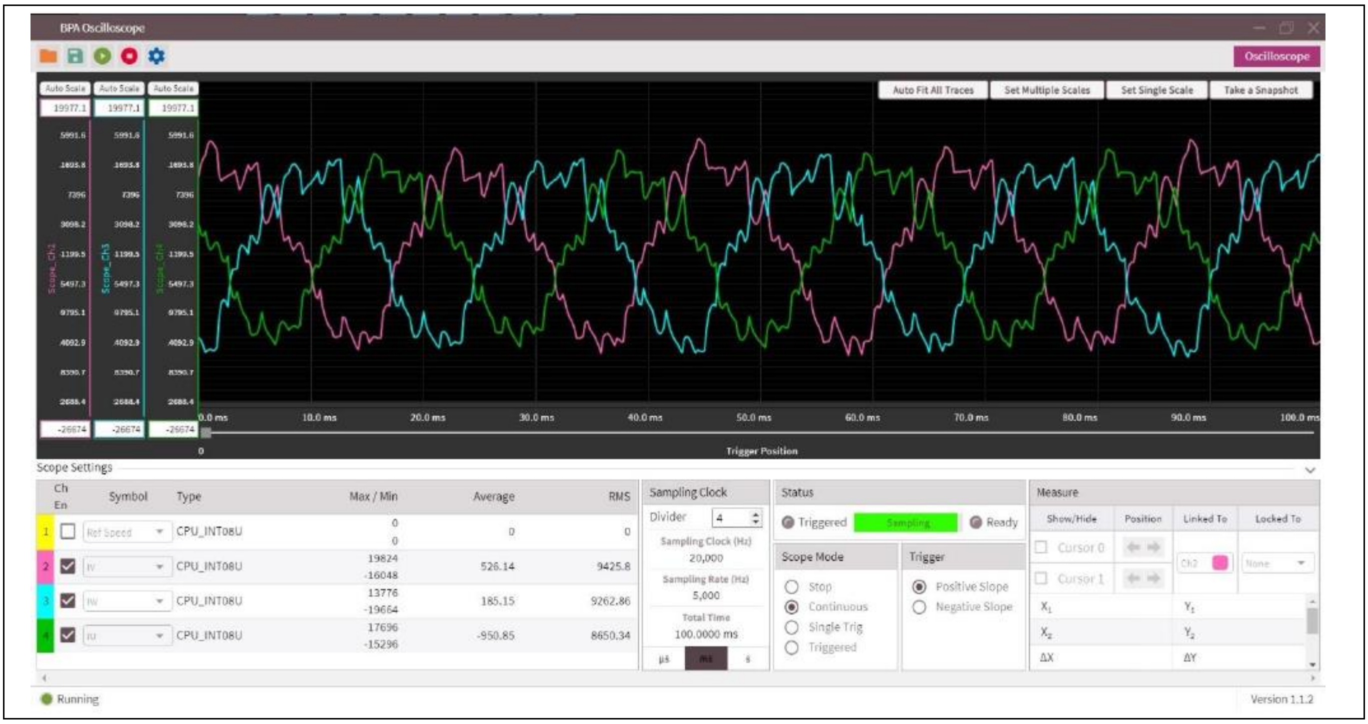


Figure 28 Oscilloscope view showing the phase currents; I_u (green), I_v (red), I_w (blue)

5.4 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. You can tune the K_p, K_i and scale parameters for flux, PLL, speed, and torque by adjusting the values in the PID tuning screen to optimize the system response as follows:

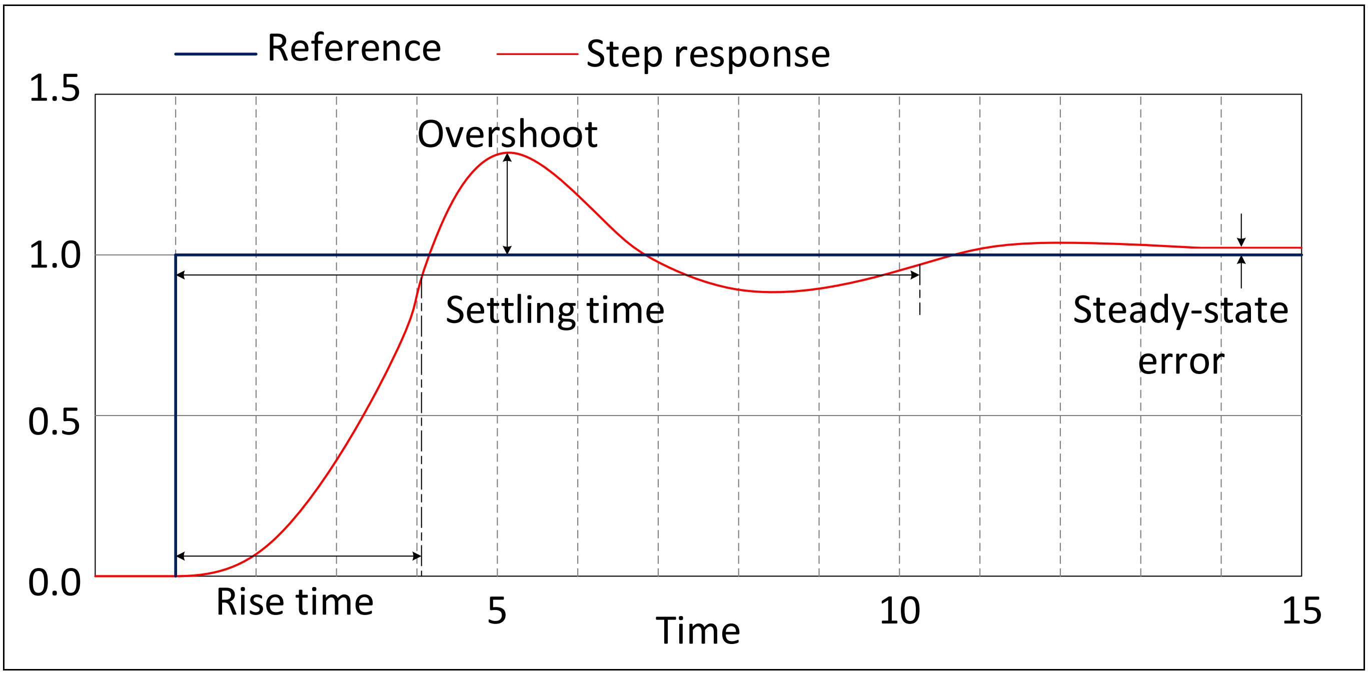


Figure 29 Step response of a control loop

1. Click inside the box and change the value according to the instructions displayed on the right-hand panel.
2. Click the **Save** button to download the new values to MOTIX™ IMD700/1A.

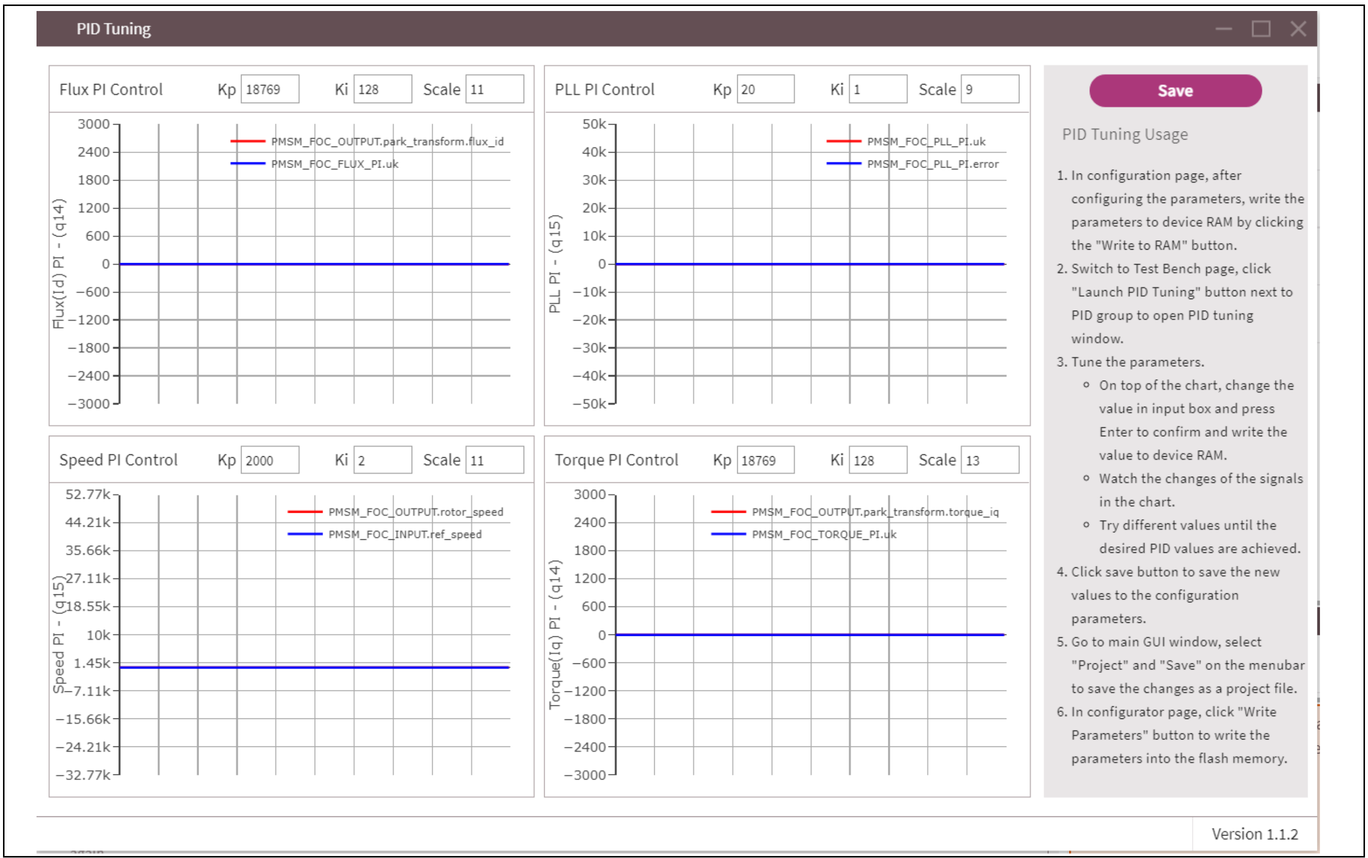


Figure 30 **PID tuning screen**

5.4.1 Tuning the V_q control loop

You need to tune only I_d or flux PI control and PLL PI control (for the PLL estimator) for V_q control. Tuning the control loop enables smooth running of the motor, producing sinusoidal phase current waveforms and compensating for motor load changes.

Each control loop has 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:

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

where K_p and 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 MOTIX™ BPA Motor Control Workbench'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. See Table 5 for the effects of increasing the proportional gain K_p or integral gain K_i of the PI controller independently:

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.

5.4.2 Tuning the speed control loop

There are four control loops:

- PLL PI control
- Flux PI control
- Torque PI control
- 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.

For V_q control-loop tuning, use the PI tuning and oscilloscope tools. If the phase current waveform is distorted when adjusting the scale value of the speed PI control, you need 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. Note that the K_p, K_i, and scale values for both flux and torque PI control should be the same when tuning the speed control of the motor.

6 Bill of materials

Table 6 Bill of materials

Reference	Qty	Value/rating	Manufacturer	Part number
C1, C2, C3	3	270 µF/35 V/radial	United Chemi-Con	EKZE350ELL271MH20D
C4, C5, C7, C8, C10, C11	6	2.2 µF/50 V/X5R/0603	Murata Electronics	GRM188R61H225ME11D
C6, C9, C12	3	4.7 µF/50 V/X5R/0805	Murata Electronics	GRM21BR61H475KE51L
C23, C25, C27	3	330 pF/25 V/X7R/0603	Wurth Electronics Inc.	8.85012E+11
C24	1	0.01 µF/25 V/X7R/0402	AVX	04023C103KAT4A
C26, C41, C44, C326	4	0.1 µF/25 V/X7R/0603	KEMET	C0603X104M3RAC7867
C28, C30, C34	3	100 pF/25 V/NP0/0402	KEMET	C0402C101J3GACTU
C29, C31	2	1 µF/25 V/X5R/0603	Samsung Electro-Mechanics	CL10A105KA8NNNC
C33, C325	2	0.1 µF/25 V/X5R/0402	Samsung Electro-Mechanics	CL05A104KA5NNNC
C35	1	1 µF/100 V/X7S/0805	TDK Corporation	C2012X7S2A105K125AB
C37, C38	2	4.7 µF/100 V/X7S/1210	TDK Corporation	CGA6M3X7S2A475K200AB
C40	1	4.7 µF/25 V/X5R/0805	Samsung Electro-Mechanics	CL21A475KAQNNNG
C43, C48, C327	3	10 µF/16 V/X5R/0603	Murata	GRM188R61C106KAALD
C45	1	0.47 µF/100 V/X7S/0805	TDK	C2012X7S2A474M125AE
C49, C328	2	0.220 µF/16 V/X7R/0603	TDK	CL10B224KO8NNNC
C50	1	0.47 µF/25 V/X7R/0603	Murata	GRM188R71E474KA12D
C51, C52	2	22 µF/16 V/X5R/0603	Samsung Electro-Mechanics	CL10A226MO7JZNC
C56, C57, C58	3	0.01 µF/25 V/X5R/0603	AVX	06033D103KAT2A
C68, C69, C329	3	2.2 µF/100 V/X7S/1206	TDK	CGA5L3X7S2A225K160AB
C181	1	0.1 µF/100 V/X7R/0603	Yageo	CC0603KRX7R0BB104
C207, C208, C209	3	2.2 µF/50 V/X5R/0603	Murata Electronics	GRM188R61H225KE11D
C301, C305, C306, C308, C309, C310, C311, C312, C318, C319	10	0.1 µF/25 V/X7R/0402	Vishay Vitramon	VJ0402Y104KXXCW1BC
C302, C303	2	15 pF/25 V/NP0/0402	Walsin Technology Corporation	0402N150J250CT
C304	1	10000 pF/25 V/X7R/0402	Kemet	C0402C103J3RACAUTO
C307	1	4.7 µF/25 V/X5R/0603	Taiyo Yuden	TMK107BBJ475MA-T

Reference	Qty	Value/rating	Manufacturer	Part number
C313, C315	2	10 µF/25 V/X5R/0603	Murata Electronics	GRM188R61E106MA73J
C314	1	10000 pF/25 V/X7R/0402	Kemet	C0402C103J3RACAUTO
C316, C317	2	1 µF/6.3 V/X5R/0402	Taiyo Yuden	JMK105BJ105KV-F
C322, C323, C324	3	2200 pF/50 V/X5R/0402	TDK	C1005X5R1H222K050BA
D1	1	Schottky/100 V/2 A/SMA	STMicroelectronic s	STPS2H100AY
D4, D5, D8, D316, D317, D318, D319	7	Zener/5.1 V/500 mW/SOD-523	On-Semi	MM5Z5V1T1G
D14	1	TVS/22 V/35.5 V/SMA	Diodes Incorporated	SMAJ22A-FDICT-ND
D301	1	Schottky/30 V/1 A/SOD323	Infineon	BAS3010A-03W
D302	1	TVS/15 V/3 A/TSLP-3-7	Infineon	ESD5V3U2U-03LRH E6327
D315	1	500 mA/30 V/TSLP-2-17	Infineon	BAS3005S-02LRH
F1	1	10 A/32 V AC/ 63 V DC/1206	Littelfuse Inc.	0458010.DR
IC301	1	IC MCU 32-bit 256 kB Flash 48VQFN	Infineon	XMC4200Q48K256BAXUM A1
IC302	1	IC linear/3.3 V/ 300 mA/TSON-10	Infineon	IFX54441LDV33XUMA1CT -ND
IC303	1	DGTL ISO 2500 V_{RMS} 6 CH GP 16 SOIC	Silicon Labs	634-SI8662BB-B-IS1
IC304	1	IC buffer/5.5 V/5TSSOP	Nexperia	74LVC1G126GW,125
J6	1	Jack connector R/A PCB 5.5x2.1 mm	Tensility International Corp.	54-00129
J7	1	Header/8-pos/1.27 mm	Sullins Connector Solutions	GRPB042VWVN-RC
LED1, LED2	2	Blue/2.85 V/0603	Osram	LB Q39G-L2OO-35-1
LED3, LED301	2	Green/2.2 V/0603	Rohm Semiconductor	SML-D12M8WT86
LED4, LED302, LED303	3	Red/2 V/0603	Lite-On Inc.	LTST-C190KRKT
L2	1	22 µH/1 A/4020	Würth Elektronik	74437324220
L301	1	Ferrite bead/60 Ω/500 mA /0603	Würth Elektronik	74279267
POT4	1	Trimmer/10k/0.5 W	Bourns Inc.	3362P-1-103TLF
Q1, Q2, Q3, Q4, Q5, Q6	6	N-channel/40 V/31 A /8TSON	Infineon	BSC007N04LS6

Reference	Qty	Value/rating	Manufacturer	Part number
Q301	1	Crystal/12 MHz/8 pF	Kyocera International Inc. Electronic Components	CX3225GA12000D0PTVCC
RS1, RS2, RS3	3	3 mΩ/4 W/2512/1%	Bourns Inc.	CSS2H-2512K-3L00F
RT1	1	Sensor 40C/125C /SOT-23-3	Microchip Technology	MCP9700T-E/TT
R35, R38, R40	3	470/0.0625 W/0402/1%	Yageo	RC0402FR-07470RL
R36	1	75k/0.1 W/0603/1%	Panasonic	ERJ-3EKF7502V
R37	1	100k/0.1 W/0603/1%	Yageo	RC0603FR-07100KL
R39	1	7.87k/0.1 W/0603/1%	Yageo	RC0603FR-077K87L
R41	1	1k/0.1W/0603/0.5%	Yageo	RT0603DRD071KL
R42	1	200/0.1 W/0603/1%	Panasonic	ERJ-3EKF2000V
R43	1	100/0.0625 W/0402/1%	Yageo	RC0402FR-07100RL
R45, R47, R54, R55, R325	5	5.1k/0.1 W/0402/5%	Panasonic	ERJ-2GEJ512X
R50	1	0.1/0.2 W/0603/1%	Yageo	PT0603FR-7W0R1L
R56, R57, R309, R311, R312, R324	6	10k/0.0625 W/0402/5%	Yageo	RC0402JR-0710KL
R61, R62, R63	3	2.2k/0.1 W/0603/1%	Yageo	RC0603FR-072K2L
R64	1	1k/0.1 W/0603/5%	Yageo	RT0603DRD071KL
R65, R66, R67	3	3.3k/0.1 W/0603/1%	Yageo	RT0603FRE073K3L
R76, R91, R104	3	47k/0.1 W/0603/1%	Yageo	RC0603FR-0747KL
R81, R95, R109	3	1.65k/0.1 W/0603/1%	Panasonic	ERJ-3EKF1651V
R301, R302	2	680/0.0625 W/0402/1%	Vishay Dale	CRCW0402680RFKEDC
R305	1	510/0.1 W/0402/1%	Panasonic	ERJ-U02F5100X
R306, R307	2	22/0.1 W/0402/5%	Panasonic	ERJ-2GEJ220X
R308	1	4.7k/0.1 W/0402/1%	Panasonic	ERJ-2RKF4701X
R310, R314	2	1M/0.0625 W/0402/1%	Yageo	RC0402FR-071ML
R316	1	0/jumper/0201	KOA Speer Electronics	RK73Z1HTTC
R318	1	32.4k/0.0625 W/0402/1%	Bourns Inc.	CR0402-FX-3242GLFCT-ND
R319	1	3.3k/0.0625 W/0402/5%	Yageo	RC0402JR-073K3L
R321, R322, R323	3	0/jumper/0.1 W/0402	Panasonic	ERJ-2GE0R00X
ST1, ST2, ST3, ST4	4	Hex standoff, #4-40 aluminum, 1/4"	Keystone Electronics	8714
SW1	1	Switch slide SPDT/200mA/30V	E-Switch	EG1218
SW2, SW3	2	Switch slide SPST/ 0.4 V AC/28 V	NKK Switches	AS11CP

Reference	Qty	Value/rating	Manufacturer	Part number
U1	1	Smart IC/three-phase motor driver	Infineon	IMD701A-Q064x128
X2, X3, X4	3	Header 4x1/0.1"	Adam Tech	PH1-04-UA
X6	1	5P side ent. 2.54 mm	Phoenix Contact	MPT 0,5/ 5-2,54 - 1725685
X302C	1	USB micro	Würth Elektronik	629105150921

7 Schematics

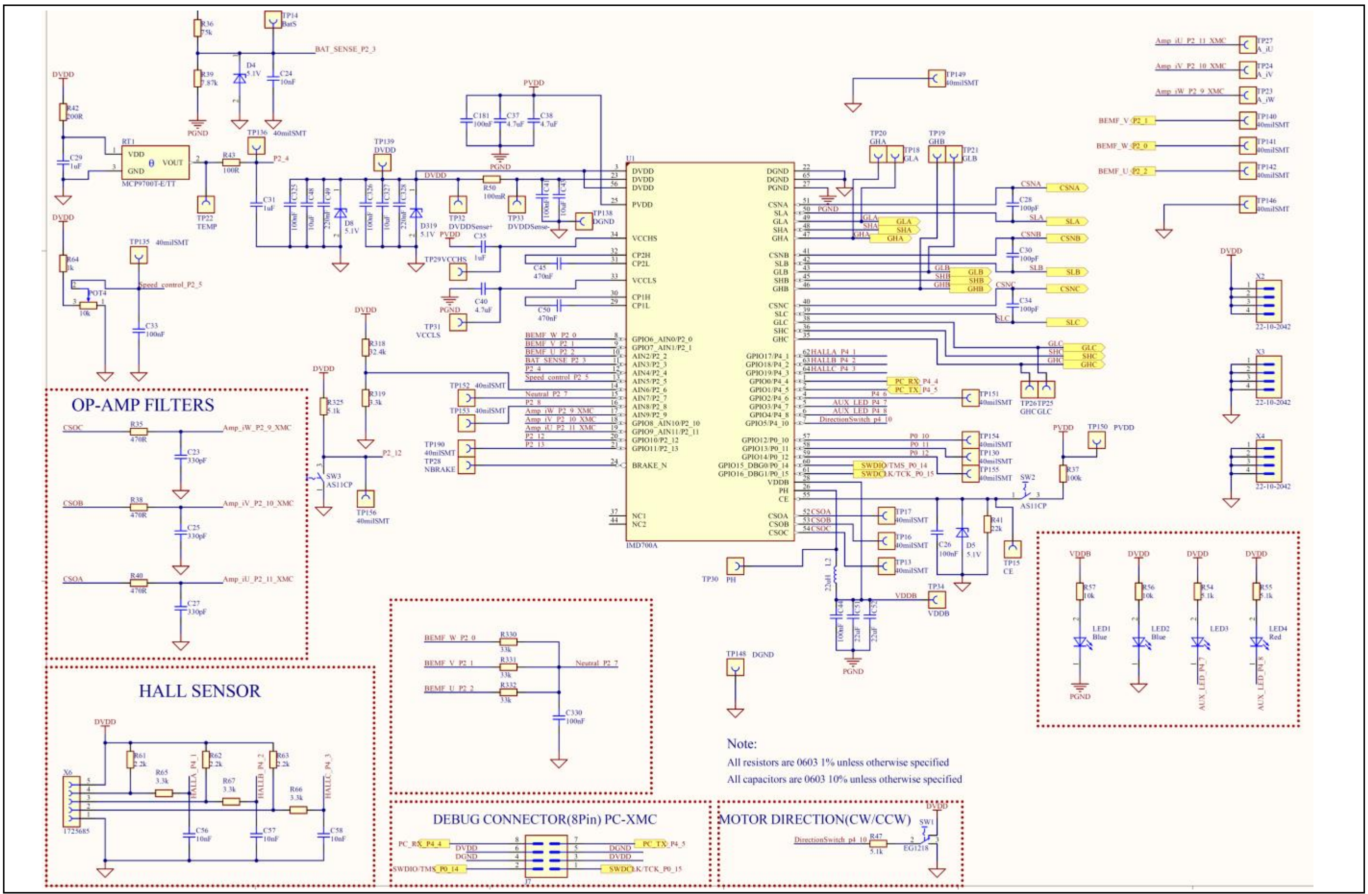


Figure 31 REF_IMD701A_720W_DC24 schematic – MOTIX™ IMD701A control and gate driver section

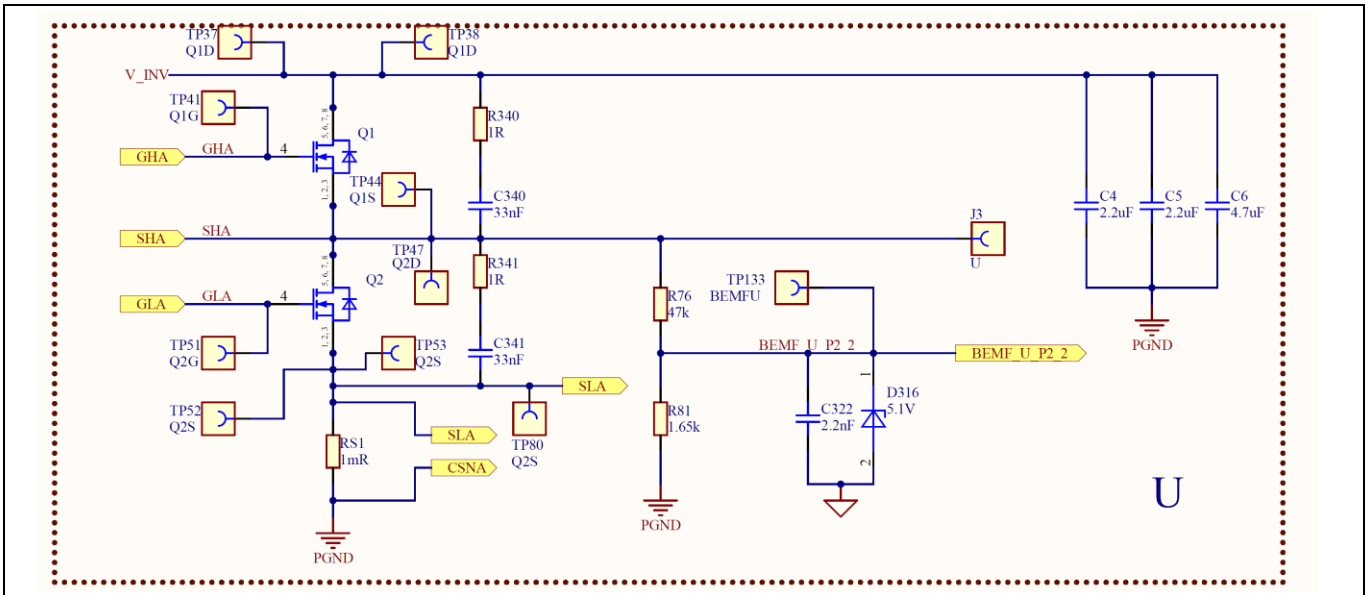


Figure 32 REF_IMD701A_720W_DC24 schematic – power stage, phase “U”

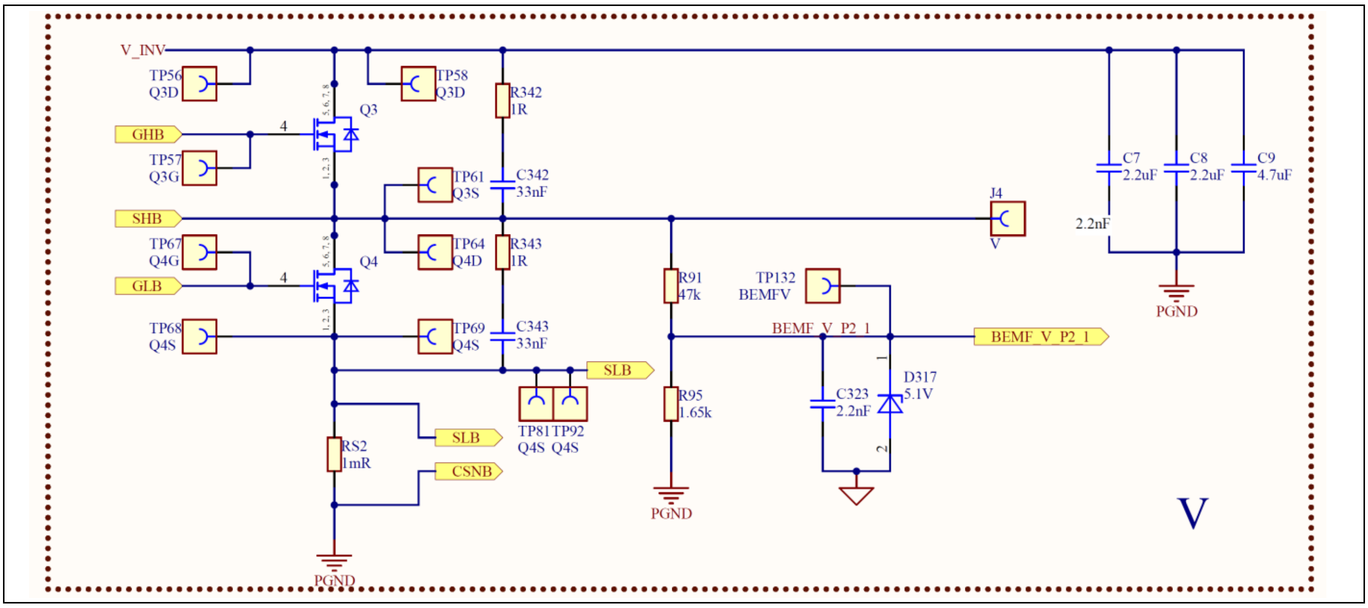


Figure 33 REF_IMD701A_720W_DC24 schematic – power stage, phase “V”

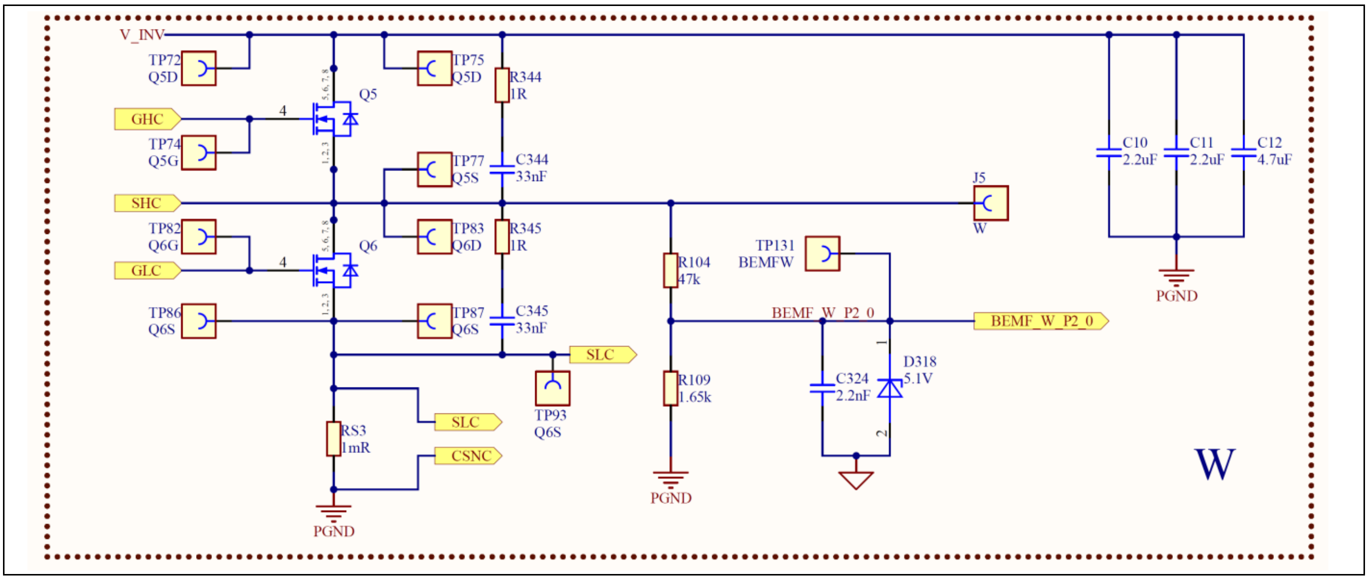


Figure 34 REF_IMD701A_720W_DC24 schematic – power stage, phase “W”

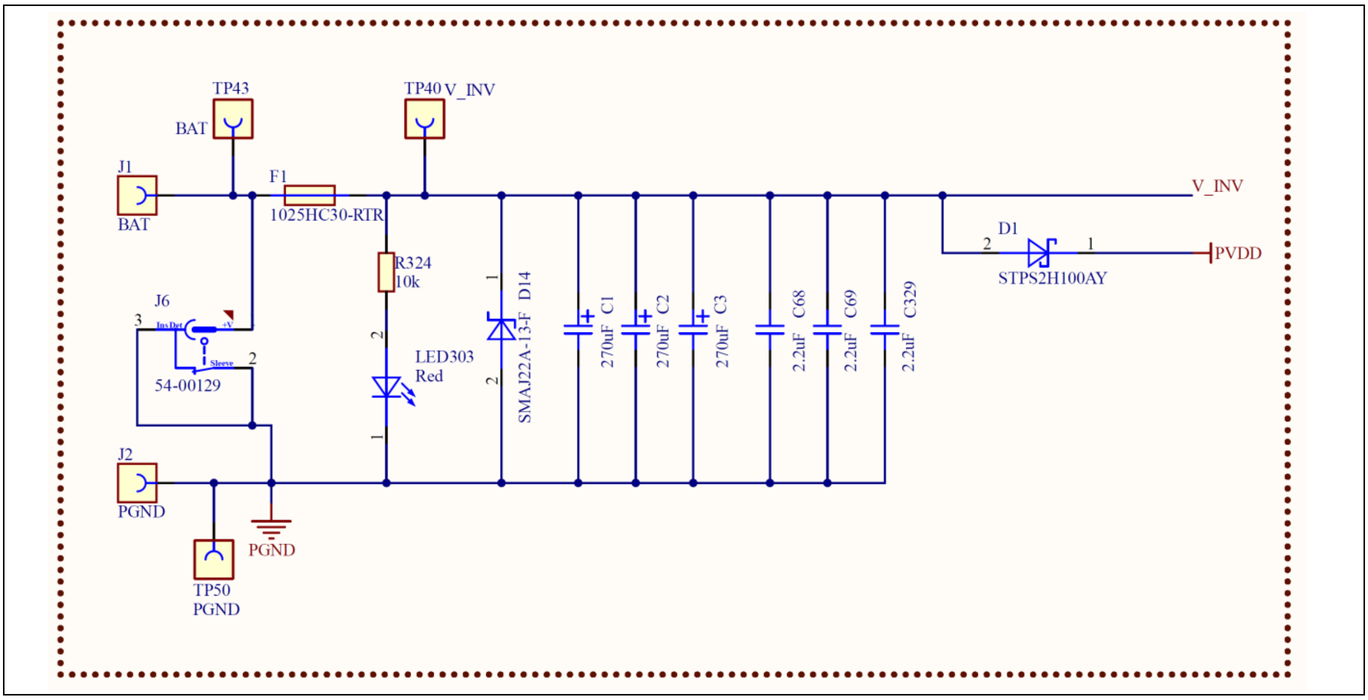


Figure 35 REF_IMD701A_720W_DC24 schematic – DC input

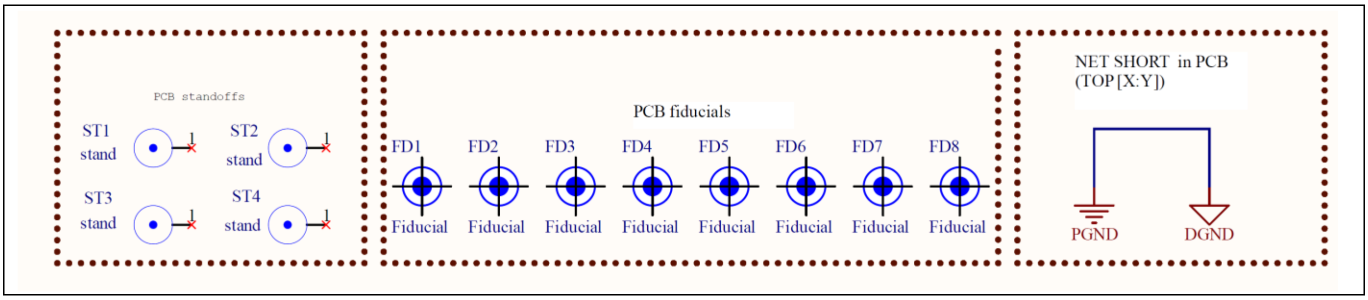


Figure 36 REF_IMD701A_720W_DC24 schematic – Standoffs and fiducials

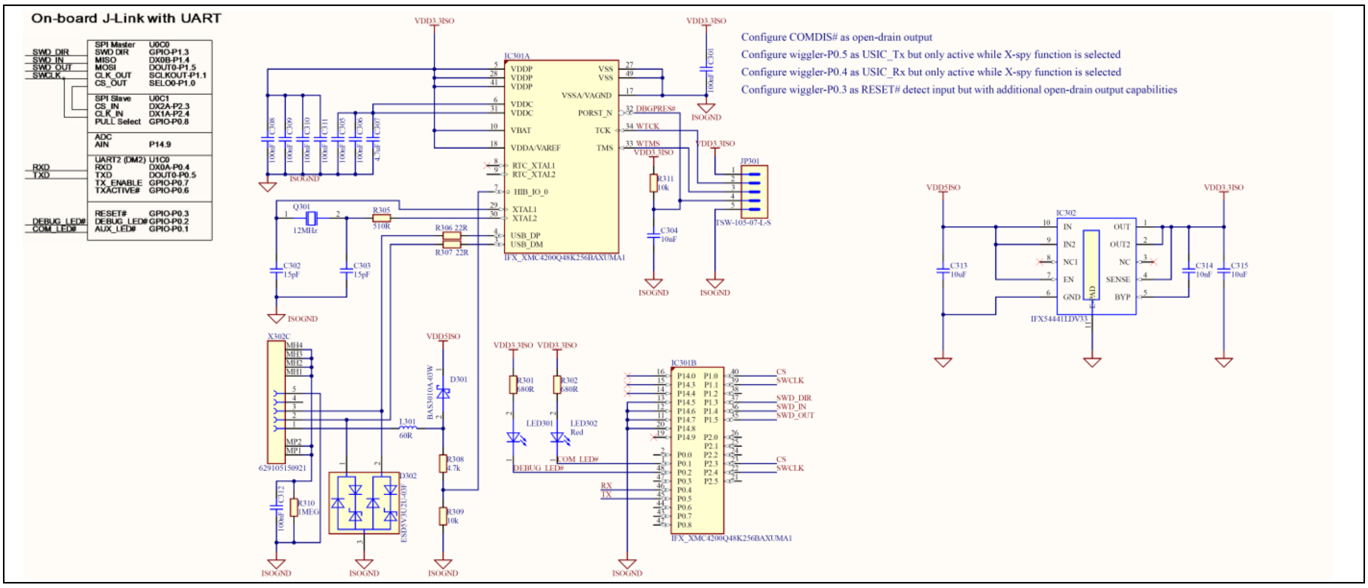


Figure 37 REF_IMD701A_720W_DC24 schematic – debugger controller section

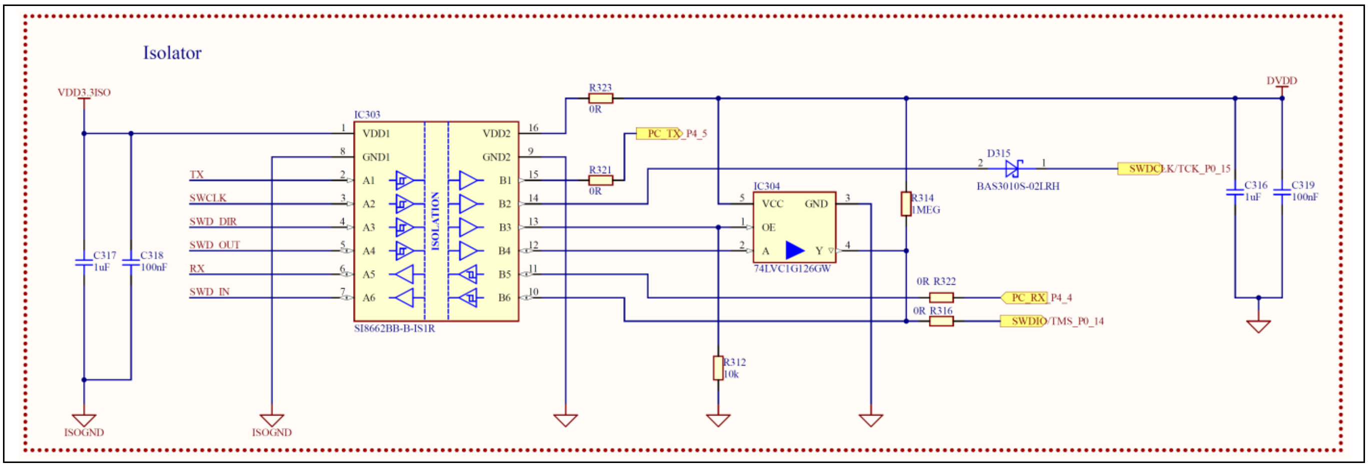


Figure 38 F_IMD701A_720W_DC24 schematic – isolators

8 PCB layout

The REF_IMD701A_720W_DC24 reference board utilizes a six-layer PCB with 2 oz. copper on each layer. Components are mounted on the top and bottom sides. The width is 83.1228 mm and the length is 83.1228°mm.

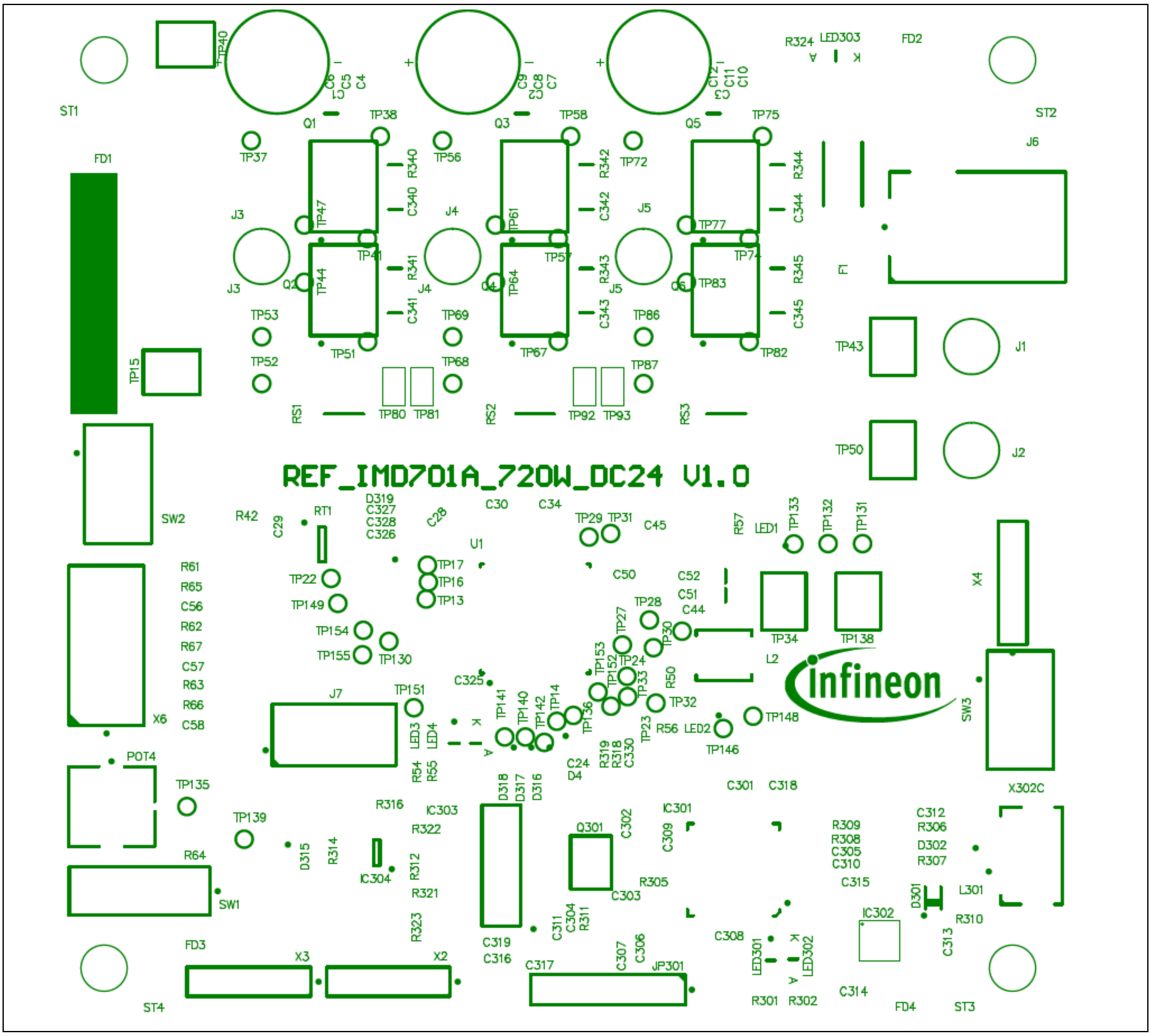


Figure 39 REF_IMD701A_720W_DC24 PCB top silkscreen

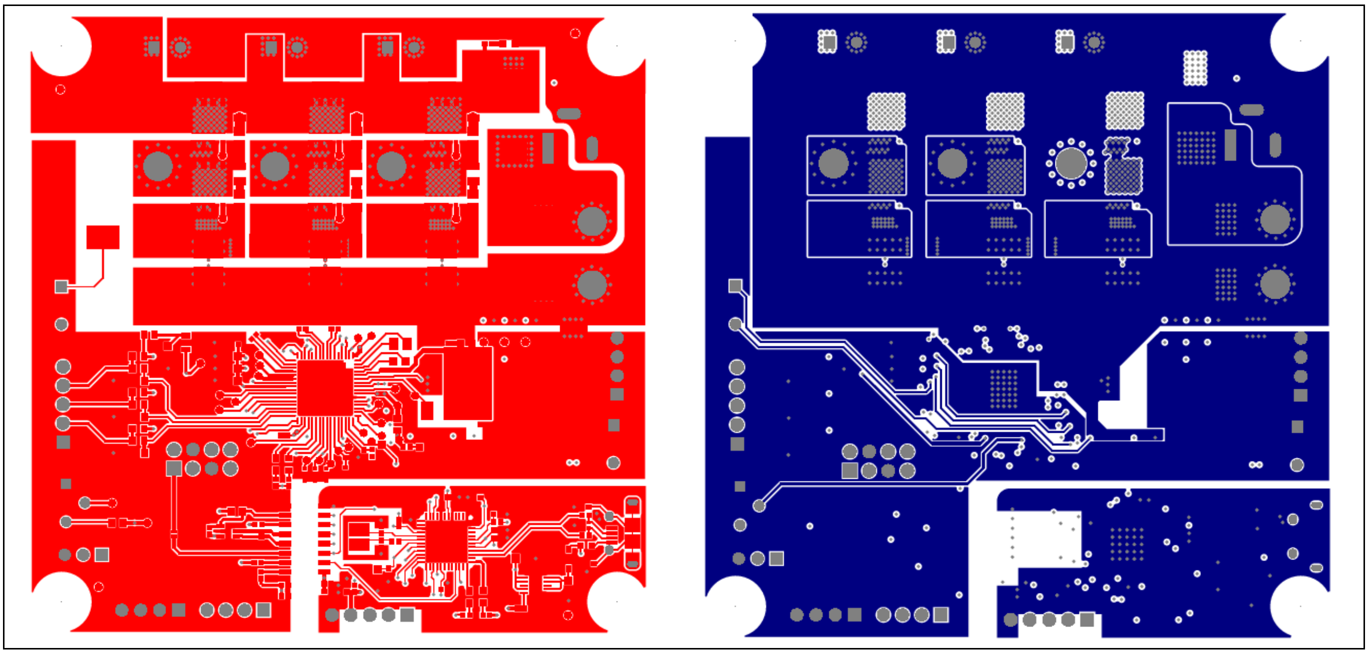


Figure 40 REF_IMD701A_720W_DC24 PCB top layer (left) and layer 2 (right)

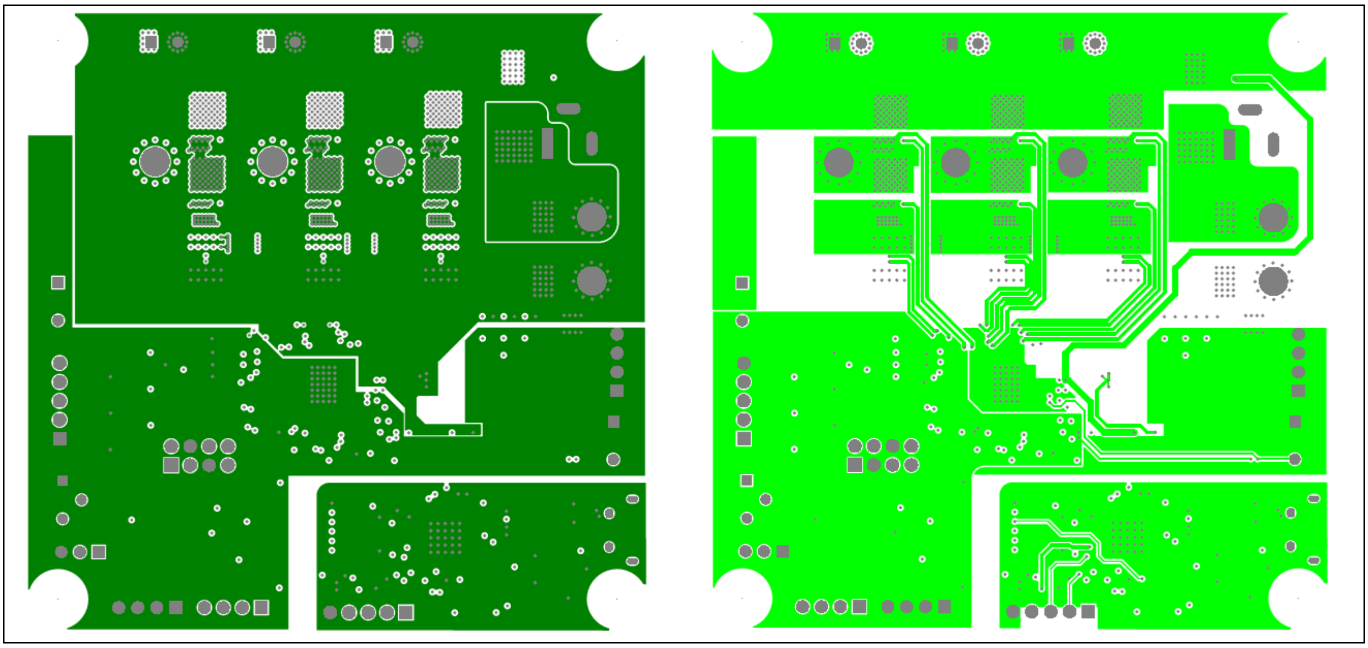


Figure 41 REF_IMD701A_720W_DC24 PCB internal layers 3 (left) and 4 (right)

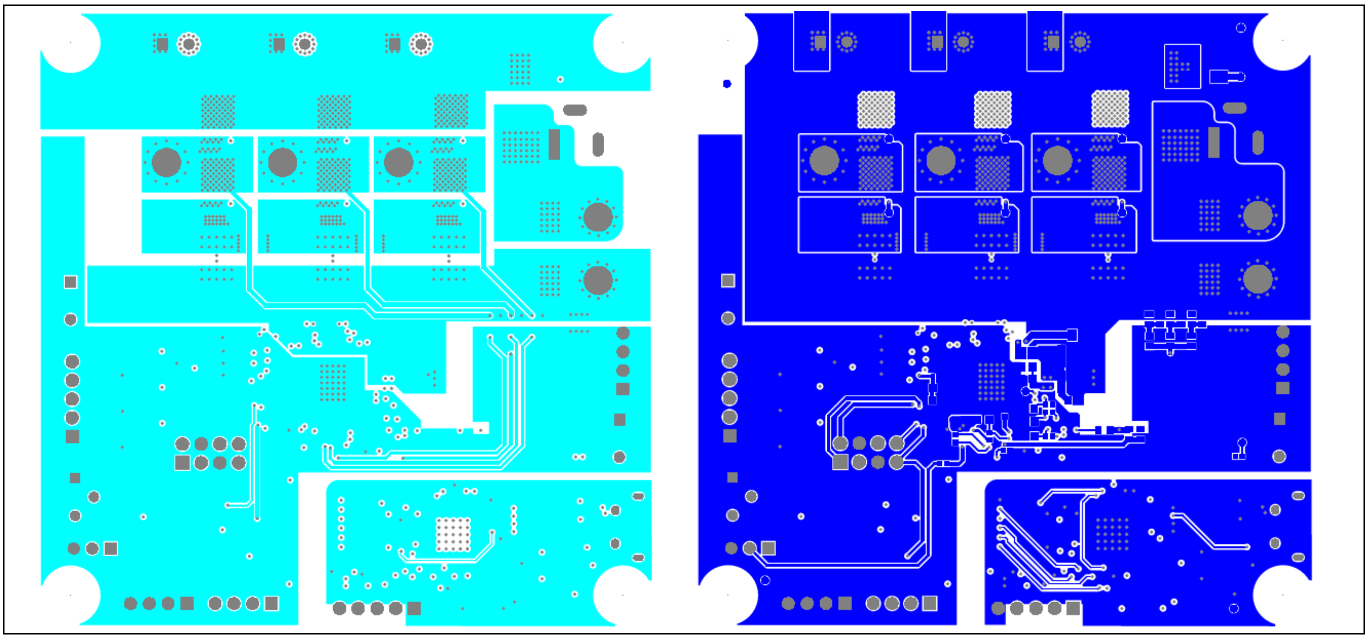


Figure 42 REF_IMD701A_720W_DC24 PCB internal layers 4 (left) bottom (right)

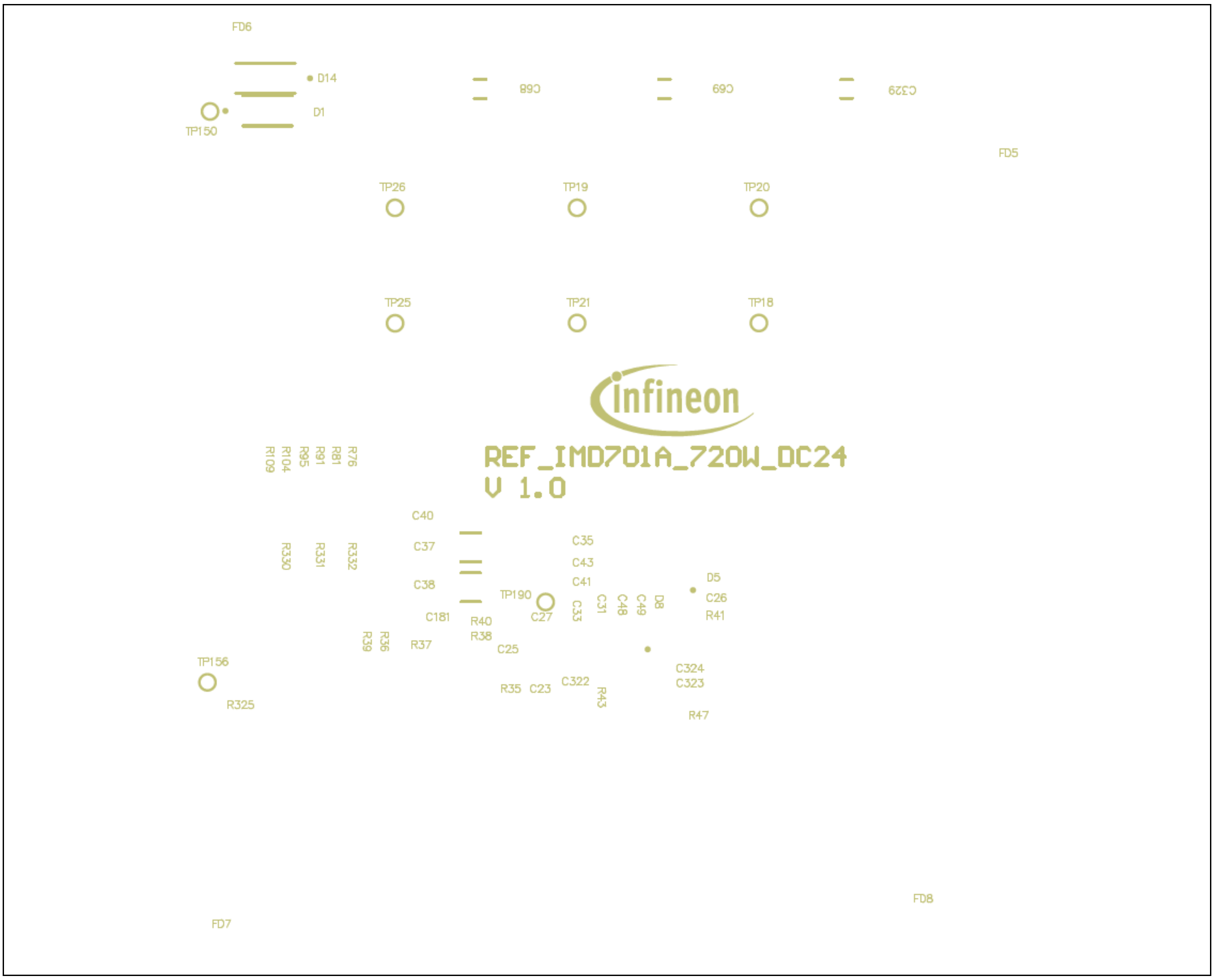


Figure 43 REF_IMD701A_720W_DC24 PCB bottom silkscreen

The PCB layout is optimized to minimize radiated EMI. This is done by keeping the loops carrying the switching currents as small as possible. See Figure 44 for HF switching current loops. Note 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.

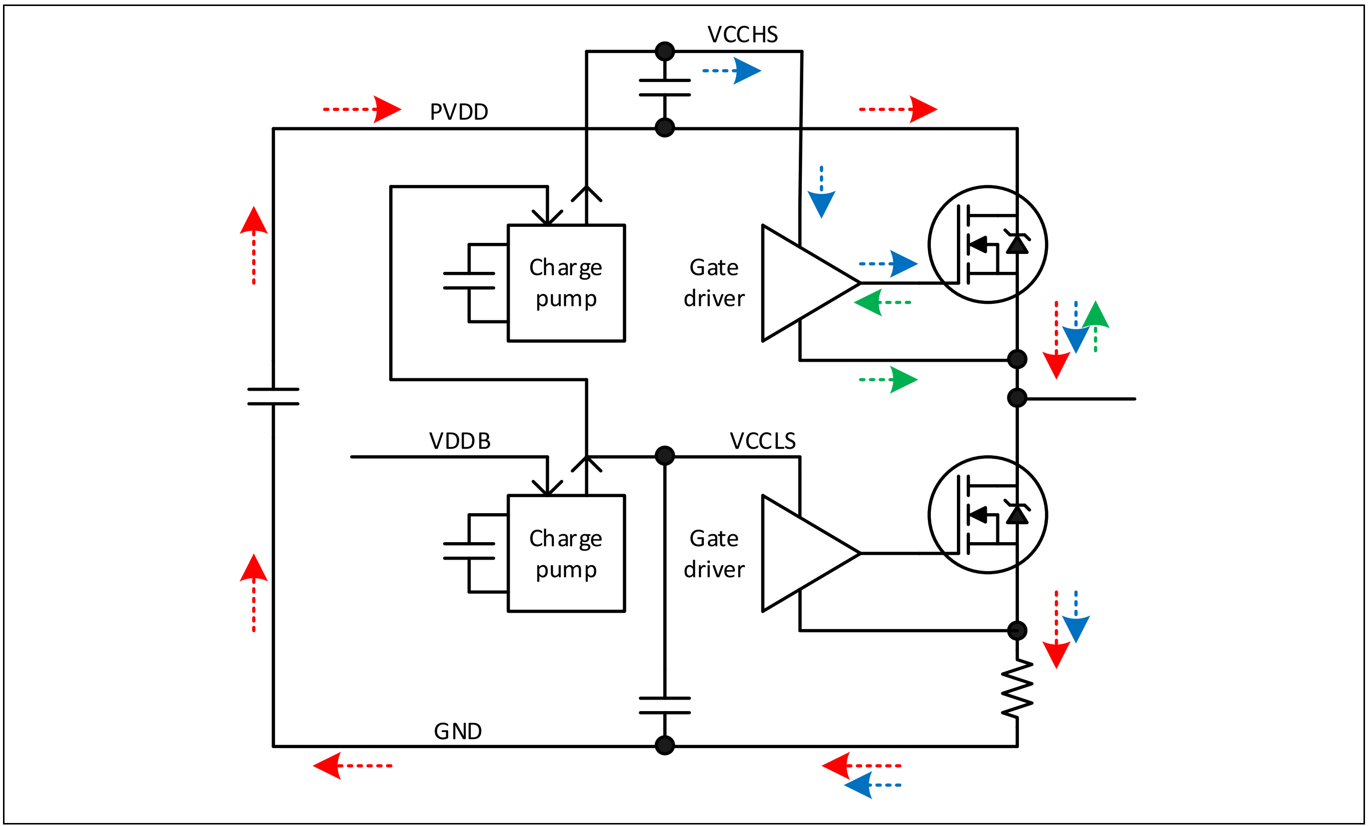
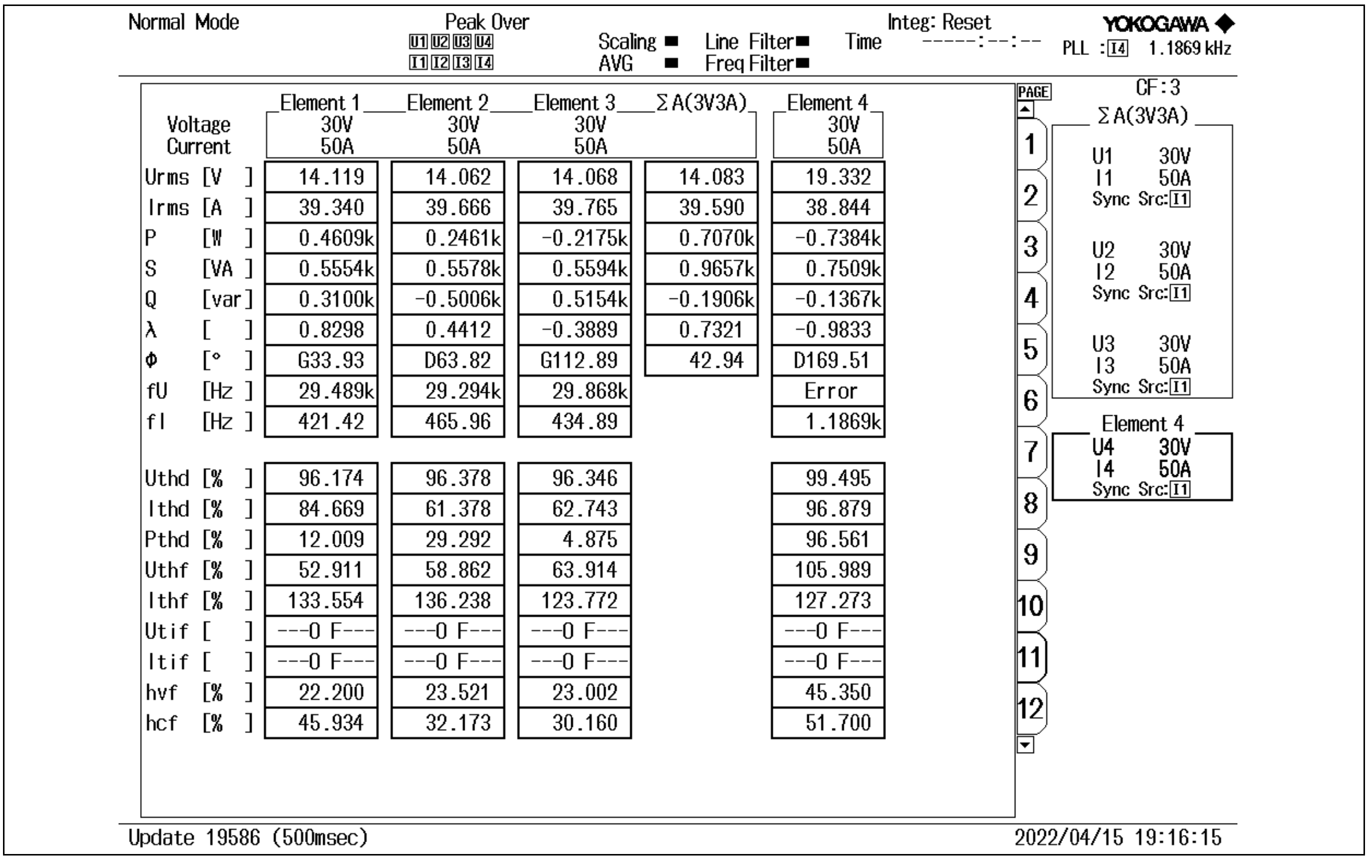


Figure 44 HF current loop for one phase
Red: main HF switching loop; blue: high-side gate drive switch-on current loop; green: high-side gate drive switch-off current loop

9 Test results

9.1 Maximum power measurements



Normal Mode | Peak Over U1 U2 U3 U4 I1 I2 I3 I4 | Scaling AVG | Line Filter Freq Filter | Time | Integ: Reset -----:--:-- | YOKOGAWA PLL : I4 1.1869 kHz

Voltage / Current	Element 1 30V 50A	Element 2 30V 50A	Element 3 30V 50A	ΣA(3V3A)	Element 4 30V 50A
Urms [V]	14.119	14.062	14.068	14.083	19.332
Irms [A]	39.340	39.666	39.765	39.590	38.844
P [W]	0.4609k	0.2461k	-0.2175k	0.7070k	-0.7384k
S [VA]	0.5554k	0.5578k	0.5594k	0.9657k	0.7509k
Q [var]	0.3100k	-0.5006k	0.5154k	-0.1906k	-0.1367k
λ [ ]	0.8298	0.4412	-0.3889	0.7321	-0.9833
Φ [°]	G33.93	D63.82	G112.89	42.94	D169.51
fU [Hz]	29.489k	29.294k	29.868k		Error
fI [Hz]	421.42	465.96	434.89		1.1869k
Uthd [%]	96.174	96.378	96.346		99.495
Ithd [%]	84.669	61.378	62.743		96.879
Pthd [%]	12.009	29.292	4.875		96.561
Uthf [%]	52.911	58.862	63.914		105.989
Ithf [%]	133.554	136.238	123.772		127.273
Utif [ ]	---0 F---	---0 F---	---0 F---		---0 F---
Itif [ ]	---0 F---	---0 F---	---0 F---		---0 F---
hvf [%]	22.200	23.521	23.002		45.350
hcf [%]	45.934	32.173	30.160		51.700

Figure 45 Input and output measurements at input voltage 20 V and larger than 720 W input power

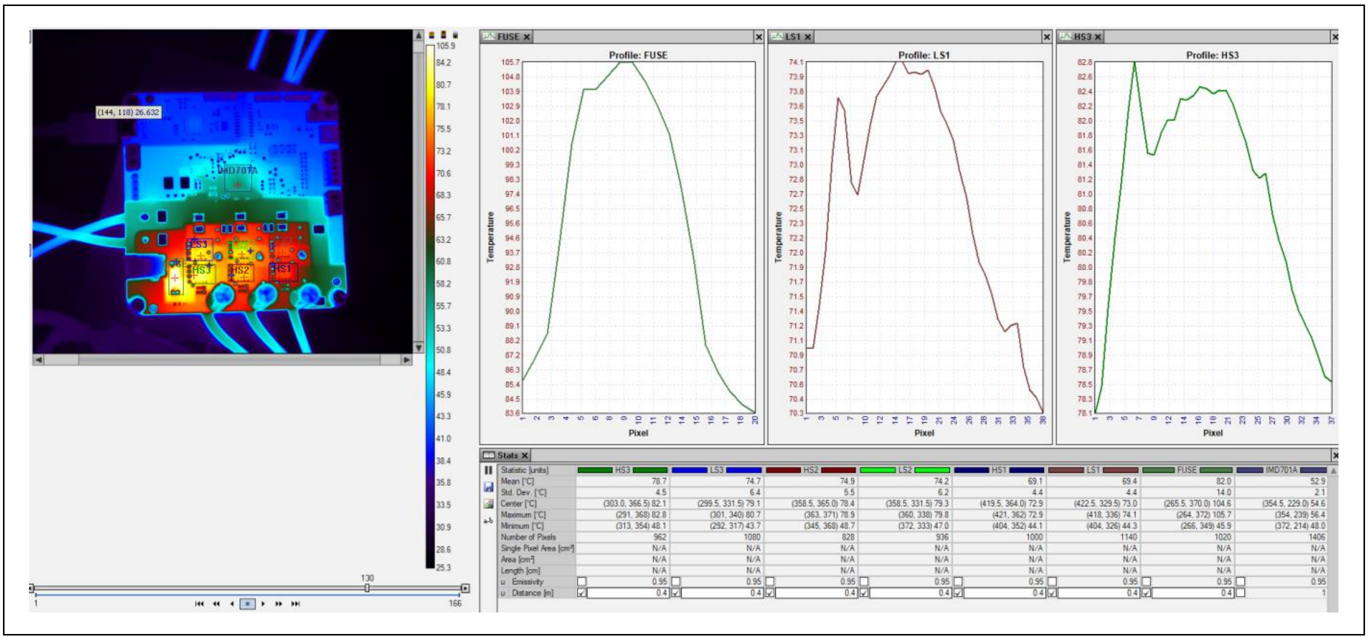


Figure 46 Thermal measurements at input voltage 20 V and larger than 720 W input power

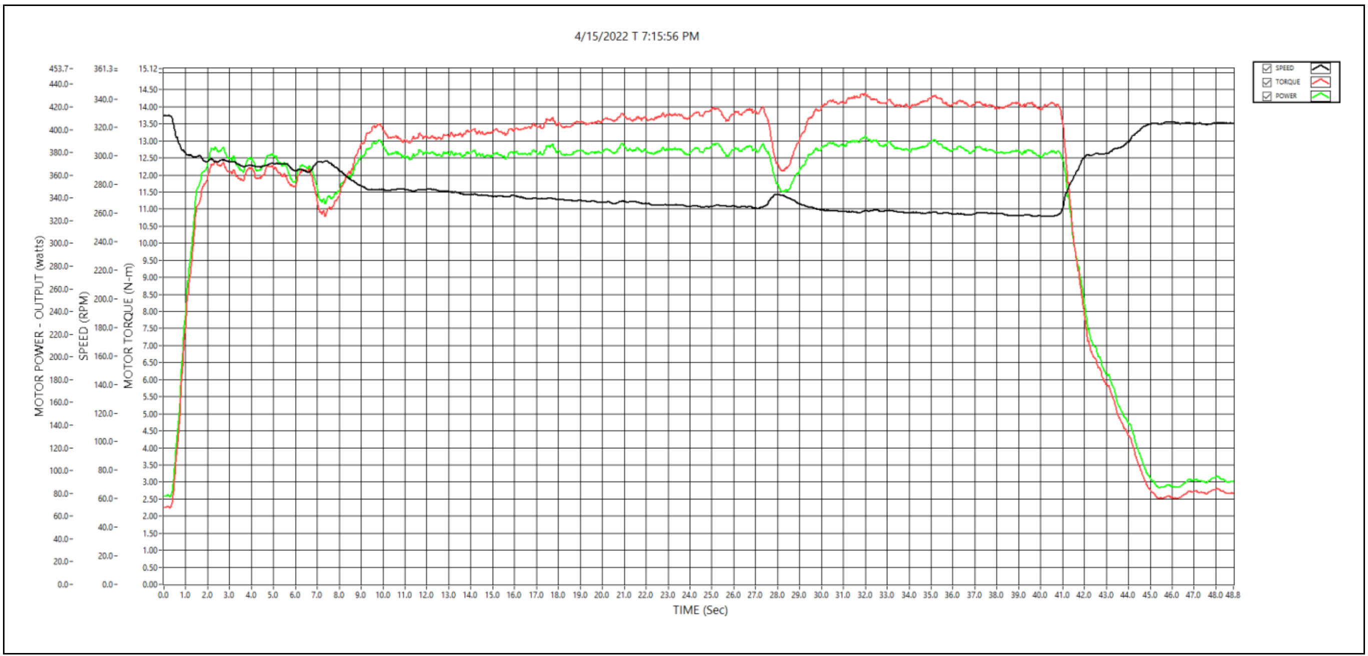


Figure 47 Motor power output measurements at input voltage 20 V and larger than 720 W input power

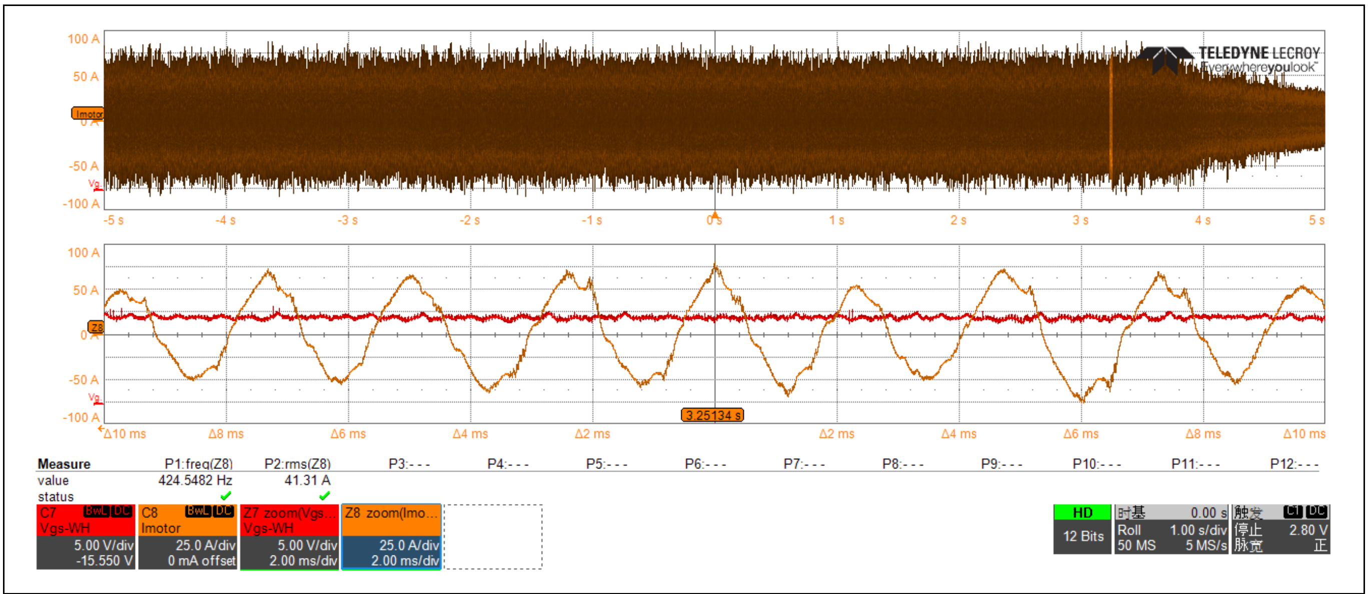


Figure 48 Phase current measurements at input voltage 20 V and larger than 720 W input power

Test result:

Maximum ratings:

- Input power: 738.4 W
- Input current: 38.8 A
- Output current: 39.59 A
- Output torque: 14 Nm
- Output power: 707 W
- Temperature at fuse: 105.7°C

- Temperature @ MOSFET (HS3): 82.8°C
- Temperature @ MOSFET (LS1): 74.1°C

9.2 VF open-loop startup

Configure the startup method to be "MOTOR_STARTUP_VF_OPEN_LOOP". Start up with the configured parameters of the v/f open loop, and switch to close loop control at the configured transition speed.

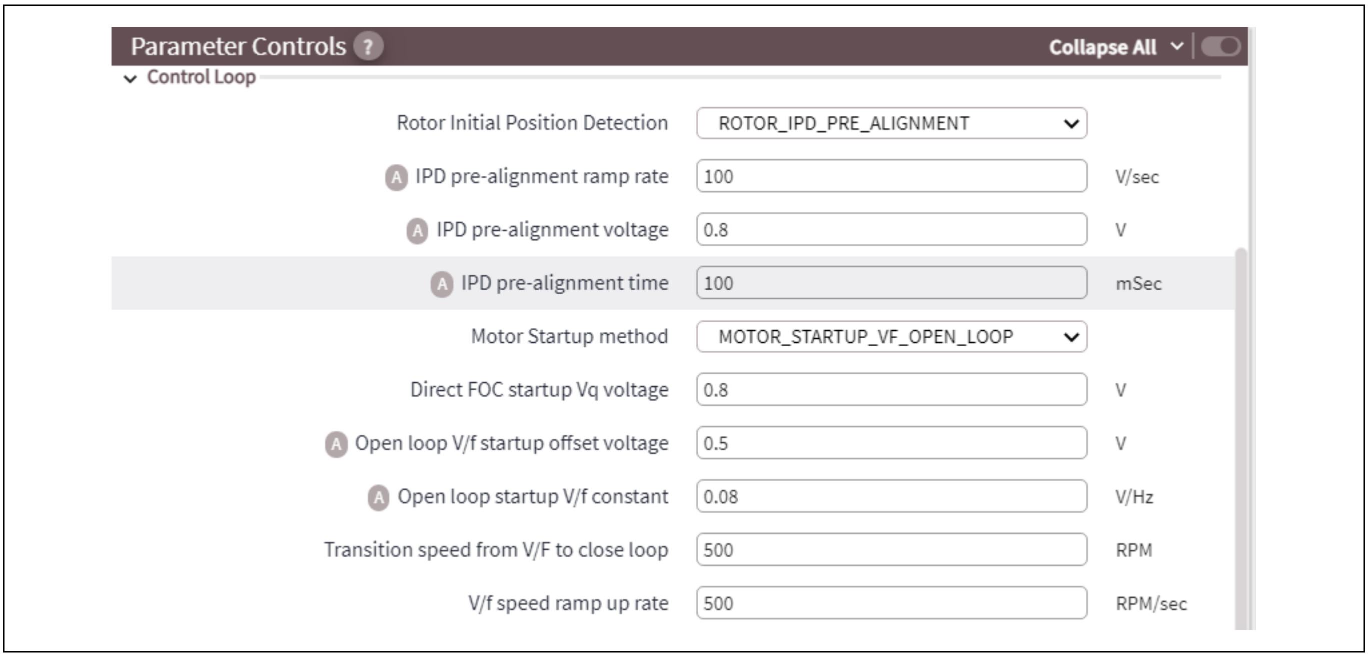


Figure 49 Control loop parameter configuration

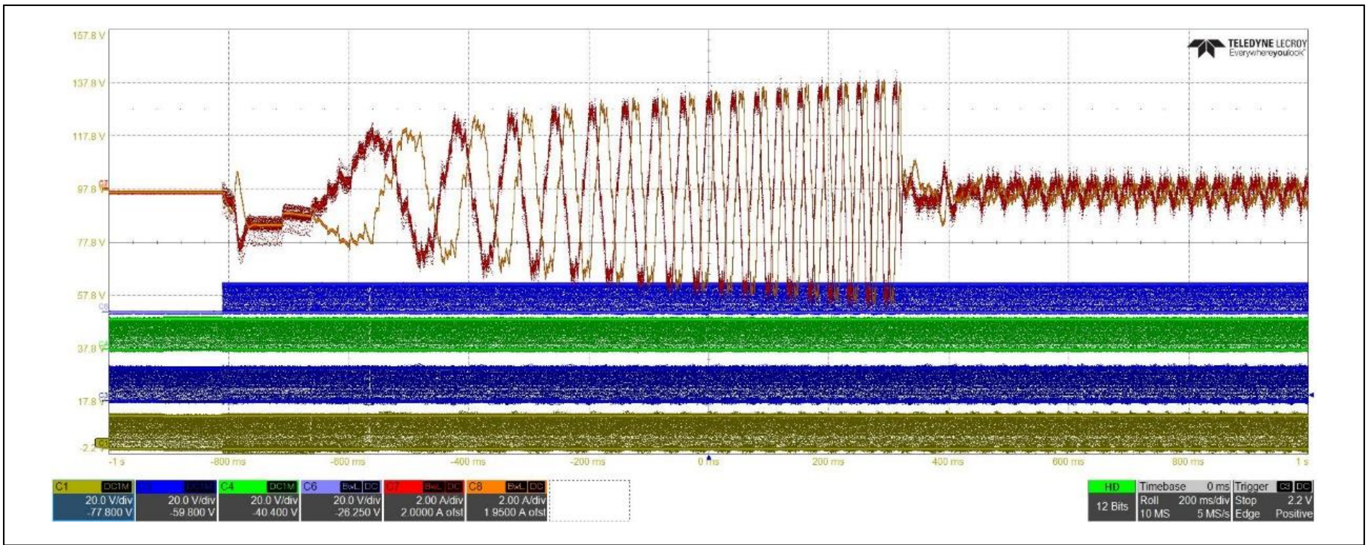


Figure 50 Startup phase current

9.3 Direct FOC startup

Configure the startup method to be "MOTOR_STARTUP_DIRECT_FOC". Start up with the configured parameters of direct FOC.

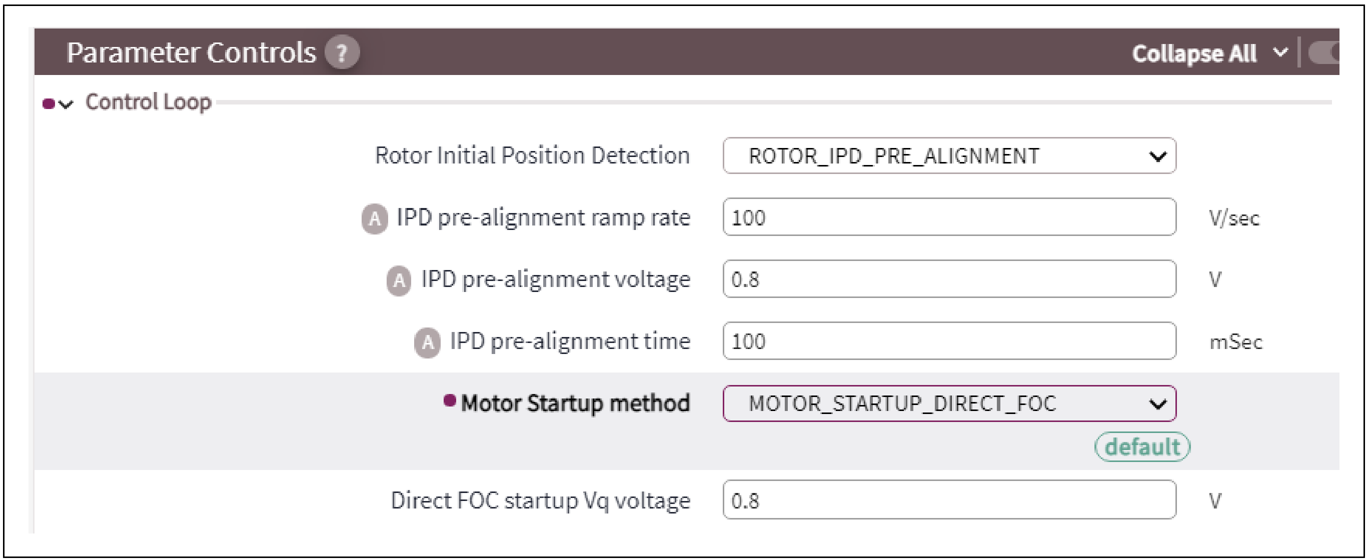


Figure 51 Control loop parameter configuration

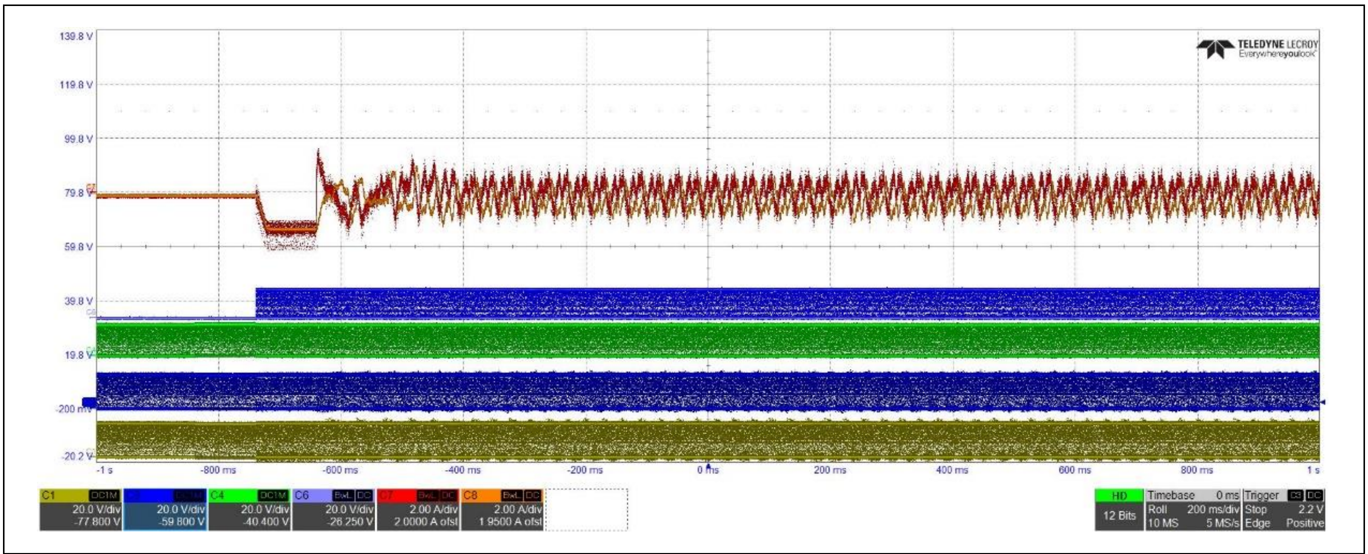


Figure 52 Startup phase current

9.4 SVM scheme

Configuration of "USER_SVM_SWITCHING_SCHEME"

Options:

- STANDARD_SVM_7_SEGMENT
- STANDARD_SVM_5_SEGMENT

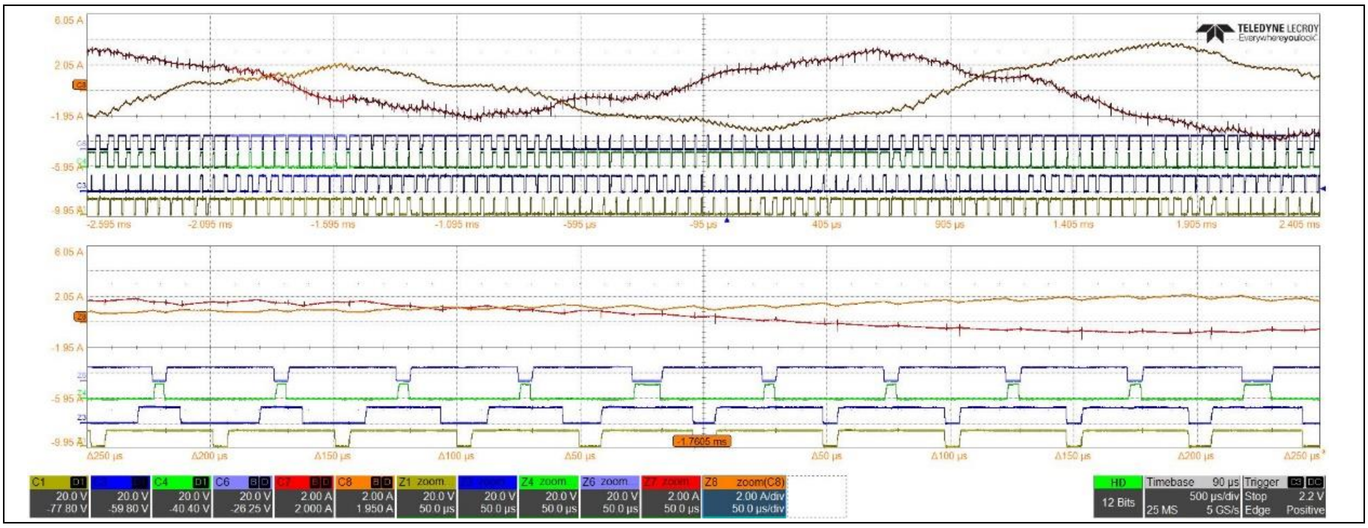


Figure 53 STANDARD_SVM_7_SEGMENT

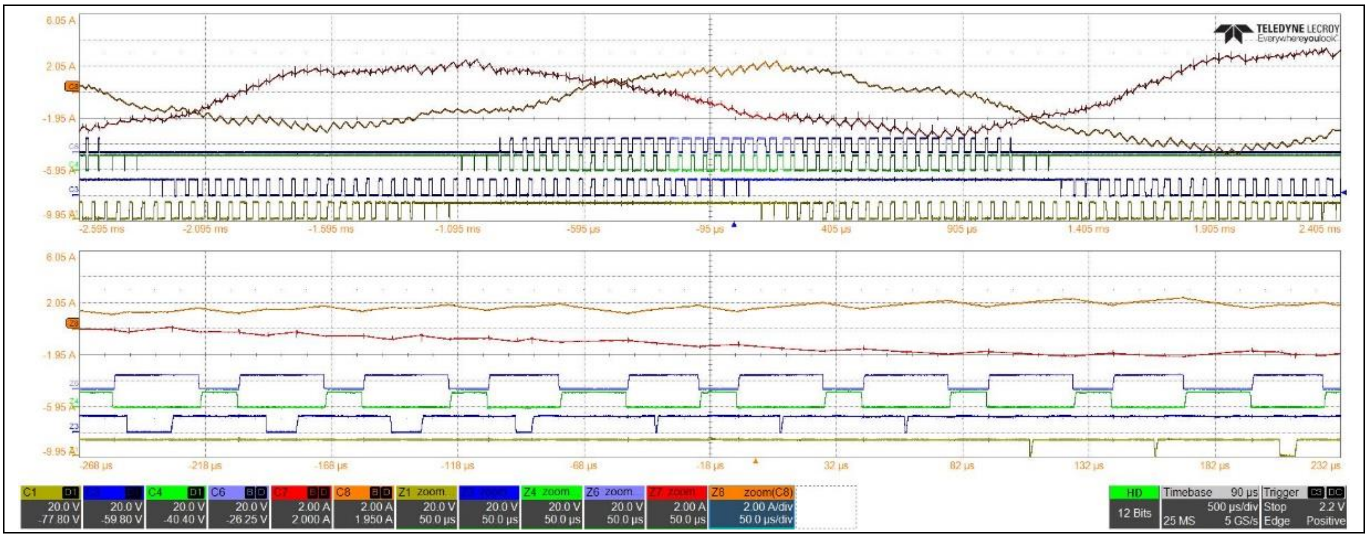


Figure 54 STANDARD_SVM_5_SEGMENT

9.5 Switching on/off profile

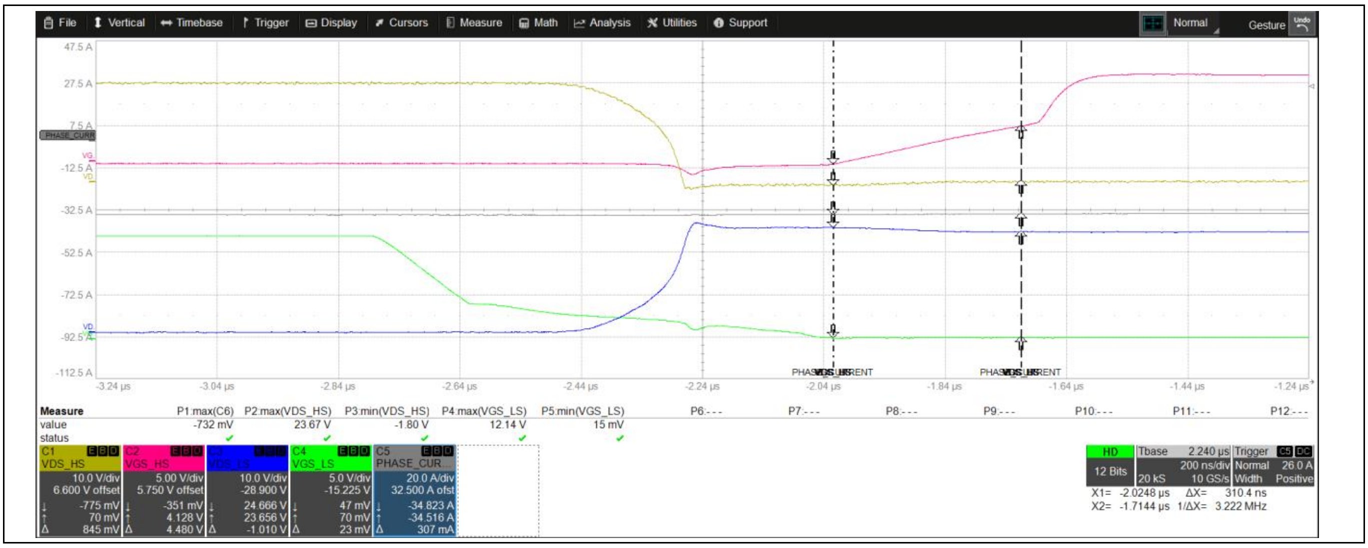


Figure 55 **Phase “W” node positive transition for 24 V input**
V_{DS_HS} (yellow), V_{GS_HS} (red), V_{DS_LS} (blue), V_{GS_LS} (green), Phase_current (gray), Parameter setting: T_{DRIVE1}=0ns, T_{DRIVE2}=310 ns

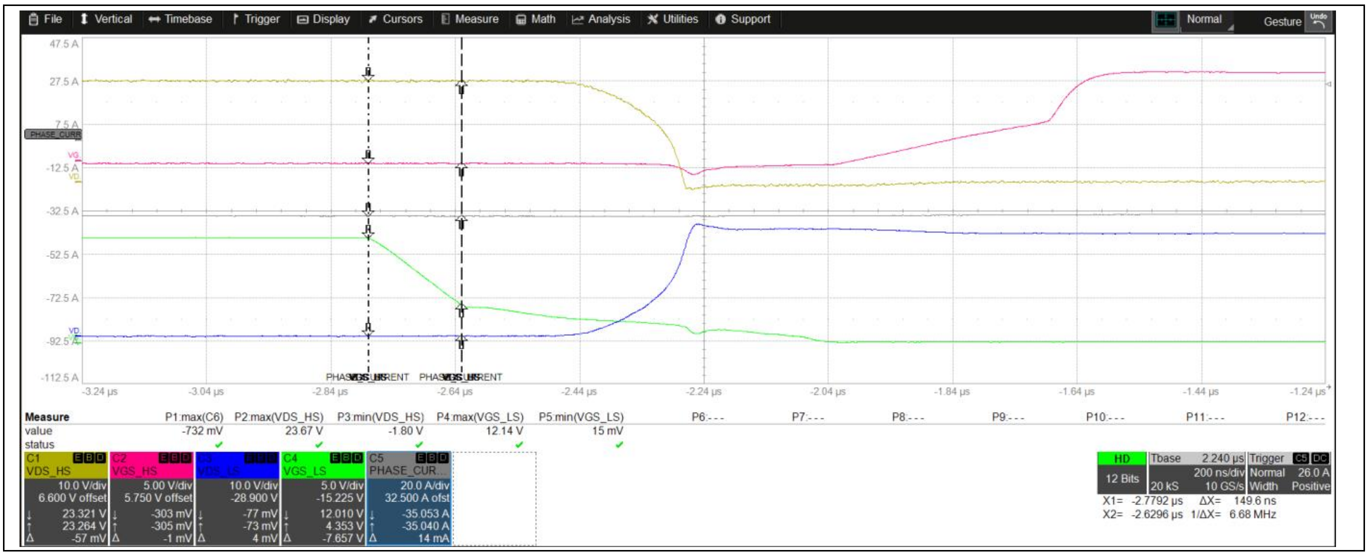


Figure 56 **Phase “W” node positive transition for 24 V input**
V_{DS_HS} (yellow), V_{GS_HS} (red), V_{DS_LS} (blue), V_{GS_LS} (green), Phase_current (gray), Parameter setting: T_{DRIVE3}=120 ns

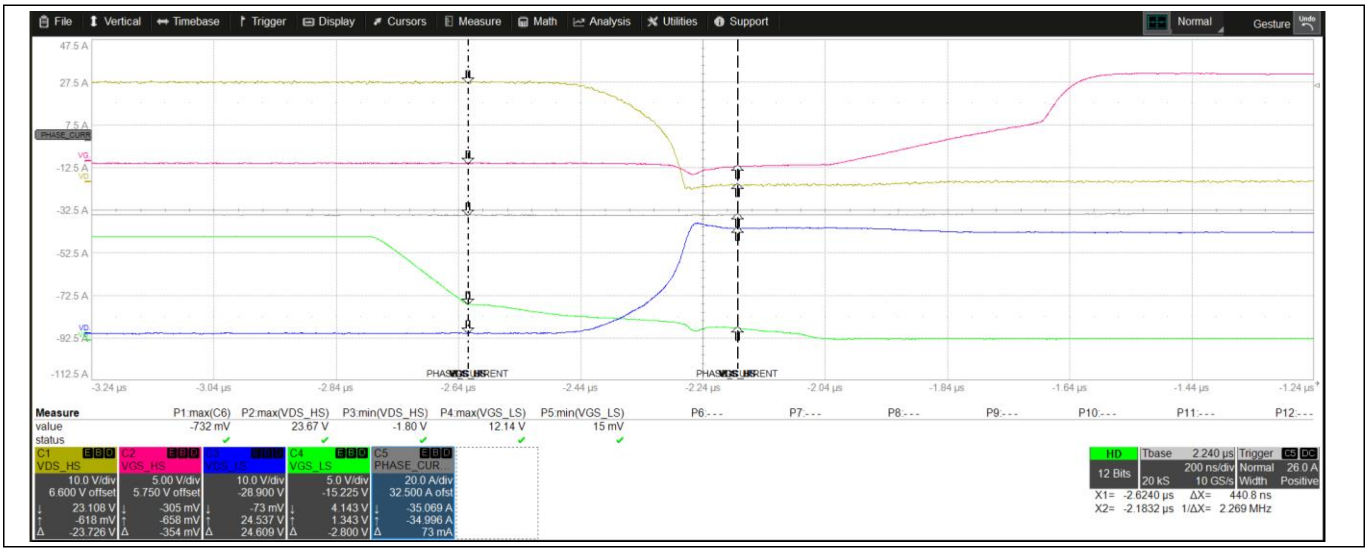


Figure 57 **Phase "W" node positive transition for 24 V input**
V_{DS_HS} (yellow), V_{GS_HS} (red), V_{DS_LS} (blue), V_{GS_LS} (green), Phase_current (gray), Parameter setting: T_{DRIVE4}=440 ns

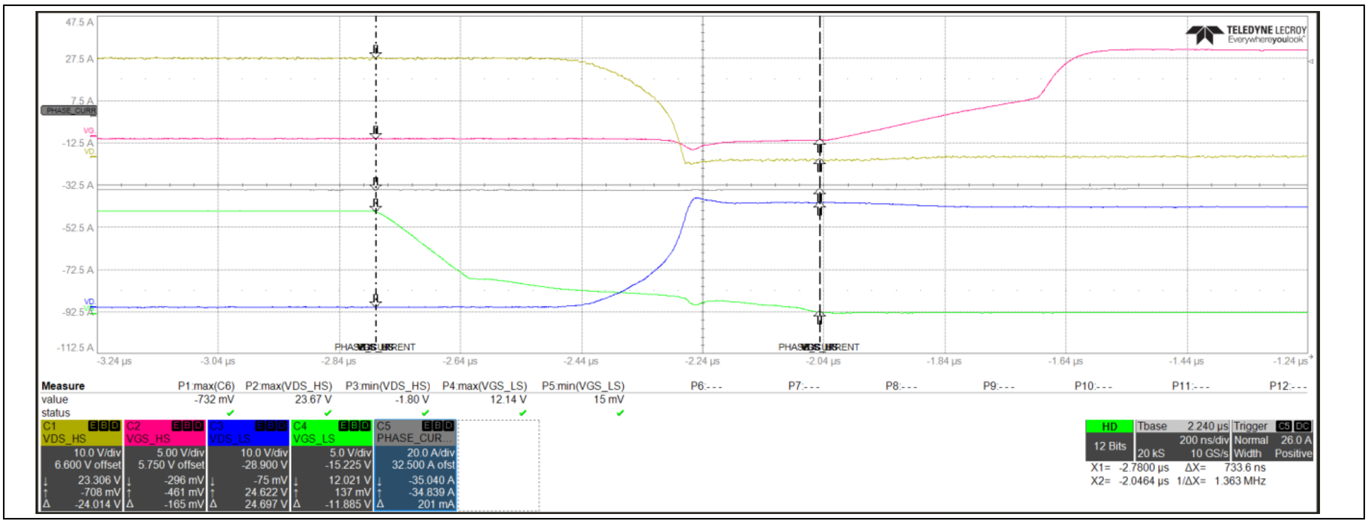


Figure 58 **Phase "W" node positive transition for 24 V input**
V_{DS_HS} (yellow), V_{GS_HS} (red), V_{DS_LS} (blue), V_{GS_LS} (green), Phase_current (gray), Parameter setting: Deadtime=750 ns

10 Summary

Based on the measured results shown in Chapter 9, this reference solution meets the target specifications. The maximum output power rating reaches 738 W with 20 V input voltage, which is higher than the specification of 720 W. In the power stage of the reference board, the hottest MOSFET's temperature is only 82.8°C occurred on the 'W' phase of the high-side MOSFET. The board can be started up with VF open-loop or direct FOC. These two-startup methods provide a smooth phase current. The maximum output in the power drill would be usually higher than 500 W. REF_IMD701A_702W_DC24 is a perfect solution for the battery-powered drill applications and other BLDC/PMSM motor-controlled applications with a high power rating.

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