REF_48V_270W_EBIKE: Compact motor drive inverter for e-Bikes

About this document

Scope and purpose

This document describes Infineon's REF_48V_270W_EBIKE motor drive inverter reference board intended for use in e-Bikes with a 250 W output power capability. It utilizes the MOTIX™ 6EDL7151 gate driver, which is a highly integrated 3-phase gate driver for motor drive applications, with integrated power supplies, integrated current sense amplifiers, and various protection features. The gate driver interacts with the XMC1400 family XMC™ XMC1404-Q064X0200 AA microcontroller, and drives the OptiMOS™ 5 IQE050N08NM5SC power MOSFETs that utilize a compact 3x3mm top-side cooled package (PG-WHSON-8).

The REF_48V_270W_EBIKE Reference Board represents a compact system intended for implementation where the small form factors plays a vital part in the overall design.

Intended audience

This document is intended for engineers who intend to implement REF_48V_270W_EBIKE in a system of their design, or wish to test the functionalities and capabilities of the essential components comprising this system.

Infineon components featured

- OptiMOS™ 5 IQE050N08NM5SC (Power MOSFET, 80 V, $R_{DS(on),max}$ = 5.0 mΩ, PQFN 3.3 x 3.3 mm^2/PG-WHSON-8 top-side-cooled package)
- MOTIX™ 6EDL7151 (three-phase BLDC or PMSM gate driver with integrated power supply system, onboard current sense amplifiers, slew rate control, integrated protection features)
- XMC™ XMC1404-Q064X0200 AA (200 KB flash, 16 KB RAM, core frequency: 48 MHz, Supply voltage range: 1.8 V – 5.5 V, optimized for motor control)
- TLE8250G (CAN transceiver, < 15 µA at 5 V standby, ISO 11898-2, receive-only mode)

Please read the sections "Important notice" and "Warnings" at the end of this document

Important notice

“Evaluation Boards and Reference Boards” shall mean products embedded on a printed circuit board (PCB) for demonstration and/or evaluation purposes, which include, without limitation, demonstration, reference and evaluation boards, kits and design (collectively referred to as “Reference Board”).

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Safety precautions

Note: *Please note the following warnings regarding the hazards associated with development systems.*

Table 1 Safety precautions

⚡	**Warning**: *The evaluation or reference board contains DC bus capacitors which take time to discharge after removal of the main supply. Before working on the drive system, wait five minutes for capacitors to discharge to safe voltage levels. Failure to do so may result in personal injury or death. Darkened display LEDs are not an indication that capacitors have discharged to safe voltage levels.*
⚡	**Warning:** *Remove or disconnect power from the drive before you disconnect or reconnect wires, or perform maintenance work. Wait five minutes after removing power to discharge the bus capacitors. Do not attempt to service the drive until the bus capacitors have discharged to zero. Failure to do so may result in personal injury or death.*
⚠	**Caution:** *The 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.*
⚠	**Caution:** *A drive that is incorrectly applied or installed can lead to component damage or reduction in product lifetime. Wiring or application errors such as undersizing the motor, supplying an incorrect or inadequate AC supply, or excessive ambient temperatures may result in system malfunction.*
⚠	**Caution:** *The evaluation or reference board is shipped with packing materials that need to be removed prior to installation. Failure to remove all packing materials that are unnecessary for system installation may result in overheating or abnormal operating conditions.*

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1 System overview

The REF_48V_270W_EBIKE Reference Board is a fully functioning motor drive inverter, designed for low-power e-Bikes.
The board size is adapted for implementation inside the down tube or cross bar (i.e. top tube) of a typical bicycle frame. Its size of 101 mm x 26.8 mm makes it possible to fit inside a tube as small as 30 mm of inner diameter to enable implementation with minimal impact on the bike frame design. It allows for direct implementation into an e-Bike frame together with a corresponding motor of their choice. It demonstrates the performance of the 3.3 x 3.3 mm^2 PQFN top-side cooled MOSFET package, as well as the versatility of 6EDL7151 configurable gate driver and their combined impact on the form factor.

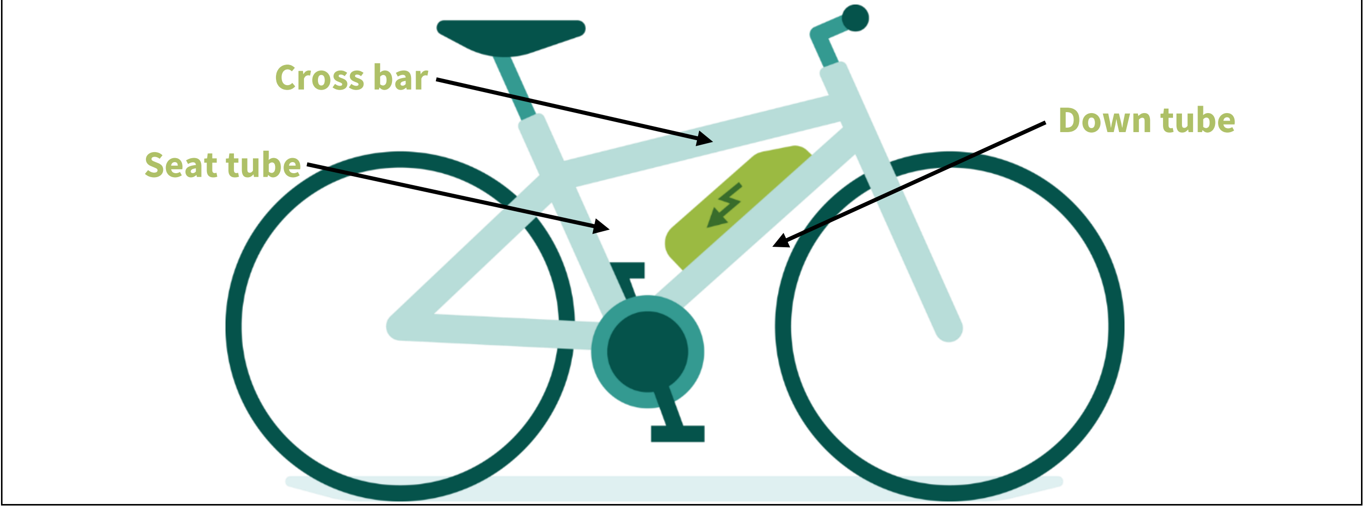


Figure 1 Bicycle frame – basic parts

The REF_48V_270W_EBIKE Reference Board is optimized for 48 V battery-powered e-Bikes (e.g., 12S to 14S Li-ion), operating with sensor-based field-oriented or vector control. The design utilizes three Hall sensors, typically integrated at the stator of a PMSM motor, to determine rotor position and speed.

The power and voltage ratings aim to accommodate the EU standard: EN 15194:2017. This is the standard governing the category of low-power e-Bikes, or as referred to in the standard: electrically powered assisted cycles – EPAC.

As stated in the EN 15194:2017:
"This European Standard is intended to cover electrically powered assisted bicycles of a type which have a maximum continuous rated power of 0.25 kW, of which the output is progressively reduced and finally cut off as the EPAC reaches a speed of 25 km/h, or sooner, if the cyclist stops pedaling.
This European Standard specifies requirements and test methods for engine power management systems, electrical circuits including the charging system for the design and assembly of electrically power assisted bicycles and sub-assemblies for systems having a rated voltage up to and including 48 V DC or integrated battery charger with a nominal 230 V AC input".

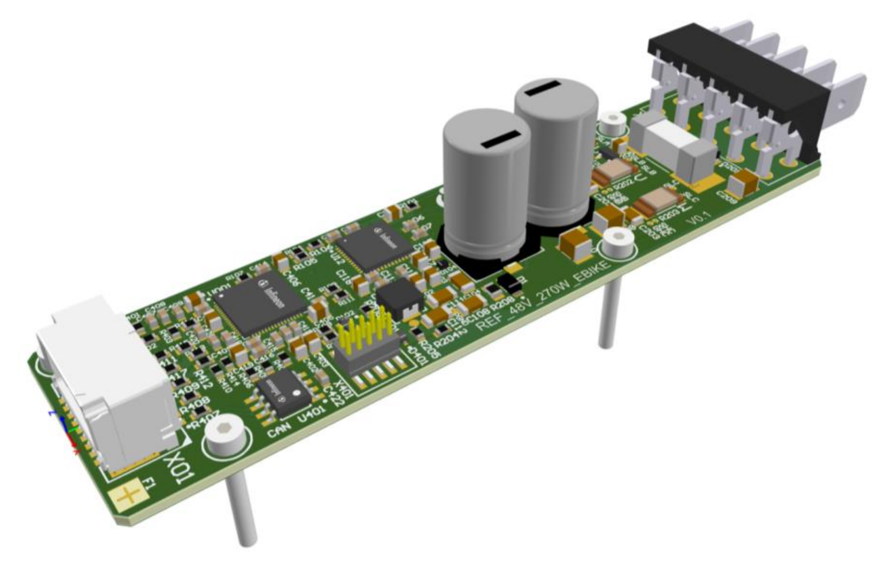


Figure 2 **REF_48V_270W_EBIKE Reference Board**

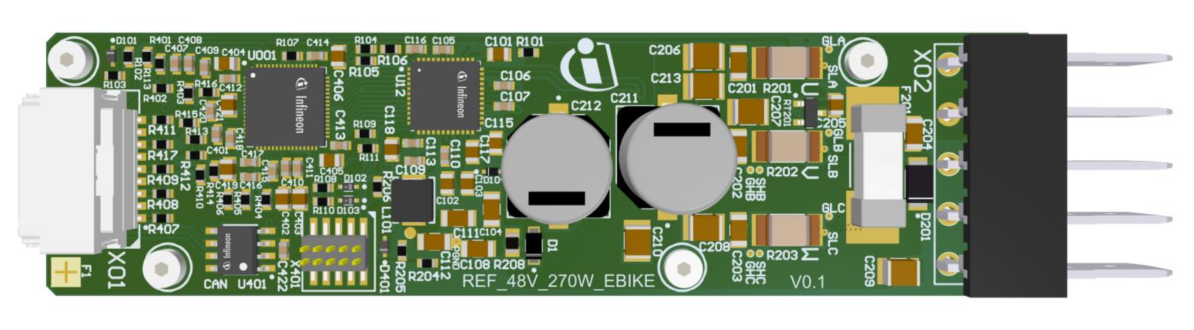


Figure 3 **REF_48V_270W_EBIKE Reference Board top-side view**

1.1 Block diagram

The REF_48V_270W_EBIKE consists of a power stage, 6EDL7151 gate driver IC with integrated supply, the XMC1404 microcontroller (MCU), and the necessary connections.

6EDL7151 gate driver IC provides the 3-phase hi- and low-side gate drivers designed to drive the hi- and low-side N-type power MOSFETs. The gate driver IC also manages the overall system supply. It utilizes a buck converter, with a linear regulator for the logic side and charge pump regulators to supply the gate drive circuits.

Current is measured via shunt resistors in the low-side MOSFET source positions. The signals are amplified via integrated amplifiers of 6EDL7151 and passed to the ADC inputs of the MCU.

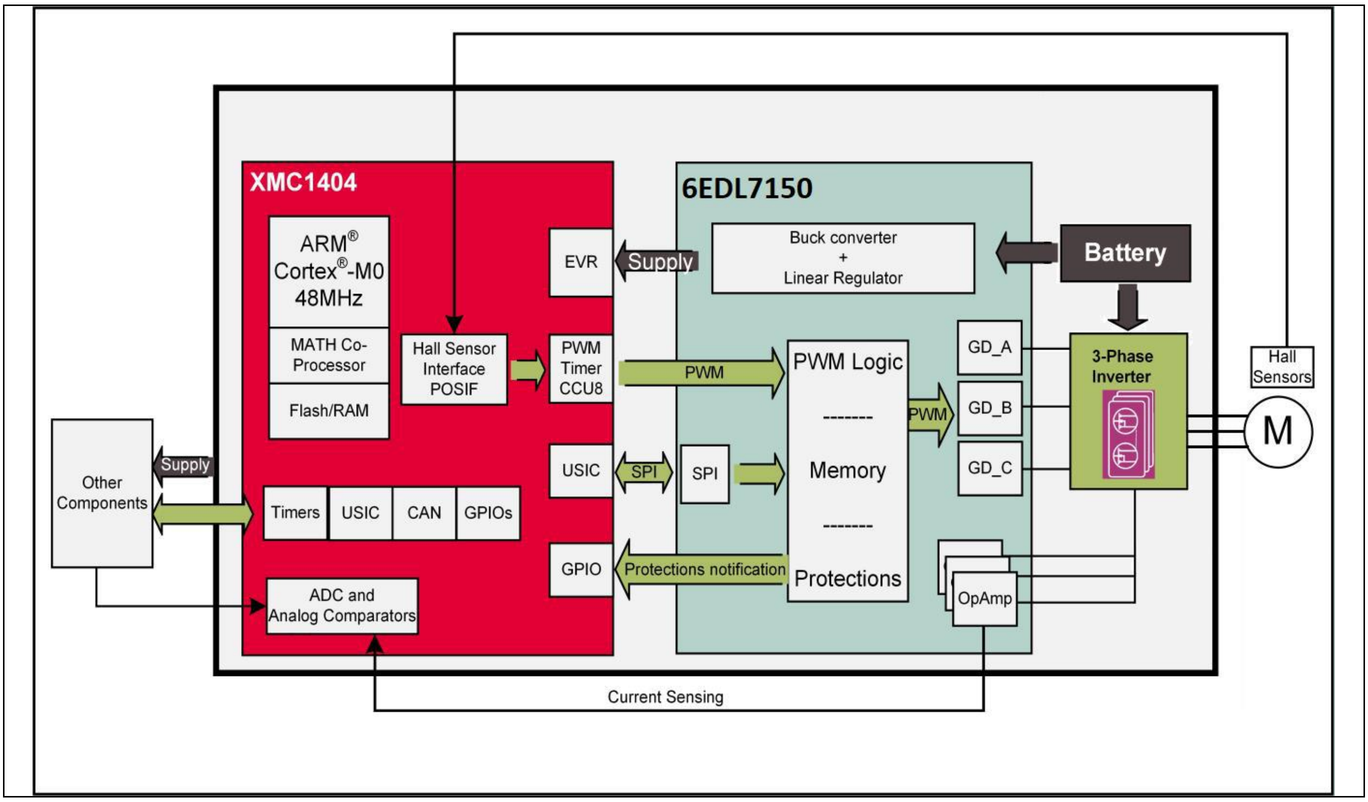


Figure 4 System block diagram

The MCU utilizes a sensored FOC motor control algorithm, estimating the rotor position by processing the signals of the three Hall position sensors (typically integrated in the motor stator). The FOC produces the six PWM control signals used by the gate drivers. The MCU also provides the interface to the gate driver IC via SPI which is used to configure the gate driver IC parameters of 6EDL7151. Dedicated error signals are also provided by the gate driver IC to the MCU in order to ensure safe operation.

The MCU additionally interfaces to external units (BMS and dashboard) and driver control inputs (brake signal, throttle signal, and ignition) through the CAN bus and analog/supply inputs and outputs.

The power stage consists of six power MOSFETs (IQE050N08NM5SC) comprising three half-bridges with a shunt resistor in the lower leg (connected to the source of the low-side MOSFET) of each half-bridge. The DC supply voltage is stabilized by several DC bus capacitors (electrolytic and ceramic) and protected by an SMD fuse.

The REF_48V_270W_EBIKE provides a 10-pin (50 mil pitch) header connector **X401** as the interface to the external debugger - KIT_XMC_LINK_SEGGER_V1. The isolated debugger is directly connected to a PC via a USB type A port.

The board provides the high-power connections to the supply/battery and the motor via a 5-pin “blade” connector intended to interface the standard 6.3 mm cable-crimped female blade connectors. The blade connector pins (connector “X02”) are visible at the right-side edge of the board in Figure 3.

The small signal connections to motor hall sensors, “throttle” and brake inputs, key-ignition, and CAN-bus, with their corresponding supply lines are provided at the left side of the board at connector X01.

1.2 Main features

Small form factor

- Dimensions: W = 26.8 mm, H ≤ 20 mm, L = 111 mm

Input and output at normal operation

- DC input voltage: 48 V_{DC} nominal (36 V to 60 V, for use with 12S to 14S Li-ion)
- Maximum input current: 14 A
- Output voltage three-phase FOC
- Maximum output peak current per phase: 15 ARMS
- Maximum output continuous current per phase: 11 ARMS
- Maximum output continuous power: 270 W

Control scheme

- Hall-based FOC
- Switching frequency: 12 ~ 20 kHz
- Three current sense shunts – LS source placement

Protection features

- Input fuse
- Output overcurrent
- Thermal shutdown

1.3 Board parameters and technical data

Table 2 REF_48V_270W_EBIKE Reference Board parameters

Parameter	Symbol	Conditions	Value	Unit
Supply voltage	V_{DC}	12S to 14S Li-ion	36 ~ 60	V
Rated power – continuous	$P_{continuous}$	V_{DC} = 48 V, T_a = 25°C	270	W
Maximum supply current – continuous	$I_{IN(max\_cont.)}$	V_{DC} = 36 V, T_a = 25°C	7.5	A
Maximum phase current – continuous	$I_{OUT(max\_cont)}$	V_{DC} = 48 V, T_a = 25°C, f_{PWM} = 20 kHz	11	A
Rated power – peak	P_{peak}	V_{DC} = 48 V, T_a = 25°C, 2 min	1000	W
Maximum supply current – peak	$I_{IN(max\_peak)}$	V_{DC} = 36 V, T_a = 25°C, 2 min	23	A
Maximum phase current – peak	$I_{OUT(max\_peak)}$	V_{DC} = 48 V, T_a = 25°C, 2 min	29	A
Maximum allowed operating temperature of power half bridges (MOSFETs and shunts)	$T_{HB(max)}$	Case temperature	110	°C
Maximum allowed operating temperature of other components	$T_{Comp.(max)}$	Case temperature	100	°C
PWM switching frequency	f_{PWM}	–	12 ~ 20	kHz
Maximum efficiency	η_{max}	V_{DC} = 48 V, T_a = 25°C, f_{PWM} = 20 kHz	97	%
Peripheral supply voltage	DVDD	R111 = 10 kΩ	5	V
Peripheral supply linear regulator overcurrent protection	DVDD_OCP	DVDD = 5 V	450	mA

1.4 Application-specific load properties

The typical recommended pedaling cadence for cyclists is between 80 RPM to 100 RPM. The torque values expected at the crank shaft could go up to around 100 Nm for shorter periods but would stay below 20 Nm in a relaxed steady cycling activity. This means that the allowed 250 W continuous assisting power is approximately set to those of a cyclist's capabilities.

24 Nm at 100 RPM roughly corresponds to the mentioned limit of 250 W continuous assisting power, however typically there may be a geared transmission between motor and crank shaft so the actual torque vs. RPM ratio in an e-Bike motor will differ.

2 Firmware description

This chapter describes the functionality of the dedicated firmware designed for the REF_48V_270W_EBIKE. The firmware supports parametric adjustments in order to operate with various motors and transmissions. It also supports further adjustments of onboard features (e.g., the FOC and the gate driver parameters).

Therefore, in order for the board to operate, the firmware must be configured correctly before flashing the firmware to the target board.

Some configurations are configurable via the dedicated GUI, alternatively the full set of available firmware configurations are accessible in the excel configurator file as described in the following sections.

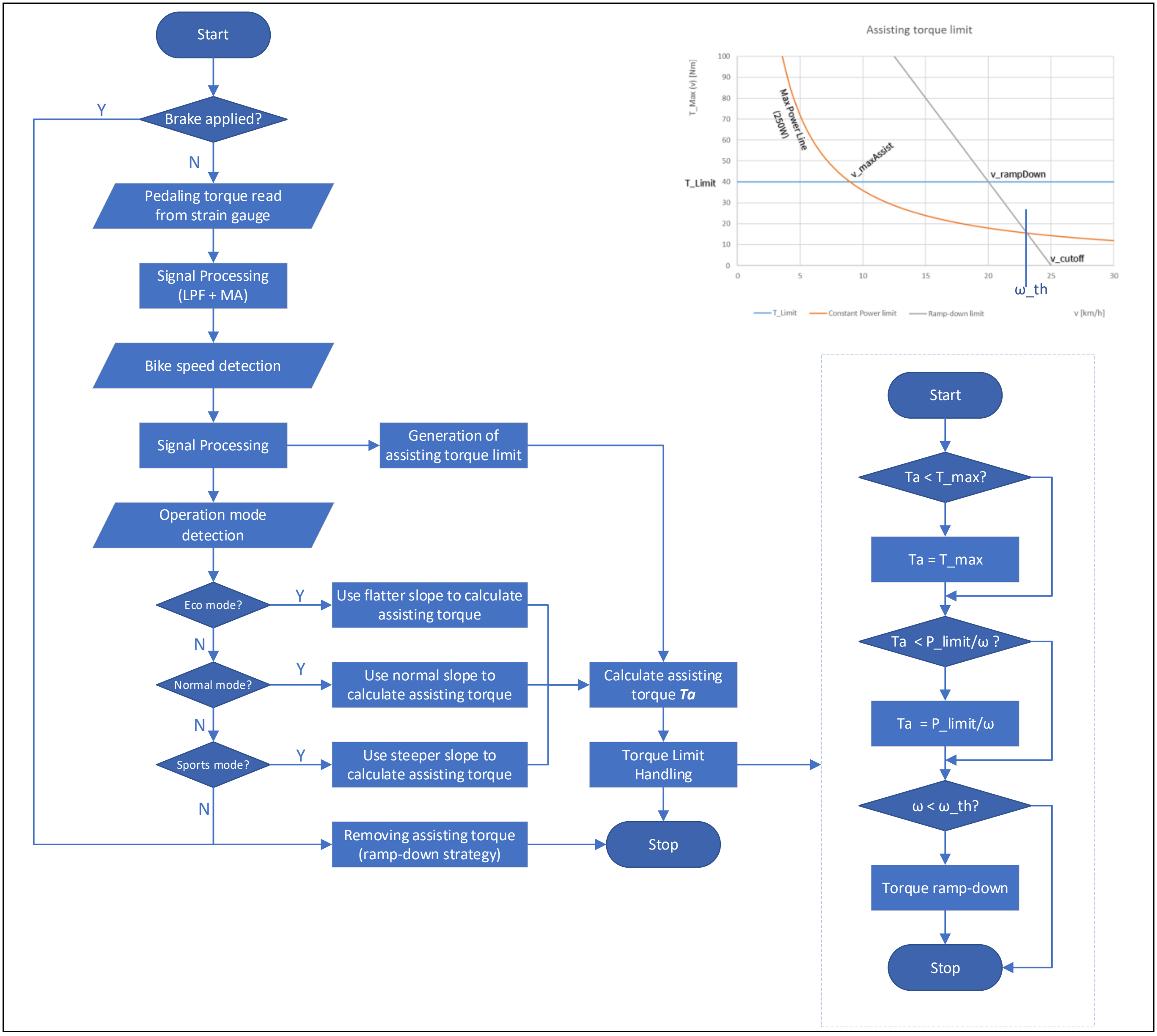
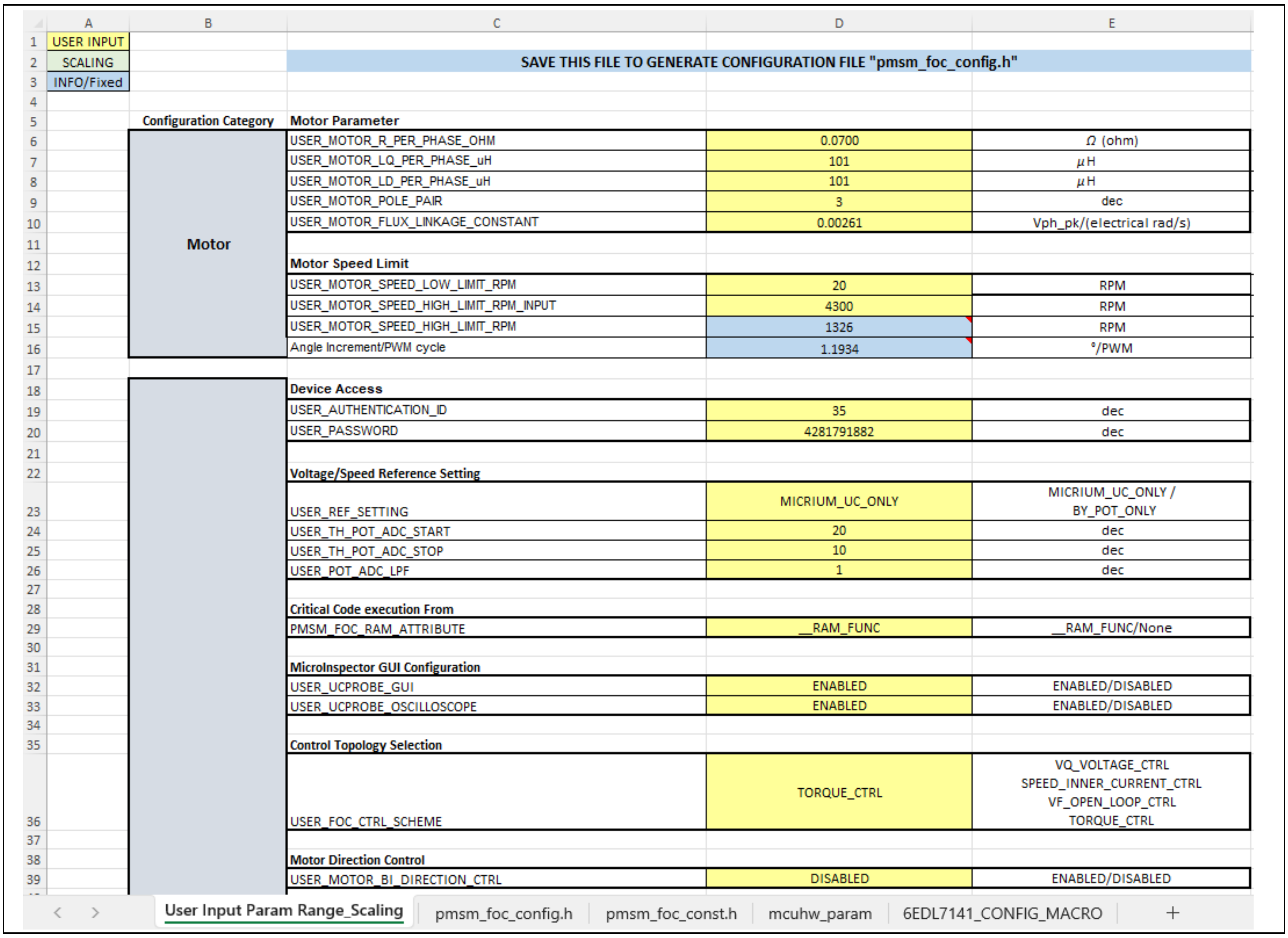


Figure 5 Firmware overview

2.1 Firmware configuration – Excel configurator file

All the firmware configurations can be configured through the Excel configurator file shown in Figure 6, that comes together with the project. All user inputs are marked as bright yellow.

Excel Configurator file in project location: */PMSM_FOC/Configuration/excel_config.xlsm*



	A	B	C	D	E
1	USER INPUT				
2	SCALING		SAVE THIS FILE TO GENERATE CONFIGURATION FILE "pmsm_foc_config.h"		
3	INFO/Fixed				
4					
5		Configuration Category	**Motor Parameter**		
6		Motor	USER_MOTOR_R_PER_PHASE_OHM	0.0700	Ω (ohm)
7			USER_MOTOR_LQ_PER_PHASE_uH	101	µH
8			USER_MOTOR_LD_PER_PHASE_uH	101	µH
9			USER_MOTOR_POLE_PAIR	3	dec
10			USER_MOTOR_FLUX_LINKAGE_CONSTANT	0.00261	Vph_pk/(electrical rad/s)
11					
12			**Motor Speed Limit**		
13			USER_MOTOR_SPEED_LOW_LIMIT_RPM	20	RPM
14			USER_MOTOR_SPEED_HIGH_LIMIT_RPM_INPUT	4300	RPM
15			USER_MOTOR_SPEED_HIGH_LIMIT_RPM	1326	RPM
16			Angle Increment/PWM cycle	1.1934	°/PWM
17					
18			**Device Access**		
19			USER_AUTHENTICATION_ID	35	dec
20			USER_PASSWORD	4281791882	dec
21					
22			**Voltage/Speed Reference Setting**		
23			USER_REF_SETTING	MICRIUM_UC_ONLY	MICRIUM_UC_ONLY / BY_POT_ONLY
24			USER_TH_POT_ADC_START	20	dec
25			USER_TH_POT_ADC_STOP	10	dec
26			USER_POT_ADC_LPF	1	dec
27					
28			**Critical Code execution From**		
29			PMSM_FOC_RAM_ATTRIBUTE	__RAM_FUNC	__RAM_FUNC/None
30					
31			**MicroInspector GUI Configuration**		
32			USER_UCPROBE_GUI	ENABLED	ENABLED/DISABLED
33			USER_UCPROBE_OSCILLOSCOPE	ENABLED	ENABLED/DISABLED
34					
35			**Control Topology Selection**		
36			USER_FOC_CTRL_SCHEME	TORQUE_CTRL	VQ_VOLTAGE_CTRL SPEED_INNER_CURRENT_CTRL VF_OPEN_LOOP_CTRL TORQUE_CTRL
37					
38			**Motor Direction Control**		
39			USER_MOTOR_BI_DIRECTION_CTRL	DISABLED	ENABLED/DISABLED

Figure 6 **Firmware Excel configurator**

2.1.1 Updating the configuration

Save the Excel file in the project location metioned before with macros enabled to update the configured parameters. After saving the file, the project *pmsm_foc_config.h* file will be generated which you can find in the same location as the Excel file. Make sure the saved Excel file is in the correct location listed above, together with the *pmsm_foc_config.h* file. You will then need to rebuild and compile the firmware code and flash into the board.

2.2 General Excel parameters description

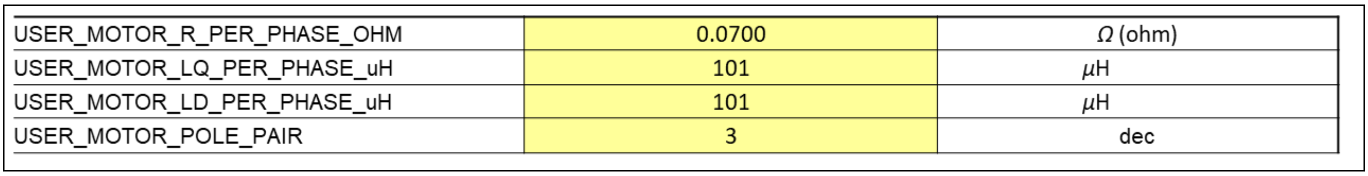
The following parameters are necessary and need to be configured before starting the motor.

2.2.1 Motor

2.2.1.1 Motor specification

- USER_MOTOR_R_PER_PHASE_OHM - Motor resistance per phase
- USER_MOTOR_LQ_PER_PHASE_uH – Motor inductance per phase
- USER_MOTOR_LD_PER_PHASE_uH – Motor inductance per phase

- USER_MOTOR_POLE_PAIR – Motor pole pair

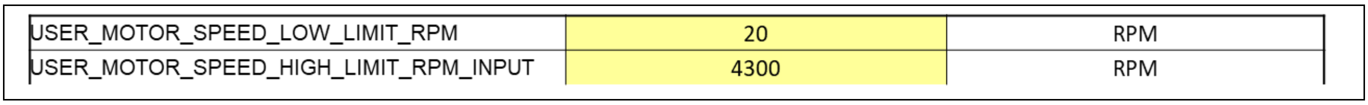


USER_MOTOR_R_PER_PHASE_OHM	0.0700	Ω (ohm)
USER_MOTOR_LQ_PER_PHASE_uH	101	µH
USER_MOTOR_LD_PER_PHASE_uH	101	µH
USER_MOTOR_POLE_PAIR	3	dec

Figure 7 **Motor specification**

2.2.1.2 Motor speed

- USER_MOTOR_SPEED_LOW_LIMIT_RPM – Motor minimum speed
- USER_MOTOR_SPEED_HIGH_LIMIT_RPM_INPUT – Motor maximum speed



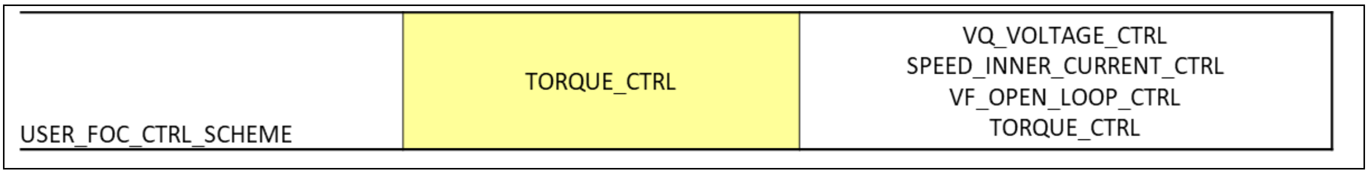
USER_MOTOR_SPEED_LOW_LIMIT_RPM	20	RPM
USER_MOTOR_SPEED_HIGH_LIMIT_RPM_INPUT	4300	RPM

Figure 8 **Motor speed**

2.2.2 Control topology

2.2.2.1 Control scheme

Dropdown list selection for different control scheme.

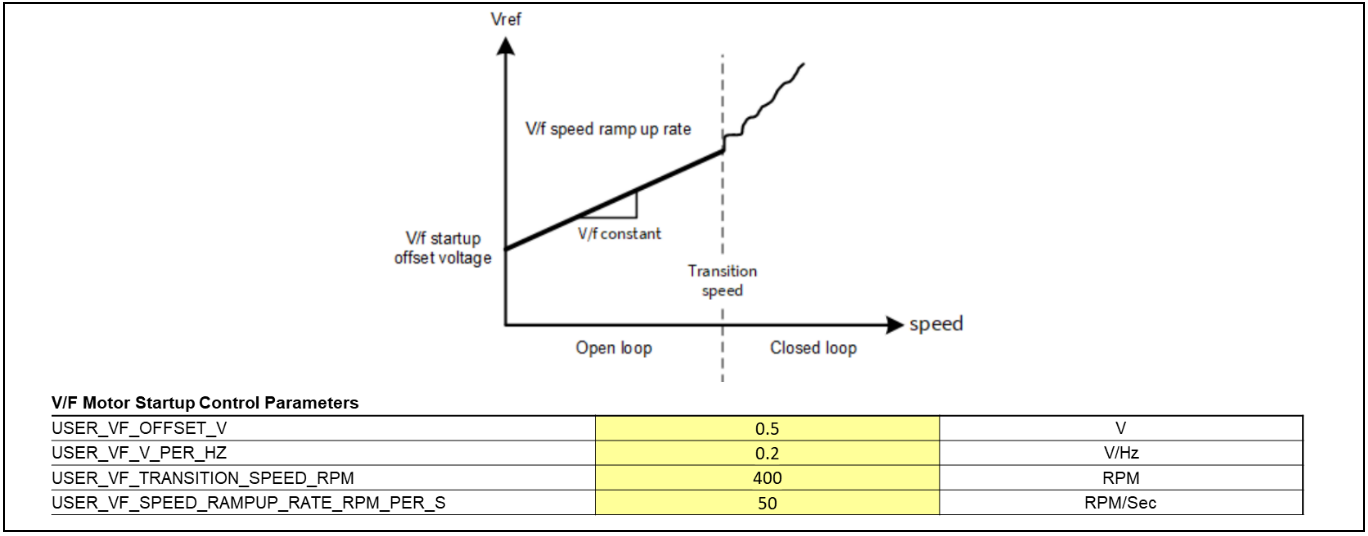


USER_FOC_CTRL_SCHEME	TORQUE_CTRL	VQ_VOLTAGE_CTRL SPEED_INNER_CURRENT_CTRL VF_OPEN_LOOP_CTRL TORQUE_CTRL

Figure 9 **Control scheme**

2.2.2.2 Open loop control

You can configure the control based on the diagram shown in Figure 10.



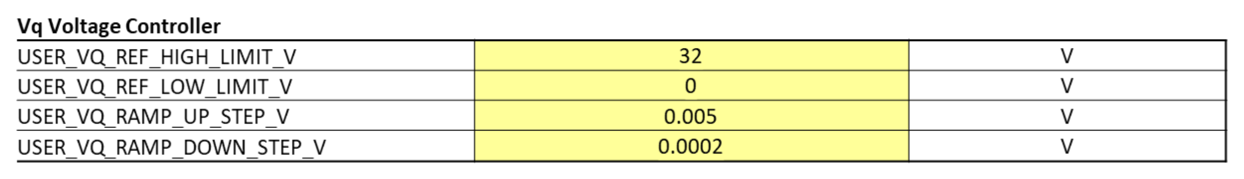
V/F Motor Startup Control Parameters

USER_VF_OFFSET_V	0.5	V
USER_VF_V_PER_HZ	0.2	V/Hz
USER_VF_TRANSITION_SPEED_RPM	400	RPM
USER_VF_SPEED_RAMPUP_RATE_RPM_PER_S	50	RPM/Sec

Figure 10 Open loop control

2.2.2.3 VQ control

- USER_VQ_REF_HIGH_LIMIT_V – High Limit of voltage. Must be less than DC Link voltage
- USER_VQ_REF_LOW_LIMIT_V – Low limit of reference voltage
- USER_VQ_RAMP_UP_STEP_V – Ramp up rate in voltage
- USER_VQ_RAMP_DOWN_STEP_V – Ramp down rate in voltage



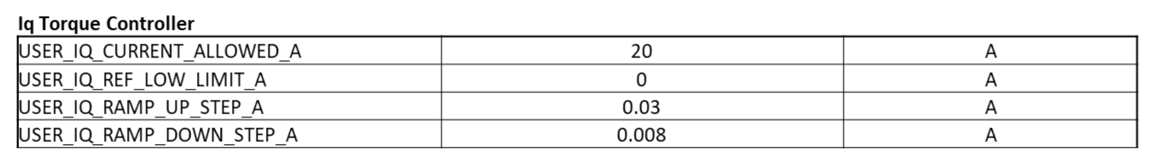
Vq Voltage Controller

USER_VQ_REF_HIGH_LIMIT_V	32	V
USER_VQ_REF_LOW_LIMIT_V	0	V
USER_VQ_RAMP_UP_STEP_V	0.005	V
USER_VQ_RAMP_DOWN_STEP_V	0.0002	V

Figure 11 VQ control

2.2.2.4 Torque control

- USER_IQ_CURRENT_ALLOWED_A – High limit of torque current
- USER_IQ_REF_LOW_LIMIT_A – Low limit of torque current
- USER_IQ_RAMP_UP_STEP_A – Ramp up rate in current
- USER_IQ_RAMP_DOWN_STEP_A – Ramp down rate in current



Iq Torque Controller

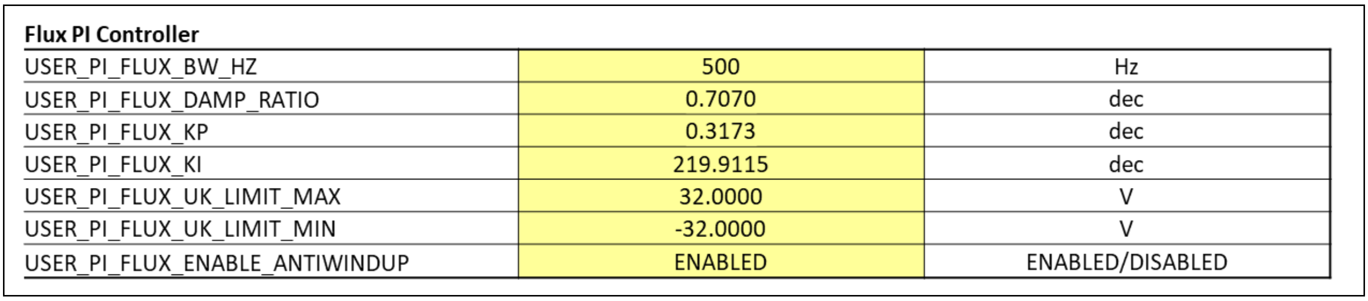
USER_IQ_CURRENT_ALLOWED_A	20	A
USER_IQ_REF_LOW_LIMIT_A	0	A
USER_IQ_RAMP_UP_STEP_A	0.03	A
USER_IQ_RAMP_DOWN_STEP_A	0.008	A

Figure 12 Torque control

2.2.2.5 Flux PI controller

Under the VQ control scheme, you only need to tune this PI controller. The flux kp and ki is auto-calculated by fine tuning of the flux bandwidth frequency.

- USER_PI_FLUX_BW_HZ - Bandwidth of a PI controller determines how quickly the controller can respond to disturbances or changes in the process variable. A higher bandwidth means the controller can respond faster and more accurately to changes, while a lower bandwidth means the controller responds more slowly.



Flux PI Controller

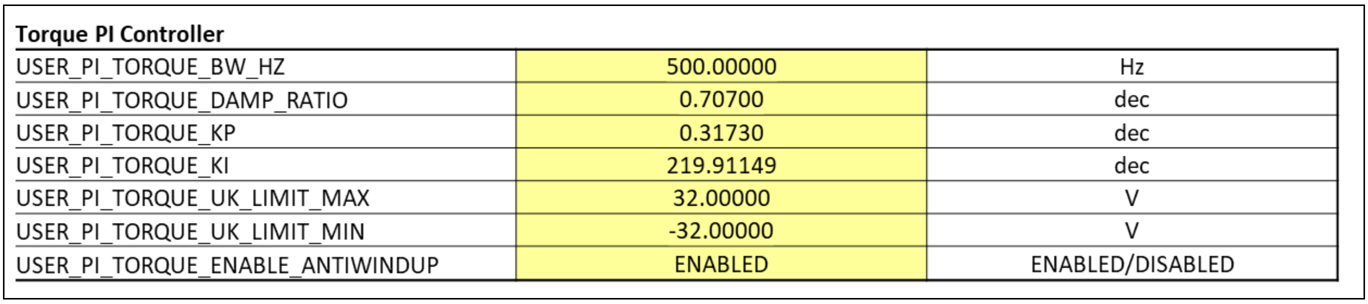
USER_PI_FLUX_BW_HZ	500	Hz
USER_PI_FLUX_DAMP_RATIO	0.7070	dec
USER_PI_FLUX_KP	0.3173	dec
USER_PI_FLUX_KI	219.9115	dec
USER_PI_FLUX_UK_LIMIT_MAX	32.0000	V
USER_PI_FLUX_UK_LIMIT_MIN	-32.0000	V
USER_PI_FLUX_ENABLE_ANTIWINDUP	ENABLED	ENABLED/DISABLED

Figure 13 **Flux PI controller**

2.2.2.6 Torque PI controller

Under the torque control scheme, you will need to tune and configure both the flux PI controller and the torque PI controller. Both use the same configuration value.

- USER_PI_TORQUE_BW_HZ - Bandwidth of a PI controller determines how quickly the controller can respond to disturbances or changes in the process variable. A higher bandwidth means the controller can respond faster and more accurately to changes, while a lower bandwidth means the controller responds more slowly.



Torque PI Controller

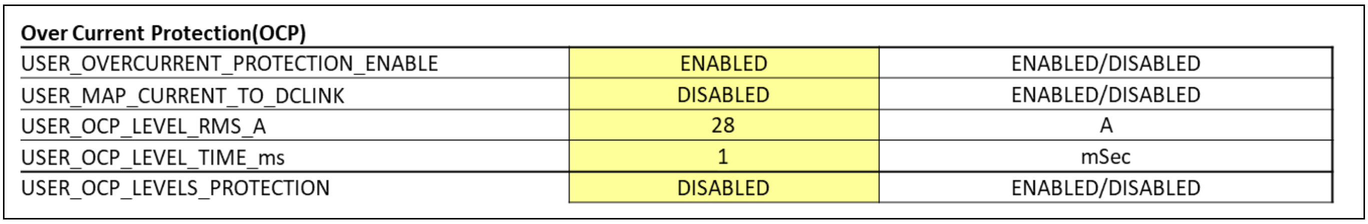
USER_PI_TORQUE_BW_HZ	500.00000	Hz
USER_PI_TORQUE_DAMP_RATIO	0.70700	dec
USER_PI_TORQUE_KP	0.31730	dec
USER_PI_TORQUE_KI	219.91149	dec
USER_PI_TORQUE_UK_LIMIT_MAX	32.00000	V
USER_PI_TORQUE_UK_LIMIT_MIN	-32.00000	V
USER_PI_TORQUE_ENABLE_ANTIWINDUP	ENABLED	ENABLED/DISABLED

Figure 14 **Torque PI controller**

2.2.3 Protection

2.2.3.1 Overcurrent protection (OCP)

- USER_MAP_CURRENT_TO_DCLINK:
  - Enable for DC Link over current protection
  - Disable and it will be phase current protection
- USER_OCP_LEVEL_RMS_A – Maximum current limit
- USER_OCP_LEVEL_TIME_ms – Total Amount of time OCP is detected before OCP triggered

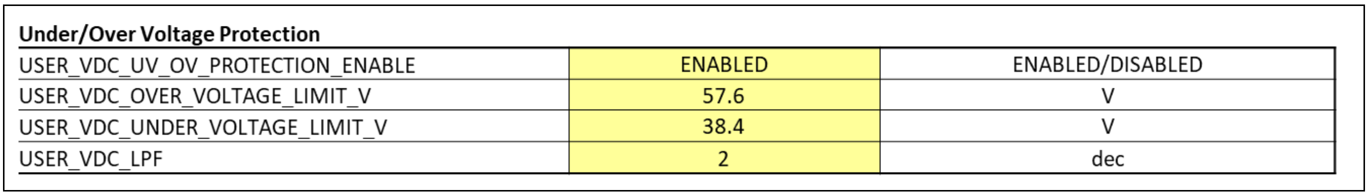


Over Current Protection(OCP)

USER_OVERCURRENT_PROTECTION_ENABLE	ENABLED	ENABLED/DISABLED
USER_MAP_CURRENT_TO_DCLINK	DISABLED	ENABLED/DISABLED
USER_OCP_LEVEL_RMS_A	28	A
USER_OCP_LEVEL_TIME_ms	1	mSec
USER_OCP_LEVELS_PROTECTION	DISABLED	ENABLED/DISABLED

Figure 15 Overcurrent protection

2.2.3.2 Under/overvoltage protection



Under/Over Voltage Protection

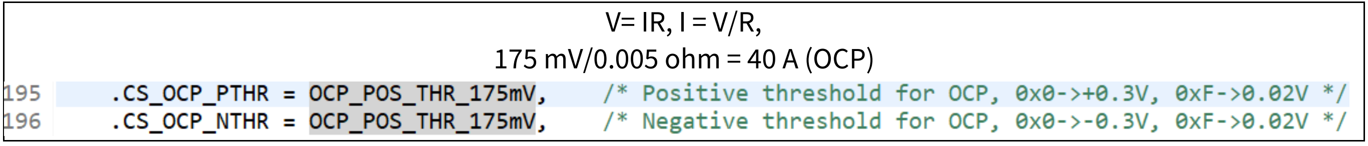
USER_VDC_UV_OV_PROTECTION_ENABLE	ENABLED	ENABLED/DISABLED
USER_VDC_OVER_VOLTAGE_LIMIT_V	57.6	V
USER_VDC_UNDER_VOLTAGE_LIMIT_V	38.4	V
USER_VDC_LPF	2	dec

Figure 16 Under/overvoltage protection

2.2.3.3 6EDL7151 Hardware overcurrent protection

Depending on the shunt resistor of the board and the user preferred OCP current value.

E.g., Shunt resistor = 5 mohm



V= IR, I = V/R,

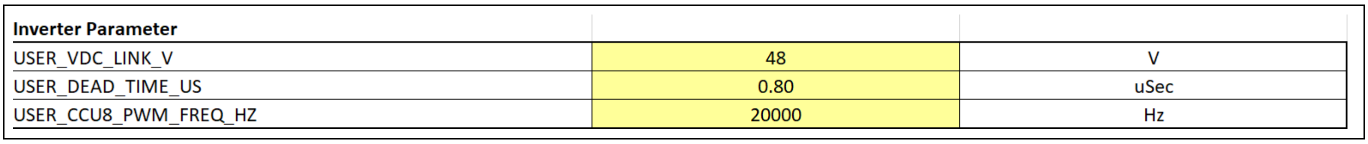
175 mV/0.005 ohm = 40 A (OCP)

```
    .CS_OCP_PTHR = OCP_POS_THR_175mV,    /* Positive threshold for OCP, 0x0->+0.3V, 0xF->0.02V */
    .CS_OCP_NTHR = OCP_POS_THR_175mV,    /* Negative threshold for OCP, 0x0->-0.3V, 0xF->0.02V */
```

Figure 17 6EDL7151 overcurrent protection

2.2.4 Hardware/inverter

2.2.4.1 Inverter parameters

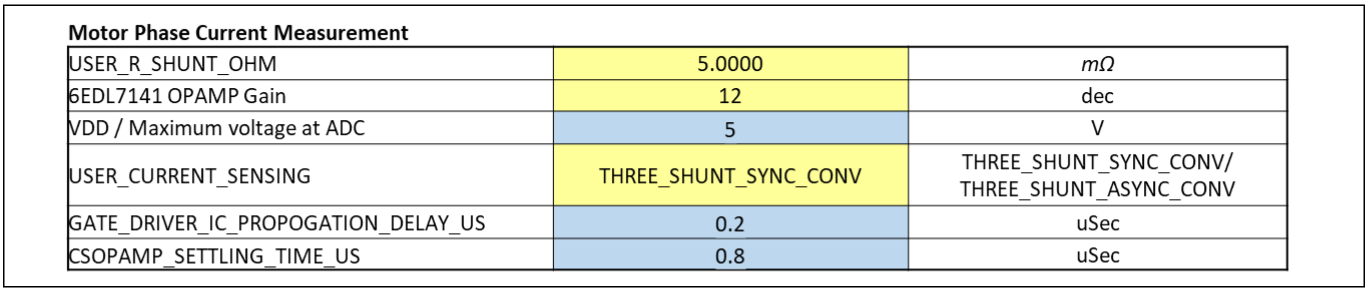


Inverter Parameter		
USER_VDC_LINK_V	48	V
USER_DEAD_TIME_US	0.80	uSec
USER_CCU8_PWM_FREQ_HZ	20000	Hz

Figure 18 Inverter parameters

2.2.4.2 Motor phase current measurement

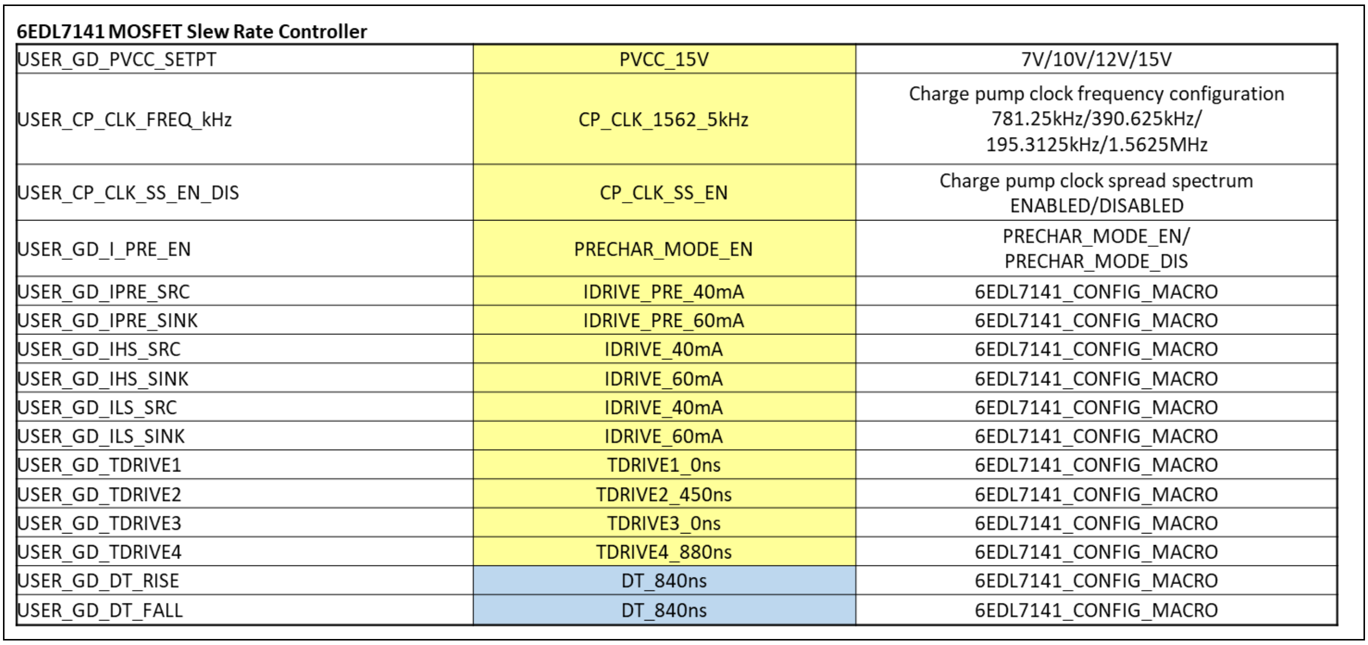
- USER_R_SHUNT_OHM – Current shunt resistance



Motor Phase Current Measurement		
USER_R_SHUNT_OHM	5.0000	*mΩ*
6EDL7141 OPAMP Gain	12	dec
VDD / Maximum voltage at ADC	5	V
USER_CURRENT_SENSING	THREE_SHUNT_SYNC_CONV	THREE_SHUNT_SYNC_CONV/ THREE_SHUNT_ASYNC_CONV
GATE_DRIVER_IC_PROPOGATION_DELAY_US	0.2	uSec
CSOPAMP_SETTLING_TIME_US	0.8	uSec

Figure 19 Motor phase current measurement

2.2.4.3 MOSFET slew rate controller

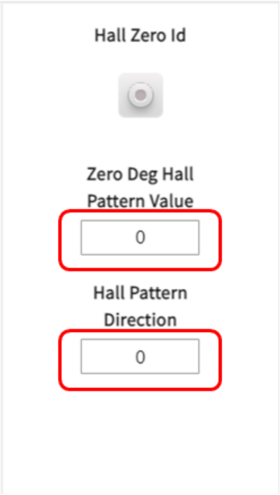


6EDL7141 MOSFET Slew Rate Controller		
USER_GD_PVCC_SETPT	PVCC_15V	7V/10V/12V/15V
USER_CP_CLK_FREQ_kHz	CP_CLK_1562_5kHz	Charge pump clock frequency configuration 781.25kHz/390.625kHz/ 195.3125kHz/1.5625MHz
USER_CP_CLK_SS_EN_DIS	CP_CLK_SS_EN	Charge pump clock spread spectrum ENABLED/DISABLED
USER_GD_I_PRE_EN	PRECHAR_MODE_EN	PRECHAR_MODE_EN/ PRECHAR_MODE_DIS
USER_GD_IPRE_SRC	IDRIVE_PRE_40mA	6EDL7141_CONFIG_MACRO
USER_GD_IPRE_SINK	IDRIVE_PRE_60mA	6EDL7141_CONFIG_MACRO
USER_GD_IHS_SRC	IDRIVE_40mA	6EDL7141_CONFIG_MACRO
USER_GD_IHS_SINK	IDRIVE_60mA	6EDL7141_CONFIG_MACRO
USER_GD_ILS_SRC	IDRIVE_40mA	6EDL7141_CONFIG_MACRO
USER_GD_ILS_SINK	IDRIVE_60mA	6EDL7141_CONFIG_MACRO
USER_GD_TDRIVE1	TDRIVE1_0ns	6EDL7141_CONFIG_MACRO
USER_GD_TDRIVE2	TDRIVE2_450ns	6EDL7141_CONFIG_MACRO
USER_GD_TDRIVE3	TDRIVE3_0ns	6EDL7141_CONFIG_MACRO
USER_GD_TDRIVE4	TDRIVE4_880ns	6EDL7141_CONFIG_MACRO
USER_GD_DT_RISE	DT_840ns	6EDL7141_CONFIG_MACRO
USER_GD_DT_FALL	DT_840ns	6EDL7141_CONFIG_MACRO

Figure 20 MOSFET slew rate controller

2.3 Motor Hall calibration

The prerequisite for the motor Hall calibration is that the motor needs to be able to run smoothly under open-loop control. The Hall calibration process will auto-update the zero-angle information and angle direction table and use the parameters to run the motor. After the Hall calibration process, the GUI interface displays the correct zero-degree Hall pattern and Hall pattern direction from the open loop motor run, as shown in Figure 21.



Hall Zero Id

Zero Deg Hall Pattern Value: 0

Hall Pattern Direction: 0

Figure 21 GUI zero-degree pattern and direction

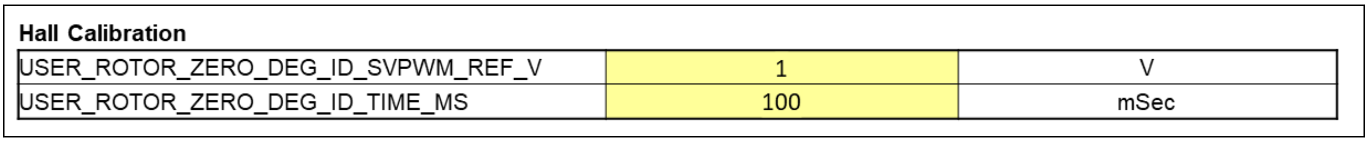
2.3.1 Hall calibration process

1. Click on the HALL Zero ID button OFF to ON the hall calibration.
2. Adjust POT to any non-zero value.
3. POT value will return to zero once the hall calibration process is completed.
4. Click on HALL Zero ID again to OFF the hall calibration.
5. Adjust POT again to run motor in closed loop

2.3.2 Hall calibration Excel configuration

During the Hall calibration process, the rotor is observed to turn abruptly and then moving continuously for a while before coming to a standstill. Depending on the motor type, you can adjust the following parameters in the Excel configurator.

- USER_ROTOR_ZERO_DEG_ID_SVPWM_REF_V
  - Init voltage. Adjust so that the motor has enough power to move the rotor.
- USER_ROTOR_ZERO_DEG_ID_TIME_MS
  - Rotor motion settling time



Hall Calibration

USER_ROTOR_ZERO_DEG_ID_SVPWM_REF_V	1	V
USER_ROTOR_ZERO_DEG_ID_TIME_MS	100	mSec

Figure 22 Hall calibration Excel configuration

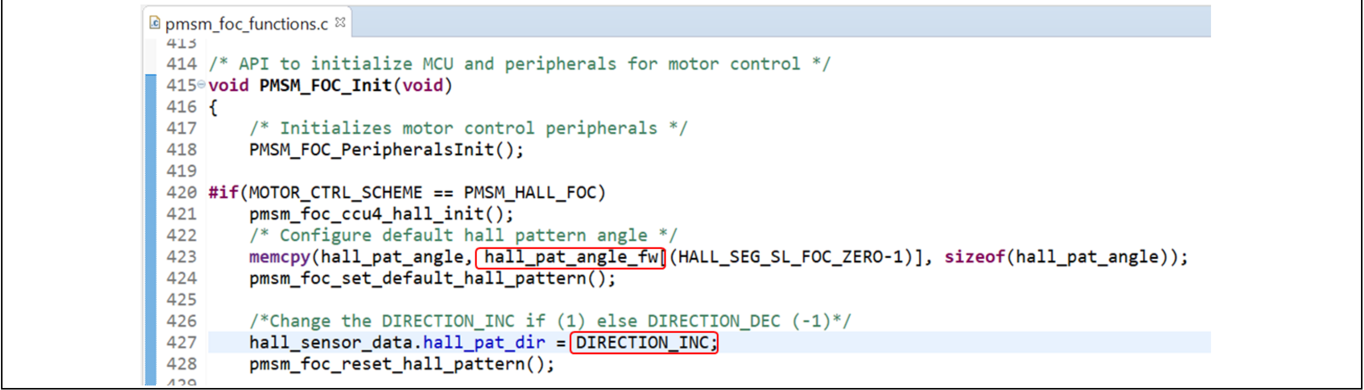
2.3.3 Hall calibration firmware configuration

The parameters are volatile and are lost after a power-off of the board. Every time the board is powered up, it is initialized with the default parameters. Therefore, you must redo the Hall calibration process again before running the motor.

Otherwise, you can overwrite the default information with the known information from the Hall calibration.

2.3.3.1 Hall direction

In the GUI interface, the Hall pattern direction gives 0, 1, and -1, which represent error, forward, and backward direction respectively. Therefore, in the firmware for forward direction, “hall_pat_angle_fw” should be replaced as in the following figure. For backward direction, “hall_pat_angle_rev” is used instead. In addition, also change the DIRECTION_INC if forward direction, else use DIRECTION_DEC if backward direction.



pmsm_foc_functions.c

```
/* API to initialize MCU and peripherals for motor control */
void PMSM_FOC_Init(void)
{
    /* Initializes motor control peripherals */
    PMSM_FOC_PeripheralsInit();

#if(MOTOR_CTRL_SCHEME == PMSM_HALL_FOC)
    pmsm_foc_ccu4_hall_init();
    /* Configure default hall pattern angle */
    memcpy(hall_pat_angle, hall_pat_angle_fw[(HALL_SEG_SL_FOC_ZERO-1)], sizeof(hall_pat_angle));
    pmsm_foc_set_default_hall_pattern();

    /*Change the DIRECTION_INC if (1) else DIRECTION_DEC (-1)*/
    hall_sensor_data.hall_pat_dir = DIRECTION_INC;
    pmsm_foc_reset_hall_pattern();
```

Figure 23 **Hall direction firmware configuration**

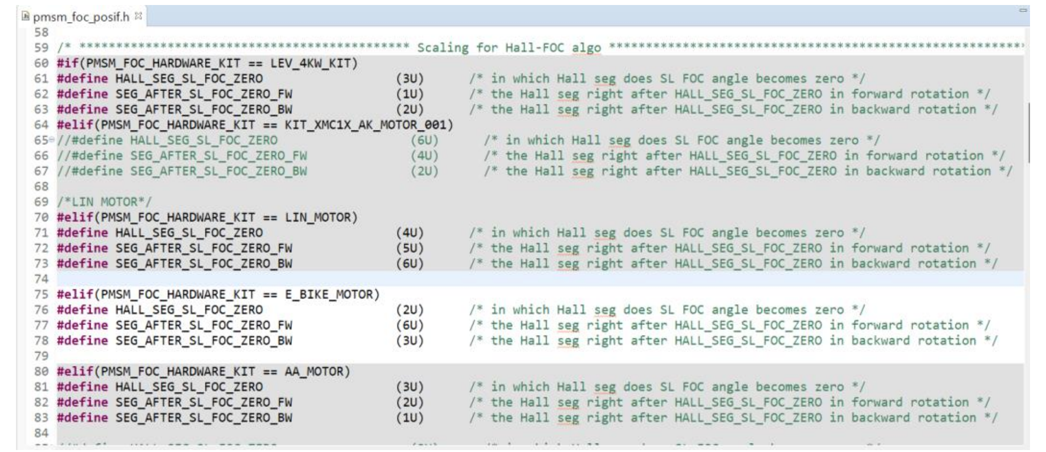
2.3.3.2 Hall pattern

Replace the Hall pattern (zero degree) value in GUI interface to the firmware code.

HALL_SEG_SL_FOC_ZERO – Zero-degree Hall pattern value shown in GUI.

- Direction increment (forward +1) follows the following pattern: 1, 3, 2, 6, 4, 5.
- Direction decrement (backward -1) follows the following pattern: 1, 5, 4, 6, 2, 3.

If the zero-degree Hall pattern is 2 with direction (forward +1), firmware configuration should be as shown in Figure 24.



pmsm_foc_posif.h

```

/* ********************************************* Scaling for Hall-FOC algo ************************************************************
#if(PMSM_FOC_HARDWARE_KIT == LEV_4KW_KIT)
#define HALL_SEG_SL_FOC_ZERO                    (3U)      /* in which Hall seg does SL FOC angle becomes zero */
#define SEG_AFTER_SL_FOC_ZERO_FW                (1U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in forward rotation */
#define SEG_AFTER_SL_FOC_ZERO_BW                (2U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in backward rotation */
#elif(PMSM_FOC_HARDWARE_KIT == KIT_XMC1X_AK_MOTOR_001)
//#define HALL_SEG_SL_FOC_ZERO                   (6U)      /* in which Hall seg does SL FOC angle becomes zero */
//#define SEG_AFTER_SL_FOC_ZERO_FW               (4U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in forward rotation */
//#define SEG_AFTER_SL_FOC_ZERO_BW               (2U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in backward rotation */

/*LIN MOTOR*/
#elif(PMSM_FOC_HARDWARE_KIT == LIN_MOTOR)
#define HALL_SEG_SL_FOC_ZERO                    (4U)      /* in which Hall seg does SL FOC angle becomes zero */
#define SEG_AFTER_SL_FOC_ZERO_FW                (5U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in forward rotation */
#define SEG_AFTER_SL_FOC_ZERO_BW                (6U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in backward rotation */

#elif(PMSM_FOC_HARDWARE_KIT == E_BIKE_MOTOR)
#define HALL_SEG_SL_FOC_ZERO                    (2U)      /* in which Hall seg does SL FOC angle becomes zero */
#define SEG_AFTER_SL_FOC_ZERO_FW                (6U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in forward rotation */
#define SEG_AFTER_SL_FOC_ZERO_BW                (3U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in backward rotation */

#elif(PMSM_FOC_HARDWARE_KIT == AA_MOTOR)
#define HALL_SEG_SL_FOC_ZERO                    (3U)      /* in which Hall seg does SL FOC angle becomes zero */
#define SEG_AFTER_SL_FOC_ZERO_FW                (2U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in forward rotation */
#define SEG_AFTER_SL_FOC_ZERO_BW                (1U)      /* the Hall seg right after HALL_SEG_SL_FOC_ZERO in backward rotation */

```

Figure 24 **Motor Hall zero pattern initialization value**

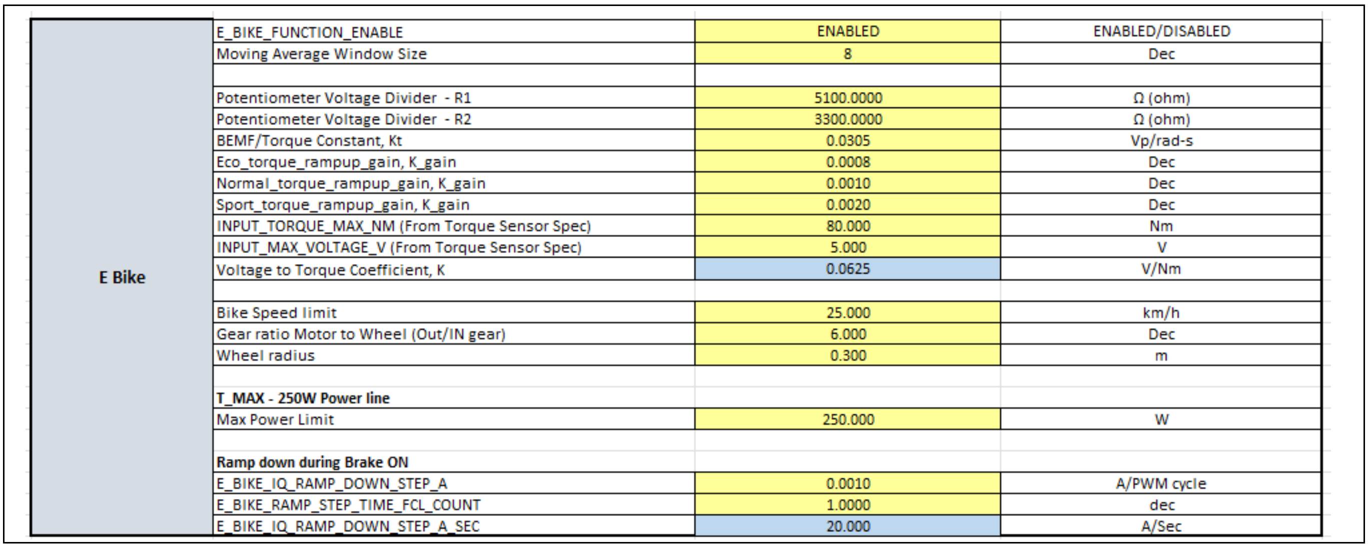
2.4 e-Bike functions

The e-Bike functionality refers to the vehicle properties and behavior. Since certain system requirements refer to vehicle properties like top speed etc., the relevant gear ratios and wheel diameters need to be determined. The following e-bike functions have been implemented in the firmware:

- Moving Average
- Throttle Strategy
  - Three operational mode-based torque assistance.
- Torque limit
  - Max. assist torque limit according to bike speed.
  - Power limit
- Brake ramp down
- Startup throttle check

2.4.1 e-Bike Excel configuration

You can find all the related e-Bike function configurations under the E Bike section as shown in Figure 25.



E Bike	E_BIKE_FUNCTION_ENABLE	ENABLED	ENABLED/DISABLED
	Moving Average Window Size	8	Dec
	Potentiometer Voltage Divider - R1	5100.0000	Ω (ohm)
	Potentiometer Voltage Divider - R2	3300.0000	Ω (ohm)
	BEMF/Torque Constant, Kt	0.0305	Vp/rad-s
	Eco_torque_rampup_gain, K_gain	0.0008	Dec
	Normal_torque_rampup_gain, K_gain	0.0010	Dec
	Sport_torque_rampup_gain, K_gain	0.0020	Dec
	INPUT_TORQUE_MAX_NM (From Torque Sensor Spec)	80.000	Nm
	INPUT_MAX_VOLTAGE_V (From Torque Sensor Spec)	5.000	V
	Voltage to Torque Coefficient, K	0.0625	V/Nm
	Bike Speed limit	25.000	km/h
	Gear ratio Motor to Wheel (Out/IN gear)	6.000	Dec
	Wheel radius	0.300	m
	T_MAX - 250W Power line		
	Max Power Limit	250.000	W
	Ramp down during Brake ON		
	E_BIKE_IQ_RAMP_DOWN_STEP_A	0.0010	A/PWM cycle
	E_BIKE_RAMP_STEP_TIME_FCL_COUNT	1.0000	dec
	E_BIKE_IQ_RAMP_DOWN_STEP_A_SEC	20.000	A/Sec

Figure 25 e-Bike Excel configuration

Table 3 Motor and vehicle parameters

Symbol	Property of	Quantity/Meaning	Unit
K_T	Motor	Torque constant	*Nm/Arms*
n_pp	Motor	number of pole pairs	dec
g_motor	Vehicle	Gear ratio - Motor ($g_{motor} = \tau_{wheel}/\tau_{motor} = \omega_{motor}/\omega_{wheel}$) CAN input – if bike has gears	dec
r_wheel	Vehicle	Wheel Diameter / Radius / Circumference	m
USER_POT_ADC_LPF	Vehicle	ADC potentiometer low-pass filter	dec
K_G K_G (1,2,3)	User/Vehicle	Input control torque gain (Throttle gain) input several values to make "operational Mode" user selectable	dec
P_max	Vehicle	Max. power limit	W
v_cutoff	Vehicle	Top speed - above which no assistance is allowed	km/h

Symbol	Property of	Quantity/Meaning	Unit
T_brake_rampDown	User/Vehicle	Rate of assisting torque ramp-down when brake is applied	s
K_{VT}	Motor	Voltage-to-Torque Coefficient. Base max torque reading and max voltage from torque sensor	V/Nm
T_{NM}	Motor	Max input torque reading form torque sensor	Nm

2.4.2 Input signal processing – Low pass filtering and moving average

To process the signal in terms of reducing noise as well as averaging out the torque ripple coming from pedaling, both a low-pass filter (LPF), and a moving-average (MA) are applied before the proportional processing.

The LPF is used to remove the noise and the high-speed interference.

Since the pedaling torque fluctuation (ripple) is periodic, a moving average function related to the pedaling period, is very effective in evening out the resulting assisting torque. MA with the configurable sampling window size shown in Figure 28 is used to average out of the torque ripple coming from the pedaling.

The example in Figure 26 uses a half-sinewave shape as the approximation of the pedaling torque. Based on that, a moving average window (T_averaging) is defined as the period of a single half sinewave length, which represents a half of a pedaling turn (T_pedaling – single side pedaling burst). The resulting average – i.e., the motor torque in this case is a constant torque without any ripples, however it is also important to consider the resulting sum of both torques.

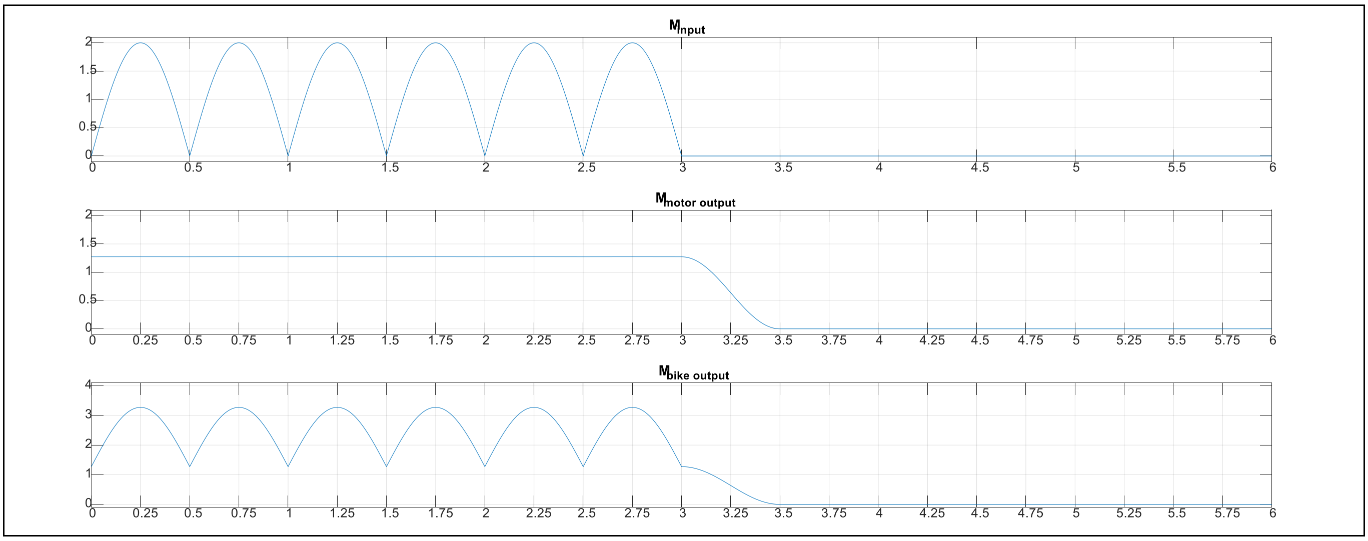


Figure 26 T_averaging = T_pedaling = 0.5 s at cadence = 60 rpm

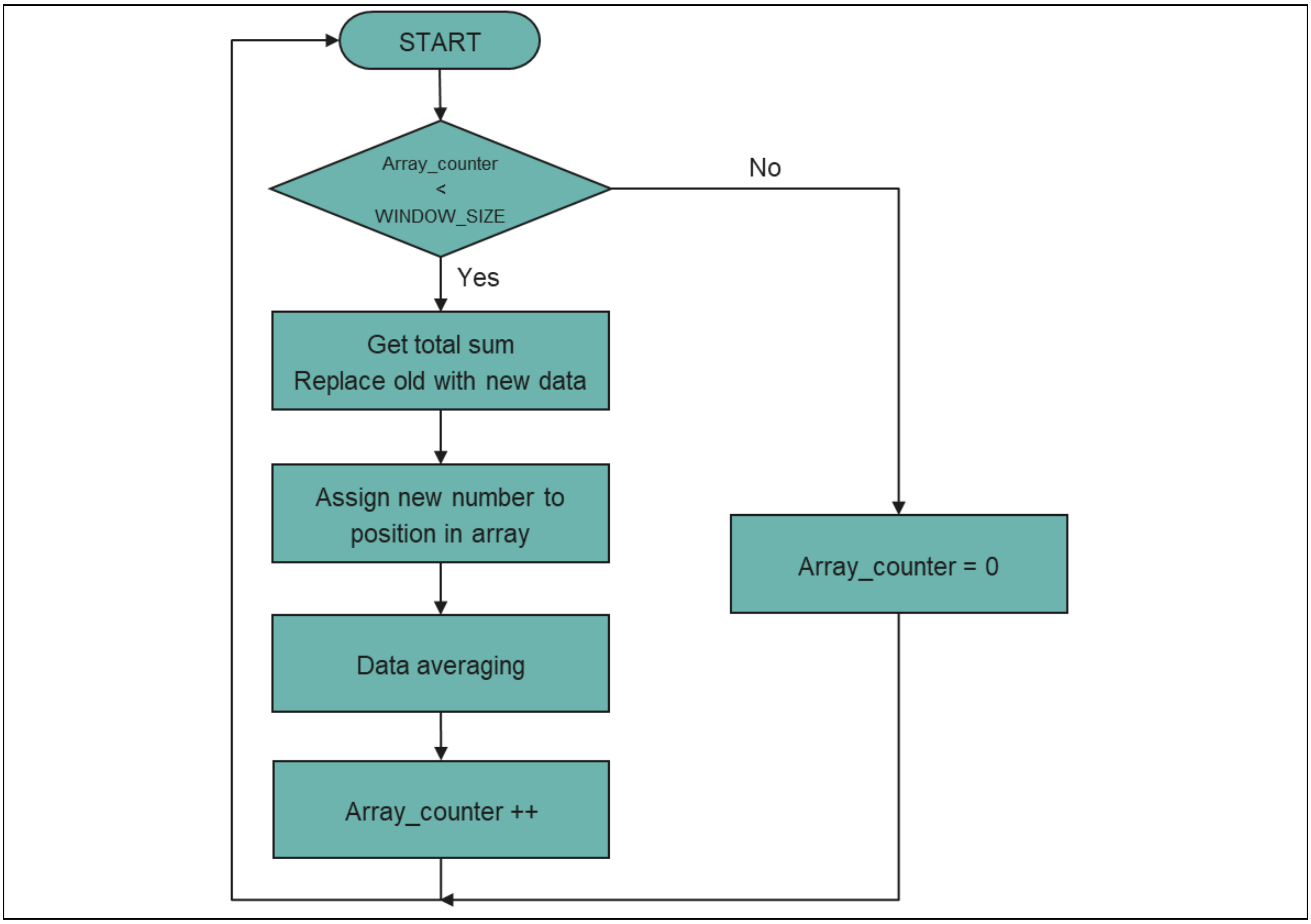
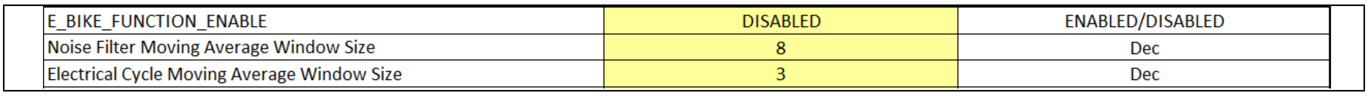


Figure 27 **Moving average flowchart**

The moving average window (T_averaging) is defined in the configuration file as "Electrical Cycle Moving Average Window Size"(see Figure 28). It is expressed in the number of electrical cycles to average the throttle reading (e.g., the number is by default the same as the pole pair number so that it represents one mechanical cycle).

The other related parameter "Noise Filter Moving Average Window Size" is a moving average filter that averages a number of the last obtained throttle samples (sampled every PWM cycle). The configuration value is the number of samples calculated in the averaging.



E_BIKE_FUNCTION_ENABLE	DISABLED	ENABLED/DISABLED
Noise Filter Moving Average Window Size	8	Dec
Electrical Cycle Moving Average Window Size	3	Dec

Figure 28 **Excel configuration for moving average window size**

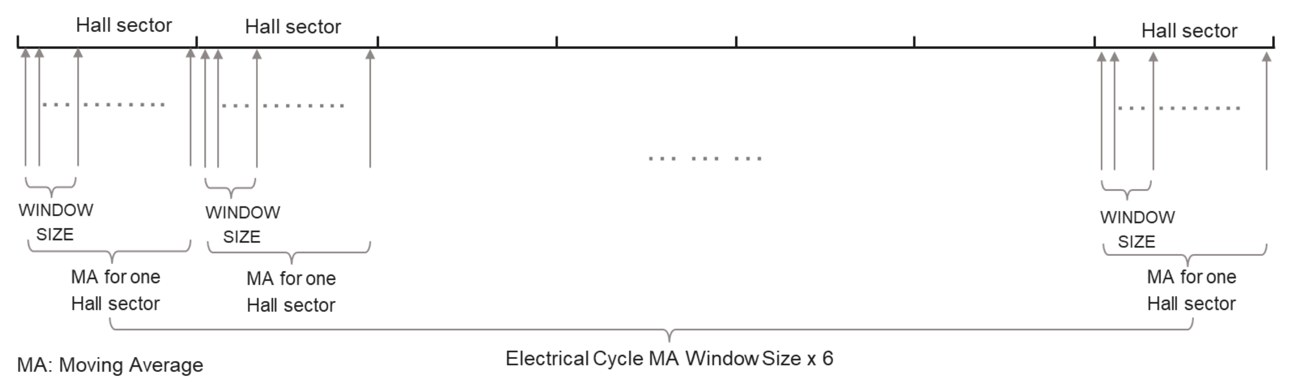


Figure 29 Moving average window size representation

2.4.3 Throttle strategy

Pedal assist e-bike/pedelecs uses a throttle strategy to control of the output torque according to the pedaling effort. This will be done by using of a torque sensor (strain gauge) and reading the output from the sensor. The sensor will have an analog output voltage of 0.74 V to 3.3 V/5 V according to the torque sensor specification.

This allows measurement of how much force a rider applies to the pedals and determine how much power the motor should output to the e-Bike. The output torque is linearly proportional to the input control signal, which may be a direct analog signal from a potentiometer. Higher input torque, higher assisting torque output is shown in Figure 30.

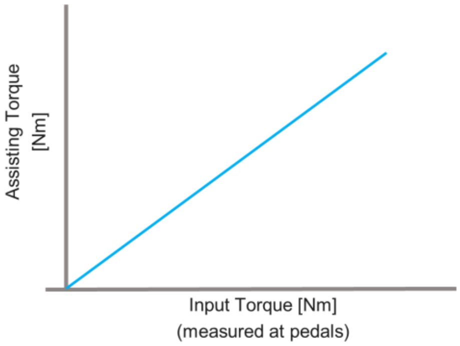


Figure 30 Assisting torque vs. input torque

2.4.3.1 Throttle mode

The input control gain could optionally be offered as a selection by you as an “Operational mode” for the torque assistance.

There will be three operational mode-based torque assistance: Each mode will have a different slope relationship of assisting torque vs. input torque. ECO, NORMAL, SPORTS as shown in Figure 31.

- Eco mode: Flatter slope of assisting torque vs. input torque
- Normal mode: Normal slope of assisting torque vs. input torque
- Sports mode: Steeper slope of assisting torque vs. input torque

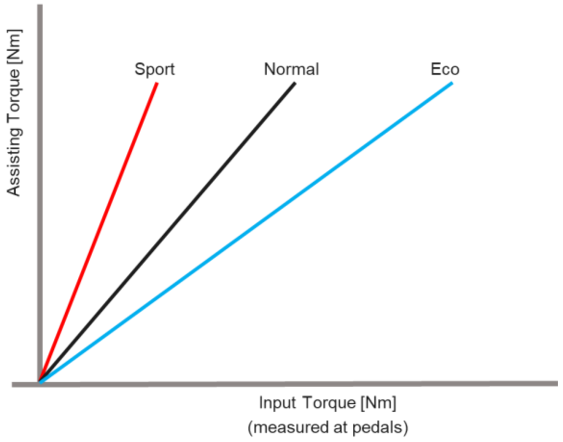


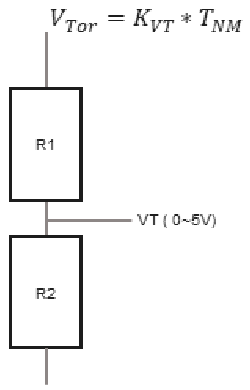
Figure 31 Three operational throttle modes

The following equations are needed to get the Torque current Iq based on the different torque gain & ADC input.

Potentiometer Voltage Divider,

$$V_{Tor} = K_{VT} * T_{NM}$$

$$V_T = V_{Tor} * \frac{R2}{R1 + R2}$$



Equation 1

ADC value reading from torque sensor,

$$ADC_{VT} * \frac{5V*(R1+R2)}{4095*R2*K_{VT}}$$

Equation 2

Assisting torque output,

$$T_{out} = K_G * T_{NM}$$

$$T_{out} = K_T * Iq$$

Equation 3

Getting torque current Iq,

$$Iq = \frac{K_G*(R1+R2)*5V}{K_t*4095*R2*K_{VT}} * ADC_{VT}$$

Equation 4

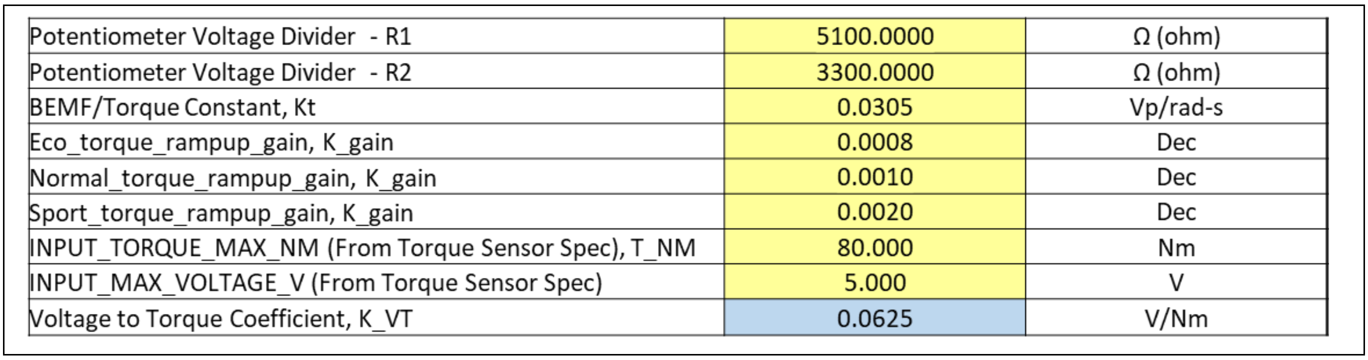
Where,

K_G = Gain constant

K_T= Torque/BEMF constant

K_{VT} = Voltage to torque coefficient

T_{NM} = Max. torque reading from torque sensor in Nm



Potentiometer Voltage Divider - R1	5100.0000	Ω (ohm)
Potentiometer Voltage Divider - R2	3300.0000	Ω (ohm)
BEMF/Torque Constant, Kt	0.0305	Vp/rad-s
Eco_torque_rampup_gain, K_gain	0.0008	Dec
Normal_torque_rampup_gain, K_gain	0.0010	Dec
Sport_torque_rampup_gain, K_gain	0.0020	Dec
INPUT_TORQUE_MAX_NM (From Torque Sensor Spec), T_NM	80.000	Nm
INPUT_MAX_VOLTAGE_V (From Torque Sensor Spec)	5.000	V
Voltage to Torque Coefficient, K_VT	0.0625	V/Nm

Figure 32 **Excel configuration torque sensor and throttle gain**

2.4.3.2 Max. assist torque limit

The max. assist torque limit is determined by the bike speed, having a reverse relationship between assisting torque and bike speed. The higher the bike speed, the lower the assisting torque max. value as shown. Max. speed is a user-defined parameter in which no output assisting torque is allowed for any speed above the user-defined speed. Figure 33 shows the relation of the assisting torque to the bike speed.

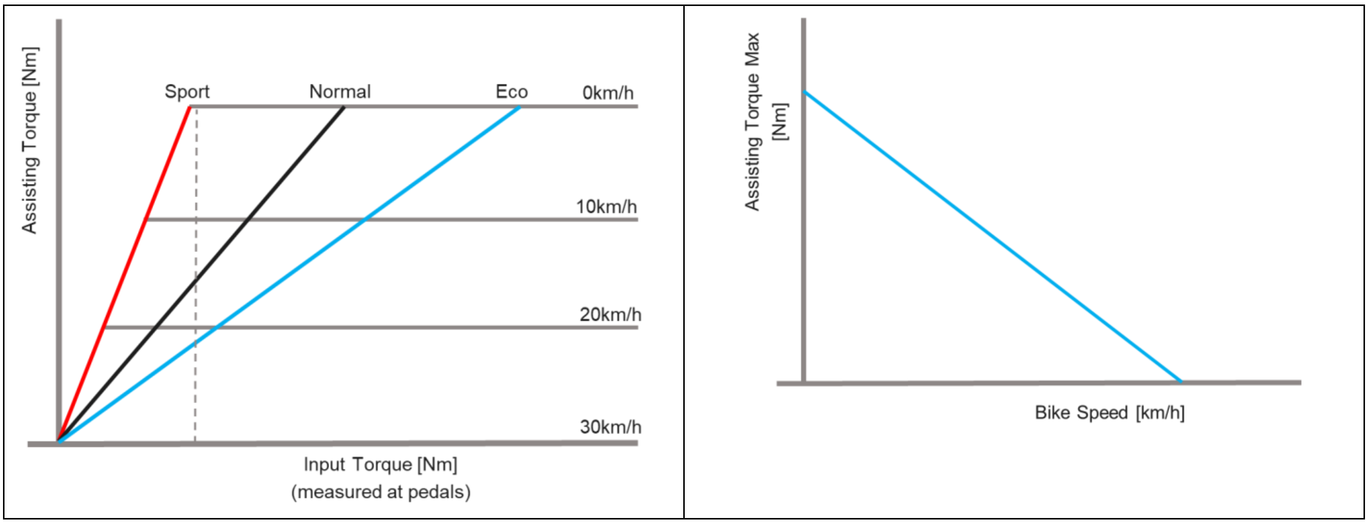
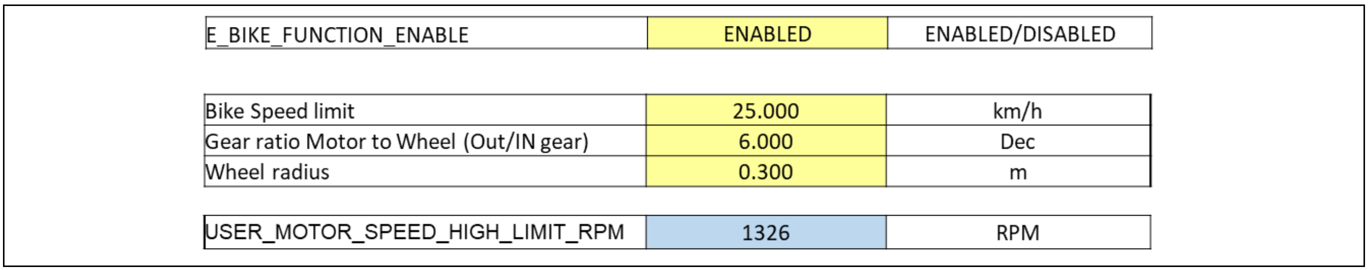


Figure 33 **Assisting torque vs. bike speed**

In the excel configurator file shown in Figure 34 you can define the bike speed limit, gear ratio of motor to wheel, and the wheel radius. Excel will calculate and convert it to a revolution per minute (rpm) value. If the E_BIKE_FUNCTION_ENABLE macro has been ENABLED, USER_MOTOR_SPEED_HIGH_LIMIT_RPM the converted rpm value will be used.



E_BIKE_FUNCTION_ENABLE	ENABLED	ENABLED/DISABLED
Bike Speed limit	25.000	km/h
Gear ratio Motor to Wheel (Out/IN gear)	6.000	Dec
Wheel radius	0.300	m
USER_MOTOR_SPEED_HIGH_LIMIT_RPM	1326	RPM

Figure 34 **Bike specification Excel configuration**

Getting the max. rpm limit from wheel radius, bike speed, and gear ratio:

$$USER\_MOTOR\_SPEED\_HIGH\_LIMIT\_RPM = \frac{25}{3*\pi*r_{wheel}} * v\_cutoff * g\_motor$$

Equation 5 **Motor speed high limit rpm**

Where,

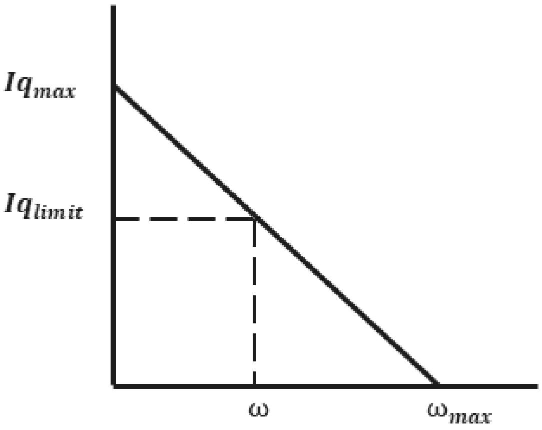
r_wheel = The radius of the bike wheel in meter (m)

v_cutoff = The user defined max bike speed in km/h

g_motor = The gear ratio of motor(input) to bike wheel(output) in outer gear: input gear

Speed ratio = Motor (input)/output (bike speed) = Gear ratio

The torque current will always be limit by the torque current limit threshold and not exceeding it.



$$Iq_{limit} = Iq_{max} - \frac{\omega}{\omega_{max}} * Iq_{max}$$

Equation 6 Torque current limit threshold

2.4.3.3 Power limiting

The assisting torque output will also be limited by the maximum power defined. This is done by calculating and getting the normalized power limit torque current threshold value. Torque current will be limited by the threshold value and not exceed the power limit torque current threshold.

Power, torque, and angular velocity,

$$P = \tau_{NM} * \omega_{mechanical}$$

$$P = \tau_{NM} * \frac{\omega_{electrical}}{Pole\ Pair}$$

$$P = K_T * Iq * \frac{\omega_e}{n\_pp}$$

Equation 7

Power base,

$$P_{base} = \frac{K_T}{n\_pp} * Iq_{base} * \omega_{e\_base}$$

Equation 8

Power max., defined by you

$$P_{max} = \frac{K_T}{n\_pp} * Iq_{max} * \omega_e$$

Equation 9

Derivative from Equation 8 and Equation 9,

$$\frac{P_{max}}{P_{base}} = \frac{Iq_{max} * \omega_e}{Iq_{base} * \omega_{e\_base}}$$

Equation 10

Normalizing of the power limit torque current threshold value,

$$\frac{P_{max}}{P_{base}} * 2^{15} * 2^{15} = \frac{Iq_{max}}{Iq_{base}} * 2^{15} * \frac{\omega_e}{\omega_{e\_base}} * 2^{15}$$

$$P_{\max\_int} * 2^{15} = Iq_{power\_\max\ \_int} * \omega_{e\_int}$$

$$Iq_{power\_max\_int} = P_{max\_int} * 2^{15} * \frac{1}{\omega_{e\_int}}$$

Equation 11

Where,

P_{max}= User-defined power, 250 W etc.

P_{base}= Max. torque sensor from specification (etc. 80 Nm) * user-defined max. speed (km/h to rad/s)

$P_{max\_int} = \frac{P_{max}}{P_{base}} * 2^{15}$

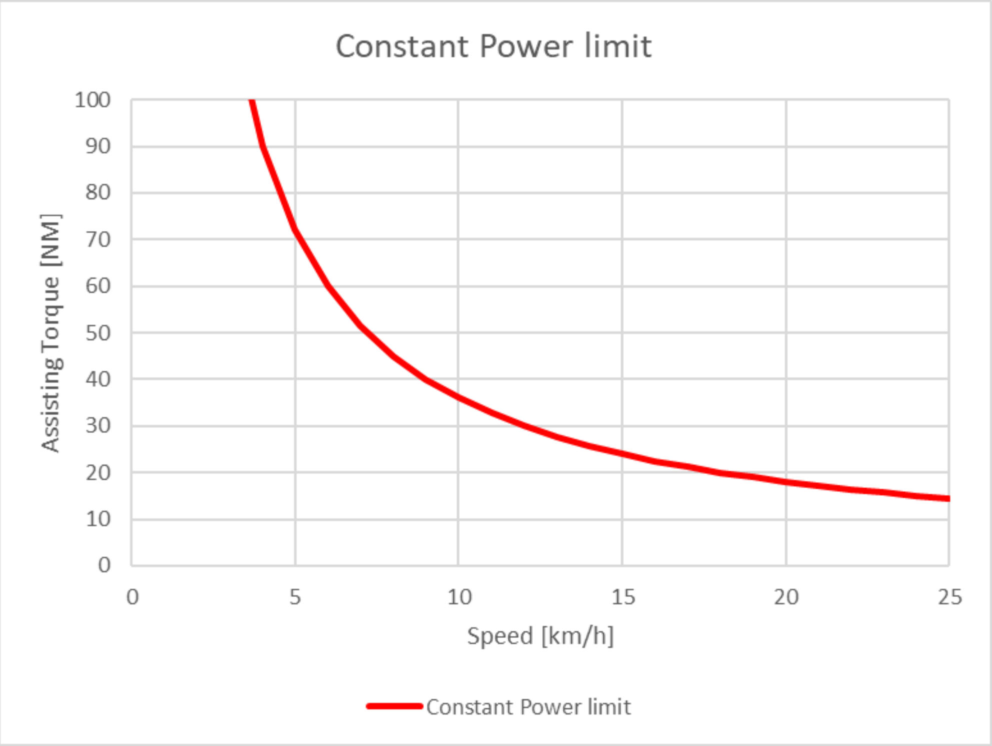


Figure 35 **Power limit in relation to speed**

2.4.4 Brake ramp down

Motor ramping down during the brake will be applied for riding comfort to avoid a sharp instantaneous change in torque.

Brake is detected on the switch level of 1/0 where no output torque is allowed whenever the brake is pressed. From the point of brake signal detection, the torque current will be ramped down to zero and goes into “MOTOR_STOP” state. There will be no torque assisting output and the motor will be in coasting. You can configure the torque current ramp down rate to determine how fast or slow the brake ramp down it would like.

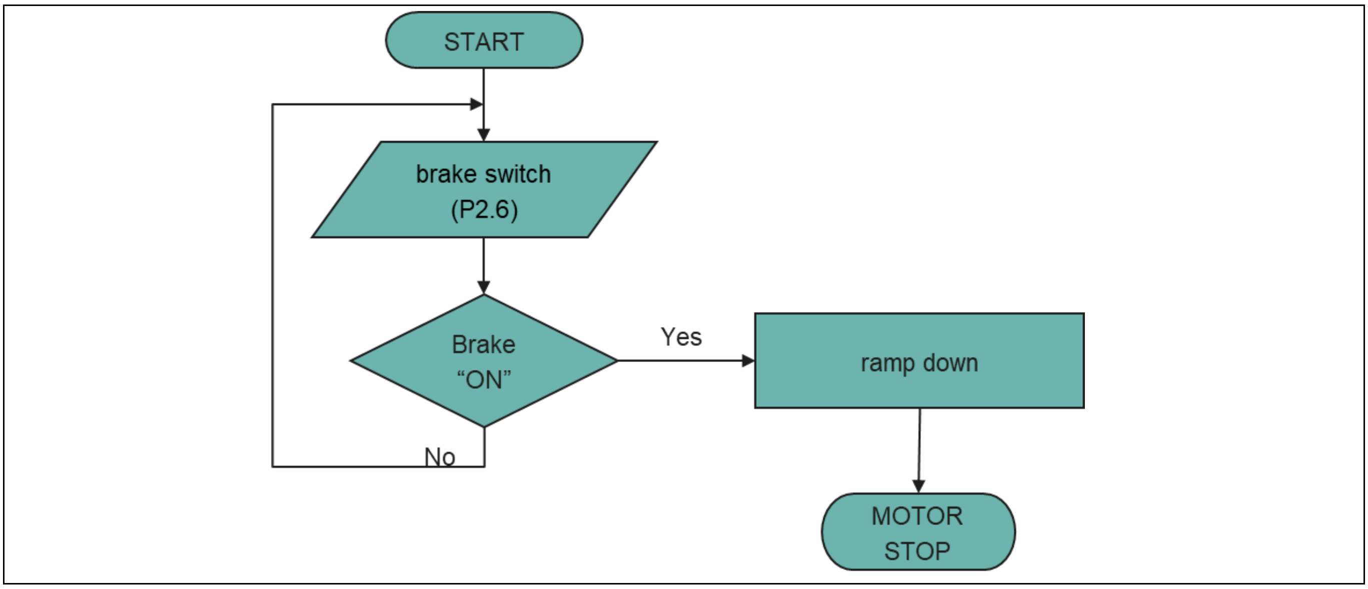
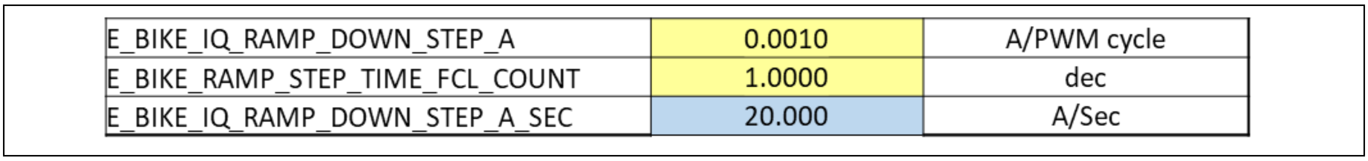


Figure 36 Brake ramp down firmware flowchart

You can configure the torque current ramp down rate to determine how fast or slow the brake ramp down it would like.



E_BIKE_IQ_RAMP_DOWN_STEP_A	0.0010	A/PWM cycle
E_BIKE_RAMP_STEP_TIME_FCL_COUNT	1.0000	dec
E_BIKE_IQ_RAMP_DOWN_STEP_A_SEC	20.000	A/Sec

Figure 37 Brake ramp down rate excel configuration

2.4.5 Start-up zero throttle check

During the first start-up, the start-up throttle check will be on, ADC potentiometer from GUI or torque sensor reading will be read. If the reading value is above a certain min/threshold value or the SYSTEM_BE_IDLE value, throttle ramping up will be disabled and motor will not start.

Once the ADC potentiometer reading shown drops below the min/threshold value, the throttle ramp will be enabled and the check will be disabled.

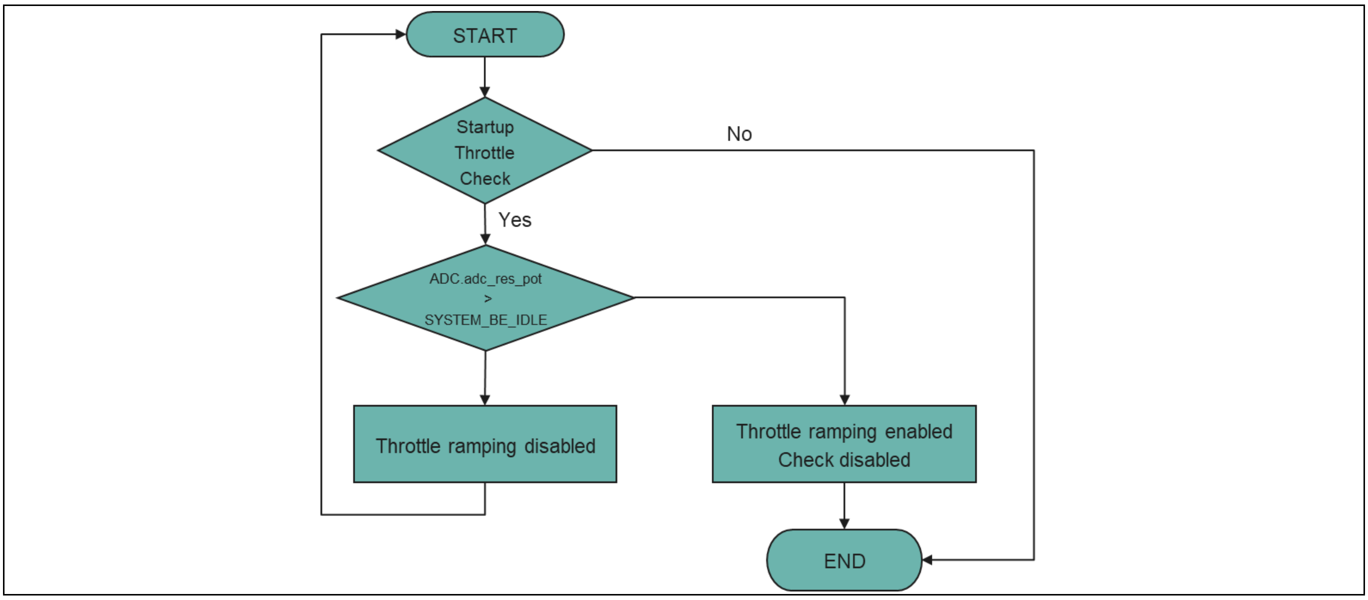


Figure 38 Start-up zero throttle check flowchart

3 e-Bike GUI

The dedicated e-Bike GUI is implemented as an application in the GUI Builder as part of the ModusToolbox™ Motor Suite.

To use the GUI as the input and control method for the REF_48V_270W_EBIKE, the USER_REF_SETTING parameter in the Excel configuration file needs to be set as MICRIUM_UC_ONLY. Alternatively, selecting BY_POT_ONLY, the microcontroller will only use the analog inputs as the control method.

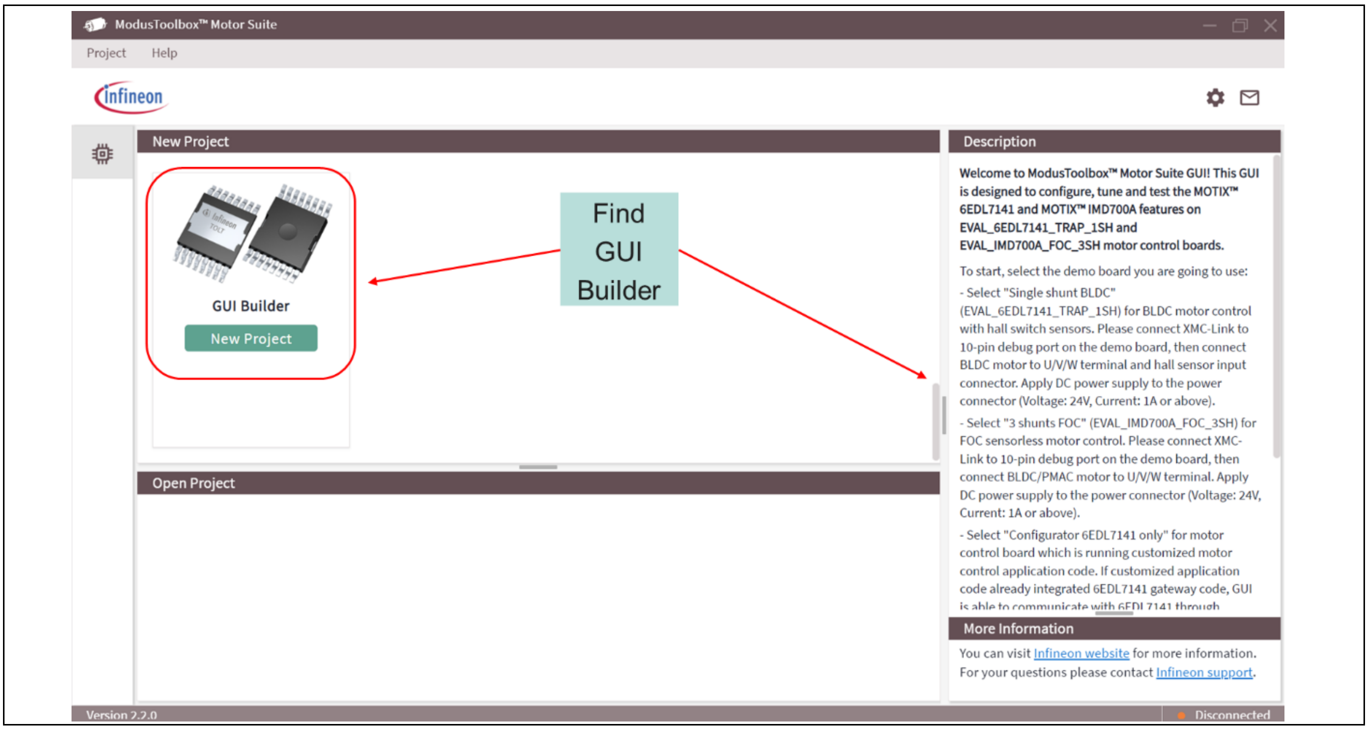
When the firmware with this setting is flashed on the microcontroller, the firmware can run independently and communicate with the PC via the XMC™ Link programmer (see section 4.4.3 for connection details).

In summary, after flashing the firmware, the microcontroller needs to be reset (or after following power ups), then it can be connected to the GUI.

3.1 GUI setup

The following steps describe the process of setting up the GUI builder.

1. Open ModusToolbox™ Motor Suite and find GUI Builder and open it.



Welcome to ModusToolbox™ Motor Suite GUI! This GUI is designed to configure, tune and test the MOTIX™ 6EDL7141 and MOTIX™ IMD700A features on EVAL_6EDL7141_TRAP_1SH and EVAL_IMD700A_FOC_3SH motor control boards.

To start, select the demo board you are going to use:

- Select "Single shunt BLDC" (EVAL_6EDL7141_TRAP_1SH) for BLDC motor control with hall switch sensors. Please connect XMC-Link to 10-pin debug port on the demo board, then connect BLDC motor to U/V/W terminal and hall sensor input connector. Apply DC power supply to the power connector (Voltage: 24V, Current: 1A or above).

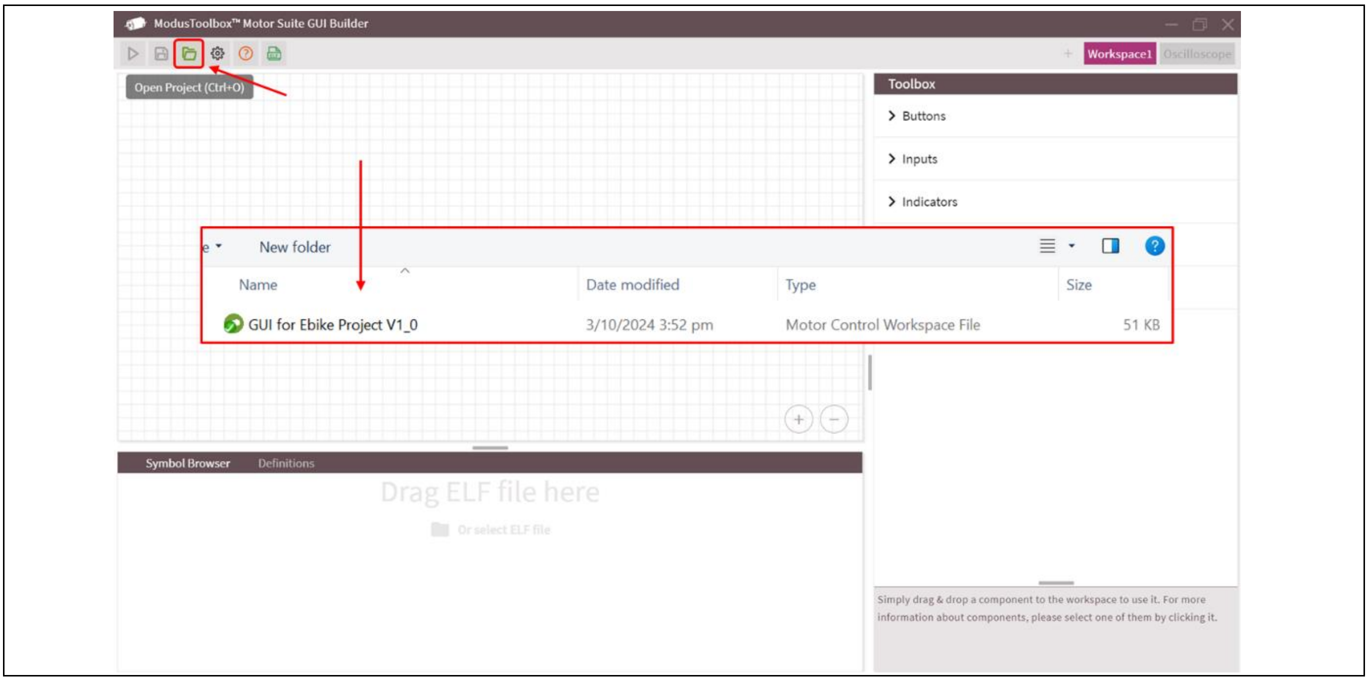
- Select "3 shunts FOC" (EVAL_IMD700A_FOC_3SH) for FOC sensorless motor control. Please connect XMC-Link to 10-pin debug port on the demo board, then connect BLDC/PMAC motor to U/V/W terminal. Apply DC power supply to the power connector (Voltage: 24V, Current: 1A or above).

- Select "Configurator 6EDL7141 only" for motor control board which is running customized motor control application code. If customized application code already integrated 6EDL7141 gateway code, GUI is able to communicate with 6EDL7141 through

You can visit Infineon website for more information. For your questions please contact Infineon support.

Figure 39 GUI Builder

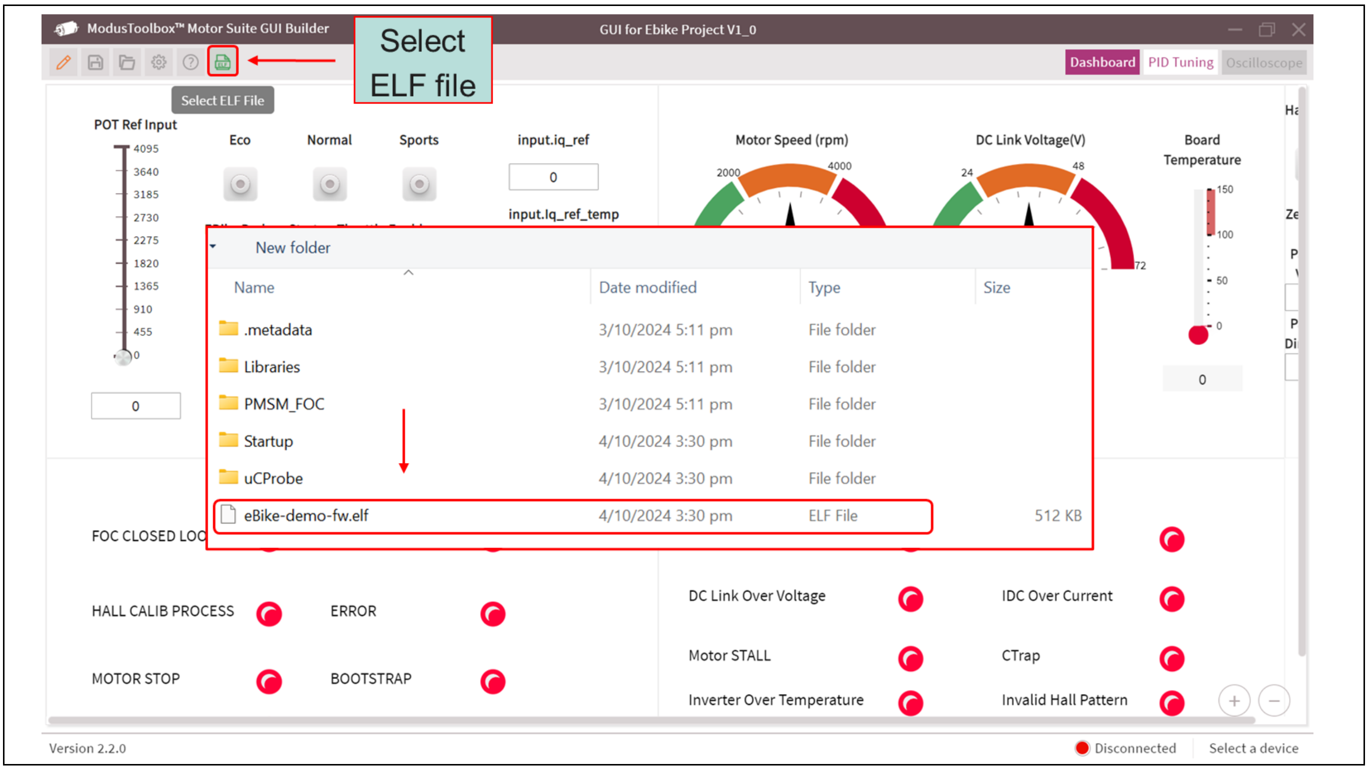
2. Go to “open project” and select the project *gui .mcws* file.



Name	Date modified	Type	Size
GUI for Ebike Project V1_0	3/10/2024 3:52 pm	Motor Control Workspace File	51 KB

Figure 40 Project GUI file selection

3. Select the ELF file.
   It can be found in *project folder/Debug/ELF file*.



Name	Date modified	Type	Size
.metadata	3/10/2024 5:11 pm	File folder	
Libraries	3/10/2024 5:11 pm	File folder	
PMSM_FOC	3/10/2024 5:11 pm	File folder	
Startup	4/10/2024 3:30 pm	File folder	
uCProbe	4/10/2024 3:30 pm	File folder	
eBike-demo-fw.elf	4/10/2024 3:30 pm	ELF File	512 KB

Figure 41 Selecting the ELF file

3.2 General GUI Builder overview

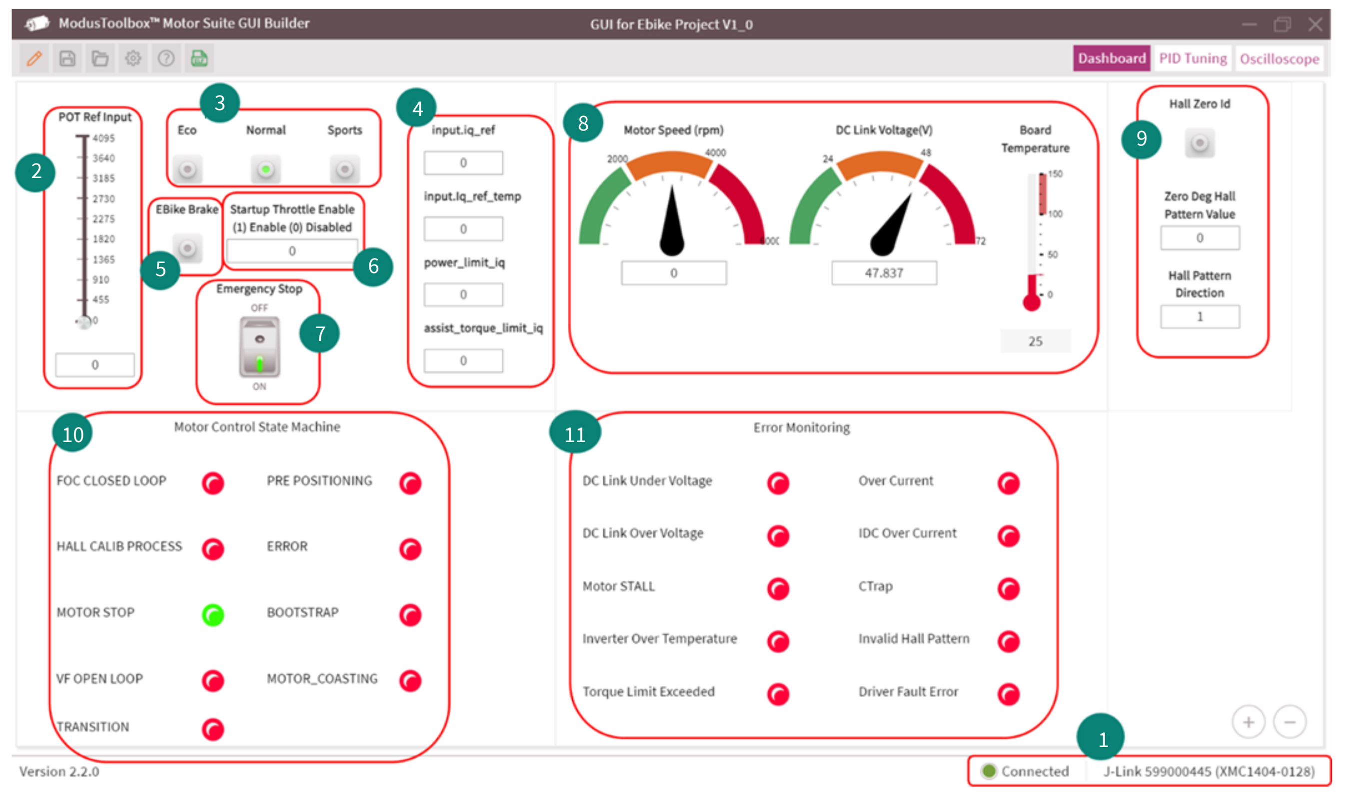


Figure 42 GUI Builder

1. GUI connection indicator: Make sure it is in Connected state before motor control.
2. During a powering off/on of the board: You can reselect the J-link device and re-connect to the GUI interface.
3. Potentiometer: You can either use the slider or key in the value (+ enter) to start the motor.
4. e-Bike mode selection button: ECO, NORMAL, and SPORT.
5. Debugging purposes: To check on torque current reference value and comparing to the current limit threshold value and power limit threshold.
6. e-Bike brake toggle button: Brake “ON” to ramp down and disable throttle. Brake ”OFF” to enable throttle.
7. Start-up throttle ramp up enable indicator
8. Emergency push button for stopping motor immediately
9. Indicator reading of the mechanical motor speed in RPM, DC link voltage, and board temperature.
10. Auto Hall calibration toggle button: “ON” to start calibration. Shows Hall pattern of the zero degree and the Hall pattern direction.
11. State machine indicator: Shows the current Motor Control State machine.
12. Error Monitoring state: To show the specific cause of error when motor fail.

4 Hardware system description

4.1 Gate driver 6EDL7151

6EDL7151 is a configurable 3-phase gate driver IC for BLDC or permanent magnet synchronous motor (PMSM) motor drive applications, in a 48-pin VQFN package. It provides three half-bridge drivers, each capable of driving a high side and low side N-type MOSFET. It also provides an integrated DC-DC synchronous buck converter, low dropout linear voltage regulator, and configurable precision current sense (CS) amplifiers.

6EDL7151 gate driver IC is controlled and configured by the onboard microcontroller (XMC1404) and is able to operate in multiple PWM modes. The MCU communicates with 6EDL7151 via an internal SPI to enable configuration.

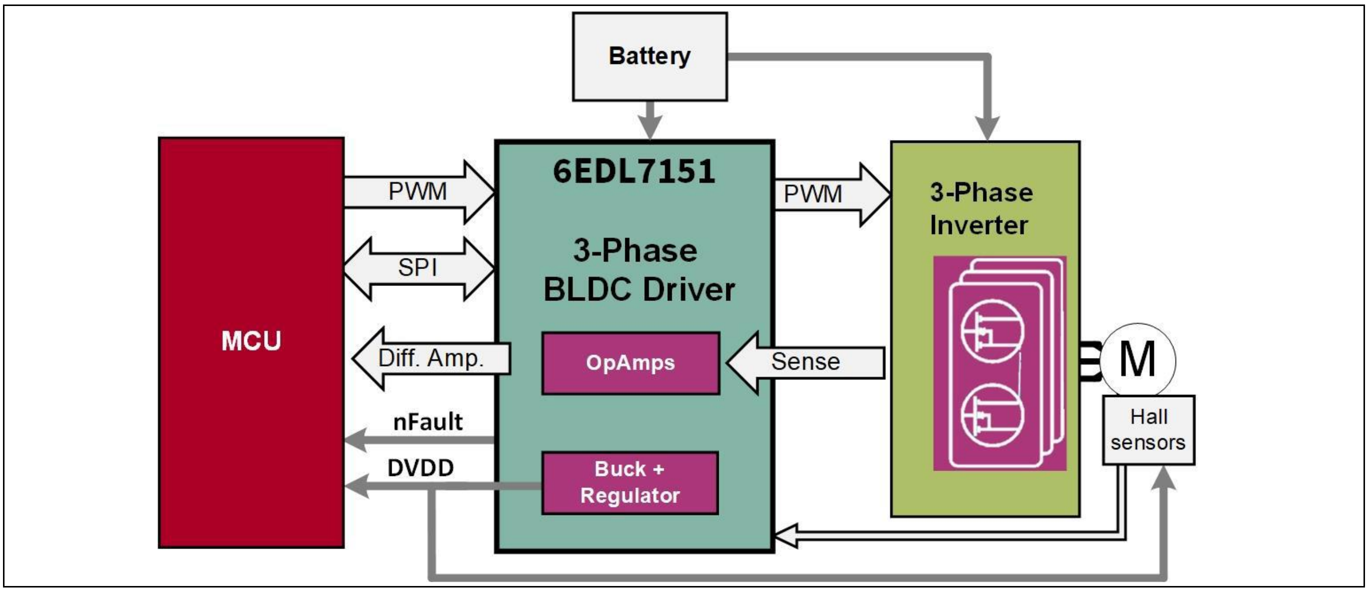


Figure 43 Top-level system block diagram using 6EDL7151

Main features of 6EDL7151

- 5.5 V to 70 V operating supply voltage (recommended operating condition)
  - 3-phase smart gate driver
  - 1.5 A sink/ 1.5 A source peak gate driver currents
  - Programmable driving voltage (7 V, 10 V, 12 V, 15 V)
  - Independently programmable high side/low side slew rate control
  - Independently programmable dead time for turn-on/off switching
- Integrated power supplies
  - High efficiency synchronous buck converter with programmable switching frequency. Supplies gate driver charge pumps, DVDD linear regulator and both internal and external components
  - Linear regulator with 300 mA current capability for MCU and other component supply (DVDD)
  - Dual charge pump for supplying gate driver even at low supply voltage
- Three integrated current sense amplifiers
  - Adjustable gain and offset
- SPI digital interface for setting of 6EDL7151 parameters

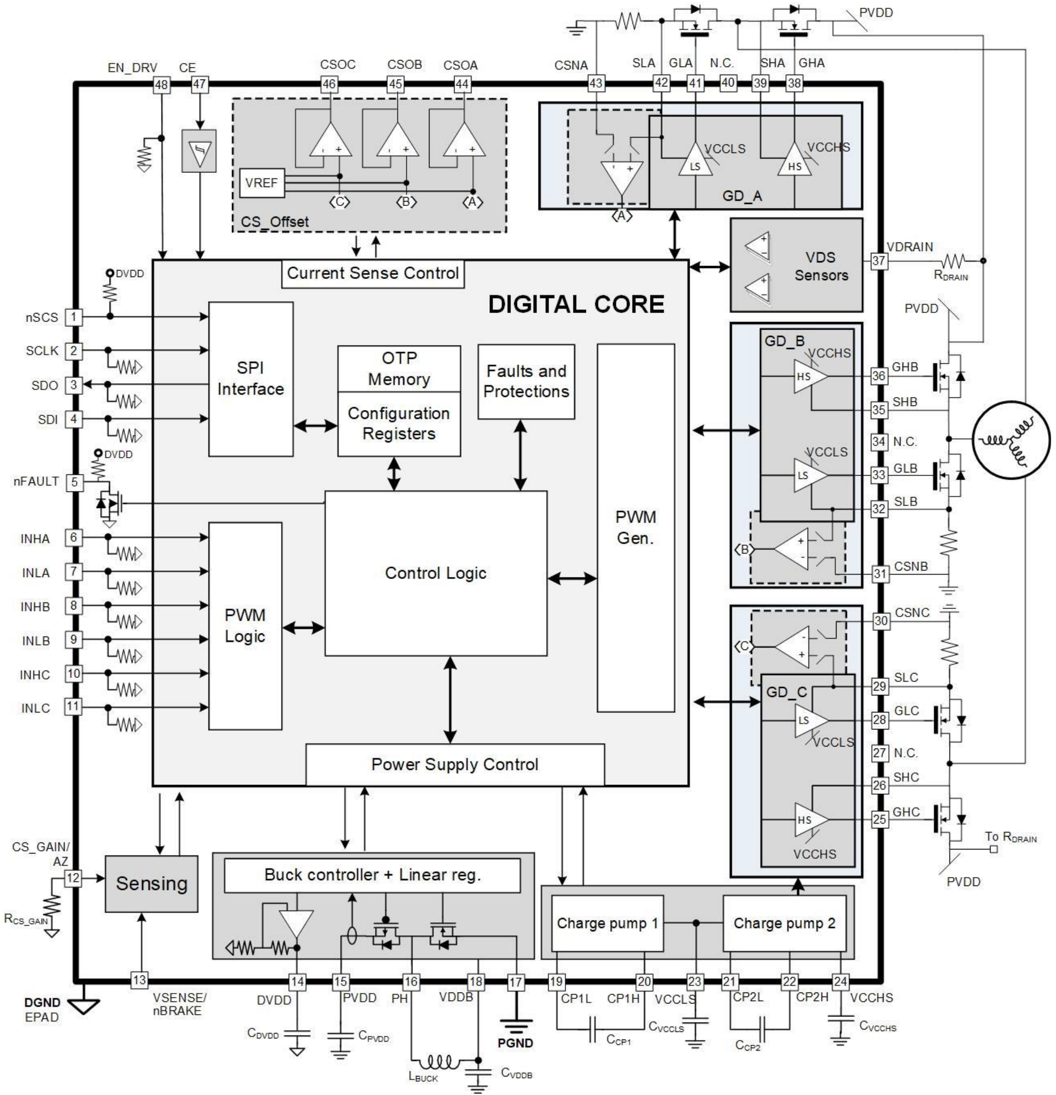


Figure 44 6EDL7151 internal block diagram

More details about 6EDL7151 can be found in the following documents:

- 6EDL7151 datasheet [1]
- Application Note: EVAL_6EDL7141_TRAP_1SH 18 V brushless DC motor drive board [3]
- Design Guide: Battery-powered BLDC motor drive design using the 6EDL71x1 series [4]

4.1.1 6EDL7151 integrated power supply (buck controller and linear regulator)

6EDL7151 is used as a one-chip solution to supply the entire system. This helps reduce the overall size of the board by eliminating the need for additional individual devices.

The onboard buck converter can operate at up to 70 V supply voltage (PVDD). The output voltage of the buck regulator may be set to 6.5 V, 7 V, or 8 V, depending on the gate drive voltage selection. 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. Intelligent overcurrent protections (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 the correct thermal limits. Two different switching frequencies, 500 kHz (default value) or 1 MHz, can be selected. The buck inductor L101 value is 22 µH intended for operation at 500 kHz.

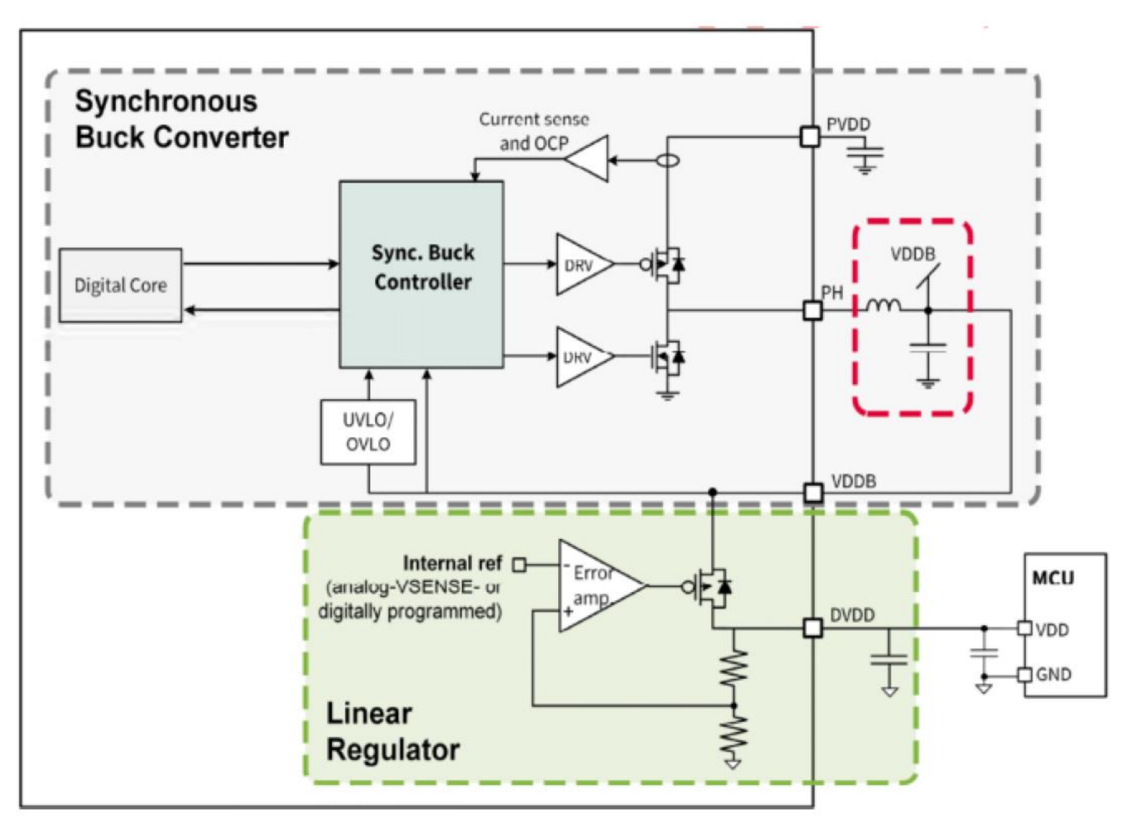


Figure 45 Detail of integrated synchronous buck converter and linear regulator

The system settings are indicated in Table 4.

The buck converter output voltage is set to $VDDB_{NOM}$ = 8 V. The selection corresponds to the gate driver charge pump supply voltage selection of PVCC = 15 V. The linear regulator is set to operate at DVDD = 5 V which is used to supply the XMC1404 microcontroller with the onboard peripherals (CAN transceiver), as well as the offboard units like the throttle potentiometer or torque sensor, motor hall sensors etc.

Table 4 Configuration of the regulators

Parameter/feature	Value	Register set
$VDDB_{NOM}$ - Buck converter output target voltage	8 V	PVCC_SETPT=b'0x
PVCC - GD supply voltage	15 V	Bitfield PVCC_SETPT = b'01
DVDD - uC supply voltage	5 V	bitfield DVDD_ST in register FUNCT_ST
Linear Regulator OCP (DVDD)	450 mA	DVDD_OCP_CFG = b'00

The DVDD output voltage is set by an external resistor R111 which at R = 10 kΩ selects the 5 V output setting at IC start-up. Alternatively, the setting can be set via the SPI interface.

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

- Output 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.

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.

4.1.2 Power supply start-up – system ignition

6EDL7151 is activated via the chip-enable (CE) pin which controls the start-up of the power supply system, given a steady battery supply voltage (PVDD). Figure 46 shows the ramp up of buck converter voltage once CE voltage goes above $V_{CE\_TH\_R}$ value.

Soft-start for the buck converter is automatically implemented using an integrated DAC for generating the target reference. Once VDDB has reached its UVLO voltage, the analog programming starts. This initiates a period of t_{AN_T} duration in which the external resistors in CS_GAIN/AZ and VSENSE/nBRAKE pins are read internally. The analog programming of these two functions can be disabled by the user via OTP programming. Therefore, reducing the start-up time.

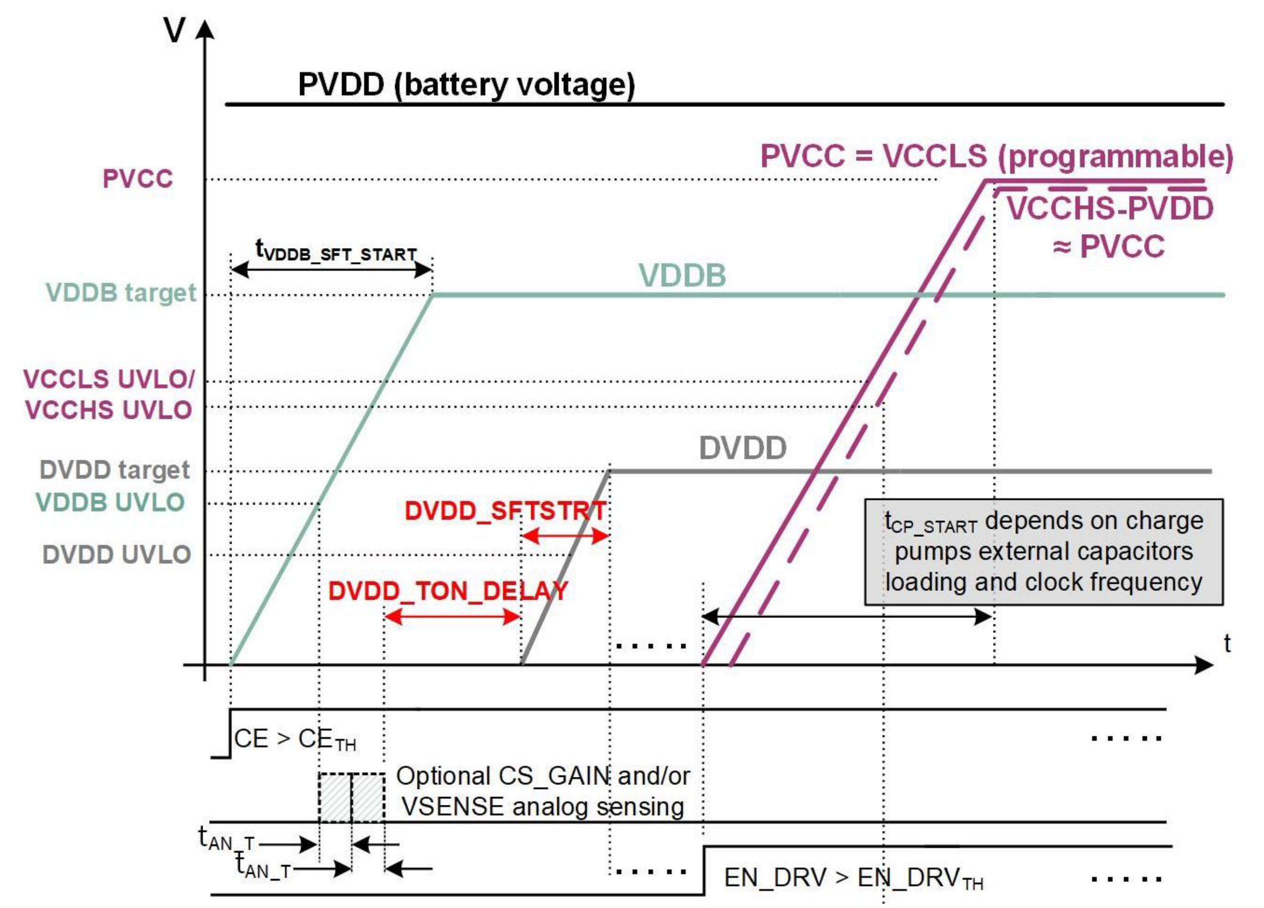


Figure 46 Start-up behavior of supply voltages at steady PVDD supply

In the REF_48V_270W_EBIKE, the CE pin can be used as an ignition switch. The IGNITION_VDD and IGNITION_IN signals connected through the X01 small signal interface header, to be connected to a key ignition switch. When the switch connects the two signals the CE is pulled up. Figure 47 shows the circuitry that protects the CE input.

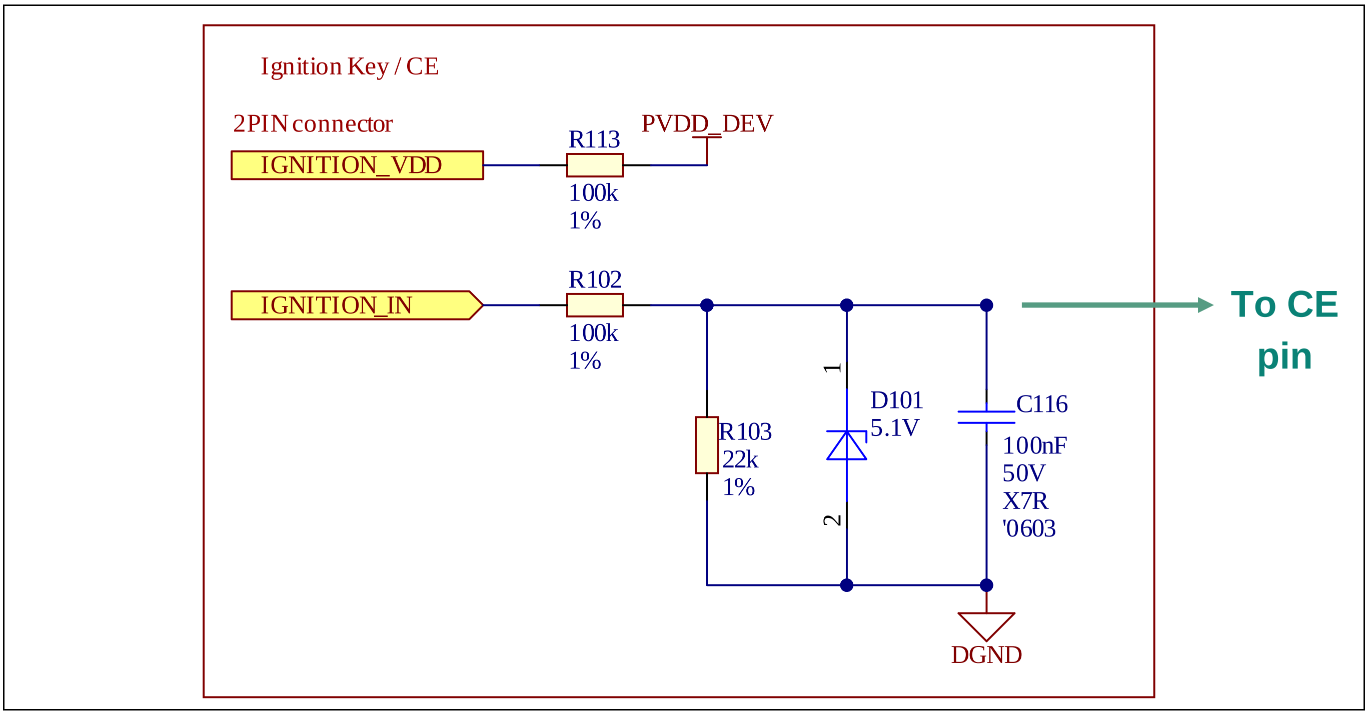


Figure 47 Chip enable external switch connection

4.1.3 Charge pumps – gate driver supply

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, and 1.56 MHz, allows flexibility for EMC optimization, with 1.56 MHz being the default setting used in REF_48V_270W_EBIKE. 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 into the charge pump clock signal in order to distribute emissions over a wider frequency range, thereby reducing peaks.

The selection of charge pump flying capacitors C102 and C103 are set at 220 nF and the tank capacitors C115 and C117 are set to 2.2 µF. 6EDL7151 provides pre-charging of the charge pump output capacitors (C115 and C117) to a voltage just below the buck converter output voltage (VDDB) 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 microcontroller to enable the gate driver stage, the charge pumps need only to 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 the GUI.

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

- Target voltage: Higher the value, 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: Smaller value results in faster ramp-up time but higher ripple.

- Charge pump flying capacitors: Smaller capacitors lead to slower start-up time.

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/normal gate-level MOSFETs to be used.

In REF_48V_270W_EBIKE, 15 V is used by default as the gate drive voltage.

4.1.4 Gate driver settings and electromagnetic compatibility (EMC)

The high- and low-side gate drivers allow operation over the full duty-cycle range up to 100 percent.

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 SPI accessible registers allow the designer to configure the gate driver current and corresponding timings described in this chapter. 6EDL7151 gate driver sets the gate currents without the need for any external gate drive components. Figure 48 shows the definition of the relevant timeframes and gate currents to be set. The exemplary charges refer to the IQE050N08NM5SC MOSFET.

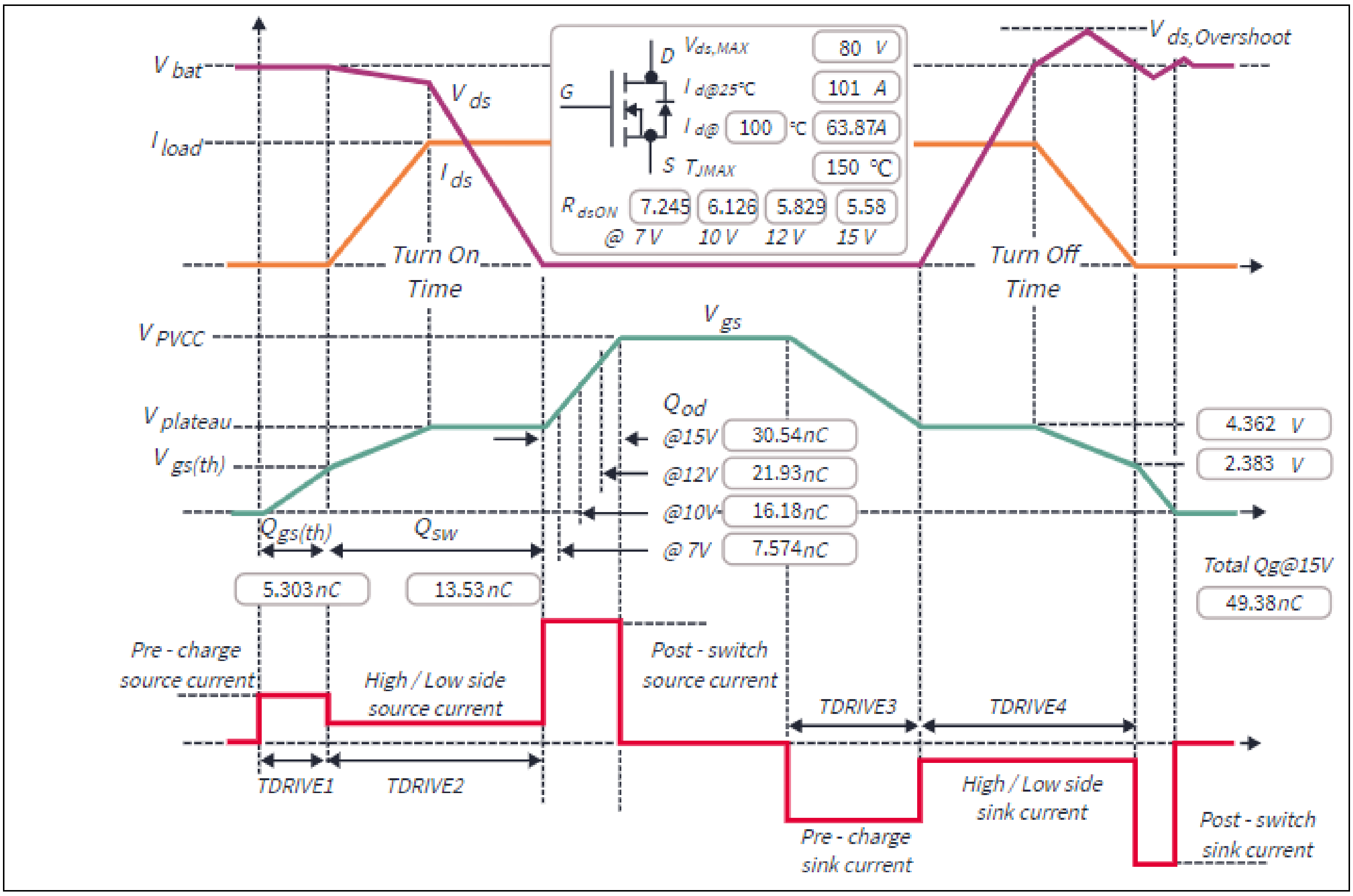


Figure 48 Settable gate driver parameters definitions

Turn ON

When the input signal from the microcontroller transitions from low to high, the gate driver switch-on sequence is triggered. The gate drive output first applies a constant current defined by the user-programmable value

I_{PRE_SRC} (Pre-charge source current) for a time defined by T_{DRIVE1}, at the end of which the MOSFET gate voltage should ideally have reached threshold voltage $V_{GS(TH)}$. However, to accommodate for the MOSFET gate charge tolerances should be set lower accordingly.

The current applied during T_{DRIVE2} determines both dI_D/dt and dV_{DS}/dt of the MOSFETs, as it will supply the current to charge the Q_{SW} of the MOSFET being driven.

Once the T_{DRIVE2} period has elapsed, the gate driver applies full current (1.5 A) to ensure the fastest full turn-on of the MOSFET by supplying the remaining charge required to raise V_{GS} to the programmed PVCC value ($Q_{OD} = Q_G – Q_{SW} – Q_{G(TH)}$).

It is also possible to skip the pre-charge period T_{DRIVE1} by setting T_{DRIVE1} = 0ns. This is used in REF_48V_270W_EBIKE due to relatively small MOSFETs, in order to cope easier with the tolerances of the consequently small gate charges. The pre-charge is also omitted at turn OFF.

Turn OFF

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 corresponding programmed discharge currents (I_{PRE_SNK}, I_{HS_SNK}, and I_{LS_SNK}) are applied, as indicated in Figure 48. After the T_{DRIVE4} the gate driver applies the full discharge current (1.5 A) to fully discharge the gate and prevent an unwanted induced turn ON that could occur during turn ON of the complementary MOSFET.

Table 5 shows the default settings used in REF_48V_270W_EBIKE. The settings have been adapted to the requirements of EMC standard CISPR 14, used to measure radiated electromagnetic emissions of the board without the final enclosure (bike frame).

Table 5 REF_48V_270W_EBIKE gate driver settings

Parameter	Description	Value	Unit
T_{ON}	Turn ON time	275	ns
T_{OFF}	Turn OFF time	190	ns
I_{PRE_SRC}	Pre-charge current value for switching ON both high- and low-side	Not used	
I_{HS_SRC}	Source current value for switching ON high-side MOSFETs	40	mA
I_{LS_SRC}	Current value for switching ON low-side MOSFETs	40	mA
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.	450	ns
I_{PRE_SNK}	Pre-charge current value for switching OFF both high- and low-side	Not used	
I_{HS_SNK}	Sink current value for switching OFF high-side MOSFETs	60	mA
I_{LS_SNK}	Current value for switching OFF low-side MOSFETs	60	mA
T_{DRIVE3}	Amount of time that I_{PRE_SNK} is applied. Shared configuration between high- and low-side drivers.	0	ns
T_{DRIVE4}	Amount of time that I_{HS_SINK} and I_{LS_SINK} and are applied. Shared configuration between high-side and low-side drivers.	60	ns
T_{DT_rising}	Dead time at turn ON	840	ns
$T_{DT\_falling}$	Dead time at turn OFF	840	ns

The resulting gate charge and discharge waveforms are shown in Figure 49, Figure 51, Figure 51, and Figure 52, at phase currents of 5 A and 10 A. The difference in turn-on and turn-off times with regard to phase current is negligible, as can be seen in the comparison of the 5 A vs 10 A waveforms. The deadtime was selected in accordance with the switching waveforms.

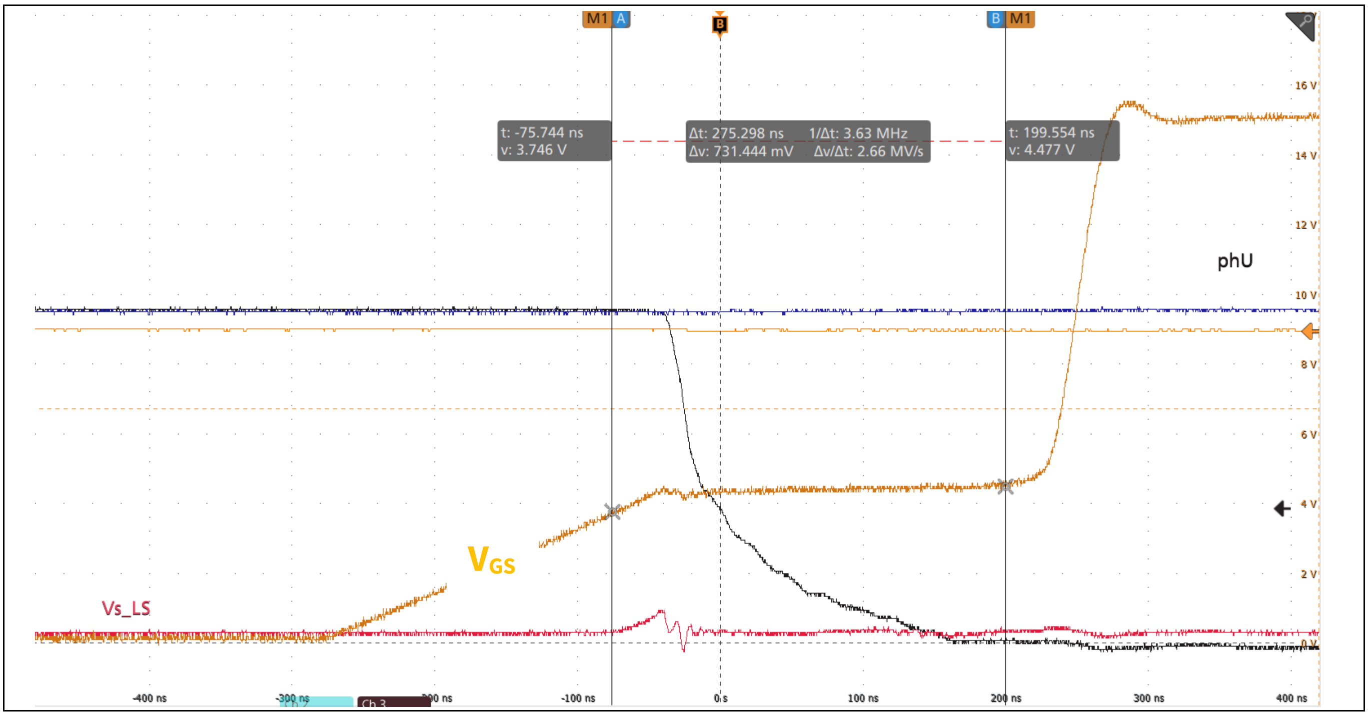


Figure 49 Gate charge (MOSFET turn-on), V_{GS} at $I_U = 5$ A, $I_G = 40$ mA, $T_{ON} = 275$ ns

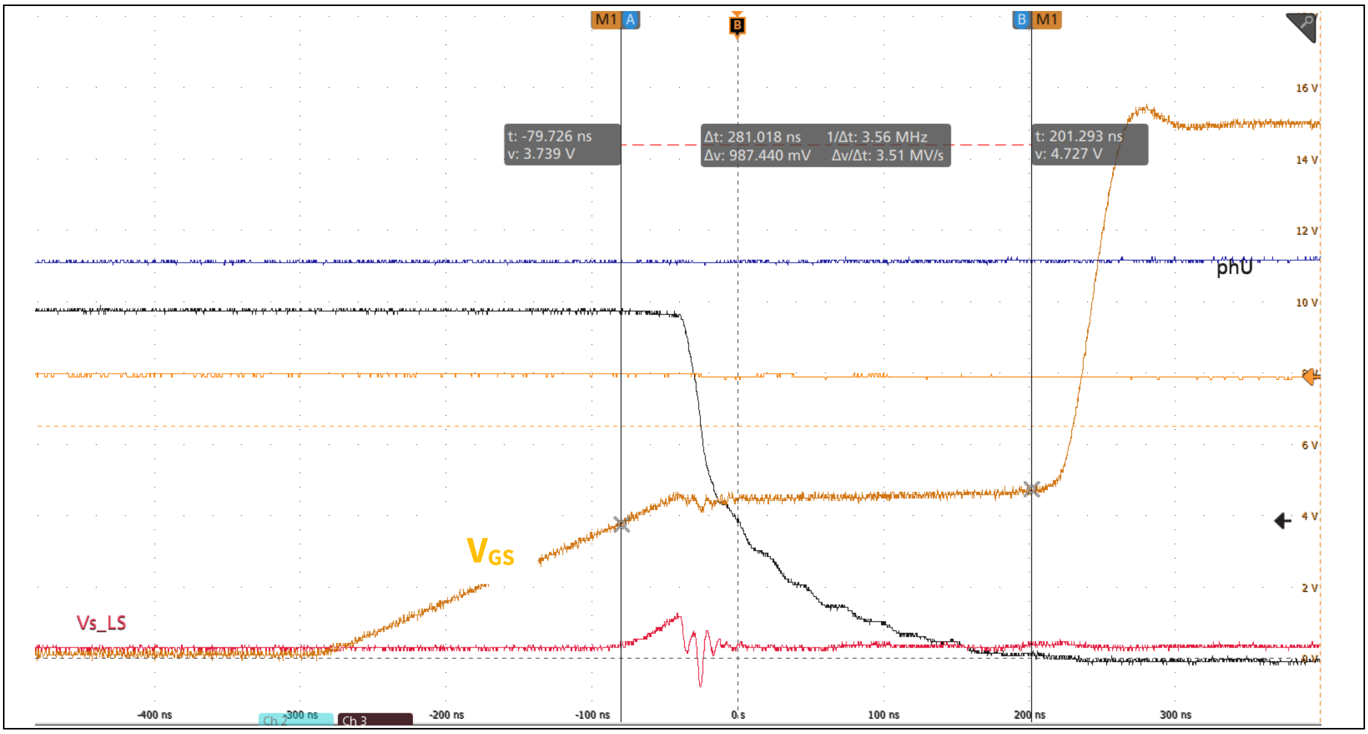


Figure 50 Gate charge (MOSFET turn-on), V_{GS} at $I_U = 10$ A, 40 mA, $T_{ON} = 281$ ns

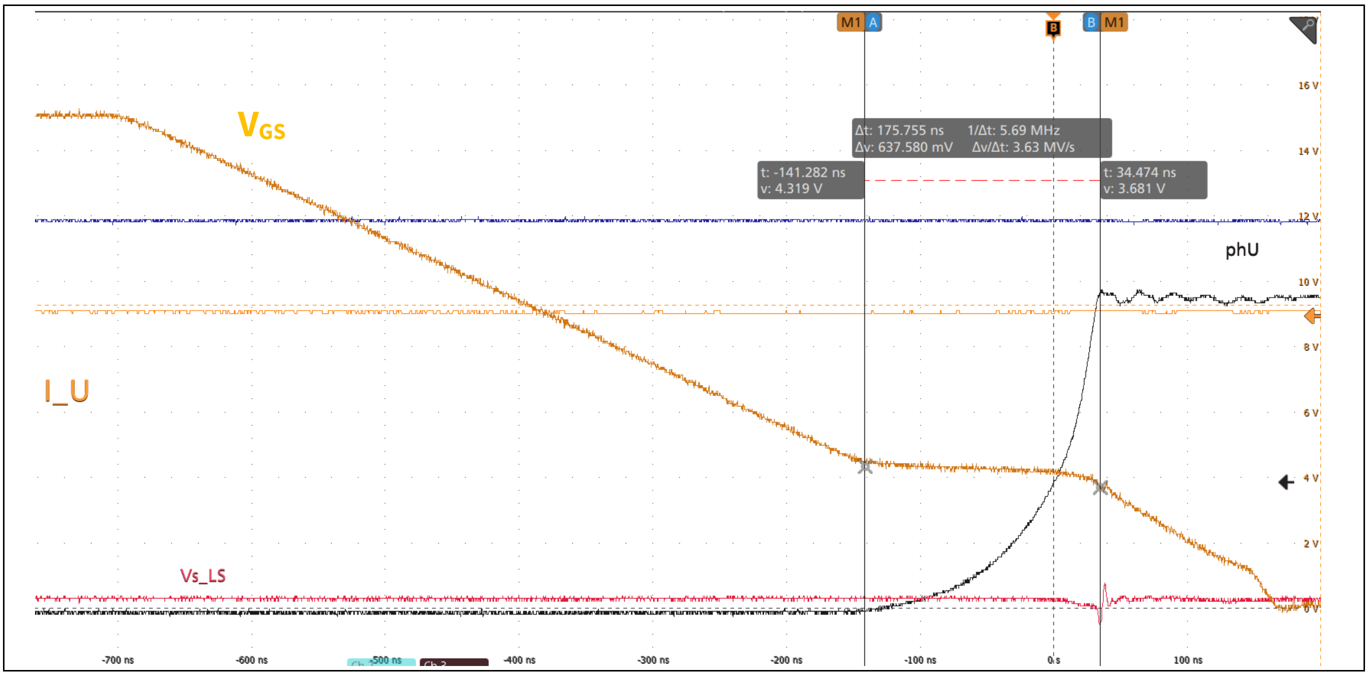


Figure 51 Gate charge (MOSFET turn-off), V_{GS} at I_U = 5 A, 60 mA, T_{OFF} = 175 ns

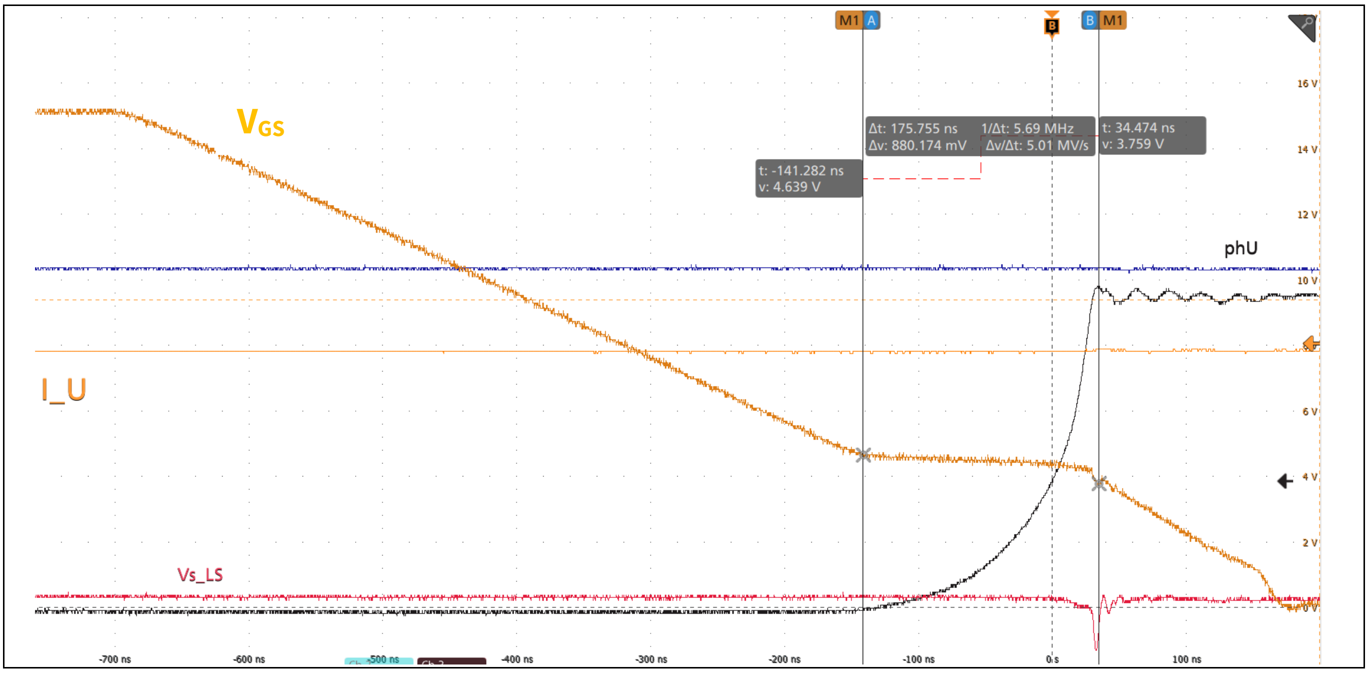


Figure 52 Gate charge (MOSFET turn-off), V_{GS} at I_U = 10 A, 60 mA, T_{OFF} = 175 ns

Figure 53 shows the resulting EMI measurement according to CISPR 14 with the corresponding limit line marked in the graph. As mentioned, the gate drive settings had been set so to pass the standard. All performance tests in this document have been performed with the gate driver settings defined in Table 5.

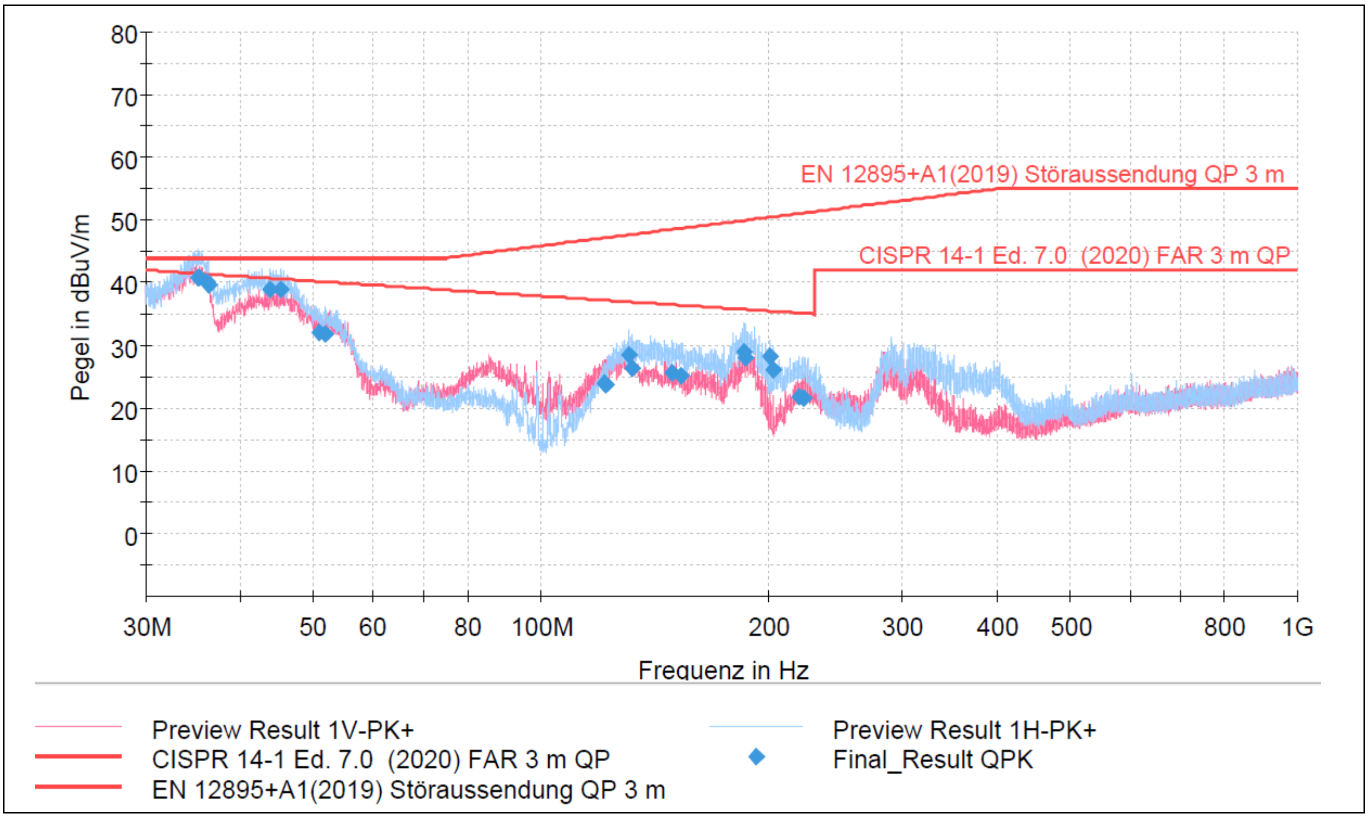


Figure 53 EMC measurement according to CISPR 14

4.1.5 Current sense amplifiers

The current is sensed via three shunt resistors in the lower leg of the half-bridge and amplified via 6EDL7151 integrated current sense amplifiers. The resistors used are 5 mΩ shunt resistors: BVT-I-R005-1.0. Therefore, the triple shunt mode is used, which means all three current sense amplifiers are enabled.

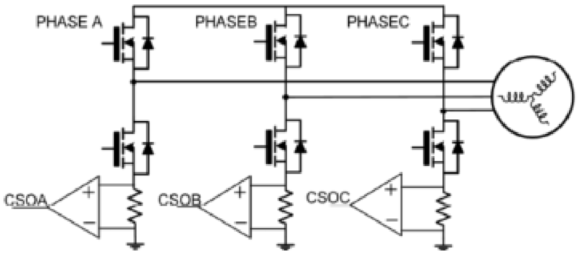


Figure 54 Triple shunt current sensing configuration

When current is sampled via leg shunts, the voltage in the shunt that needs to be amplified appears only when the low side MOSFET is turned on. Amplifier timing mode “GL ON” sets the amplifier functionality so that the CSOx pin is connected to the amplifier only when the same leg or phase GLx signal is active.

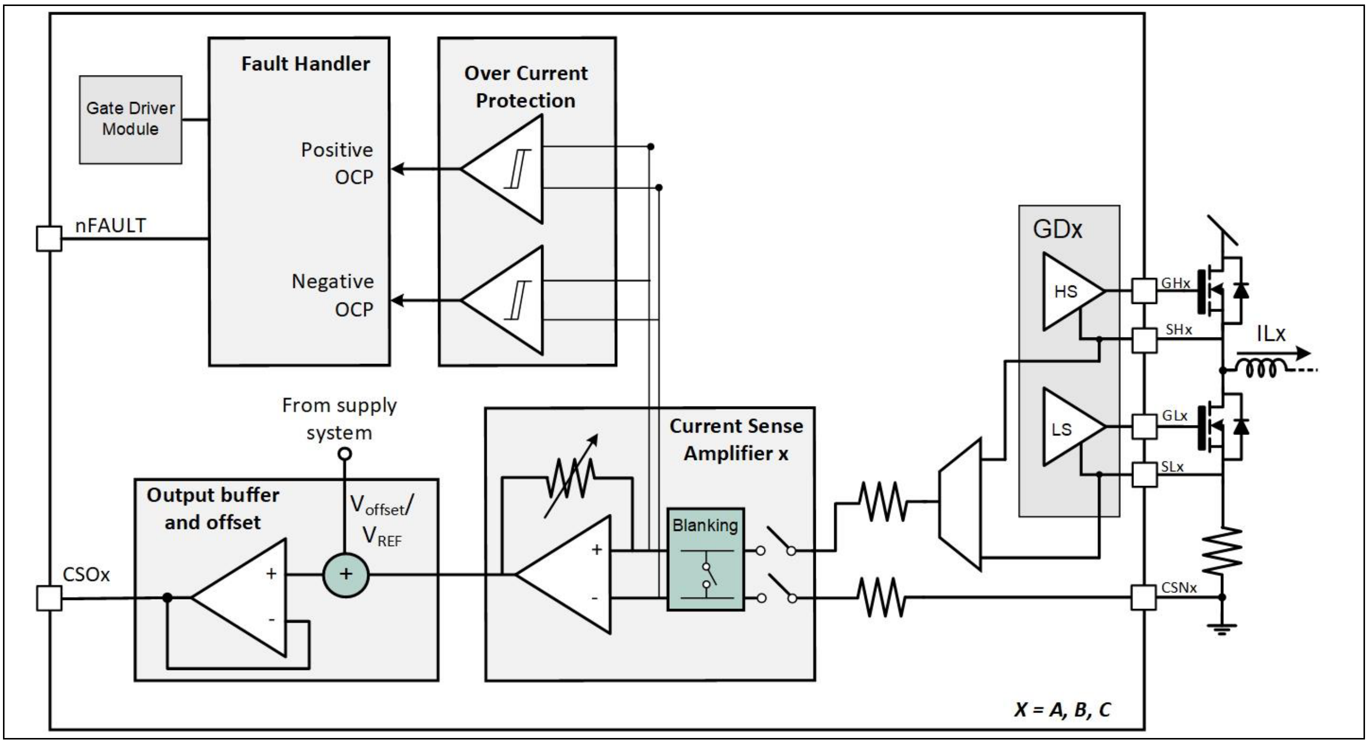


Figure 55 Current sense amplifier – simplified block diagram (source: 6EDL7151 datasheet)

Current sense amplifier gain selection

The closed loop gain G_{CS} of the internal amplifiers is configured either via resistor R109 (i.e. R_{CS_GAIN} in the datasheet), or SPI.

Considering the range of measured output currents, the gain G_{CS} = 64 is set by default. The resistor R109 = 11 kΩ, is provided in order to set the default gain at the initiation of the IC. The setting might typically be overridden via SPI settings in order to adapt to the specific system requirements according to the motor being used.

Output buffer offset voltage

The output buffer allows adding a variable-offset voltage to the sense amplifier output. The offset amount can be set to four different values by programming the internally generated level. With this implementation, the negative current in current shunts can be measured.

4.2 Microcontroller XMC1404

The XMC1400 series devices are optimized for motor control, power conversion, and LED Lighting applications and human machine interface (HMI).

Figure 56 PG-VQFN-64 package

The XMC1404-Q064X0200 AA in the PG-VQFN-64 package is a 32-bit Microcontroller with Arm® Cortex®-M0 with a focus on low-cost embedded control applications.

The microcontroller is used to interpret the incoming control and feedback signals and provide the 3-phase PWM signals to 6EDL7151 gate driver, as well as to provide the interface for 6EDL7151 parameter settings programmed via the SPI connection, by connecting to the PC via the XMC™ Link programmer/debugger.

Table 6 Microcontroller pinout and peripheral usage in REF_48V_270W_EBIKE

Connected device/peripheral	Signal name	PCB – signal name	Signal type (XMC™ side)	XMC™ peripheral unit	Channel of XMC™ peripheral	XMC1404 port/PIN
Debugger	DBG0	SWDIO/TMS	D_I/O	–	–	P0.14
	DBG1	SWDCLK/TCK	D_I	–	–	P0.15
6EDL7151/GD digital control	GD_UH	INHA	D_O	CCU80	CCU80.OUT10	P3.3
	GD_UL	INLA	D_O	CCU80	CCU80.OUT11	P3.2
	GD_VH	INHB	D_O	CCU80	CCU80.OUT20	P3.1
	GD_VL	INLB	D_O	CCU80	CCU80.OUT21	P3.0
	GD_WH	INHC	D_O	CCU80	CCU80.OUT00	P1.0
	GD_WL	INLC	D_O	CCU80	CCU80.OUT01	P1.1
6EDL7151/SPI	SDI	MOSI	D_O	USIC	–	P0.0
	SDO	MISO	D_I	USIC	–	P0.1
	SCLK	SCLK	D_O	USIC	–	P0.3
	SCS_N	NSCS	D_O	USIC	–	P0.4
6EDL7151/current sense amplifiers output	V_ADC(I_u)	A_CSOA	A_I	VADC0	VADC0.G0CH4	P2.11
	V_ADC(I_v)	A_CSOB	A_I	VADC0	VADC0.G0CH3	P2.10
	V_ADC(I_w)	A_CSOC	A_I	VADC0	VADC0.G0CH2	P2.9

Connected device/peripheral	Signal name	PCB – signal name	Signal type (XMC™ side)	XMC™ peripheral unit	Channel of XMC™ peripheral	XMC1404 port/PIN
6EDL7151/current sense amplifier gain / Auto-Zero	CS_GAIN/AZ	XMC_CS_GAIN	D_O	GPIO	P1.2	P1.2
6EDL7151/driver enable	DRV_EN_1	XMC_EN_DRV	D_O	GPIO	P0.7	P0.7
	DRV_EN_2	XMC_EN_DRV_CLK	D_O	GPIO (Or CCU41)	P4.6 (or CCU41.OUT2)	P4.6
6EDL7151/nBRAKE	VSENSE/ nBRAKE	XMC_nBRAKE	D_O	GPIO	P1.3	P1.3
nFAULT - CTRAP0	nFAULT	nFAULT	D_I	ERU		P0.12
Hall sensors	Hall A	Hall_0	D_I	POSIF1	POSIF1.IN0B	P4.1
	Hall B	Hall_1	D_I	POSIF1	POSIF1.IN1B	P4.2
	Hall C	Hall_2	D_I	POSIF1	POSIF1.IN2B	P4.3
CAN transceiver	RXD	D_CANRX	D_I	CAN1	RXDC	P4.8
	TXD	D_CANTX	D_O	CAN1	TXD(C)	P4.9
	NEN	D_NEN	D_O	GPIO	P4.10	P4.10
	NRM	D_NRM	D_O	GPIO	P4.11	P4.11
Analog inputs - Control	V_throttle pot.	A_THROT	A_I	VADC	G1CH7	P2.5
	V_brake switch	A_BRAKE	A_I	VADC	G0CH0	P2.6
Analog inputs - Sensors	T_MOTOR	A_TMOTOR	A_I	VADC	G0CH7	P2.2
	T_HB1	A_THB1	A_I	VADC	G1CH6	P2.4
	V_DC_link	A_VDC	A_I	VADC0.G1CH5	G1CH5	P2.3

The X401 header provides the interface to the XMC™ Link programmer/debugger.

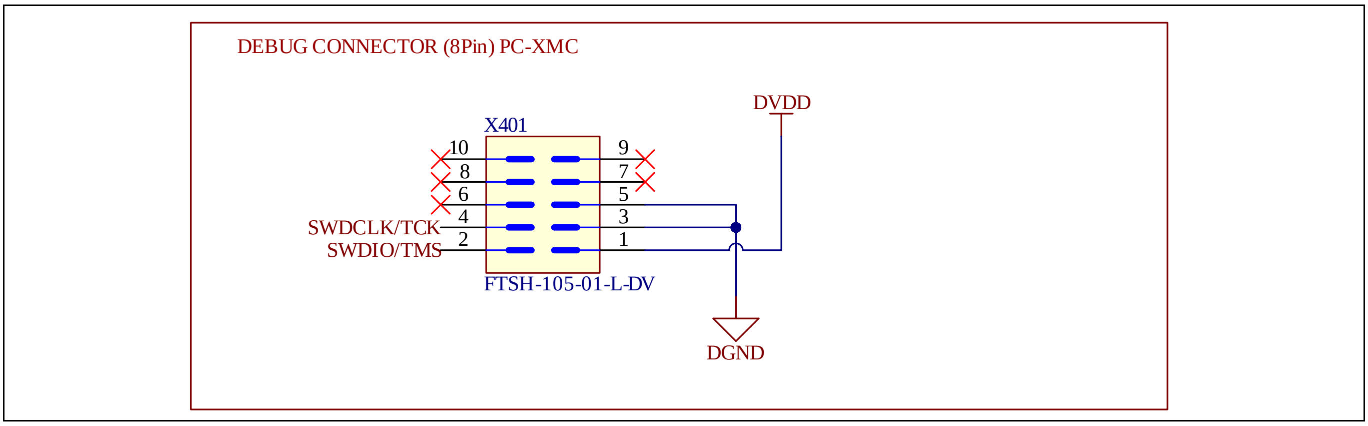


Figure 57 **XMC1404 microcontroller debug interface**

Figure 58 XMC™ Link connection

4.3 Power output stage

The topology of each of the 3-phase power outputs is a half bridge consisting of a high-side and a low-side power MOSFET, and a current sensing shunt resistor in the leg of the half-bridge (the low-side MOSFET source node) as shown in Figure 59.

The triple-shunt current sensing configuration is implemented in the REF_48V_270W_EBIKE, meaning that shunts are provided and used for current measurements at all three half-bridges.

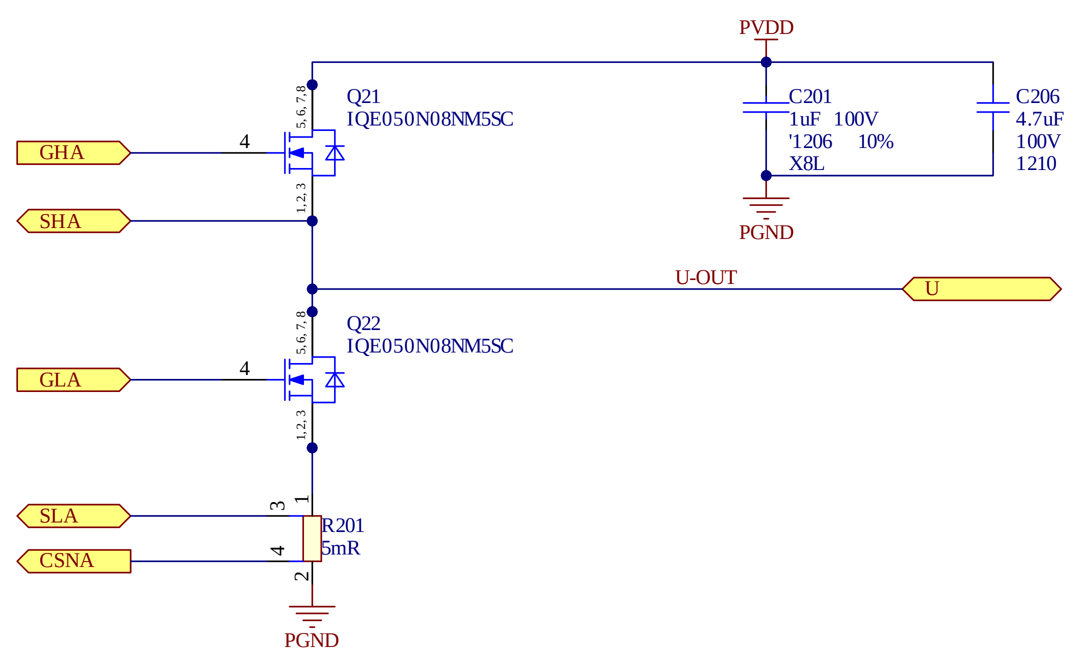


Figure 59 Power half-bridge - phase U

Kelvin connections are implemented for sensing the shunt voltage, as is supported by 6EDL7151. At the same time the gate driver connection to the low side MOSFET source, and the source node kelvin connection of the shunt, share the same PCB trace since the same IC pin is used. This method is made possible by the principle of sampling current only at the middle of the PWM cycles, so that the measurement is not affected by the interfering signals introduced during MOSFET switching.

4.3.1 Power MOSFET – IQE050N08NM5SC

MOSFET features:

- N-channel, normal level
- OptiMOS™ 5 Power MOSFET
- $V_{(BR)DSS}$ = 80 V
- $R_{DS(on),max}$ = 5.0 mΩ
- PQFN 3.3x3.3 / PG-WHSON-8 top-side cooled package

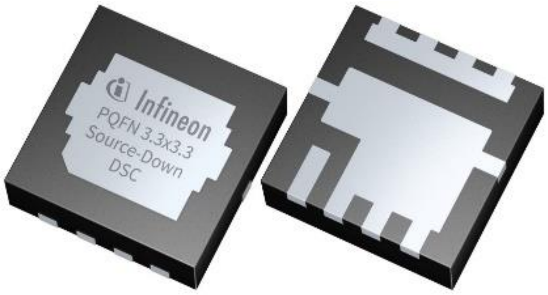


Figure 60 PQFN 3.3x3.3 package with top-side cooling

The IQE050N08NM5SC is a normal level N-channel power MOSFET, in a small 3.3 mm x 3.3 mm package. The package has a source down connection and a thermal tab making it suitable for top-side cooling.

The $R_{DS(on),max}$ of 5 mΩ is a maximum rated value at conditions of: V_{GS} = 10 V, I_D = 20 A. However, the V_{GS} can be further increased since it is rated up to 20 V. The REF_48V_270W_EBIKE uses V_{GS} = 15 V to drive the MOSFET gates. This V_{GS} further reduces the $R_{DS(on)}$ (see Figure 61) and thus reduces the conduction losses during operation.

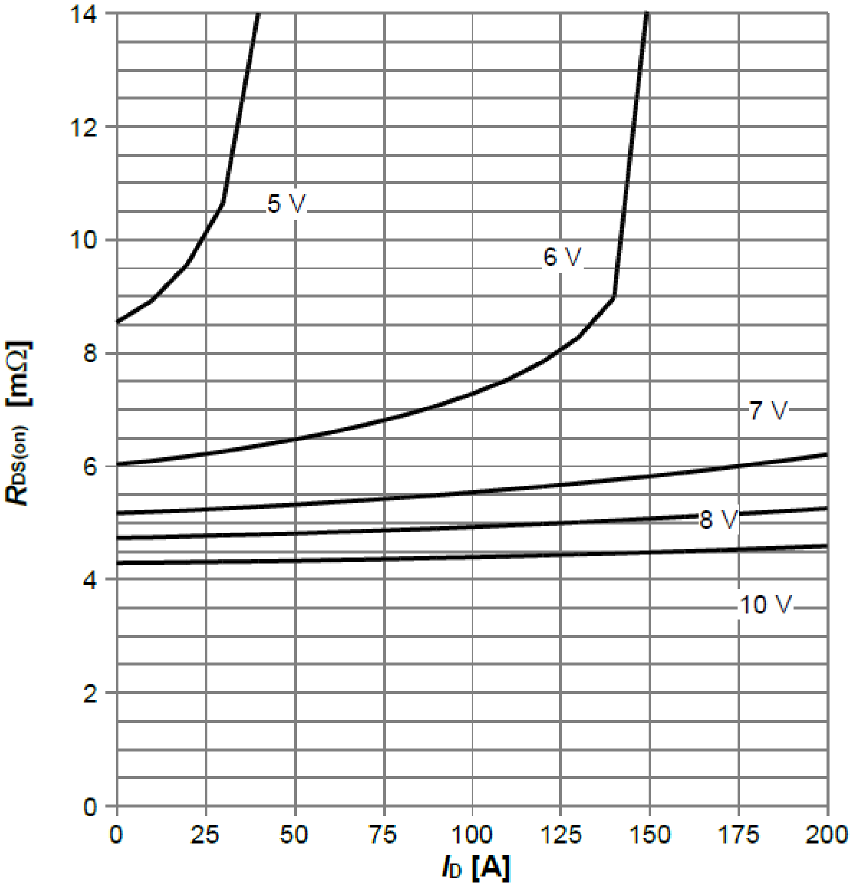


Figure 61 Typical drain-source on resistance of IQE050N08NM5SC

4.3.2 Layout

Top-side cooling is utilized by populating the MOSFETs on the bottom side of the PCB, facing the heatsink. The MOSFETs are pressed against the heatsink with the addition of a thermal interface material (TIM) pad which ensures a good thermal transfer and also provides the electrical insulation between the thermal pad and the heatsink.

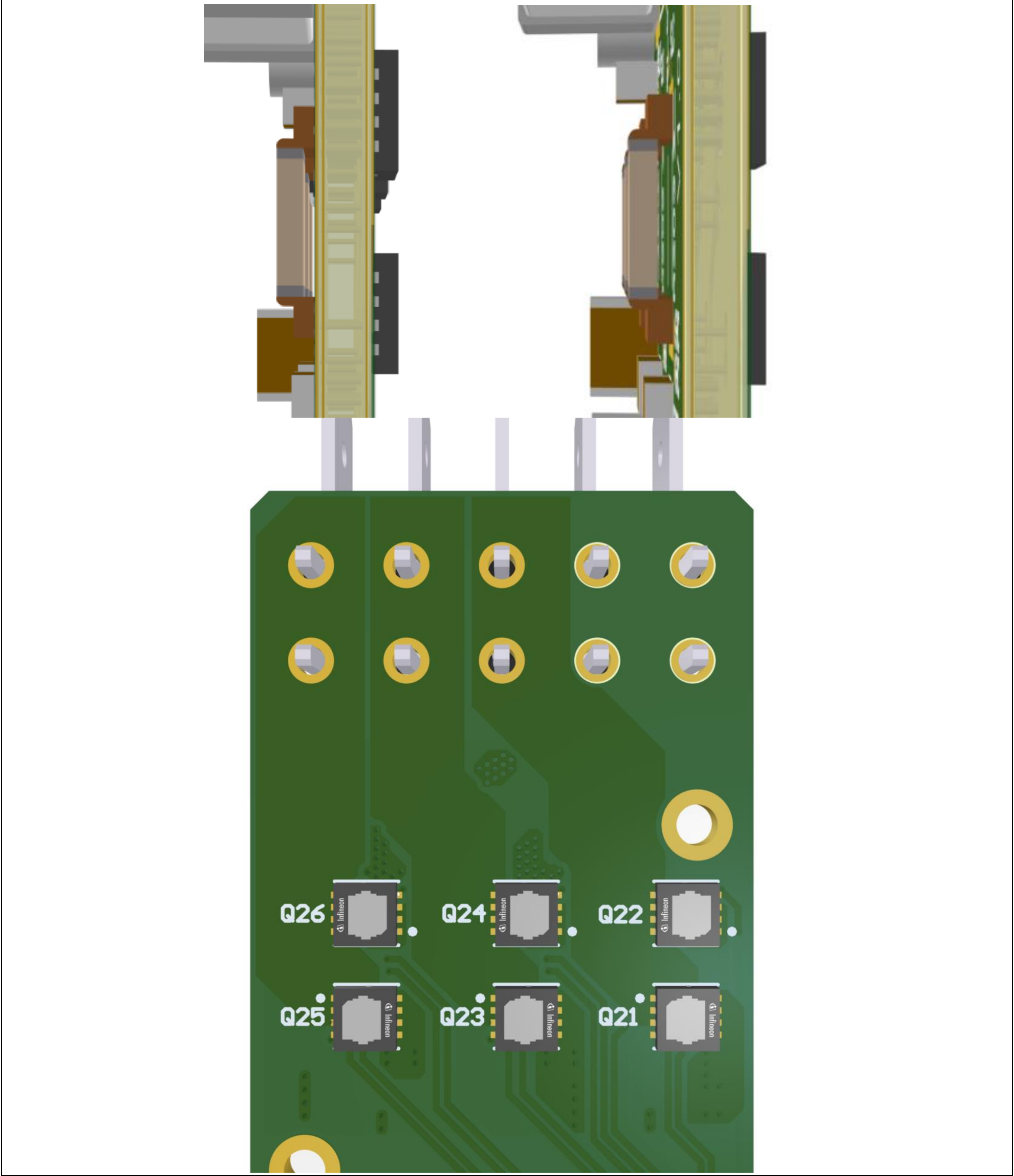


Figure 62 **Layout of the power half-bridges**

The power half-bridges are constructed in a way that the two MOSFETs are located on the opposite side of the board from the shunt resistors as can be seen in Figure 62 This way the loop inductance of the half bridge can be kept to a minimum, which reduces overshoots during switching. Reduced overshoot behavior leads to further performance improvements in EMI behavior and may also reduce the necessary overhead of the MOSFET breakdown voltage, so that lower $R_{DS(on)}$ can be used.

4.4 Interconnections

Power and small signal connections are located on the opposite sides of the REF_48V_270W_EBIKE PCB. In Figure 63, the power connections – X02 are visible on the right and the small signal connector X01 is on the left side of the board. This section explains the connections necessary for operation.

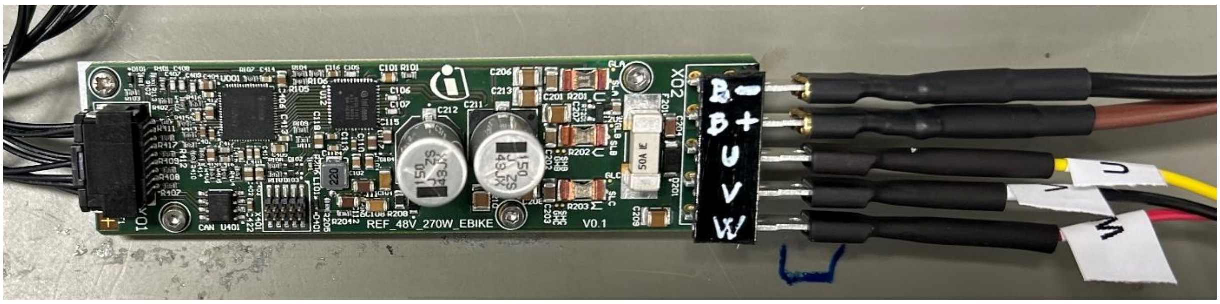


Figure 63 REF_48V_270W_EBIKE with X01 and X02 harnesses connected

Attention: ***When connecting a laboratory power supply, it is necessary to make the connections before powering up the supply unit in order to utilize the power supply's soft start, thus preventing excessive inrush current that can damage the onboard capacitors or cause destructive overshoots.***

Attention: ***When connecting to a battery, it is necessary to establish the connection using a pre-charge circuit (e.g., resistor, thus preventing excessive inrush current that can damage the onboard capacitors or cause destructive overshoots.***

4.4.1 Power connection

X02 is a 5-pin blade connector used for the power/high current connections. This connector provides the connection (pin 5 and pin 4) for the main DC power supply or battery used to power the board. Pins 1, 2, and 3 connect to the motor phases U, V, and W.

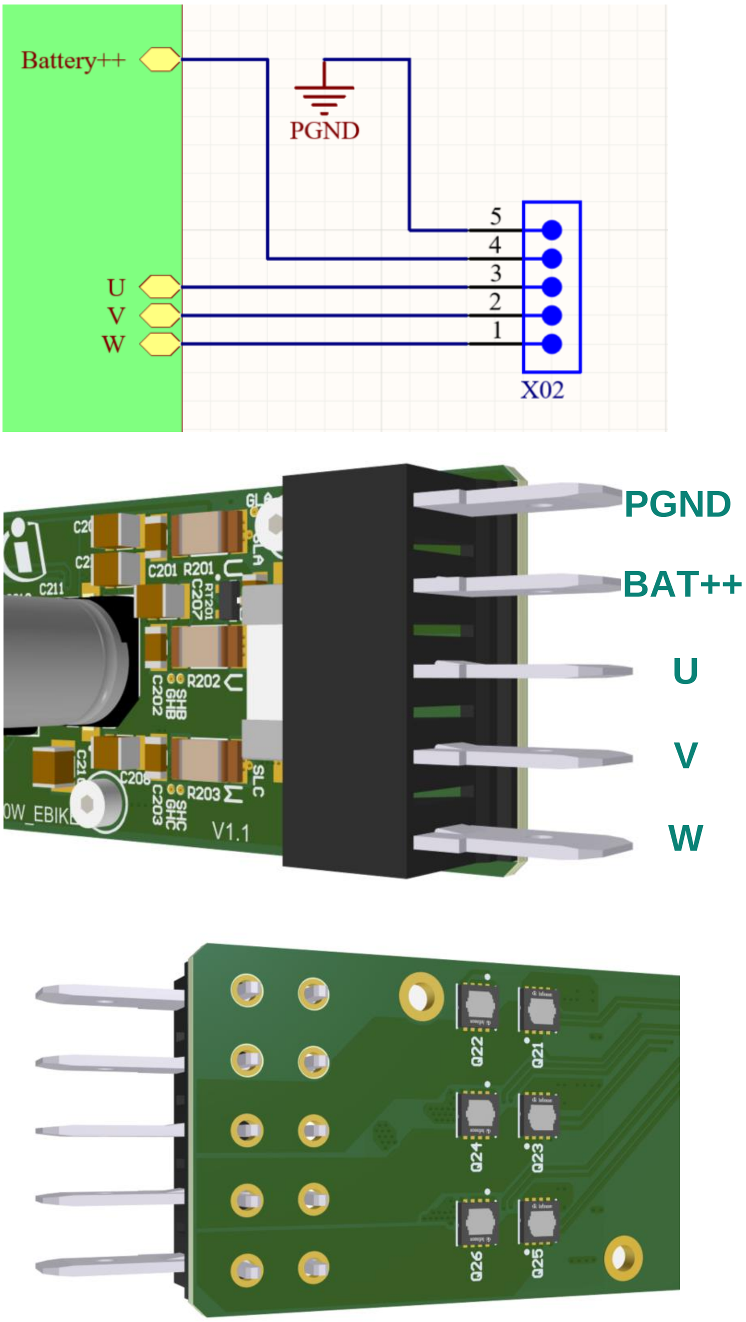


Figure 64 **Power connections**

Table 7 shows the pinout as is indicated in Figure 64.

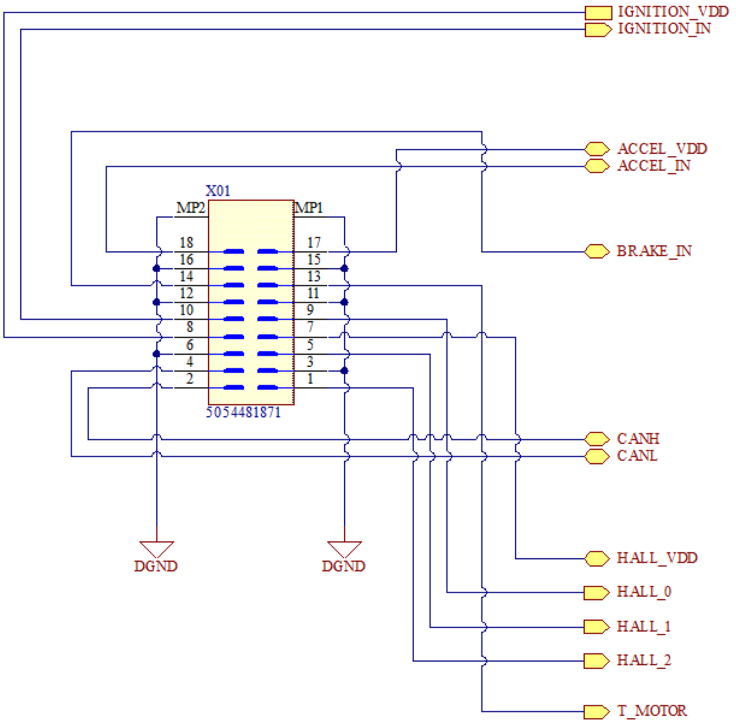
Table 7 **X02 – power connections**

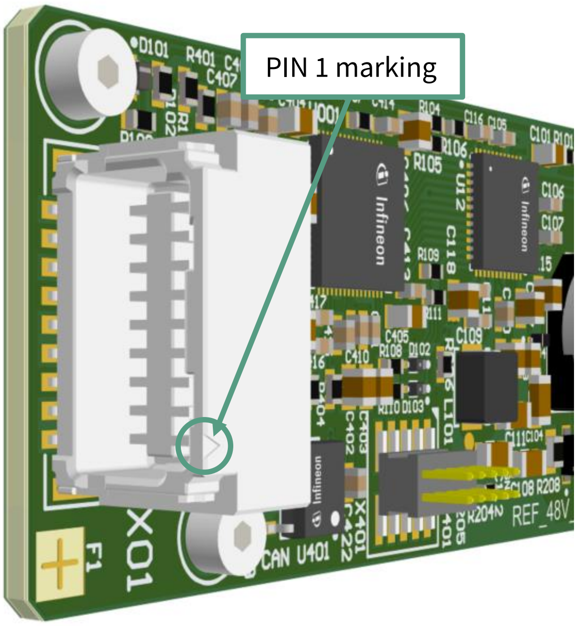
Signal name	Pin number	Description
PGND	5	Power supply GND or battery "-" power connection
Battery ++	4	Power supply or battery "+" power connection
Motor Phase U	3	Motor phase "U" power connection
Motor Phase V	2	Motor phase "V" power connection

Signal name	Pin number	Description
Motor Phase W	1	Motor phase “W” power connection

4.4.2 Small signal and interface connection

The small signal connector X01 (Molex 505448-1871) with its cable harness counterpart (Molex 505432-1801) provides the necessary motor feedback and system interface connections. The pinout pattern in the schematics represents the physical orientation of the pins as seen from the board front indicated in Figure 65 (the triangle notch indicates pin 1).




PIN 1 marking

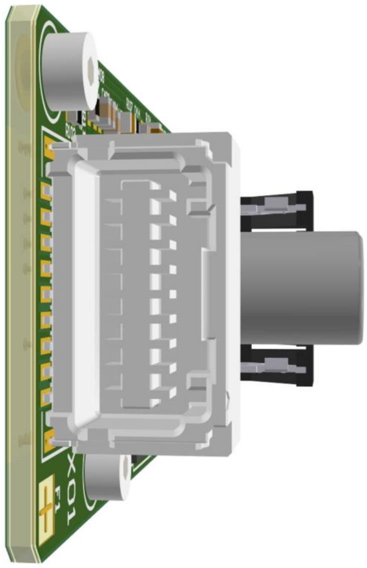


Figure 65 Cable harness for X01

The pinout is described in Table 8. The GND connections on the board are connected to a single ground copper plane, however their functionality is assigned accordingly in Table 8, since the individual signals will typically fan out to various locations on the e-Bike.

Table 8 X01 – small signal connector

Signal name	Pin number	Description
IGNITION_VDD	8	Connect to IGNITION_IN to power up the board
IGNITION_IN	10	Chip enable of 6EDL7151 – connect to IGNITION_VDD to power up board
ACCEL_VDD	17	Supply for accelerator control (potentiometer or a pedaling torque sensor/strain gauge)
ACCEL_IN	18	Accelerator control analog input
ACCEL_GND	16	GND for accelerator control
BRAKE_IN	14	Brake sensor analog input
BRAKE_GND	12	GND for brake sensor
T_MOTOR	13	Motor temperature sensor analog input with internal pull-up resistor
T_MOTOR_GND	11	GND for motor temperature sensor
HALL_VDD	7	Supply for motor hall position sensors
HALL_0	9	Motor hall position sensor “0” input
HALL_1	5	Motor hall position sensor “1” input
HALL_2	1	Motor hall position sensor “2” input
HALL_GND	3	GND for motor hall position sensors
CANH	2	CAN-High line
CANL	4	CAN-Low line
CAN_GND	6	GND reference for CAN bus

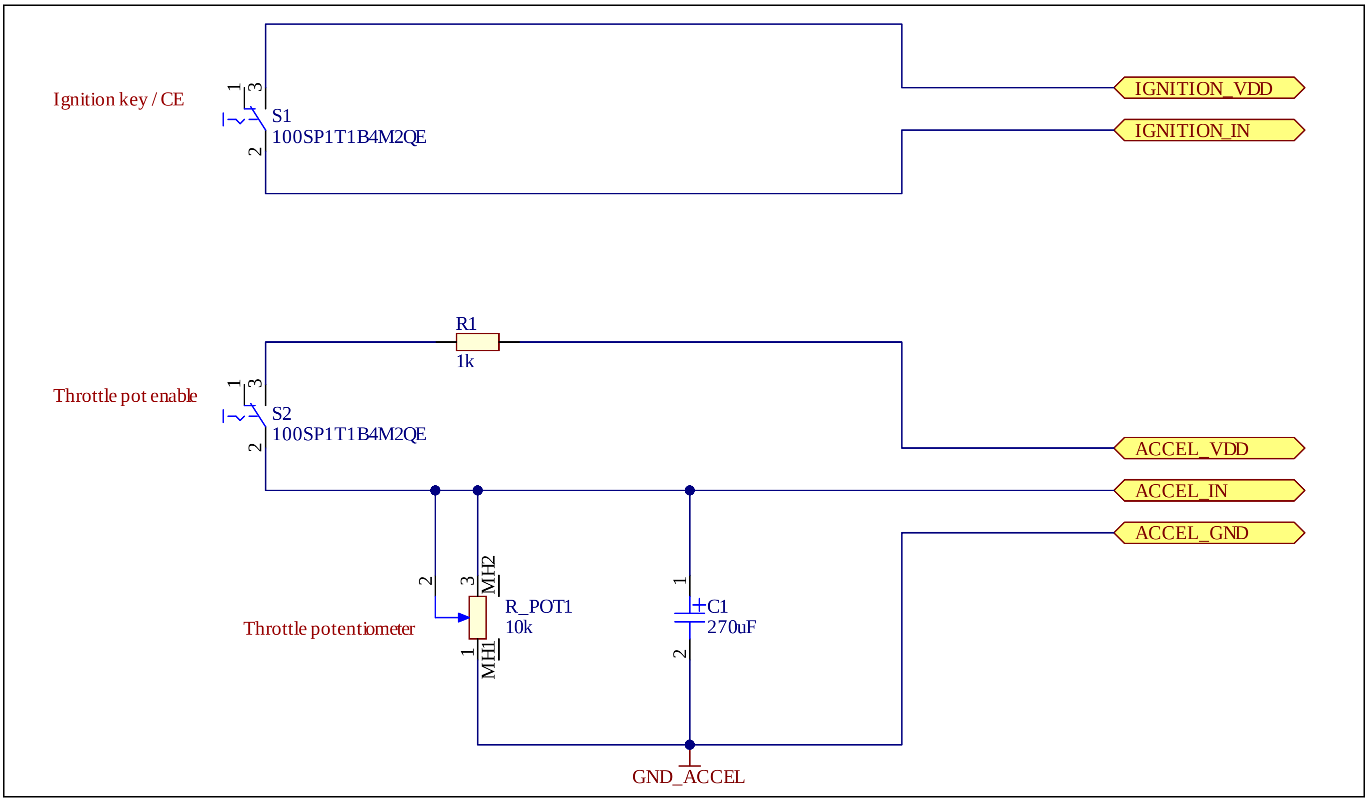


Figure 66 Example of a test setup control board

A minimal test board required to power up and run the REF_48V_270W_EBIKE board is shown in Figure 66. The connections on the right side of the schematic indicate the signals of the REF_48V_270W_EBIKE X01 connector.

After connecting the battery or power supply, switch S1 enables 6EDL7151 IC by connecting the “ignition” pins. The S2 switch activates the accelerator potentiometer by connecting it to the peripheral 5 V supply. When disconnected by S2, the accelerator potentiometer pulls the “ACCEL_IN” signal to 0 V. The C1 capacitor is provided to slow down the switching transitions.

4.4.3 Connection of the XMC™ Link programmer/debugger

In order to flash the firmware, or connect the board to the PC to use the GUI for REF_48V_270W_EBIKE, the XMC™ Link programmer/debugger connects to the header X401.

The smaller ribbon header with a 50mil pitch header connector is used. The red wire indicates a pin 1 polarity of the cable as shown in Figure 67.

Figure 67 Connection of the XMC™ Link to X401

4.5 Heatsink and M2 screw threading

The REF_48V_270W_EBIKE is provided with a semi-cylindrical heatsink, adapted to the proposed implementation inside a bicycle frame tube as shown in Figure 71.

The heatsink is made from anodized aluminum, and accommodates a tube with an inner diameter of 30 mm. For a different tube installation, the heatsink dimensions would need to be adjusted. The dimensions of the threaded holes are indicated in Figure 68 and Figure 69.

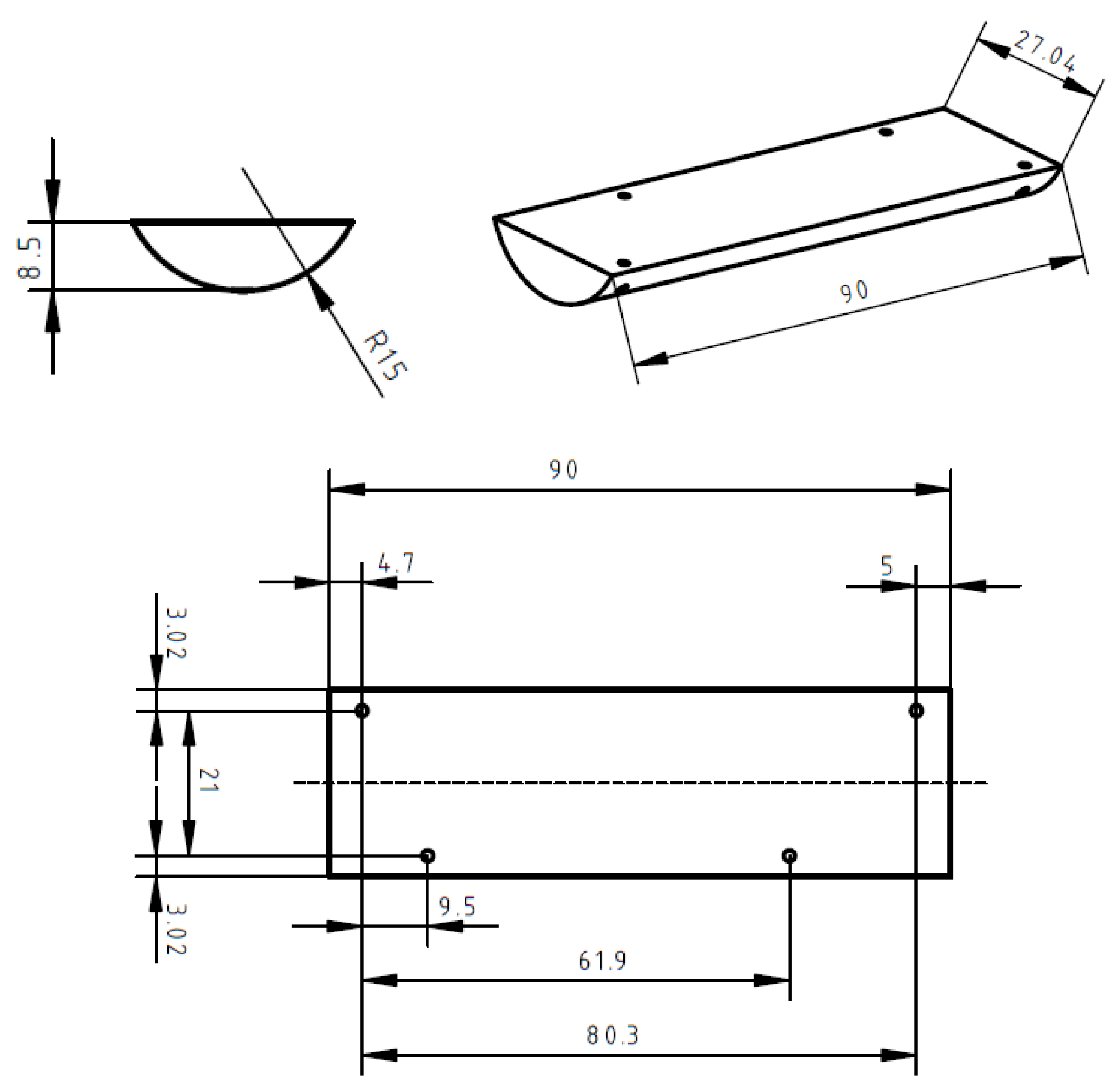


Figure 68 Heatsink drawing with M2 threaded holes indicated

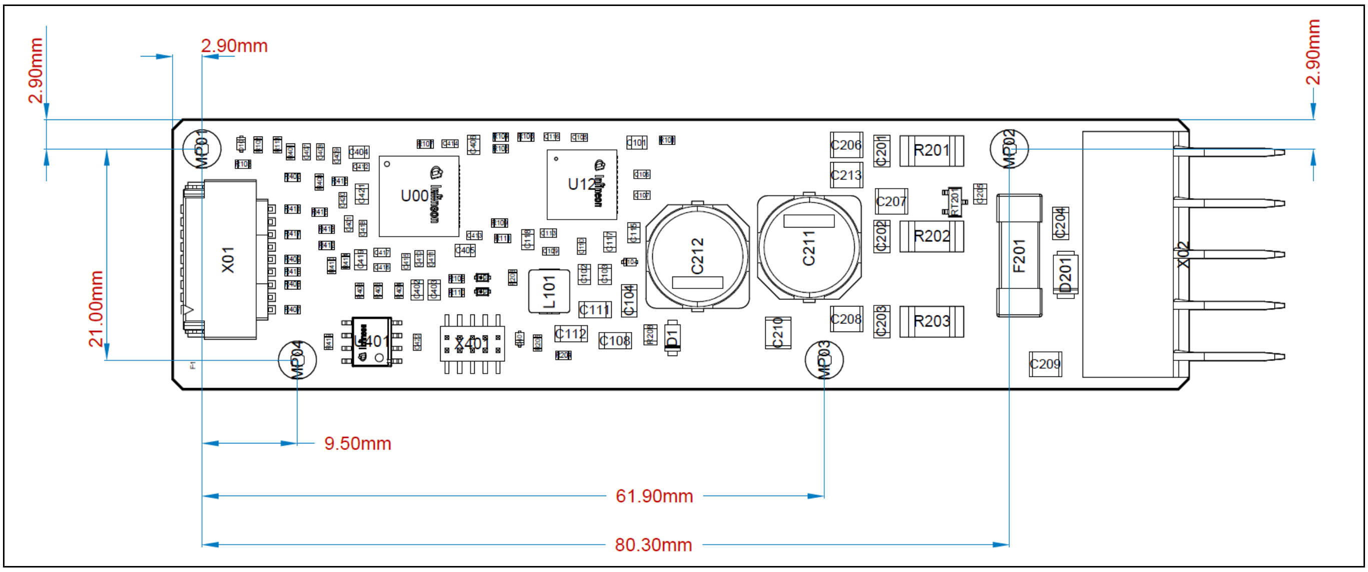


Figure 69 PCB mounting screws pattern drawing (M2 threading)

In order to accommodate for the MOSFET package thickness and the thermal pad thickness, the board stand-off from the heatsink is achieved by 1 mm thick spacers (nylon washers), thus achieving the correct compression of the TIM pad.

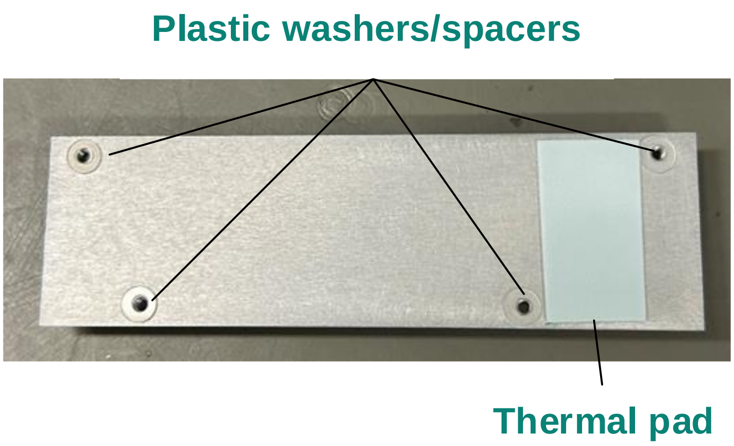


Figure 70 Heatsink with TIM pad and nylon washers/spacers

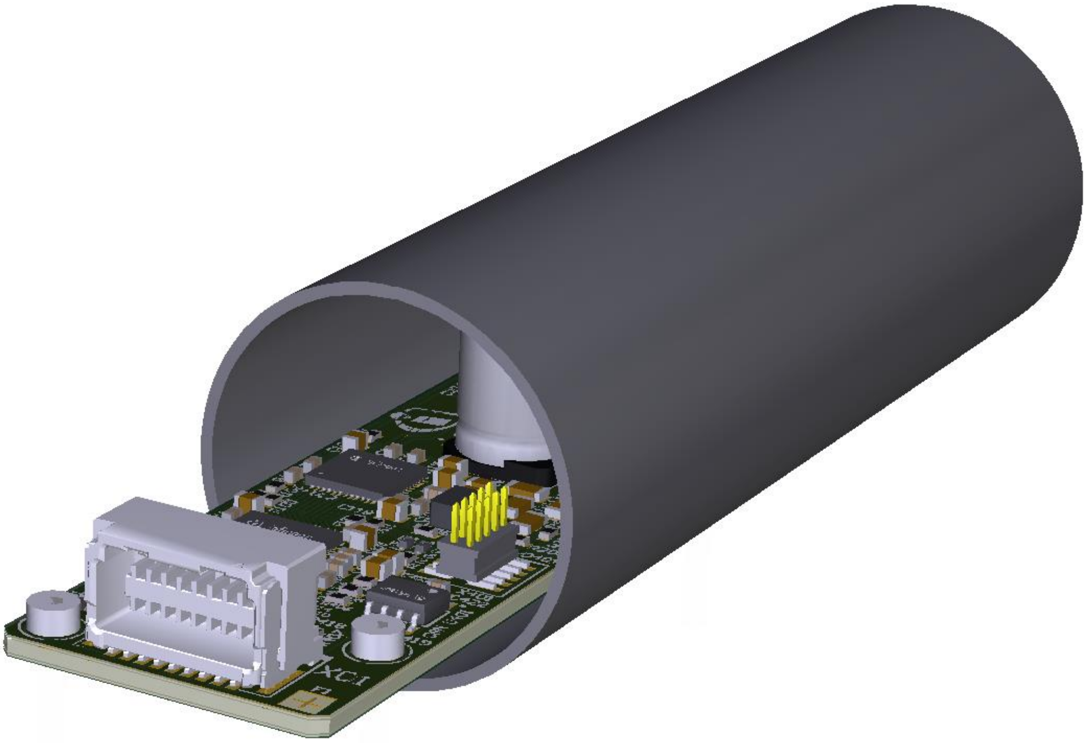


Figure 71 Example implementation inside a cylinder/tube (internal diameter = 30 mm)

5 Test results

The following tests have been conducted on various setups and various operating conditions as described.

5.1 Phase current sine wave

The initial test aims to show the general shape of the phase currents at a considerable load. The conditions are listed in Table 9.

Table 9 Conditions – phase currents sine wave

Condition	Description	Value
Motor	Motor used	QBL5704-116-04-042
V_DC	Supply Voltage	48 V
v_m	Motor rotational speed	2570 RPM
f_el	Electrical frequency of the motor	171 Hz
P_IN	DC supply power/input power of the board	265 W
P_OUT	AC output power of the board	255 W
I_OUT	Phase output current	9.76 A_{RMS}

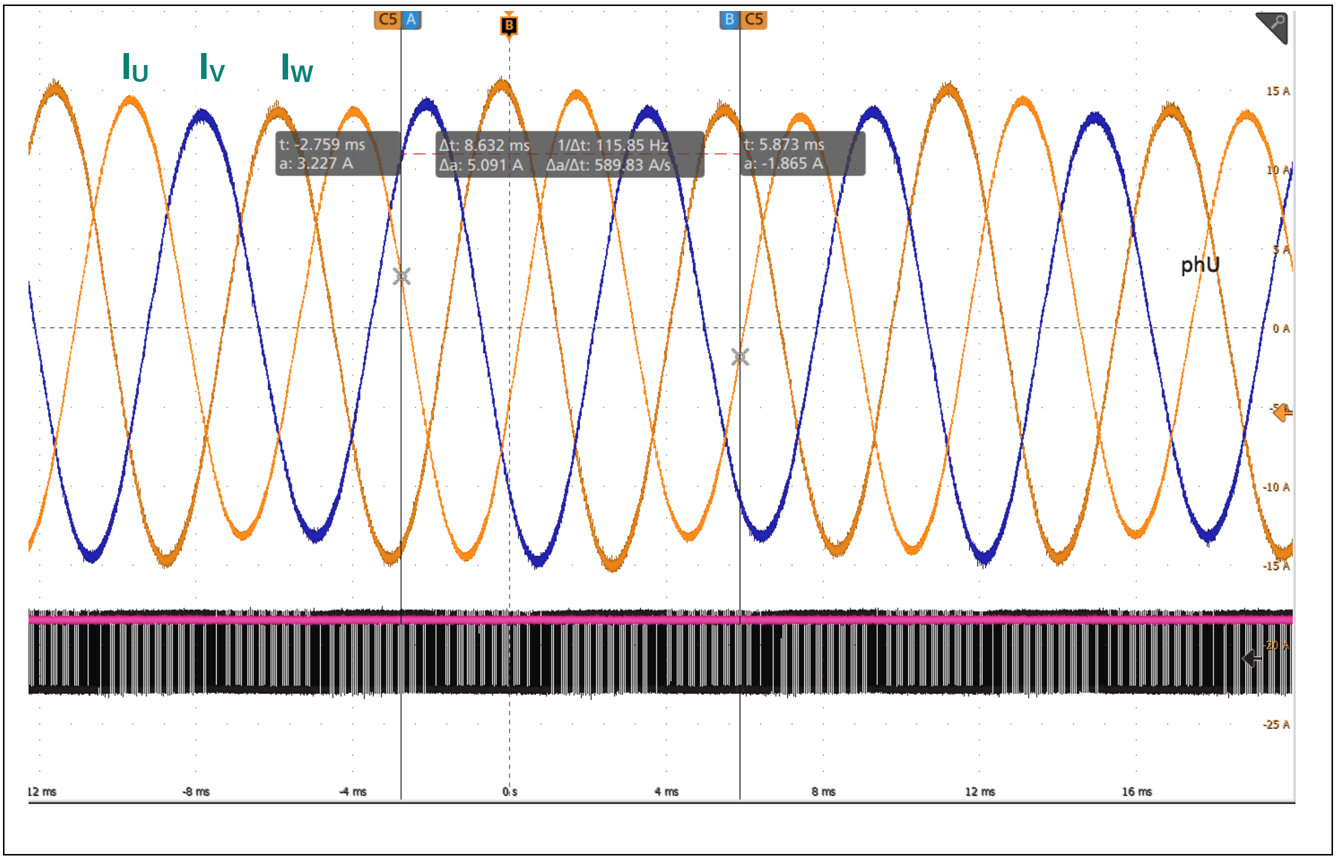


Figure 72 Three phase currents I_U, I_V, I_W, and U_{PWM_U}

5.2 Continuous power

In the continuous power test, the main observation is focused on the temperature of individual parts of the system while driving the system at the rated output power. In particular the main focus is the temperature of the power MOSFETs and the shunt resistors, since these components are primarily exhibiting increased power dissipation corresponding to increase of output power. The graph in Figure 73 shows the temperature plots of two of the half bridge temperatures T_{HBU} and T_{HBW} settling near 80°C after 20 mins of operation in the operating point described in Table 10. The temperatures of half bridges are measured via thermocouple sensors placed between the high-side and low-side MOSFET of an individual half-bridge on the bottom side of the PCB. Figure 74 shows the thermal image of the maximum temperatures of the top of the PCB, right before the power cut-off at 20 mins of operation.

Table 10 Conditions – continuous power

Condition	Description	Value
Motor	Motor used	MY1020D
V_DC	Supply Voltage	48 V
T_a	Ambient temperature	25°C
v_m	Motor rotational speed	2650 RPM
τ_m	Motor load torque	0.66 Nm
f_el	Electrical frequency of the motor	133 Hz
P_IN	DC supply power / input power of the board	284 W
I_IN	DC supply current	6 A
P_OUT	AC output power of the board	257 W
I_OUT	Phase output current	11 A_{RMS}

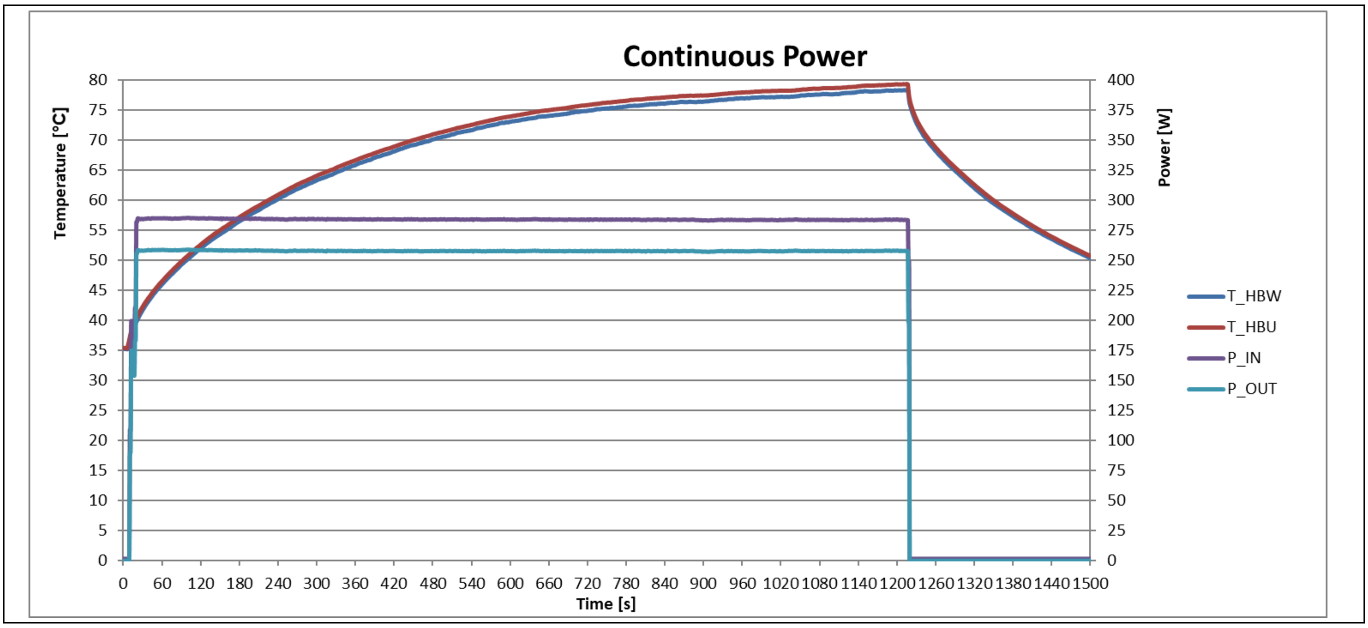


Figure 73 Temperature plots during continuous load

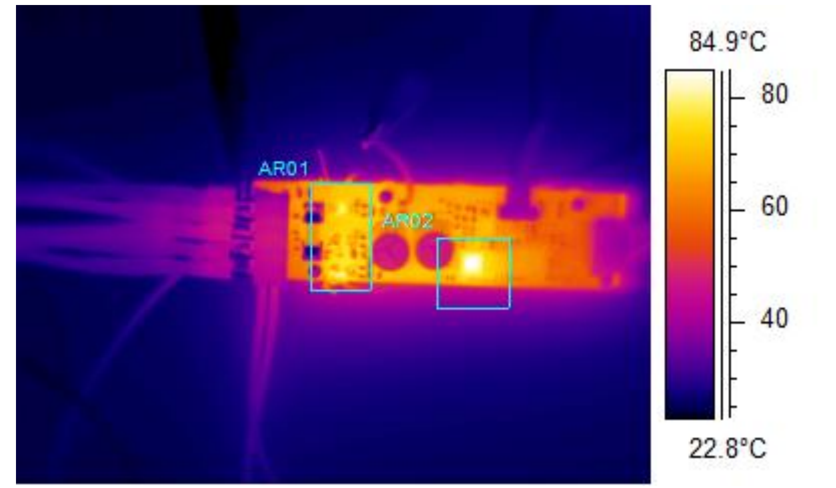


Figure 74 Thermal image of the board top-side – AR01: Shunt resistors; AR02: 6EDL7151

5.3 Peak power

A similar test is performed to check for the maximum/peak power or output current condition that the board can withstand for a limited period of time. The conditions are shown in Table 11. The input and output current waveforms are shown in Figure 76.

Table 11 Conditions – peak power

Condition	Description	Value
Motor	Motor used	MY1020D
V_DC	Supply Voltage	48 V
T_a	Ambient temperature	25°C
v_m	Motor rotational speed	3120 RPM
τ_m	Motor load torque	2.87 Nm
f_el	Electrical frequency of the motor	156 Hz
P_IN	DC supply power / input power of the board	1100 W
I_IN	DC supply current	23 A
I_OUT	Phase output current	29 A_{RMS}
P_m	Mechanical output power of the motor	939 W
t_duration	Duration of applied peak power	2.5 min

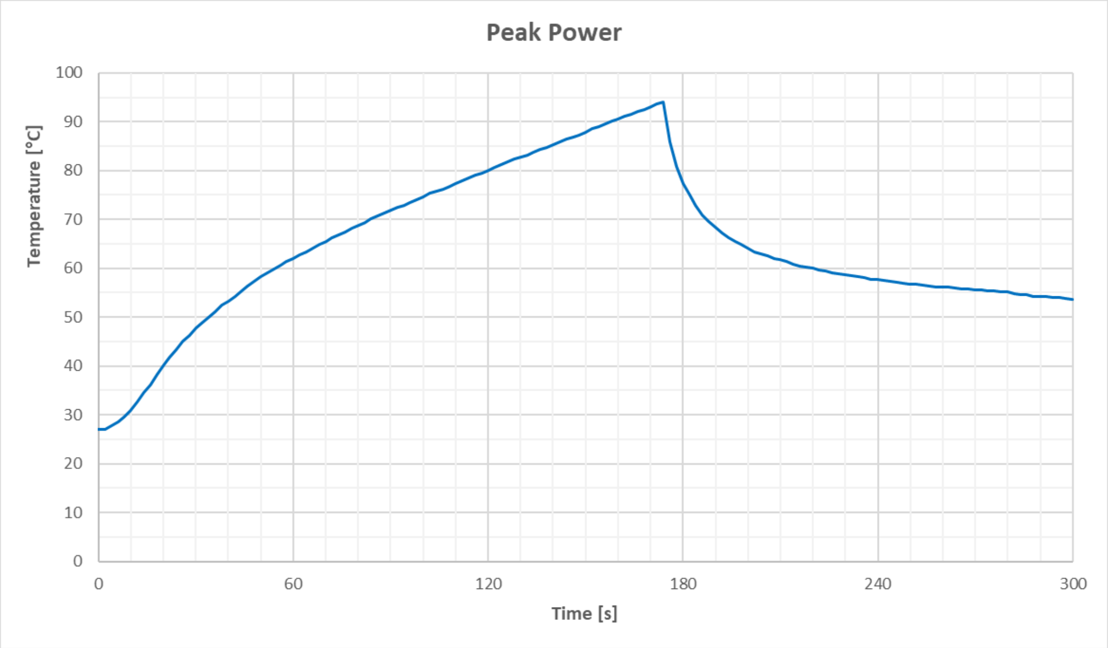
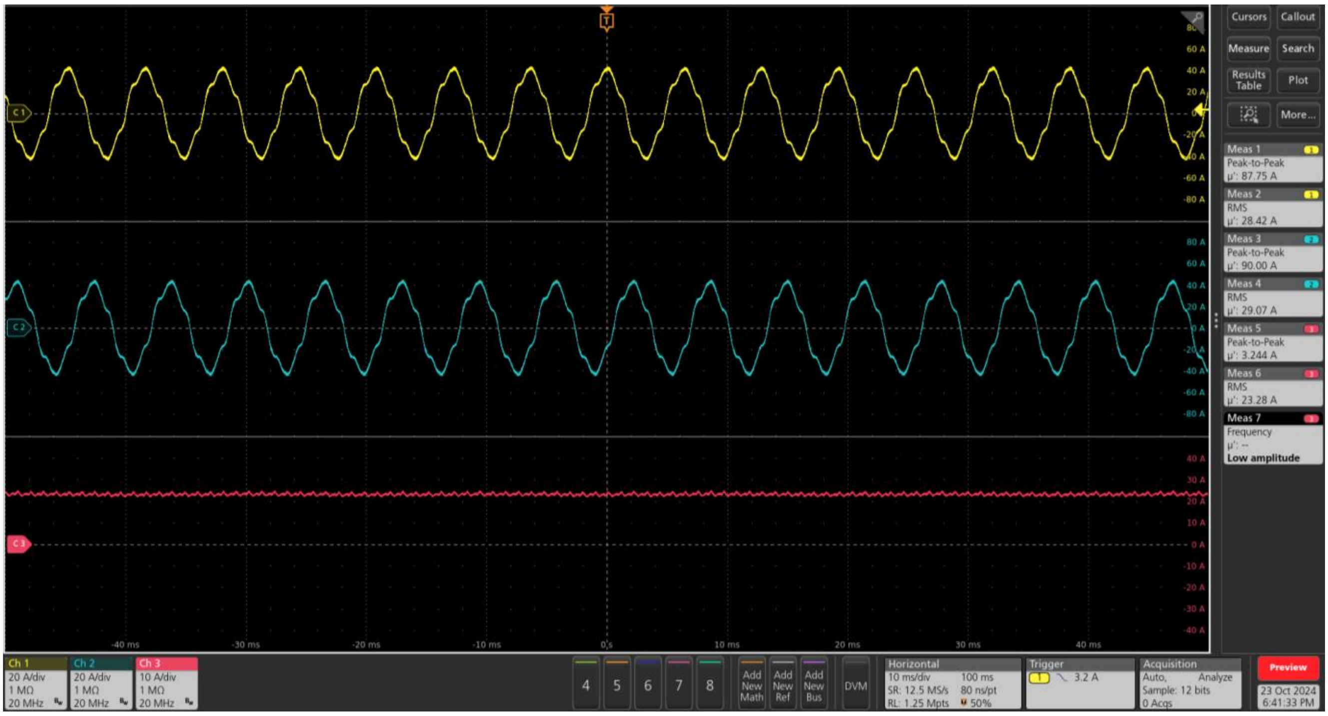


Figure 75 Half-bridge temperature plot at 1 kW



Meas 1
Peak-to-Peak
µ': 87.75 A

Meas 2
RMS
µ': 28.42 A

Meas 3
Peak-to-Peak
µ': 90.00 A

Meas 4
RMS
µ': 29.07 A

Meas 5
Peak-to-Peak
µ': 3.244 A

Meas 6
RMS
µ': 23.28 A

Meas 7
Frequency
µ': --
Low amplitude

Ch 1
20 A/div
1 MΩ
20 MHz

Ch 2
20 A/div
1 MΩ
20 MHz

Ch 3
10 A/div
1 MΩ
20 MHz

Horizontal
10 ms/div 100 ms
SR: 12.5 MS/s 80 ns/pt
RL: 1.25 Mpts 50%

Trigger
1 3.2 A

Acquisition
Auto, Analyze
Sample: 12 bits
0 Acqs

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6:41:33 PM

Figure 76 Supply current I_VDC and phase currents, I_U and I_V during peak power

5.4 Efficiency

The efficiency was measured with a load proportional to the motor speed. The result is shown in Figure 77.

Table 12 Conditions – continuous

Condition	Description	Value
Motor	Motor used	QBL5704-116-04-042
Load	Motor used as break with resistive load	QBL5704-116-04-042
V_DC	Supply Voltage	48 V
T_a	Ambient temperature	25°C

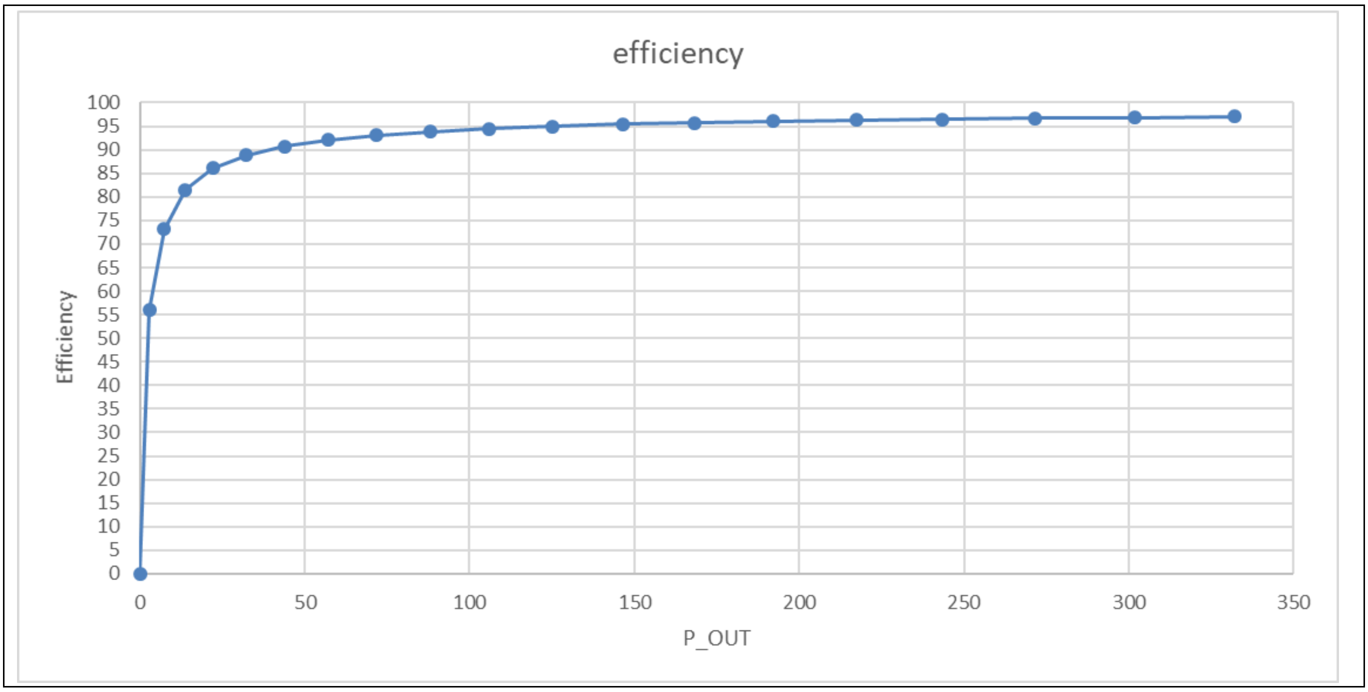

Figure 77 Efficiency vs. output power

5.5 Power limiting

As described in section 2.4.3, the output power can be limited and the limit is configurable. Figure 78 shows an example where the output limit is set to 200 W in Vq mode. Above the set limit, the throttle input no longer affects output power.

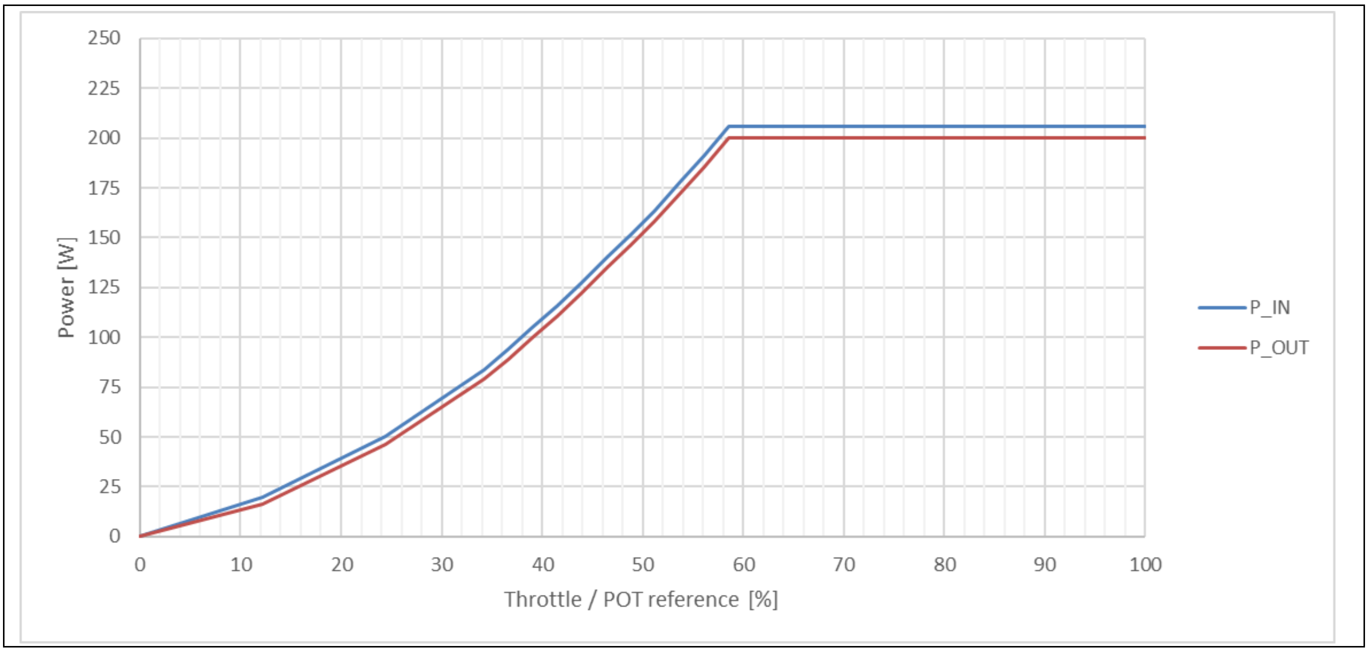

Figure 78 Output power limitation of 200 W

6 Schematics

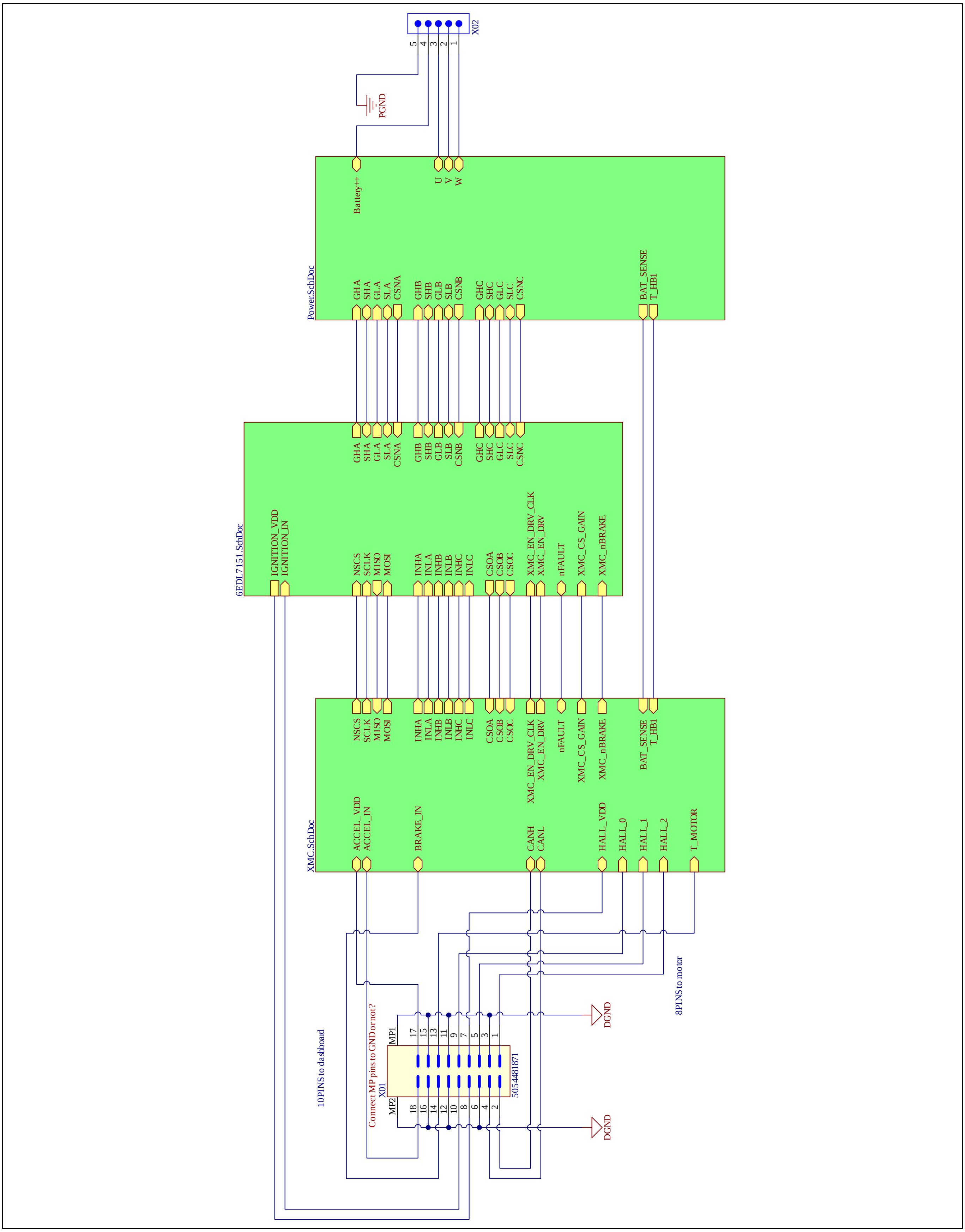

Figure 79 REF_48V_270W_EBIKE – Top-level schematic

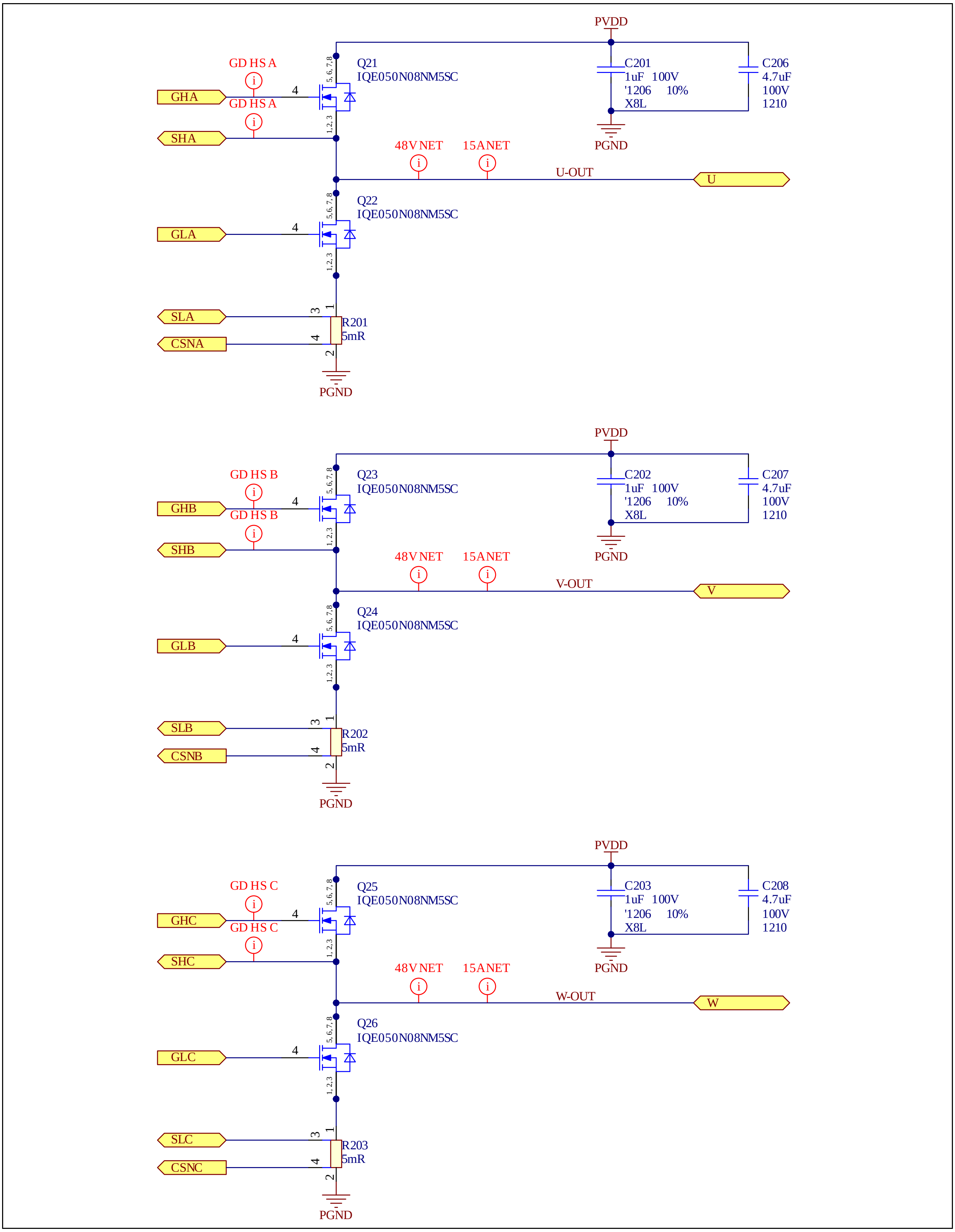

Figure 80 REF_48V_270W_EBIKE – Power – 3-phase power inverter stage schematic

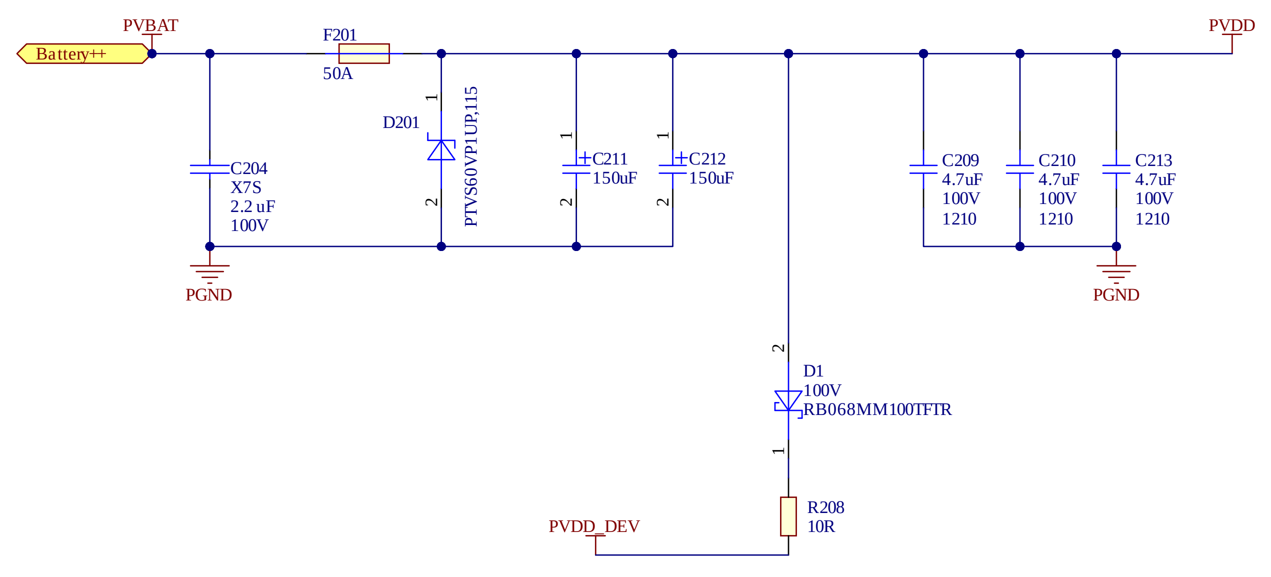

Figure 81 REF_48V_270W_EBIKE – Power – DC input section schematic

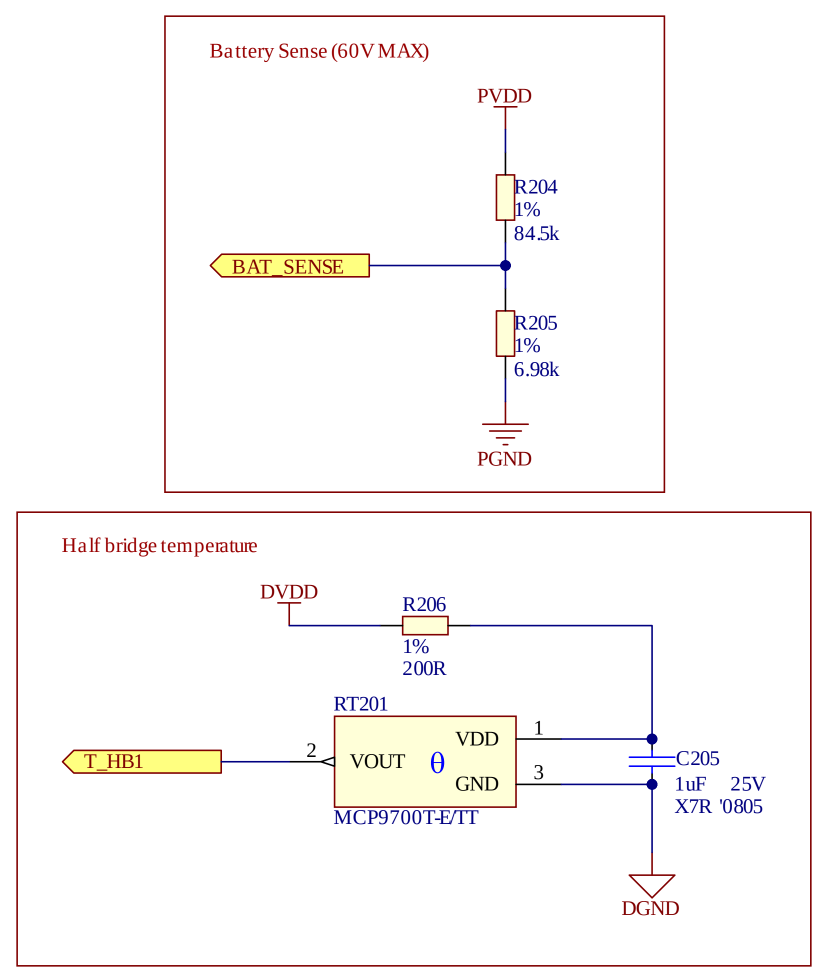

Figure 82 REF_48V_270W_EBIKE – Power – battery voltage divider and half bridge temperature sensor schematic

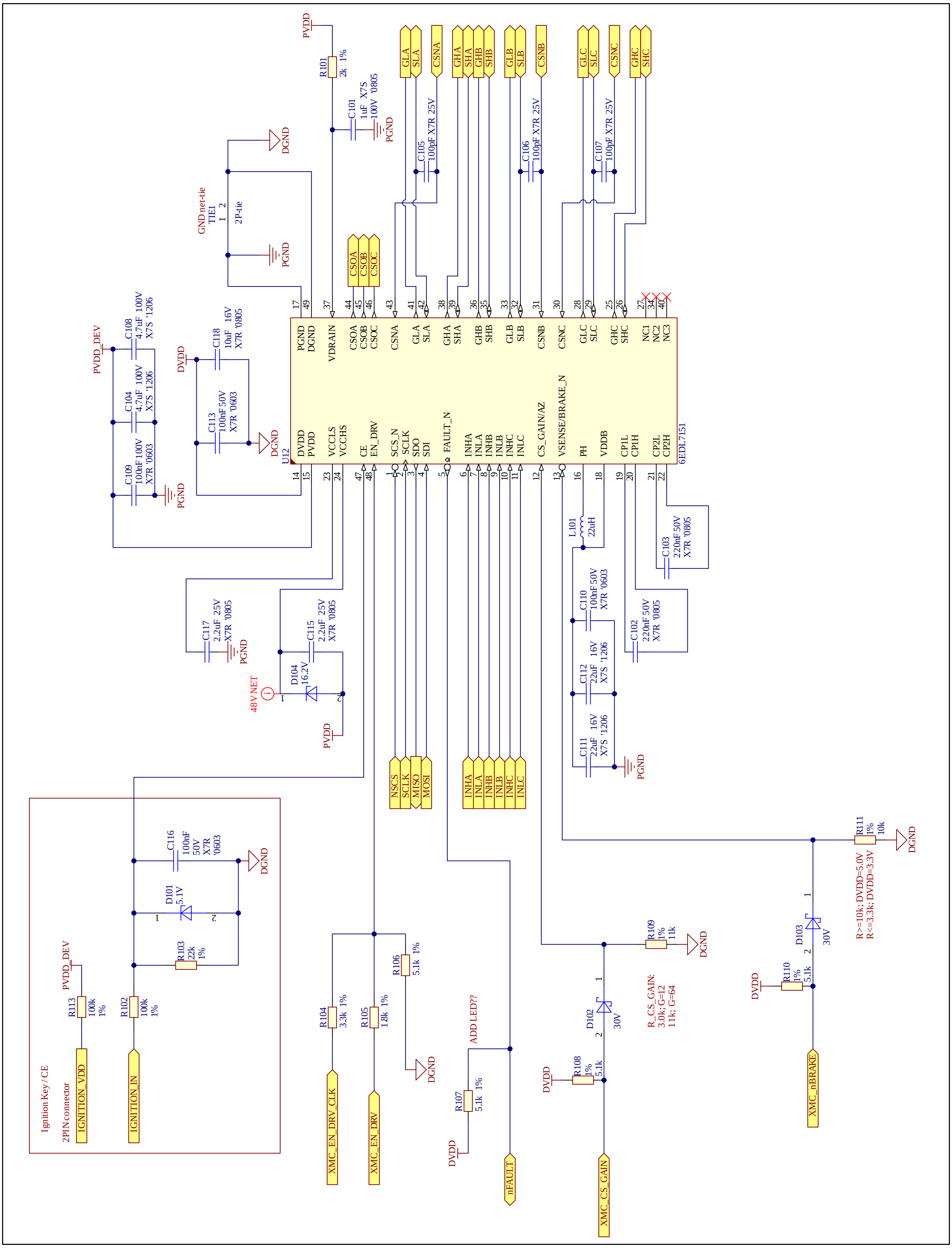

Figure 83 REF_48V_270W_EBIKE – 6EDL7151 gate driver section schematic

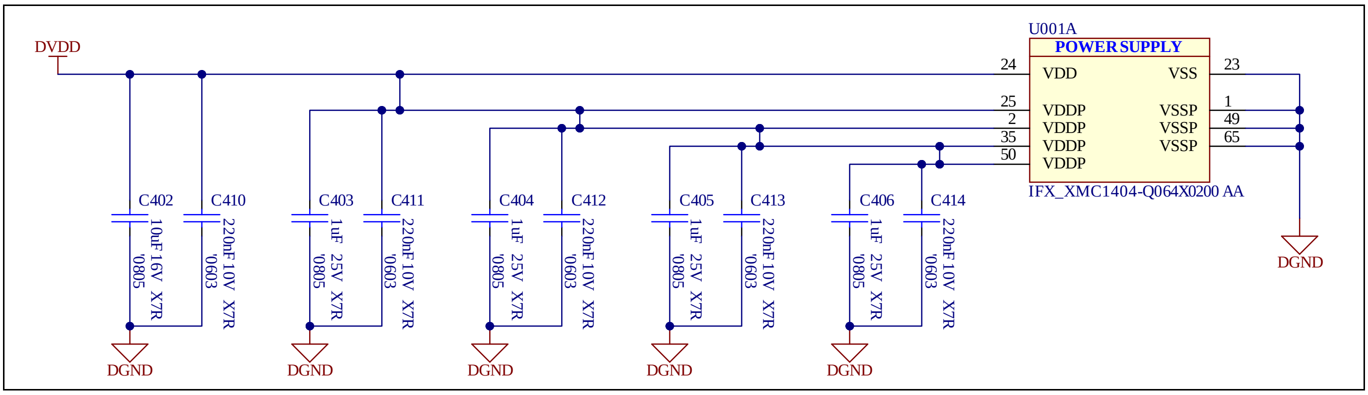

Figure 84 REF_48V_270W_EBIKE – XMC™ – XMC1404 microcontroller power supply section schematic

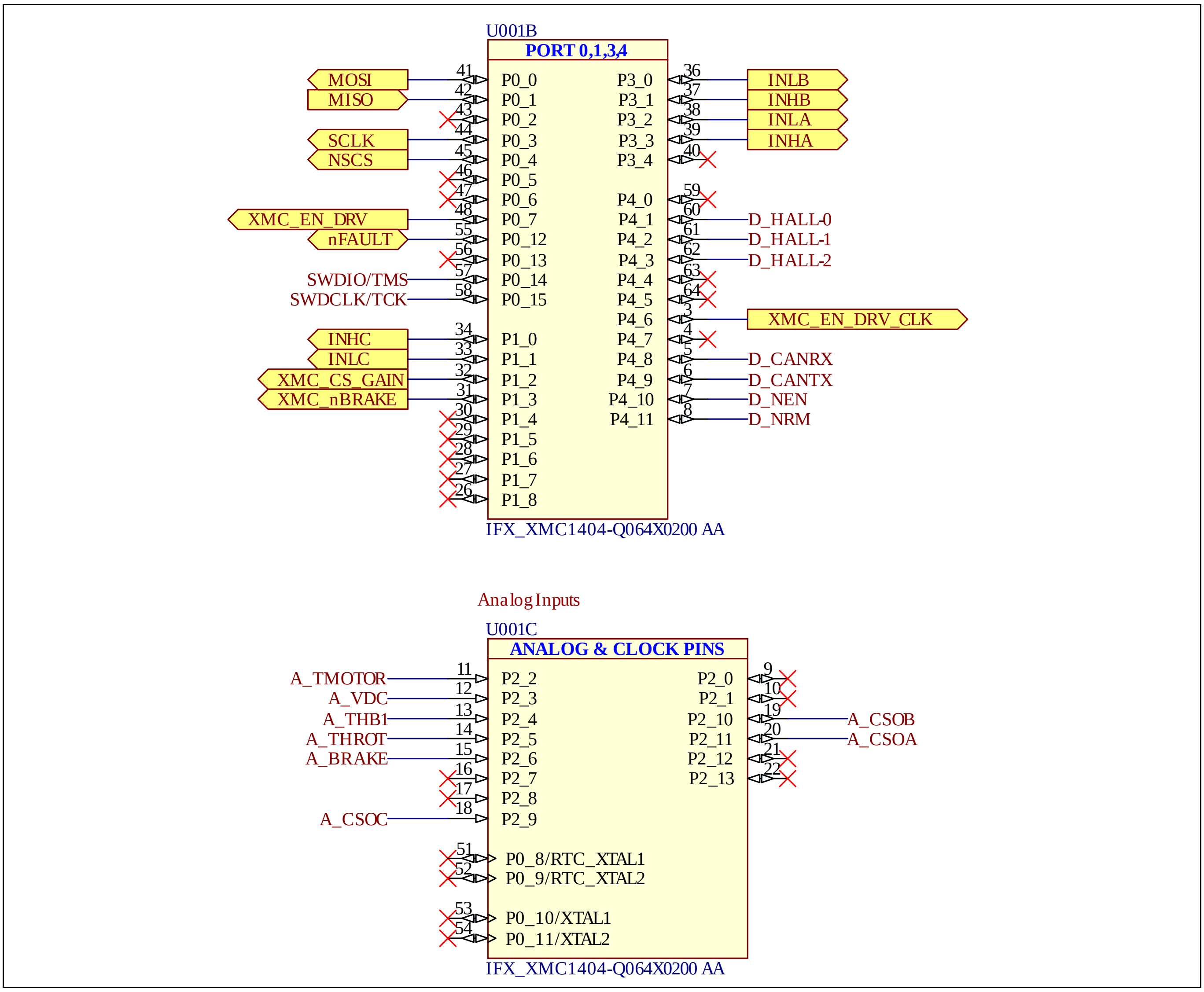

Figure 85 REF_48V_270W_EBIKE – XMC™ – XMC1404 microcontroller digital and analog section schematic

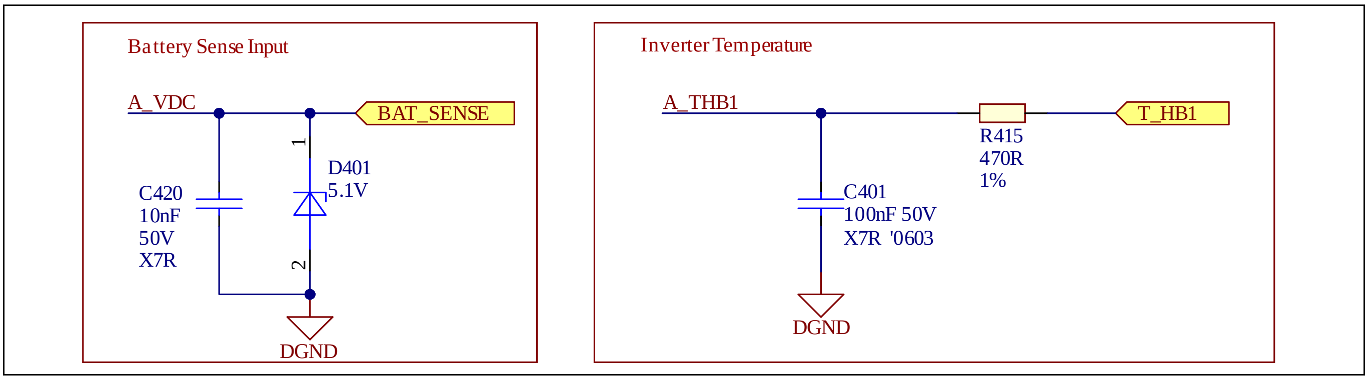

Figure 86 REF_48V_270W_EBIKE – XMC™ – battery voltage and inverter temperature analog input protection and filtering schematic

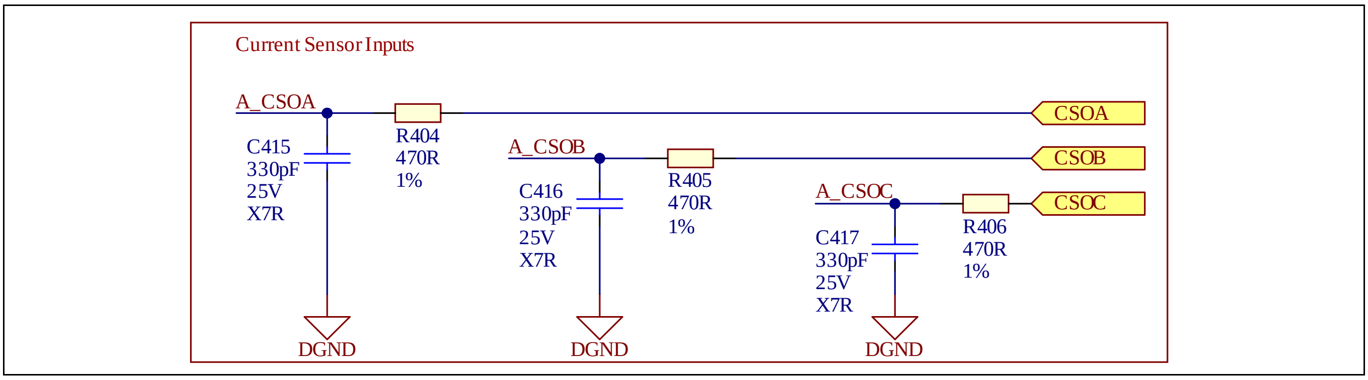

Figure 87 REF_48V_270W_EBIKE – XMC™ – current sense input filtering schematic

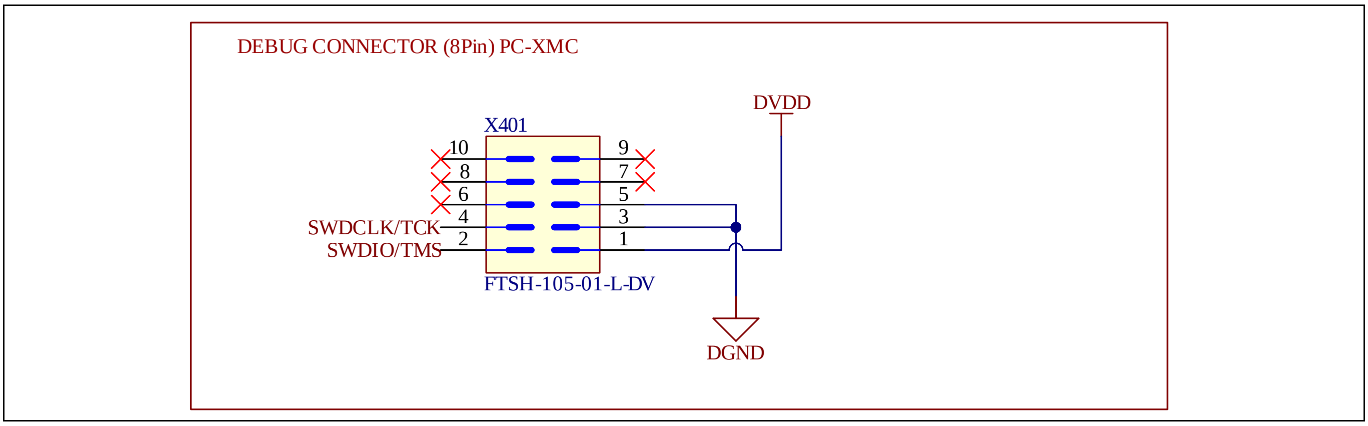

Figure 88 REF_48V_270W_EBIKE – XMC™ – XMC1404 microcontroller debug interface schematic

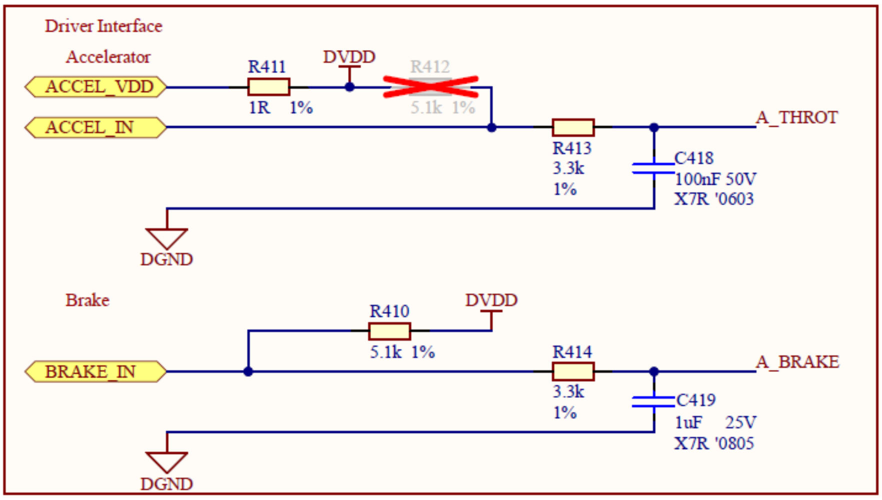

Figure 89 REF_48V_270W_EBIKE – XMC™ – throttle and brake analog input interface schematic

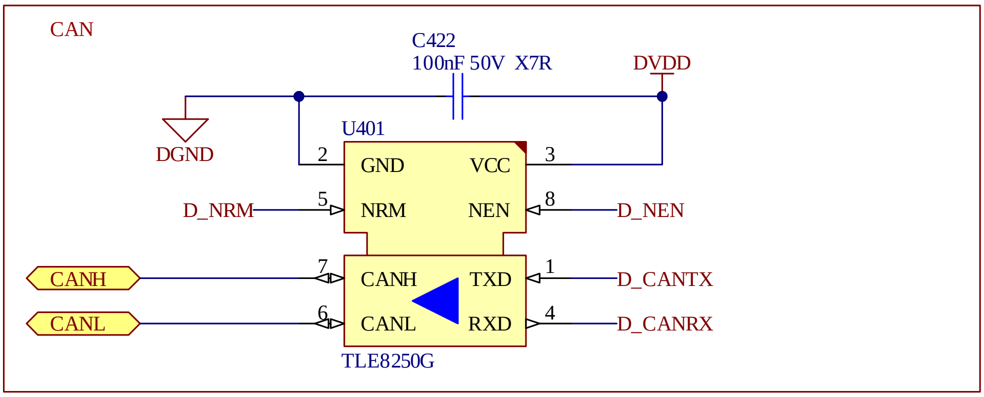

Figure 90 REF_48V_270W_EBIKE – XMC™ – CAN transceiver TLE8250G schematic

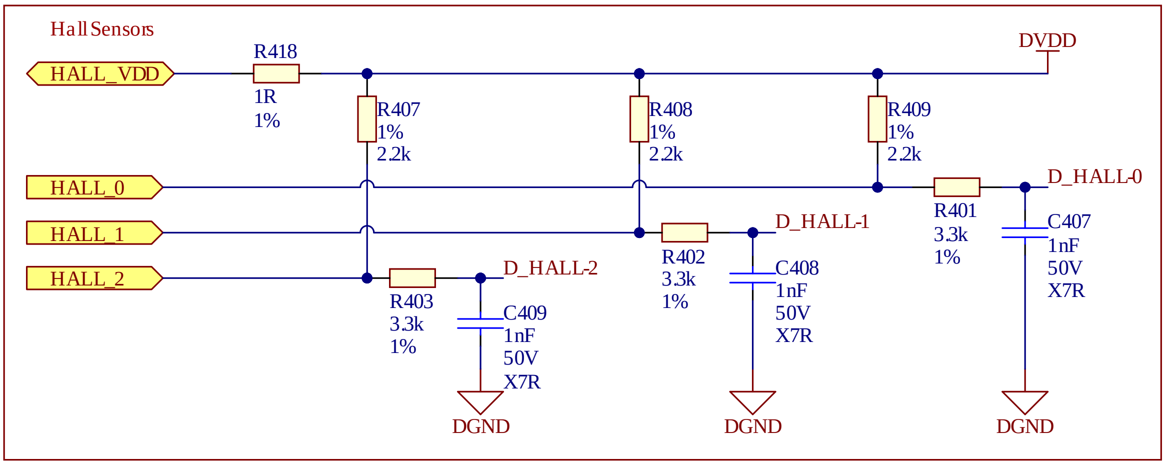

Figure 91 REF_48V_270W_EBIKE – XMC™ – Hall sensor interface schematic

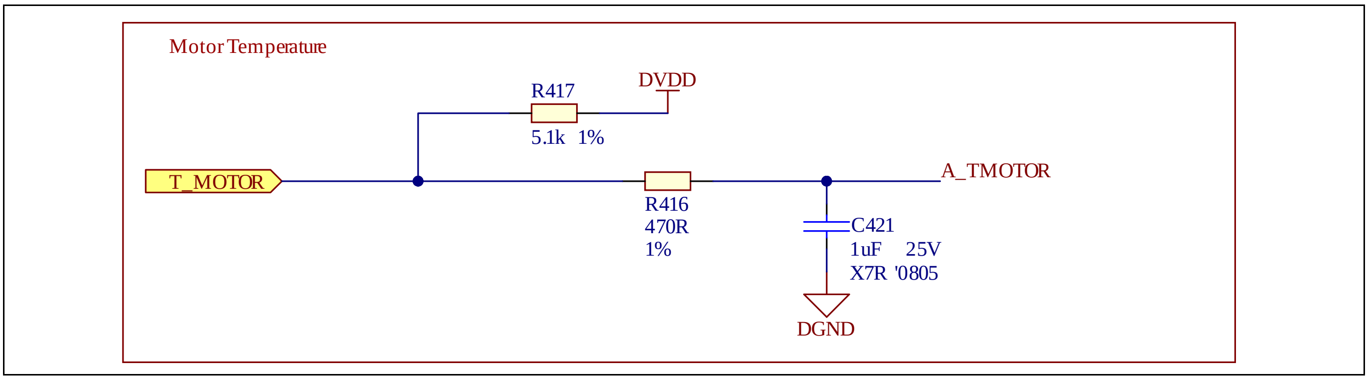

Figure 92 REF_48V_270W_EBIKE – XMC™ – motor temperature sensor interface schematic

7 Bill of materials

Table 13 Bill of materials – REF_48V_270W_EBIKE

Reference	Qty	Value/Rating	Manufacturer	Part number
C101	1	1 uF, 100 V, 10%, X7S, '0805	Murata	GCM21BC72A105KE36L
C102, C103	2	220 nF, 50 V, 10%, X7R, '0805	KEMET	C0805C224K5RACAUTO
C104, C108	2	4.7 uF, 100 V, 10%, X7S, '1206	Murata	GRM31CC72A475KE11L
C105, C106, C107	3	100 pF, 25 V, 10%, X7R, '0603	KEMET	C0603C101K3GAC7867
C109	1	100 nF, 100 V, 10%, X7R, '0603	Samsung Electro-Mechanics	CL10B104KC8NNNC
C110, C113, C116, C401, C418, C422	6	100 nF, 50 V, 10%, X7R, '0603	KYOCERA AVX	KAM15AR71H104KM
C111, C112	2	22 uF, 16 V, 20%, X7S, '1206	Murata	GCM31CC71C226ME36L
C115, C117	2	2.2 uF, 25 V, 10%, X7R, '0805	Samsung Electro-Mechanics	CL21B225KAFNNNG
C118, C402	2	10 uF, 16 V, 10%, X7R, '0805	TAIYO YUDEN	EMK212BB7106KG-T
C201, C202, C203	3	1 uF, 100 V, 10%, X8L, '1206	Murata	GCJ31CL8EL105KA07L
C204	1	2.2 uF, 100 V, 10%, X7S, C_1206_HD	TDK Corporation	C3216X7S2A225K160AE
C205, C403, C404, C405, C406, C419, C421	7	1 uF, 25 V, 10%, X7R, '0805	Samsung Electro-Mechanics	CL21B105KAFNNNE
C206, C207, C208, C209, C210, C213	6	4.7 uF, 100 V, 10%, X8L, 1210	Murata	GCM32DL8EL475KE07L
C211, C212	2	150 uF, 63 V, 20%, Aluminum electrolytic, 10.30 mm L X 10.30 mm W X 16.80 mm H	Panasonic	EEHZS1J151P
C407, C408, C409	3	1 nF, 50 V, 10%, X7R, '0603	KYOCERA AVX	KGM15AR71H102KM
C410, C411, C412, C413, C414	5	220 nF, 10 V, 10%, X7R, '0603	KYOCERA AVX	0603ZC224KAT2A
C415, C416, C417	3	330 pF, 25 V, 10%, X7R, '0603	KYOCERA AVX	KGM15AR71E331KT
C420	1	10 nF, 50 V, 10%, X7R, '0603	KYOCERA AVX	KGM15AR71H103KT
D1	1	Schottky Diode, 100 V, 2 A	ROHM Semiconductors	RB068MM100TFTR
D101, D401	2	Zener Diode, 5.1 V, 500 mW	ON Semiconductor	MM5Z5V1T1G
D102, D103	2	Schottky Diode, 30 V	Infineon	BAS3005A-02V

Reference	Qty	Value/Rating	Manufacturer	Part number
D104	1	Zener Diode, 16.2 V	ON Semiconductor	MM5Z16VT1G
D201	1	TVS, 60 V	Nexperia	PTVS60VP1UP,115
F201	1	Fuse, SMD, 50 A	Littelfuse	0456050.DRSD
L101	1	22 uH, 1.2 A, 20%, 500 mR	Bourns	SRP4020TA-220M
Q21, Q22, Q23, Q24, Q25, Q26	6	80 V, 5 mΩ, 3.3x3.3 package	Infineon	IQE050N08NM5SC
R101	1	2 kΩ, 1%, '0603	Yageo	RC0603FR-072KL
R102, R113	2	100 kΩ, 1%, '0603	Yageo	RC0603FR-07100KL
R103	1	22 kΩ, 1%, '0603	Yageo	RC0603FR-0722KL
R104, R401, R402, R403, R413, R414	6	3.3 kΩ, 1%, '0603	Yageo	RC0603FR-073K3L
R105	1	1.8 kΩ, 1%, '0603	Yageo	RC0603FR-071K8L
R106, R107, R108, R110, R410, R417	6	5.1 kΩ, 1%, '0603	Yageo	RC0603FR-075K1L
R109	1	11 kΩ, 1%, '0603	Yageo	RC0603FR-0711KL
R111	1	10 kΩ, 1%, '0603	Yageo	RC0603FR-0710KL
R201, R202, R203	3	5 mΩ, 3 W, 1%, 50 ppm/K, 2512(6332)	Isabellenhuette	BVT-I-R005-1.0
R204	1	84.5 kΩ, 1%, '0603	Yageo	RC0603FR-0784K5L
R205	1	6.98 kΩ, 1%, '0603	Yageo	RC0603FR-076K98L
R206	1	200 Ω, 1%, '0603	Yageo	RC0603FR-07200RL
R208	1	10 Ω, 500 mW, 5%, 0805	Vishay	CRCW080510R0JNEAHP
R404, R405, R406, R415, R416	5	470 Ω, 1%, '0603	Yageo	RC0603FR-07470RL
R407, R408, R409	3	2.2 kΩ, 1%, '0603	Yageo	RC0603FR-072K2L
R411, R418	2	1 Ω, 1%, '0603	Yageo	RC0603FR-071RL
R419	1	120 Ω, 1%, '0603	Yageo	RC0603FR-07120RL
RT201	1	Active Thermistor IC	Microchip Technology	MCP9700T-E/TT
U001	1	XMC1400 AA-Step, ARM® Cortex®-M0 32-bit	Infineon	XMC1404-Q064X0200 AA
U12	1	3-phase gate driver IC	Infineon	6EDL7151
U401	1	CAN-Transceiver	Infineon	TLE8250G

Reference	Qty	Value/Rating	Manufacturer	Part number
X01	1	Connector, 18 Pin, 1.25 mm Pitch	Molex	505448-1871
X02	1	WR-FAST THT Male Header Angled Blade, pitch 5.08 mm	Würth Elektronik	638263122005
X401	1	SMT Micro Header, 1.27 mm Pitch, 10 Pin	Samtec	FTSH-105-01-L-DV

8 Conclusion

The REF_48V_270W_EBIKE reference board has been designed as a motor drive inverter for low-power e-Bikes or pedelecs. It is optimized for use with 48 V batteries like 12S to 14S Li-ion battery packs. The objective of designing a layout that is adapted for implementation inside a typical tube of a bicycle frame has been successfully met. The semi-cylindrical heatsink provided with REF_48V_270W_EBIKE accommodates installation of the board into a 30 mm inner diameter tube. Accurate fitting in alternative tube dimensions can be achieved with some adaptation of the heatsink shape.

The accompanying firmware uses sensor-based field-oriented or vector control utilizing three hall sensors, and measures phase currents in the low side source connection of each half bridge. The user can control the board via external analog signals controlling throttle and brake, or can alternatively control the board via PC connecting via the XMC™ Link debugger using the dedicated GUI. The PC connection also provides the user to set the various configuration parameters necessary to adapt the system to the properties of the motor and vehicle to be used.

The board has been successfully tested in various cases. Firstly, the gate driver switching properties had been set according to radiated emissions measurements (EMI). The corresponding performance tests were then carried out using the established parameters meeting the EMI criteria.

It is important to note that the EMI measurements should also be performed in the final system when the board is implemented inside the bicycle frame. At that point the configuration parameters can be reevaluated and adapted to the final design.

The 3.3 mm x 3.3 mm package of the IQE050N08NM5SC power MOSFET, has been proven to perform very successfully in the application. The board has been successfully tested for a continuous rating at loads up to 270 W at 11 A_{RMS} for up to 20 minutes while monitoring the maximum settling temperatures in order to assure performance requirements are met. The tests were performed without any forced convection, with the heatsink being placed on a flat surface of the bench, so to represent worst case heat extraction. It is expected that the moving e-Bike will further contribute to the heat dissipation efficiency, thus improving the performance even further.

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[5] EU standard: EN 15194:2017

Revision history

Document revision	Date	Description of changes
V 1.0	2024-11-12	Initial release

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