

USER GUIDE PRD-07560

CRD25DA12N-FMC 25 kW Three-Phase Inverter



This document is prepared as a user guide to install and operate Wolfspeed® evaluation hardware.

All parts of this user guide are provided in English, and the Cautions are provided in English, Mandarin, and Japanese. If the end user of this board is not fluent in any of these languages, it is your responsibility to ensure that they understand the terms and conditions described in this document, including without limitation the hazards of and safe operating conditions for this board.

本文件中的所有内容均以英文书写，“注意”部分的内容以英文、中文和日语书写。作为本板子的终端用户，即使您不熟悉上述任何一种语言，您也应当确保正确理解本文件中的条款与条件，包括且不限于本板子的危险隐患以及安全操作条款。

当書類のすべての内容は英語で書きます。「注意点」の内容は英語、中国語、また日本語で書きます。当ボードの端末使用者は上記の言語が一つでもわからないなら、当端末使用者は当書類の条約と条件が理解できるのを確保すべきです。そして、当ボードの危険や安全に使用する条件を含み、また限りません。

Note: This Wolfspeed-designed evaluation hardware for Wolfspeed components is a fragile, high-voltage, high-temperature power electronics system that is meant to be used as an evaluation tool in a lab setting and to be handled and operated by highly qualified technicians or engineers. When this hardware is not in use, it should be stored in an area that has a storage temperature ranging from -40° Celsius to 105° Celsius. If this hardware is transported, to avoid any damage to electronic components, special care should be taken during transportation to avoid damaging the board or its fragile components and the board should be transported carefully in an electrostatic discharge (ESD) bag, or with ESD or shorting protection that is the same as, or similar to, the protection that is or would be used by Wolfspeed when shipping this hardware. Please contact Wolfspeed at <https://forum.wolfspeed.com/> if you have any questions about the protection of this hardware during transportation. The hardware does not contain any hazardous substances, is not designed to meet any industrial, technical, or safety standards or classifications, and is not a production-qualified assembly.

本样机（易碎、高压、高温电力电子系统）由Wolfspeed为评估其功率半导体产品而设计，用以作为在实验室环境下由专业的技术人员或工程师处理和使用的评估工具。本样机不使用时，应存储在-40°~105°温度范围的区域内；如需运输样机，运输过程中应该特别小心，避免损坏电路板等易碎组件。如果您对此硬件在运输之中的保护有任何疑问，请联系<https://forum.wolfspeed.com/>。样机应放置在防静电包装袋内谨慎运输，避免损坏电子组件。本样机不含任何有害物质，但其设计不符合任何工业、技术或安全标准或分类，也不是可用于生产的组件。

このクリーのコンポーネント用評価ハードウェアは壊れやすい高電圧の高温パワーエレクトロニクスシステムであり、ラボ環境での評価ツールとして使用され、優秀な技術者やエンジニアによって処理され、操作されることを意図している。ハードウェアが使用されていない場合、保管温度が-40℃から105℃の範囲に保管してください。このハードウェアを輸送する場合は、輸送中にボードまたはその壊れやすいコンポーネントに損傷を与えないよう特別な注意を払う必要がある。また電子部品の損傷を避けるためにボードを静電気放電（ESD）袋に静置して慎重に輸送すべき。ハードウェアの輸送中の保護について質問があれば、<https://forum.wolfspeed.com/>に連絡してください。ハードウェアには危険物質が含まれていないが、工業的、技術的、安全性の基準または分類に適合するように設計されておらず、生産適格組立品でもない。



CAUTION

PLEASE CAREFULLY REVIEW THE FOLLOWING PAGES, AS THEY CONTAIN IMPORTANT INFORMATION REGARDING THE HAZARDS AND SAFE OPERATING REQUIREMENTS RELATED TO THE HANDLING AND USE OF THIS BOARD.

DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD. THERE CAN BE VERY HIGH VOLTAGES PRESENT ON THIS EVALUATION BOARD WHEN CONNECTED TO AN ELECTRICAL SOURCE, AND SOME COMPONENTS ON THIS BOARD CAN REACH TEMPERATURES ABOVE 50° CELSIUS. FURTHER, THESE CONDITIONS WILL CONTINUE FOR A SHORT TIME AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED.

Please ensure that appropriate safety procedures are followed when operating this board, as any of the following can occur if you handle or use this board without following proper safety precautions:

DEATH ▲ SERIOUS INJURY ▲ ELECTROCUTION ▲ ELECTRICAL SHOCK ▲ ELECTRICAL BURNS ▲ SEVERE HEAT BURNS

You must read this document in its entirety before operating this board. It is not necessary for you to touch the board while it is energized. All test and measurement probes or attachments must be attached before the board is energized. You must never leave this board unattended or handle it when energized, and you must always ensure that all bulk capacitors have completely discharged prior to handling the board. Do not change the devices to be tested until the board is disconnected from the electrical source and the bulk capacitors have fully discharged.

警告

请认真阅读以下内容，因为其中包含了处理和使用本板子有关的危险隐患和安全操作要求方面的重要信息。

请勿在通电情况下接触板子，在操作板子前应使大容量电容器的电荷完全释放。接通电源后，该评估板上通常会存在危险的高电压，板子上一些组件的温度可能超过 50 摄氏度。此外，移除电源后，上述情况可能会短时持续，直至大容量电容器电量完全释放。

操作板子时应确保遵守正确的安全规程，否则可能会出现下列危险：

死亡 ▲ 严重伤害 ▲ 触电 ▲ 电击 ▲ 电灼伤 ▲ 严重的热烧伤

请在操作本板子前完整阅读本文档。通电时禁止接触板子。所有测试与测量探针或附件必须在板子通电前连接。通电时，禁止使板子处于无人看护状态，且禁止操作板子。必须确保在操作板子前，大容量电容器已释放了所有电量。只有在切断板子电源，且大容量电容器完全放电后，才可更换待测试器件。

警告

ボードの使用、危険の対応、そして安全に操作する要求などの大切な情報を含むので、以下の内容をよく読んでください。

通電している時、ボードに接触するのは禁止です。ボードを処分する前に、大容量のコンデンサーで電力を完全に釈放すべきです。通電してから、ボードにひどく高い電圧が存在している可能性があります。ボードのモジュールの温度は 50 度以上になるかもしれません。また、電源を切った後、上記の状況がしばらく持続する可能性がありますので、大容量のコンデンサーで電力を完全に釈放するまで待ってください。

ボードを操作するとき、正確な安全ルールを守るのを確保すべきです。さもないと、以下の危険がある可能性があります：

死亡 ▲ 重症 ▲ 感電 ▲ 電撃 ▲ 電気の火傷 ▲ 厳しい火傷

当ボードを操作する前に、完全に当書類をよく読んでください。通電している時にボードに接触する必要がありません。通電する前に必ずすべての試験用のプローブあるいはアクセサリをつないでください。通電している時に無人監視やボードを操作するのは禁止です。ボードを操作する前に、大容量のコンデンサーで電力を完全に釈放するのを必ず確保してください。ボードの電源を切った後、また大容量のコンデンサーで電力を完全に釈放した後、試験設備を取り換えることができます。

CONTENTS

1. INTRODUCTION	6
2. DESIGN FEATURES	7
2.1 Key System Specifications	7
2.2 Subsystem Functional Groups.....	8
2.3 I/O Pinout.....	10
2.3.1 Aux Power Connector Pinout	10
2.3.2 High Power Terminals.....	11
2.3.3 Voltage Feedback Connector Pinout.....	11
2.3.4 CAN Port Pinout	11
2.3.5 Resolver Connector Pinout.....	12
2.3.6 Relay Connector Pinout.....	13
2.3.7 Spare Connector Pinout	14
2.3.8 Metrology	15
3. SYSTEM DESCRIPTION	17
3.1 Power Stage.....	18
3.2 Gate Drivers	21
3.3 Current Sensing	22
3.4 Voltage Sensing	24
3.5 NTC.....	26
3.6 Position Sensing.....	26
3.7 Additional Circuitry	28
4. CONTROLLER AND FIRMWARE.....	30
4.1 Microcontroller	30
4.2 Firmware	34
4.2.1 Code Composer Studio Project	34
4.2.2 CAN Communication GUI.....	36
5. PERFORMANCE DATA.....	38
5.1 Heatsink.....	38
5.2 Inductance.....	39
5.3 Experimental Validation.....	40
5.3.1 Setup	40

5.3.2 Experimental Results	41
5.3.3 Thermal Safe Operating Area	43
5.4 Simulation	44
5.4.1 Power Stage	45
5.4.2 Controller	46
5.4.3 Load	46
5.4.4 Performance Monitor	47
5.4.5 Default Parameters	48
5.4.6 Validation	49
5.4.7 Efficiency Predictions	51
6. MECHANICAL ASSEMBLY	52

1. INTRODUCTION

This user guide provides an overview of the Wolfspeed CRD25DA12N-FMC 25 kW three-phase inverter reference design including key system specifications, sub-system functional descriptions, performance test data, and mechanical assembly. The CRD25DA12N-FMC design was developed to provide power electronics engineers with a hardware evaluation platform and reference design files to support early design-in activities of the Wolfspeed WolfPACK™ baseplate-less power module platform. In conjunction with this user guide, the complete suite of reference design files including schematics, PCB layout, Gerber files, BOM, and 3D CAD files are available for download from the [CRD25DA12N-FMC landing page](#) on Wolfspeed's website.

The CRD25DA12N-FMC is a complete, easy-to-use, flexible power stage designed around the CCB021M12FM3T (1200 V / 21 mΩ) Wolfspeed WolfPACK six-pack power module. As demonstrated in the block diagram below, this design intends to provide everything needed to quickly evaluate performance out of the box while also providing the resources to expand its capabilities to suit target end-application needs. To this end, included on this single-PCB solution is DC bus capacitance with low-inductance power planes, gate drivers, current and voltage sensing, thermal management, and various control peripherals.

By default, the CRD25DA12N-FMC is designed to be evaluated as a simple three-phase inverter topology, but the flexibility of the generic power stage makes it simple to adapt to other applications. As such, the design is ideal for evaluating or scaling up to higher power levels in industrial motor drives, power supplies, and renewable energy applications, or as the bi-directional active front end (AFE) stage for off-board electric vehicle (EV) fast charging.

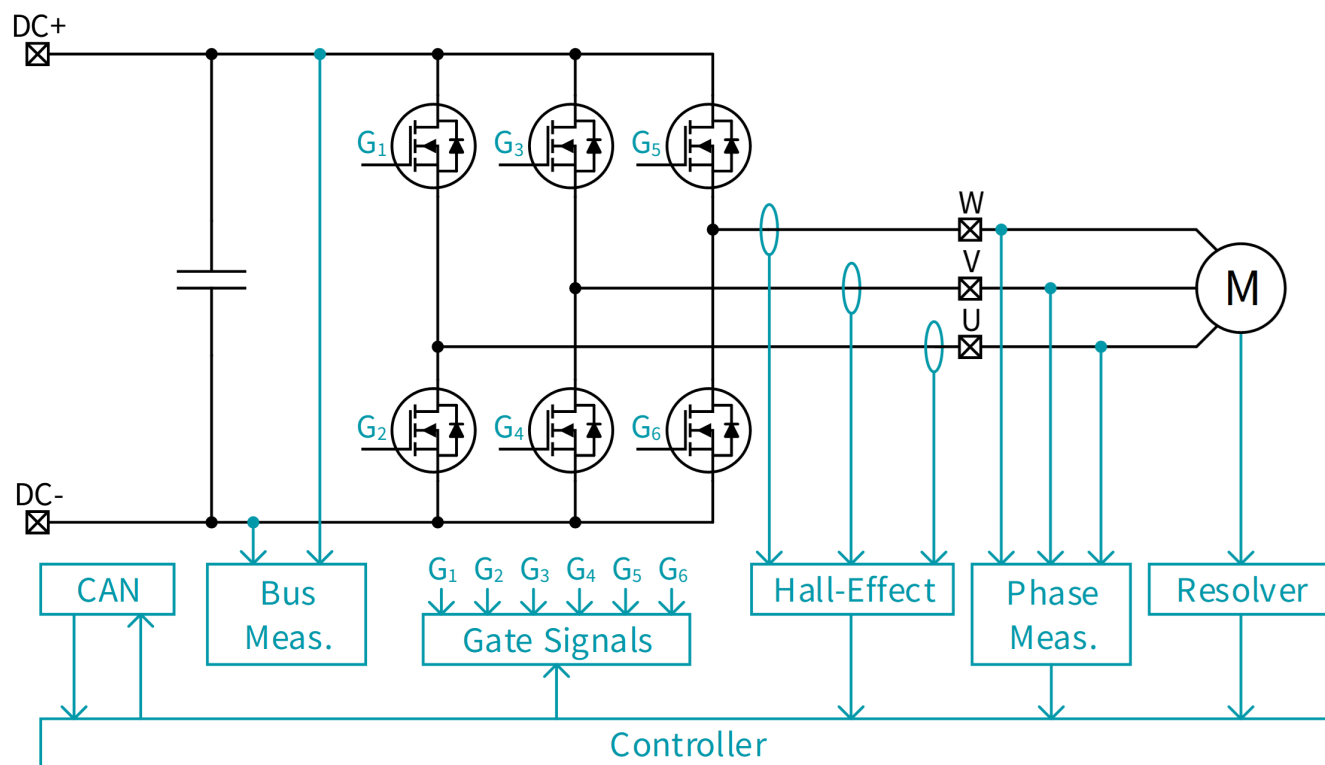


Figure 1: CRD25DA12N-FMC Block Diagram

2. DESIGN FEATURES

This section highlights the design features of the CRD25DA12N-FMC design including key system specifications, a description of the various functional circuit groups, and a general I/O pinout definition.

2.1 Key System Specifications

- Single CCB021M12FM3T (1200 V / 21 mΩ) Wolfspeed WolfPACK six-pack power module
- General purpose controller with customizable firmware
- Integrated hall-effect current measurements
- Integrated resolver circuitry for rotational position feedback
- Isolated substrate temperature measurement
- Isolated CAN communication for real-time monitoring and adjustments
- Separate turn-on and turn-off gate resistors for switching loss optimization
- DC bus and phase voltage measurement circuitry
- Dedicated overcurrent detection hardware
- Spare GPIO and ADC header pins for adding custom auxiliary hardware
- Spare LEDs for customization during testing and evaluation
- Controllable current amplifier for operating external relays
- Detailed characterization of the thermal solution for improved simulation predictions
- Integrated gate measurement connectors for easy system troubleshooting and evaluation

Table 1: CRD25DA12N-FMC Ratings

Symbol	Parameter	Min.	Typ.	Max.	Unit
P_{OUT}	Output Power	—	—	25	kW
V_{DC}	DC Bus Voltage	—	800	1000	V
V_{AUX}	Low-Power Auxiliary Voltage	10.8	12	13.2	
I_{AUX}	Low-Power Auxiliary Current	—	—	5	A
I_{OUT}	Output Phase Current	—	—	30	A_{RMS}
f_s	Switching Frequency ¹	—	20	100	kHz
$R_{th,ja}$	Thermal Resistance, Junction-to-Ambient ¹		1.571		°C/W

¹Refer to Performance Data section for more information

2.2 Subsystem Functional Groups

The figures below show the subsystem functional groups of the evaluation board from a top and side profile view with descriptions of each labeled subsystem given in Table 2. A full system description of each functional group is provided in Section 3.

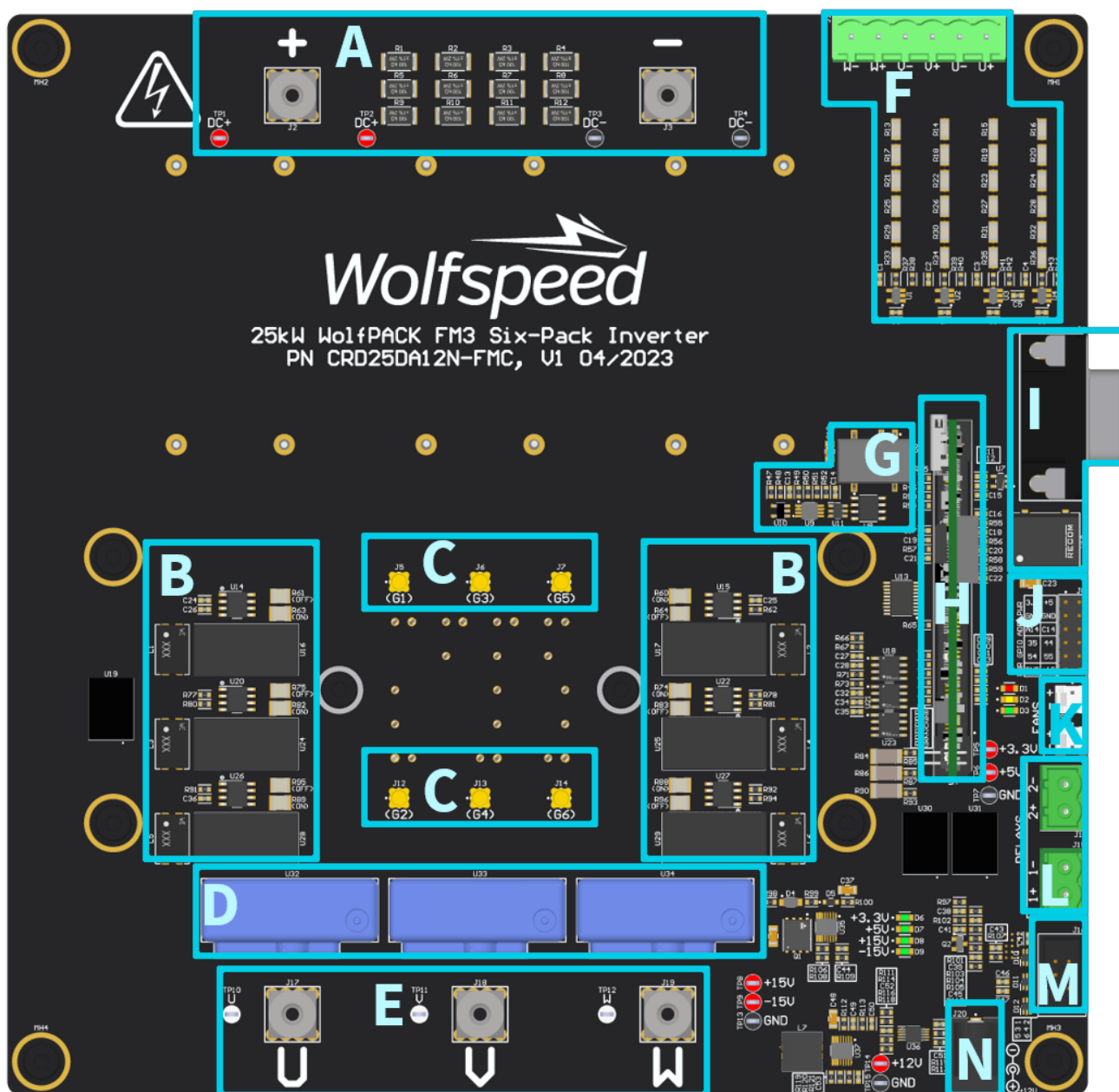


Figure 2: CRD25DA12N-FMC Top View

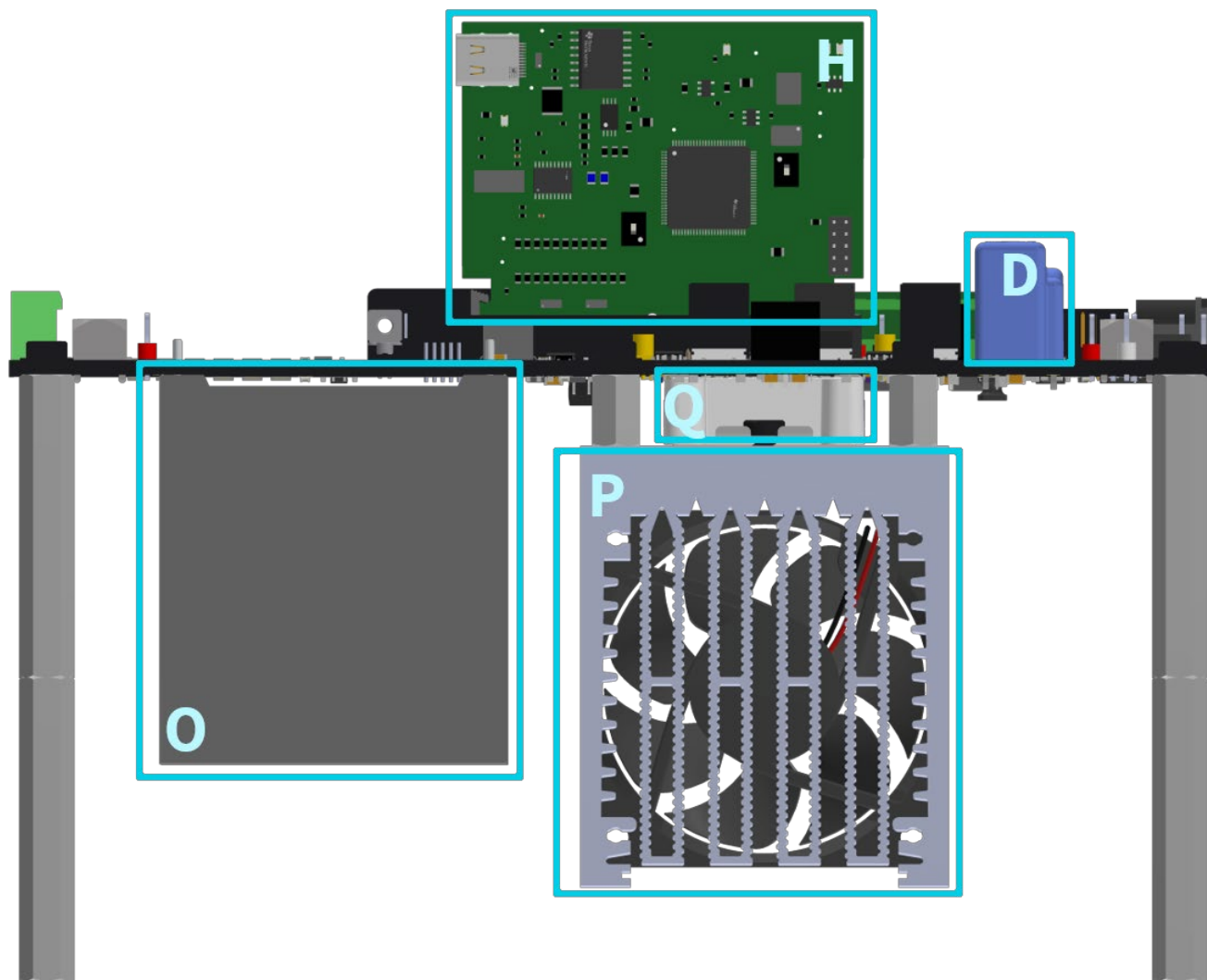


Figure 3: CRD25DA12N-FMC Side View

Table 2: Subsystem Functional Group Descriptions

Label	Description
A	Input DC Voltage Terminals
B	MOSFET Gate Drivers
C	Gate Measurements
D	Current Sensors
E	Output AC Voltage Terminals
F	Phase Voltage Feedback
G	Isolated NTC Circuit

Label	Description
H	F280039C Control Card
I	Isolated CAN Port
J	Spare ADCs and GPIOs
K	Fan Power
L	Relay Control
M	Encoder Feedback
N	+12V Input Power
O	Bulk DC-Link Capacitor
P	Heatsink + Fan Assembly
Q	CCB032M12FM3 WolfPACK Module

2.3 I/O Pinout

The design features a variety of ports for connecting external sensors, controlling external hardware, and communicating directly with the onboard controller. Each of these interfaces will be discussed in the later sections of this document. This section provides a quick reference to the pinouts of the various ports.

2.3.1 Aux Power Connector Pinout

The controller and auxiliary low-voltage hardware are powered from an external +12V supply. The power is applied through a CUI Devices® PJ-102AH barrel connector with the pinout shown in. The recommended mating connector is CUI Devices PP3-002A.

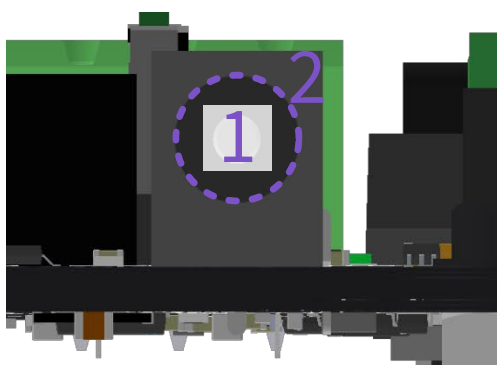


Figure 4: J20 Input Power Connector Pin Numbers

Table 3: J20 Input Power Connector Pinout

Pin #	Name	Type	Description
1	+12V	Power	+12V Power
2	GND	Power	Ground

2.3.2 High Power Terminals

The high-power input DC bus and output phase connections are made through Würth Elektronik® 7460307 terminals. These terminals include internal M4 threads to support mounting high-power wires or bus bars directly to the terminals with M4 screws.

2.3.3 Voltage Feedback Connector Pinout

The voltage feedback uses a Phoenix Contact® 1755778 connector with the pinout shown below. The recommended mating connector is either Phoenix Contact 1792799 or Phoenix Contact 1757051, depending on the desired orientation of the wires. Using Phoenix Contact 1792799 results in wires that are parallel with the circuit board and using Phoenix Contact 1757051 results in wires that are perpendicular to the circuit board.

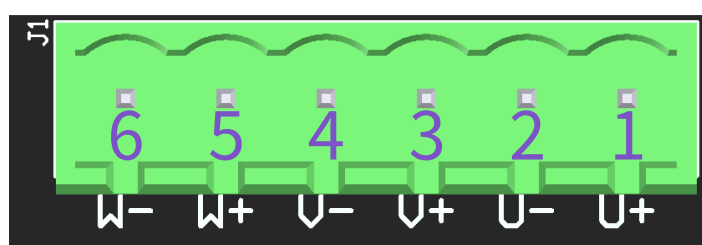


Figure 5: J1 Voltage Feedback Connector Pin Numbers

Table 4: J1 Voltage Feedback Connector Pinout

Pin #	Name	Type	Description
1	U+	Analog (I)	Positive Differential Phase U Voltage Feedback
2	U-	Analog (I)	Negative Differential Phase U Voltage Feedback
3	V+	Analog (I)	Positive Differential Phase V Voltage Feedback
4	V-	Analog (I)	Negative Differential Phase V Voltage Feedback
5	W+	Analog (I)	Positive Differential Phase W Voltage Feedback
6	W-	Analog (I)	Negative Differential Phase W Voltage Feedback

2.3.4 CAN Port Pinout

The isolated CAN port is a standard male DB9 connector (Amphenol® L717SDE09PA4CH4RC309) with the pinout shown in below. This CAN port can be mated with any standard DB9 female connector.

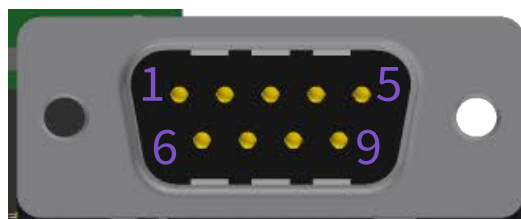


Figure 6: J4 CAN Port Pin Numbers

Table 5: J4 CAN Port Pinout

Pin #	Name	Type	Description
1	NC0	—	No Connect
2	CAN_L	Digital (I/O)	Isolated CAN Low
3	V-	Power	Isolated Ground
4	NC1	—	No Connect
5	SHLD	Power	Isolated Ground
6	O(V-)	—	No Connect
7	CAN_H	Digital (I/O)	Isolated CAN High
8	NC2	—	No Connect
9	V+	Power	Isolated +5V Power

2.3.5 Resolver Connector Pinout

The design includes circuitry to attach a resolver for mechanical position feedback. The connector is Würth Elektronik 61200621621 with the pinout shown below. Although any 0.1 in (2.54 mm) female header connector can be used to attach the resolver, it is recommended to use a connector with a matching shroud to ensure proper orientation when attaching the resolver.

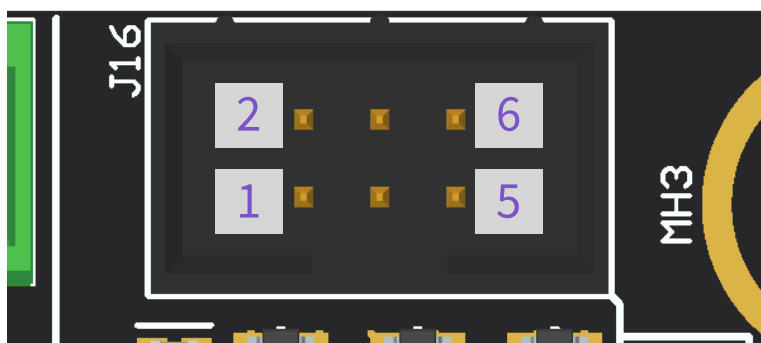


Figure 7: J16 Resolver Connector Pin Numbers

Table 6: J16 Resolver Connector Pinout

Pin #	Name	Type	Description
1	EXC_P	Digital (O)	Positive Differential Resolver Excitation Signal
2	EXC_N	Digital (O)	Negative Differential Resolver Excitation Signal
3	SIN_P	Analog (I)	Positive Differential Signal Resolver Sine Feedback
4	SIN_N	Analog (I)	Negative Differential Signal Resolver Sine Feedback
5	COS_P	Analog (I)	Positive Differential Signal Resolver Cosine Feedback
6	COS_N	Analog (I)	Negative Differential Signal Resolver Cosine Feedback

2.3.6 Relay Connector Pinout

The design includes circuitry to drive external relays. The connectors for these relays are Phoenix Contact 1755778 with the pinout shown below. The recommended mating connector is either Phoenix Contact 1792757 or Phoenix Contact 1754449, depending on the desired orientation of the wires. Using Phoenix Contact 1792757 results in wires that are parallel with the circuit board, and using Phoenix Contact 1754449 results in wires that are perpendicular to the circuit board.

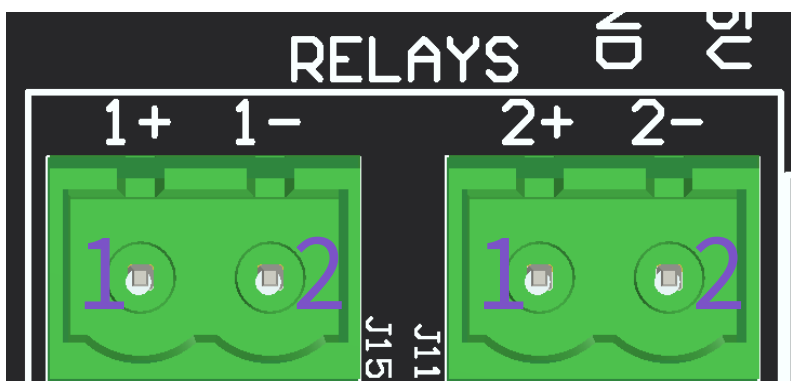


Figure 8: J11 and J15 Relay Connector Pin Numbers

Table 7: J11 and J15 Relay Connector Pinout

Pin #	Name	Type	Description
1	+12V	Power	+12V Power
2	GND	Power	Controlled Ground

2.3.7 Spare Connector Pinout

The design includes spare input/output pins which are connected directly to the controller following the pinout shown below. The connector part number is Würth Elektronik 61301221121. The headers use standard 0.1 in (2.54 mm) spacing between the pins, so any female header pins with this spacing can be used for mating.

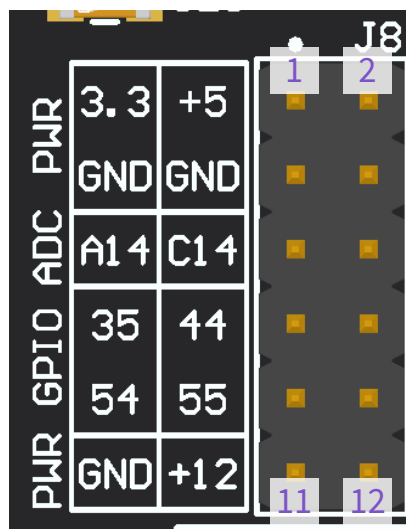


Figure 9: J8 Spare Connector Pin Numbers

Table 8: J8 Spare Connector Pinout

Pin #	Name	Type	Description
1	+3.3V	Power	+3.3V Power
2	+5V	Power	+5V Power
3	GND	Power	Ground
4	GND	Power	Ground
5	A14	Analog (I)	Connected to Controller Analog A14
6	C14	Analog (I)	Connected to Controller Analog C14
7	GPIO35	Digital (I/O)	Connected to Controller GPIO35
8	GPIO44	Digital (I/O)	Connected to Controller GPIO44
9	GPIO54	Digital (I/O)	Connected to Controller GPIO54
10	GPIO55	Digital (I/O)	Connected to Controller GPIO55
11	GND	Power	Ground
12	+12V	Power	+12V Power

2.3.8 Metrology

This design includes a variety of test points and probe connection points to measure various signals on the board in order to evaluate the design and test various control schemes.

To measure the gate signals, each of the six MOSFETs are connected to a dedicated MMCX connector, which are connected across the MOSFET gate and source terminals. These measurements use Molex® 0734151471 connectors and are in the locations shown below. These are standard MMCX connectors intended to be monitored directly with an oscilloscope probe. Notably, during system operation, the gate measurements can float at the full bus voltage. Therefore, the gate measurements should not be monitored using single-ended oscilloscope probes due to the safety risks of high-voltage potentials being applied to the oscilloscope reference. It is recommended to perform these gate measurements with high-isolation probes such as the Tektronix® IsoVu™ series of probes.

The design also includes several through-hole test points to measure the high-power connections and the low-power voltage rails. These test points are in the physical locations indicated in the figure below and are connected to the signals described in Table 9. The test points can be used to perform a variety of measurements such as measuring the output phase voltages, the DC-bus voltage, and/or the auxiliary power rails.

Table 9: Test Point Descriptions

Ref Designator	Signal	Color	Description
TP1	DC+	Red	Positive DC-Link Voltage
TP2	DC+	Red	Positive DC-Link Voltage
TP3	DC-	Black	Negative DC-Link Voltage
TP4	DC-	Black	Negative DC-Link Voltage
TP5	+3.3V	Red	+3.3V Power
TP6	+5V	Red	+5V Power
TP7	GND	Black	Ground
TP8	+15V	Red	+15V Power
TP9	-15V	Red	-15V Power
TP10	U_OUT	White	U Phase
TP11	V_OUT	White	V Phase
TP12	W_OUT	White	W Phase
TP13	GND	Black	Ground
TP14	+12V	Red	+12V Power
TP15	GND	Black	Ground

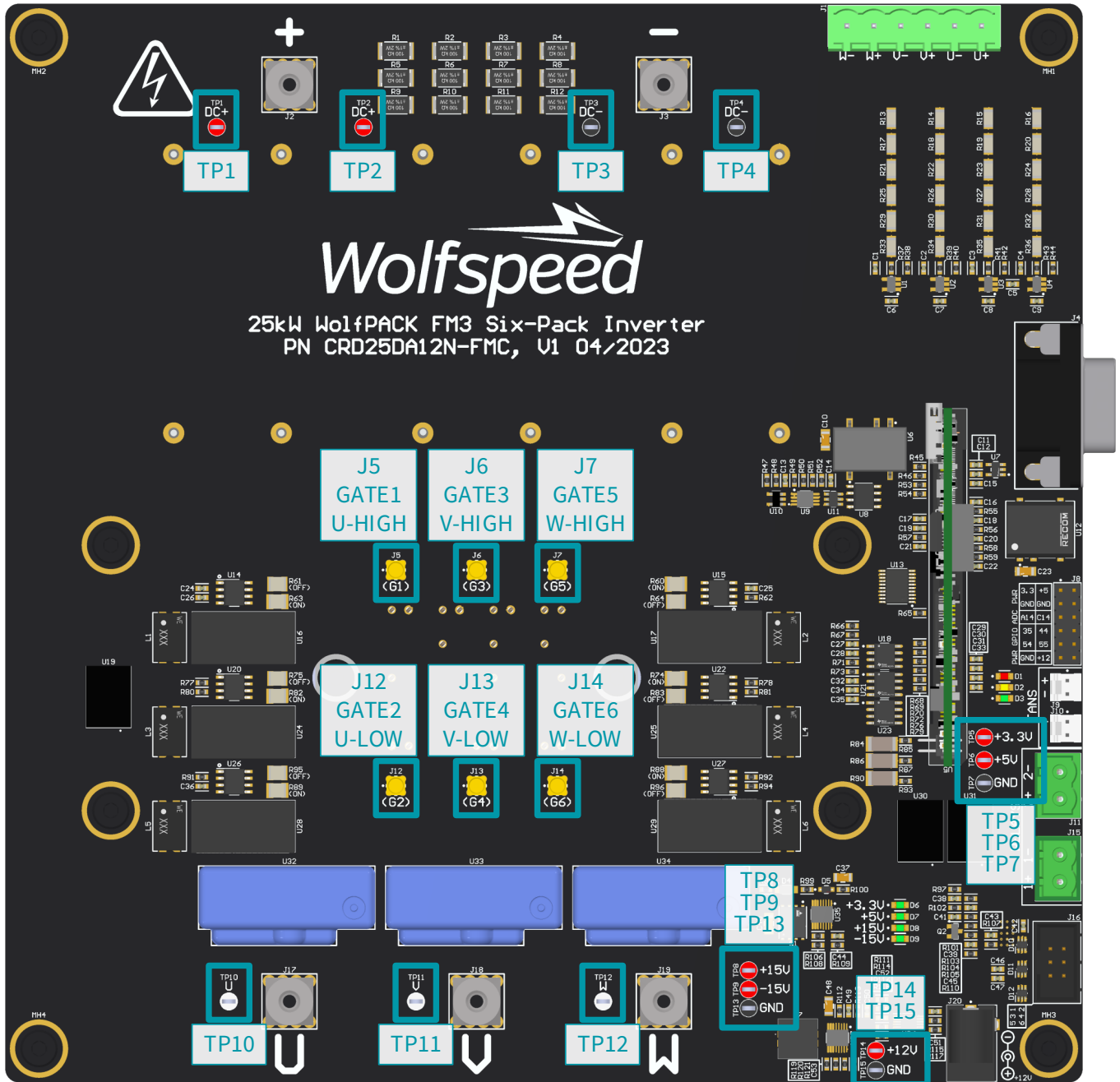


Figure 10: Gate and Test Point Measurement Locations

3. SYSTEM DESCRIPTION



CAUTION

IT IS NOT NECESSARY FOR YOU TO TOUCH THE BOARD WHILE IT IS ENERGIZED. WHEN DEVICES ARE BEING ATTACHED FOR TESTING, THE BOARD MUST BE DISCONNECTED FROM THE ELECTRICAL SOURCE AND ALL BULK CAPACITORS MUST BE FULLY DISCHARGED.

SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50° CELSIUS. THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED. DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD.

PLEASE ENSURE THAT APPROPRIATE SAFETY PROCEDURES ARE FOLLOWED WHEN OPERATING THIS BOARD AS SERIOUS INJURY, INCLUDING DEATH BY ELECTROCUTION OR SERIOUS INJURY BY ELECTRICAL SHOCK OR ELECTRICAL BURNS, CAN OCCUR IF YOU DO NOT FOLLOW PROPER SAFETY PRECAUTIONS.

警告

通电时不必接触板子。连接器件进行测试时，必须切断板子电源，且大容量电容器必须释放完所有电荷。

板子上一些组件的温度可能超过 50 摄氏度。移除电源后，上述情况可能会短暂持续，直至大容量电容器完全释放电荷。通电时禁止触摸板子，应在大容量电容器完全释放电荷后，再操作电路板。

请确保在操作电路板时已经遵守了正确的安全规程，否则可能会造成严重伤害，包括触电死亡、电击伤害、或电灼伤。大容量电容器已释放了所有电量。只有在切断板子电源，且大容量电容器完全放电后，才可更换待测试器件。

警告

通电している時にボードに接触する必要がありません。設備をつないで試験する時、必ずボードの電源を切ってください。また、大容量のコンデンサーで電力を完全に釈放してください。

ボードのモジュールの温度は 50 度以上になるかもしれません。電源を切った後、上記の状況がしばらく持続する可能性がありますので、大容量のコンデンサーで電力を完全に釈放するまで待ってください。通电している時にボードに接触するのは禁止です。大容量のコンデンサーで電力をまだ完全に釈放していない時、ボードを操作しないでください。

ボードを操作している時、正確な安全ルールを守っているのを確保してください。さもなければ、感電、電撃、厳しい火傷などの死傷が出る可能性があります。

3.1 Power Stage

The power stage of this design uses three 65 μF low-inductance capacitors in parallel to form a total of 195 μF of DC-link capacitance. The capacitors used are KEMET® C4AQQEW5650A3BJ film capacitors with a voltage rating of 1.1 kV. They are charged through the input DC terminals and connect directly to the DC+ and DC- terminals of the power module using low-inductance copper pours. The DC-link capacitor circuitry and the connections to the power module are shown in the figures below. The printed circuit board used in this design features interleaved DC+ and DC- copper layers to increase the flux cancellation between layers and reduce the inductance between the capacitors and the power module input pins. The interleaved layers are indicated in the stack-up shown in Table 10, which shows the signals/planes on each circuit board layer in the area around the DC bus.

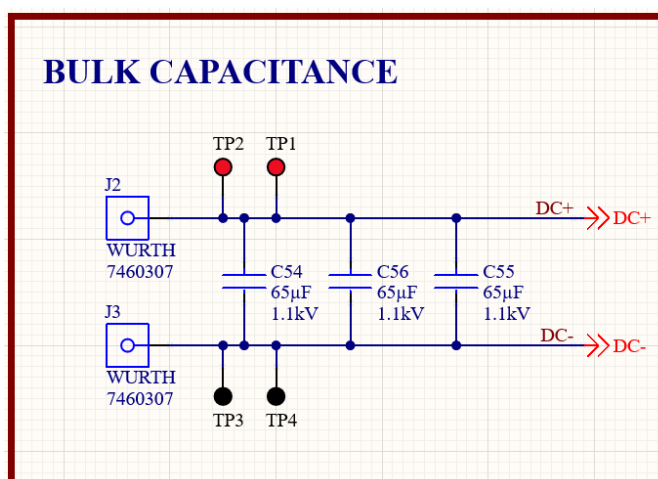


Figure 11: DC Bus Circuitry

Table 10: DC Bus Printed Circuit Board Layer Stack-up

Layer #	Primary Signals
1	Gate
2	Source
3	DC-
4	DC+
5	DC-
6	DC+

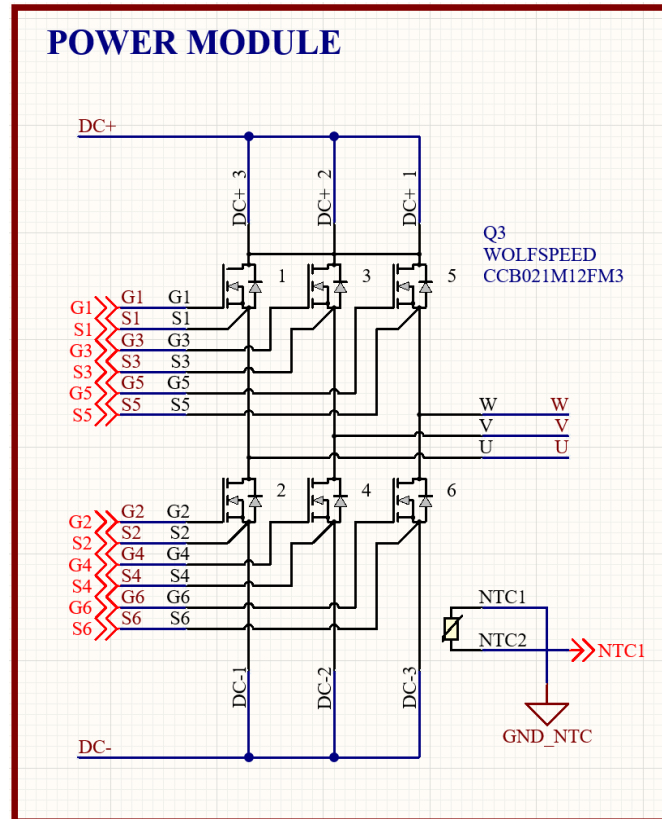


Figure 12: Wolfspeed CCB021M12FM3T Power Module Circuit Connections

To ensure that the system is stored at a safe touch potential, the design includes bleed resistors which discharge the bus to less than 50 V in under 3 minutes when input voltage is removed from the system. These resistors are connected to the DC bus at all times to ensure the bus is always depleted after system shut down. The circuit bleed resistors are shown below.

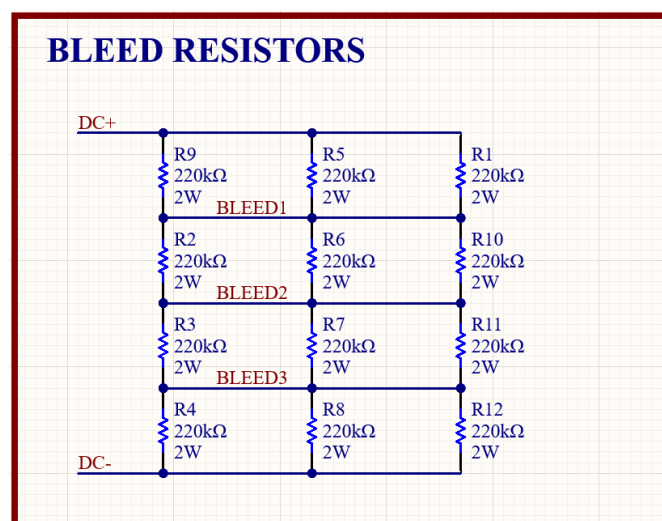


Figure 13: Bleed Resistors Connected to DC Bus

The output of each phase is independently measured with a hall-effect current transducer between the power module and the output power terminals of the PCB, as shown below. These connections feature wide copper pours to minimize inductance and maximize ampacity. These measurements provide feedback to the controller for detecting overcurrent events and for close-loop system control. These sensors and the corresponding measurement circuitry are discussed in more detail in the Current Sensing section of this document.

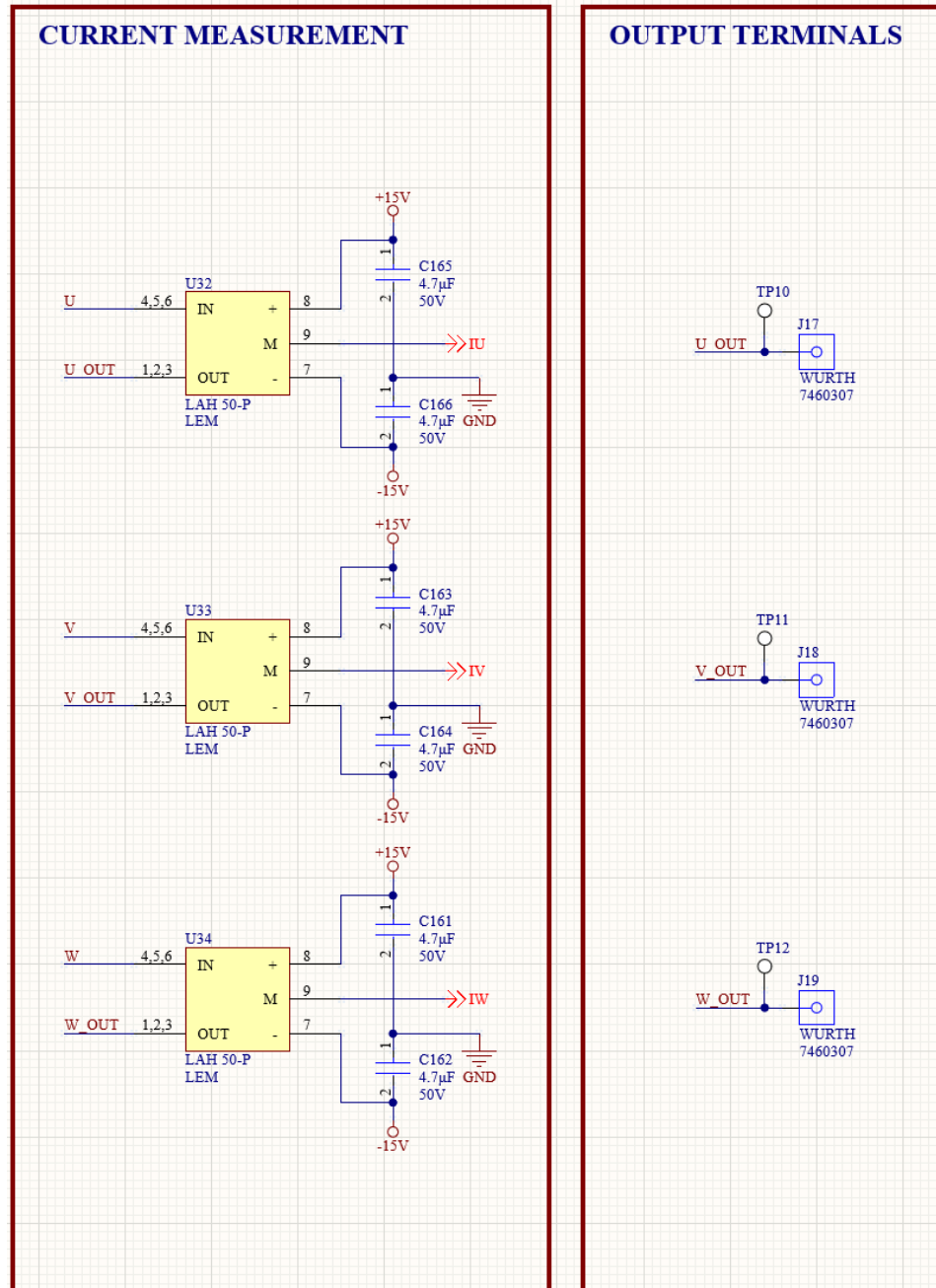


Figure 14: Output Hall-Effect Sensor Power Connections

3.2 Gate Drivers

Each of the MOSFET switch positions is driven with a dedicated power supply and gate driver integrated circuit (IC), both of which have continuous isolation barriers of over 2 kV. The circuit for one switch position is shown in the figure below. To prevent undesired coupling, there is an isolation gap between the controller signals and the high-voltage MOSFET connections. No copper crosses this isolation barrier, and the only components which cross the barrier are the isolated power supplies and gate driver ICs. The power supplies generate the isolated +15 V and -3 V rails required to properly bias the MOSFET gates and enough power to drive the MOSFETs at high switching frequencies.

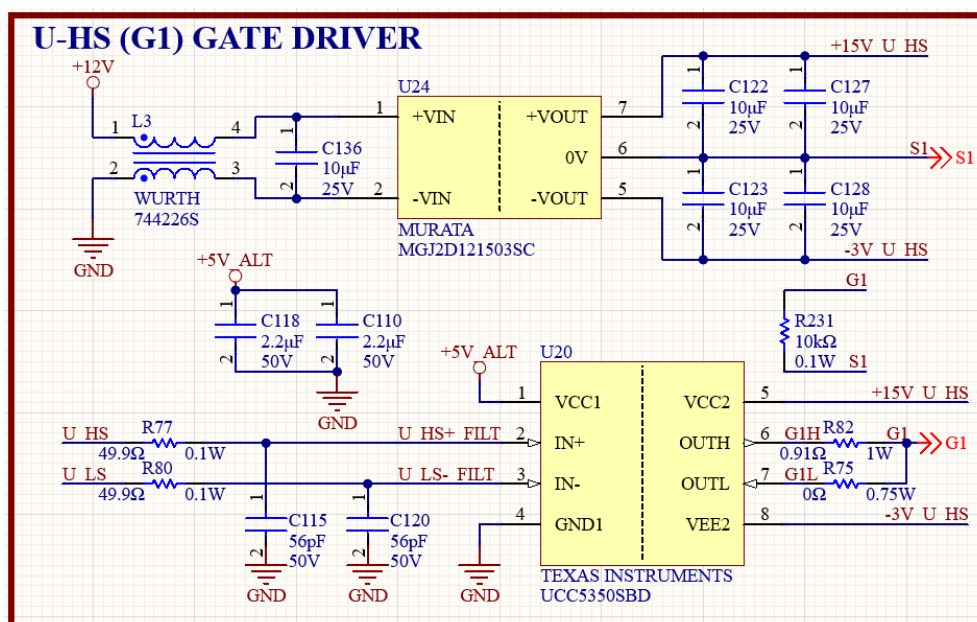


Figure 15: Gate Driver Circuit for One MOSFET Switch Position

For the gate driver IC, the design uses the Texas Instruments® UCC5350SBD isolated gate driver, which has a sink/source drive strength of ± 5 A. The selected gate driver IC includes a split output capable of sinking/sourcing current through separate turn-on and turn-off gate resistor. The split output allows users to independently optimize the turn-on and turn-off switching losses and edge rates. In traditional single output circuits, the same gate resistor must be used for both transition states, which could result in increased switching losses. By default, this design employs a $0.91\ \Omega$ turn-on resistor and a $0\ \Omega$ turn-off resistor, though these values can easily be changed by a user to reach the desired performance targets. The gate driver circuit includes input signal interlocks which prevent the IC from turning on when the high-side and low-side switch positions are simultaneously commanded on. This feature enables users to confidently evaluate prototype control software without the risk of shoot-through due to command errors from the controller. The gate driver IC also includes other built-in functionalities such as undervoltage lockout, low propagation delay, and high common-mode transient immunity. Some of the general specifications of the gate driver used in this design are shown in Table 11, and more details about the built-in features of the gate driver IC can be found in the Texas Instruments UCC5350SBD datasheet.

Table 11: Gate Driver Operating Parameters

Symbol	Parameter	Min.	Typ.	Max.	Unit
P_{DRIVE}	Power Per Gate Driver ¹	—	—	1.7	W
I_O	Output Peak Current ($T_A = 25\text{ }^{\circ}\text{C}$)	—	—	± 5	A
$V_{GATE,HIGH}$	High Level Output Voltage	—	15	—	V
$V_{GATE,LOW}$	Low Level Output Voltage	—	-3	—	
$R_{G(EXT)-ON}$	External Turn-On Resistance	—	0.91	—	Ω
$R_{G(EXT)-OFF}$	External Turn-Off Resistance	—	0	—	

¹ The gate driver power supply can be populated with Murata Power Solutions Inc. MGJ2D121503SC or with RECOM R12P21503D. This rating is the worse-case value of the two options.

3.3 Current Sensing

Each phase output of this design is directly measured using LEM® LAH 50-P closed-loop hall-effect transducers capable of measuring up to 50 ARMS with a rated bandwidth of 200 kHz. These sensors can be employed for custom closed-loop control schemes and/or overcurrent protection. The LEM LAH 50-P transducer has an insulation voltage rating of 1000 V between the primary and secondary circuits, enabling this sensor to be employed without requiring additional isolation. These sensors output a proportional current rather than a proportional voltage since an output current signal has improved immunity against electrical noise. Additionally, compared to open-loop transducers, closed-loop transducers are favored due to their higher accuracy and lower temperature drift. The maximum output phase current of this design is 30 ARMS which is safely within the operating range of the selected sensors. In order to drive these hall-effect sensors, this design includes bipolar $\pm 15\text{ V}$ power rails which power the sensors. The power connections for one of the hall-effect transducers are shown below.

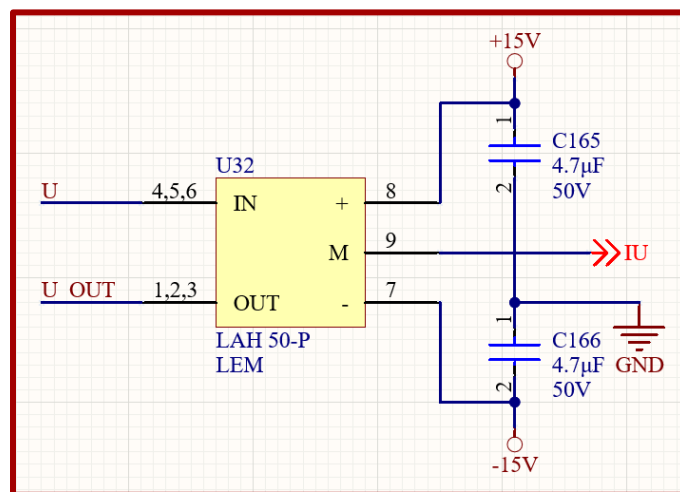


Figure 16: Hall-Effect Transducer Power Connections

The current signal output from the hall-effect transducers is converted to a voltage, filtered, and scaled before being sensed with dedicated analog-to-digital converter (ADC) inputs on the controller. The voltage conditioning for the current sensors is shown in the figures below.

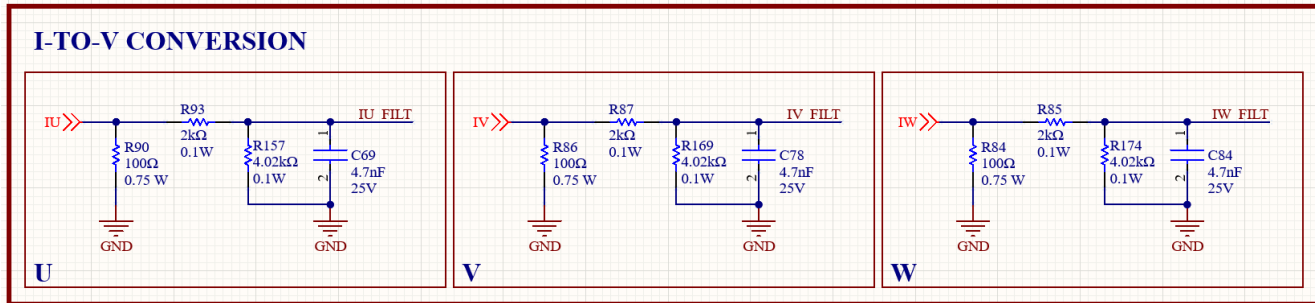


Figure 17: Current Measurement Conversion to Voltage and Filtering

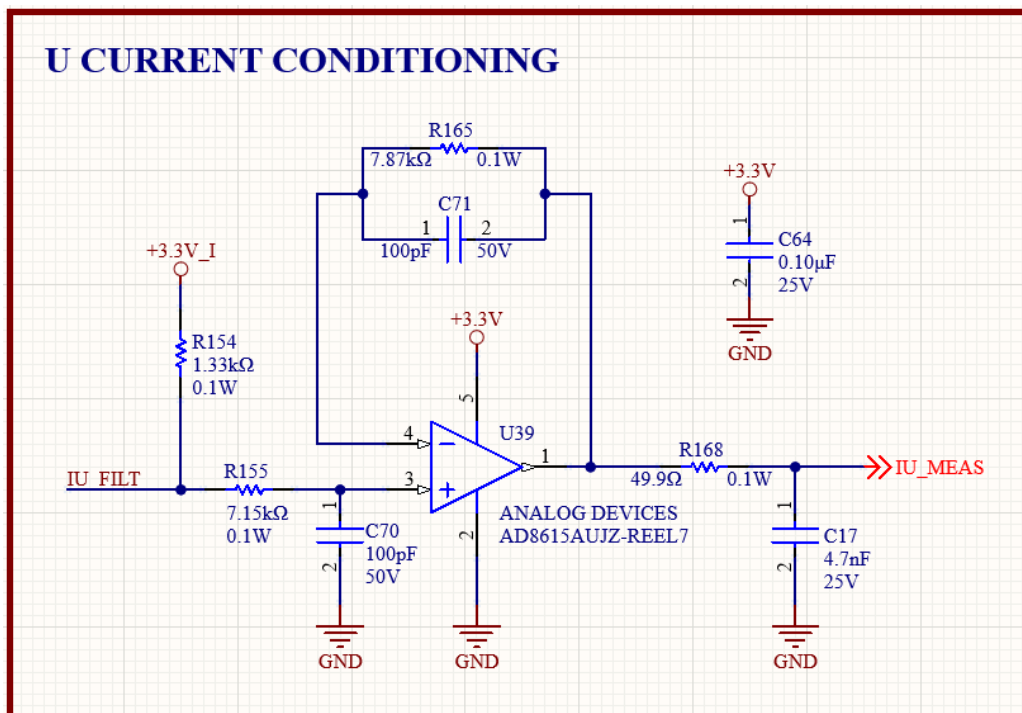


Figure 18: Current Measurement Conditioning

In addition to the ADC measurements, the filtered current signals are also connected directly to comparators for detecting overcurrent events (both positive and negative magnitude currents). This circuitry enables users to shut the system down if the system enters an unsafe or undesired operating condition. Notably, the overcurrent detection could instead be employed using the controller ADC measurements. These hardware-defined overcurrent circuits enable users to evaluate alternative approaches when computing power and/or available input pins are limited. An example of the overcurrent detection circuit for one phase is shown below. The overcurrent trip limits can be adjusted by varying the reference resistors, R66, R67, R71, and R73 shown in the reference voltage circuit below.

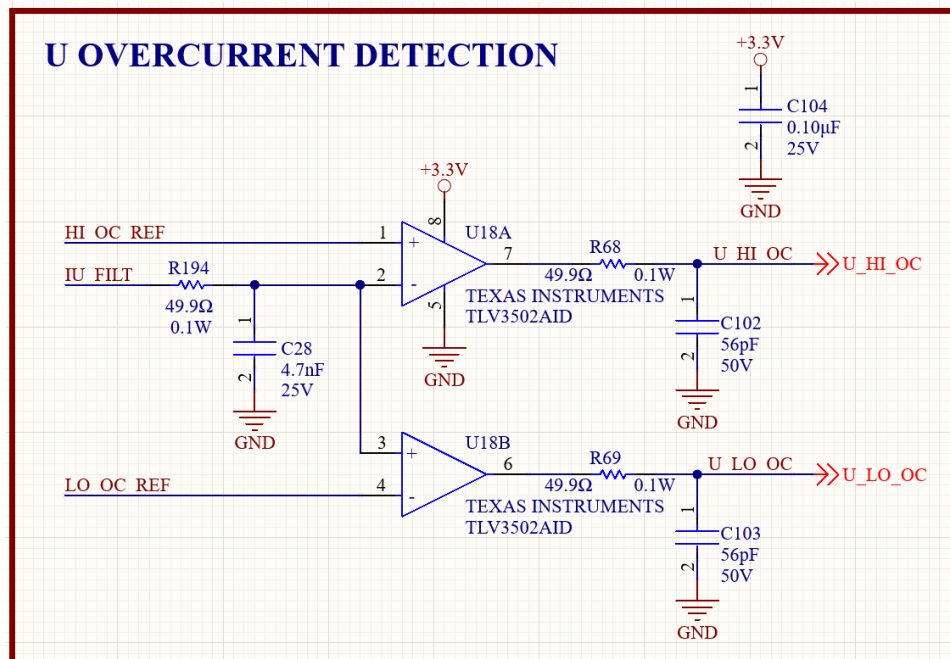


Figure 19: Overcurrent Detection Circuit

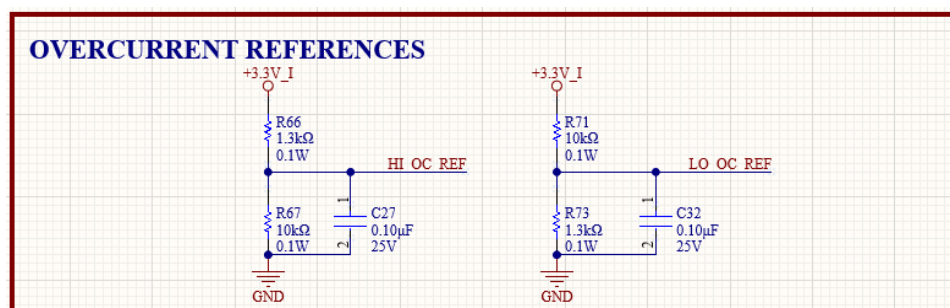


Figure 20: Overcurrent Trip References

3.4 Voltage Sensing

The design includes the built-in hardware necessary to perform differential voltage measurements of the DC bus. These connections are included on the circuit by default, so users do not need to add any hardware connections for this functionality. In many configurations, this DC bus measurement can be paired with the phase current measurements to operate the design in closed-loop mode. The DC voltage conditioning circuit is shown below.

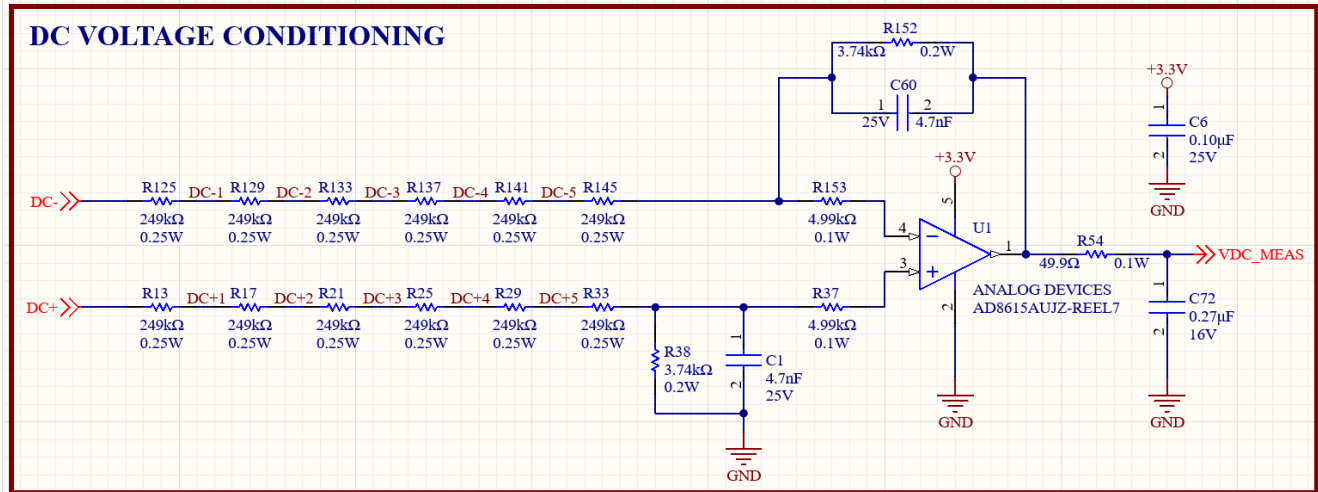


Figure 21: Differential DC Voltage Conditioning

For control schemes where phase voltages are required, the design also includes the hardware necessary to perform differential voltage measurements of the output signals. These differential inputs can be placed close to the target load and can measure the output voltage as line-to-line or line-to-neutral. These measurements have multiple target use cases depending on the application. For example, these measurements can be used to directly monitor the voltages applied to the terminals of a motor. Alternatively, the feedback voltage signals could be used to measure input line voltages if this design is utilized as a building block for an active front end (AFE). These phase voltage measurements are not required in many control schemes but are included for users who want to evaluate control schemes which require them. The voltage conditioning circuit for one phase is shown below.

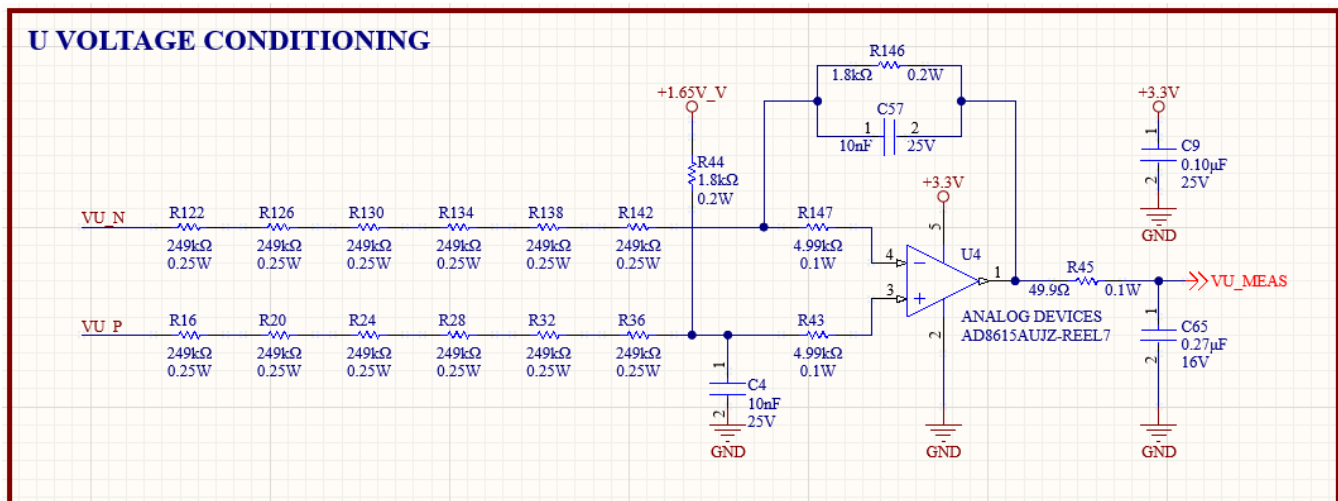


Figure 22: Differential Phase Voltage Conditioning

3.5 NTC

The CCB021M12FM3T power module used in this design includes a negative temperature coefficient (NTC) sensor for monitoring the substrate temperature inside the module. While this temperature is not the junction temperature of the MOSFETs, this measurement can be employed to estimate the device temperatures and detect problematic operating conditions. This design has provisions to directly measure the power module NTC. The circuit converts the voltage to a digital 50 kHz pulse-width modulated (PWM) signal with varying duty cycle. The PWM signal is processed through a digital isolator and the output signal can be directly measured by the controller. The duty cycle varies depending on the measured NTC temperature and follows

$$T_{NTC} = -(4.26587 \times 10^{-4})d^3 + 0.0607083d^2 - 4.24309d + 216.674$$

where d is the measured duty cycle [0-100] and T_{NTC} is the calculated temperature [°C]. This relationship was fit to experimental data. The NTC circuit used in this design is shown below.

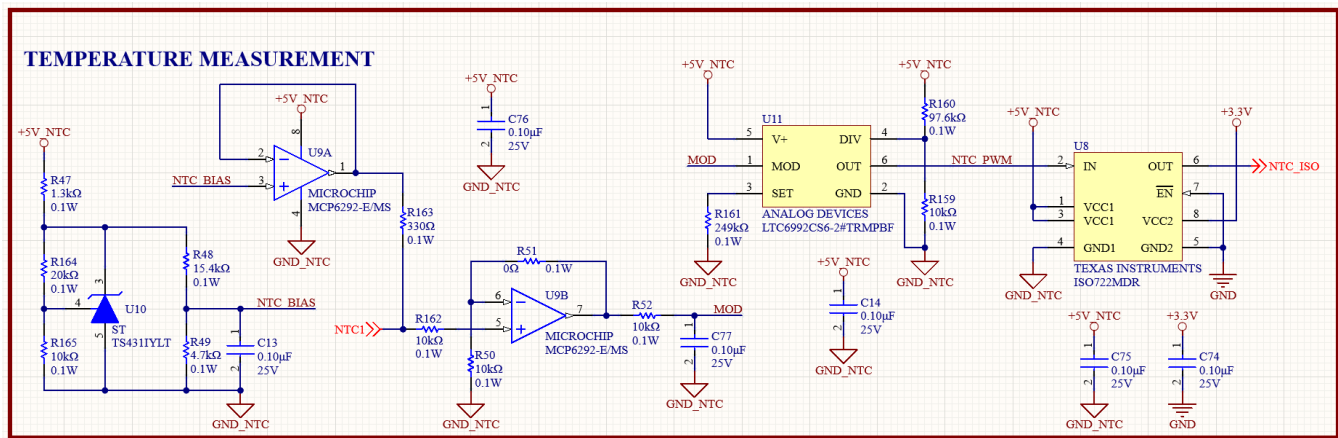


Figure 23: NTC Measuring Circuit

3.6 Position Sensing

This design includes provisions for measuring the mechanical position of a motor or other rotating device through a resolver sensor. The resolver is a common position measuring technique due to its few electrical components which enables operation in high vibration environments. To operate a resolver, an excitation sinusoidal signal is sent to the resolver and the resolver sensor returns the cosine and sine signals related to the sensor position. For the excitation signal in this design, the controller generates a PWM signal which is converted with on-board hardware to a sinewave and amplified. These excitation circuits are shown below.

RESOLVER CONDITIONING

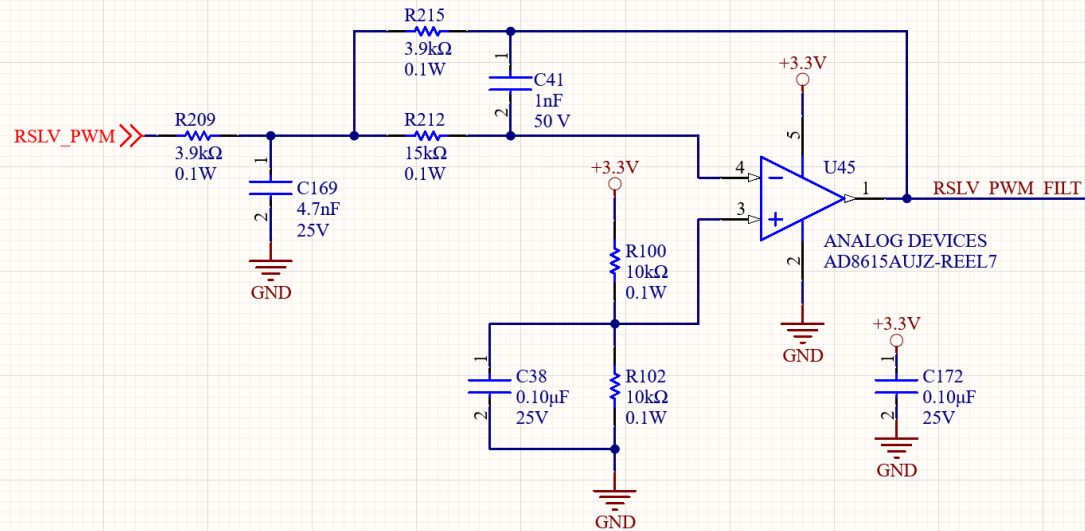


Figure 24: Resolver PWM to Sinewave

RESOLVER DIFFERENTIAL SIGNAL

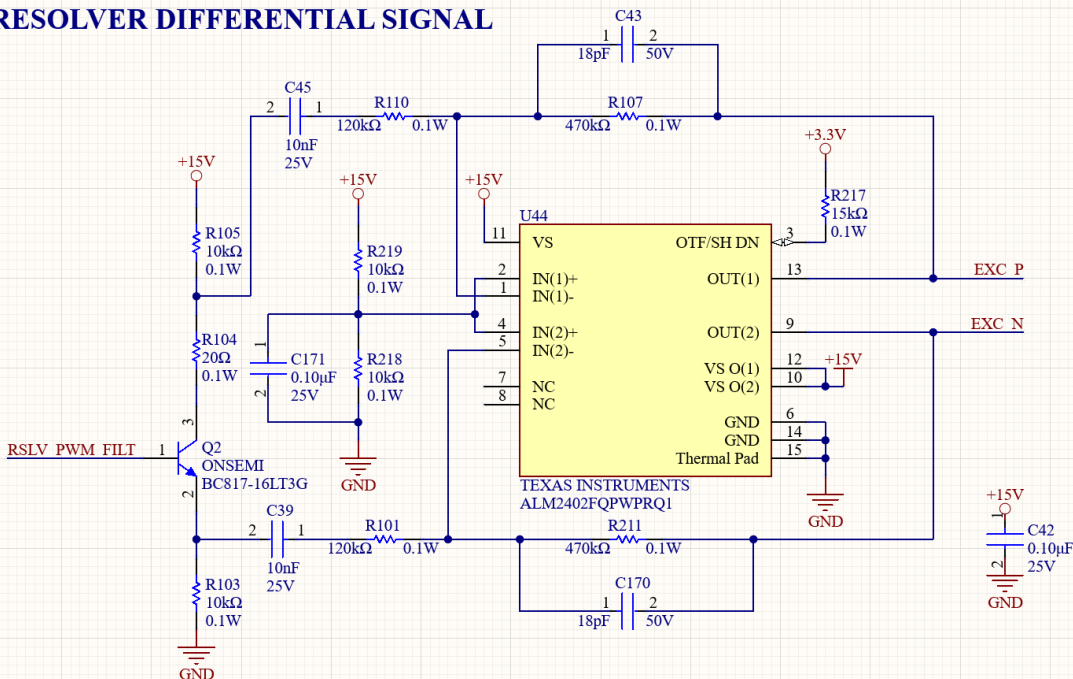


Figure 25: Resolver Excitation Amplifier

The sine and cosine differential feedback signals from the resolver are conditioned through an operational amplifier circuit to filter them and to center the signals at 1.5V rather than 0V. With this adjustment, the signals can be measured directly with the ADCs of the +3.3V controller. The conditioning circuit for the sine feedback is shown in below.

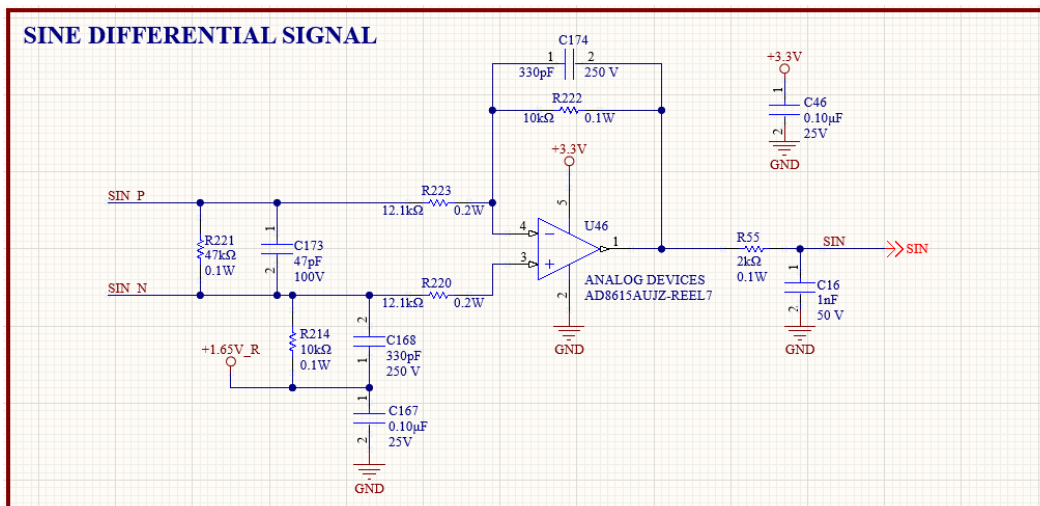


Figure 26: Resolver Sine Signal Conditioning

3.7 Additional Circuitry

The circuit includes several provisions for customization by a user to fit specific application needs. Along with the ability for swapping the controller and loading firmware off the board, this circuit includes hardware connections for attaching additional sensors and equipment based on customization needs. First, this circuit includes three LEDs with no predefined functionality. The three LEDs vary in color (green, yellow, red) allowing users to add custom warnings or feedback during system initialization and testing. These LEDs are shown below.

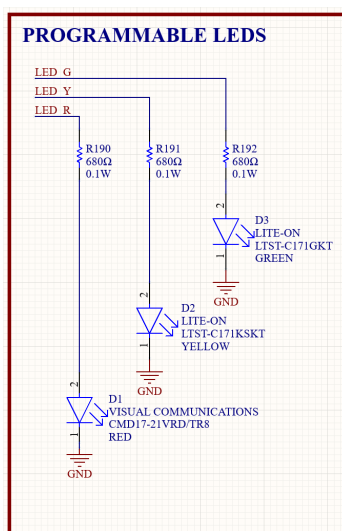


Figure 27: Customizable LEDs

Second, this design includes exposed header pins which connect to multiple analog-to-digital converter (ADC) pins and general-purpose input/output (GPIO) pins of the controller. Similar to the LEDs, these pins do not serve an inherent function and instead serve to provide users with easy access to controller pins and therefore to customization opportunities. By default, each signal is connected to a 0 Ω resistor and a not populated filter capacitor. Depending on the application, various resistor and capacitor sizes can be soldered to introduce a hardware-level filter. The spare connector headers also include a direct link to the three power rails on the circuit board (+3.3V, +5V, and +12V) and multiple ground connections so users can power a variety of external circuits or sensors. The circuit for these connections is shown below.

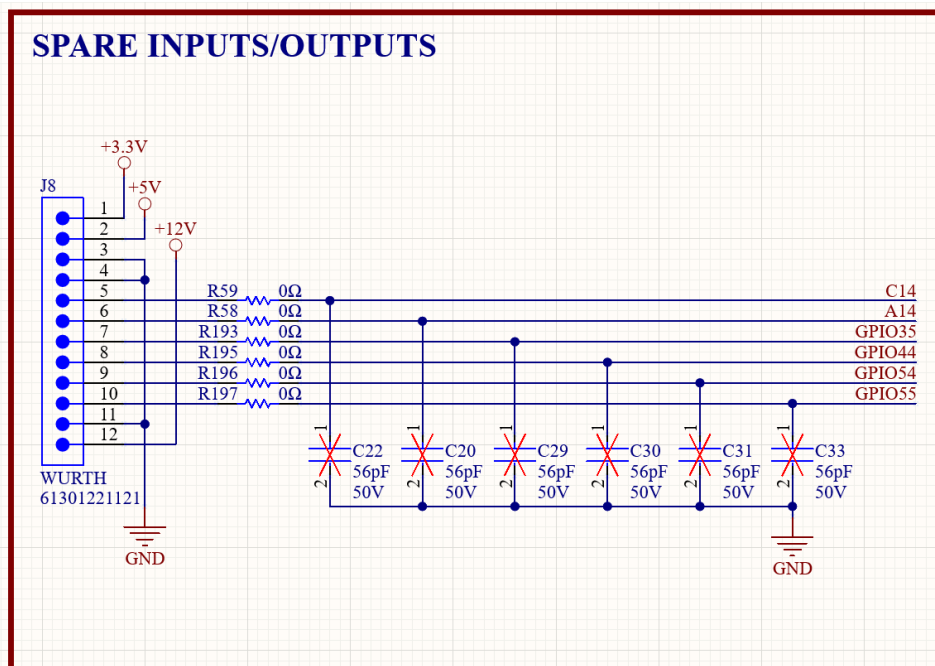


Figure 28: Spare ADCs, GPIOs, and Power Rail Connections

Third, the circuit board supports operating two external +12V relays for applications such as incorporating the circuit into an overall larger fault detection setup. For example, the circuit can drive relays can be used in series with a fault circuit or emergency shutdown equipment so a fault can be triggered in a higher-level system. Alternatively, the circuit can drive relays to operate higher-power equipment such as charge/discharge relays or in-rush current limiting equipment. Although the circuit was intended to drive relays, these connections can be used to drive any higher current equipment. Each relay connection is attached to a freewheeling diode and a low-side controlled transistor capable of operating up to 8A. However, this current is primarily limited by the input +12V power connector which is pin limited to 5A for the entire +12V rail, assuming that a suitable input power supply is used to power the circuit. If high currents are required for the external relay circuit, it is recommended to power those with another power source (other than this circuit board) and simply use these outputs to control the circuit. These relay driving circuits are designed to be general in nature and thus their purpose can be customized based on specific application needs. The relay driving circuit is shown below.

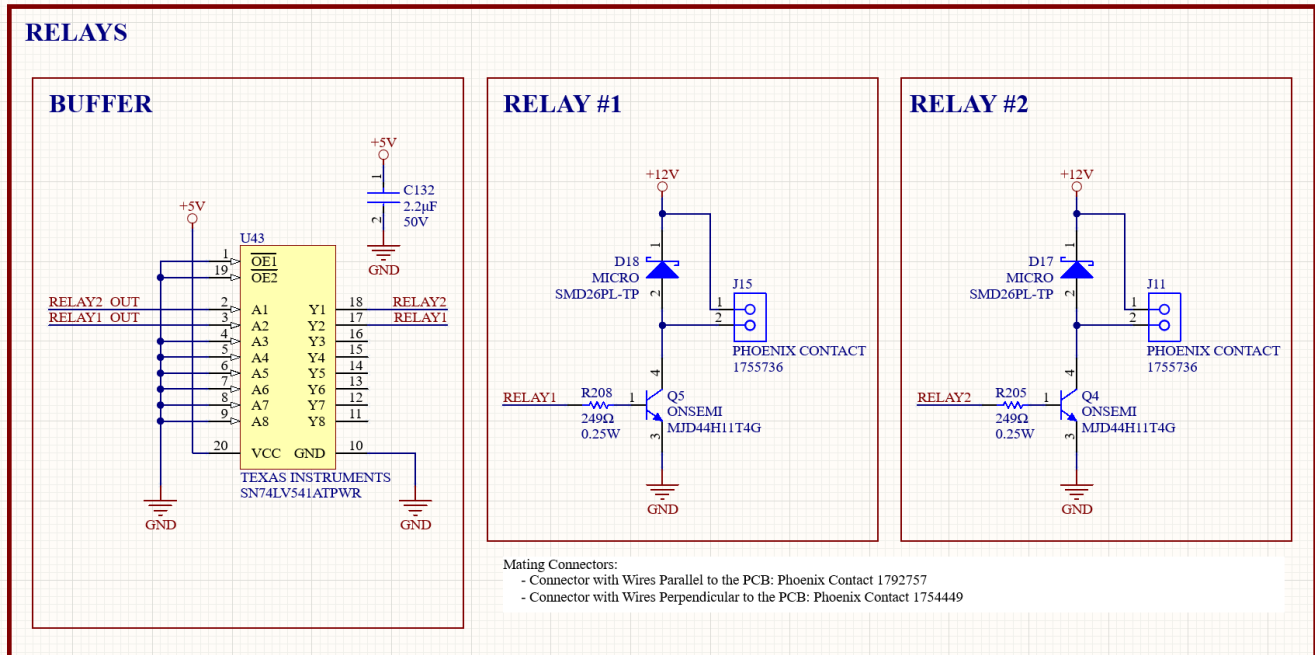


Figure 29: Relay Driving Circuit

4. CONTROLLER AND FIRMWARE

4.1 Microcontroller

The controller stage of the CRD25DA12N-FMC inverter system was designed around the F280039C controlCARD™ (TMDSCNCD280039C) from Texas Instruments (TI) C2000™ family of real-time microcontrollers. The controlCARD plugs directly into the inverter board via a Samtec® HSEC8-160-01-L-DV-A-BL high-speed edge connector (U5) as shown below. The on-board isolated XDS110 USB-to-JTAG debug probe is a convenient interface to run and debug firmware without additional hardware by connecting a USB-C cable between J1:A and a host computer. More information about running firmware is provided in the next section.

While the CRD25DA12N-FMC inverter was exclusively tested with the F280039C controlCARD, theoretically, any microcontroller daughter card with an equivalent pinout could be used. To this end, and to aid with user code development, the complete pinout of U5 along with signal descriptions of utilized pins is provided below.

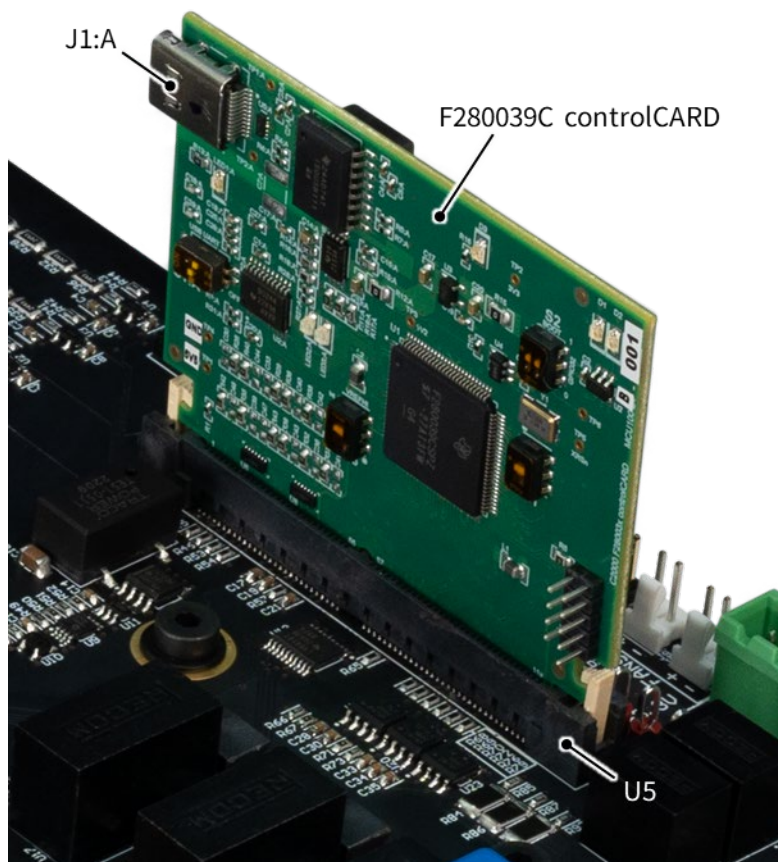


Figure 30: F280039C controlCARD plugged into U5

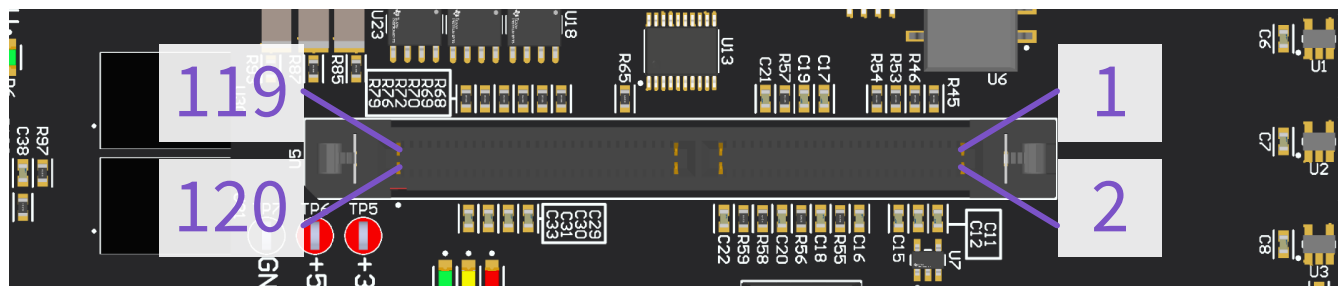


Figure 31: U5 Controller Connector Pin Numbers

Table 12: U5 Controller Connector Pinout

#	Name	Type	Description	Description	Type	Name	#
1	NC	—	No Connect	No Connect	—	NC	2
3	NC	—	No Connect	No Connect	—	NC	4
5	NC	—	No Connect	No Connect	—	NC	6
7	GND_0	Power	Ground	No Connect	—	NC	8
9	VU_MEAS	Analog (I)	U Differential Voltage Meas.	Ground	Power	GND_1	10
11	VV_MEAS	Analog (I)	V Differential Voltage Meas.	No Connect	—	NC	12
13	GND_2	Power	Ground	No Connect	—	NC	14
15	NC	—	No Connect	Ground	Power	GND_3	16
17	VW_MEAS	Analog (I)	W Differential Voltage Meas.	No Connect	—	NC	18
19	GND_4	Power	Ground	No Connect	—	NC	20
21	VDC_MEAS	Analog (I)	DC Differential Voltage Meas.	Ground	Power	GND_5	22
23	NC	—	No Connect	No Connect	—	NC	24
25	NC	—	No Connect	No Connect	—	NC	26
27	NC	—	No Connect	No Connect	—	NC	28
29	GND_6	Power	Ground	Resolver Sine Feedback	Analog (I)	SIN	30
31	NC	—	No Connect	No Connect	—	NC	32
33	IU_MEAS	Analog (I)	U Current Meas.	Resolver Cosine Feedback	Analog (I)	COS	34
35	GND_7	Power	Ground	Spare Controller Analog Input	Analog (I)	A14	36
37	IV_MEAS	Analog (I)	V Current Meas.	Ground	Power	GND_8	38
39	IW_MEAS	Analog (I)	W Current Meas.	Spare Controller Analog Input	Analog (I)	C40	40
41	NC	—	No Connect	No Connect	—	NC	42
43	NC	—	No Connect	No Connect	—	NC	44
45	NC	—	No Connect	Ground	Power	GND_9	46
47	GND_10	Power	Ground	+5V Power	Power	5V_0	48

#	Name	Type	Description	Description	Type	Name	#
49	U_HS_PWM	Digital (O)	High-Side Phase U PWM Control	High-Side Phase W PWM Control	Digital (O)	W_HS_PWM	50
51	U_LS_PWM	Digital (O)	High-Side Phase U PWM Control	Low-Side Phase W PWM Control	Digital (O)	W_LS_PWM	52
53	V_HS_PWM	Digital (O)	High-Side Phase V PWM Control	No Connect	—	NC	54
55	V_LS_PWM	Digital (O)	Low-Side Phase V PWM Control	No Connect	—	NC	56
57	NTC_ISO	Digital (I)	Temperature PWM Meas.	No Connect	—	NC	58
59	NC	—	No Connect	No Connect	—	NC	60
61	NC	—	No Connect	No Connect	—	NC	62
63	NC	—	No Connect	Resolver Excitation PWM	Digital (O)	RSLV_PWM	64
65	GND_11	Power	Ground	No Connect	—	NC	66
67	NC	—	No Connect	No Connect	—	NC	68
69	NC	—	No Connect	No Connect	—	NC	70
71	NC	—	No Connect	No Connect	—	NC	72
73	NC	—	No Connect	Gate Driver Disable	Digital (O)	GD_DIS	74
75	NC	—	No Connect	No Connect	—	NC	76
77	NC	—	No Connect	No Connect	—	NC	78
79	U_HI_OC	Digital (I)	Phase U High Overcurrent	No Connect	—	NC	80
81	U_LO_OC	Digital (I)	Phase U Low Overcurrent	No Connect	—	NC	82
83	GND_12	Power	Ground	+5V Power	Power	5V_1	84
85	NC	—	No Connect	No Connect	—	NC	86
87	CAN_RX	Digital (I/O)	Non-isolated CAN RX	Non-Isolated CAN TX	Digital (I/O)	CAN_TX	88
89	NC	—	No Connect	Spare Controller GPIO	Digital (I/O)	GPIO35	90
91	V_HI_OC	Digital (I)	Phase V High Overcurrent	Spare Controller GPIO	Digital (I/O)	GPIO44	92
93	V_LO_OC	Digital (I)	Phase V Low Overcurrent	Red LED Control	Digital (O)	LED_R	94

#	Name	Type	Description	Description	Type	Name	#
95	LED_Y	Digital (O)	Yellow LED Control	Green LED Control	Digital (O)	LED_G	96
97	GND_13	Power	Ground	+5V Power	Power	5V_2	98
99	W_HI_OC	Digital (I)	Phase W High Overcurrent	Spare Controller GPIO	Digital (I/O)	GPIO54	100
101	W_LO_OC	Digital (I)	Phase W Low Overcurrent	Spare Controller GPIO	Digital (I/O)	GPIO55	102
103	NC	—	No Connect	No Connect	—	NC	104
105	NC	—	No Connect	Relay Control	Digital (O)	RELAY1_OUT	106
107	NC	—	No Connect	Relay Control	Digital (O)	RELAY2_OUT	108
109	NC	—	No Connect	No Connect	—	NC	110
111	GND_111	Power	Ground	+5V Power	Power	5V_3	112
113	NC	—	No Connect	No Connect	—	NC	114
115	NC	—	No Connect	No Connect	—	NC	116
117	NC	—	No Connect	No Connect	—	NC	118
119	NC	—	No Connect	+5V Power (Disabled)	Digital (I)	~RST	120

4.2 Firmware

Wolfspeed provides firmware that consists of basic open-loop three-phase sine-PWM control of the inverter along with a graphical user interface (GUI) that manipulates the parameters of the open-loop control from a host computer via the CAN communication protocol. Altogether, this control suite allows the user to test the reference design at the desired test conditions without the need to modify the controller firmware. Alternatively, the provided firmware source code can be modified at the user's discretion or used as a starting point for users to develop and implement their own application-specific control law. The firmware and GUI for the CRD25DA12N-FMC reference design can be requested separately from Wolfspeed's website on the [CRD25DA12N-FMC landing page](#).

4.2.1 Code Composer Studio Project

The CRD25DA12N-FMC firmware is provided as a [Code Composer Studio™ \(CCS\)](#) project. The project was developed and tested with CCS version 12.3.0, so this version or newer is recommended to build and run this project. If not installed, download and install CCS from TI's website. The [CCS User's Guide](#) provides more details about CCS installation and use.

The software project was also developed and built with TI's [C2000Ware](#) to provide device-specific drivers and libraries. C2000Ware version 4.03.00.00 was used for development and testing, so this version or newer is recommended. C2000Ware is a separate installation from CCS, so if not installed, download and install C2000Ware from TI's website.

Once the required software is installed, the following instructions can be used to import and run the provided CRD25DA12N-FMC Firmware CCS project. To import the project into CCS, click **Project → Import CCS Projects** and browse to the local directory where the downloaded project was saved <Local Directory>\CRD25DA12N-FMC Firmware and click **Select Folder**. Verify the *CRD25DA12N-FMC Firmware* project was discovered and click **Finish**. Once properly imported, the project should look like the figure below.

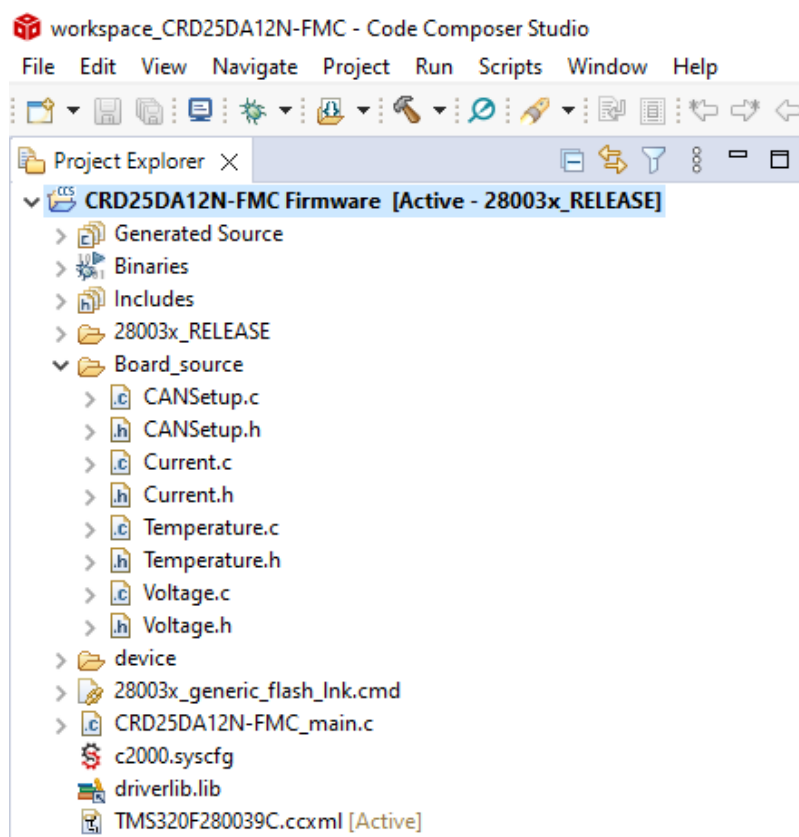


Figure 32: CRD25DA12N-FMC Firmware CCS Project Explorer View

The default build configuration is *28003x_RELEASE* with the linker command file *28003x_generic_flash_lnk.cmd* specified to run the program from Flash memory and the *TMS320F280039C.ccxml* target configuration file to use the on-board XDS110 USB Debug Probe on the F280039C controlCARD. The *Board_source* folder contains all of the hardware-specific source files to run the design. This includes the drivers for current, voltage, and temperature sensing, along with the CAN communication protocol. An empty *c2000.syscfg* file is provided if it is desired to use the SysConfig functionality for further code development and generation, although the project was not originally developed with the SysConfig tool.

To build the project, click **Project → Build Project** or click on the **Build** icon button on the toolbar. Monitor the **Console** pane to confirm the project was successfully built without any errors. Address any errors listed in the **Problems** pane, if they occur. If there are no errors, go to **Run → Debug** or click on the **Debug** icon to launch a debug session. Once the debug session is launched, the program will be halted at the start of *main()*. Go to **Run → Resume** or click the **Resume** icon to start running the code. Add desired variables to the **Expressions** pane and click the **Continuous Refresh** icon to continuously monitor them during the debug session.

4.2.2 CAN Communication GUI

In addition to the open-loop three-phase sine-PWM control law being executed by the code, a CAN communication protocol is also operating in the background to provide the ability to manipulate the parameters of the open-loop control from a host computer using the Wolfspeed provided GUI. Once downloaded and extracted, run the *FMC Inverter CAN Interface.exe* file where the *Communication Setup* dialog shown below will appear.

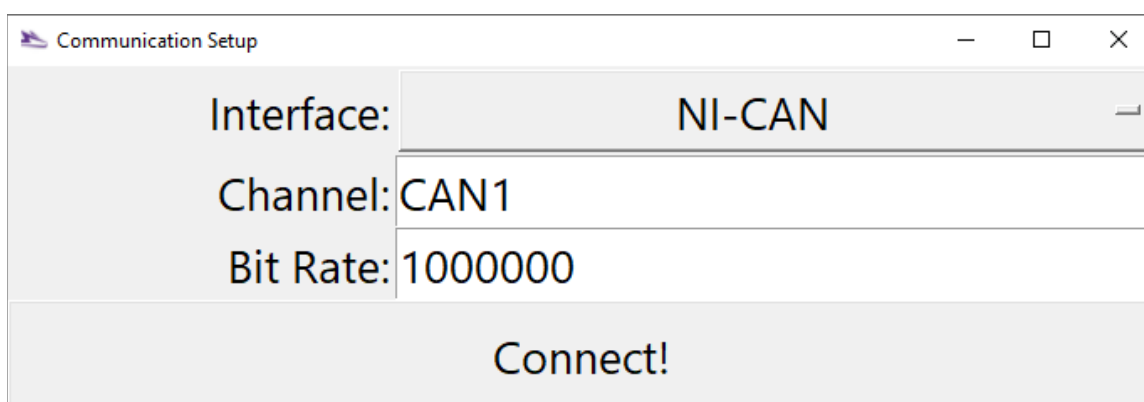
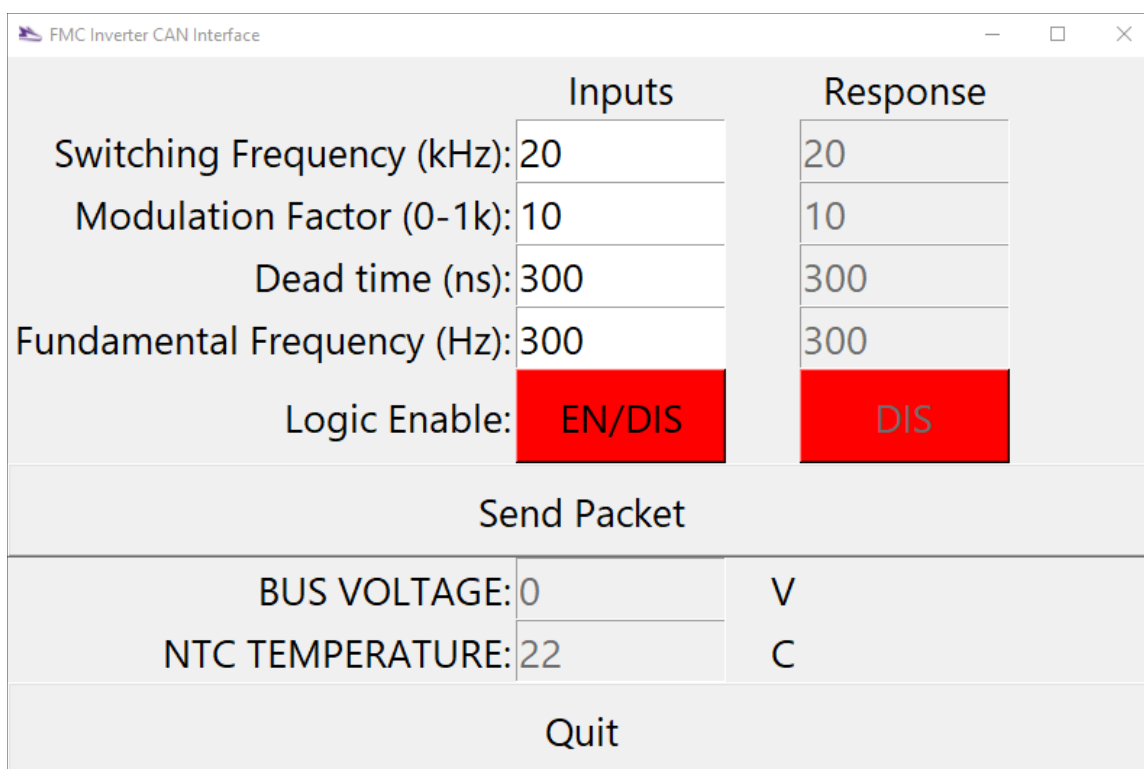


Figure 33: Communication Setup Dialog Box

Click on the drop-down menu to select the proper **Interface** and input the correct settings for **Channel** and **Bit Rate** as determined by the CAN hardware adapter being used. The GUI was built using the python-can library which provides support for various hardware adapters. Please refer to the python-can library documentation to find a list of the available [CAN Interface Modules](#) and how each setting should be configured. Once communication is established by clicking **Connect!**, the *FMC Inverter CAN Interface* GUI control window will pop up and will look like what is shown below. A command window will also show a log of the raw CAN packets that are sent and received on the CAN bus. If there is an invalid packet, a warning will be printed, and the errors will be displayed in this window. By default, the CAN packets are transmitted and encoded/decoded in code approximately once every second.



Inputs		Response
Switching Frequency (kHz):	20	20
Modulation Factor (0-1k):	10	10
Dead time (ns):	300	300
Fundamental Frequency (Hz):	300	300
Logic Enable:	EN/DIS	DIS
Send Packet		
BUS VOLTAGE:	0	V
NTC TEMPERATURE:	22	C
Quit		

Figure 34: FMC Inverter CAN Interface GUI

The GUI control panel provides **Inputs** fields that consist of four numerical inputs and one toggle-button. Pressing the **Send Packet** button sends a new CAN packet with the populated values of each input field. A description of each Inputs field is given below.

Switching Frequency field is the frequency of the output PWM in kHz. The default value is 20 = 20 kHz. The input range is 1 – 100.

Modulation Factor field is the modulation factor (depth) of the reference sinusoidal wave for the output PWM, scaled by a factor of 1000. The default value is 10 = 0.01 MF. The input range is 0 – 1000.

Dead time field is the dead-time between the complementary high-side and low-side switch position PWM for each bridge-leg in nanoseconds (ns). The default value is 300 = 300 ns dead-time. The input range is 100 – 2000.

Fundamental Frequency field is the fundamental frequency of the reference sinusoidal wave in Hz. The default value is 300 = 300 Hz. The input range is 1 – 500.

Logic Enable toggle-button enables and disables the PWM logic of all six switch positions. By default, the logic is disabled, so the toggle-button is highlighted red (DIS). When enabled, the toggle-button will turn green (EN).

The **Response** field displays the values contained in the most recent packet sent from the controller, indicating the status of each control parameter or confirming values were properly updated after a new input packet was sent. Also included in the information sent by the controller in each packet are the feedback values for the measured **Bus Voltage** (V) and **NTC Temperature** (°C). Pressing the **Quit** button will close the GUI.

5. PERFORMANCE DATA

5.1 Heatsink

The thermal performance of the module and system is influenced by its ability to reject heat from the device junction to its ambient environment. The baseplate-less design of the Wolfspeed CCB021M12FM3T already reduces the device thermal impedance compared to a similarly sized power modules since less material (i.e. baseplate) is present in the thermal path. To further maintain thermal integrity, this design uses the Fischer Elektronik® LA6 heatsink with a 33 CFM integrated axial fan to cool the power module.

The junction-to-heatsink thermal impedance Z_{th} for the power module is provided in the device datasheet. However, to evaluate the thermal performance of this reference design, the thermal impedance of the heatsink was also characterized. Characterizing the heatsink within the system was performed using a Siemens® Simcenter POWER3ster™, which is an all-in-one thermal evaluation instrument to determine the thermal impedance of devices and applications. The single pulse transient thermal impedance measurements of the module, heatsink, and their combination is shown below. Note that these measurements are for a single switch position of the power module.

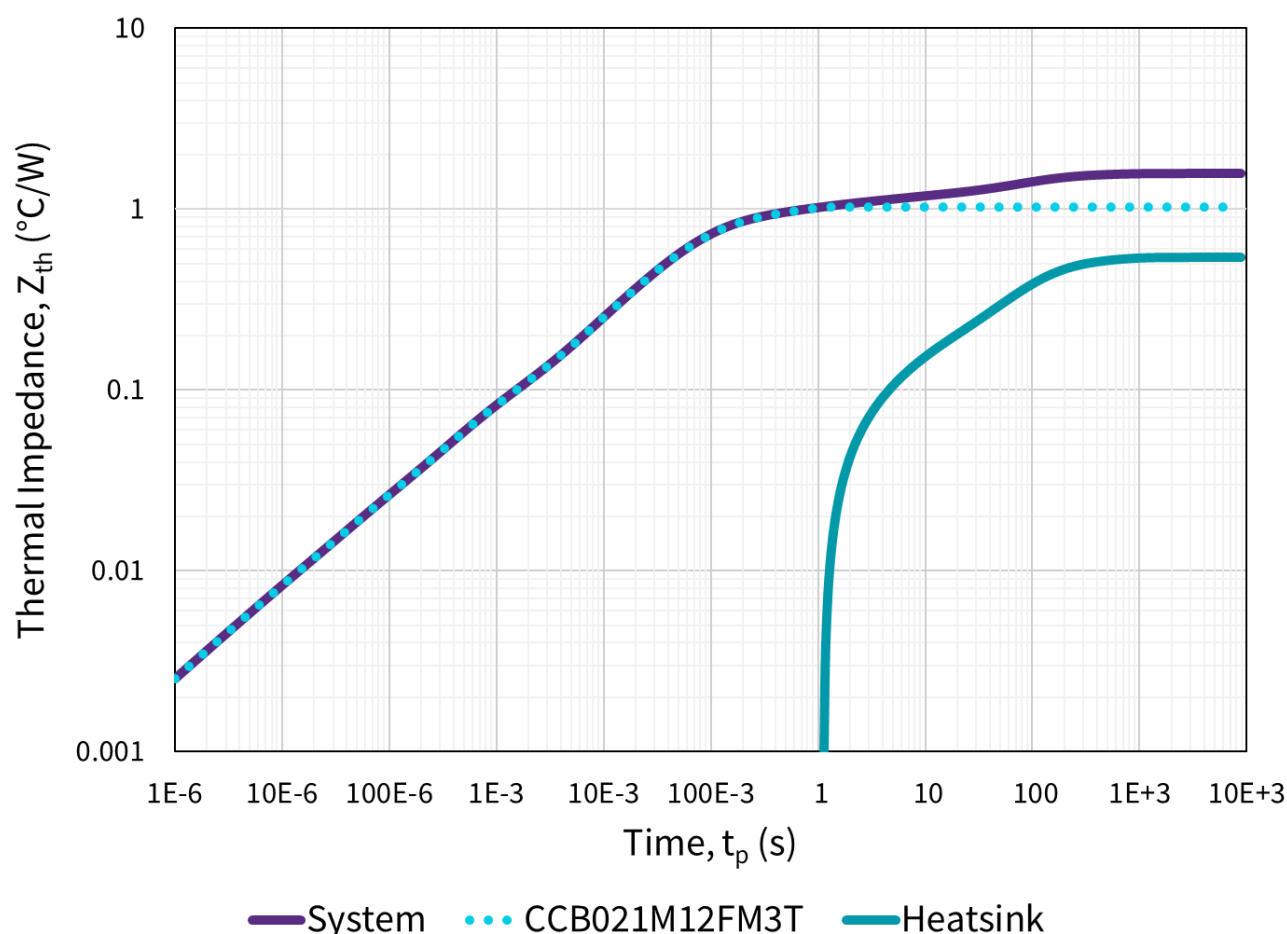


Figure 35: Transient Thermal Impedance Measurements

The resulting junction-to-ambient thermal resistance R_{th} for the entire system is $1.571\text{ }^{\circ}\text{C/W}$. From the device datasheet, the module junction-to-heatsink R_{th} is $1.032\text{ }^{\circ}\text{C/W}$. Note that this value already includes the pre-applied TIM layer. Therefore, the contribution of the heatsink to the overall R_{th} is approximately $0.539\text{ }^{\circ}\text{C/W}$. The extracted 4th order Cauer network of the heatsink performance is shown below. This thermal network can be used in tandem with the PLECS® model of the Wolfspeed CCB021M12FM3T to simulate this reference design. This is discussed in more detail in the “Simulation” section of this document.

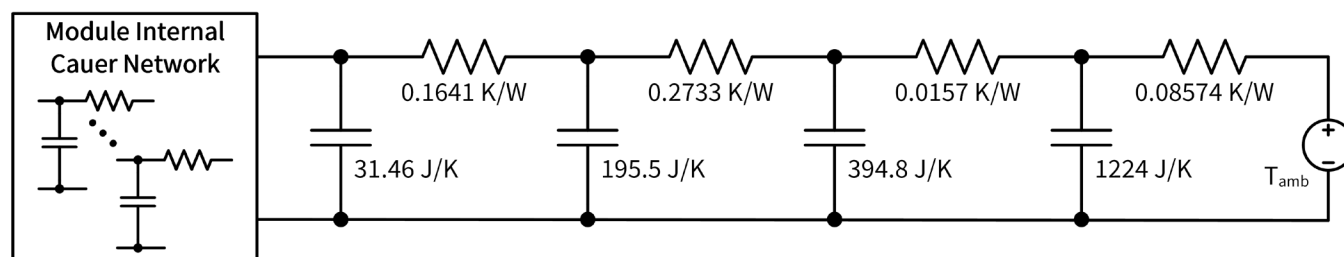


Figure 36: Heatsink 4th Order Cauer Network

5.2 Inductance

The layout of the printed circuit board was designed with multiple interleaved copper layers in order to minimize the board inductance. To validate the low-inductance design, the commutation inductance of the board (from DC+ to DC-) was measured with a Keysight® 42941A impedance probe attached to a Keysight E4990A impedance analyzer. The resulting inductance measurement is shown in Figure 37. Due to the interleaved copper layers, the board demonstrates only 8.6 nH of inductance at 10 MHz.

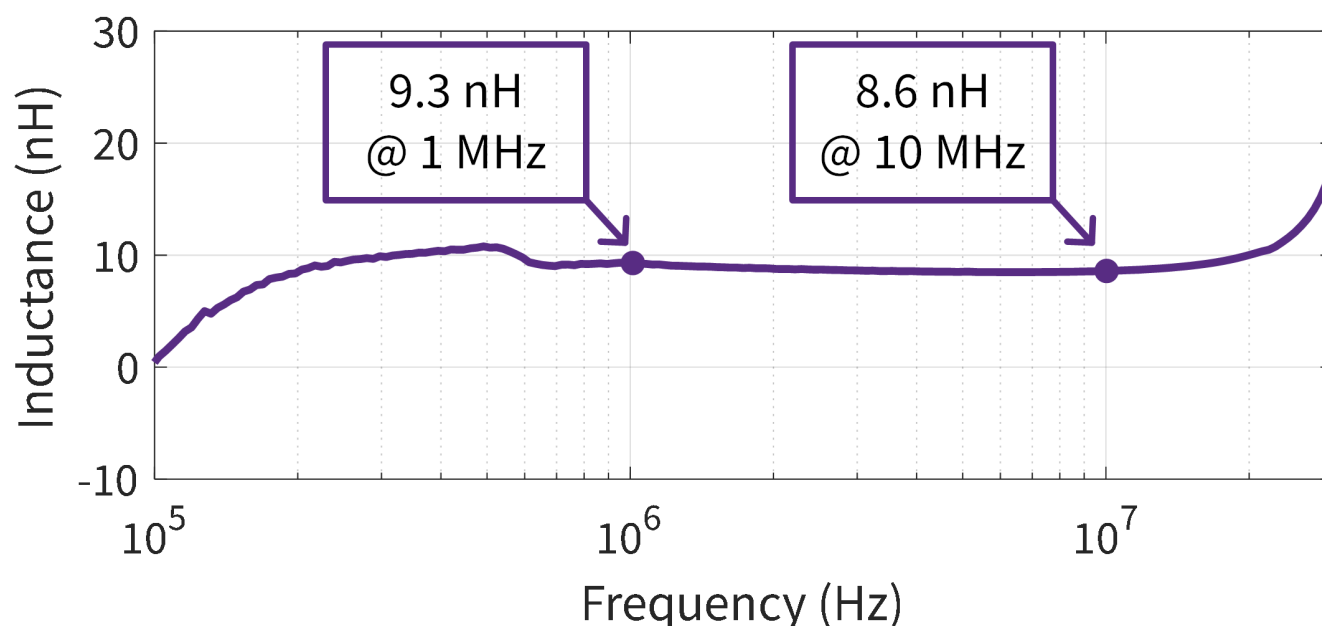


Figure 37: Measured circuit board commutation inductance

5.3 Experimental Validation

5.3.1 Setup

The system was loaded with one Würth Elektronik 760801301 inductor per phase in a wye connected configuration. The Würth Elektronik 760801301 inductors have a rated inductance of 180 μH and dc resistance of 20 m Ω . The design was powered with a Magna Power TSD1000-30/208+LXI power supply unit (PSU) with a rated output of up to 1000 V and 30 kW. The experimental setup is shown below. The output currents, phase voltages, and gate voltages were measured using a Tektronix MSO58B oscilloscope with a rated bandwidth of 1 GHz. These measurements were performed with isolated high-bandwidth probes which are summarized below.

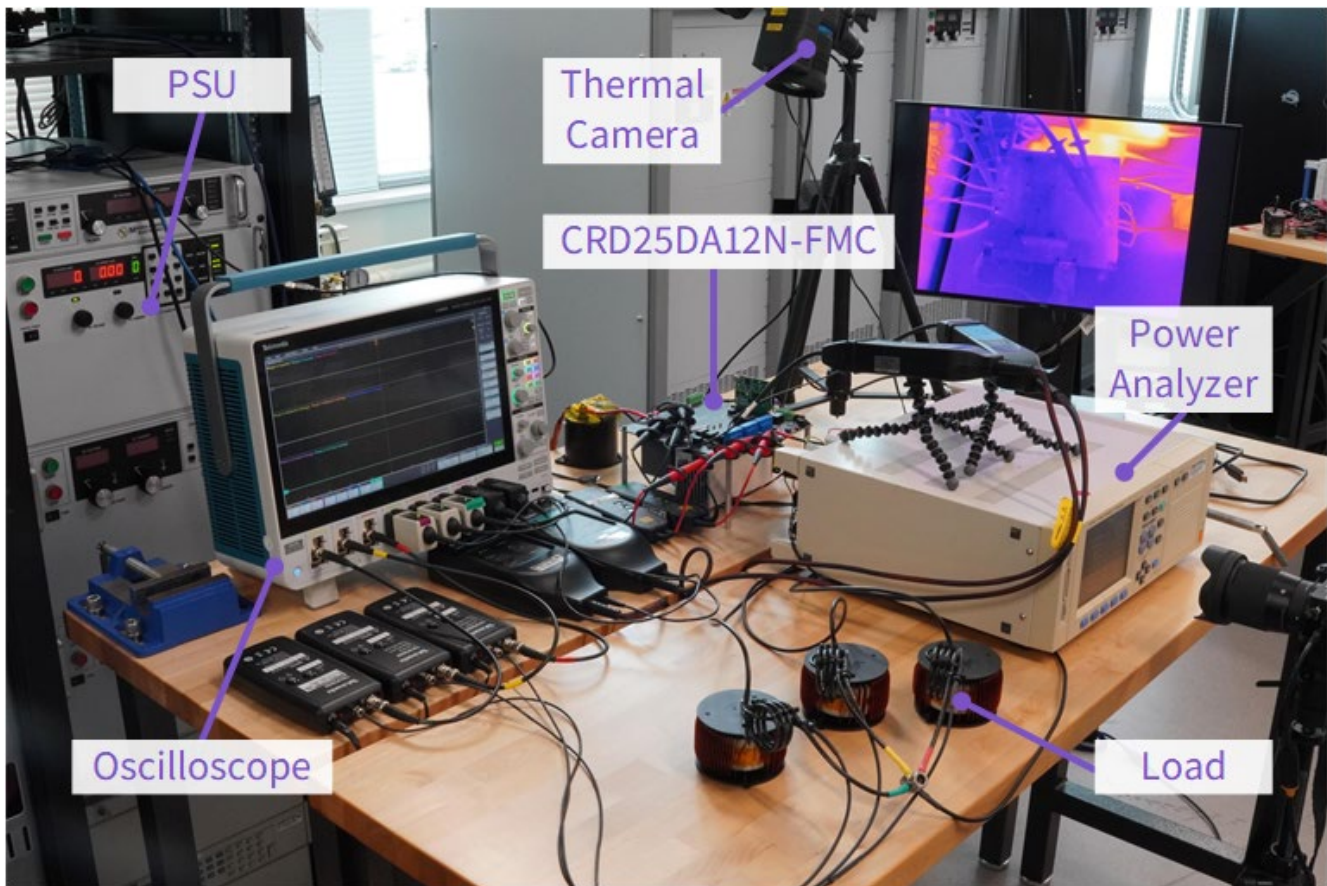


Figure 38: Experimental Setup

Table 13: Experimental Setup Oscilloscope Probes

Measurement	Probe	Description
I_U, I_V, I_W	PEM® CWT UM/3/B/1/160	600 A, 30 MHz, Rogowski Coil
V_U, V_V, V_W	Tektronix THDP0200	1.5 kV, 200 MHz, Differential Probe
$V_{GS,U,LS}, V_{GS,U,HS}$	Tektronix IsoVu™ TIVH05	50X Tip, 500 MHz, Optically Isolated Probe

5.3.2 Experimental Results

The system was evaluated at several operating conditions to validate the system performance. Parameters such as the switching frequency (f_{sw}), deadtime (t_{dead}), and modulation index (mf) were evaluated at a range of values. An example waveform is shown below in Figure 39, demonstrating the system operation over the duration of several fundamental periods at the full load current of 30 A_{rms} ($mf = 41$). Here the inverter is operating at a bus voltage of 800 V, a switching frequency of 20 kHz, with 300 ns of deadtime.

Additional measurements were performed for shorter time durations to validate other system performance parameters. An example short duration measurement is shown below in Figure 40 for the same operating conditions as previously described. Inspection of the oscilloscope screenshot shows the system is operating with sufficient deadtime since the switch transitions are completed before the complementary switches begin to turn on. Similarly, the phase voltages have minimal overshoot and ringing as indicated by the maximum phase voltage of 1.021 kV on an 800 V DC bus and the short duration for the transient ringing to end. Minimal overshoot and ringing are also observed in the gate voltage measurements.

To validate the long-term performance of the evaluation board, the inverter was operated for over an hour under the same test conditions: $I_{load} = 30$ A_{rms}, $V_{bus} = 800$ V, $f_{sw} = 20$ kHz, $t_{dead} = 300$ ns, and $T_{ambient} = 21$ °C. The thermal image in Figure 41 was taken at the end of the allotted time, demonstrating adequate thermal performance of the power PCB. The temperature scale is in degree Celsius. At that time, the NTC temperature was reading 38 °C.

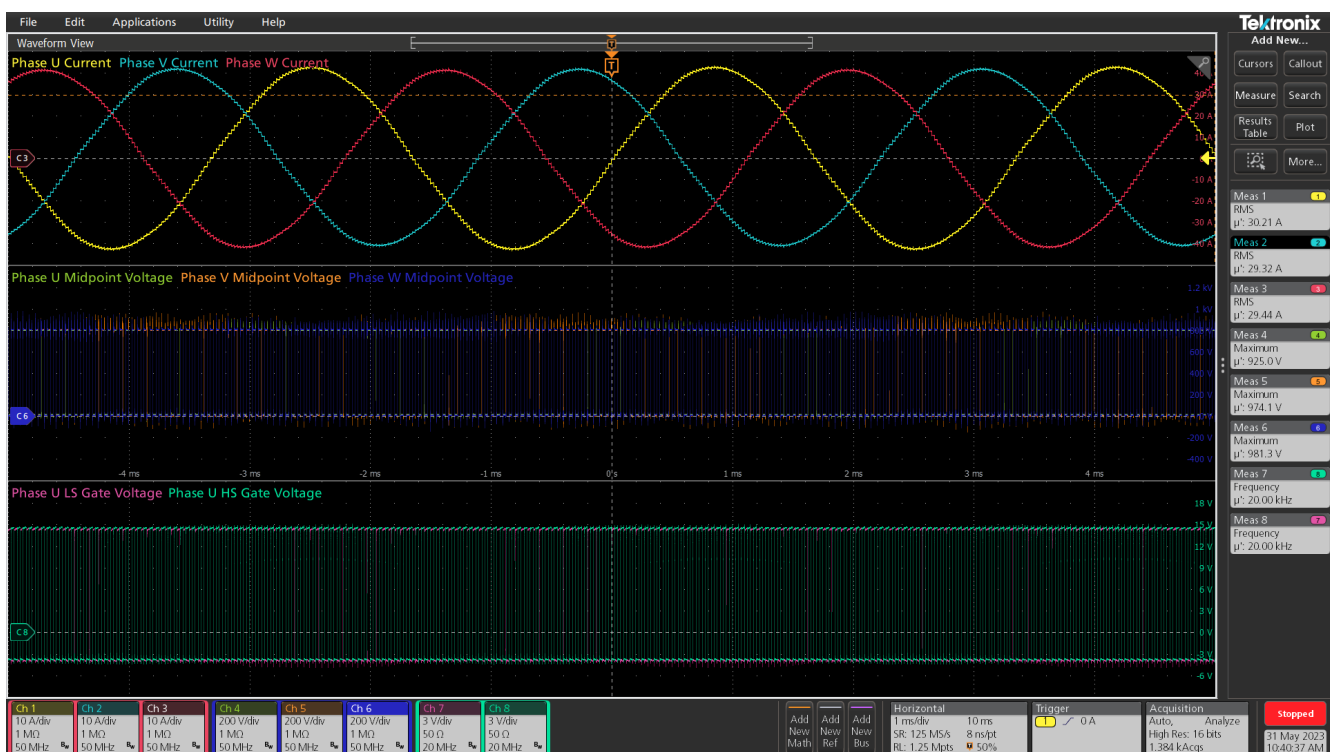


Figure 39: Experimental Measurements at $V_{bus} = 800$ V, $f_{sw} = 20$ kHz, $t_{dead} = 300$ ns, and 30 A_{rms} ($mf = 41$)

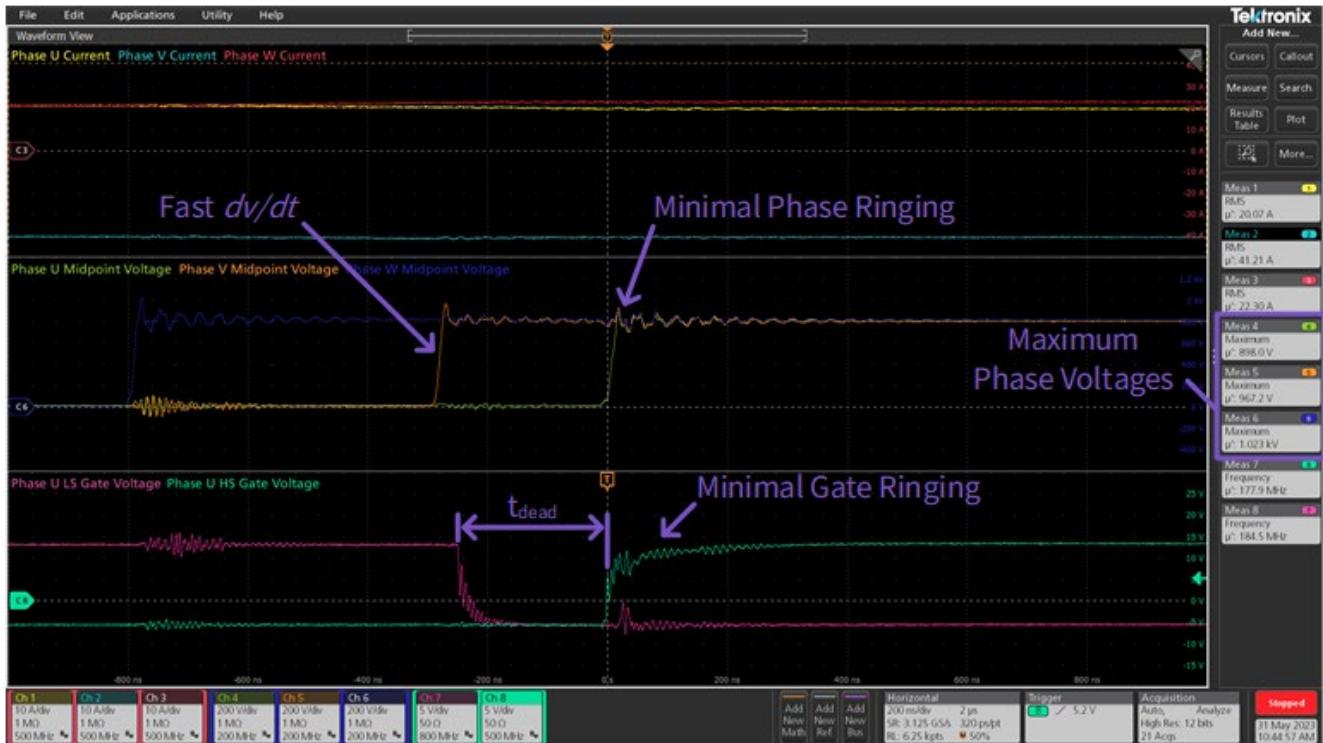


Figure 40: System Switching Performance at $V_{bus} = 800\text{ V}$, $f_{sw} = 20\text{ kHz}$, $t_{dead} = 300\text{ ns}$, and 30 A_{rms} ($mf = 41$)

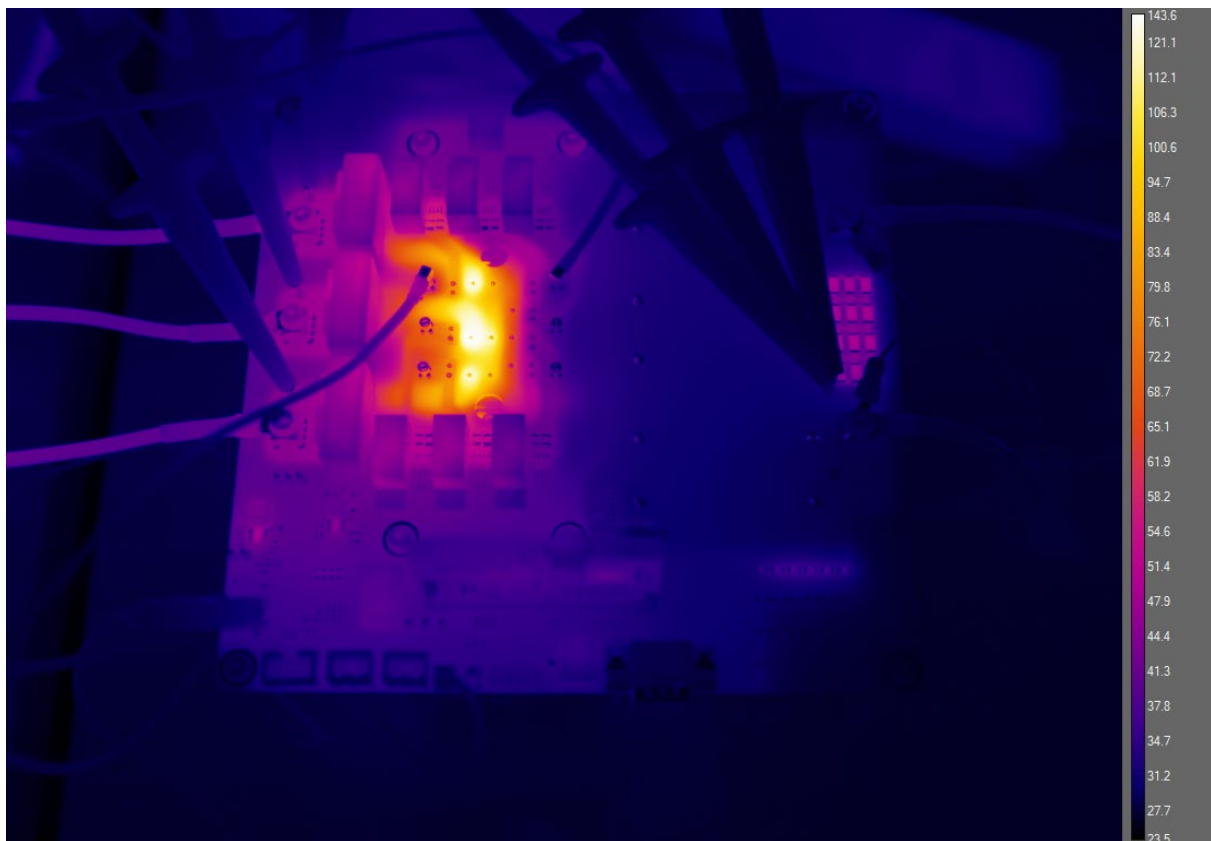


Figure 41: Thermal Image of CRD25DA12N-FMC PCB after one hour.

5.3.3 Thermal Safe Operating Area

As described in the datasheet for the Wolfspeed CCB021M12FM3T, the package is limited to 30 Arms by the pins of the module. At high switching frequency, the module is further limited by the junction temperature of the die due to the higher switching losses at elevated switching frequencies. Using the default gate resistors on the CRD25DA12N-FMC ($R_{G(EXT)-ON} = 0.91 \Omega$ and $R_{G(EXT)-OFF} = 0 \Omega$), the system is able to operate at rated pin current up to 100 kHz for a bus voltage of 800 V and an ambient temperature of 25 °C. Current derating is required to achieve higher switching frequencies. This safe operating area shown below was generated from a combination of simulated and experimental results.

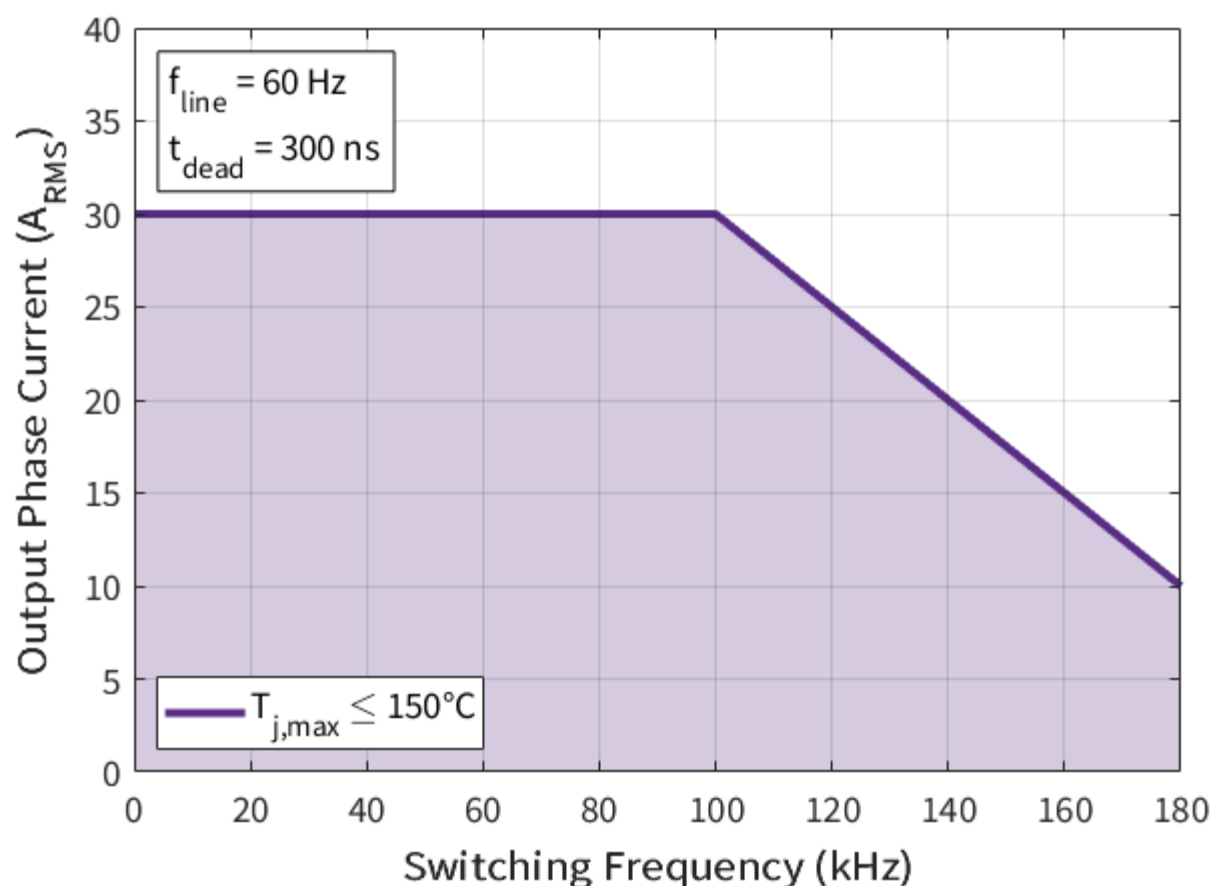


Figure 42: Thermal Safe Operating Area for $T_{ambient} = 25 \text{ °C}$

5.4 Simulation

A PLECS® simulation of the hardware is included as a download with the design files. The simulation is shown below, and the various subsystems are explained in the following sections. The simulation can be employed by interested users as a replacement for purchasing the hardware, as a tool to evaluate whether to purchase the hardware, and/or as a tool for making custom modifications to the controller. This simulation requires an active license of PLECS in order to run the simulation (PLECS Standalone 4.6.0 or newer is recommend). Licenses for PLECS can be purchased at <https://www.plexim.com/products/plecs>. More information about how to use PLECS can be found in the help guides on the PLECS website and in the program documentation. For users not familiar with PLECS, tutorials covering basic usage of the software are available at <https://www.plexim.com/support/tutorials>.

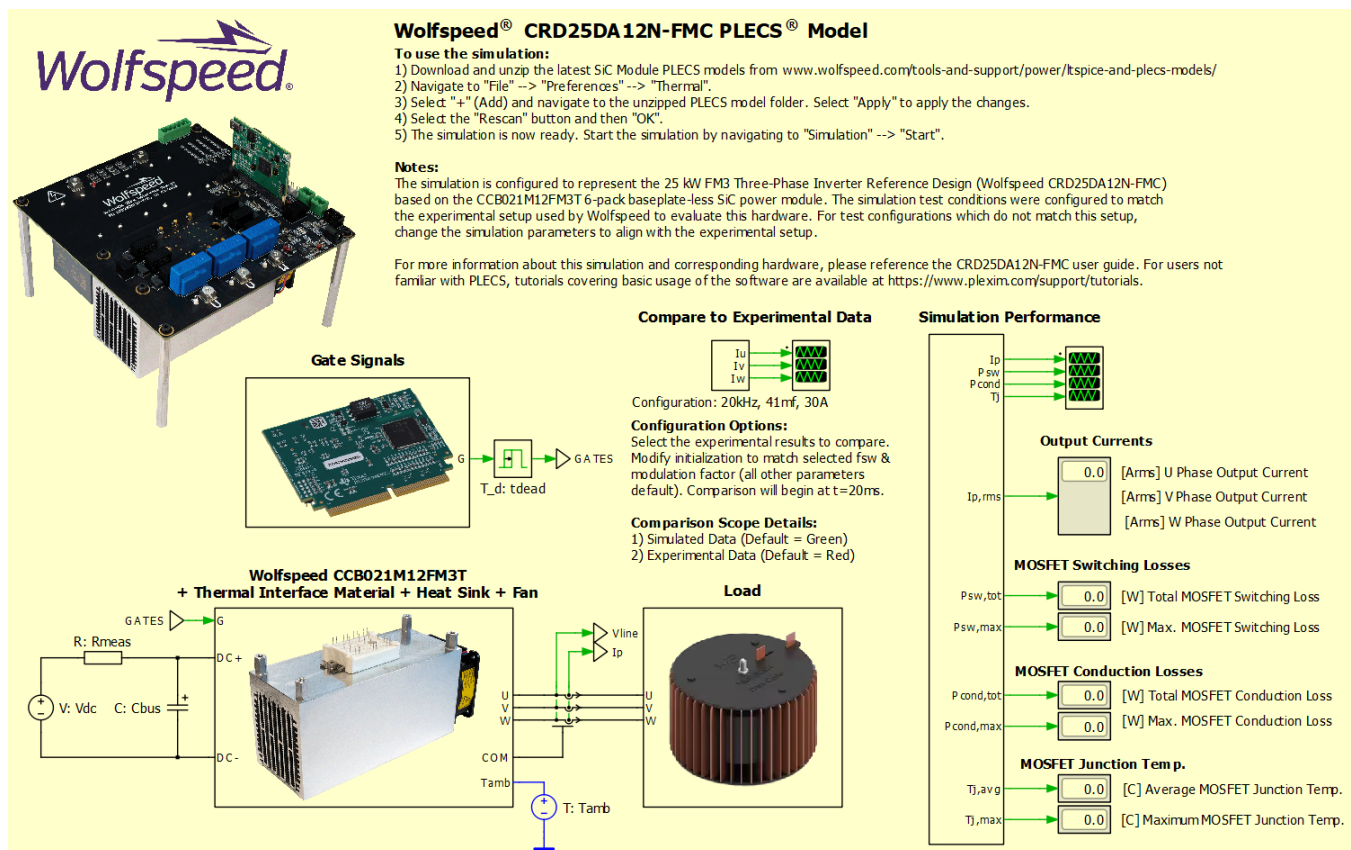


Figure 43: CRD25DA12N-FMC Simulation

As with the actual hardware, the power stage of the inverter uses the Wolfspeed CCB021M12FM3T six-pack baseplate-less module. The top-level of the simulation is shown below. To run the model, users need to direct PLECS to the thermal model for the MOSFET and body diode which can be downloaded from <https://www.wolfspeed.com/tools-and-support/power/ltspice-and-plecs-models/>. To add the device models to the simulation:

- 1) Download “**All SiC Module PLECS Models**” from the page linked above and unzip the models into a suitable directory
- 2) In PLECS, navigate to “File” → “Preferences” → “Thermal”.
- 3) Select “+” (Add) and navigate to the unzipped PLECS model folder. Select “Apply” to apply the changes.
- 4) Select the "Rescan" button and then "OK".
- 5) The simulation is now ready. Start the simulation by navigating to “Simulation” → “Start”

5.4.1 Power Stage

The power stage subsystem includes the power module MOSFET models and the corresponding thermal networks to the ambient temperature. As described in the “Heatsink” section of this document, the thermal impedance of the heatsink in this system was directly measured and a 4th order Cauer network was fit to the data. When paired with the PLECS model of the Wolfspeed CCB021M12FM3T, this produces an accurate thermal model of the entire system. This pairing is shown in the simulation power stage subsystem shown below.

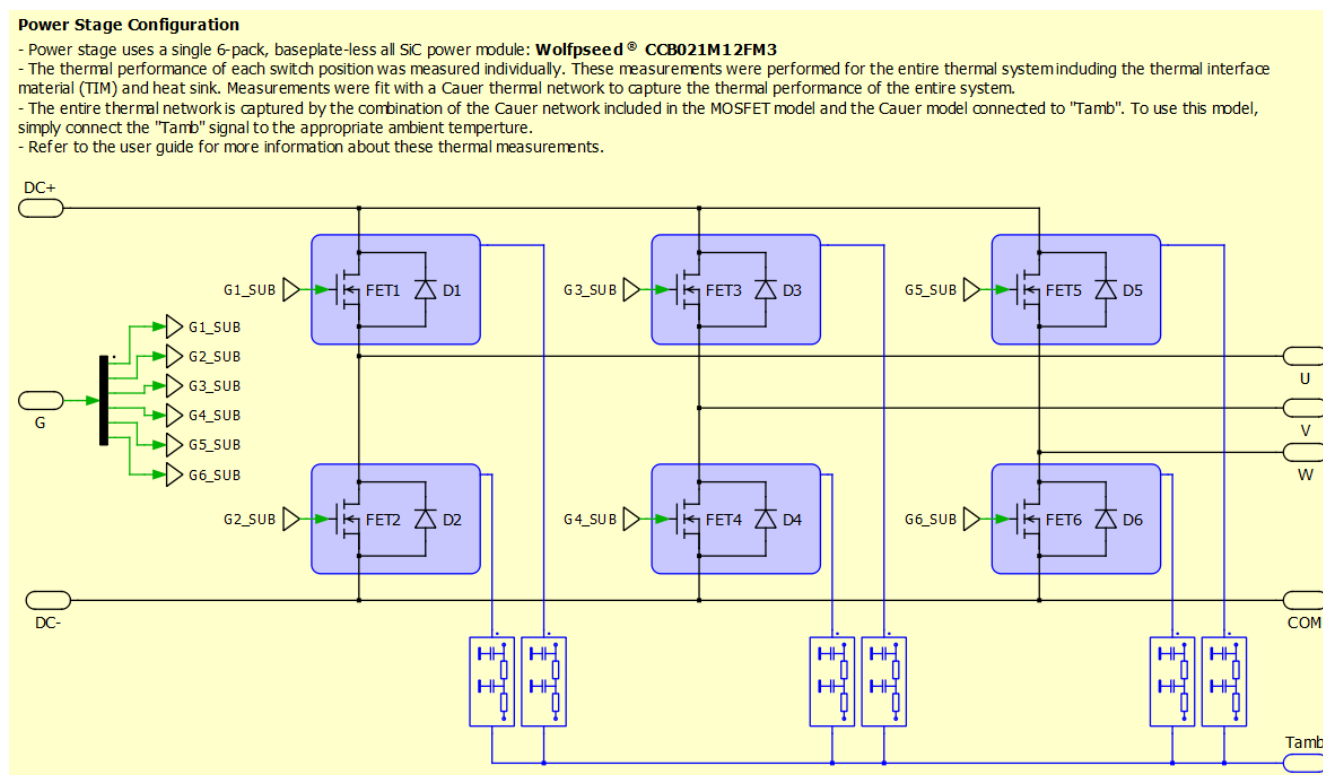


Figure 44: Power Stage Subsystem

5.4.2 Controller

The simulation parameters are configured to match the experimental testbed used to validate the hardware discussed in the “Experimental Validation” section of this document. To match that configuration, the simulation uses sine-PWM (SPWM) modulation for generating the gate signals and is operated in an open-loop configuration. The SPWM modulation controller used to generate the gate signals is shown below.

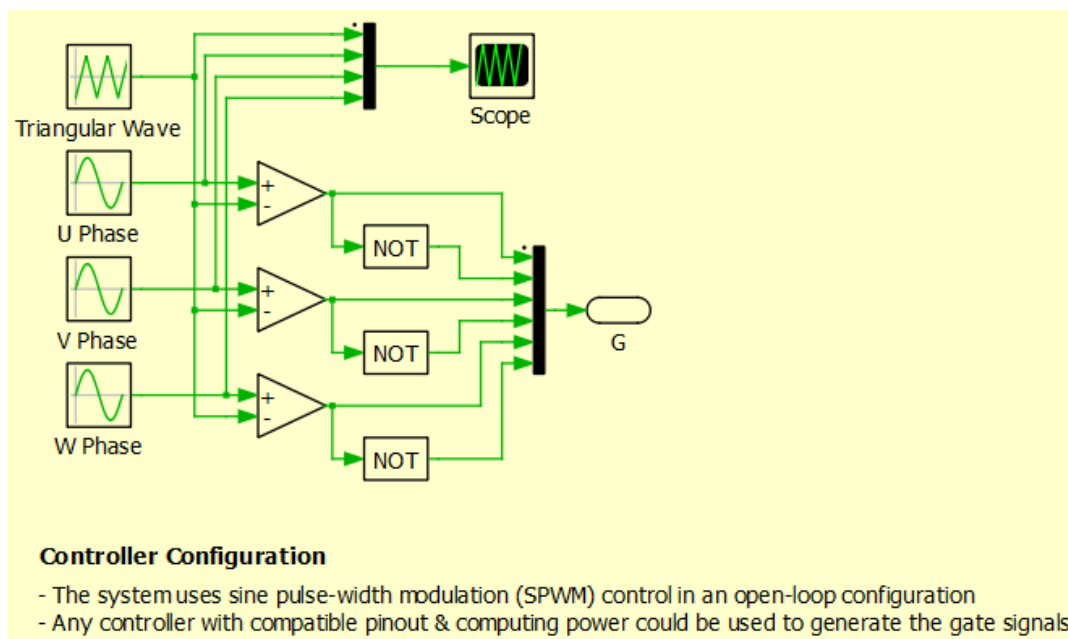


Figure 45: Gate Signals Subsystem

5.4.3 Load

The load in the simulation uses the parameters of one Würth Elektronik 760801301 inductor per phase in a wye connection. This matches the experimental setup discussed earlier in this document. The simulation is a series RL load using the nominal inductance (180 μH) and dc resistance (20 $\text{m}\Omega$) values from the inductor datasheet. The load subsystem is shown below

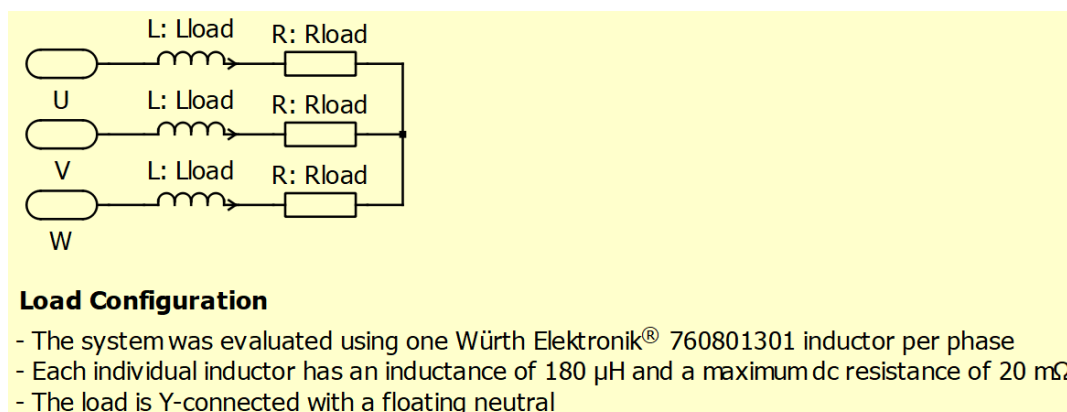


Figure 46: Load Subsystem

5.4.4 Performance Monitor

The simulation includes a subsystem to monitor the primary performance characteristics of the model (output currents, switching losses, conduction losses, and junction temperature). This subsystem is shown below.

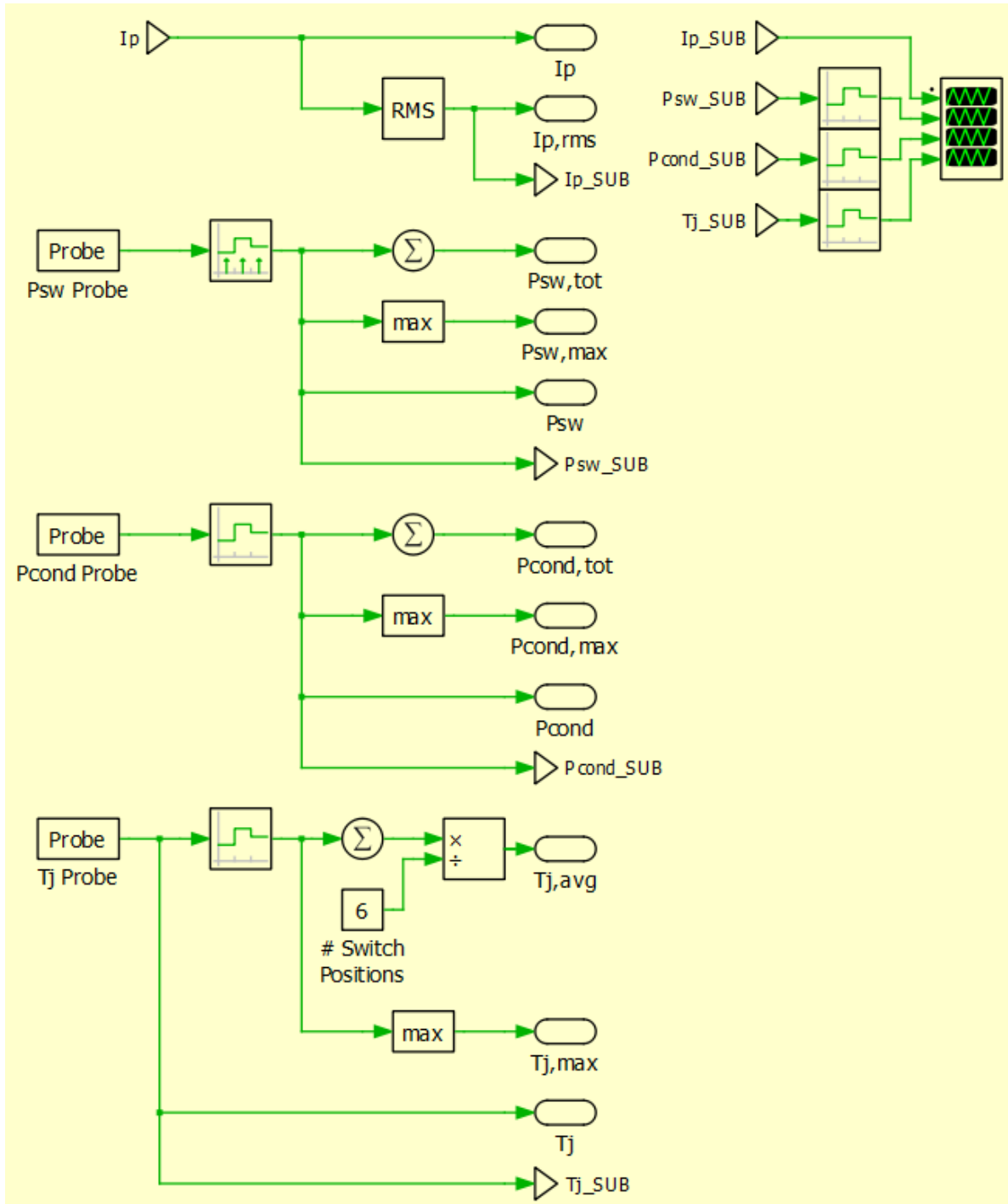


Figure 47: Simulation Performance Subsystem

5.4.5 Default Parameters

The simulation values are populated using the initialization script found by navigating to “Simulation” → “Simulation parameters...” → “Initialization”. The default parameters which have been tested are shown below. As mentioned previously, these default parameters align with the experimental testbed used to evaluate the hardware. For testing other configurations, such as changing the line frequency, users may have to adjust load parameters to properly evaluate the system at those operating conditions.

```

1 %*****
2 %***** FLAGS *****
3 %*****
4 SIMTYPE = 0; % 0: ignore thermal capacitance (faster)
5 % 1: consider thermal capacitance (important for transient analysis)
6
7 %*****
8 %***** USER DEFINED PARAMETERS *****
9 %*****
10 % defined in CAN interface
11 mf = 41; % [0-1000] modulation factor
12 fline = 300; % [Hz] output line frequency
13 fsw = 20e3; % [Hz] switching frequency
14 tdead = 300e-9; % [s] dead time
15 % defined by selected operating conditions
16 Vdc = 800; % [V] input dc voltage
17 Tamb = 25; % [C] ambient temperature
18 % defined on circuit board
19 Rgon = 0.91; % [ohm] turn-on gate resistance
20 Rgoff = 0; % [ohm] turn-off gate resistance
21
22 %*****
23 %***** DEVICE PARAMETERS *****
24 %*****
25 Ronm = 31.4e-3; % [ohm] MOSFET on resistance @30A and 125C
26 Vsd = 3.774; % [V] body diode forward voltage
27 Rond = 39.5e-3; % [ohm] diode on resistance
28 Gint = 0; % [S] MOSFET initial conductivity
29
30 %*****
31 %***** THERMAL PARAMETERS *****
32 %*****
33 Tint = Tamb; % [C] initial temperature, assume everything starts at ambient
34 Rtim = 0; % [K/W] thermal resistance of thermal interface material (TIM)
35 % default = 0 K/W since it is lumped with power module thermal impedance
36 Chs = 0; % [J/K] heat sink thermal capacitance
37 % default = 0 J/K since it is lumped with the power module thermal impedance
38 % Cauer thermal network for heat sink (see user guide for more information)
39 Rcomb1 = 0.1641; % [K/W] case-to-ambient thermal Cauer resistance 1
40 Rcomb2 = 0.2733; % [K/W] case-to-ambient thermal Cauer resistance 2
41 Rcomb3 = 0.0157; % [K/W] case-to-ambient thermal Cauer resistance 3
42 Rcomb4 = 0.08574; % [K/W] case-to-ambient thermal Cauer resistance 4
43 if SIMTYPE == 0 % ignore thermal capacitance (faster)
44 Ccomb1 = 0; % [J/K] case-to-ambient thermal Cauer capacitance 1
45 Ccomb2 = 0; % [J/K] case-to-ambient thermal Cauer capacitance 2
46 Ccomb3 = 0; % [J/K] case-to-ambient thermal Cauer capacitance 3
47 Ccomb4 = 0; % [J/K] case-to-ambient thermal Cauer capacitance 4
48 elseif SIMTYPE == 1 % consider thermal capacitance (important for transient analysis)
49 Ccomb1 = 31.46; % [J/K] case-to-ambient thermal Cauer capacitance 1
50 Ccomb2 = 195.5; % [J/K] case-to-ambient thermal Cauer capacitance 2
51 Ccomb3 = 394.8; % [J/K] case-to-ambient thermal Cauer capacitance 3
52 Ccomb4 = 1224; % [J/K] case-to-ambient thermal Cauer capacitance 4
53 end
54 mosfet = 'file:CCB021M12FM3'; % [.xml] MOSFET thermal model
55 diode = 'file:CCB021M12FM3_bodydiode'; % [.xml] body diode thermal model
56
57 %*****
58 %***** OPERATING PARAMETERS *****
59 %*****
60 Lload = 180e-6; % [H] line-to-neutral load inductance (Würth Elektronik 760801301)
61 Rload = 20e-3; % [ohm] load resistance (Würth Elektronik 760801301)
62 Iint = 0; % [A] initial load current
63 Vn = Vdc/2; % [V] initial voltage of neutral forming capacitors
64 Cbus = 195e-6; % [F] dc bus capacitance on reference design
65 Rmeas = 0.1e-3; % [R] resistor to split dc voltage and capacitors
66 phs = 236; % [degree] phase shift of reference sine waves
67 % used to time align simulation and experimental data comparisons

```

Figure 48: Default Simulation Parameters

5.4.6 Validation

The performance of the simulation can be easily evaluated using the “Compare to Experimental Data” section of the simulation. One configuration of this subsystem is shown below. This subsystem imports experimentally measured output currents from a stored CSV file and compares the simulated output currents to this imported data. The imported data is from the same setup as described in the “Experiment Validation” section of this document. Note that the data is down sampled from the original sampling rate to reduce the CSV file size.

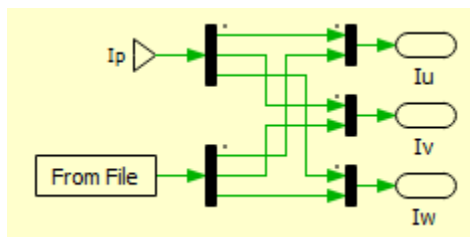


Figure 49: Compare Experimental Data Subsystem

By clicking on the configurable subsystem, users can select experimental data to compare against the simulation results. Each file is saved by the name “XXkHz, YYmf, ZZA” where XX is the experimental data switching frequency (kHz), YY is the modulation factor (unitless, 0-1000), and ZZ is the output current (A_{rms}). For these comparisons to be viewed properly, users need to ensure that the switching frequency (f_{sw}) and modulation factor (mf) in the initialization script match the selected configuration settings and all other settings are set to the default values. An example comparison for $f_{sw} = 20$ kHz, mf = 41 is shown below. The green waveforms are the simulated values and the red waveforms are the experimental values.

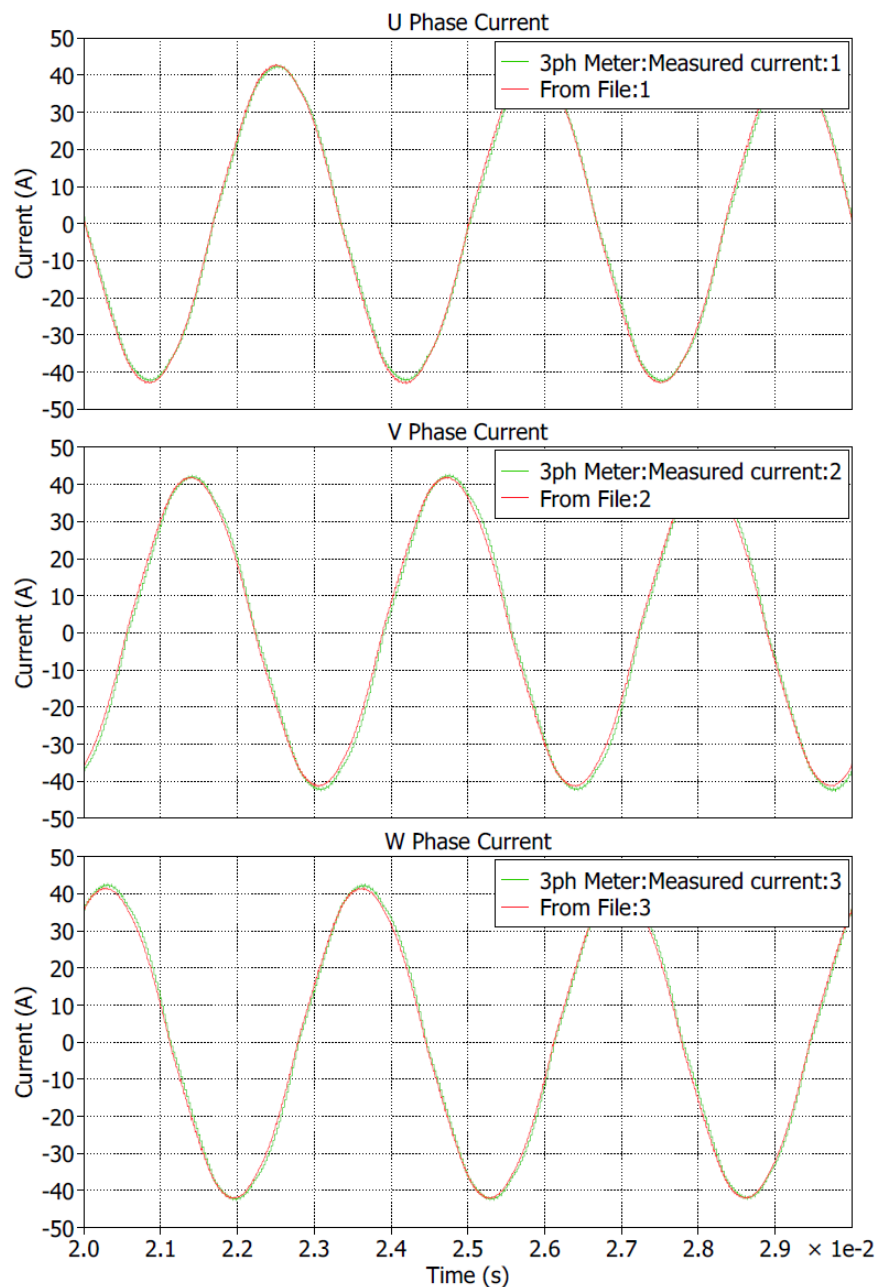


Figure 50: Example Simulation Validation

5.4.7 Efficiency Predictions

Using the simulation and the empirically measured thermal network, the system efficiency can be predicted. The results of this analysis are shown in Figure 51. At full load, the system is over 98% efficient across the complete range of rated switching frequencies. Additionally, at the default system switching frequency of 20 kHz, the system operates above 99% efficiency from 5 kW to 25 kW, peaking at 99.5% efficiency.

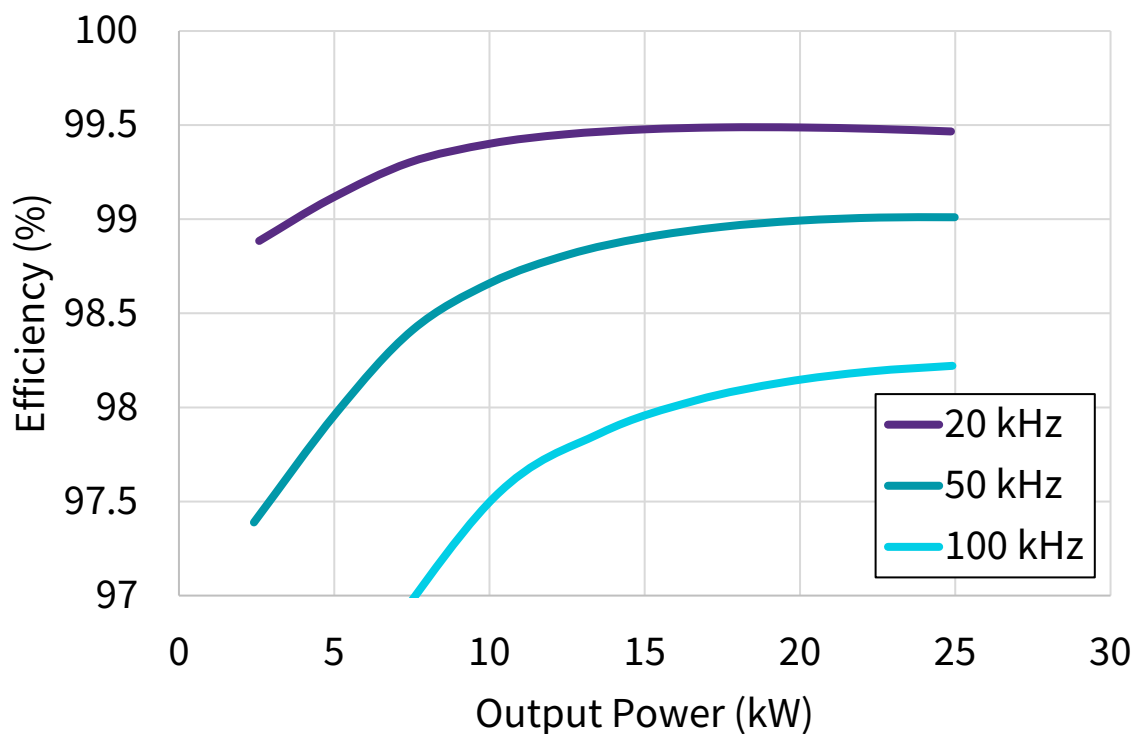
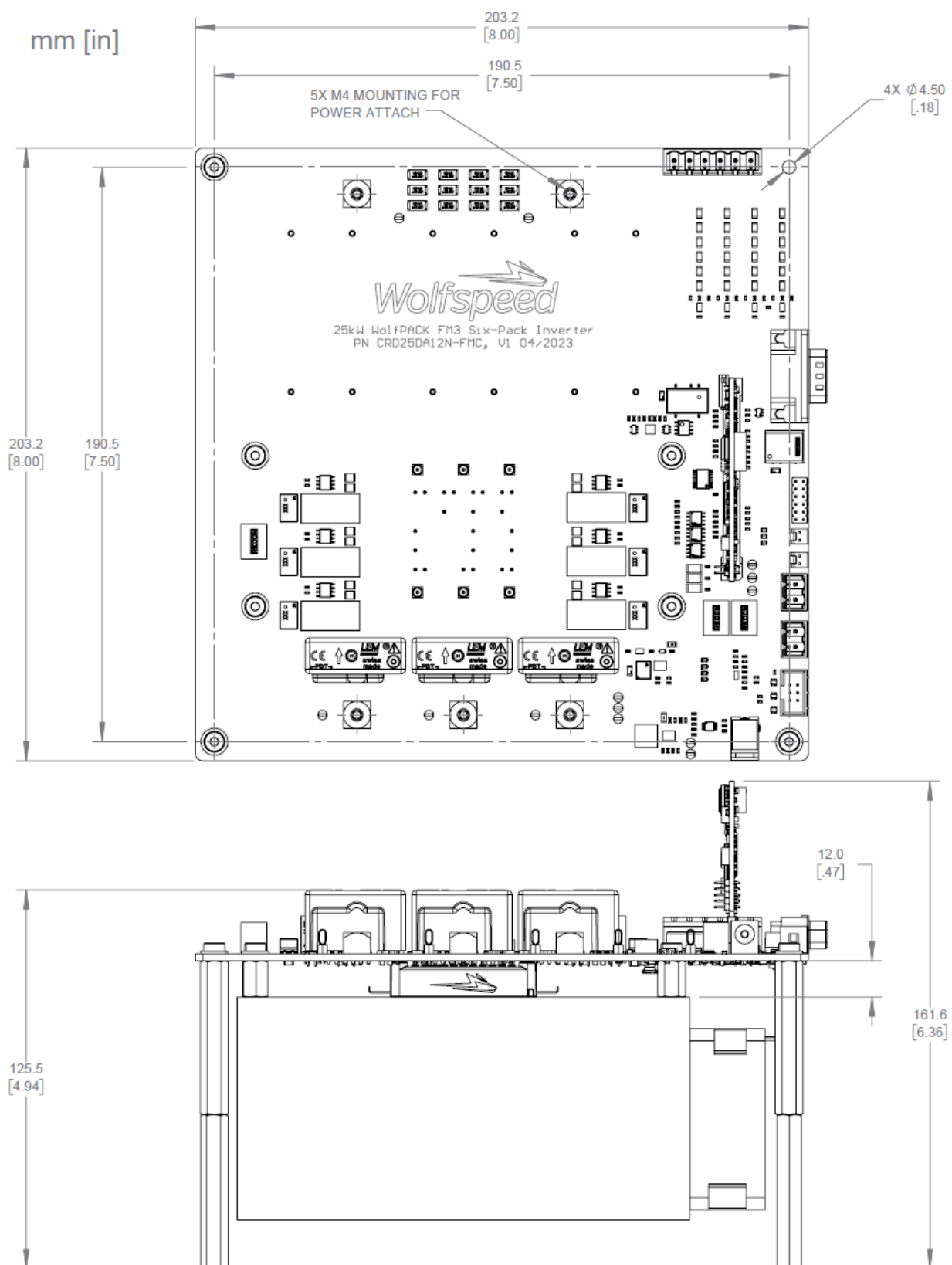


Figure 51: Predicted System Efficiency Based on Simulation for $T_{ambient} = 25^{\circ}C$

6. MECHANICAL ASSEMBLY



REVISION HISTORY

Date	Revision	Changes
May 2023	Rev. 0	Initial Release
Sept 2023	Rev. 1	Formatted to match updated Wolfspeed template Updated Controller section to include firmware and GUI, now called Controller and Firmware Added Performance Data section covering heatsink, inductance, experimental validation, thermal SOA and simulation details

IMPORTANT NOTES

PURPOSES AND USE

Wolfspeed, Inc. (on behalf of itself and its affiliates, “Wolfspeed”) reserves the right in its sole discretion to make corrections, enhancements, improvements, or other changes to the board or to discontinue the board.

THE BOARD DESCRIBED IS AN ENGINEERING TOOL INTENDED SOLELY FOR LABORATORY USE BY HIGHLY QUALIFIED AND EXPERIENCED ELECTRICAL ENGINEERS TO EVALUATE THE PERFORMANCE OF WOLFSPEED POWER SWITCHING DEVICES. THE BOARD SHOULD NOT BE USED AS ALL OR PART OF A FINISHED PRODUCT. THIS BOARD IS NOT SUITABLE FOR SALE TO OR USE BY CONSUMERS AND CAN BE HIGHLY DANGEROUS IF NOT USED PROPERLY. THIS BOARD IS NOT DESIGNED OR INTENDED TO BE INCORPORATED INTO ANY OTHER PRODUCT FOR RESALE. THE USER SHOULD CAREFULLY REVIEW THE DOCUMENT TO WHICH THESE NOTIFICATIONS ARE ATTACHED AND OTHER WRITTEN USER DOCUMENTATION THAT MAY BE PROVIDED BY WOLFSPEED (TOGETHER, THE “DOCUMENTATION”) PRIOR TO USE. USE OF THIS BOARD IS AT THE USER’S SOLE RISK.

OPERATION OF BOARD

It is important to operate the board within Wolfspeed’s recommended specifications and environmental considerations as described in the Documentation. Exceeding specified ratings (such as input and output voltage, current, power, or environmental ranges) may cause property damage. If you have questions about these ratings, please contact Wolfspeed prior to connecting interface electronics (including input power and intended loads). Any loads applied outside of a specified output range may result in adverse consequences, including unintended or inaccurate evaluations or possible permanent damage to the board or its interfaced electronics. Please consult the Documentation prior to connecting any load to the board. If you have any questions about load specifications for the board, please contact Wolfspeed at forum.wolfspeed.com for assistance.

Users should ensure that appropriate safety procedures are followed when working with the board as serious injury, including death by electrocution or serious injury by electrical shock or electrical burns can occur if you do not follow proper safety precautions. It is not necessary in proper operation for the user to touch the board while it is energized. When devices are being attached to the board for testing, the board must be disconnected from the electrical source and any bulk capacitors must be fully discharged. When the board is connected to an electrical source and for a short time thereafter until board components are fully discharged, some board components will be electrically charged and/or have temperatures greater than 50° Celsius. These components may include bulk capacitors, connectors, linear regulators, switching transistors, heatsinks, resistors and SiC diodes that can be identified using board schematic. Users should contact Wolfspeed for assistance if a board schematic is not included in the Documentation or if users have questions about a board’s components. When operating the board, users should be aware that these components will be hot and could electrocute or electrically shock the user. As with all electronic evaluation tools, only qualified personnel knowledgeable in handling electronic performance evaluation, measurement, and diagnostic tools should use the board.

USER RESPONSIBILITY FOR SAFE HANDLING AND COMPLIANCE WITH LAWS

Users should read the Documentation and, specifically, the various hazard descriptions and warnings contained in the Documentation, prior to handling the board. The Documentation contains important safety information about voltages and temperatures.

Users assume all responsibility and liability for the proper and safe handling of the board. Users are responsible for complying with all safety laws, rules, and regulations related to the use of the board. Users are responsible for (1) establishing protections and safeguards to ensure that a user's use of the board will not result in any property damage, injury, or death, even if the board should fail to perform as described, intended, or expected, and (2) ensuring the safety of any activities to be conducted by the user or the user's employees, affiliates, contractors, representatives, agents, or designees in the use of the board. User questions regarding the safe usage of the board should be directed to Wolfspeed at forum.wolfspeed.com.

In addition, users are responsible for:

- compliance with all international, national, state, and local laws, rules, and regulations that apply to the handling or use of the board by a user or the user's employees, affiliates, contractors, representatives, agents, or designees.
- taking necessary measures, at the user's expense, to correct radio interference if operation of the board causes interference with radio communications. The board may generate, use, and/or radiate radio frequency energy, but it has not been tested for compliance within the limits of computing devices pursuant to Federal Communications Commission or Industry Canada rules, which are designed to provide protection against radio frequency interference.
- compliance with applicable regulatory or safety compliance or certification standards that may normally be associated with other products, such as those established by EU Directive 2011/65/EU of the European Parliament and of the Council on 8 June 2011 about the Restriction of Use of Hazardous Substances (or the RoHS 2 Directive) and EU Directive 2002/96/EC on Waste Electrical and Electronic Equipment (or WEEE). The board is not a finished end product and therefore may not meet such standards. Users are also responsible for properly disposing of a board's components and materials.

NO WARRANTY

THE BOARD IS PROVIDED "AS IS" WITHOUT WARRANTY OF ANY KIND, INCLUDING BUT NOT LIMITED TO ANY WARRANTY OF NON-INFRINGEMENT, MERCHANTABILITY, OR FITNESS FOR A PARTICULAR PURPOSE, WHETHER EXPRESS OR IMPLIED. THERE IS NO REPRESENTATION THAT OPERATION OF THIS BOARD WILL BE UNINTERRUPTED OR ERROR FREE.

LIMITATION OF LIABILITY

IN NO EVENT SHALL WOLFSPEED BE LIABLE FOR ANY DAMAGES OF ANY KIND ARISING FROM USE OF THE BOARD. WOLFSPEED'S AGGREGATE LIABILITY IN DAMAGES OR OTHERWISE SHALL IN NO EVENT EXCEED THE AMOUNT, IF ANY, RECEIVED BY WOLFSPEED IN EXCHANGE FOR THE BOARD. IN NO EVENT SHALL WOLFSPEED BE LIABLE FOR INCIDENTAL, CONSEQUENTIAL, OR SPECIAL LOSS OR DAMAGES OF ANY KIND, HOWEVER CAUSED, OR ANY PUNITIVE, EXEMPLARY, OR OTHER DAMAGES. NO ACTION, REGARDLESS OF FORM, ARISING OUT OF OR IN ANY WAY CONNECTED WITH ANY BOARD FURNISHED BY WOLFSPEED MAY BE BROUGHT AGAINST WOLFSPEED MORE THAN ONE (1) YEAR AFTER THE CAUSE OF ACTION ACCRUED.

INDEMNIFICATION

The board is not a standard consumer or commercial product. As a result, any indemnification obligations imposed upon Wolfspeed by contract with respect to product safety, product liability, or intellectual property infringement do not apply to the board.