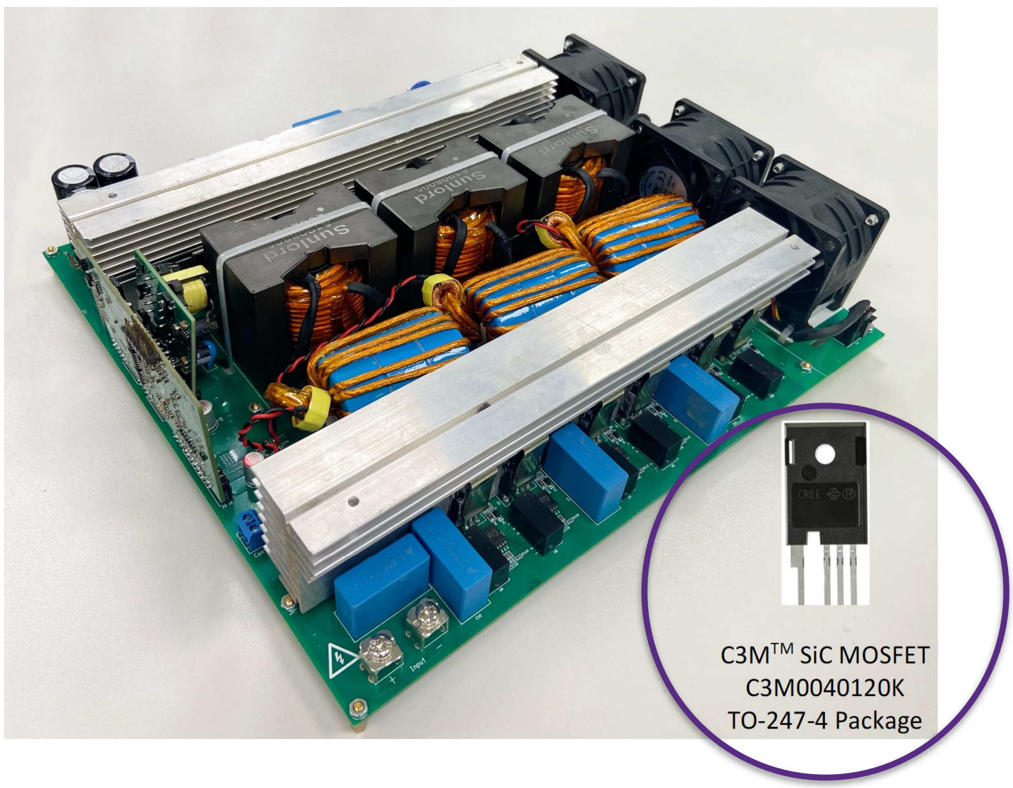
USER GUIDE PRD-05777

CRD-30DD12N-K: 30kW THREE-PHASE INTERLEAVED LLC DC/DC CONVERTER

30kW 三相交错 LLC-直流变换器

30kW 三相交錯 LLC DC/DC 变換器



User Guide
Wolfspeed Power Applications

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This document is prepared as an application note 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.

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。

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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 sic_power@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-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sic_power@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。

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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 the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-30DD12N-K, 30kW DC/DC converter for an electric vehicle (EV) off-board fast charger and similar applications.

The design of Wolfspeed's 30KW, DC/DC converter (P/N CRD-30DD12N-K) is based upon one of Wolfspeed's latest generation of SiC MOSFETs - C3M0040120K (1200V, 40mΩ, TO-247-4) and SiC Schottky Diodes C6D20065D (650V, 10A*2, TO-247-3), C6D10065A (650V, 10A, TO-220-2). The converter is the DC/DC stage of a unidirectional off-board charger. As shown in Figure 1, it operates from a rectified DC voltage (V_dclink) at the input side DC terminals and provides an isolated output voltage (V_bat) at the battery side DC terminals.

The Y-connected three-phase interleaved LLC resonant topology is selected for the converter to achieve both high efficiency and wide voltage regulation. The primary side consists of three half-bridge LLC resonant circuits, while the secondary side consists of six full-bridge rectifier circuits. The primary side and secondary side are isolated by three high-frequency transformers. The converter operates in a 135-250kHz switching frequency range. The heat generated by the power MOSFETs and power Diodes is dissipated via the two tooled heatsinks. The power density is up to 6.5kW/L. A block diagram is shown in Figure 1.

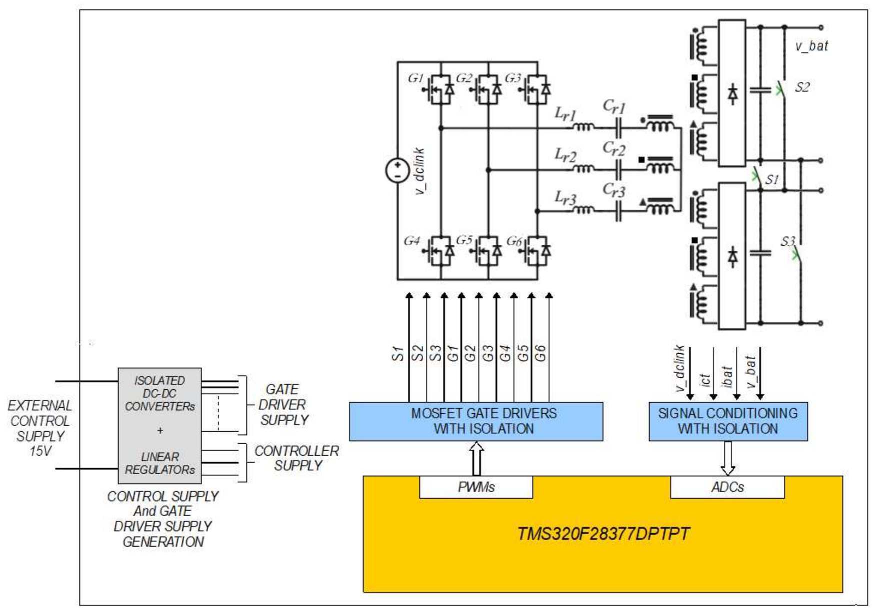


Figure 1: Block Diagram of Wolfspeed's CRD-30DD12N-K, 30KW High Efficiency DC/DC

The bus voltage varies between 650VDC and 850VDC. This varied bus voltage, along with the reconfiguration of series or parallel connection of the secondary side without any additional power component, makes it possible to realize wide output voltage range between 200Vdc and 1000Vdc with high efficiency and high power density. In parallel mode, the output voltage range is 200Vdc~500Vdc; in series mode, the output voltage range is 500Vdc~1000Vdc. The peak efficiency of the DC/DC converter can be above 98%.

Since the main purpose of the reference design is to show the performance of SiC in the power converter for EV applications, it doesn't focus on battery charging technique. For this reason there is no battery charging algorithm built in, and it must not be connected to any battery directly. An electronic load or a resistive load should be used for charging tests.

2. DESCRIPTION

This reference design board uses Wolfspeed's SiC MOSFETs C3M0040120K in three half-bridges on the primary side and uses Wolfspeed's SiC Schottky Diodes C6D20065D and C6D10065A in full-bridge rectifiers on the secondary side. A single SiC MOSFET or SiC Schottky Diode is used for each position.

Flexible gain control methods include the conventional variable frequency control and phase shift control. It can also automatically reconfigure the primary side operation between half-bridge (3 phases) and full-bridge (2 phases). The flexible control method plus the high performance of 1200V SiC MOSFETs enables high-efficiency operation for wide-output voltage range. When the required voltage gain is below 250V, it is out of the high-efficiency range of the variable frequency control for a 3-phase half-bridge structure. In this case, the control will restart and switch the primary-side structure from 3-phase operation to 2-phase operation by disabling phase C and enabling hybrid control with variable frequency and phase shift. This control methodology ensures optimum efficiency is achieved throughout the entire output voltage range and load range.

The operation range of the evaluation board is shown in Table 1. The evaluation board is designed to support the DC bus voltage of a PFC (Power Factor Correction) rectifier. In a typical application, the DC bus voltage is regulated by the PFC stage according to the battery-side voltage. In this reference design, since it is DC/DC stage only, input voltage needs to be set based on output voltage (battery voltage) as the curve shown in Figure 2.

Secondary Configuration	Input Voltage (V)	Output Battery Side Voltage (V)
Parallel	650-660	200-300 Settable
	660-840	Vin*0.458
	840-850	390-500V Settable
Series	650-660	500-600 Settable
	660-840	Vin*0.916
	840-850	770-1000 Settable

Table 1a: Output voltage ranges

Bus Input Voltage (V)	Output Battery Side Voltage (V)	Max. Output Power	Max. Output Current	Secondary Configuration
650V~850V	200V~250V	30kW	66A	Parallel
	250V~500V		100A	
	500V~1000V		50A	Series

Table 1b: Overall Charging Operation

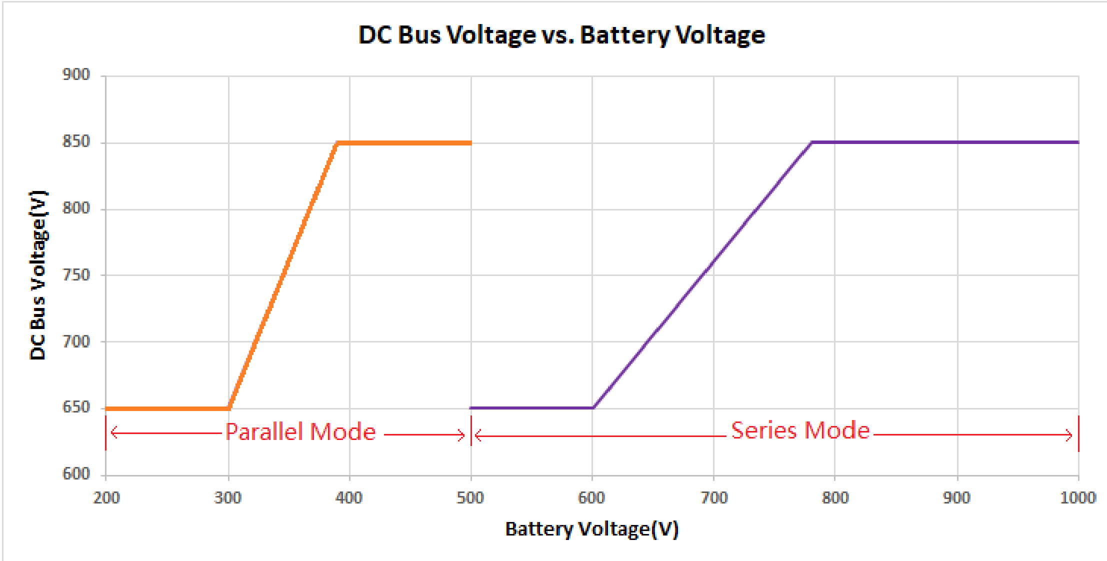


Figure 2: Battery Voltage vs. Bus Voltage Curve

A user should follow the operations as shown in Table 1 and Figure 2 and not overload the converter out of the SOA (Safe Operation Area). Please refer to Table 6 in Section 7.3 of this User Guide for protection details.

A GUI communicates to the unit via a controller area network (CAN) communication bus. It is used to display operational information and provide related user controls, such as On/Off, Parallel/Series, the selection of Max Output Power and Max Output Current, and the output voltage. Please note that the output voltage can only be set at the upper and lower limits of the bus voltage, otherwise the output voltage is calculated based on the input DC voltage to enable high efficiency at all input and output voltages.

3. ELECTRICAL PERFORMANCE CHARACTERISTICS

PARAMETER		TEST CONDITIONS	MIN	NOM	MAX	UNITS
Input Characteristics						
Vin	Input voltage		650	800	850	V
I_{in}	Input current				47	A
Output Characteristics						
V_{OUT1}	Output voltage	Secondary side in parallel	200	366	500	V
$P_{OUT1\ max}$	Output power				30000	W
$I_{OUT\ 1}$	Output current (3-ph HB)				100	A
	Output current (2-ph FB)				66	A
V_{OUT2}	Output voltage	Secondary side in series	500	733	1000	V
$P_{OUT2\ max}$	Output power				30000	W
$I_{OUT\ 2}$	Output current				50	A
V_{ripple}	Output voltage ripple				±2%	
System Characteristics						
η_{peak}	Peak efficiency	V_{IN} = 850V, V_{OUT} = 390V, I_{OUT} = 46A /Parallel	98.1%	98.3%		
$\eta_{full\ load}$	Full load efficiency /Secondary Series	V_{IN} = 850V, V_{OUT} = 1000V, I_{OUT} = 30A	97.9%	98.1%		
		V_{IN} = 850V, V_{OUT} = 780V, I_{OUT} = 38A	97.9%	98.1%		
		V_{IN} = 750V, V_{OUT} = 687V, I_{OUT} = 44A	97.3%	97.5%		
		V_{IN} = 650V, V_{OUT} = 595V, I_{OUT} = 50A	96.8%	97.0%		
		V_{IN} = 650V, V_{OUT} = 500V, I_{OUT} = 50A	95.9%	96.1%		
	Full load efficiency /Secondary Parallel	V_{IN} = 850V, V_{OUT} = 500V, I_{OUT} = 60A	97.9%	98.1%		
		V_{IN} = 850V, V_{OUT} = 390V, I_{OUT} = 77A	97.8%	98.0%		
		V_{IN} = 720V, V_{OUT} = 660V, I_{OUT} = 45A	97.9%	98.1%		
		V_{IN} = 650V, V_{OUT} = 595V, I_{OUT} = 77A	96.8%	97.0%		
		V_{IN} = 650V, V_{OUT} = 500V, I_{OUT} = 50A	95.9%	96.1%		

Table 2: Characteristics of Wolfspeed's CRD-30DD12N-K, 30kW DC/DC Converter

3.1. APPLICATION

The primary application for Wolfspeed's CRD-30DD12N-K reference design board is the DC/DC stage of EV off-board fast chargers. However, for this reference design the output must be connected to a resistive load or electronic load. Constant Resistor (CR) mode is recommended when using an electronic load. A battery test is not allowed since a battery-charging algorithm has not been implemented in the design.

3.2. FEATURES

Some of the features and limitations of Wolfspeed's CRD-30DD12N-K reference design board are listed below:

- Wide voltage range (650V-850V voltage range for bus-side terminals and 200V-1000V voltage range for battery-side terminals).
- Maximum output current is limited to 50A (secondary side in series) or 100A (secondary side in parallel), maximum output power is limited to 30kW.
- Peak efficiency > 98.3%.
- Protection functions are shown in Table 6.
- Easy to test using a GUI communicating via CAN. See Section 6 and Section 13 for details.

4. SCHEMATICS

Note: Complete design files, including full-size schematics, are available for download from the Wolfspeed reference design website: (https://www.wolfspeed.com/power/products/reference-designs/)

Schematics of the power, control, and auxiliary-power boards are shown in Figures 3 through 7.

4.1. POWER BOARD

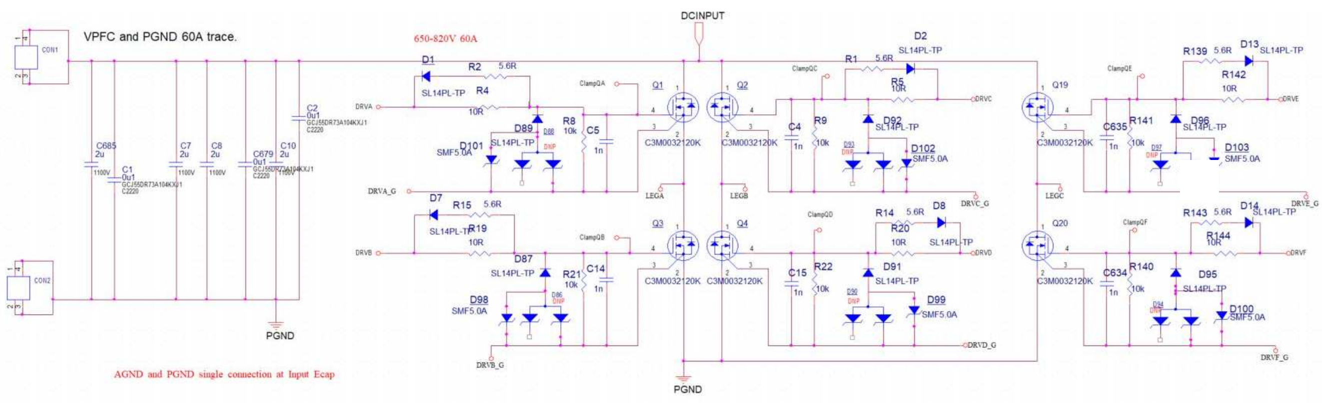
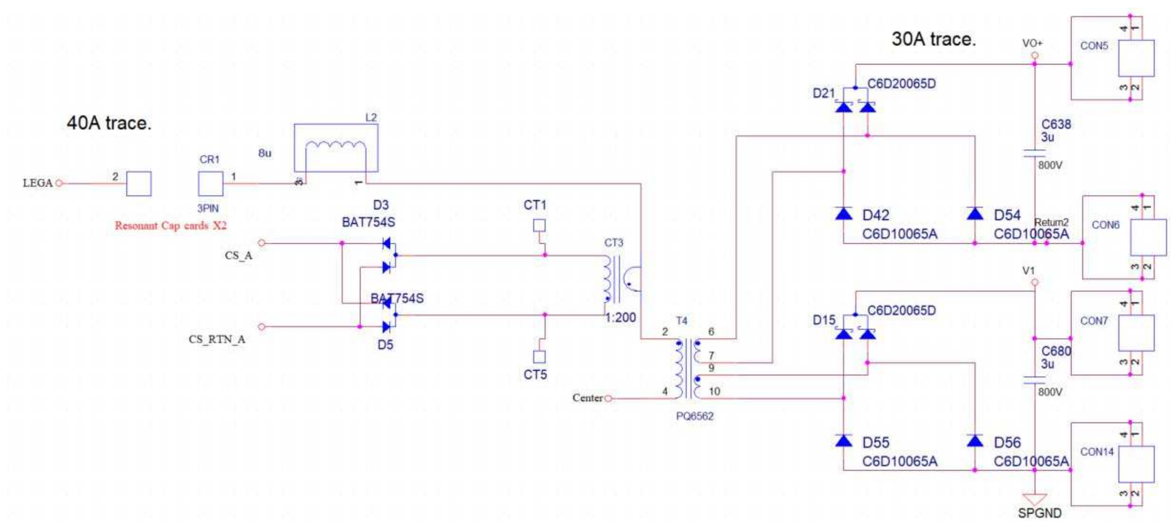


Figure 3a: 6 SiC MOSFETs on the primary side of the converter along with their gate-drive circuit



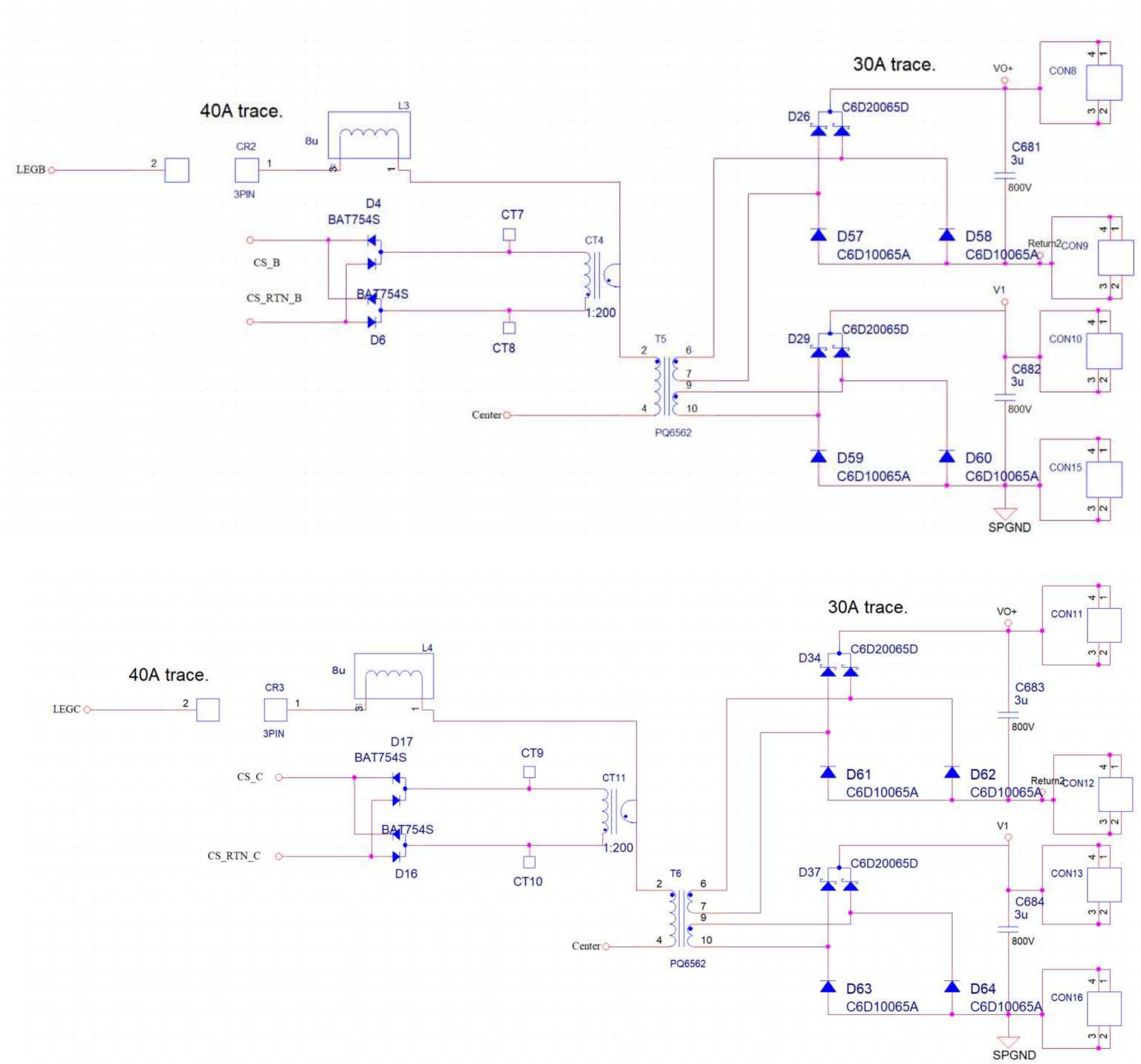


Figure 3b: Resonant tank circuits on the primary side and the rectifying circuits on the secondary side for each phase

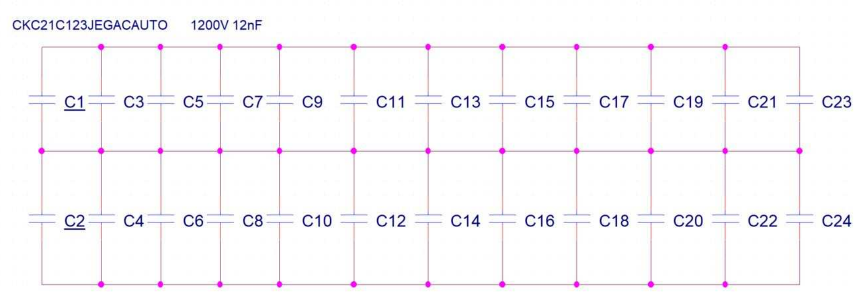


Figure 3c: Resonant capacitor cards for each phase

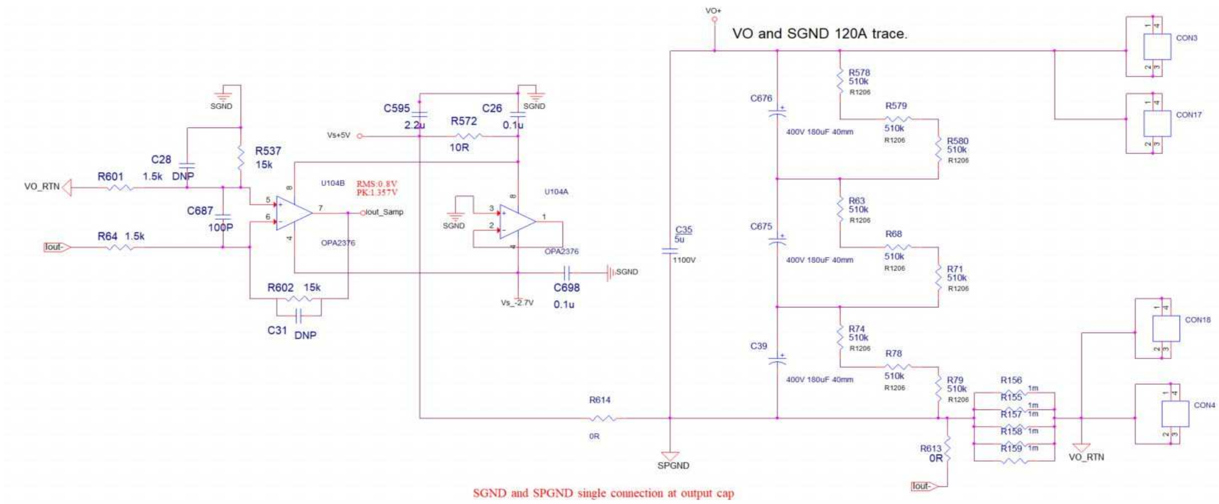


Figure 3d: Filter capacitor and current sampling circuit at DC output

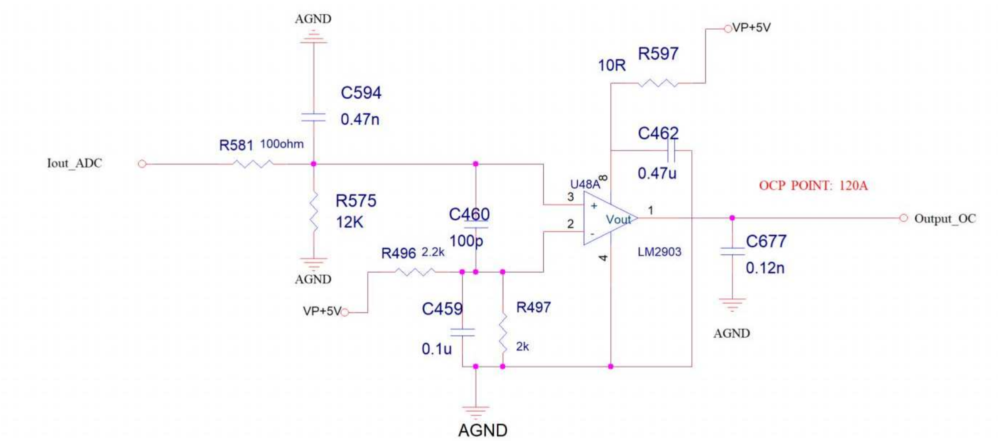


Figure 3e: Overcurrent detection circuit for output current

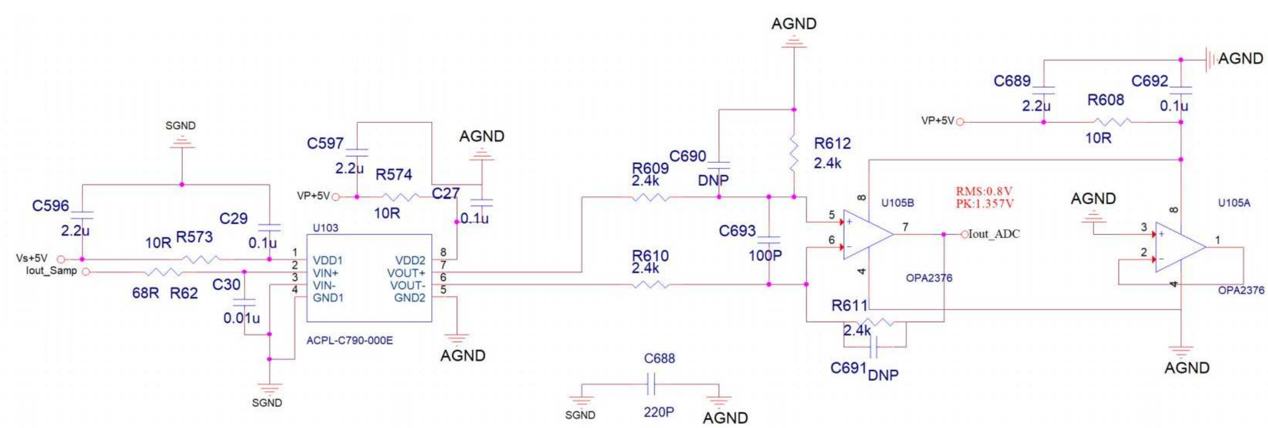


Figure 3f: Isolation and amplification circuit for output current sampling

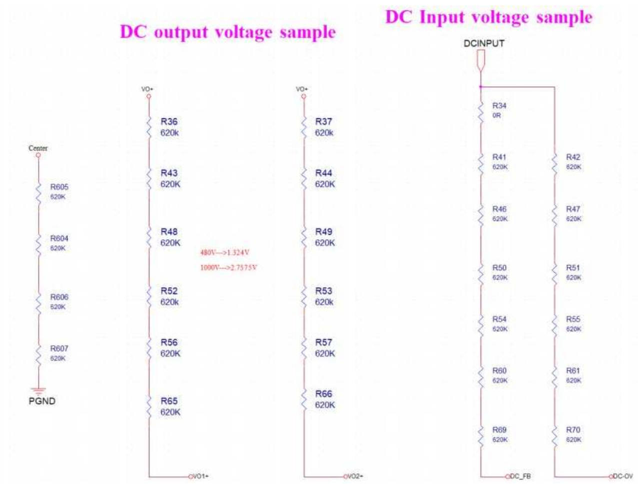


Figure 3g: Resistors for DC input and DC output voltage sampling

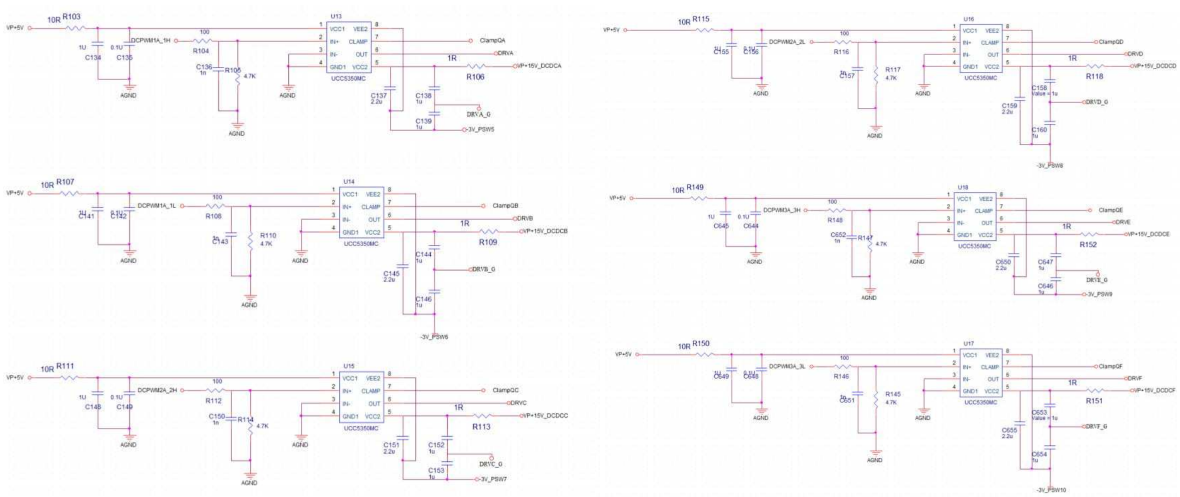


Figure 3h: DC/DC primary-side gate drives

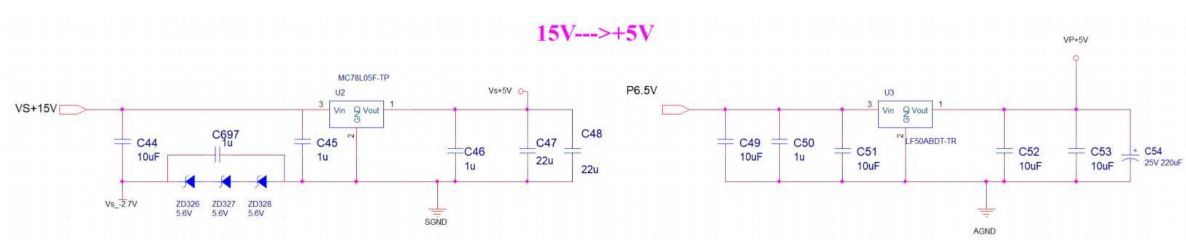


Figure 3i: Power supply for signal circuits

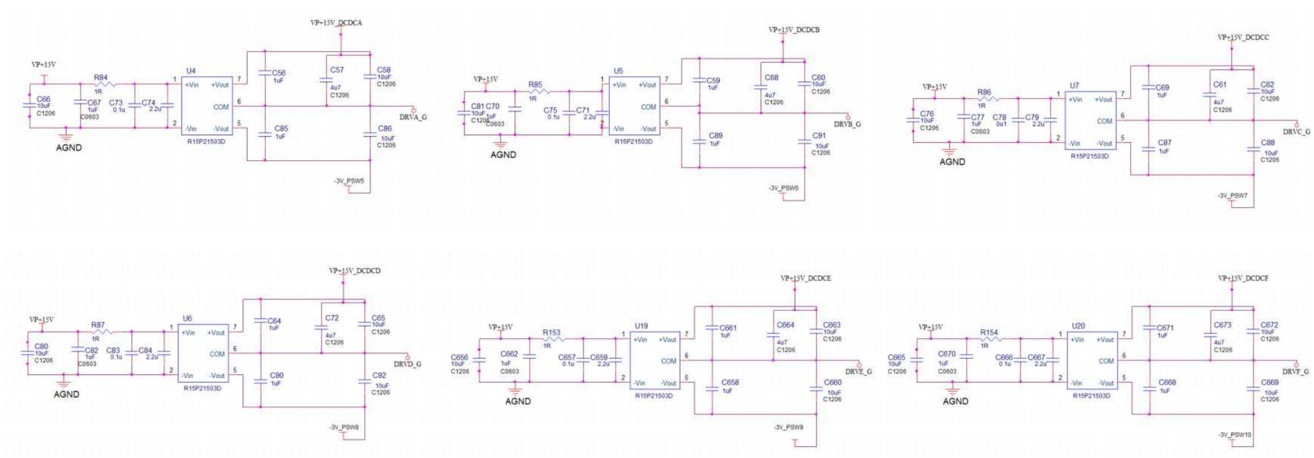


Figure 3j: Power supply for gate driver

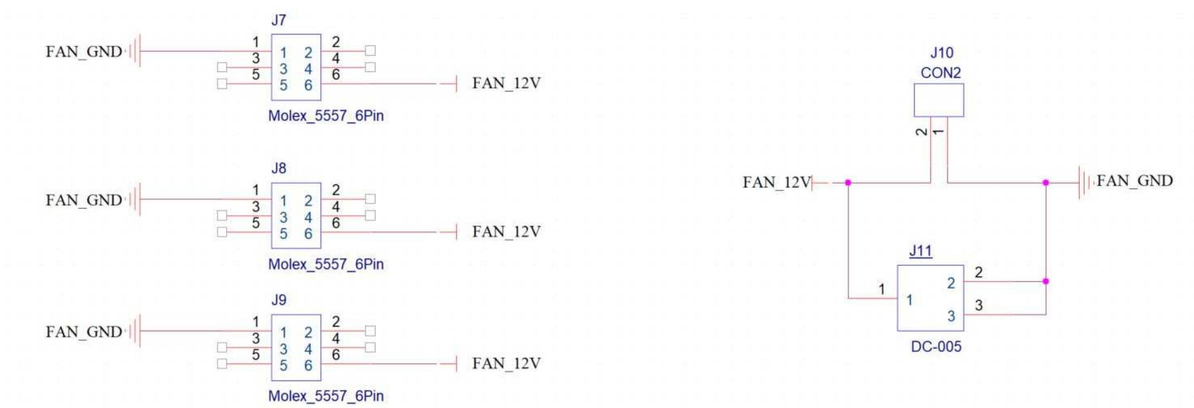


Figure 3k: Power supply for fan

4.2. CONTROL BOARD

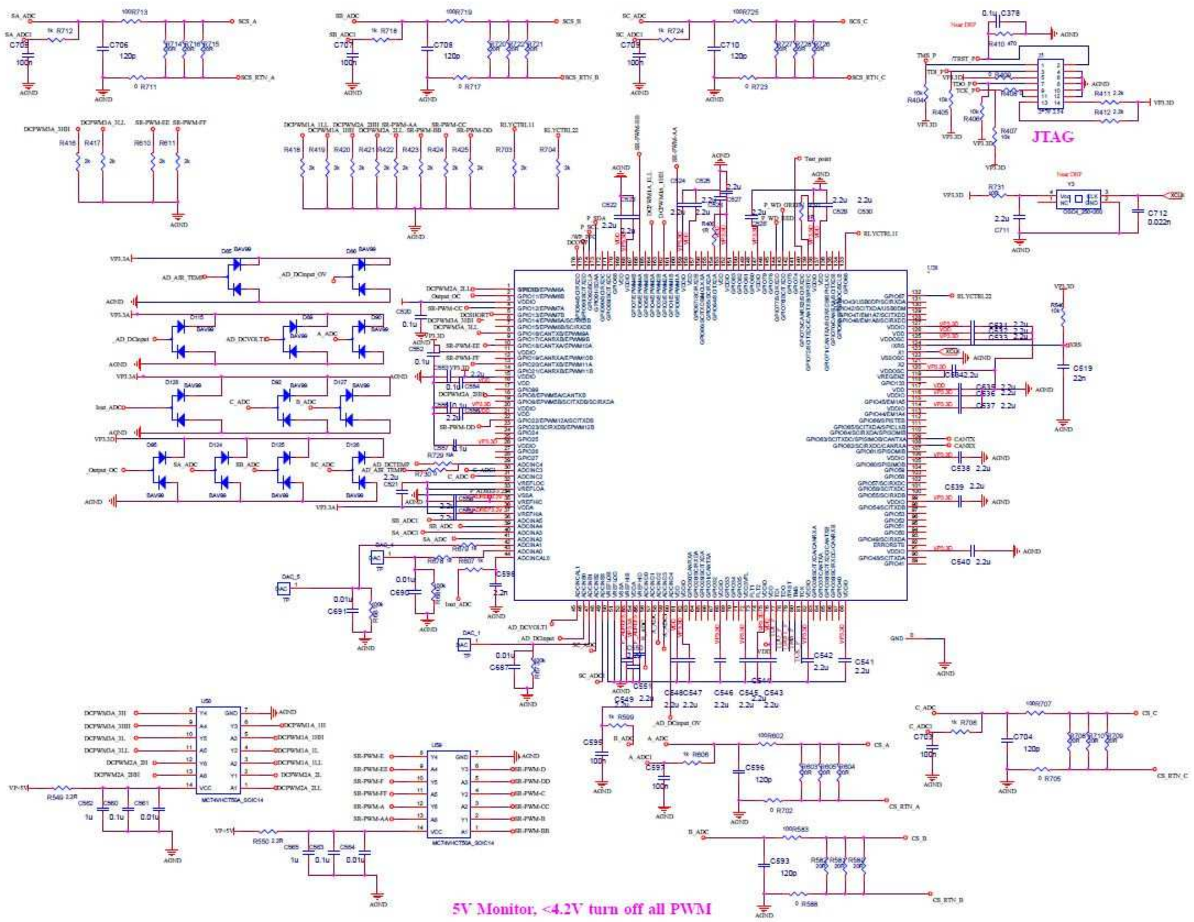


Figure 4a: Controller and peripheral circuits

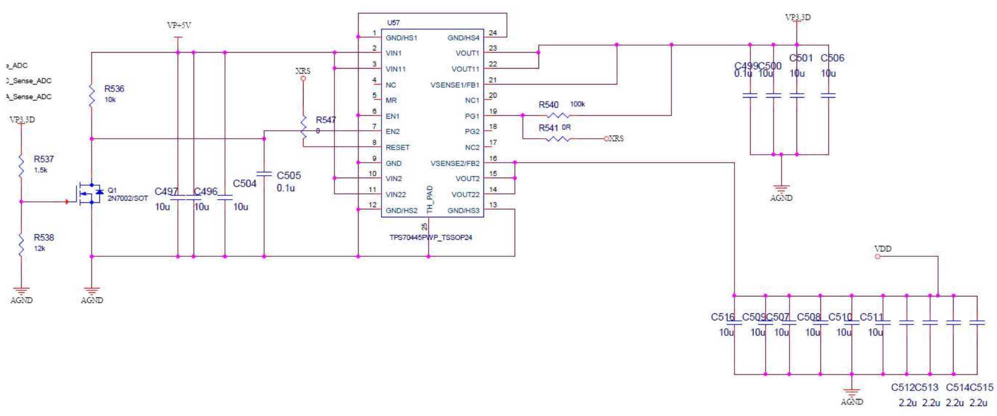


Figure 4b: Power supply for controller

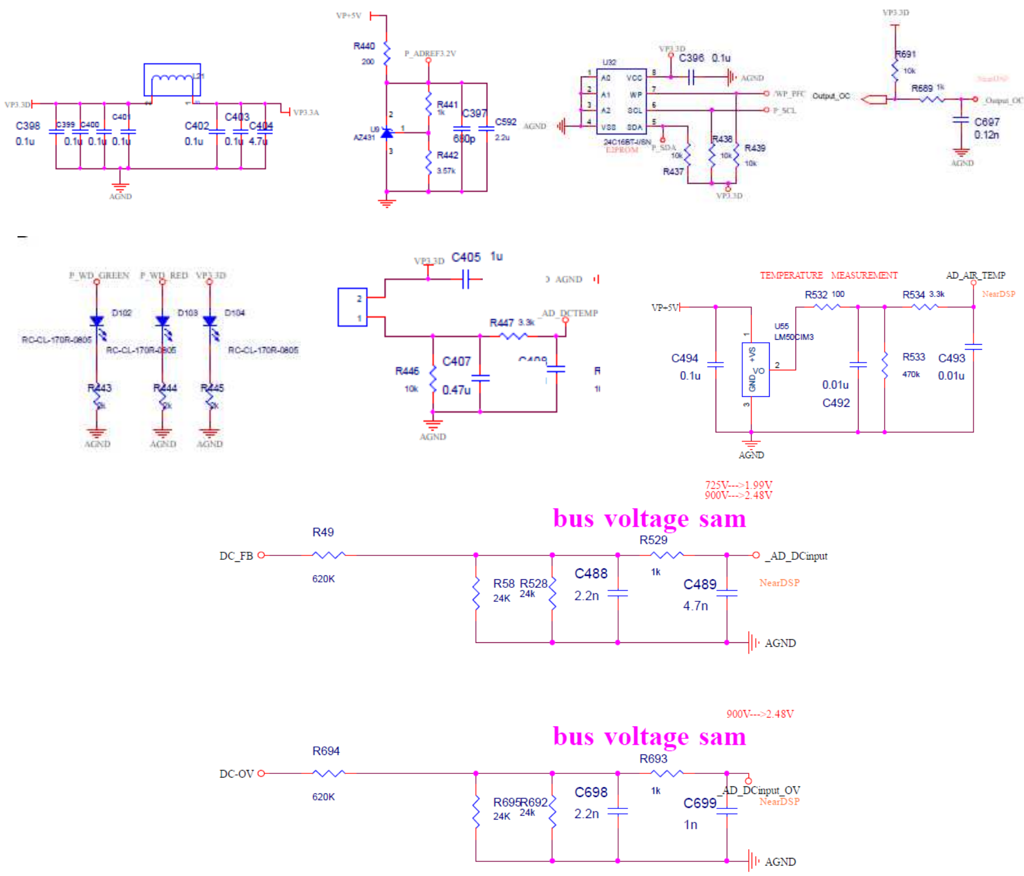


Figure 4c: Reference voltage and bus voltage sampling circuits

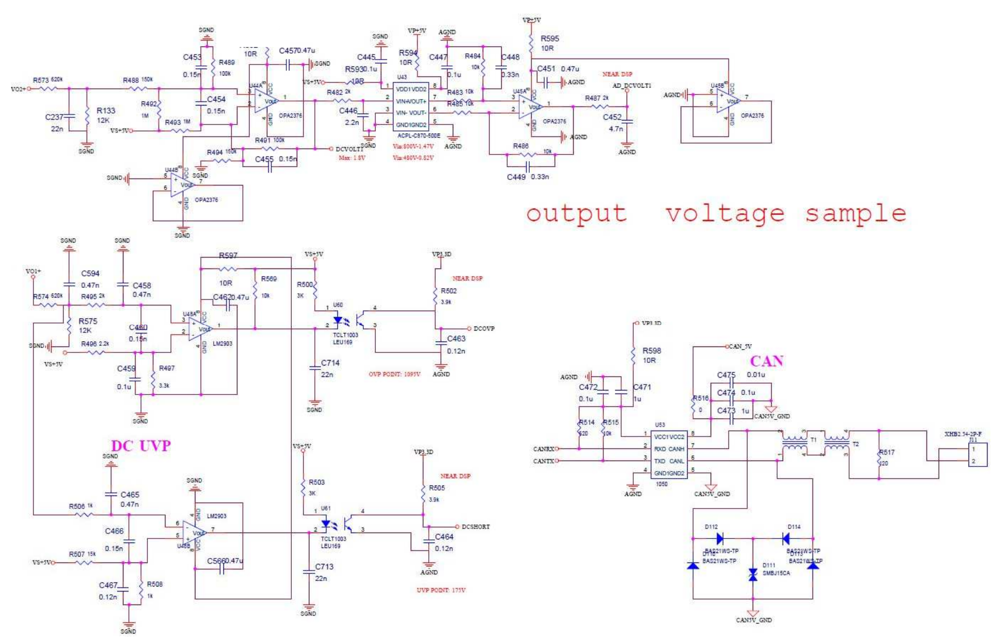


Figure 4d: Battery voltage sample and CAN interface

4.3. CONNECTIONS TO MAIN BOARD

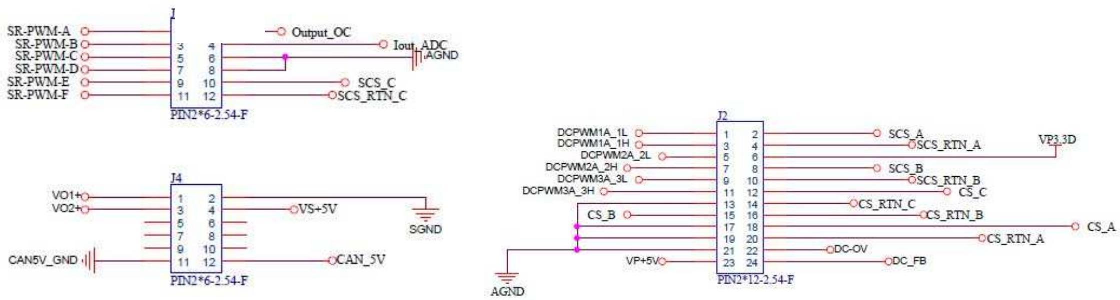


Figure 5: Connectors of Control Board to Main Board

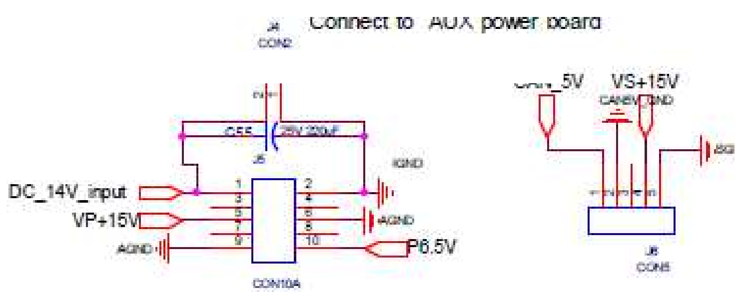


Figure 6: Connectors of Auxiliary Power Board to Main Board

4.4. AUXILIARY POWER BOARD SCHEMATIC

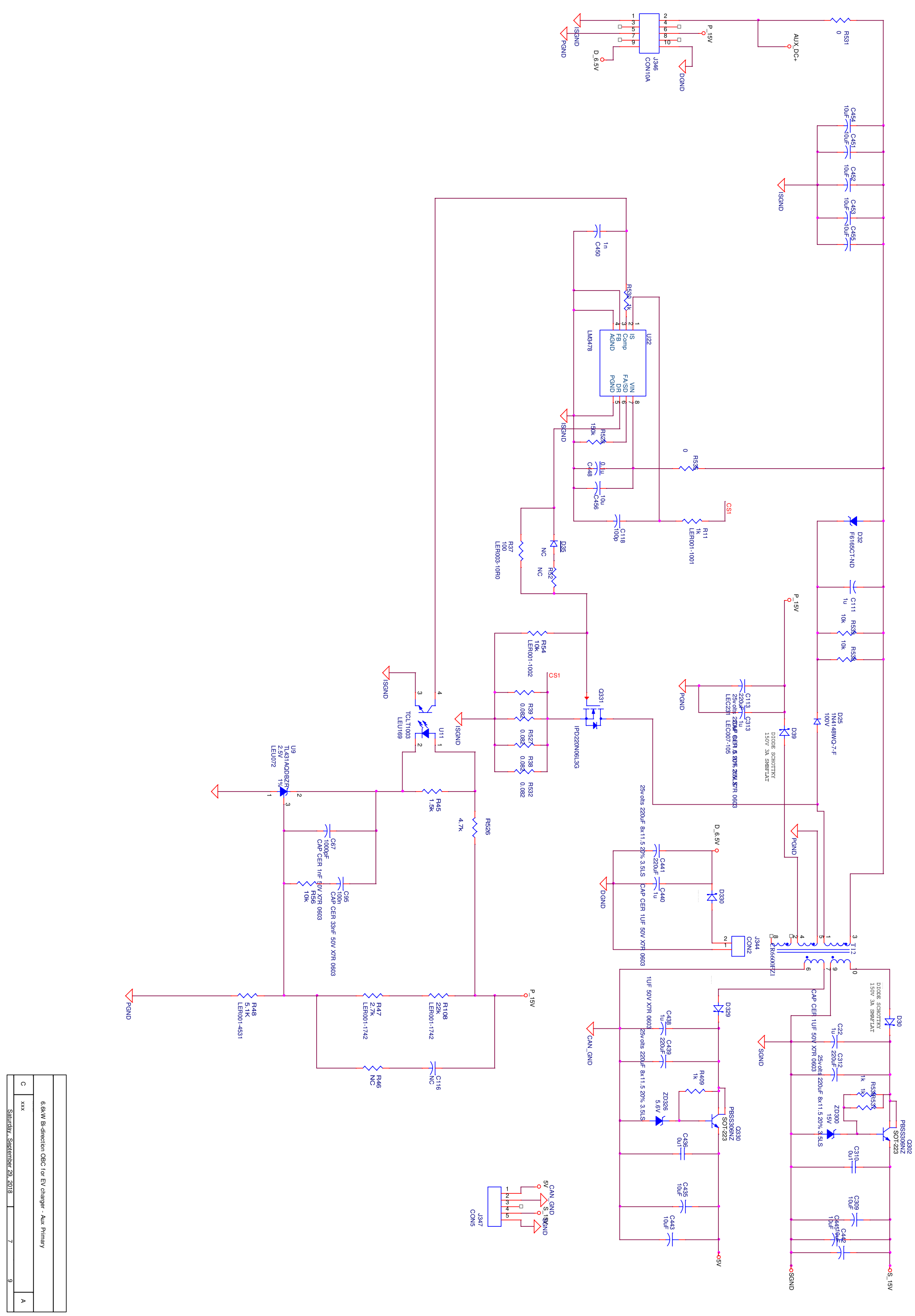


Figure 7: Schematic of Auxiliary Power Board

5. HARDWARE DESCRIPTION

5.1. POWER BOARD

As illustrated by Figure 3a, a three-phase LLC topology is selected for the converter. The bus-side DC terminals are CON1(+) and CON2(-) followed by four film capacitors that absorb the high-frequency ripple on the DC input port. The battery-side DC terminals are CON3 & CON17(+) and CON14 & CON18(-). The half-bridge at the DC bus side is composed of SiC MOSFETs Q1, Q3, Q2, Q4, Q19, Q20. The battery-side full-bridge rectifiers are composed of SiC Schottky Diodes D15, D21, D26, D29, D34, D37, D46, D55, D56, D57, D58, D59, D60, D61, D62, D63, and D64 followed by six film capacitors and three electrolytic capacitors. Three identical transformers isolate these two sides from each other. The transformers are constructed with a three-legs gapped PQ6562 ferrite core with a turns ratio of 12:11:11. Each eleven-turn secondary winding of these transformers are separately connected to a full-bridge diode rectifier. The six rectifiers are divided into two sets of three in parallel. By connecting terminals CON5~CON16 in two different ways, the two sets of rectifiers can be configured in parallel or series. Each resonant tank has a current transformer sensing current on the primary side.

The key parameters for each resonant tank are shown as below:

Primary inductance of transformer	Resonant Inductor	Resonant Capacitor
40uH	11.8uH	12nF/2*11=66nF

Table 3: Key Parameters of Resonant Tanks

As illustrated by Figures 3h and 3j, all Texas Instruments, Inc. gate drivers (P/N: UCC5350MCQDQ1) are separately powered by isolated, DC/DC power supplies with V_{IN} = +15V and V_{OUT} = +15V/-3V from RECOM Power GmbH. (P/N: R15P21503D).

5.2. CONTROL BOARD

As illustrated by Figure 4a to 4d, the control board, which carries out the control algorithm of the entire system, is designed around a Texas Instruments Inc. controller (P/N: TMS320F28377D). The power supply for the control board is an isolated, 7V@1A, power supply whose output is then tightly regulated to +5.0V by a linear regulator. This 5.0V rail then supplies another precision linear regulator IC, U57, from Texas Instruments Inc. (P/N: TPS70445), which provides both a 3.3V and a 1.2V rail. All output drive signals are buffered and shifted to a +5V level by a Fairchild Semiconductor International Inc. level-shifter (P/N: MC74HCT50A). The reference voltage for the controller's ADC (Analog-to-Digital Converter) is 3.3V. This reference is created by a reference IC U9, (P/N: AZ431-2.5V) from the +5.0V rail.

The reference ground of the control board is the negative terminal of the bus-side port. The voltage sample signal and OVP/UVP (Over/Under Voltage Protection) signals of the battery-side DC port are isolated by optocouplers before they are fed into the controller for further processing. The bus-side voltage sample and OVP signals are directly fed to the controller through a voltage divider.

5.3. AUXILIARY POWER BOARD

The typical input voltage of the auxiliary power board is 14 V (J4, net “Aux_DC+” and net ”ISGND” in Figure 7). It provides four isolated output voltages, as shown in Table 4.

Input/Outputs	Net Name	Comments
Input	14V	14V Typical Input of the Auxiliary Power Board
Output 1	P_15V	15V Power Supply for MOSFET Gate Drivers
Output 2	S_15V	15V Power Supply for MOSFET Gate Drivers
Output 3	5V	5V Output for CAN Communication
Output 4	D_6.5V	Controller Power Supply

Table 4: Input and Outputs of Auxiliary Power Board

6. COMMUNICATION

6.1. GRAPHICAL USER INTERFACE (GUI)

A Windows C# GUI in conjunction with USB-CAN tools (GCAN: USBCAN-I) is provided for testing. Connector J11 is used for CAN, as shown in Figure 10b. The control board and USB-CAN both provide isolation for CAN signal. The detailed CAN data format is shown in Section 6.2 and section 13.2 to 13.3.

The over/under voltage-protection is indicated by the back color of the voltage value, as shown in Figure 8b. "Green" indicates "Normal Operation" while "Red" means "Warning Issued." The ambient temperature sensed by the IC is displayed in the panel as well.

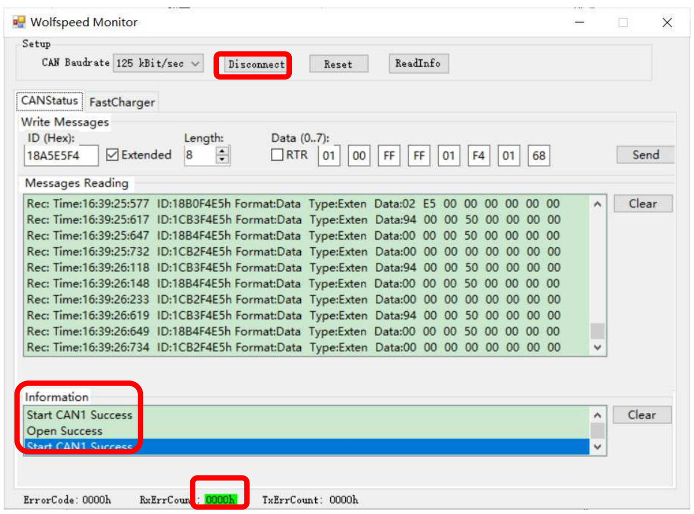


Figure 8a: CAN Status Tab after Connection

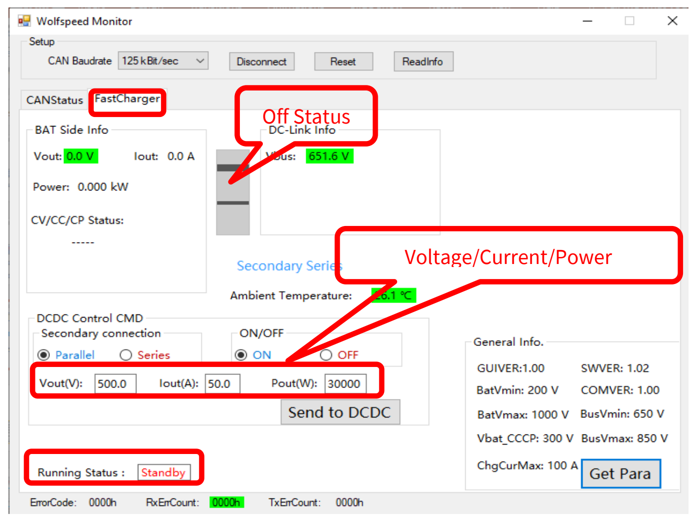


Figure 8b: Connected to Control Board <Off Mode>

The configuration "Secondary Connection" (Parallel/Series) can only be changed when the converter is shut down. This can be done in three steps: send an "OFF" command to shut down the converter, choose the desired connection mode, and then send an "ON" command. The converter will shut down and ignore any other configuration bits once it receives the CAN frame with the "OFF" configuration. The "Running Status" will be in "standby" mode. If the converter is shut down, it will start, as configured, once it receives the CAN frame with the "ON" configuration. Accordingly, the running status will display in the left-bottom area, including "Standby", "Protection", "Power On", "Soft-start Init", "Soft-start", "Normal @3ph Half Bridge", and "Normal @ Full Bridge phA/B".

Voltage reference (Vout), current reference (Iout), and power reference (Pout) are the desired values for output. The current reference is recommended to be 50A for series mode and 100A for parallel mode, and the power reference is recommended to be 30kW. The digital controller will check the value range each time.

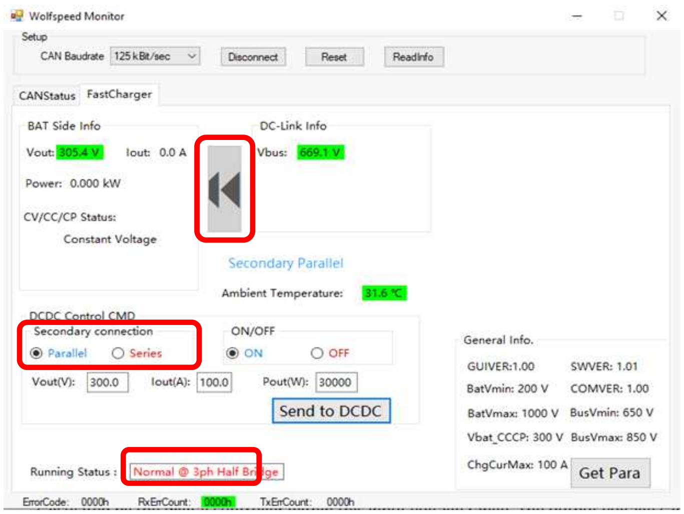


Figure 8c: Secondary in Parallel & 3ph Half-Bridge Operation

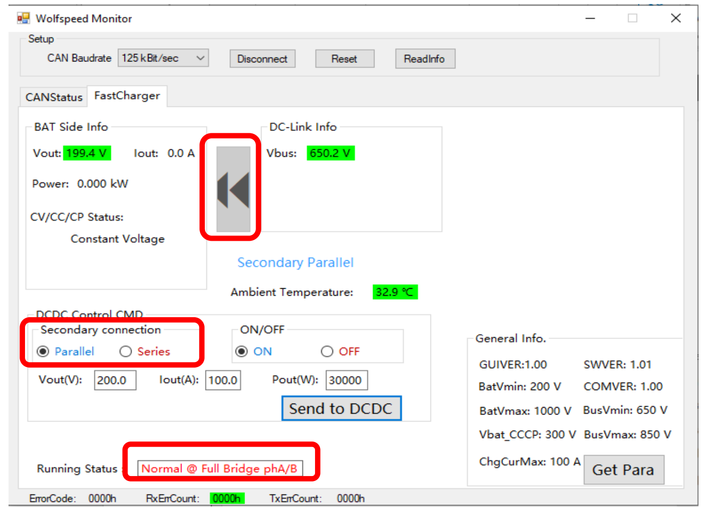


Figure 8d: Secondary in Parallel & Full-Bridge phA/B Operation

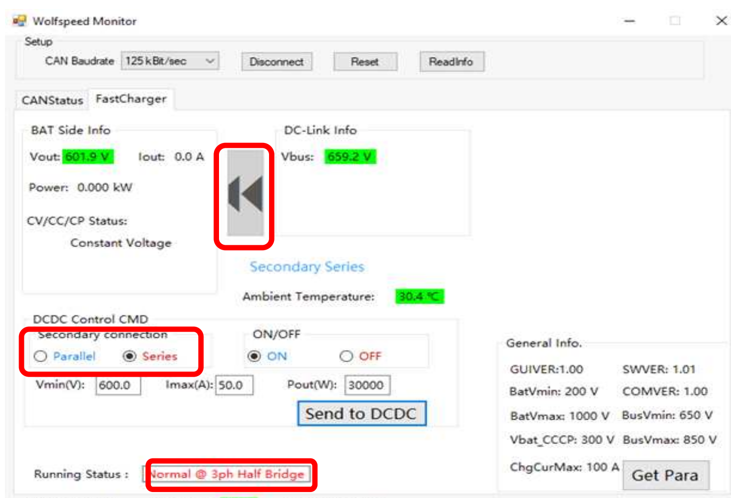


Figure 8e: Secondary in Series Operation

In secondary series mode, the output voltage range is 500V~1000V, and the output voltage setting is ignored when the input voltage is between 660V and 840V. The output voltage is calculated by the digital controller within this input voltage range. The output voltage can be set only when the input voltage is within 650V~660V and 840V~850V. Please refer to Section 2 for details.

In secondary parallel mode, the output voltage range is 200V~500V. Please refer to Section 2 for details. In addition, the control method will change to 2-phase shift mode if the output voltage is in the range of 200V to 250V.

6.2. CAN

COMMUNICATION DATA FORMAT

The reference design communicates over a CAN V2.0B bus at 125K bps (bits per second) using extended frame format (29 bits extend ID). The data length is 8 bytes in big endian format. All registered CAN messages are listed in Section 13.2 and 13.3.

Example: “0x18A5E5F4” is sent as the message identifier and “0x0001753013EC01F4” as the CAN data. The DCDC unit is placed in Secondary in Series mode, when the input voltage is between 650V and 660V, its output voltage is set to 510V, and it can supply maximum output current 50A. Care must be taken to ensure that the Byte0 in the CAN instruction matches the correct connection mode on the secondary side. When the Byte1 is 0x01, changes to Byte0 will be ignored by the digital controller.

Message Identifier: 0x18A5E5F4					
Data	Byte0 = 0x00	Byte1= 0x01	Byte2+Byte3= 0x7530	Byte4+Byte5 = 0x13EC	Byte6+Byte7 = 0x01F4
Property	Secondary Side: In Series	On	Output Power: 0x7530*1W=30000W	DC Voltage: 0x13EC*0.1V = 510V	DC Current: 0x01F4*0.1A = 50A

Table 5: Example of Control Command

7. TEST SETUP

<u>CAUTION</u>

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^{o} 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。

7.1. EQUIPMENT

DC Input Source: The input source must be an adjustable DC source with an output range between 600Vdc and 900Vdc. It must be capable of supplying at least 35000W.The testing shown in this document uses a power source from ITECH (P/N: IT6036D-1500-60).

Output Load: Two programmable high-voltage electronic loads from EA (P/N: ELR 11500-60) in parallel or a high-voltage resistor bank may be used. Each must be capable of sinking 100A of load current supplied from the evaluation board whose output can be 1000Vdc/33kW.

EMI Filter: Two EMI filters. One is for the input, P/N: SJD210DH-75, 1000V/75A from SAIJI ELECTRONIC or equivalent. The other one for the output, P/N: SJD320DH-200, 1000V/200A from SAIJI ELECTRONIC or equivalent.

Multimeter and shunt: Four multimeters from KEYSIGHT (P/N: 34461A), a 200A/75mV shunt, and a 50A/50mV shunt. These are used to measure input/output voltage and input/output current.

Oscilloscope: A >=300MHz digital or analog oscilloscope with >=100MHz differential voltage probes and isolated current probes (i.e. hall effect), should be used.

Low voltage power supplies: The following LV power supplies with isolated grounds should be used and must be obtained separately:

1) 14Vdc @ 1.5A capability is required to supply the auxiliary power board.
2) 12Vdc @ 12A capability in total is required to power the cooling fans.

7.2. RECOMMENDED TEST SETUP

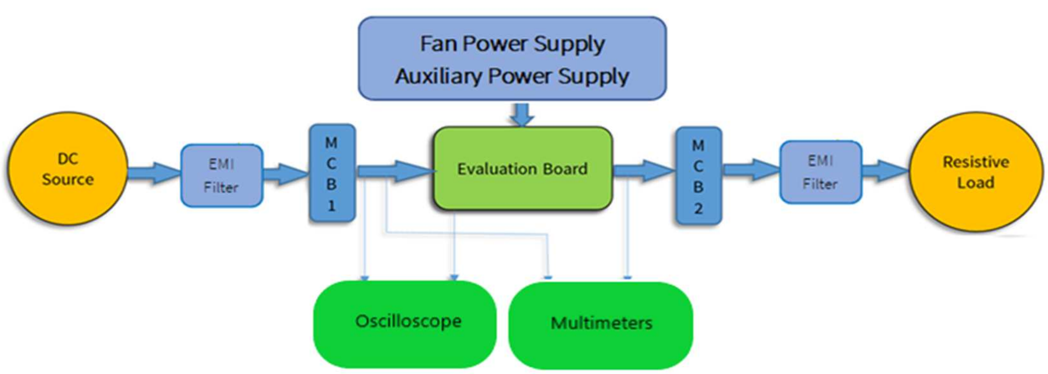


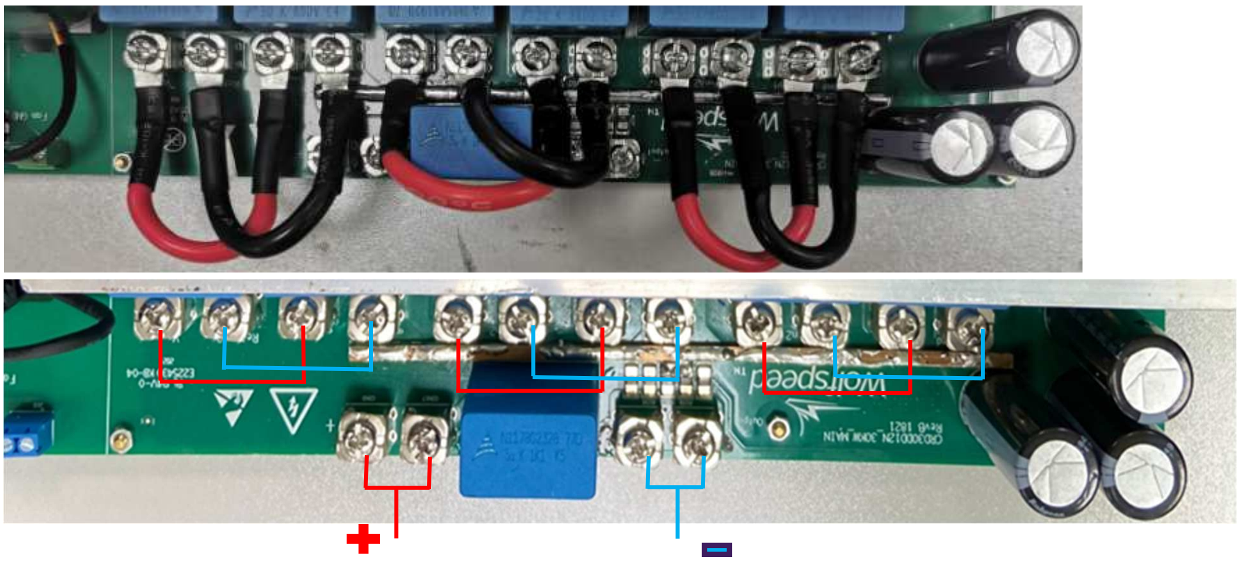
Figure 9: Converter Test Setup

The DC source is connected to **bus**-side terminals and the load is connected to the **battery**-side terminals.

- Connect the DC source to the input of the evaluation board through EMI filter, current shunt, and MCB1. MCB1 is optional.
- Connect the output of the evaluation board through EMI filter, current shunt, and MCB2 to a resistive load or an electronic load (in CR mode). MCB2 is optional.
- Connect multimeters to the input/output of the demo and the shunts to measure input/output voltage and input/output current.
- Use appropriately rated voltage and current probes and connect to the oscilloscope.

Parallel /series terminals: Refer to Figure 10a for wiring details to connect the output in parallel or series mode.

Wiring approach of Secondary side in parallel mode (Output: 200V~500V)：



Wiring approach of Secondary side in series mode (Output: 500V~1000V)：

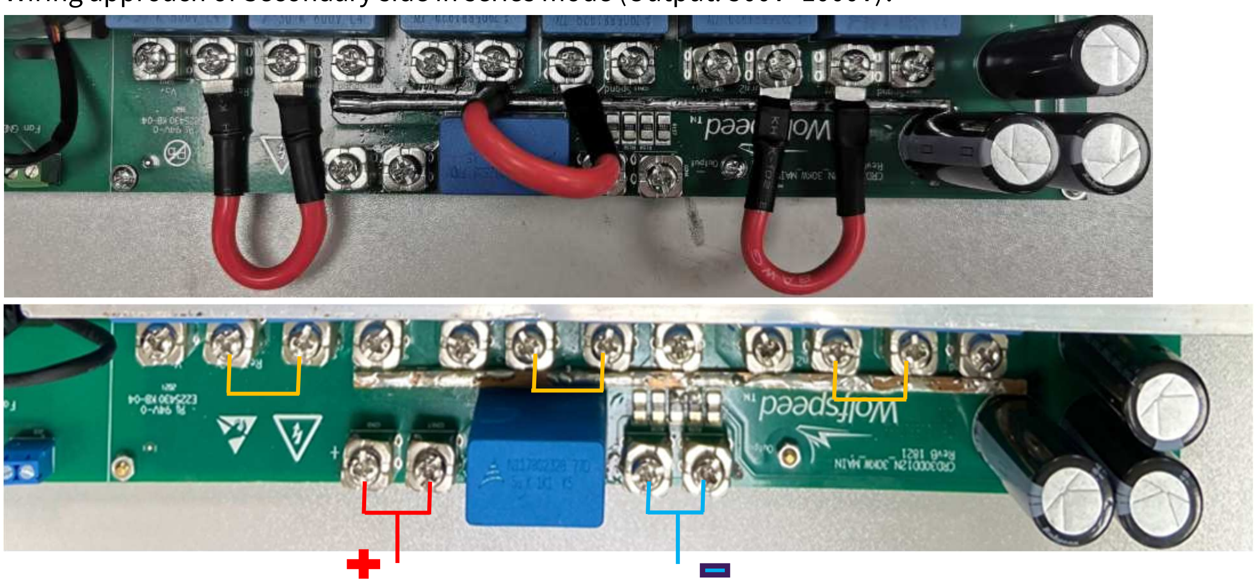


Figure 10a: Wiring approach of Secondary side

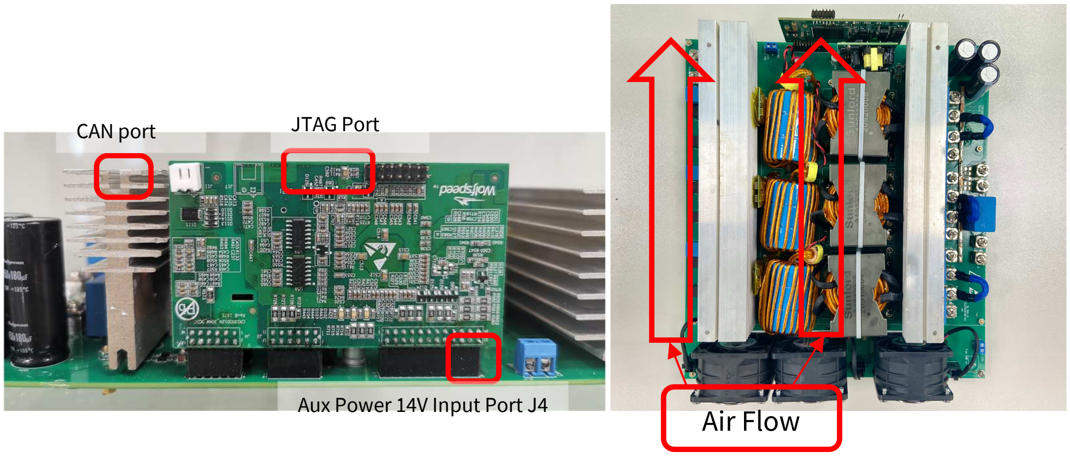


Figure 10b: Setup of the Reference Design

Recommended Wire Gauge: Cable with a minimum AWG#6 wire gauge is recommended to carry the DC current input and two AWG#6 wires in parallel to carry the DC output currents.

7.3. PROTECTIONS

Table 6 describes various protection functions in the reference design. OCP (Over Current Protection) for the LLC resonant tank and short-circuit protection are one-shot protections that require a system reset to clear and restart.

In addition, do not overload the converter outside the operating specs. The power/current limitation function is only a precaution with limited accuracy and therefore should not be relied upon. More importantly, overload will lead to operation under unexpected input and output relation, which may cause damage.

Power Signal	Protection	Trip Point for Battery Side	Trip Point for Bus Side
DC Voltage	OVP	>1050V @ Secondary in Series >550V @ Secondary in parallel	>870V
	UVP	---	<600V
Short Circuit Protection	short	<300V @ Secondary in Series <100V @ Secondary in parallel	---
LLC Tank Current	OCP	---	75A (peak)
Output Power Limitation	CP	30kW±1.5kW	---
Output Current Limitation	CC	66A±1.5A@Vout ∈ [200V,250V] 100A±1.5A@Vout ∈ (250V,500V] 50A±1.5A@Vout ∈ [500V,1000V]	---

Table 6: Protection Details

7.4. EXTERNAL POWER SUPPLY SETTINGS

The requirements for the isolated power supplies are shown in Table 7. A single 14V DC power supply connected to J4 is used to power the on-board auxiliary power board.

Control Board Connector Designator	Power Supply	Voltage (V)	Current 1 (A) (PWM Off)	Current 2 (A) (Full-Bridge Normal Operation)	Current 3 (A) (3 phases Half-Bridge Normal Operation)
J4	+14V for AUX power	+14V +/-5%	0.35	0.49	0.56

Table 7: Auxiliary Power Supply Requirements

7.5. MEASURED PARAMETERS

All power MOSFET pins are exposed. Their gate and drain voltages must be measured with caution. Probes should be connected to them only after the removal of input power and only after all bulk capacitors have been fully discharged.

NAME	DESCRIPTION
Efficiency	Calculate with Input /Output Current and Input /Output Voltage
Input /Output Current	DC current at DC terminal
Input /Output Voltage	High voltage at DC terminal
LLC Tank Current	LLC tank current at three phases
Vgs /Vds Signals	voltage across gate to source or drain to source of SiC MOSFETs
Auxiliary Power Board Outputs	Please refer to Figure 7 and Table 4 for details
3.3V /1.2V Controller Supply	+3.3V supply for Controller's I/O; +1.2V supply for Controller's core

Table 8: Parameters that can be measured

8. TESTING THE UNIT

CAUTION

*****HIGH VOLTAGE RISK*****

THERE CAN BE VERY HIGH VOLTAGES PRESENT ON THIS BOARD WHEN CONNECTED TO AN ELECTRICAL SOURCE, AND SOME COMPONENTS ON THIS BOARD CAN REACH TEMPERATURES ABOVE 50° CELSIUS. FURTHER, THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRCIAL 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.

The connectors on the board have very high voltage levels present when the board is connected to an electrical source, and thereafter until the bulk capacitors are fully discharged. Please ensure that appropriate safety procedures are followed when working with these connectors 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. When devices are being attached for testing, the board must be disconnected from the electrical source and all bulk capacitors must be fully discharged. After use the board should immediately be disconnected from the electrical source. After disconnection any stored-up charge in the bulk capacitors will continue to charge the connectors. Therefore, you must always ensure that all bulk capacitors have completely discharged prior to handling the board.

Wolfspeed

警告

*****高压危险*****

通电后，评估板上会存在危险的高电压，且板子上一些组件的温度会超过 50 摄氏度。断电后，上述情况可能会持续存在，尤其是大容量电容器可能会残存危险的高电压。通电时禁止对板子进行任何操作。操作板子前，请确保大容量电容器电量已完全释放。

板子上的连接器在通电时存在危险的高电压。即使已断电情况下，在大容量电容电量完全释放前，其连接器仍可能存在危险的高电压。请确保在正确的安全流程下进行操作，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。操作板子前，请务必切断供电电源，并且确认大容量电容器电量已完全释放。使用后应立即切断板子电源。切断电源后，其连接器由于大容量电容存在而仍可能有危险的高电压。因此，在接触板子前，除断电外还需要确保大容量电容器电量已完全释放。

警告

高圧危険

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。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、ボードに接触しないでください。ボードのコネクターは充電中また充電した後、ひどく高い電圧が存在しているので、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。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。使用後、すぐにボードの電源を切ってください。電源を切った後、大容量のコンデンサーに貯蓄している電量はコネクターに持続的に入るので、ボードを操作する前に、必ず大容量のコンデンサーの電力を完全に釈放するのを確保してください。

Notes:

1. The Secondary connection mode (series/parallel) on the GUI must match the actual hardware connection mode. This cannot be changed via CAN communication after the converter start-up.

2. Please wire the terminals on the secondary side properly and set the connection mode on the GUI correctly, according to the desired output voltage range. The converter should operate as series mode when the output voltage is targeted in the range of 500-1000Vdc and as parallel mode for output 200-500Vdc.

3. Please do not overload the converter. Please refer to Table 1, Table 2, and Section 3.2.

4. There is no current inrush limiter for either port. The DC input voltage must be increased gradually (soft-start).

5. Always remember to connect the cooling fans to their power supplies and operate the cooling fans when operating the board.

8.1. STARTUP PROCEDURE

1. Double-check the setup: Make sure the polarity is correct, the DC source is connected to the **input** terminals, and the load is connected to the **output** terminals.

2. Keep MCB1 in open position and the DC source output disabled.

3. Ensure that the load is less than 1KW and then close MCB2.

4. Apply 14Vdc to J4 on the power board. Check that the current draw is approximately the same as shown in Table 7. Check the +3.3V LED (on) and watchdog LED (blinking) on the control board.

5. Connect the GUI to the system. Send “OFF” command after it is connected successfully.

6. Apply power to the cooling fans.

7. Put MCB1 in the ON position. Turn on the DC supply and increase it slowly from 0V to the required voltage (650Vdc ~ 850Vdc).

8. Verify that the measured values in the GUI were reported correctly.

9. Send ON command with settings of “Series” or “Parallel” according to the actual connection mode of the secondary side terminals, the desired voltage reference, current reference, and power reference.

10. After the output voltage has reached steady-state regulation, increase the load up to desired value up to 30kW. The step-load change should not exceed 2KW for each step.

11. Check the efficiency under load conditions of interest.

8.2. TURN OFF PROCEDURE

1. Decrease the load to 2KW in less than 2KW steps.

2. Use GUI to send OFF command.

3. Disable the output of the DC power supply.

4. Open MCB1 after the DC source has fully discharged its output.

5. Turn OFF load and MCB2 after the bus side capacitors are fully discharged.

6. **Capacitors may remain charged for at least 30 minutes after the circuit is turned OFF if step 4 or step 5 is skipped. They must be allowed to fully discharge before handling the board. Please check terminal voltages with a multimeter to ensure that the board has fully discharged and is therefore safe to handle.**

7. Turn OFF the 14Vdc power supply on J4. The unit should be fully discharged before the auxiliary power supply is disabled.

9. PHOTOS OF REFERENCE DESIGN

Figure 11 shows the locations of the terminals, key components, and daughter-boards on the Power Board.

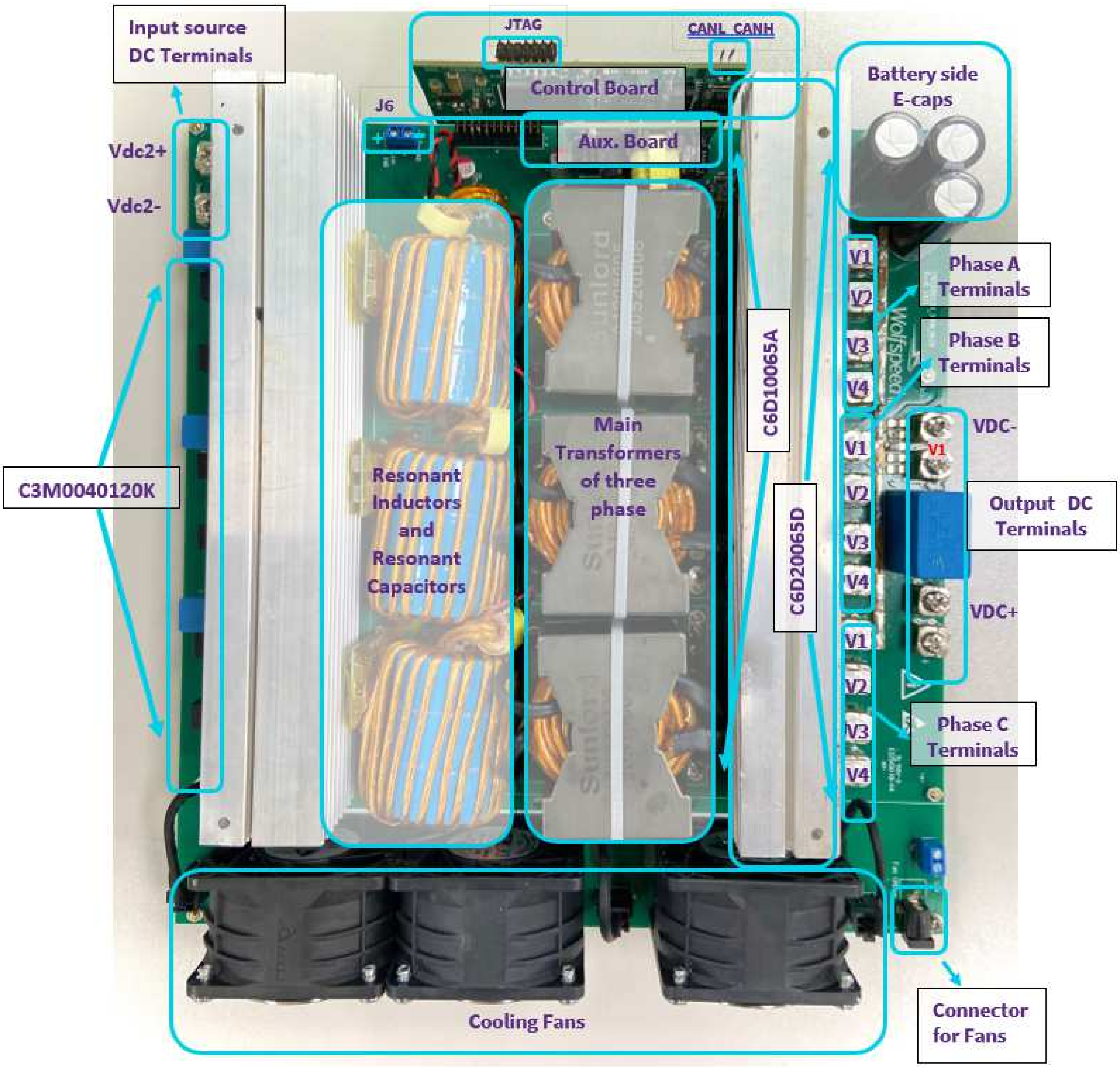


*Figure 11: Top View of PCBA (275mm*255mm*65mm)*

10. PERFORMANCE DATA

Below is measured performance data of Wolfspeed's CRD-30DD12N-K reference design board under various conditions. Table 9, Table 10, and Figure 12 indicates the performance data.

Input Voltage (Vac)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)
650.04	3217.7	10	503.44	3055.4	94.96
650.07	6251.7	20	500.42	6064.1	97.00
650.01	9432.9	30	499.76	9199.1	97.52
650.06	12354.4	40	500	12040.0	97.46
650	15469.4	50	500.12	15042.1	97.24
650.2	18585.3	60	28.584	18017.6	96.95
650.03	21804.0	70	499.97	21067.7	96.62
649.98	25022.9	80	501.03	24079.0	96.23
649.94	26054.7	90	501.41	25050.4	96.15
720.02	3129.2	10	659.9	3018.9	96.48
720.06	6271.7	20	660.3	6136.8	97.85
720.04	9105.6	30	659.93	8943.4	98.22
720.02	12162.6	40	660.16	11948.9	98.24
720	15271.2	50	659.81	15008.7	98.28
720.1	18280.5	60	660.29	17950.6	98.20
720.1	21084.5	70	660	20683.1	98.10
720.1	24310.6	80	660.16	23809.3	97.94
720.01	27713.9	90	660.25	27096.0	97.77
720.05	30888.7	100	660.23	30136.2	97.56
850.2	3347.7	10	1000.08	3128.8	93.46
850.08	6220.9	20	999.68	5988.8	96.27
849.97	9303.8	30	999.55	9050.9	97.28
850.03	12254.9	40	999.46	11961.5	97.61
850.1	15469.9	50	999.43	15126.4	97.78
850	18666.9	60	1000.96	18284.5	97.95
850.01	21618.3	70	1000.56	21184.9	97.99
850.03	24519.1	80	999.46	24050.0	98.09
850.07	27567.6	90	999.65	27054.5	98.14
850.09	30586.7	100	999.46	30011.8	98.12

Table 9: Efficiency Data (Secondary Series Mode)

Input Voltage (Vac)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)
650.14	3125.2	10	252.2	2952.5	94.47
650.03	5971.0	20	250.19	5764.9	96.55
649.98	8930.7	30	250.29	8700.8	97.43
649.96	11532.2	40	250.33	11238.3	97.45
650.03	14174.6	50	250.33	13791.2	97.30
649.89	17283.2	60	250.6	16767.6	97.02
650.01	20321.3	70	249.96	19647.4	96.68
650.06	23215.6	80	250.35	22358.3	96.31
650.53	25987.4	90	251.22	25055.9	96.42
750.05	3077.5	10	344.01	2957.1	96.09
750.1	6152.7	20	344.16	6018.3	97.82
750.0	8904.9	30	343.9	8731.6	98.05
750.0	12152.7	40	344.12	11946.1	98.30
750.0	15298.4	50	343.96	15039.3	98.31
750.0	18402.0	60	343.78	18077.0	98.23
750.0	20643.3	70	343.81	20255.9	98.12
750.03	24562.0	80	343.85	24074.0	98.01
750.05	27130.1	90	343.79	26546.8	97.85
750.04	29957.3	100	343.96	29256.5	97.66
850.05	3405.3	10	500.38	3167.7	93.02
850.03	6382.9	20	499.89	6145.6	96.28
850.08	9394.2	30	499.85	9129.3	97.18
850.1	12326.5	40	499.81	12017.9	97.50
850.02	15609.8	50	500.61	15246.6	97.67
850.1	18498.2	60	500.54	18086.0	97.77
849.94	21593.6	70	500.21	21143.4	97.92
850	24537.8	80	499.7	24048.1	98.00
850.03	27885.2	90	500.54	27341.0	98.05
850.12	30861.1	100	500.35	30265.2	98.07

Table 10: Efficiency Data (Secondary Parallel Mode)

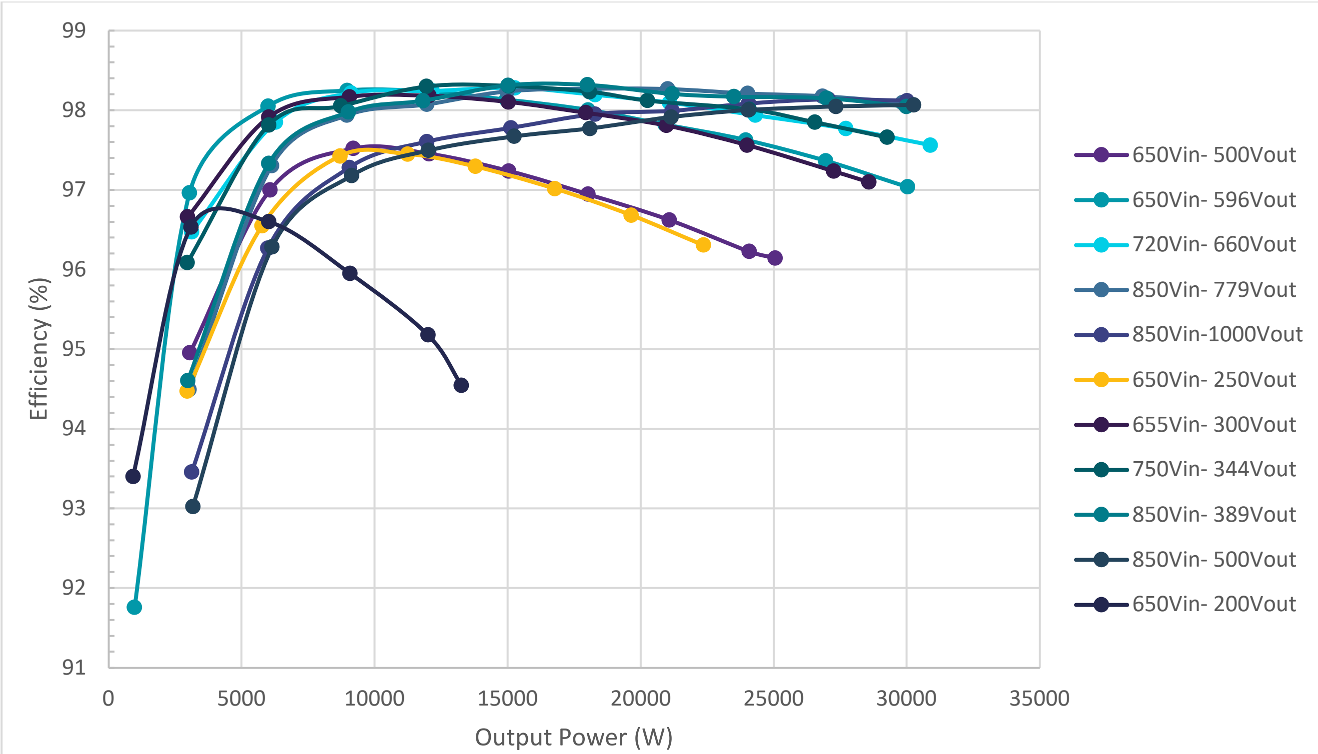
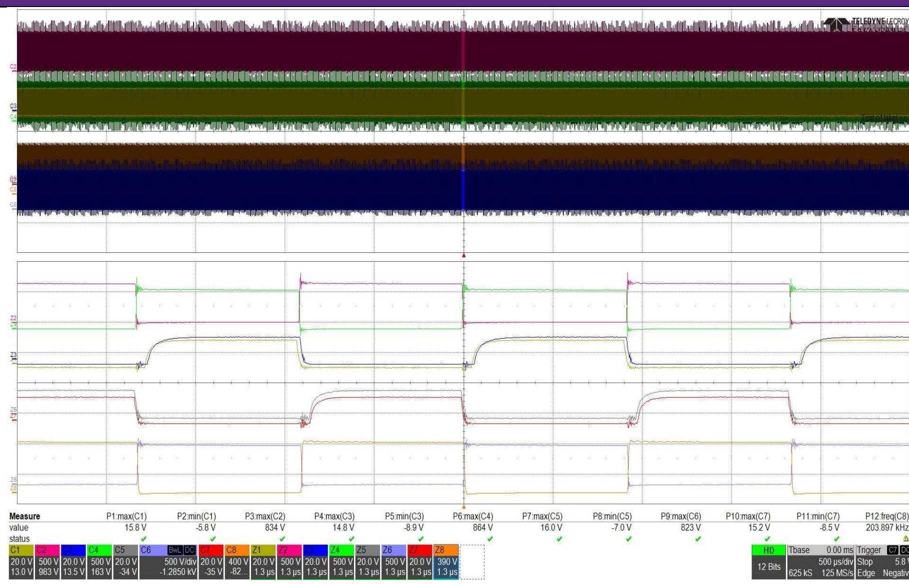
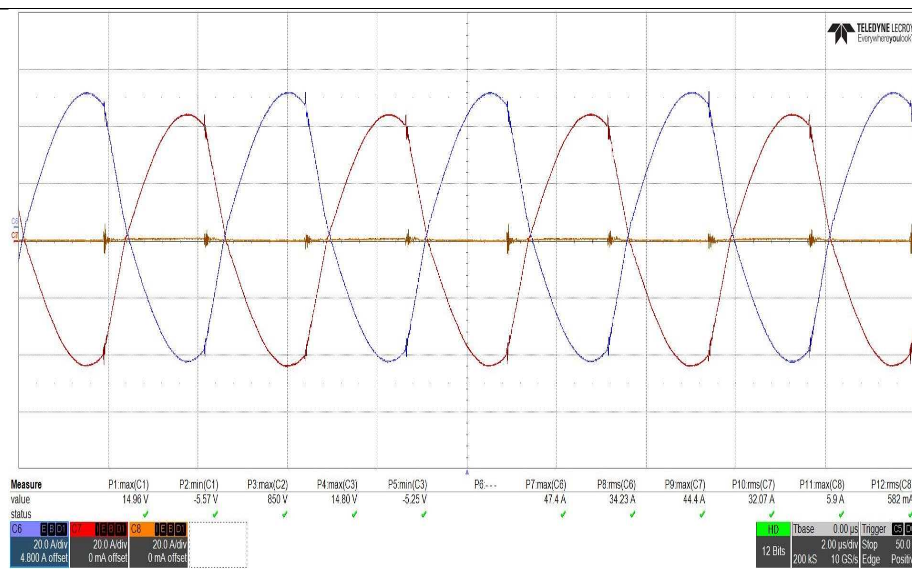


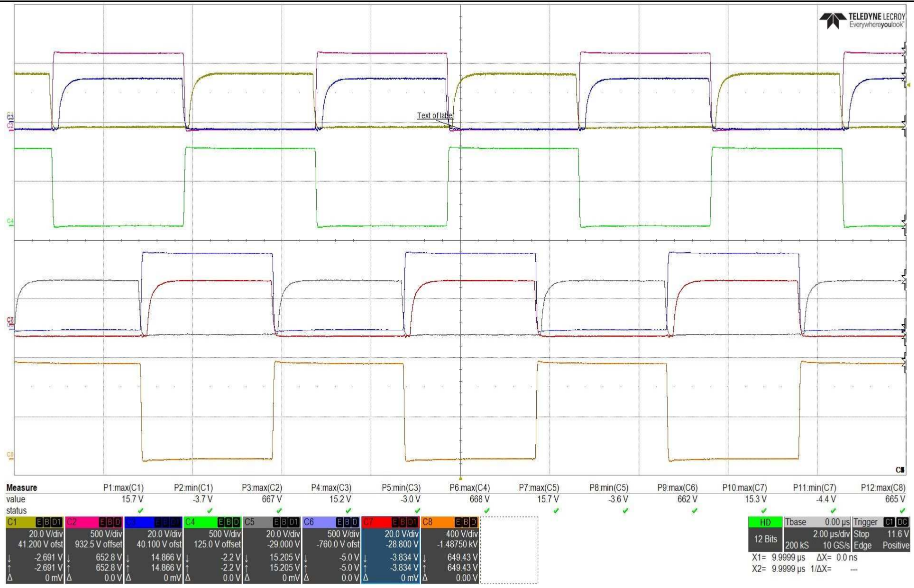
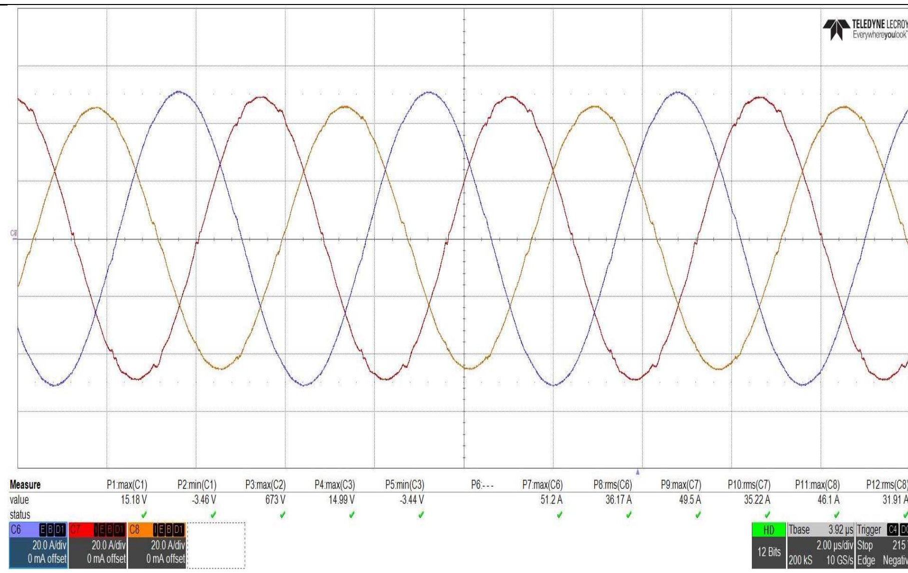
Figure 12: Efficiency Data

11. TYPICAL WAVEFORMS

Operational waveforms are presented in Table 11 and Table 12.

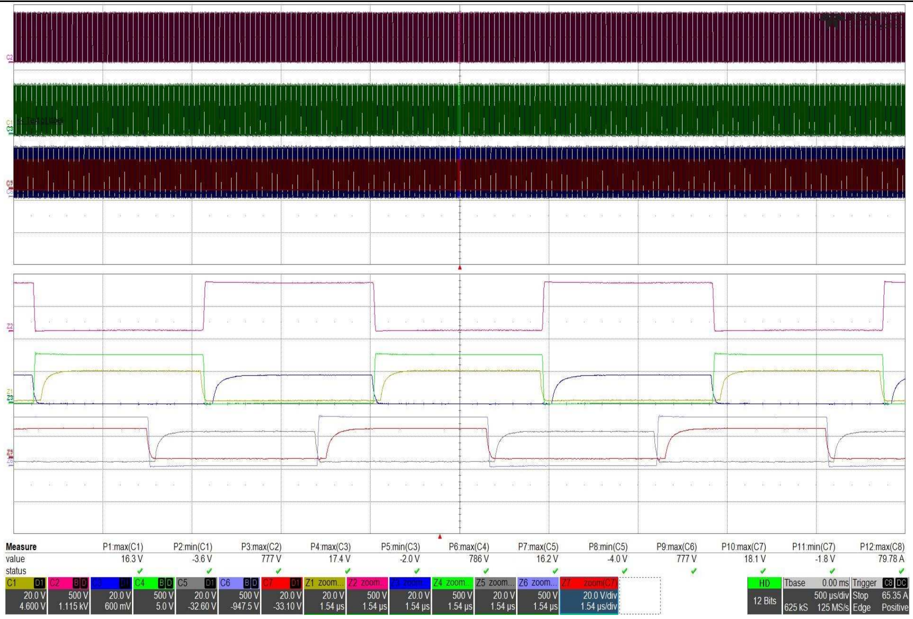
DC/DC Secondary Series Mode:

Condition	Waveform
DC/DC Secondary Series Mode Bus Side Input: 650Vdc Battery Side Output: 200Vdc/66A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: Vds Q4 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Series Mode Bus Side Input: 650Vdc Battery Side Output: 200Vdc/60A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

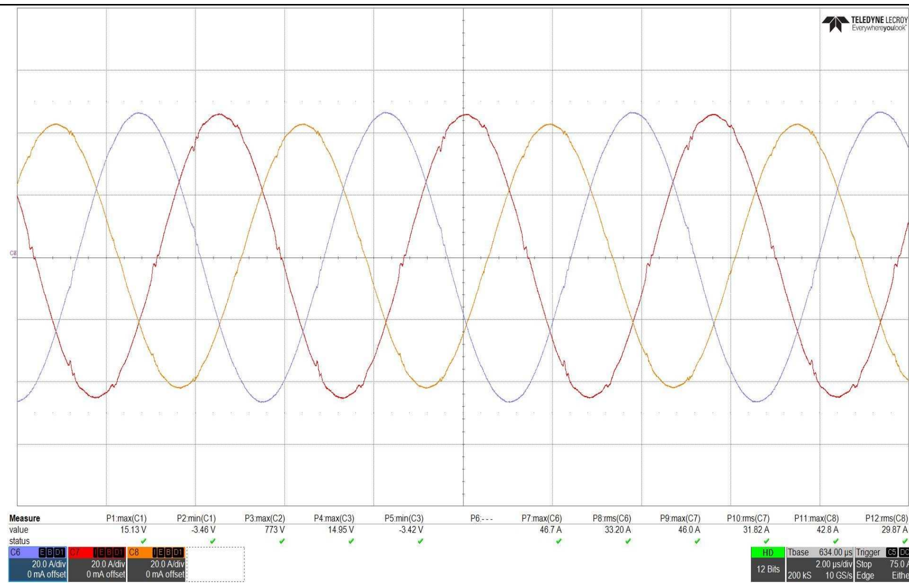
DC/DC Secondary Series Mode Bus Side Input: 655Vdc Battery Side Output: 300Vdc/100A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: Vds Q4 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Series Mode Bus Side Input: 655Vdc Battery Side Output: 300Vdc/100A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

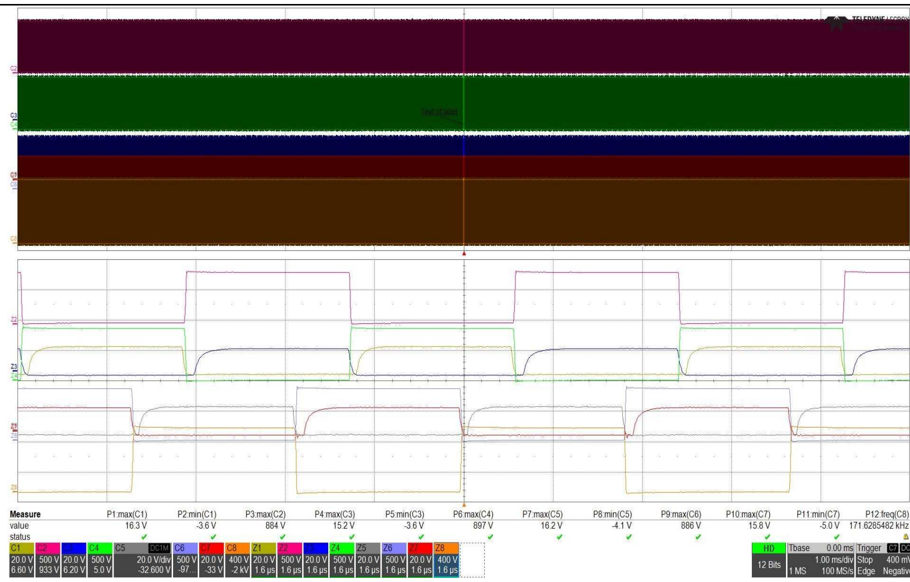
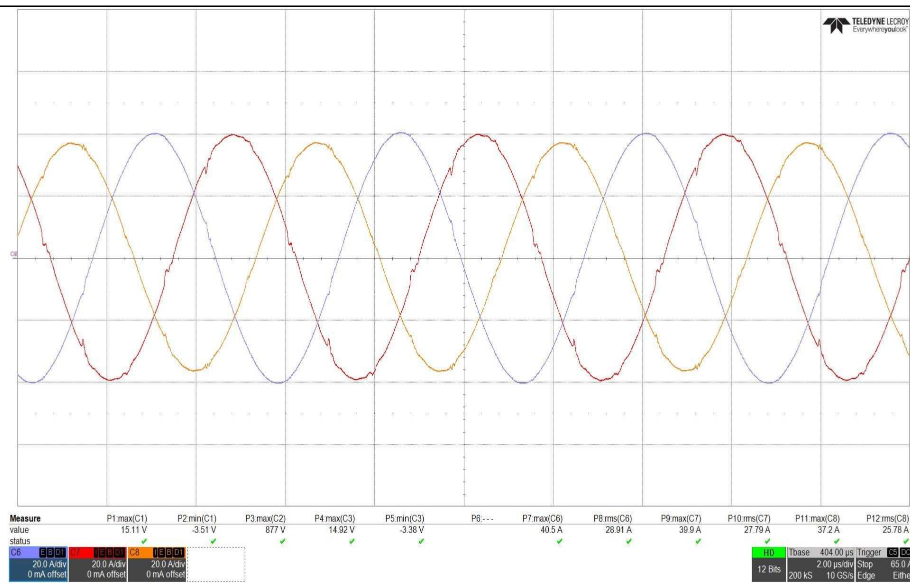
<table>
<tr>
<td>DC/DC Secondary
Series Mode

Bus Side Input:
750Vdc

Battery Side
Output: 340Vdc/88A</td>
<td>
CH1: Vgs Q3 20V/div CH2: Vds Q3 500V/div CH3: Vgs Q1 20V/div CH4: Vds Q1 500V/div
CH5: Vgs Q4 20V/div CH6: Vds Q4 500V/div CH7: Vgs Q2 20V/div CH8: Vds Q2 500V/div</td>
</tr>
<tr>
<td>DC/DC Secondary
Series Mode

Bus Side Input:
750Vdc

Battery Side
Output: 340Vdc/88A</td>
<td>
CH6: IL2 20A/div CH7: IL3 20A/div CH8: IL4 20A/div</td>
</tr>
</table>

DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 390Vdc/76.5A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: Vds Q4 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 390Vdc/76.5A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

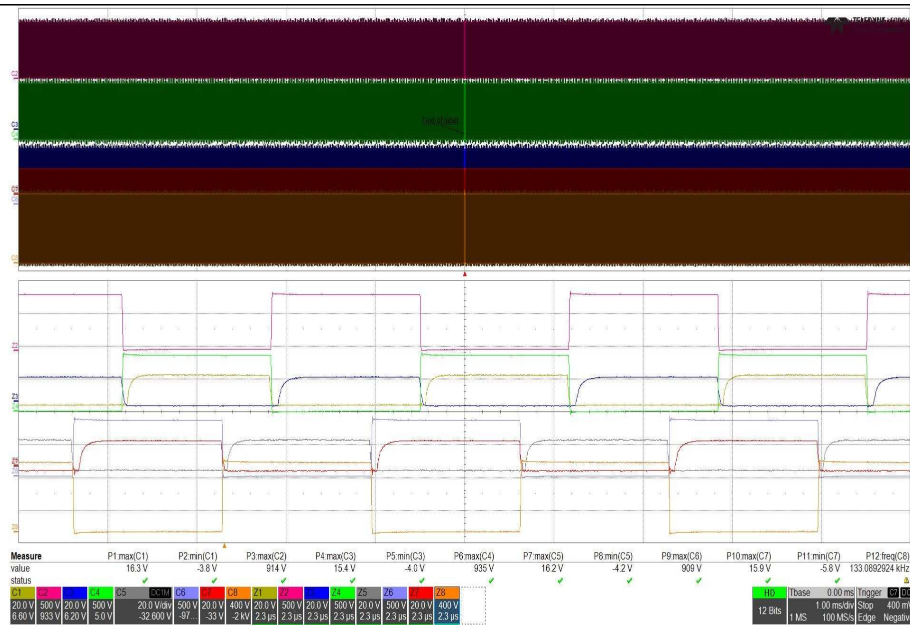
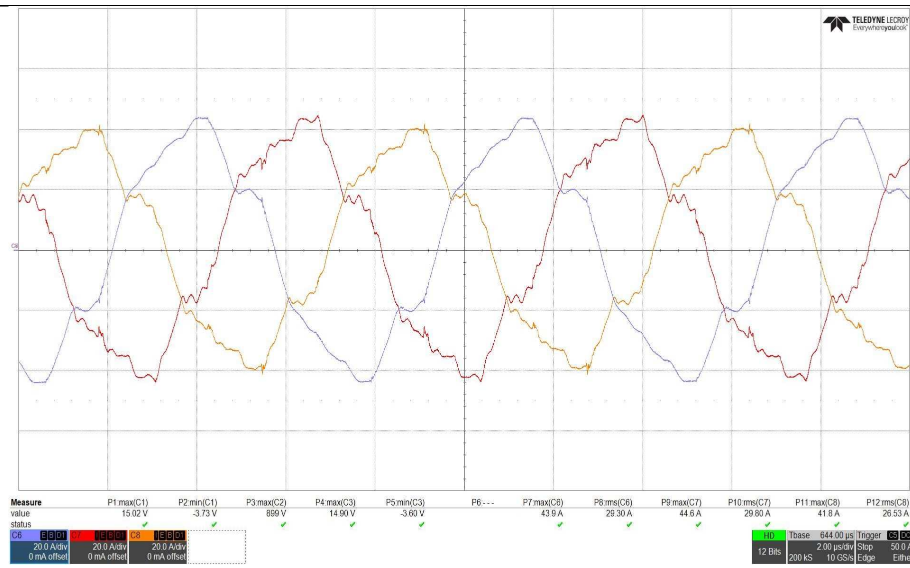
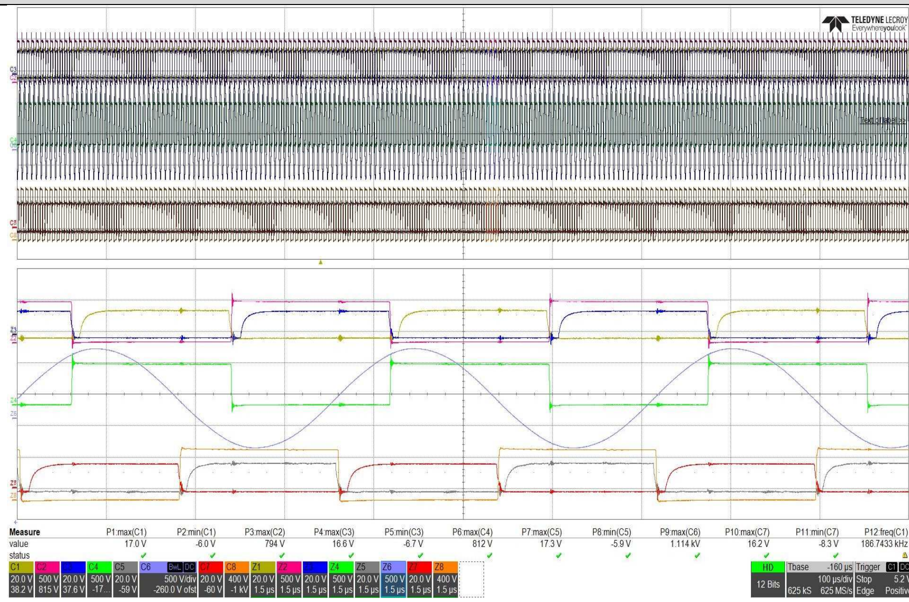
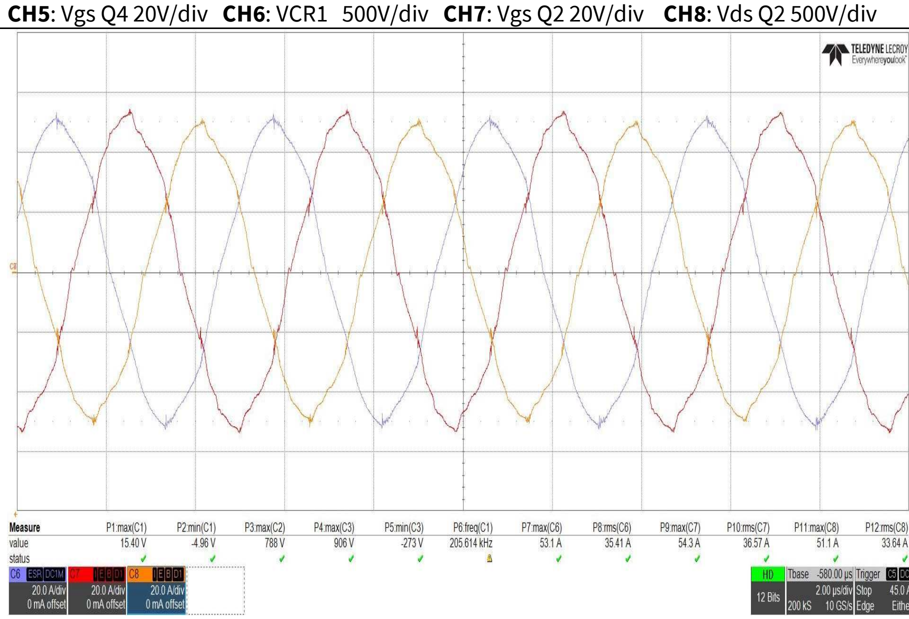
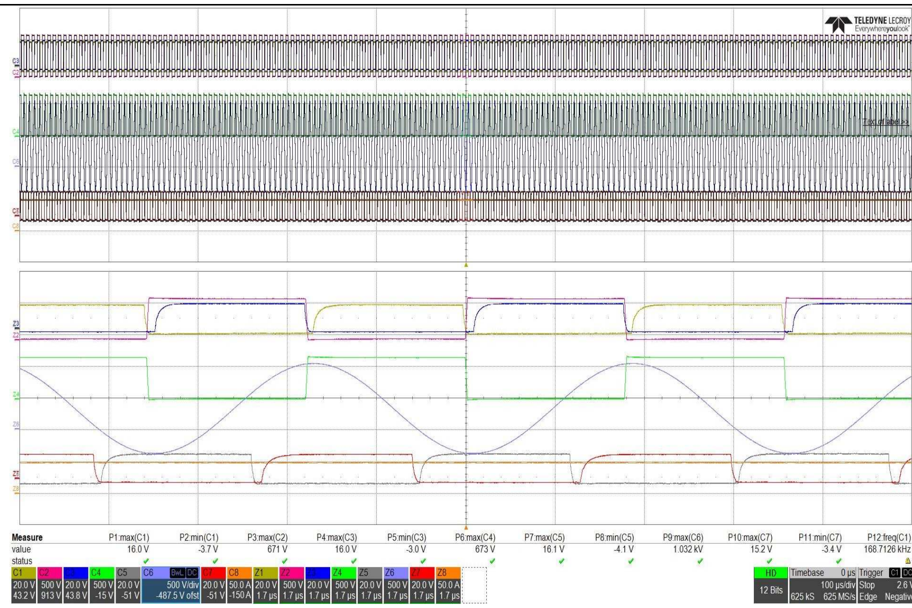
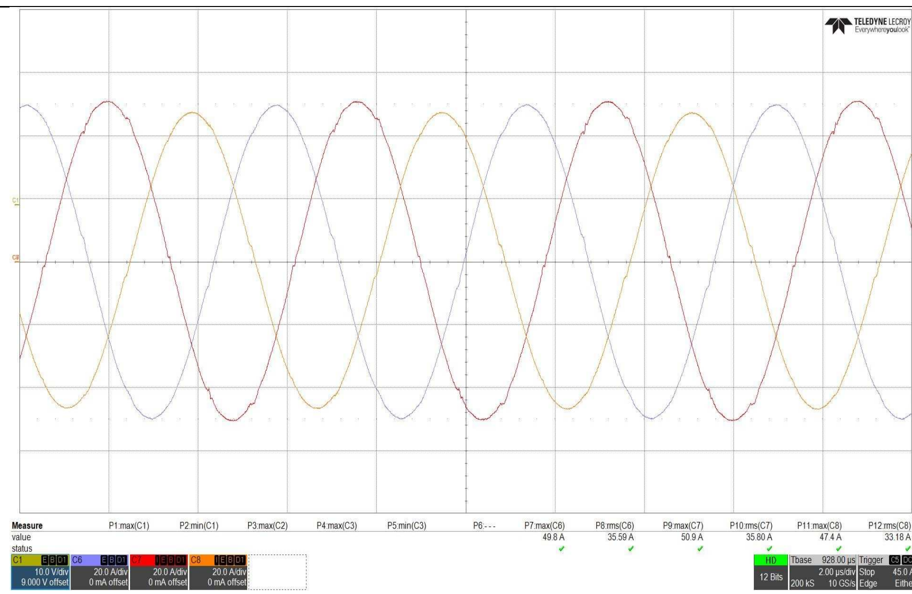
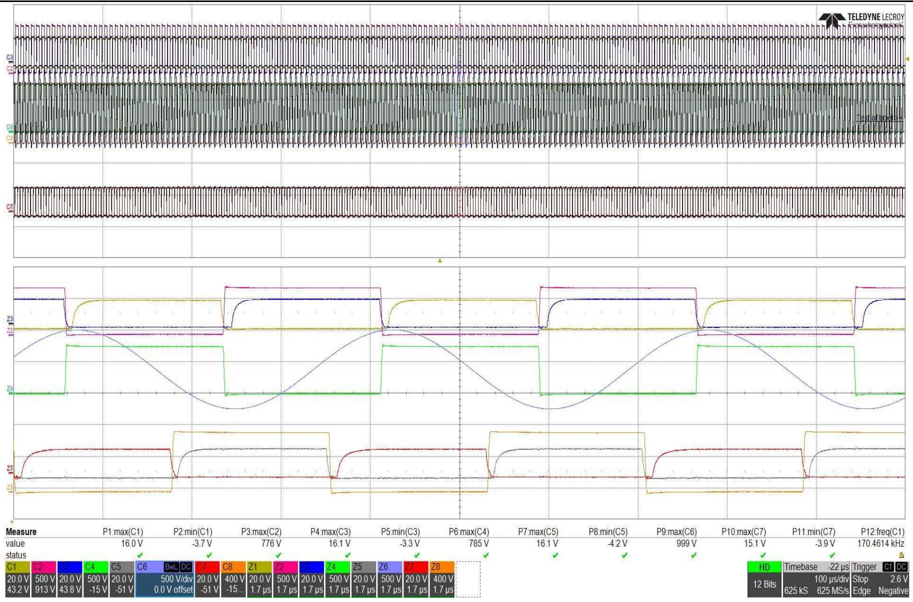
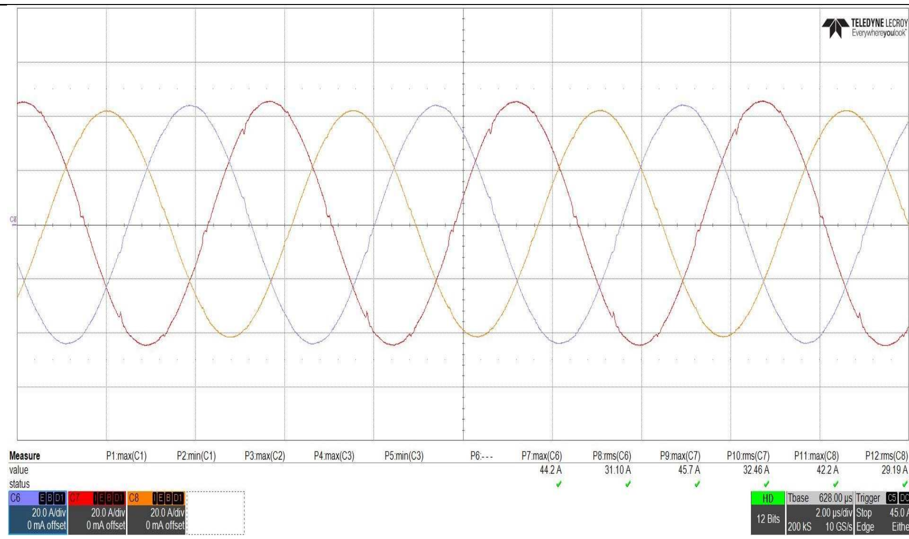
DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 500Vdc/60A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: Vds Q4 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 500Vdc/60A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

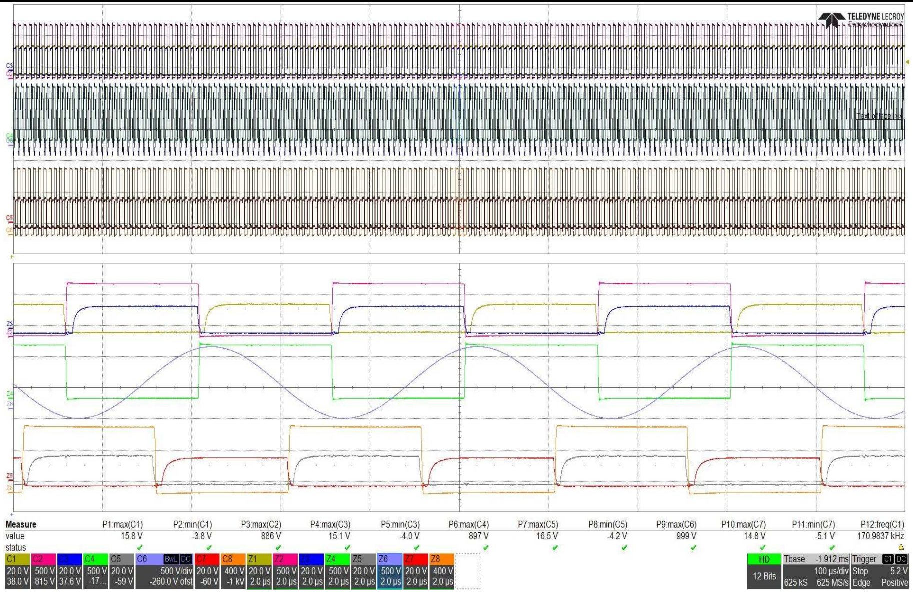
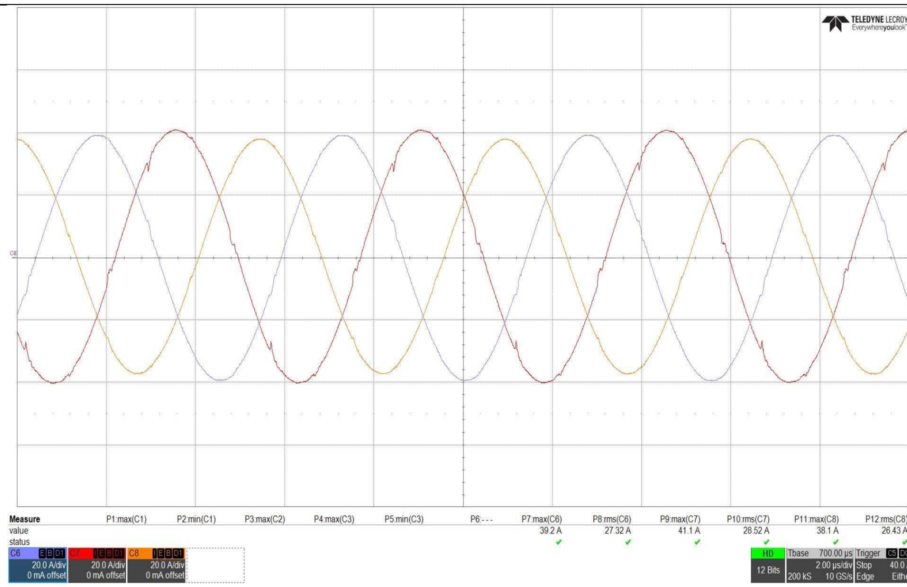
Table 11: DC/DC Secondary Series Mode Waveforms

DC/DC Secondary Parallel Mode: (Resistive Load)

Condition	Waveform
DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 500Vdc/50A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: VCR1 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 500Vdc/50A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 600Vdc/50A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: VCR1 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 600Vdc/50A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

DC/DC Secondary Parallel Mode Bus Side Input: 750Vdc Battery Side Output: 690Vdc/43A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: VCR1 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Parallel Mode Bus Side Input: 750Vdc Battery Side Output: 690Vdc/43A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 780Vdc/38A	 **CH1**: Vgs Q3 20V/div **CH2**: Vds Q3 500V/div **CH3**: Vgs Q1 20V/div **CH4**: Vds Q1 500V/div **CH5**: Vgs Q4 20V/div **CH6**: VCR1 500V/div **CH7**: Vgs Q2 20V/div **CH8**: Vds Q2 500V/div
DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 780Vdc/38A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

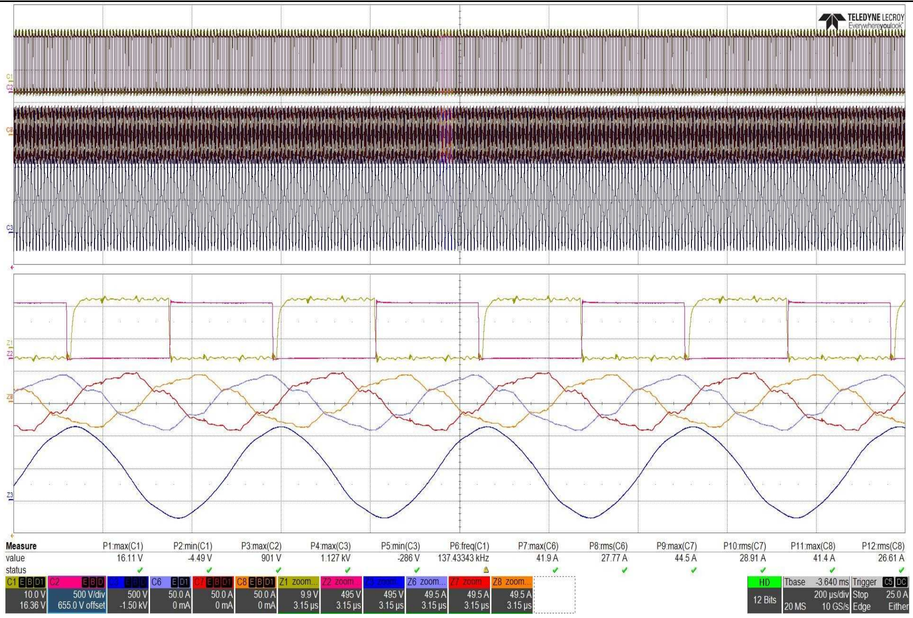
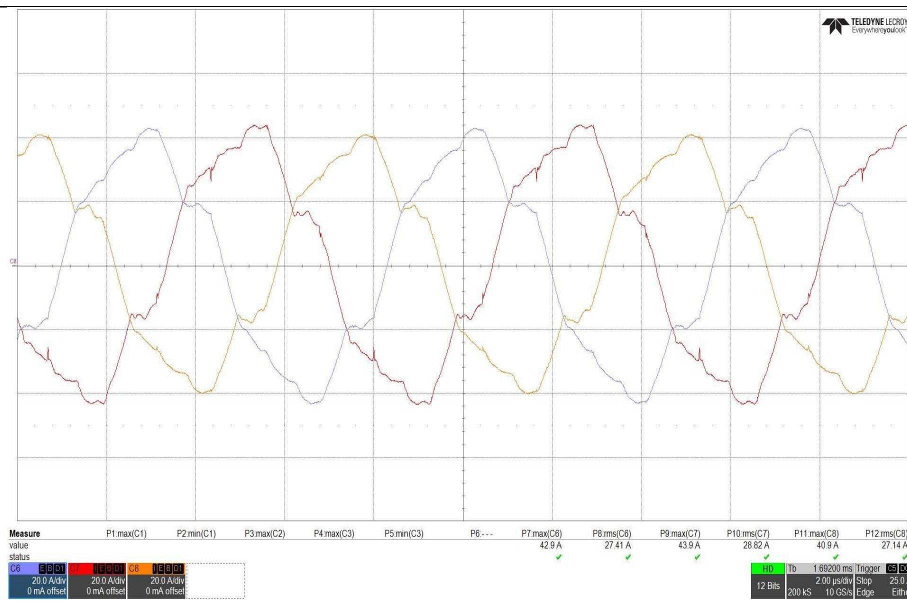
DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 1000Vdc/30A	 **CH1**: Vgs_Q4 20V/div **CH2**: Vds_Q4 500V/div **CH3**: VCR2 500V/div **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div
DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 1000Vdc/30A	 **CH6**: IL2 20A/div **CH7**: IL3 20A/div **CH8**: IL4 20A/div

Table 12: DC/DC Secondary Parallel Mode Waveforms

12. THERMAL DESIGN AND TEST RESULTS

In a thermal test of the unit, forced air cooling was applied to the board using the attached fans at an ambient temperature of 30ºC. The thermal test was performed at 660V DC input and full load (30kW with 300V/100A) with the secondary configured in parallel mode. T-type thermal couples and an acquisition unit from Keysight Technologies Inc. (P/N:34972A) are used to measure the case temperature of components.

The test results under these conditions are shown in Table 13 and Table 14. The highest junction temperature of any MOSFET in the design was determined to be 111°C. This value was calculated based on the measured case temperature, the thermal resistance of the MOSFET, and the calculated power loss. Because the maximum junction temperature of the C3M0040120K is 175°C, the integrated heat sink design has allowed the MOSFETs to remain within their thermal derating guidelines.

Thermal couples are used in the test.

	Test 1	Test 2	Test 3	Test 4	Test 4	Test 5	Rated Temp	Derating Requirement	Result
Vin (V)	650	650	850	650	650	850			
Vout (V)	200	300	500	500	600	1000			
Power (kW)	20	30	30	25	30	30			
Resonant Choke L2 (°C)	79.8	68.4	52	76.6	68.7	51.6	155	130	Pass
Resonant Choke L3 (°C)	60.7	52.4	42	58.2	53	41.9	155	130	Pass
Transformer T6 Coil (°C)	136	135	94.6	134.5	135.8	95	180	160	Pass
Transformer T5 Coil (°C)	141.3	126.1	101.4	140.7	127.2	102.5	180	160	Pass

Table 13: Thermal Test Results of Magnetic Components

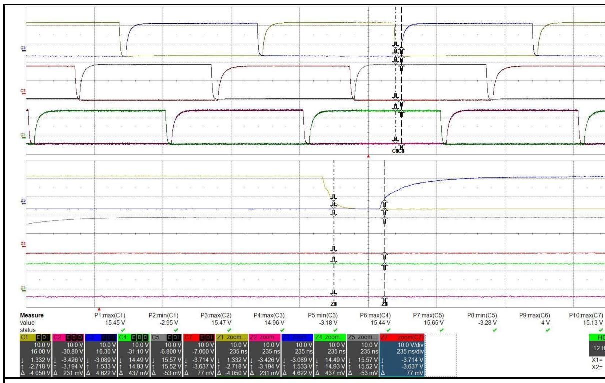
Temperature of semiconductors is shown in the table below.

Description	Rth (j-c) (c/w)	Calculated Power loss (watts)	Measured Case Temp. (°C)	Calculated Junction Temp. (°C)	Max. operating junction temperature (°C)	Result
Vin=650Vdc Vout= 200Vdc 20KW						
LC MOSFET Q1	0.46	53.4	86.2	110.8	175	Pass
LLC MOSFET Q3	0.46	53.4	86.6	111.2	175	Pass
LLC MOSFET Q2	0.46	53.4	82.5	107.1	175	Pass
LLC Diode D15	0.64	33.4	73.08	94.4	175	Pass
LLC Diode D21	0.64	33.4	82.43	103.8	175	Pass
LLC Diode D56	1.38	16.7	66.02	89	175	Pass
Vin=650Vdc Vout= 300Vdc 30KW						
LLC MOSFET Q1	0.46	41	77.2	96.1	175	Pass
LLC MOSFET Q3	0.46	41	72.9	91.8	175	Pass
LLC MOSFET Q2	0.46	41	73.4	92.3	175	Pass
LLC Diode D15	0.64	33.4	67.3	88.7	175	Pass
LLC Diode D21	0.64	33.4	82.4	103.8	175	Pass
LLC Diode D56	1.38	16.7	67.3	90.3	175	Pass
Vin=850Vdc Vout= 500Vdc 30kW						
LLC MOSFET Q1	0.46	27.7	50.9	63.6	175	Pass
LLC MOSFET Q3	0.46	27.7	51.7	64.4	175	Pass
LLC MOSFET Q2	0.46	27.7	49.9	62.6	175	Pass
LLC Diode D15	0.64	12.8	53.3	61.5	175	Pass
LLC Diode D21	0.64	12.8	54.4	62.6	175	Pass
LLC Diode D56	1.38	6.4	48.4	57.2	175	Pass

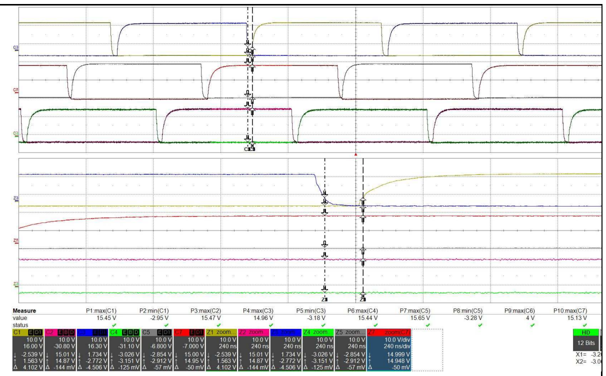
Table 14: Thermal Test Results of SiC Power MOSFETs and Diodes

13. APPENDIX

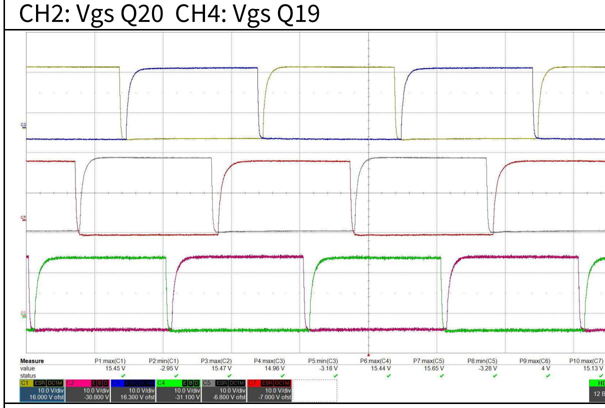
13.1. PWM TIMING



Td1 dead time=174ns
CH1: Vgs Q3 CH3: Vgs Q1
CH5: Vgs Q4 CH7: Vgs Q2
CH2: Vgs Q20 CH4: Vgs Q19



Td2 dead time =137ns
CH1: Vgs Q3 CH3: Vgs Q1
CH5: Vgs Q4 CH7: Vgs Q2
CH2: Vgs Q20 CH4: Vgs Q19



CH1: Vgs Q3 CH3: Vgs Q1
CH5: Vgs Q4 CH7: Vgs Q2
CH2: Vgs Q20 CH4: Vgs Q19

Table 15: Gate Signals and Timings

13.2. CAN MESSAGES FROM DCDC

Message Identifier	**0x18B2F4E5**			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Output Voltage	Output Current	Input Voltage	Output Power
Unit	0.1V	0.1A	0.1V	1W
Bias	0			
Data Format	integer			
Time interval	0.5 seconds			

Table 16: Overall Charge Status

Message Identifier	0x18B0F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Ambient Temperature	Reserved 0xFFFF	Reserved 0xFFFF	Reserved 0xFFFF
Unit	0.1 °C	NA		
Bias	50 °C	NA		
Data Format	integer			
Time interval	3 seconds			

Table 17: Temperature

Message Identifier	0x18B3F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	DCDC status. See Table 19a for details.	Reserved 0xFFFF	Reserved 0xFFFF	Charge state 0: Constant Voltage 1: Constant Current 2: Constant Power
Unit	NA			
Bias	0			
Data Format	integer			
Time interval	0.5 seconds max.			

Table 18a: Charge Status, DCDC Information

Converter Status	Comments	Converter Status	Comments
Bit15	Reserved	Bit7	1: Output OVP 0: normal (default)
Bit14	1: Output short circuit 0: normal (default)	Bit6	1: Input OVP 0: normal (default)
Bit13	1: LLC Resonant Tank OCP 0: normal(default)	Bit5	1: AC abnormal 0: normal (default)
Bit12	1: Input UVP 0: normal(default)	Bit4	1: Ambient OTP 0: normal (default)
Bit11	1: Power Off 0: Power On	Bit3	Reserved
Bit10	1: Calibration Error 0: normal (default)	Bit2	Reserved
Bit9	1: Primary side Full Bridge 0: Primary side 3 phases LLC (default)	Bit1	Reserved
Bit8	1: Secondary side in Parallel 0: Secondary side in Series	Bit0	1: CAN error 0: normal (default)

Table 18b: Bit Definition for DC/DC Status

Message Identifier	0x18B8F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Com. Software Version	Min. Input Voltage	Max. Input Voltage	Max. Charge Current
Unit	0.01	0.1V		0.1A
Bias	0			
Data Format	integer			
Time interval	Reply to 0x18A8E5F4			

Table 19: Part I of DC/DC Specification

Message Identifier	0x18B9F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	DCDC Software Version	Min. Charge Voltage	Max. Charge Voltage	Max. Charge Power
Unit	0.01	0.1V		
Bias	0			
Data Format	integer			
Time interval	Reply to 0x18A8E5F4			

Table 20: Part II of DC/DC Specification

13.3. CAN MESSAGES TO DCDC

Message Identifier	0x18A5E5F4				
Data	Byte0	Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	0: Secondary Series 1: Secondary Parallel	0: OFF 1: ON	Output Power	Output DC Voltage	Output DC Current
Unit	NA		1W	0.1V	0.1A
Bias	0				
Data Format	integer				

Table 21: Control Command

Message Identifier	0x18A8E5F4			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Reserved 0xFFFF	Reserved 0xFFFF	Reserved 0xFFFF	Reserved 0xFFFF
Unit	NA			
Bias	0			
Data Format	integer			

Table 22: Command for Querying DC/DC Specification

14. Revision History

Date	Revision	Changes
March 2022	1	First issue