USER GUIDE PRD-07560

CRD25DA12N-FMC 25 kW Three-Phase Inverter

CRD25DA12N-FMC 25 kW 三相逆变器

CRD25DA12N-FMC 25 kW 三相インバーター

User Guide
Wolfspeed Power Applications

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

All parts of this application note 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.

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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-40ºC~105ºC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るべき。ハードウエ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.

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。

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。

CAUTION

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件。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

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ー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

This user guide provides an overview of Wolfspeed's 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 CCB021M12FM3 (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.

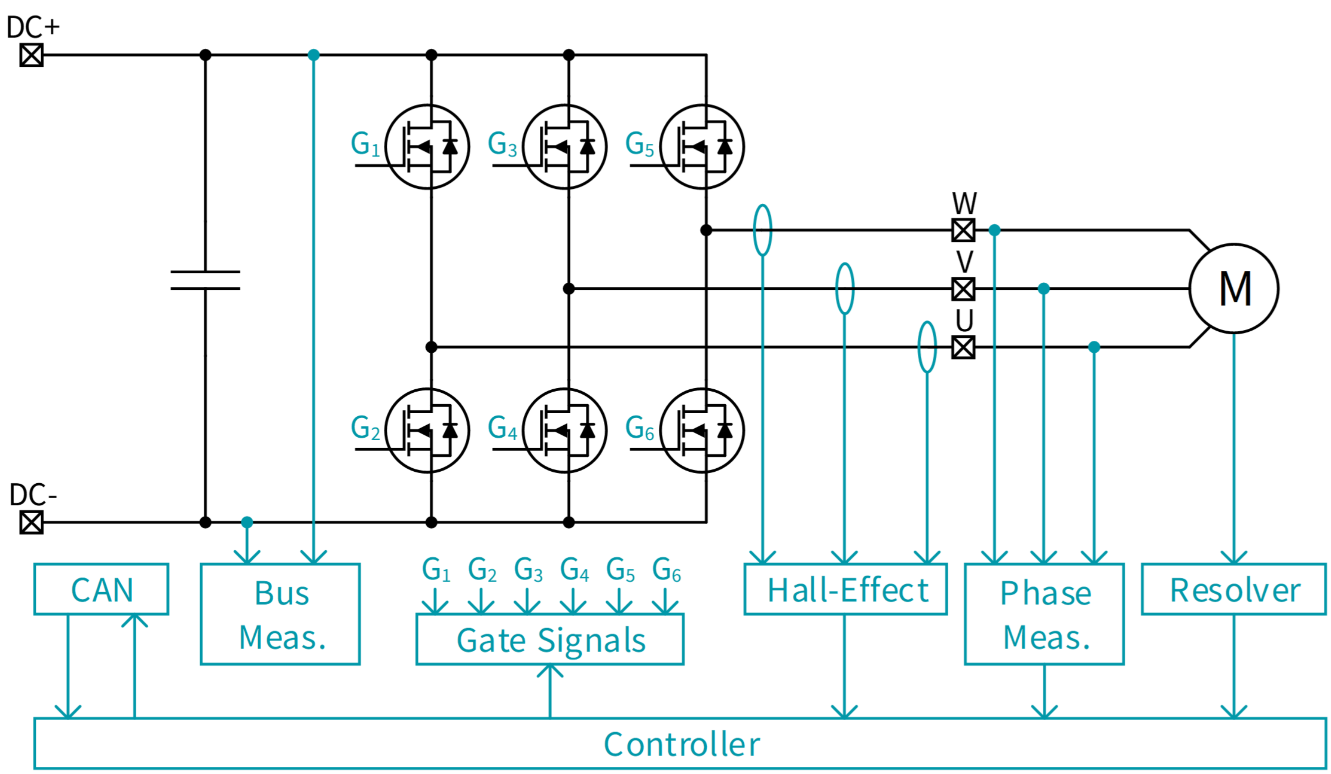


Figure 1: CRD25DA12N-FMC Block Diagram

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 CCB021M12FM3 (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	—	20	100	kHz

2.2. Subsystem Functional Groups

The figures below show the system blocks that makeup the evaluation board from a top-side perspective and a side view. Table 2 describes each labelled subsystem.

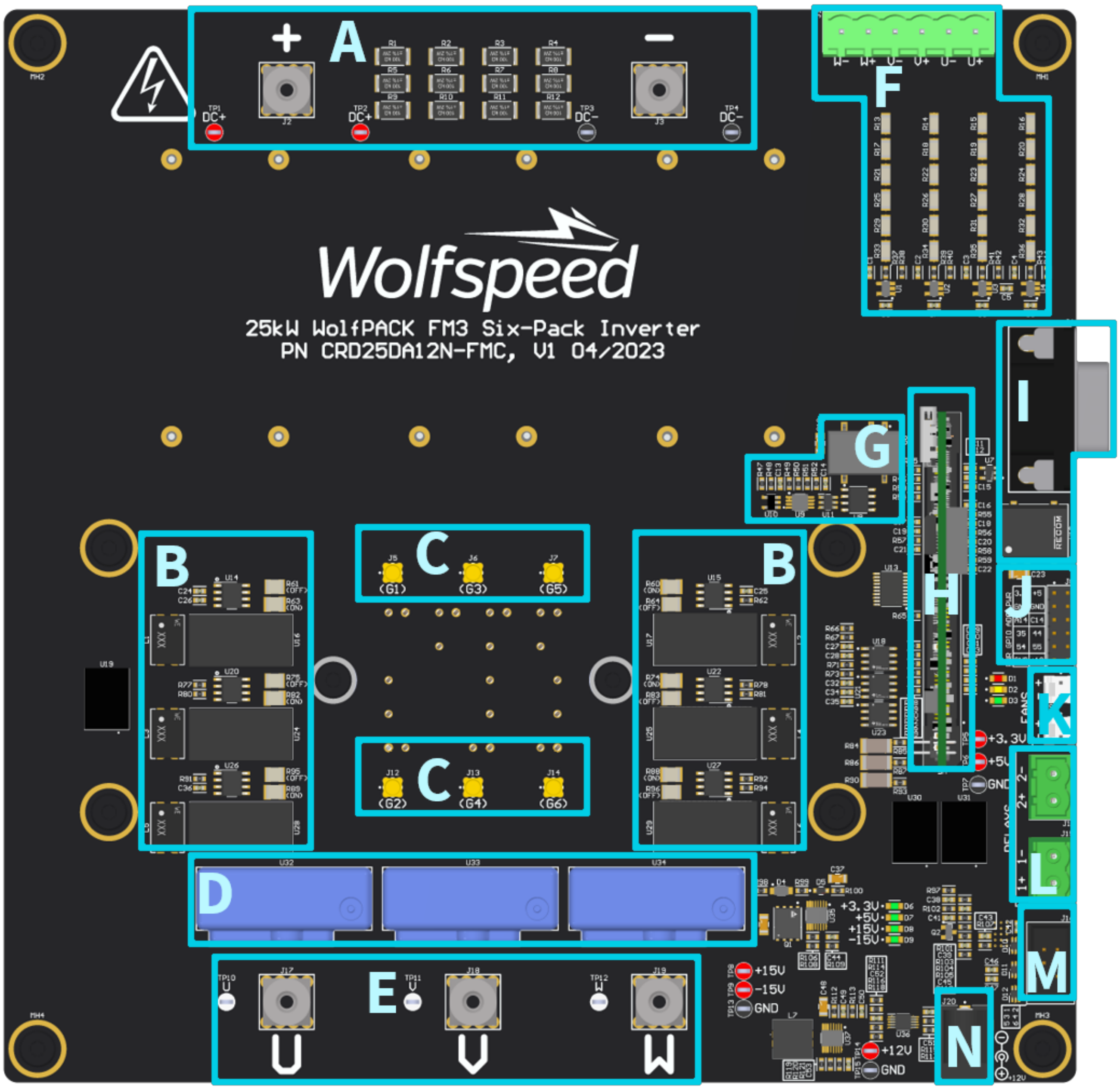


Figure 2: CRD25DA12N-FMC Top View

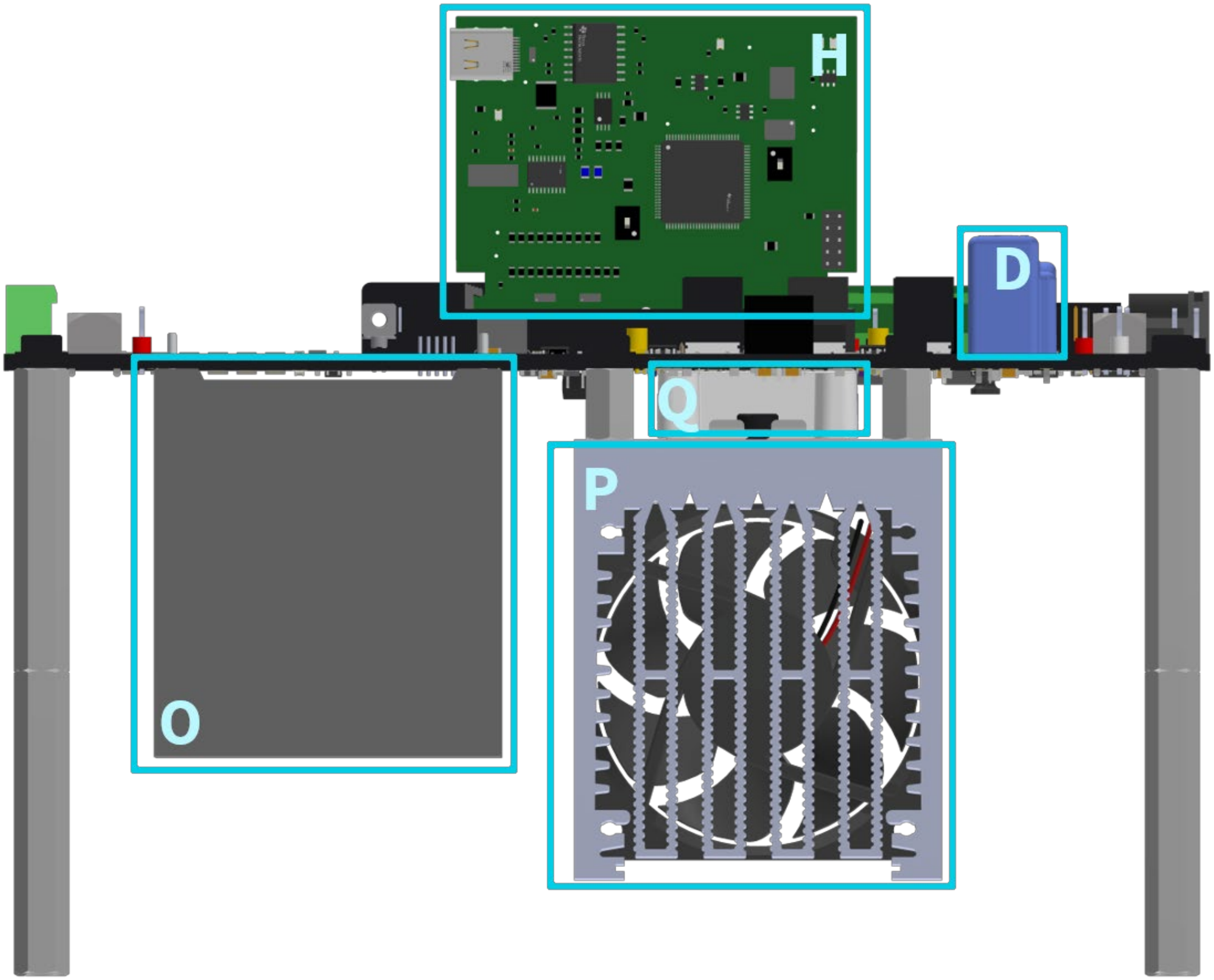


Figure 3: CRD25DA12N-FMC Side View

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	Control Card
I	Isolated CAN
J	Spare ADCs and GPIOs
K	Fan Power
L	Relay Control
M	Encoder Feedback
N	+12V Input Power
O	Bulk DC-Link Capacitor
P	Aluminum Heatsink
Q	Wolfspeed CCB032M12FM3 SiC 1.2kV Six-Pack 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.

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.

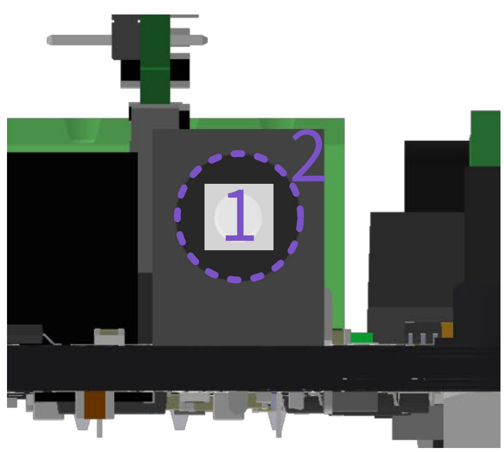


Figure 4: J20 Input Power Connector Pin Numbers

Table 3: J20 Input Power Connector Pinout

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

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.

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.

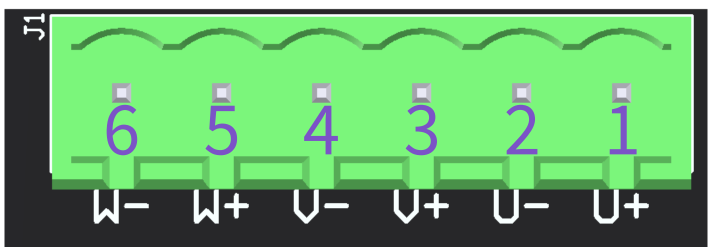


Figure 5: J1 Voltage Feedback Connector Pin Numbers

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

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.

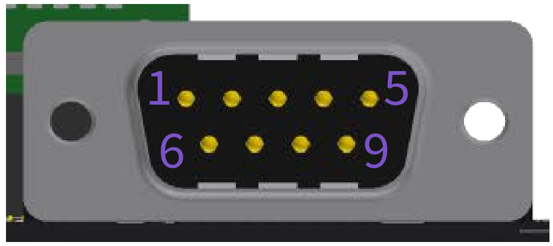


Figure 6: J4 CAN Port Pin Numbers

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

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.

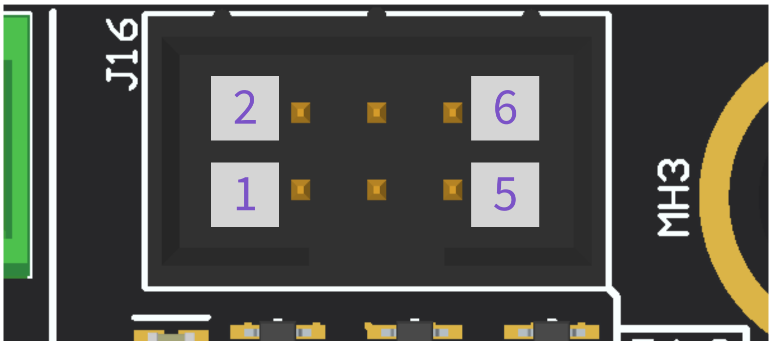


Figure 7: J16 Resolver Connector Pin Numbers

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

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.

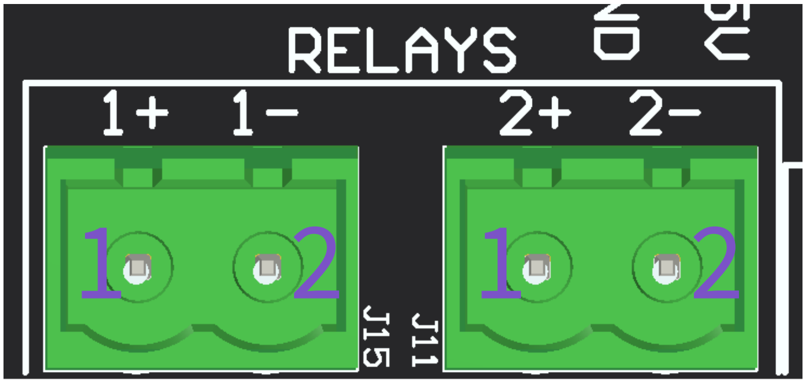


Figure 8: J11 and J15 Relay Connector Pin Numbers

Table 7: J11 and J15 Relay Connector Pinout

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

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.

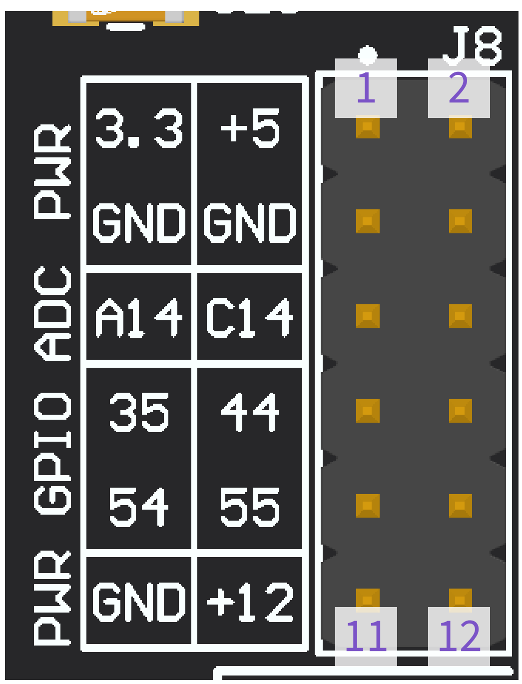


Figure 9: J8 Spare Connector Pin Numbers

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

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.

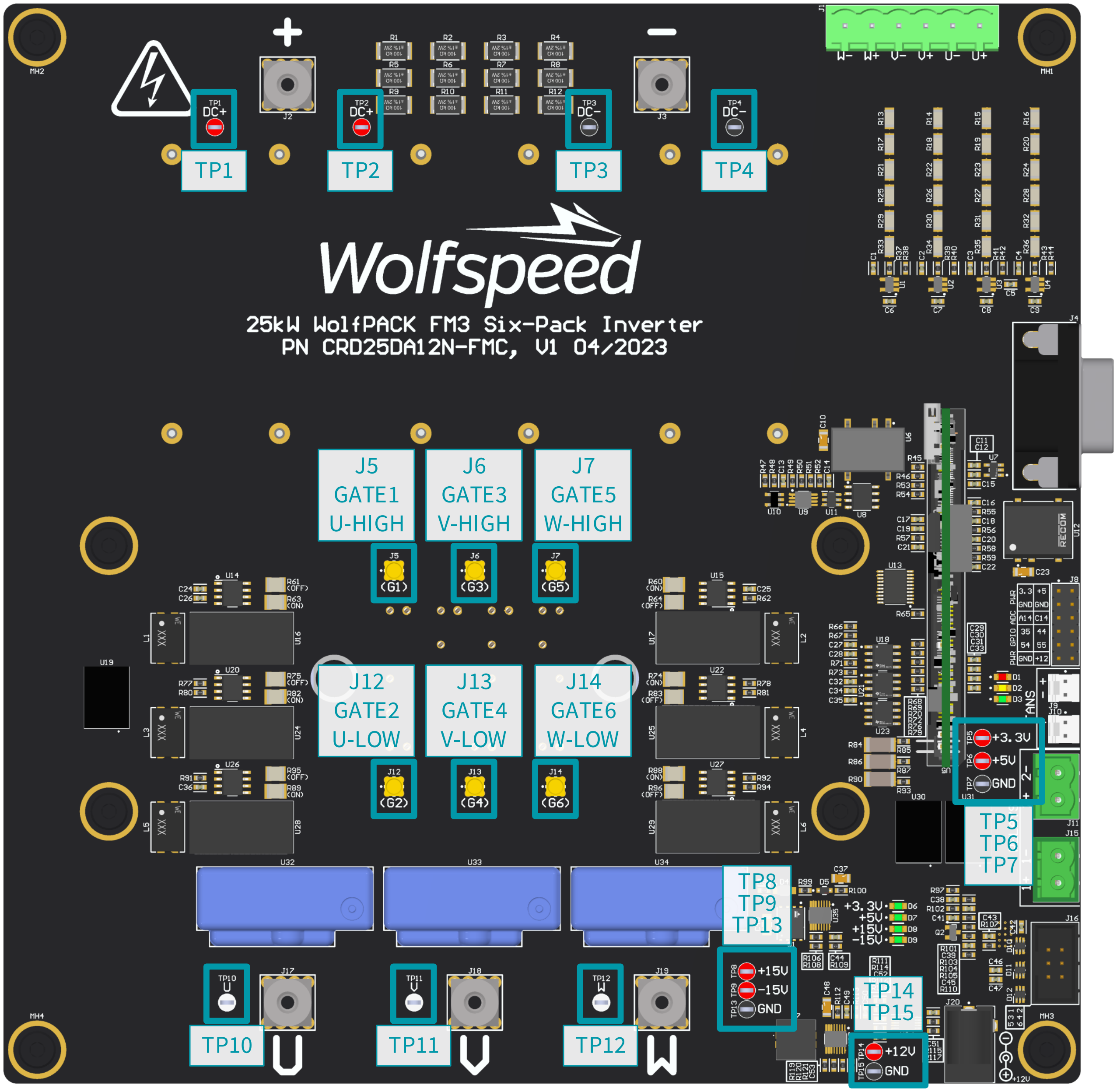


Figure 10: Gate and Test Point Measurement Locations

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

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 MUCH BE FULLY DISCHARGED.

SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50^{0} 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。

警告

通電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。通電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.

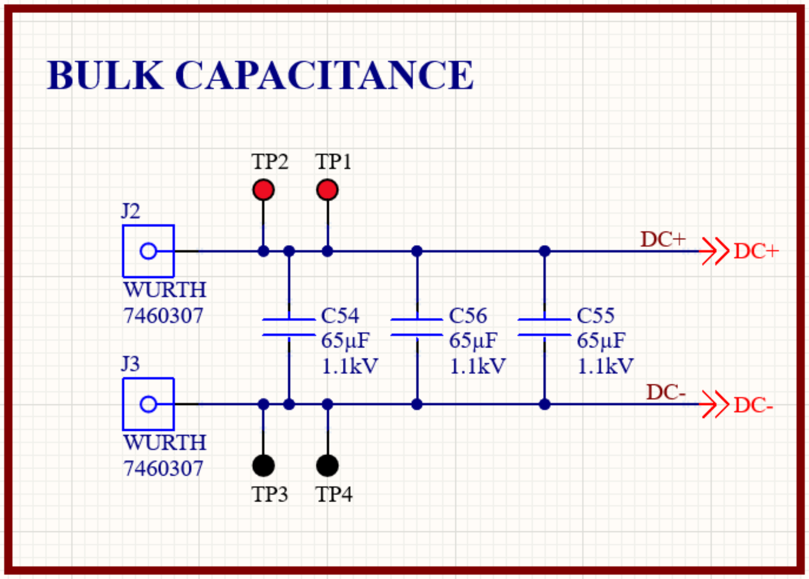


Figure 11: DC Bus Circuitry

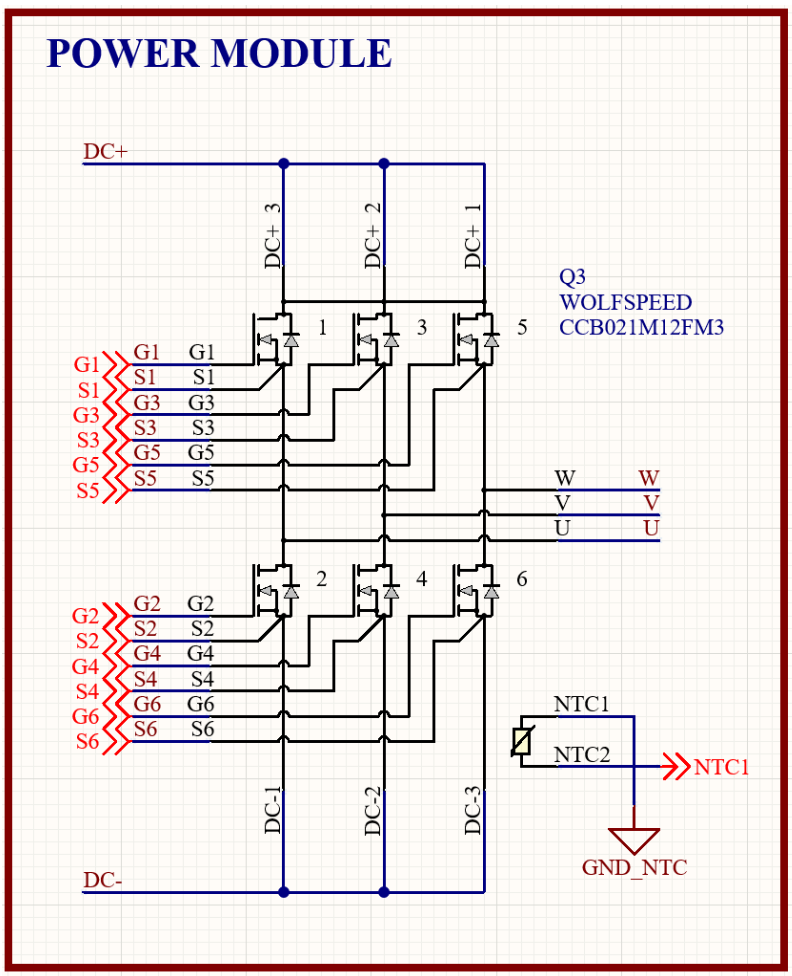


Figure 12: Wolfspeed CCB021M12FM3 Power Module Circuit Connections

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+

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.

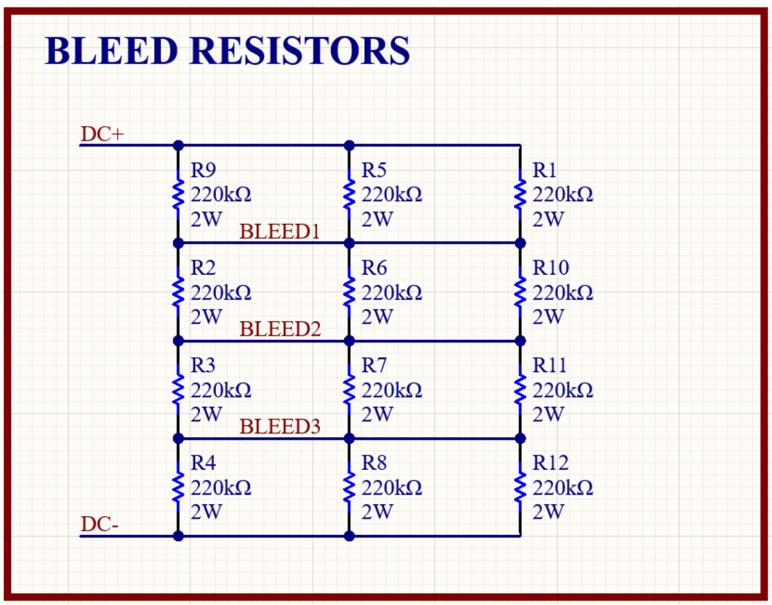


Figure 13: Bleed Resistors Connected to DC Bus

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.

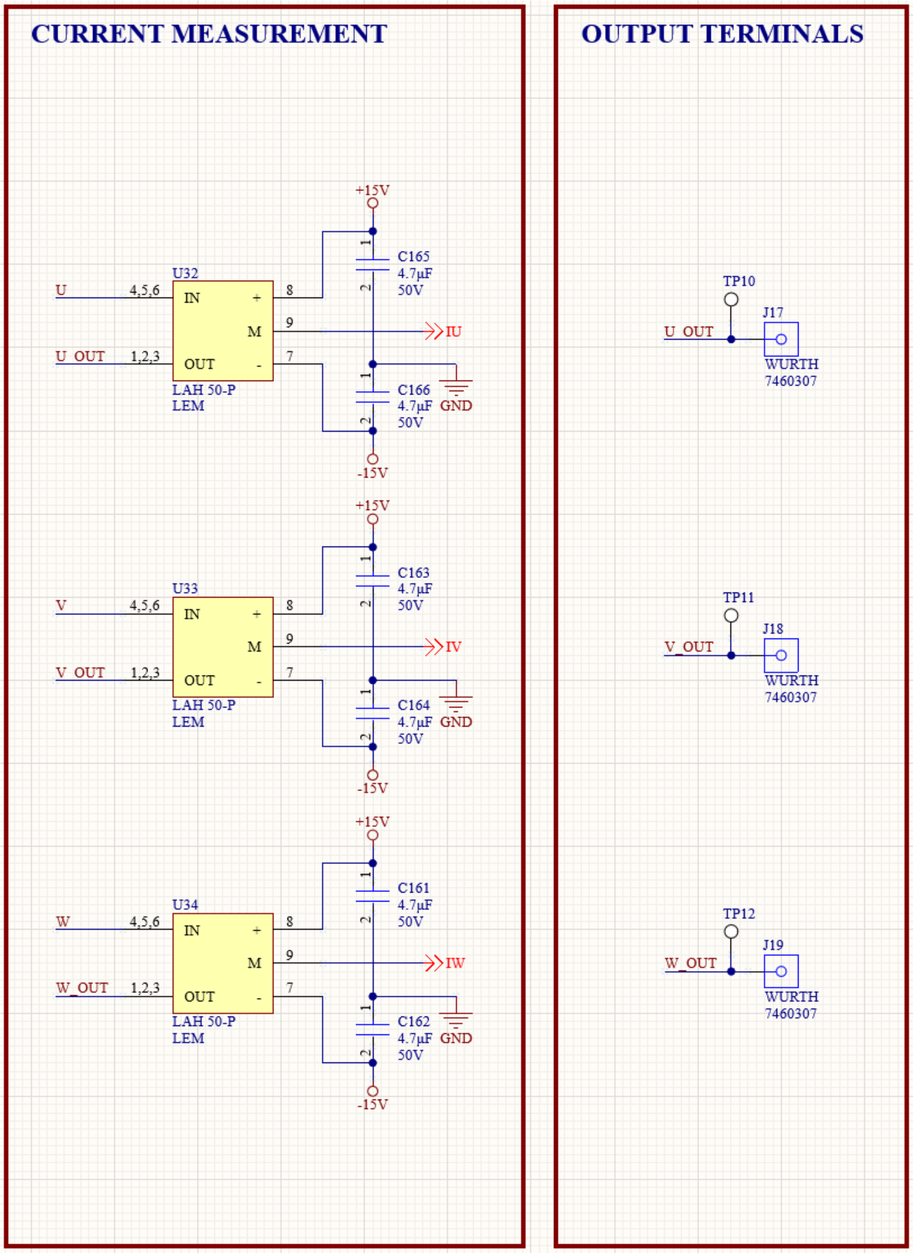


Figure 14: Output Hall-Effect Sensor Power Connections

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.

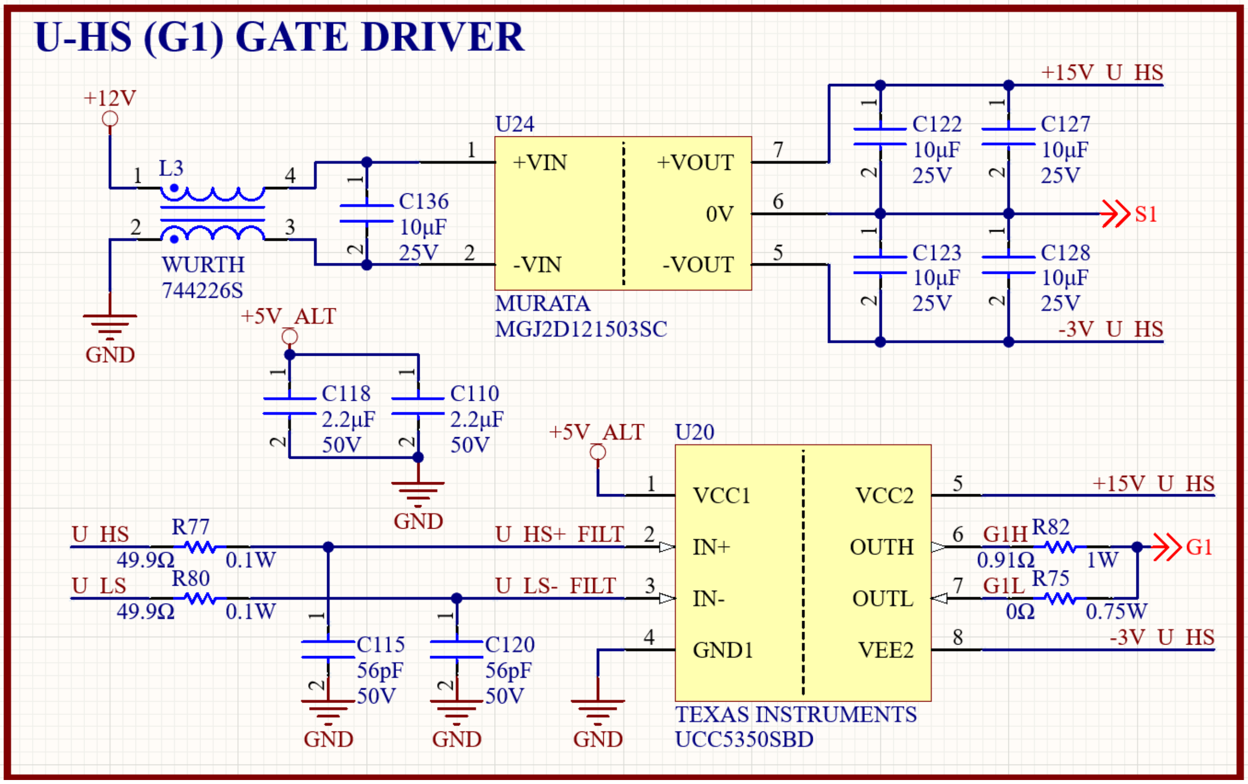


Figure 15: Gate Driver Circuit for One MOSFET Switch Position

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 Ω turn-on resistor and a 0 Ω 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 °C)	—	—	±5	A
$V_{GATE,HIGH}$	High Level Output Voltage	—	15	—	V
$V_{GATE,LOW}$	Low Level Output Voltage	—	-3	—	V
$R_{G(EXT)-ON}$	External Turn-On Resistance	—	0.91	—	Ω
$R_{G(EXT)-OFF}$	External Turn-Off Resistance	—	0	—	Ω

[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 ±15 V power rails which power the sensors. The power connections for one of the hall-effect transducers are shown below.

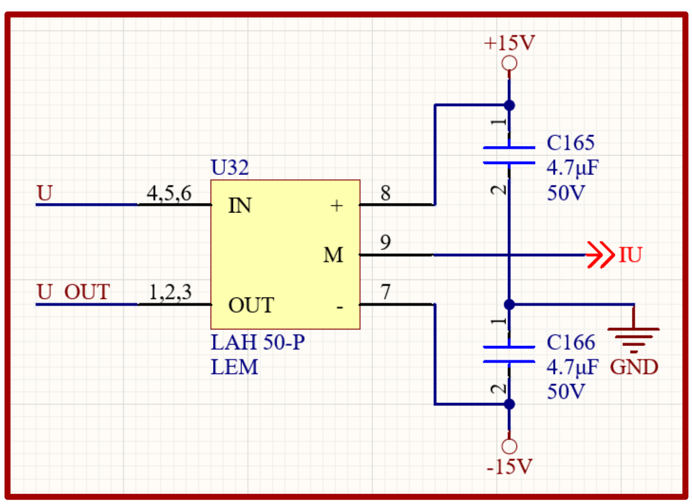


Figure 16: Hall-Effect Transducer Power Connections

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.

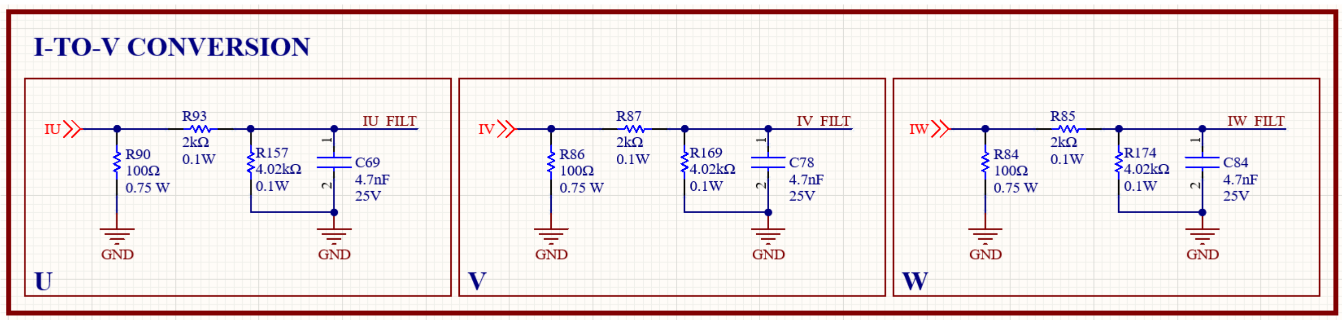


Figure 17: Current Measurement Conversion to Voltage and Filtering

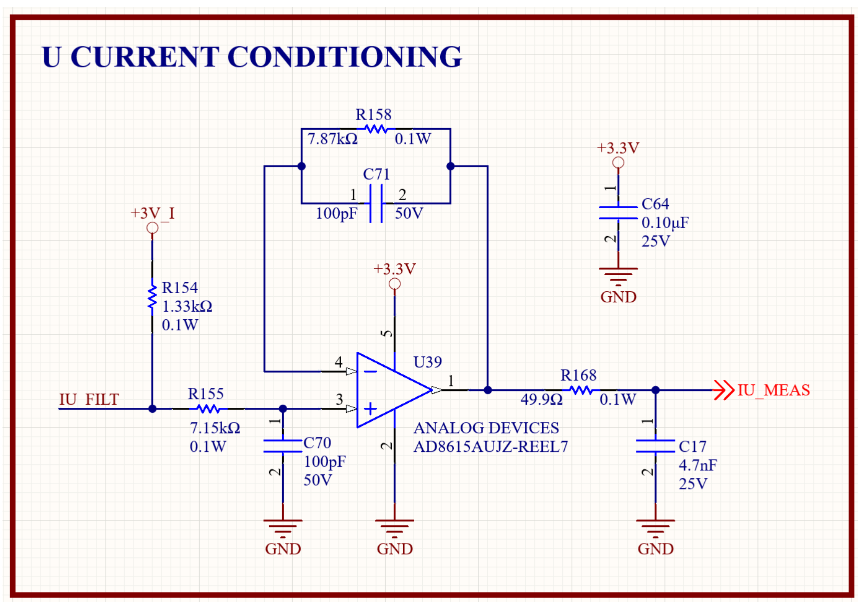


Figure 18: Current Measurement Conditioning

In additional 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.

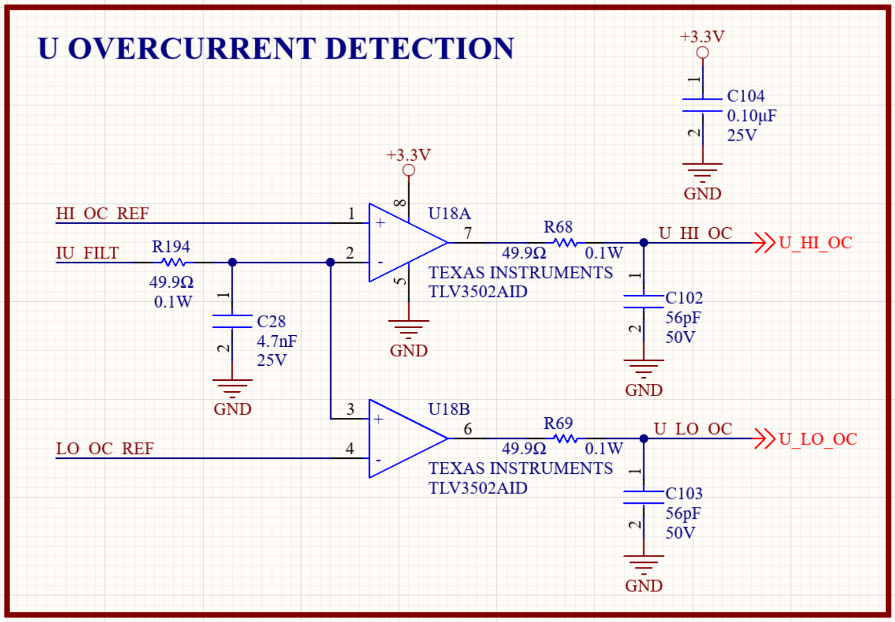


Figure 19: Overcurrent Detection Circuit

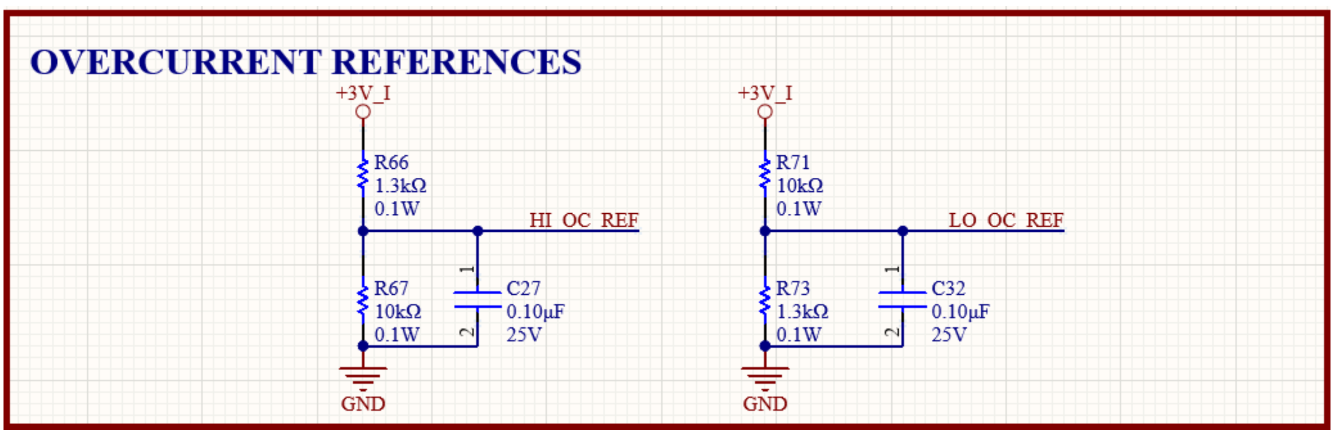


Figure 20: Overcurrent Trip References

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.

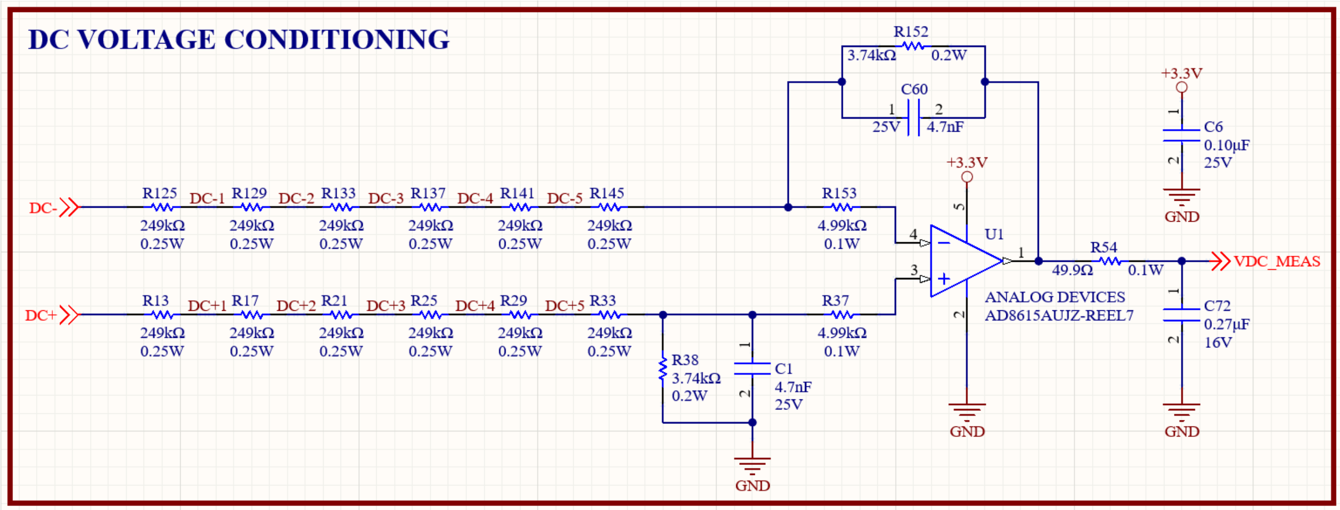


Figure 21: Differential DC Voltage Conditioning

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.

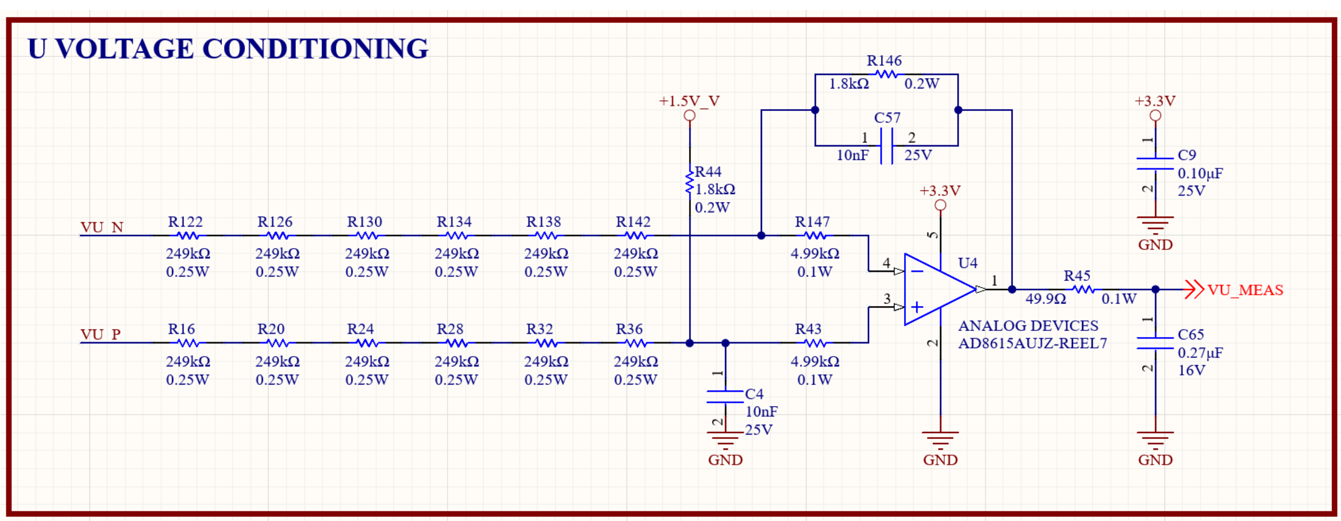


Figure 22: Differential Phase Voltage Conditioning

3.5. NTC

The CCB021M12FM3 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.

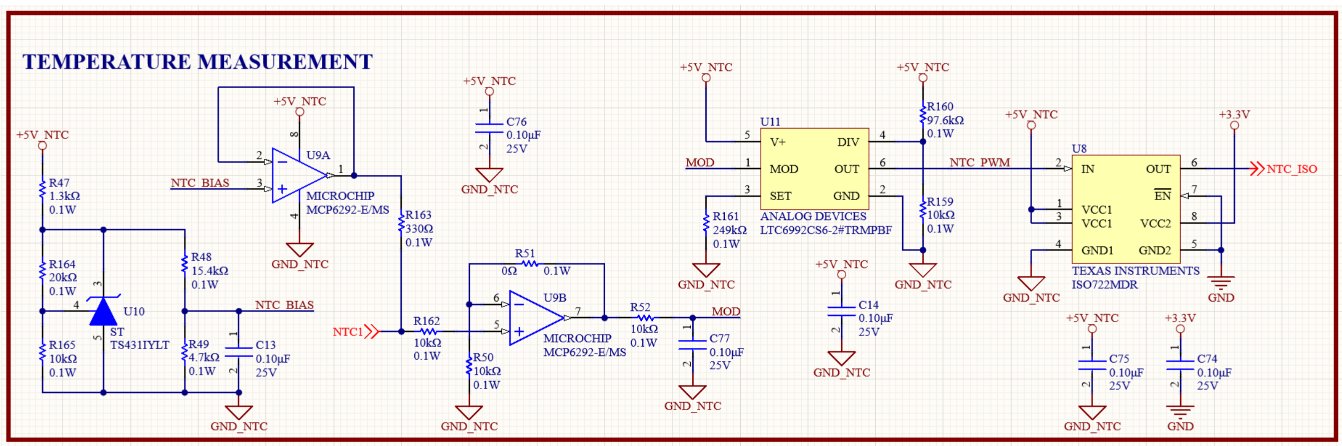


Figure 23: NTC Measuring Circuit

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.

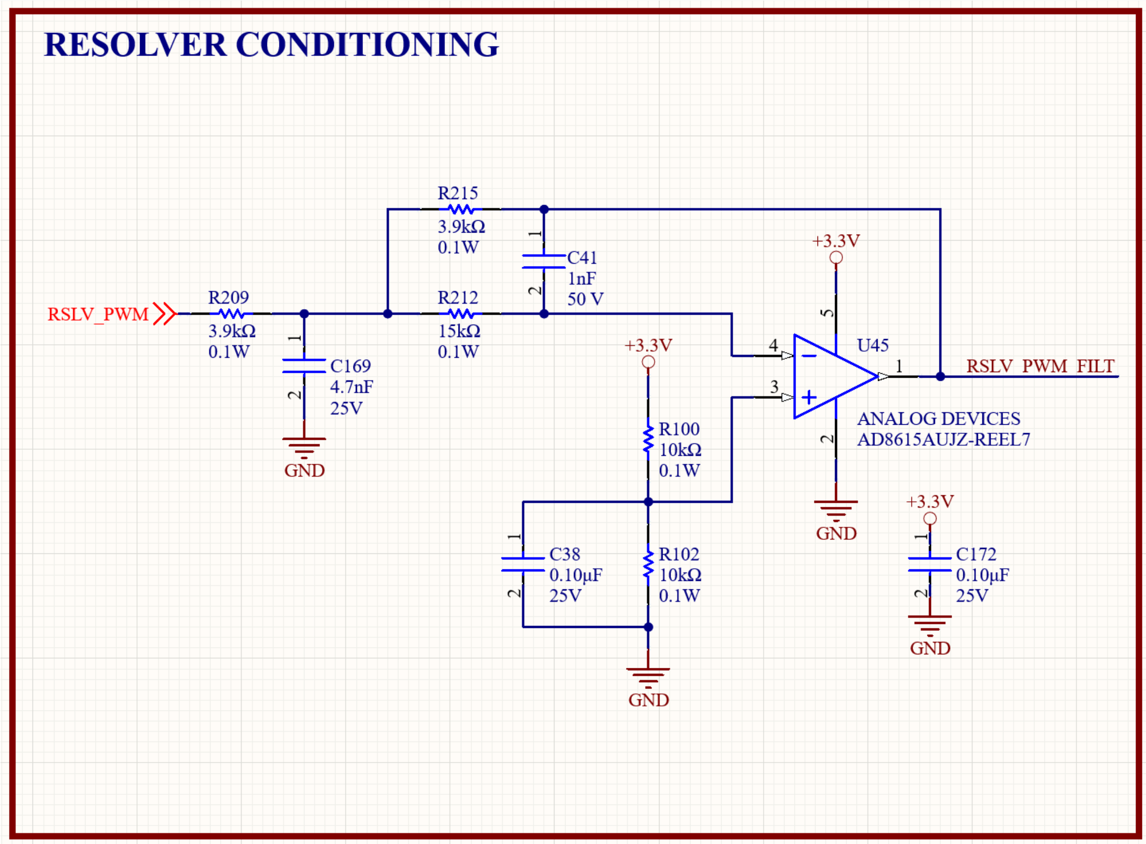


Figure 24: Resolver PWM to Sinewave

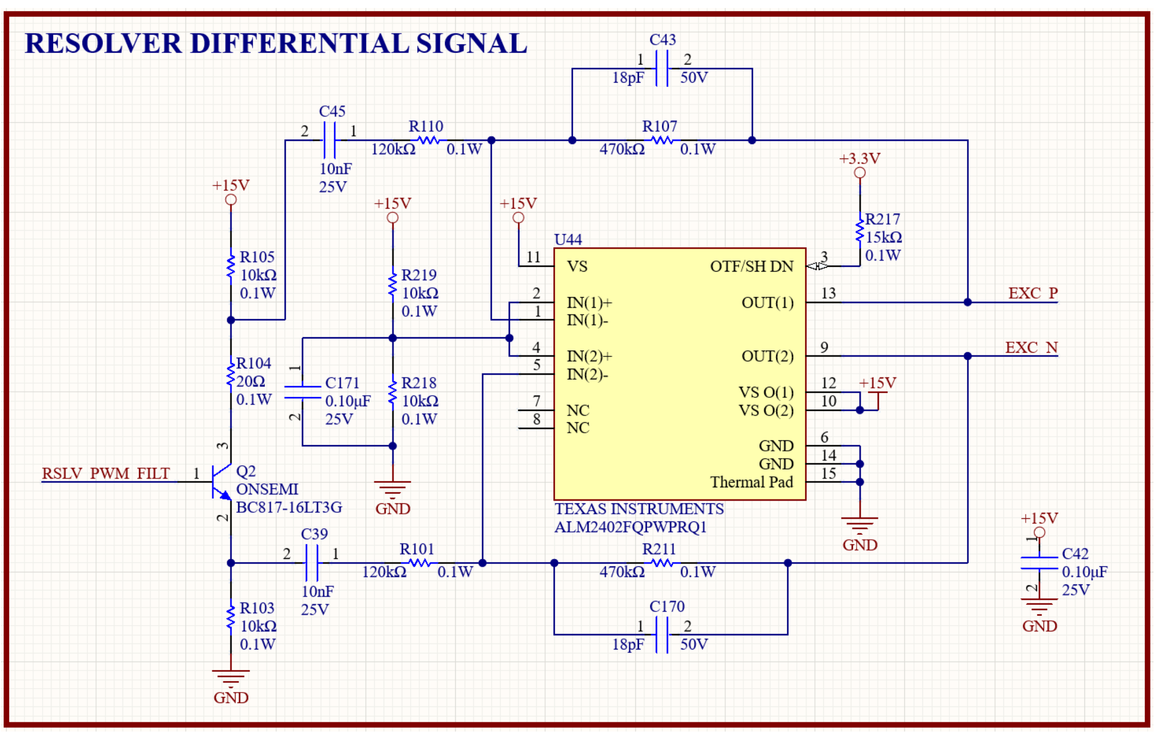


Figure 25: Resolver Excitation Amplifier

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.

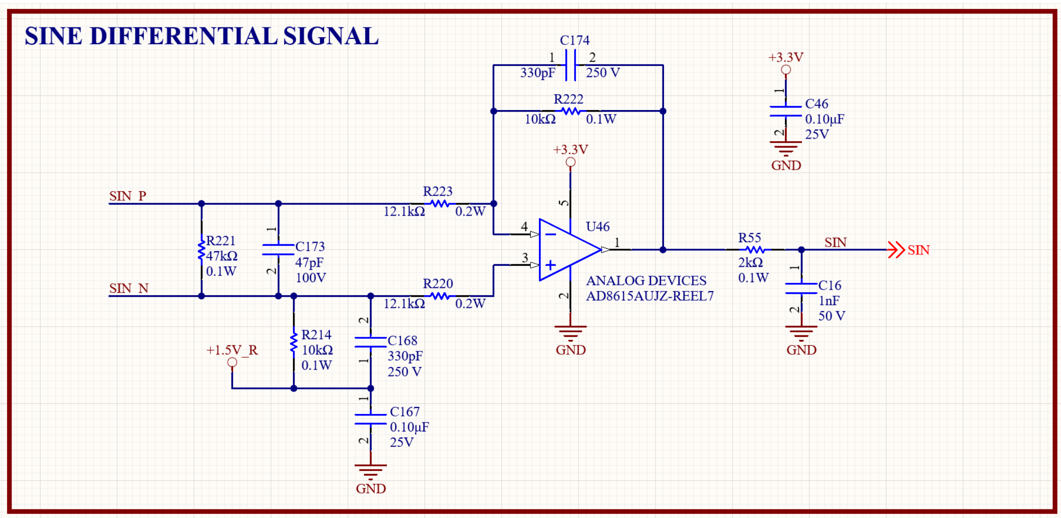


Figure 26: Resovler Sine Signal Conditioning

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.

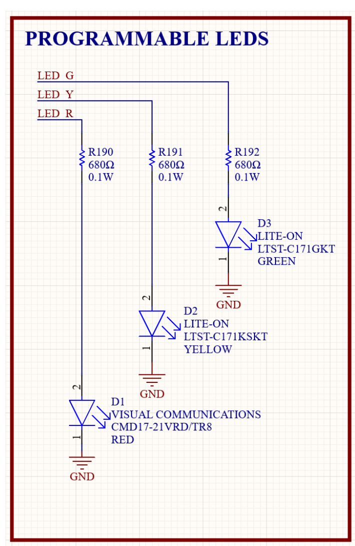


Figure 27: Customizable LEDs

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.

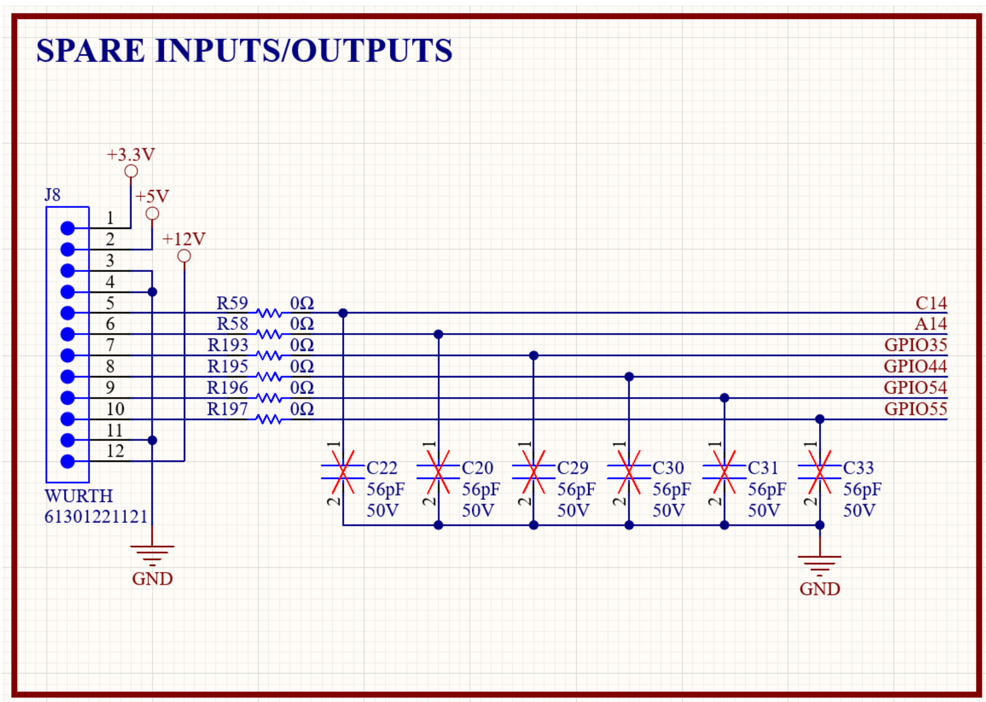


Figure 28: Spare ADCs, GPIOs, and Power Rail Connections

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.

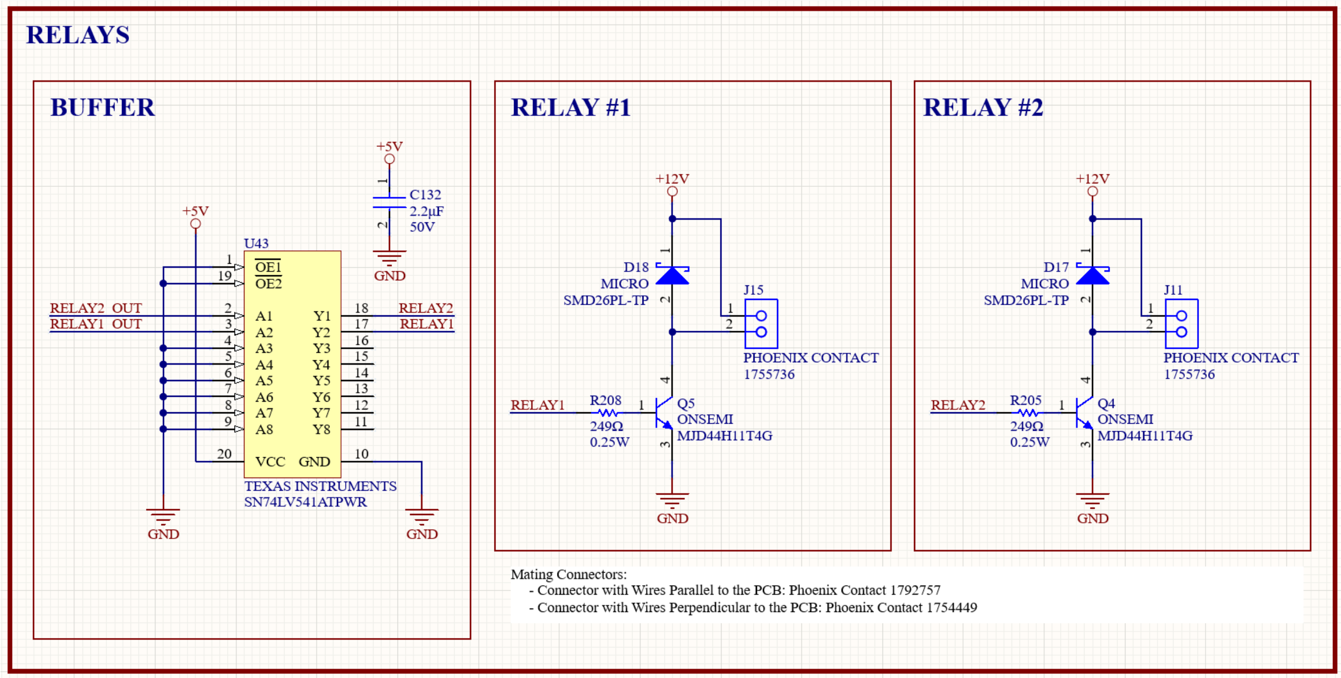


Figure 29: Relay Driving Circuit

3.8. Controller

The controller connector is Samtec HSEC8-160-01-L-DV-A-BL with the pinout shown below. The system has been tested with the Texas Instruments TMDSCNCD280039C controller. However, any controller with equivalent pinout could be utilized.

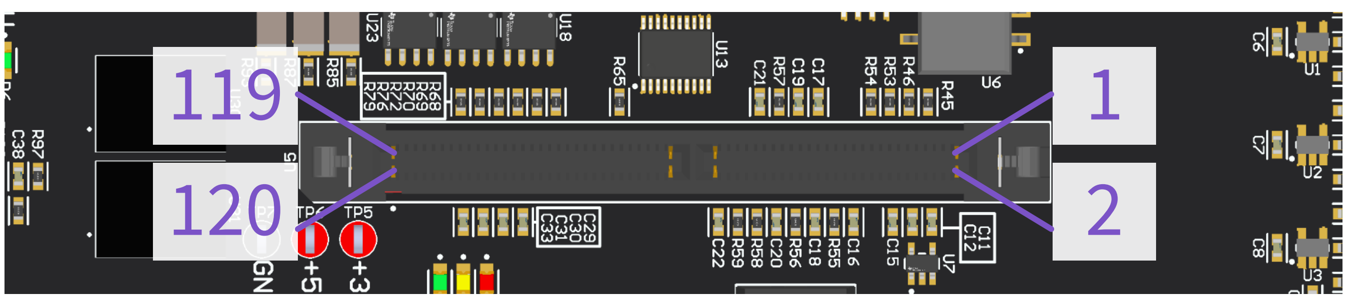


Figure 30: U5 Controller Connector Pin Numbers

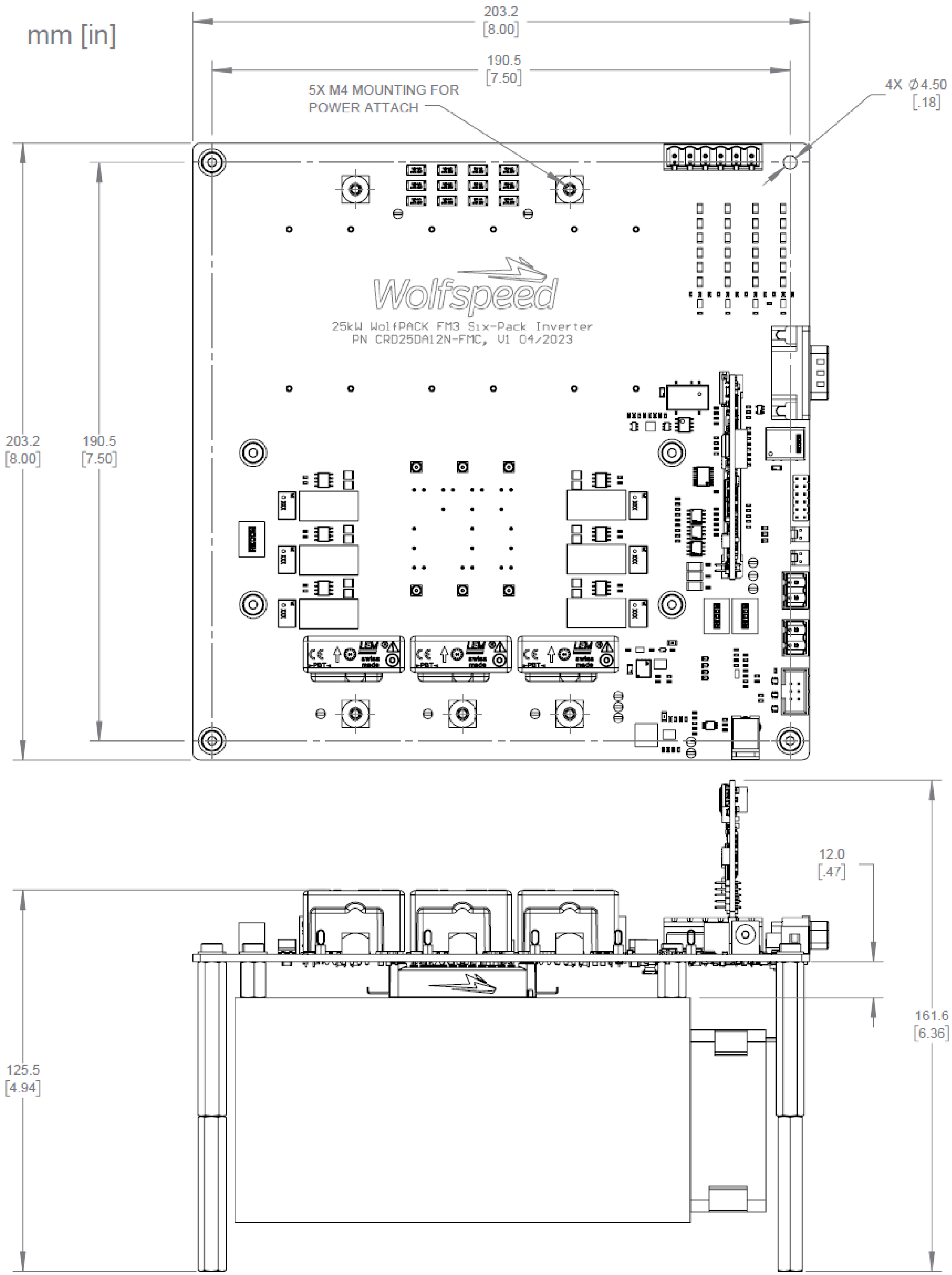
Table 12: U5 Controller Connector Pinout

#	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 (1)	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

#	Name	Type	Description	Description	Type	Name	#
47	GND_10	Power	Ground	+5V Power	Power	5V_0	48
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

#	Name	Type	Description	Description	Type	Name	#
93	V_LO_OC	Digital (I)	Phase V Low Overcurrent	Red LED Control	Digital (O)	LED_R	94
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. MECHANICAL ASSEMBLY



REVISION HISTORY

Date	Revision	Changes
May 2023	Rev. 0	Initial Release

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.