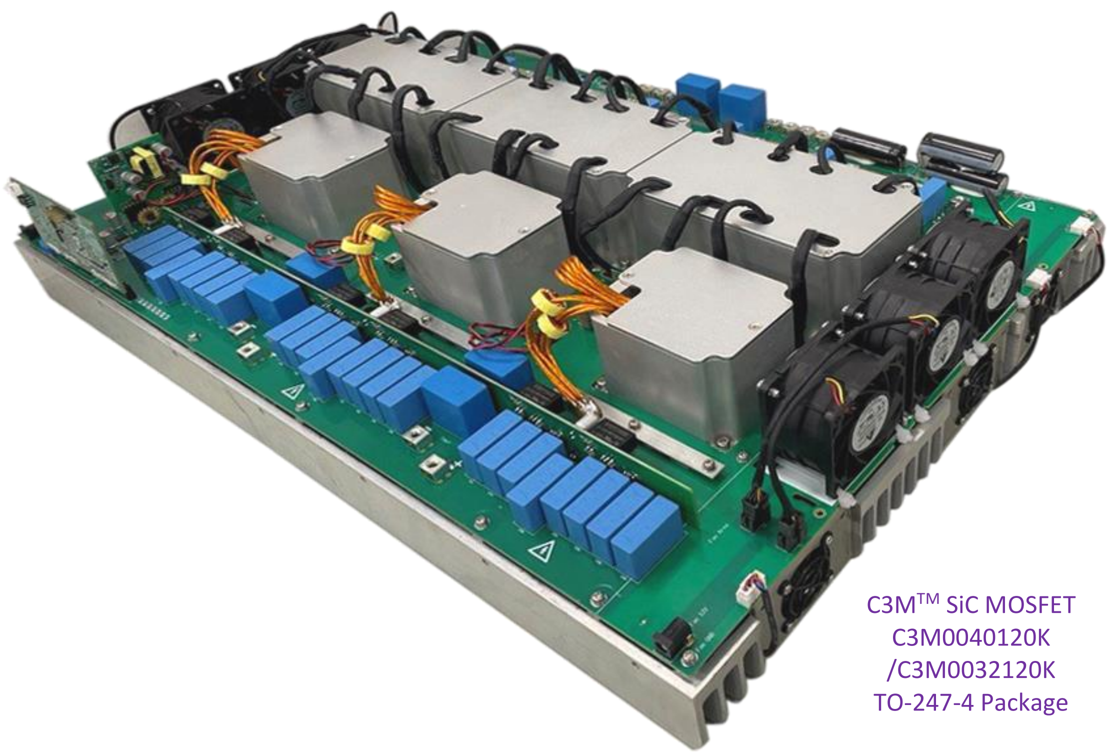
USER GUIDE PRD-07229

CRD-60DD12N-K: 60kW THREE-PHASE INTERLEAVED LLC DC/DC CONVERTER

60kW 三相交错 LLC-直流/直流变换器

60kW 三相交錯 LLC DC/DC 変換器



User Guide

Wolfspeed Power Applications

Wolfspeed, Inc. 4600 Silicon Drive Durham, NC 27703, USA	沃孚半导体有限责任公司 4600 Silicon Drive Durham, NC 27703, USA	クリー株式会社 4600 Silicon Drive Durham, NC 27703, USA

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.

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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 forum.wolfspeed.com if you have any questions about the protection of this hardware during transportation. The hardware does not contain any hazardous substances, is not designed to meet any industrial, technical, or safety standards or classifications, and is not a production- qualified assembly.

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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。

Wolfspeed

CONTENTS

1. INTRODUCTION

This User Guide provides the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-60DD12N-K, 60kW DC/DC converter for an electric vehicle (EV) off-board fast charger and similar applications.

The design of Wolfspeed's 60KW, DC/DC converter (P/N CRD-60DD12N-K) is based upon one of Wolfspeed's latest generation of SiC MOSFETs - C3M0040120K (1200V, 40mΩ, TO-247-4) or C3M0032120K (1200V, 32mΩ, TO-247-4 for high efficiency version) and SiC Schottky diodes C6D20065D (650V, 10A*2, TO-247-3). 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 high efficiency, high power rating, low input and output current ripple, good current sharing and wide output voltage range. 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 six high-frequency transformers. The converter operates in a 120-250kHz switching frequency range. The heat generated by the power MOSFETs and power diodes is dissipated via a cooling plate. The power density is up to 4.83kW/L. The block diagram of the converter is shown in Figure 1.

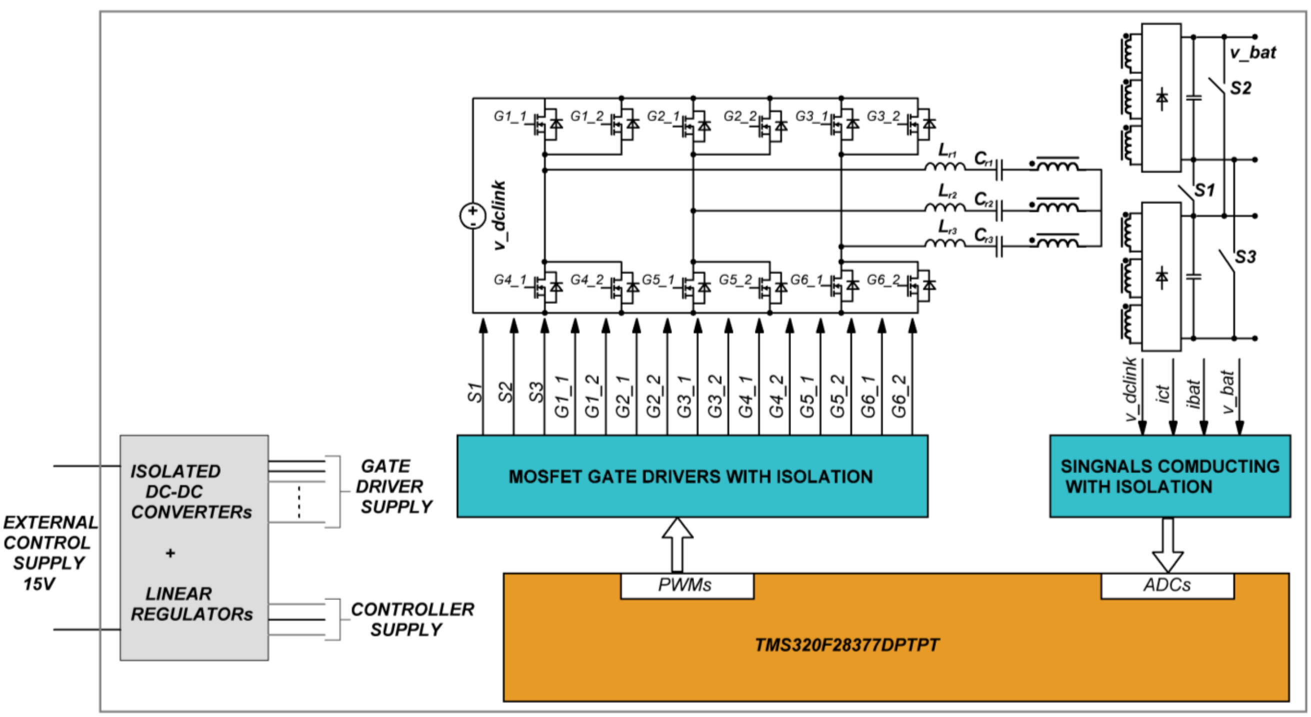

Figure 1: Block Diagram of Wolfspeed's CRD-60DD12N-K, 60kW High Efficiency DC/DC

In an off-board charging application, the AC/DC front end supplies an adjustable bus voltage to the input of the DC/DC between 650VDC and 870VDC. This varied bus voltage, along with the reconfiguration of series or parallel connection of the secondary side, makes it possible to provide a wide output voltage range between 200VDC and 1000VDC with high efficiency and high power density. In parallel mode, the output voltage range is 200VDC to 500VDC. In series mode, the output voltage range is 500VDC to 1000VDC. The peak efficiency of the DC/DC converter can exceed 98% depending on the operating conditions.

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 or C3M0032120K, in three half-bridges on the primary side and uses Wolfspeed's SiC Schottky diodes, C6D20065D, in full-bridge rectifiers on the secondary side. Two parallel SiC MOSFETs are used for each position of the primary side and a single SiC Schottky diode is used for each position of the secondary side.

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 a wide-output voltage range. When the required output voltage 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 state machine 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 operate from the output 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 only the DC/DC stage, then input voltage needs to be set based on output voltage (battery voltage) as the curve shows in Figure 2.

Secondary Configuration	Input Voltage (V)	Output Battery Side Voltage (V)
Parallel	650-660	200-327V
	660-840	Vin*0.411
	840-870	345-500V
Series	650-660	500-542
	660-840	Vin*0.822
	840-870	690-1000

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	60kW	133A	Parallel
	250V~500V		200A	
	500V~1000V		100A	Series

Table 1b: Overall Charging Operation

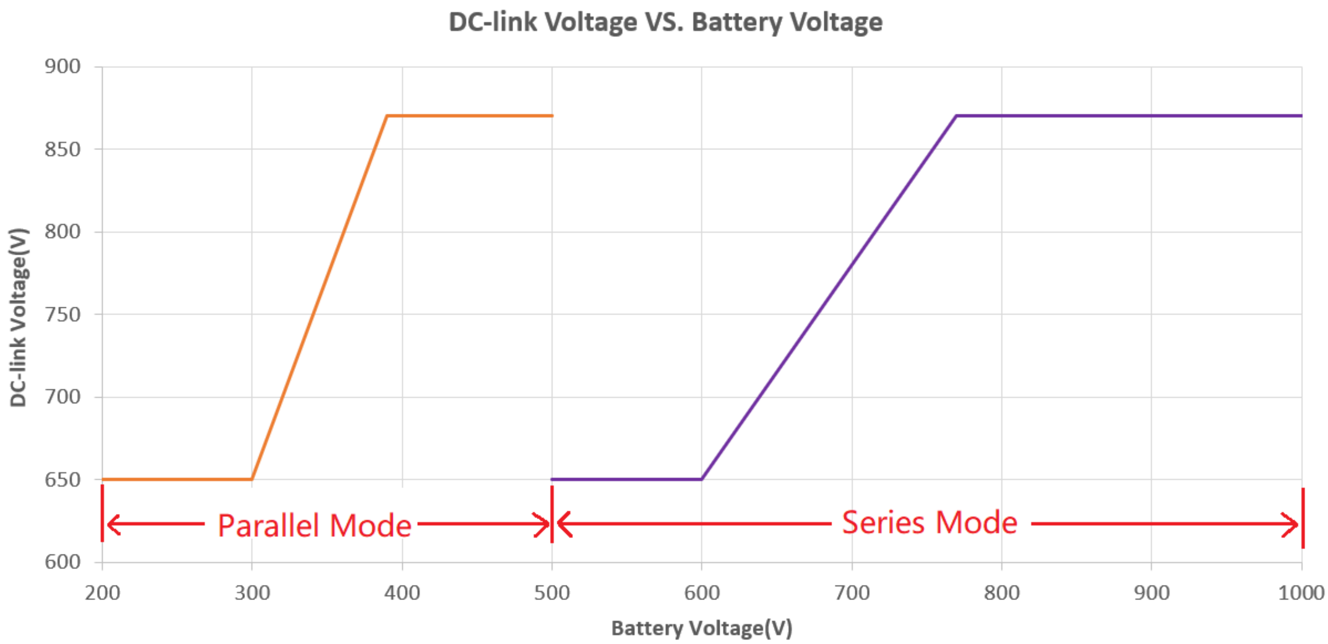

Figure 2: DC Bus Voltage vs. Battery Voltage Curve

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 with 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, Max. Output Current, and the output voltage. Please note that the output voltage can only be set when the input voltage ranges from 650V to 660V or 840V to 870V, 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

Table 2: Characteristics of Wolfspeed's CRD-60DD12N-K, 60kW DC/DC Converter

PARAMETER		TEST CONDITIONS	MIN	NOM	MAX	UNITS
Input Characteristics						
Vin	Input voltage		650	800	870	V
I_{in}	Input current				94	A
Output Characteristics						
V_{OUT1}	Output voltage	Secondary side in parallel	200	333	500	V
$P_{OUT1\ max}$	Output power	Secondary side in parallel			60000	W
$I_{OUT\ 1}$	Output current (3-ph HB)	Secondary side in parallel			200	A
$I_{OUT\ 1}$	Output current (2-ph FB)	Secondary side in parallel			130	A
V_{OUT2}	Output voltage	Secondary side in series	500	666	1000	V
$P_{OUT2\ max}$	Output power	Secondary side in series			60000	W
$I_{OUT\ 2}$	Output current	Secondary side in series			100	A
V_{ripple}	Output voltage ripple				±2%	
System Characteristics						
η_{peak}	Peak efficiency	V_{IN} = 850V, V_{OUT} = 708V, I_{OUT} = 34A /Parallel	98.2%	98.5%		
$\eta_{full\ load}$	Full load efficiency /Secondary Series	V_{IN} = 870V, V_{OUT} = 1000V, I_{OUT} = 55A	98.1%	98.4%		
		V_{IN} = 850V, V_{OUT} = 708V, I_{OUT} = 85A	97.7%	98.0%		
		V_{IN} = 730V, V_{OUT} = 600V, I_{OUT} = 100A	96.6%	96.9%		
		V_{IN} = 650V, V_{OUT} = 540V, I_{OUT} = 100A	96.2%	96.5%		
		V_{IN} = 650V, V_{OUT} = 500V, I_{OUT} = 100A	96.4%	96.7%		
	Full load efficiency /Secondary Parallel	V_{IN} = 870V, V_{OUT} = 500V, I_{OUT} = 110A	98.0%	98.3%		
		V_{IN} = 850V, V_{OUT} = 354V, I_{OUT} = 170A	97.6%	97.9%		
		V_{IN} = 730V, V_{OUT} = 300V, I_{OUT} = 200A	96.3%	96.6%		
		V_{IN} = 650V, V_{OUT} = 270V, I_{OUT} = 200A	95.9%	96.2%		
		V_{IN} = 650V, V_{OUT} = 250V, I_{OUT} = 200A	96.3%	96.6%		

Note: The efficiency data in Table 2 is the test result of Wolfspeed's CRD-60DD12N-K C3M0040120K version

3.1. APPLICATION

The primary application for Wolfspeed's CRD-60DD12N-K reference design board is the DC/DC stage of an EV off-board fast charger. 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-60DD12N-K reference design board are listed below:

- Wide voltage range (650V-870V voltage range for bus-side terminals and 200V-1000V voltage range for battery-side terminals).
- Maximum output current is limited to 100A (secondary side in series) or 200A (secondary side in parallel), maximum output power is limited to 60kW.
- Peak efficiency > 98.5%.
- 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

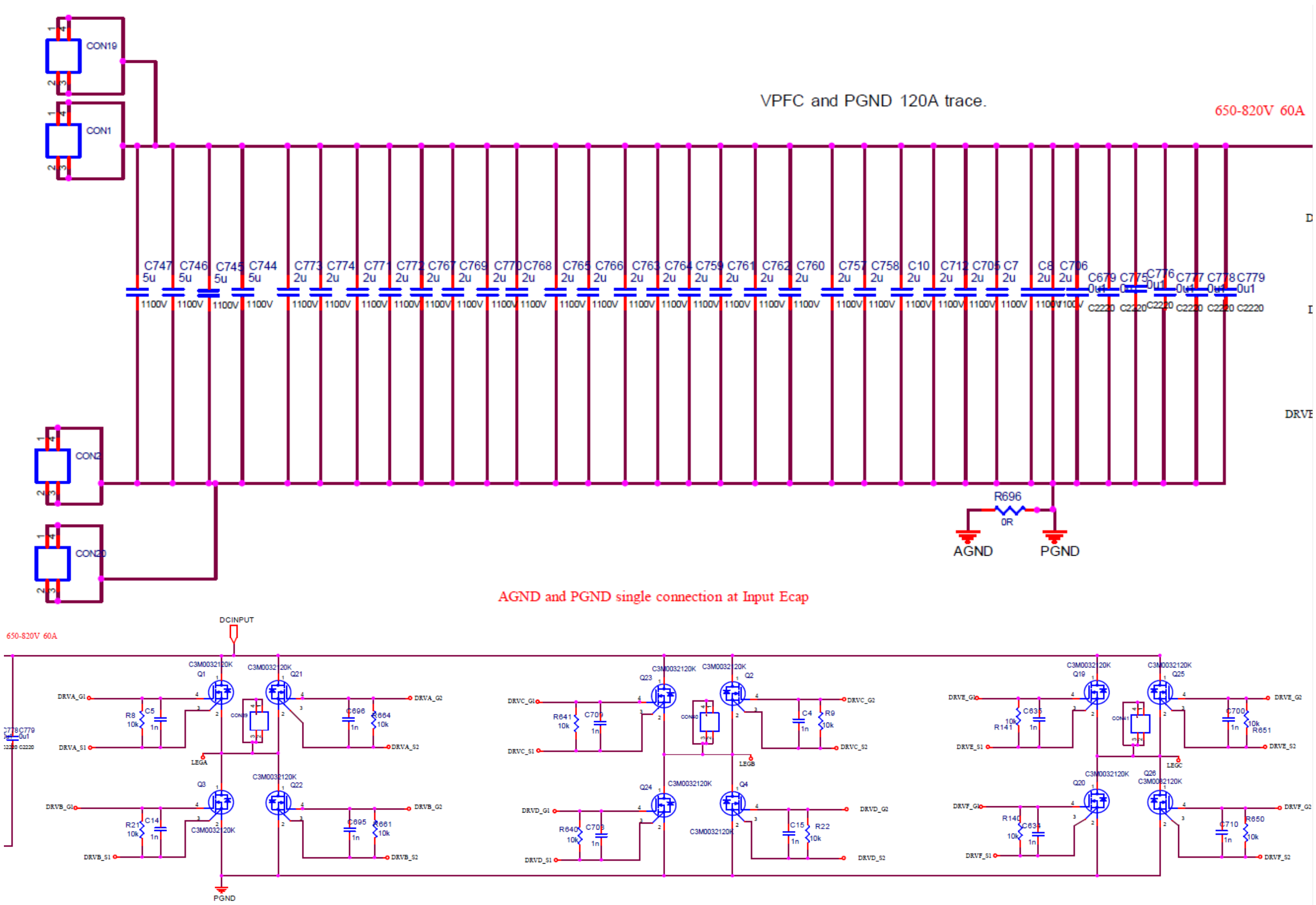

Figure 3a: Input filter capacitors and 12 SiC MOSFETs on the primary side of the converter along with their gate drive circuit

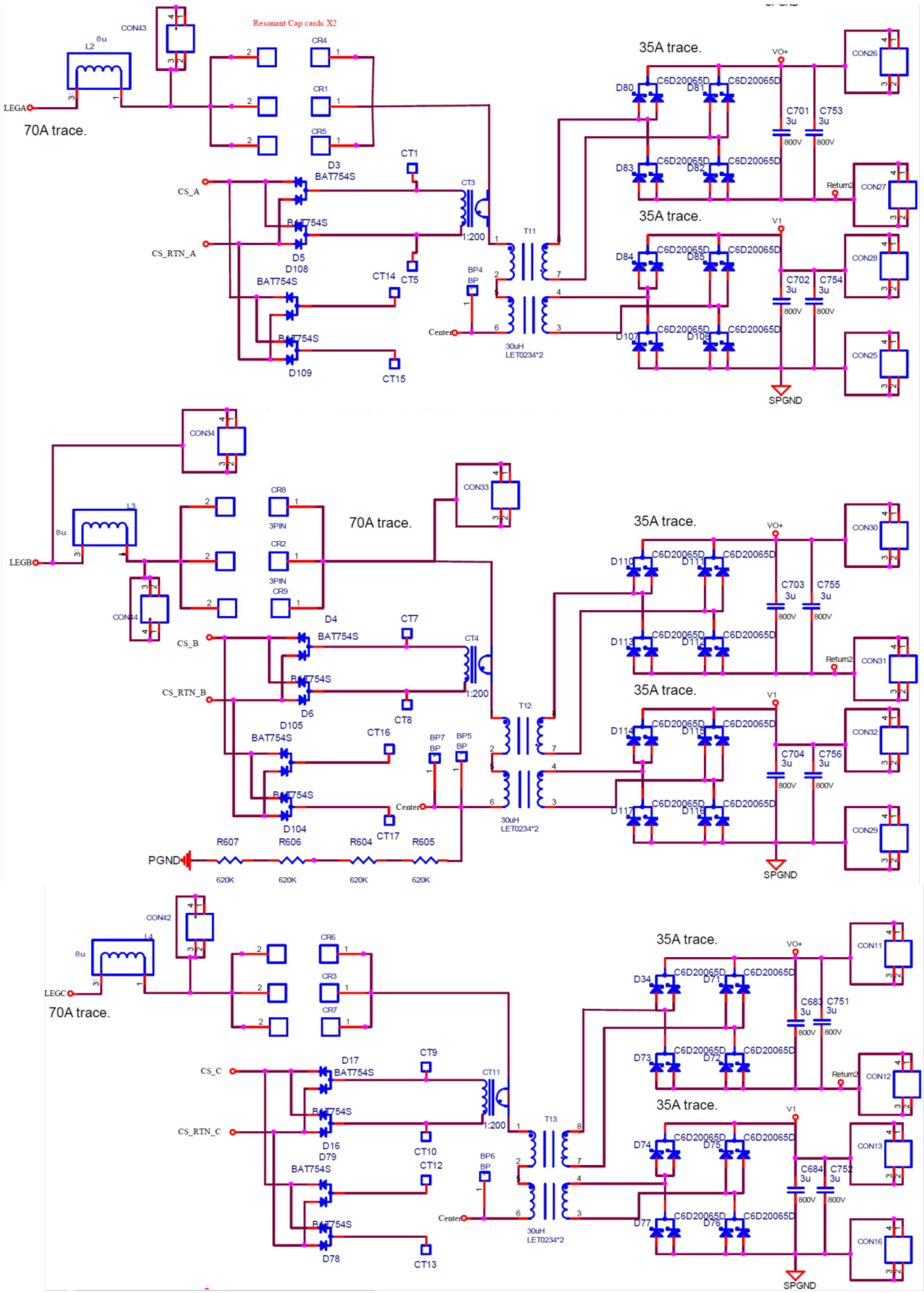

Figure 3b: Resonant tank circuits on the primary side and the rectifying circuits on the secondary side for each phase

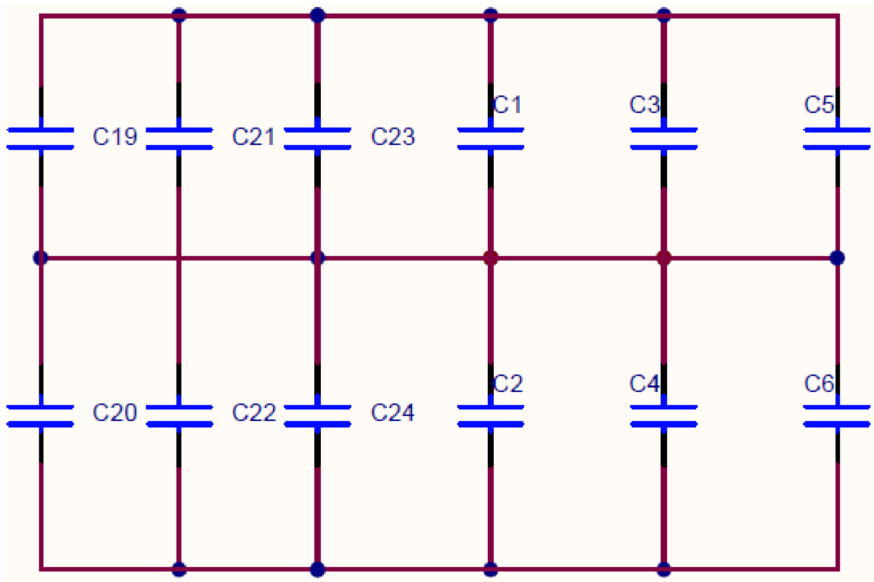

Figure 3c: Resonant capacitor cards for each phase

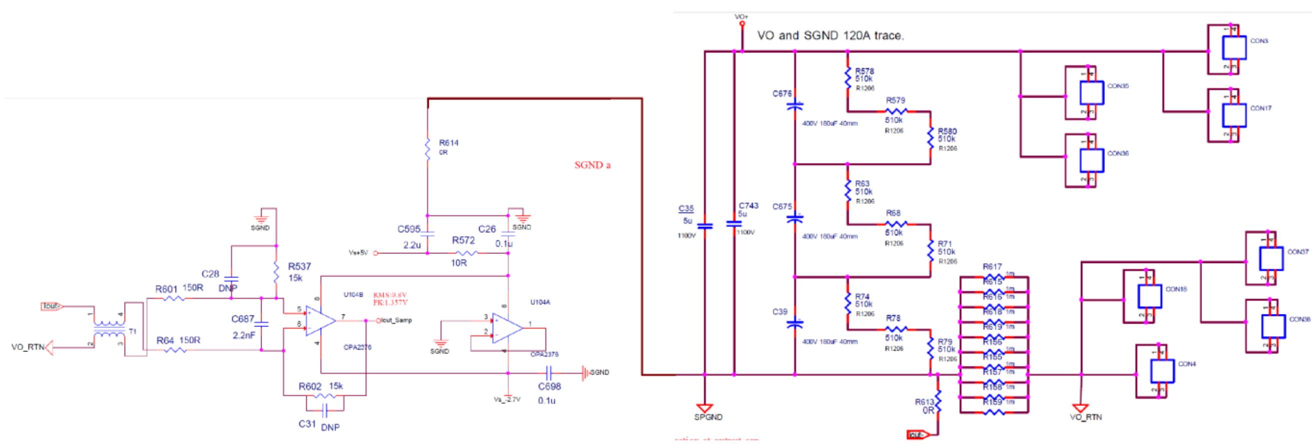

Figure 3d: Filter capacitor and current sampling circuit at DC output

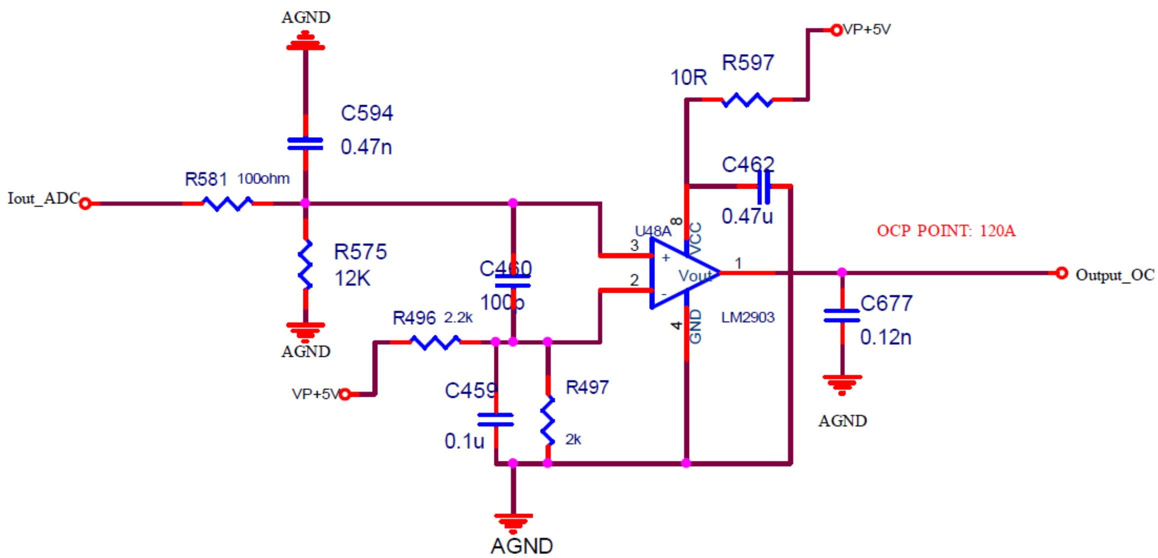

Figure 3e: Overcurrent detection circuit for output current

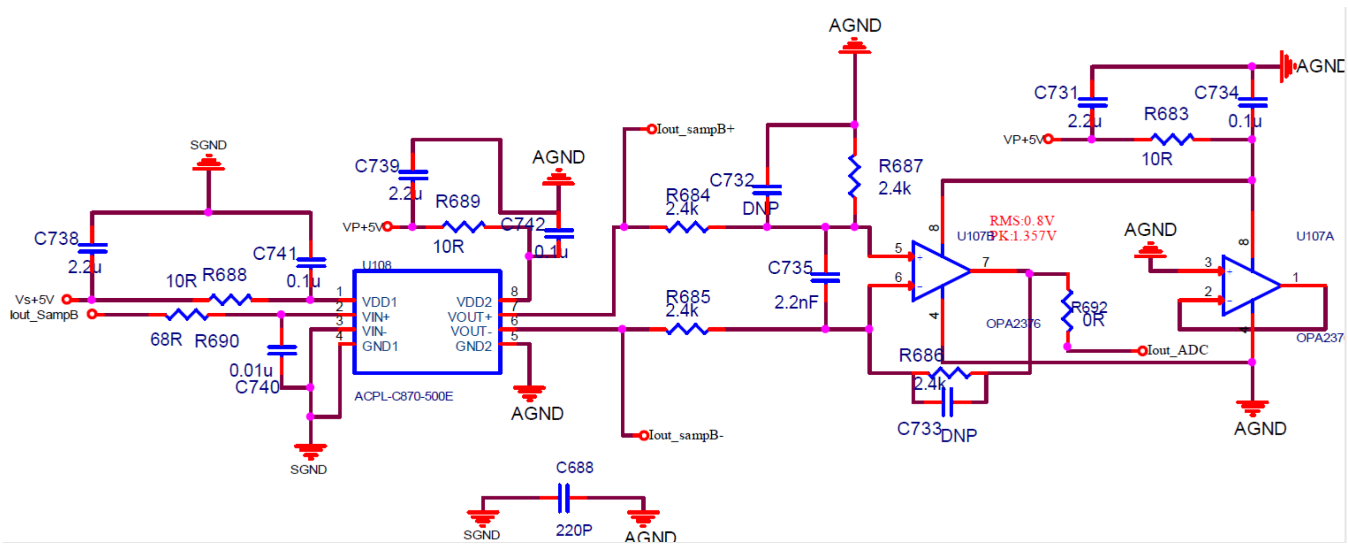

Figure 3f: Isolation and amplification circuit for output current sampling

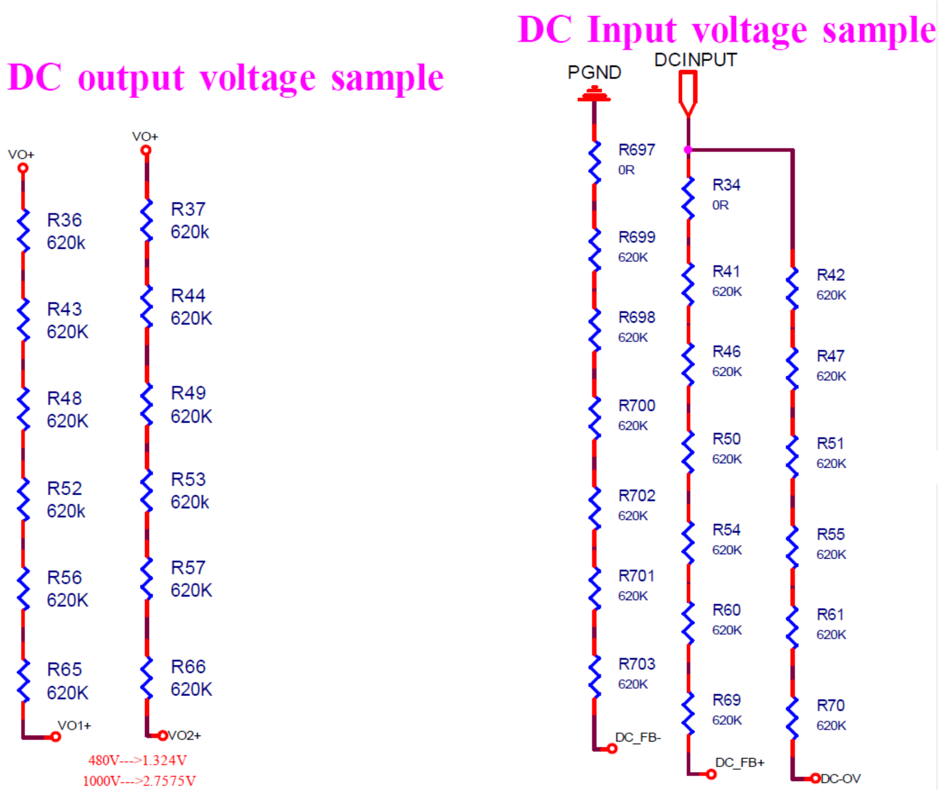

Figure 3g: Resistors for DC input and DC output voltage sampling

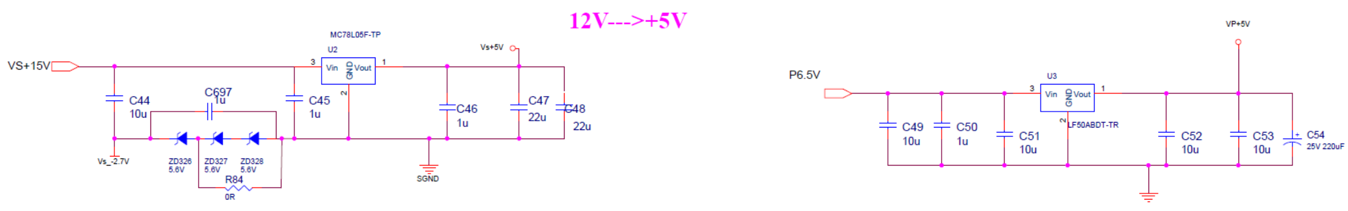

Figure 3h: Power supply for signal circuits

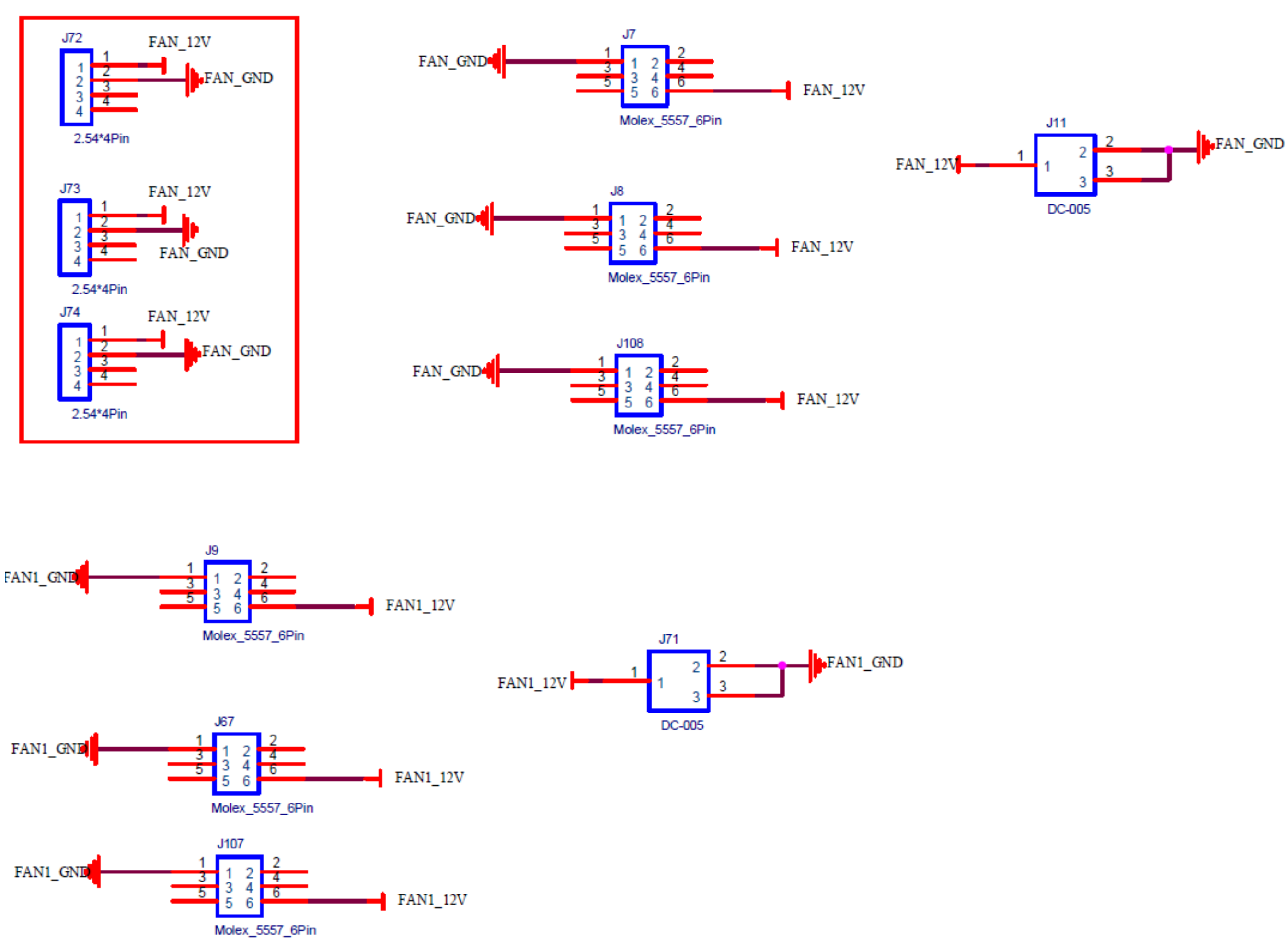

Figure 3i: Power supply for fan

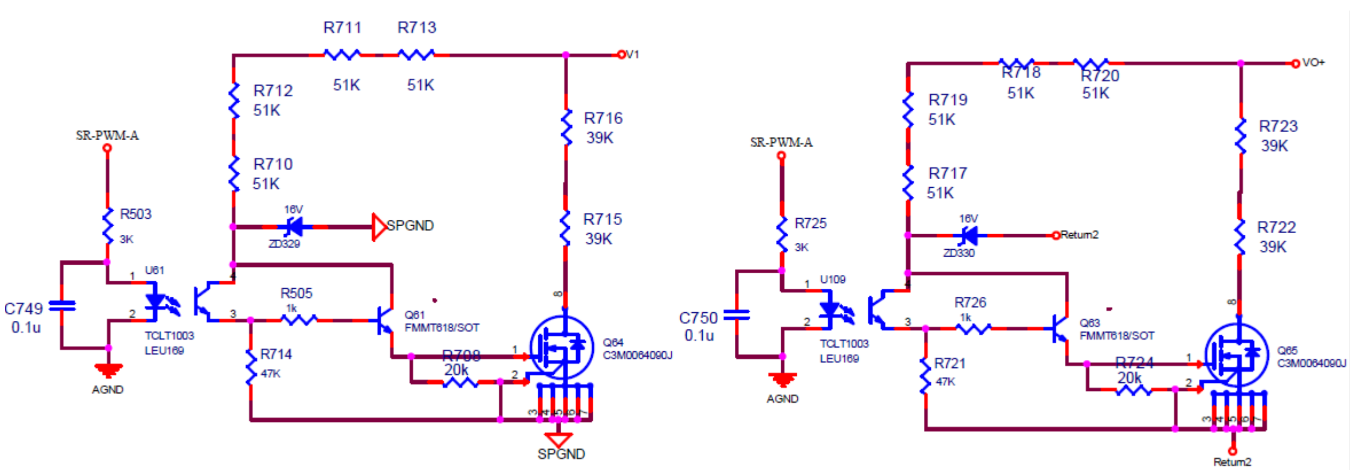

Figure 3j: Series mode output voltage balancing circuit (Active in series mode light load only)

4.2. CONTROL BOARD

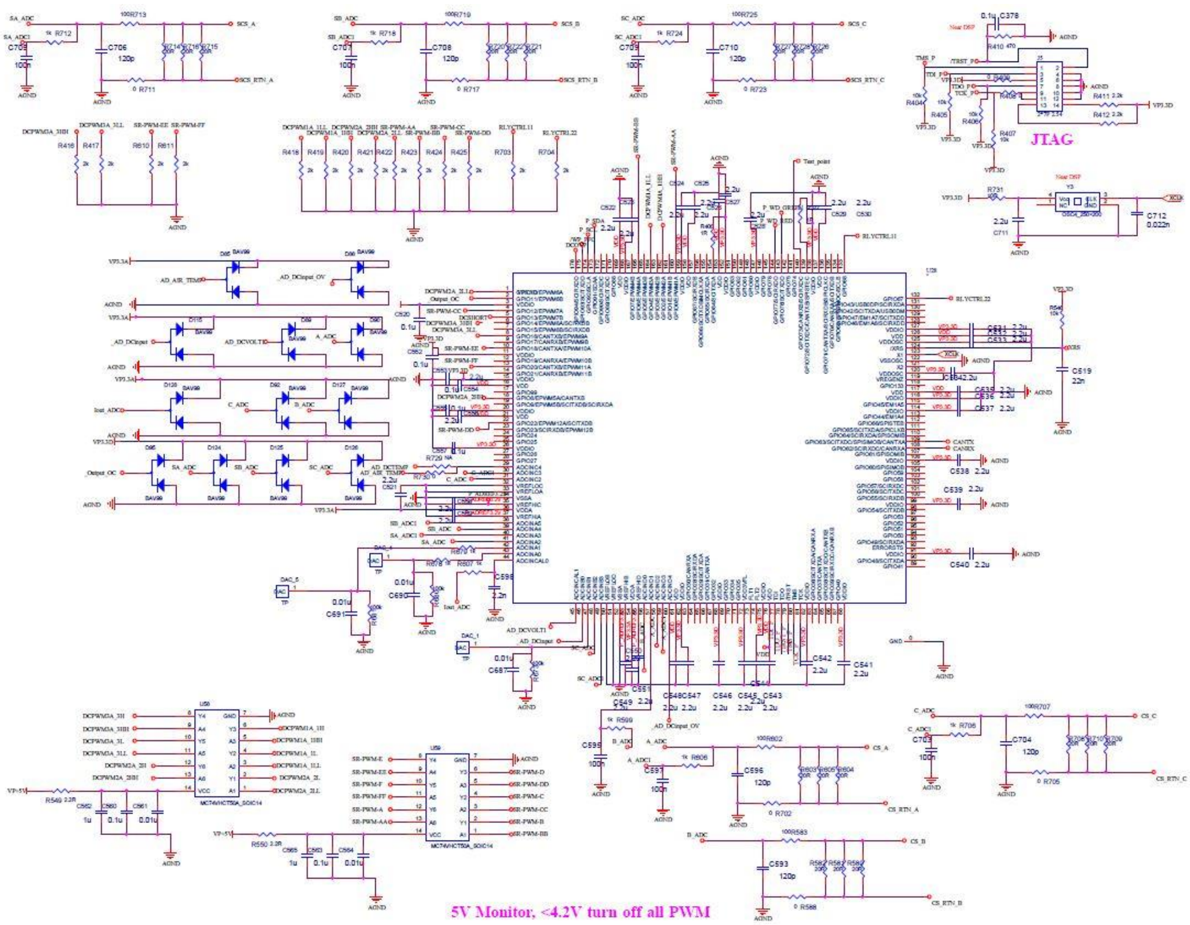

Figure 4a: Controller and peripheral circuits

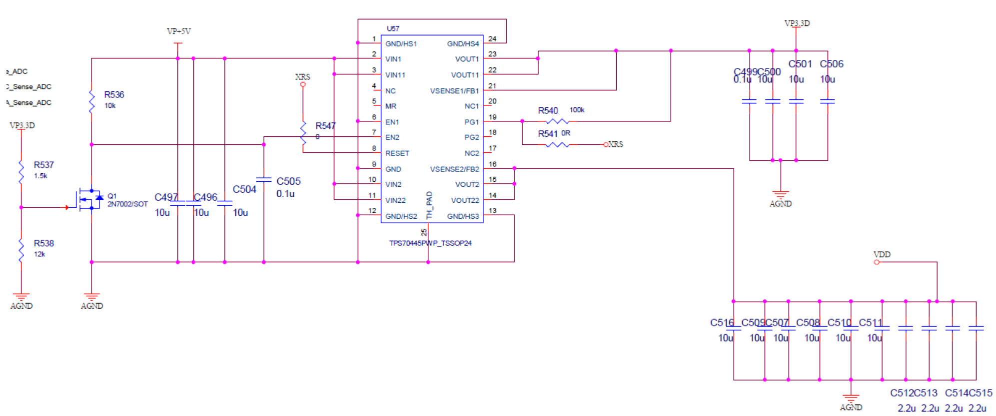

Figure 4b: Power supply for controller

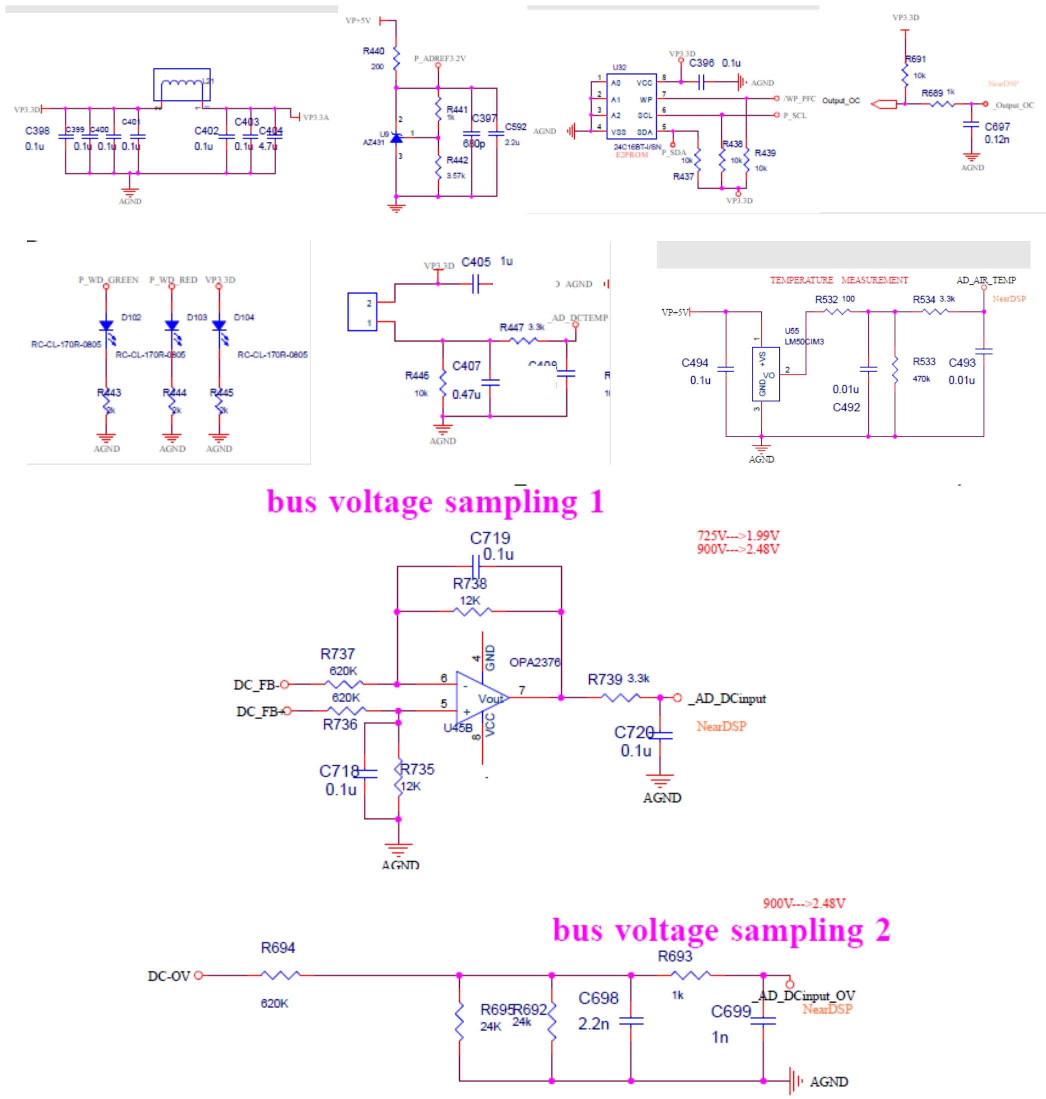

Figure 4c: Reference voltage and bus voltage sampling circuits

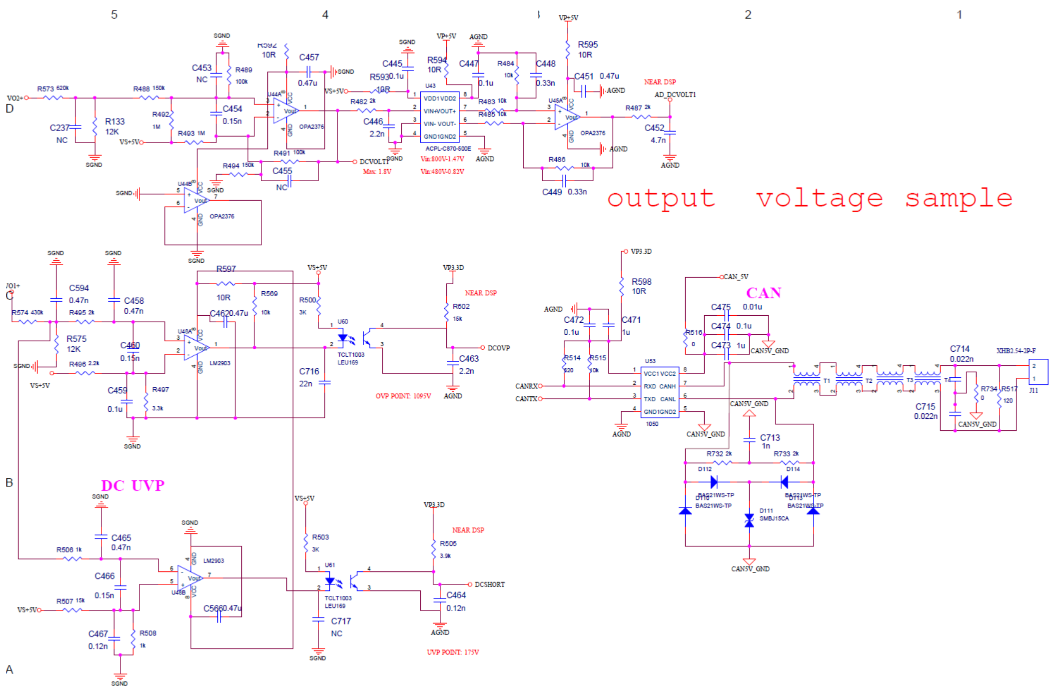

Figure 4d: Battery voltage sample and CAN interface

4.3. CONNECTIONS TO MAIN BOARD

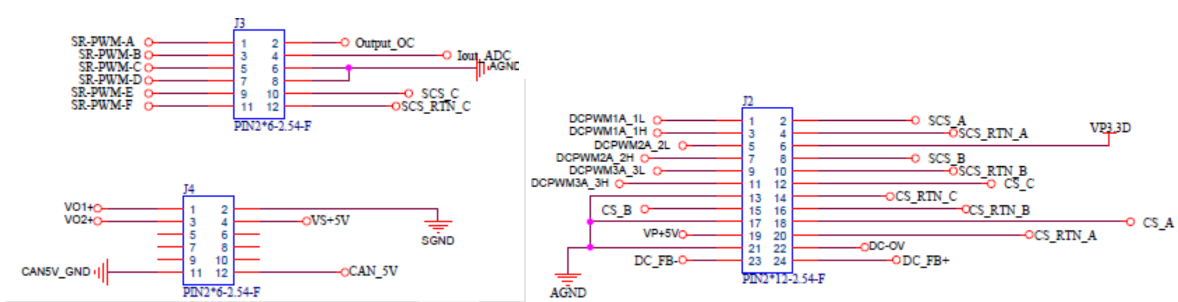

Figure 5: Connectors of Control Board to Main Board

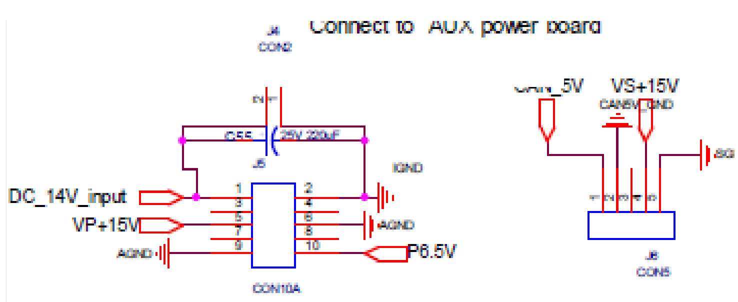

Figure 6: Connectors of Auxiliary Power Board to Main Board

4.4. AUXILIARY POWER BOARD SCHEMATIC

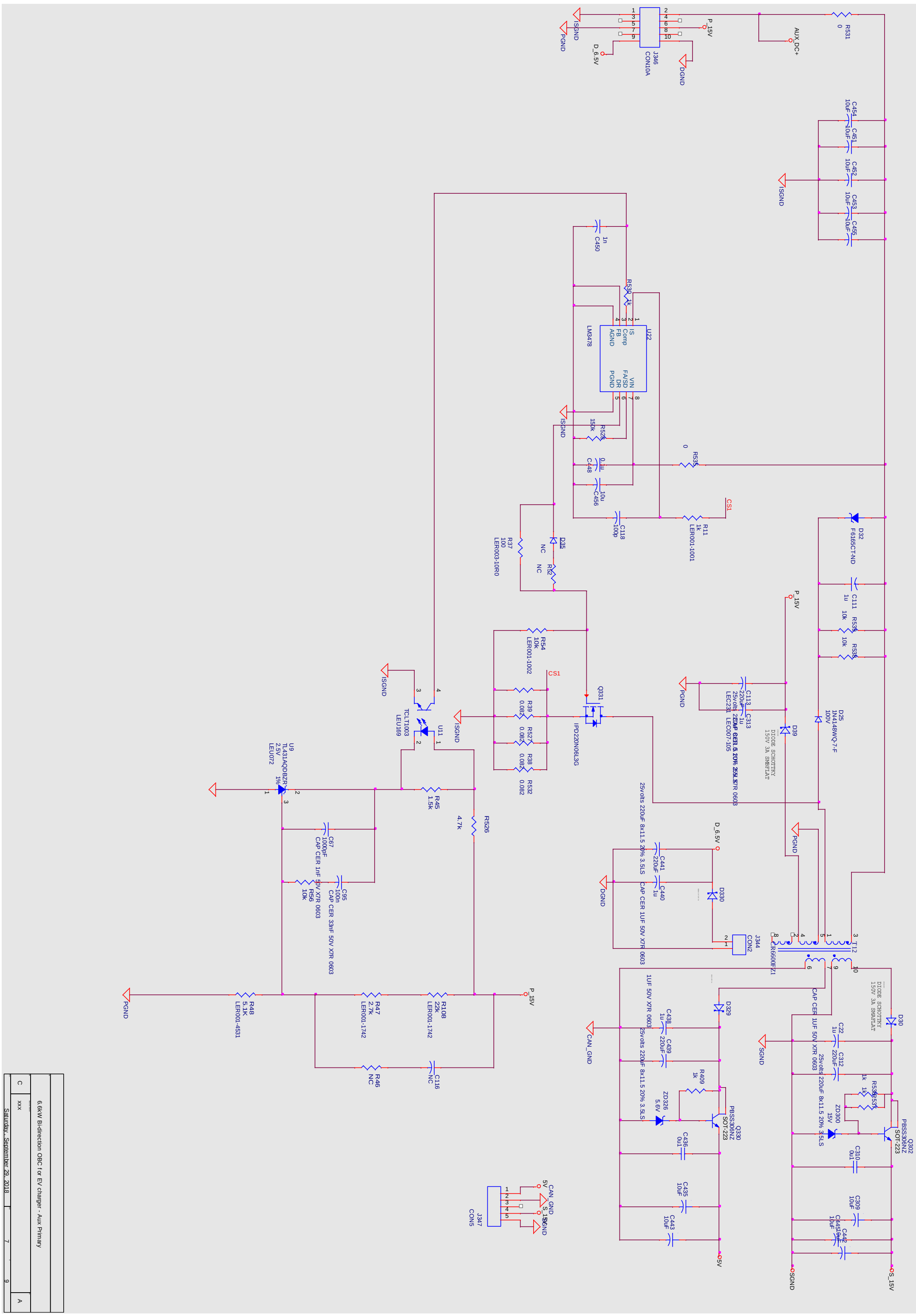

Figure 7: Schematic of Auxiliary Power Board

4.5. DRIVER BOARD SCHEMATIC

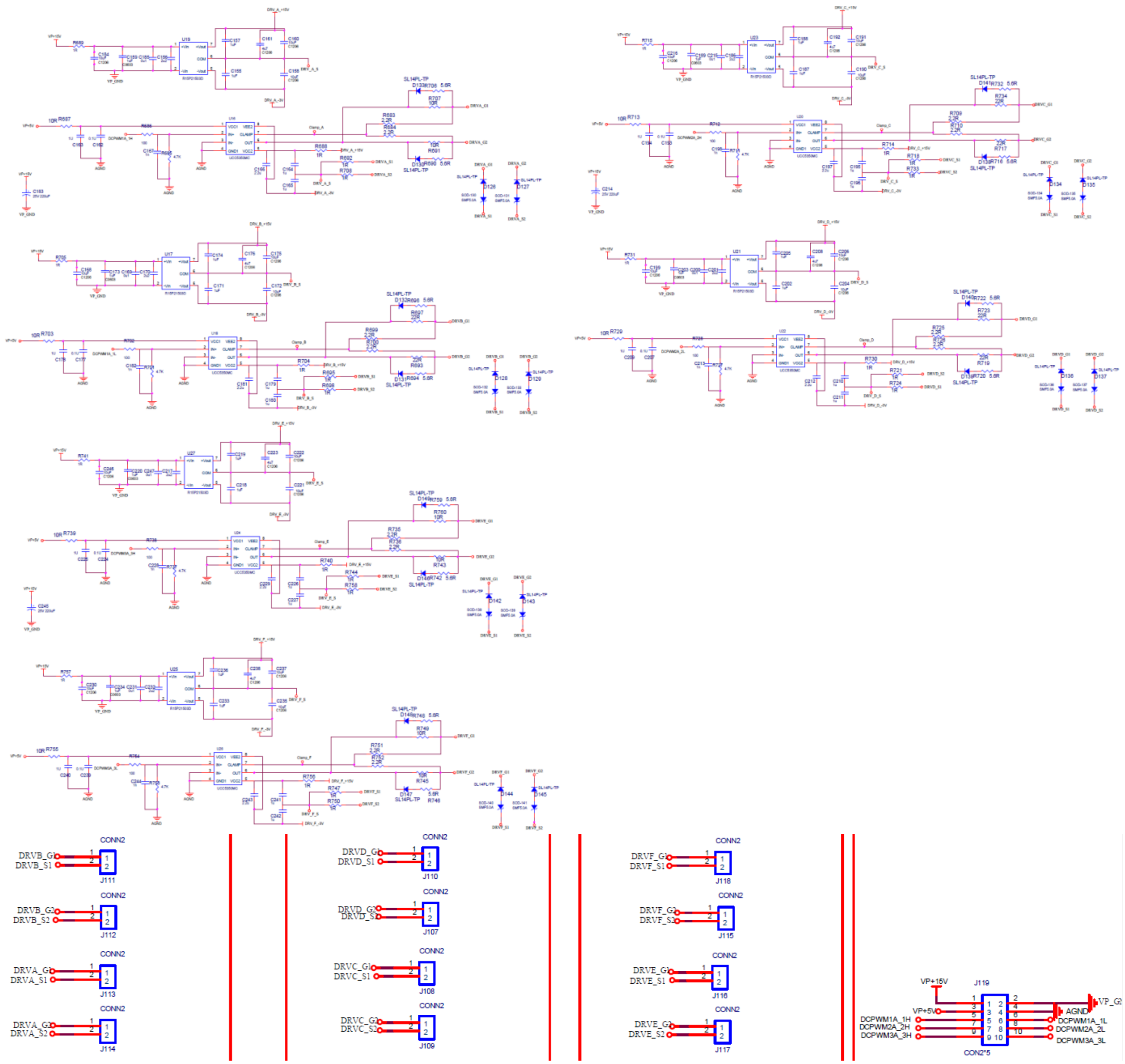

Figure 8: Schematic of Driver Board

5. HARDWARE DESCRIPTION

5.1. POWER BOARD

As illustrated by Figure 3a, a three-phase LLC topology is selected for the converter. The input side positive DC bus terminals are CON1 and CON19, and the negative DC bus input terminals are CON2 and CON20. The input DC bus has 4 film capacitors which absorb the high-frequency ripple on the DC input port. The output (battery side) positive DC terminals are CON3, CON17, CON35 and CON36, and the negative DC terminals are CON14, CON18, CON37 and CON38. The half-bridge at DC bus side is composed of SiC MOSFETs Q1, Q3, Q2, Q4, Q19, Q20, Q21, Q22, Q23, Q24, Q25, Q26. The battery side full-bridge rectifiers are composed of SiC Schottky diodes D34, D71, D72, D73, D74, D75, D76, D77, D80, D81, D82, D83, D84, D85, D106, D107, D110, D111, D112, D113, D114, D115, D116, D117. The battery side DC bus has 12 film capacitors and 3 electrolytic capacitors. Six identical transformers isolate these two sides from each other. The transformers are constructed with a 3-leg gapped PQ6562 ferrite core with a turns ratio of 12:10:10. Each of the 10-turns secondary windings of these transformers is separately connected to a full-bridge diode rectifier. The six rectifiers are divided into two sets that can be connected in parallel or series using terminals CON11~ CON13, CON16 and CON25~ CON32. Parallel or series configuration should be based on the output voltage range as described in Table 1. Two SiC MOSFETs Q64 and Q65 are used to balance the upper and lower output DC link capacitor voltages when configured in series mode at no-load or light-load condition. Each resonant tank has a current transformer to sense the primary side resonant inductor current.

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

Primary inductance of transformer	Resonant Inductor	Resonant Capacitor
30uH	7.5uH	12nF/2*17=102nF

Table 3: Key Parameters of Resonant Tanks

As illustrated by Figure 8, 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 level-shifter. The reference voltage for the controller's ADC (Analog-to-Digital Converter) is 3.3V. This reference is created by a reference IC U9, from the +5.0V rail.
The reference ground of the control board is the negative terminal of the input bus. The voltage sample signal and OVP/UVP (Over/Under Voltage Protection) signals of the battery-side DC bus are isolated by optocouplers before they are fed into the controller for further processing. The sampled input bus side voltage and OVP signals are directly fed to the controller after a voltage divider.

5.3. AUXILIARY POWER BOARD

The typical input voltage of the auxiliary power board is 14.5 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	14.5V	14.5V 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 sampling circuits
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 the 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.

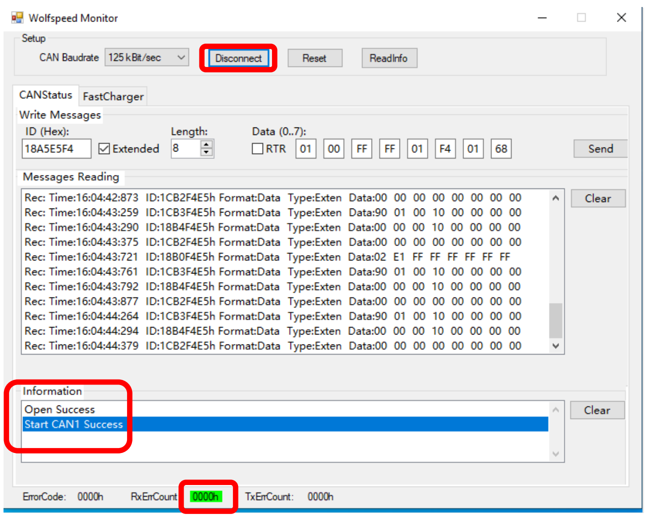

Figure 8a: CAN Status Tab after Connection

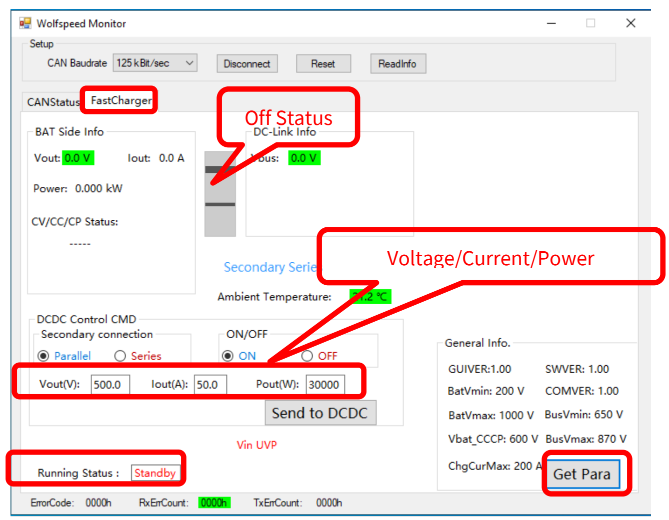

Figure 8b: Connected to Control Board <Off Mode>

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 100A under series mode, 200A under parallel mode, and 130A max under full-bridge mode. The power reference is recommended to be 60kW. The digital controller will check the value range each time.

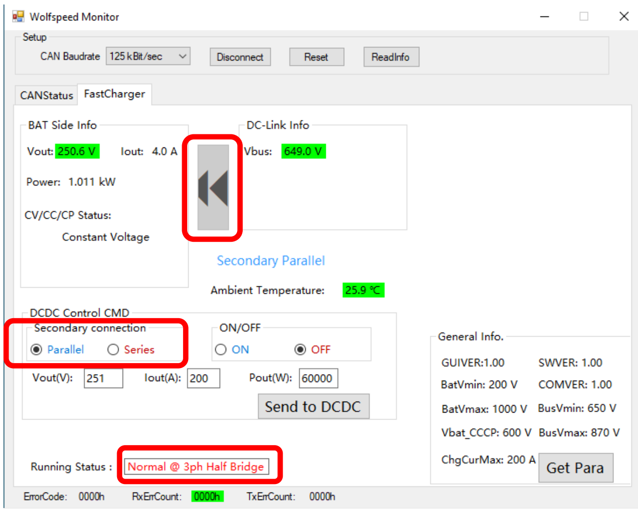

Figure 8c: Secondary in Parallel & 3ph Half Bridge Operation

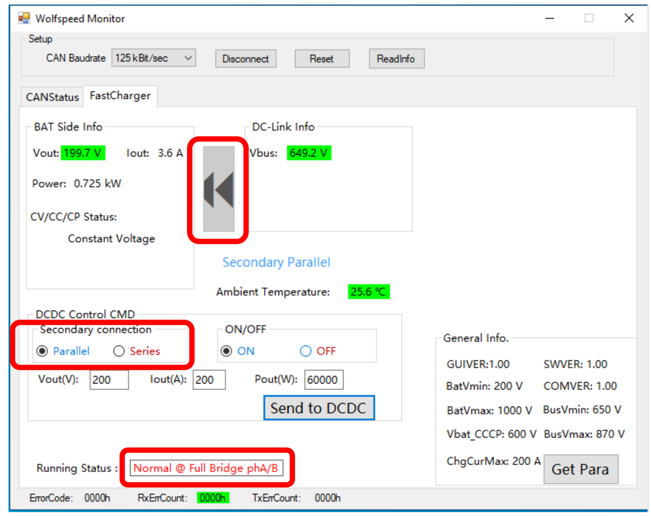

Figure 8d: Secondary in Parallel & Full Bridge phA/B Operation

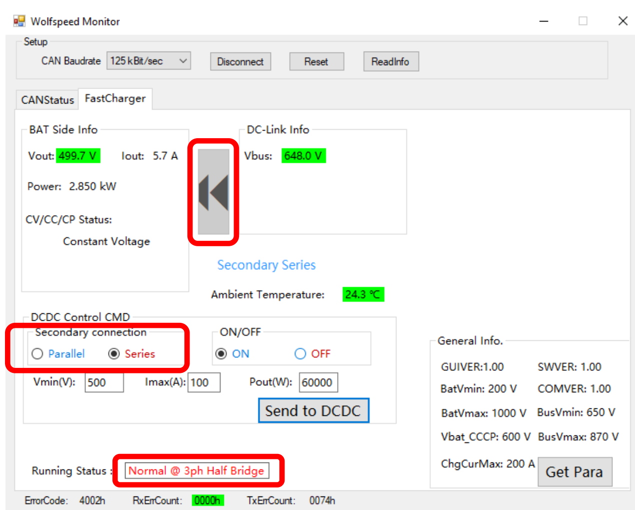

Figure 8e: Secondary in Series Operation

In secondary side 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~870V. Please refer to Section 2 for details.

In secondary side 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 100A. 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= 0xEA60	Byte4+Byte5 = 0x13EC	Byte6+Byte7 = 0x01F4
Property	Secondary Side: In Series	On	Output Power: 0xEA60*1W=60000W	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

*****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。

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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。

7.1. EQUIPMENT

DC Input Source: Two DC sources in parallel from ITECH (P/N: IT6036D-1500-60) are applied in this reference design. The input source must be an adjustable DC source whose output can be adjusted between 600VDC and 900VDC. It must be capable of supplying at least 70000W.

Output Load: In this design, three programmable high-voltage electronic loads from EA (P/N: ELR 11500-60) are used in parallel with a high-voltage resistor bank as the output load. This combination can draw more than 200A current from the unit.

EMI Filter: Two EMI filters, one for the input and one for the output, from SAIJI ELECTRONIC (P/N: SJD320DH-200). The rated voltage of the filter must be greater than 1000VDC, and the rated current must be greater than 150A.

Multimeter and shunt: Four multimeters from KEYSIGHT (P/N: 34461A) and two 200A/75mV shunts. These are used to measure input/output voltage and input/output currents.

Oscilloscope: A 300MHz or greater digital or analog oscilloscope with 100MHz or greater differential voltage probes and isolated current probes (i.e. hall effect).

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

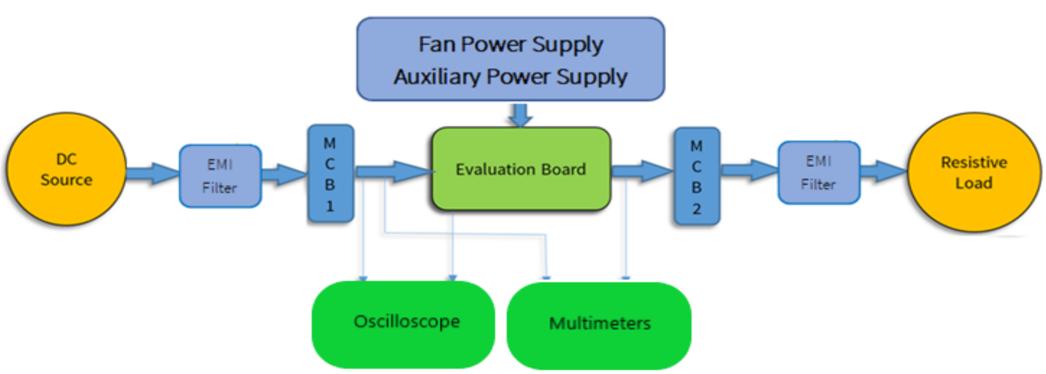


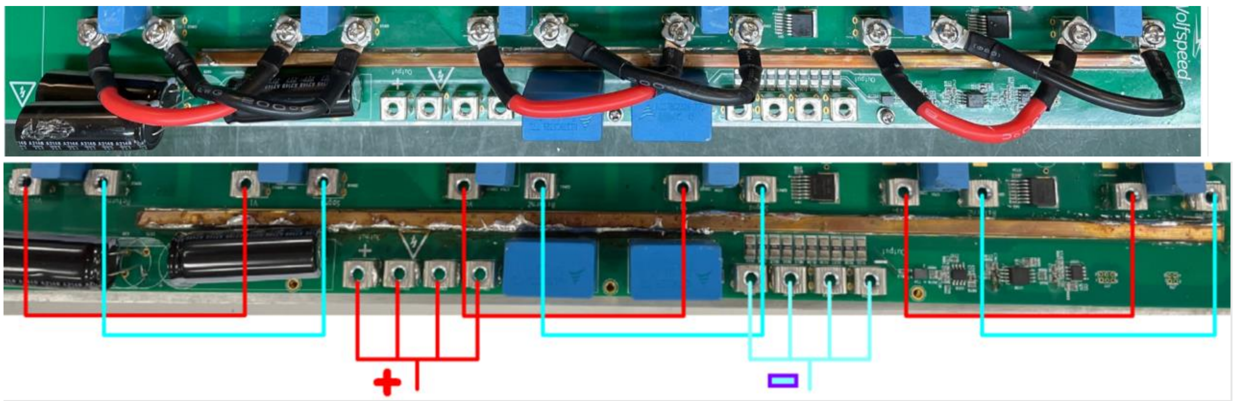
Figure 9: Converter Test Setup

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

- Connect DC source + EMI filter to the evaluation board through MCB1.
- Connect a pure resistive load or an electronic load (on CR mode) to MCB2.
- Connect current shunts and multimeters to measure input/output voltage and input/output currents.
- 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)：

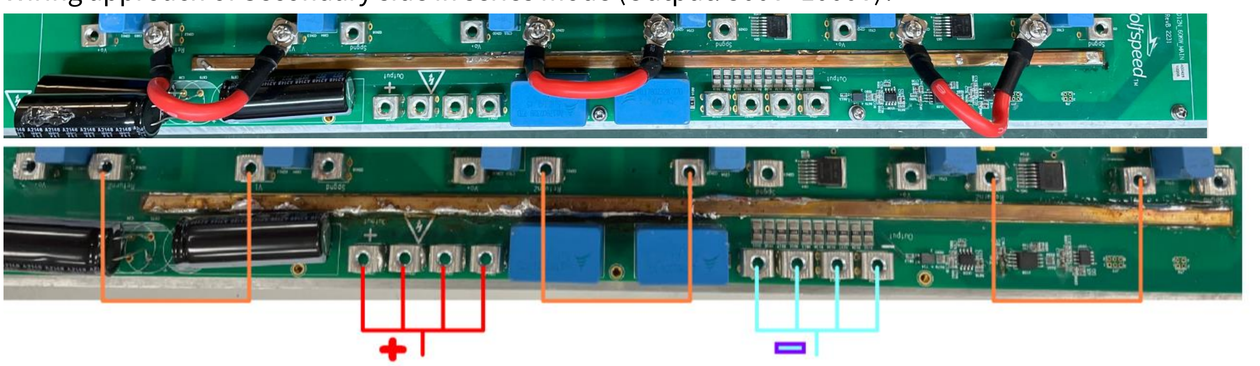


Figure 10a: Wiring approach of Secondary side

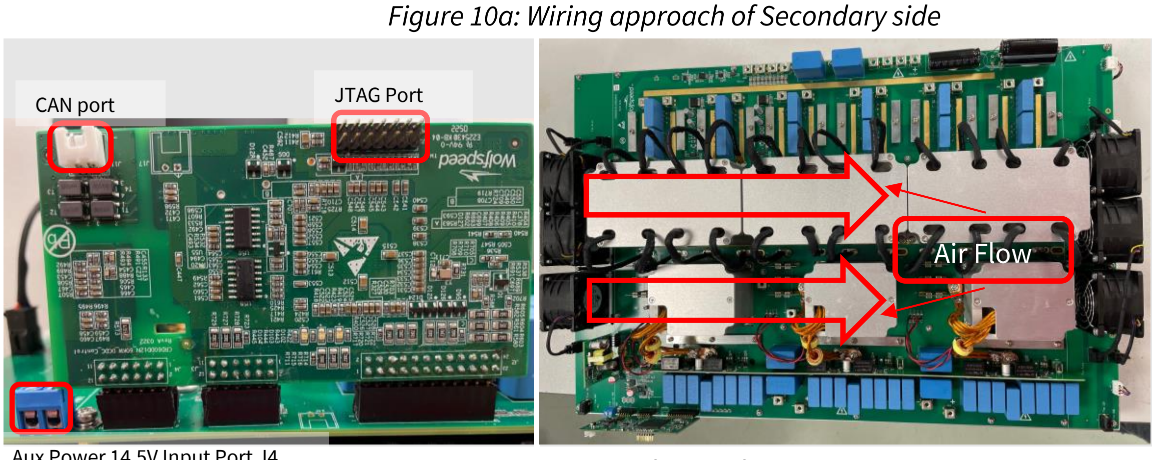


Figure 10b: Setup of the Reference Design

Recommended Wire Gauge: Cable with a minimum AWG#6 wire gauge is recommended to carry the DC current input and four 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	>890V
	UVP	---	<600V
Short Circuit Protection	short	<300V @ Secondary in Series <100V @ Secondary in parallel	---
LLC Tank Current	OCP	---	120A (peak)
Output Power Limitation	CP	60kW±1.5kW	---
Output Current Limitation	CC	133A±1.5A@Vout ∈ [200V,250V] 200A±1.5A@Vout ∈ (250V,500V] 100A±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 14.5V 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	+14.5V for AUX power	+14V +/-5%	0.35	0.63	0.77

Table 7: Auxiliary Power Supply Requirements

7.5. MEASURED PARAMETERS

All power MOSFET pins are exposed. Their gate drive 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
V_{GS} /V_{DS} 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 which 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.

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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。

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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. 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. Do not overload the converter. Refer to Table 1, Table 2, and Section 3.2 for voltage, current and power limits.

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

5. Always remember to connect the cooling fans to their power supplies and run them continuously while operating the unit.

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 (DC supply) 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 and turn them on.

7. Put MCB1 in the ON position. Turn on the DC supply and increase it slowly from 0V to the required voltage (650VDC ~ 870VDC).

8. Verify that the measured DC bus voltages in the GUI are 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 to desired value, up to 60kW. 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. Do not handle the board before these capacitors are fully discharged. Please check voltages of both input and output terminals 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.

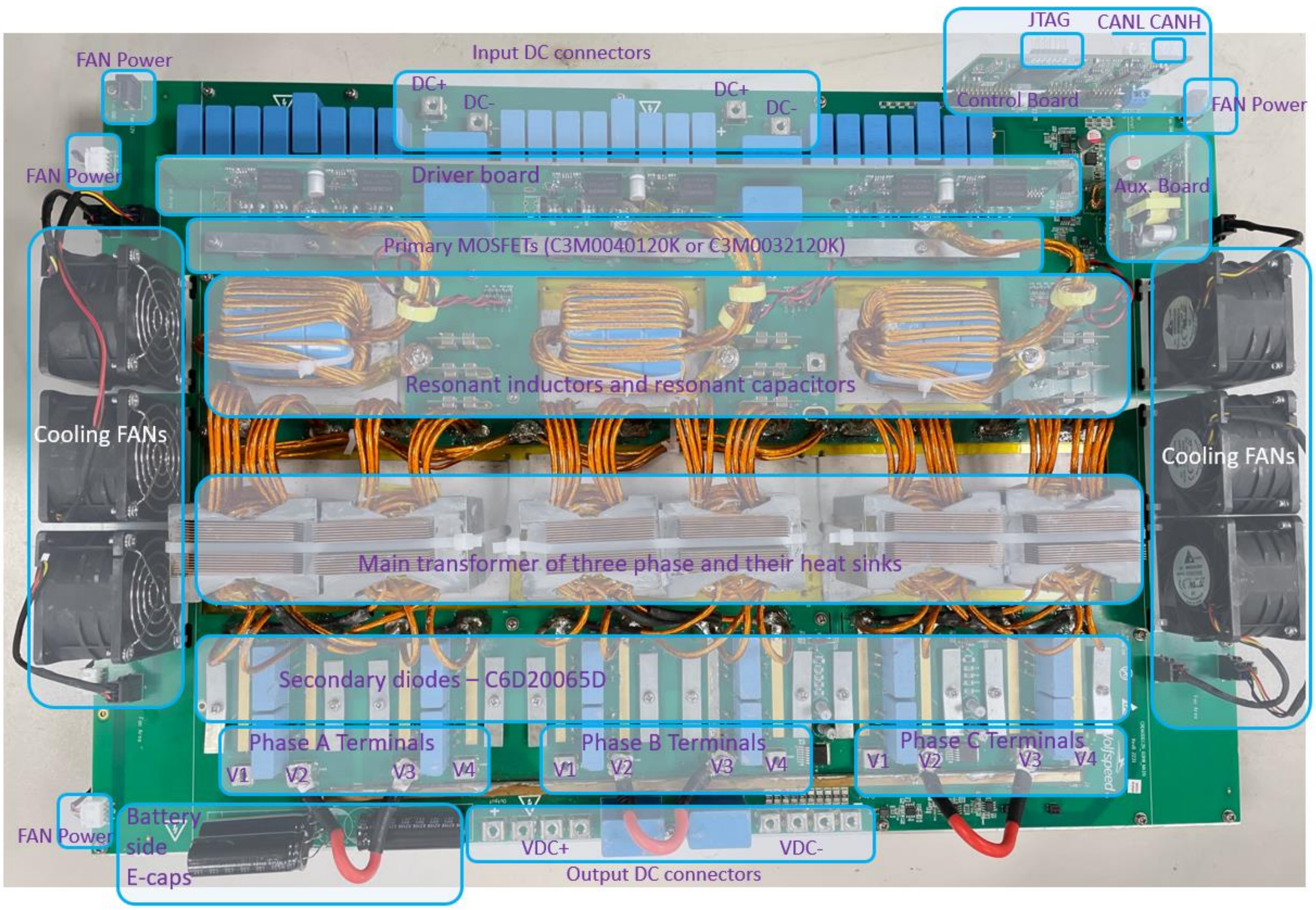


*Figure 11: Top View of PCBA (490mm*390mm*65mm)*

10. PERFORMANCE DATA

Below is measured performance data of Wolfspeed's CRD-60DD12N-K reference design board under various conditions. Table 9, Table 10, and Figure 12 show the performance data based on C3M0040120K.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
650	12191	20	500	12017	98.57
650	24584	40	500	24048	97.82
650	30799	50	501	30059	97.60
650	37088	60	501	36103	97.35
650	51923	80	503	50237	96.75
650	12258	20	540	12067	98.44
650	24550	40	541	24113	98.22
650	30777	50	540	30182	98.07
650	36908	60	540	36120	97.87
650	49823	80	536	48284	96.91
650	55066	90	532	53163	96.54
720	12279	20	600	12094	98.49
720	24499	40	600.	24106	98.40
720	30522	50	601	30013	98.33
720	36668	60	601	35985	98.14
720	49248	80	600	48154	97.78
720	61066	100	592	61235	96.95
850	12247	20	708	12067	98.53
850	24366	40	708	24021	98.58
850	30550	50	708	30096	98.51
850	36727	60	709	36157	98.45
850	48850	80	708	47994	98.25
849	61235	100	709	60025	98.02
850	12362	20	1001	12075	97.68
850	24519	40	1000	24128	98.41
854	30553	50	1001	30079	98.45
857	36699	60	1000	36129	98.45
869	48890	80	1000	48114	98.41
870	55056	100	971	54176	98.40

Table 9: Efficiency Data (Secondary Series mode)

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
650	12578	20	209	12198	96.98
650	18826	30	200	18070	95.98
649	25389	40	201	24179	95.23
649	27711	44	200	26290	94.87
651	12260	20	250	12056	98.33
650	24665	40	250	24109	97.75
650	30966	50	250	30189	97.49
650	37283	60	252	36272	97.29
650	51998	80	251	50210	96.56
651	12269	20	270	12065	98.34
651	24615	40	271	24152	98.12
650	30841	50	271	30215	97.97
650	37039	60	273	36196	97.72
651	49810	80	268	48157	96.68
651	54782	90	266	52738	96.27
721	12282	20	301	12081	98.37
721	24530	40	300	24112	98.29
720	30687	50	300	30124	98.17
720	36880	60	301	36159	98.05
720	49549	80	300	48349	97.58
720	61188	100	296	59143	96.66
851	12238	20	355	12043	98.40
851	24448	40	355	24084	98.51
851	30659	50	354	30184	98.45
850	36772	60	355	36170	98.36
850	49046	80	356	48154	98.18
850	61357	100	354	60068	97.90
870	12357	20	501	12033	97.38
870	24554	40	502	24103	98.17
869	30590	50	500	30058	98.26
869	49717	80	499	48872	98.30
869	55084	100	480	54146	98.30

Table 10: Efficiency Data (Secondary Parallel mode)

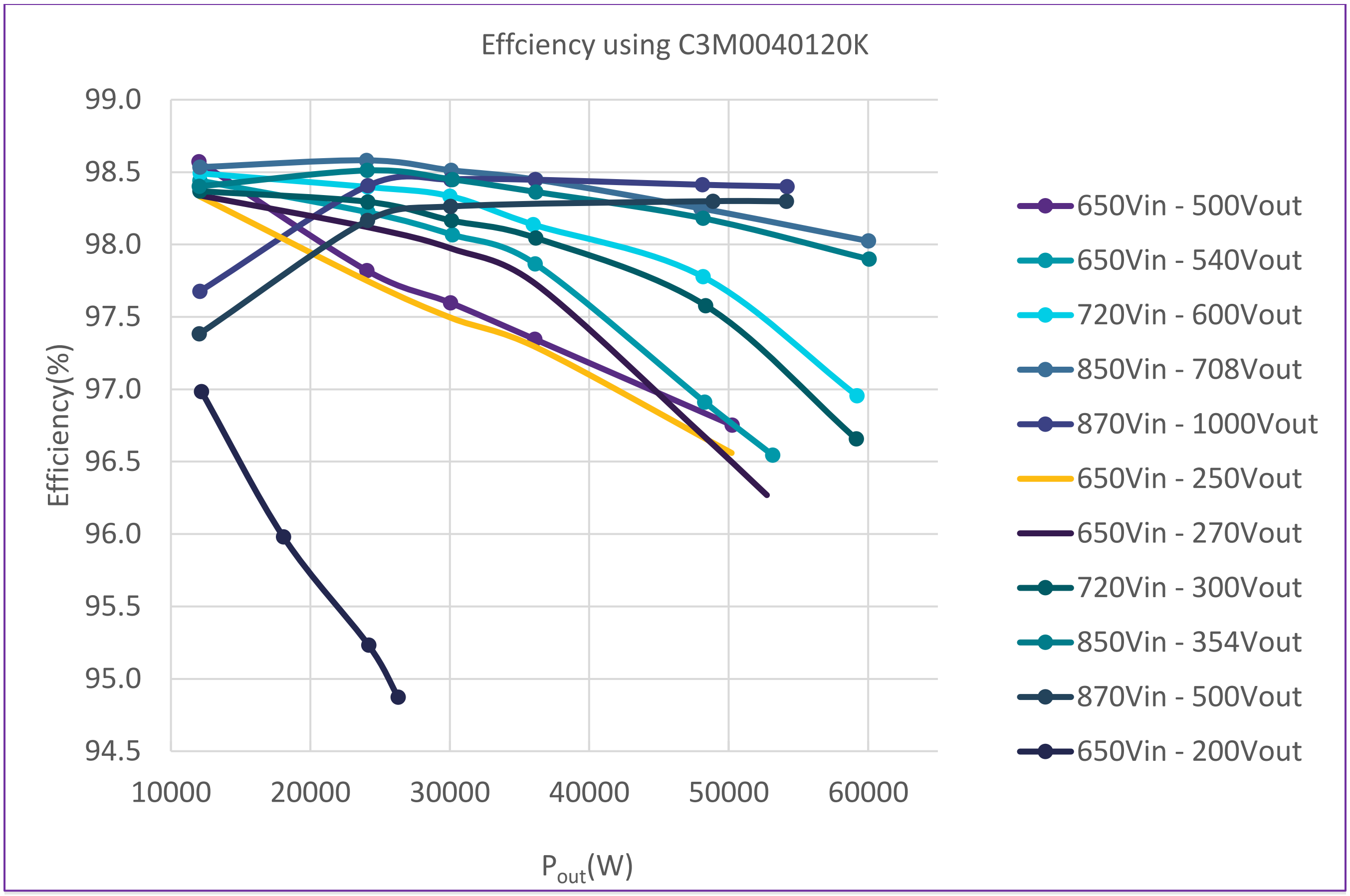


Figure 12: Efficiency Data

Below is measured performance data of Wolfspeed's CRD-60DD12N-K reference design board under various conditions. Table 11, Table 12, and Figure 13 show the performance data based on C3M0032120K.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
651	12330	20	501	12102	98.15
650	24600	40	501	24081	97.89
650	30838	50	500	30122	97.68
650	37089	60	501	36149	97.46
649	51750	80	501	50145	96.90
651	12278	20	541	12076	98.35
650	24567	40	541	24128	98.21
650	30760	50	541	30168	98.08
650	36917	60	541	36183	97.89
650	49175	80	538	47631	96.86
649	55322	90	532	53297	96.34

721	12287	20	600	12088	98.38
720	24485	40	600	24089	98.38
720	30656	50	600	30127	98.28
720	36805	60	600	36122	98.15
720	49248	80	600	48101	97.67
727	61930	100	600	59954	96.81
850	12316	20	709	12096	98.21
850	24439	40	709	24069	98.48
849	30757	50	709	30286	98.47
849	36771	60	709	36188	98.42
849	49106	80	708	48249	98.25
849	61335	100	709	60136	98.04
870	12509	20	1001	12155	97.17
870	24736	40	1001	24264	98.09
870	30706	50	1000	30156	98.21
869	36966	60	1001	36399	98.46
870	49096	80	1000	48270	98.32
869	58244	90	1000	57250	98.29

Table 11: Efficiency Data (Secondary Series mode)

Input Voltage (Vdc)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)
650	12431	20	202	12064	97.05
650	18822	30	201	18060	95.95
650	25481	40	200	24358	95.60
650	27541	44	201	26261	95.35
649	12265	20	251	12040	98.17
650	24685	40	251	24146	97.82
650	30935	50	250	30193	97.60
650	37203	60	251	36227	97.38
649	51330	80	249	49623	96.67
651	12256	20	271	12052	98.33
651	24561	40	271	24115	98.18
650	30815	50	271	30206	98.03
650	36969	60	272	36177	97.86
651	50086	80	269	48530	96.89
651	55141	90	267	53201	96.48
730	12241	20	301	12038	98.34

730	24133	40	300	23727	98.32
730	30722	50	301	30173	98.21
730	36840	60	300	36130	98.07
730	49414	80	300	48304	97.75
729	61392	100	301	59763	97.35
850	12289	20	355	12073	98.25
850	24444	40	354	24071	98.47
850	30599	50	355	30124	98.45
850	36710	60	355	36118	98.39
850	49034	80	355	48149	98.20
849	61427	100	355	60196	98.00
870	12386	20	501	12045	97.25
870	24516	40	501	24054	98.11
870	30711	50	501	30169	98.24
870	36701	80	500	36080	98.31
870	48984	100	501	48179	98.36

Table 12: Efficiency Data (Secondary Parallel mode)

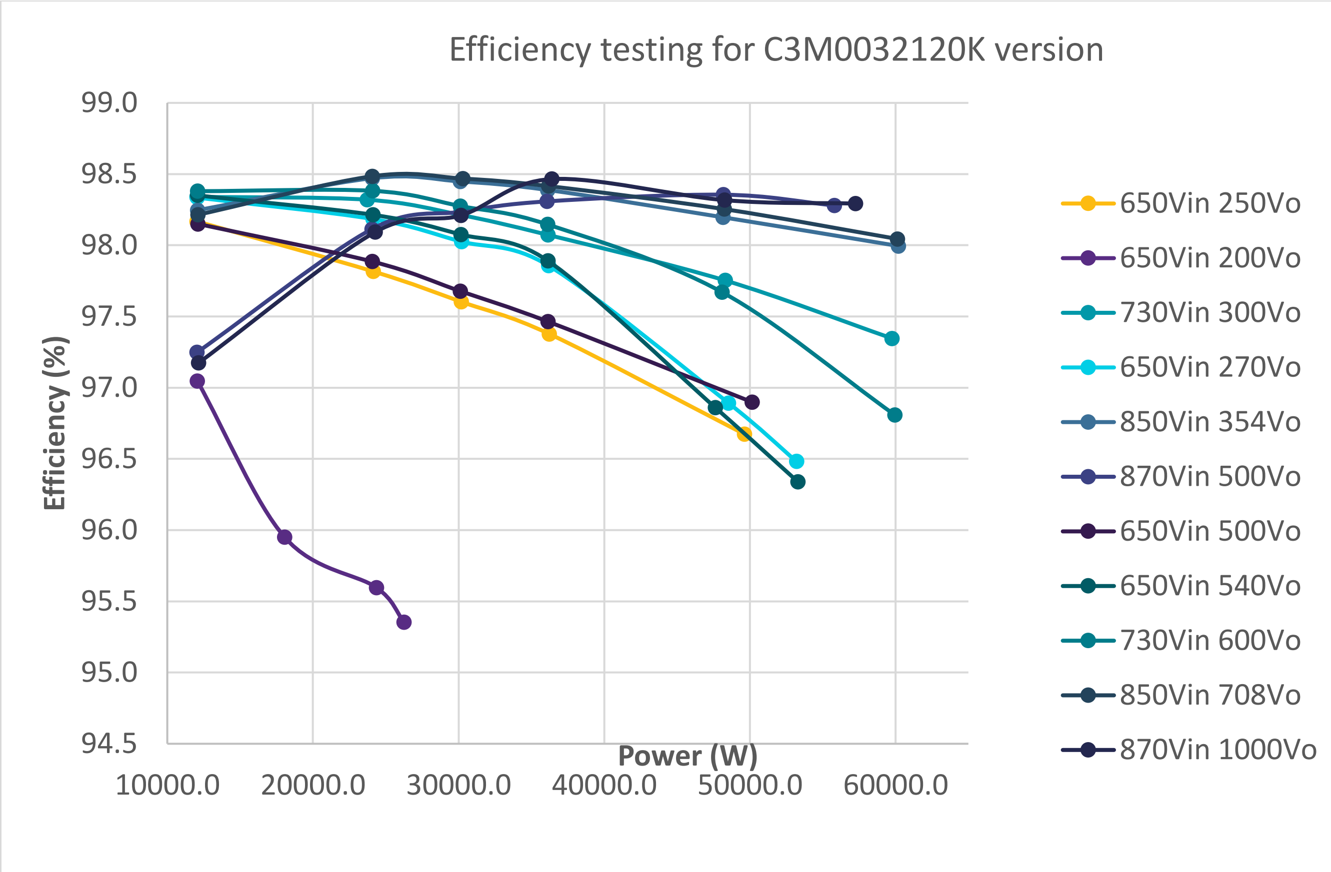


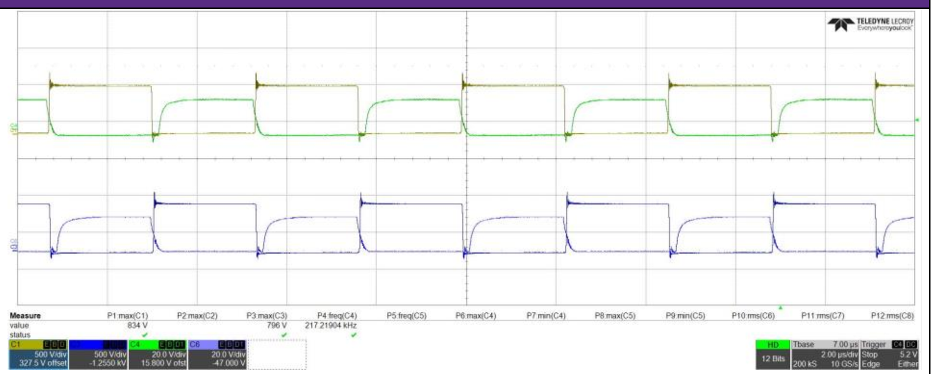
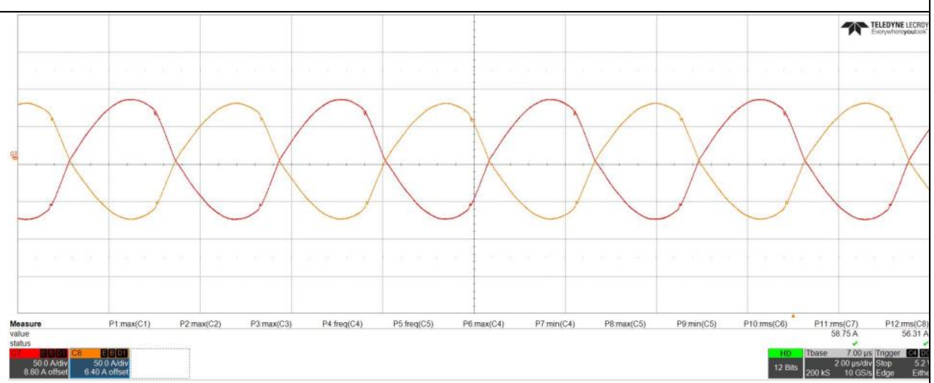
Figure 13: Efficiency Data

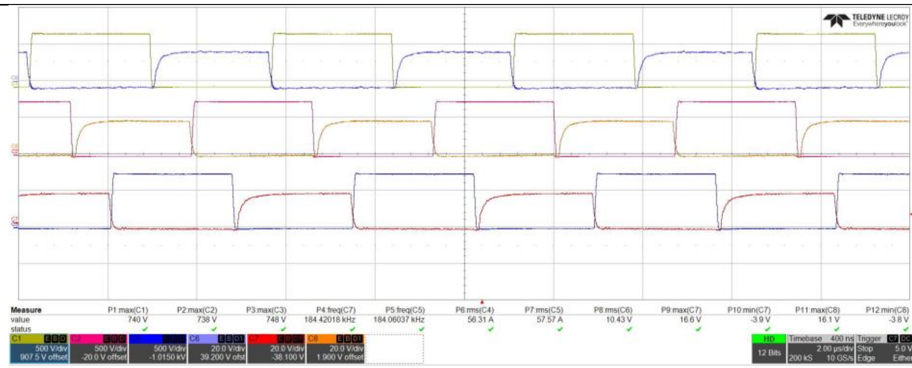
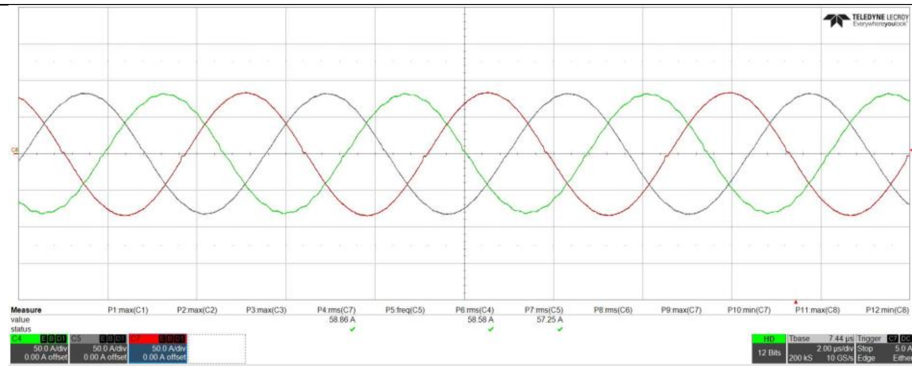
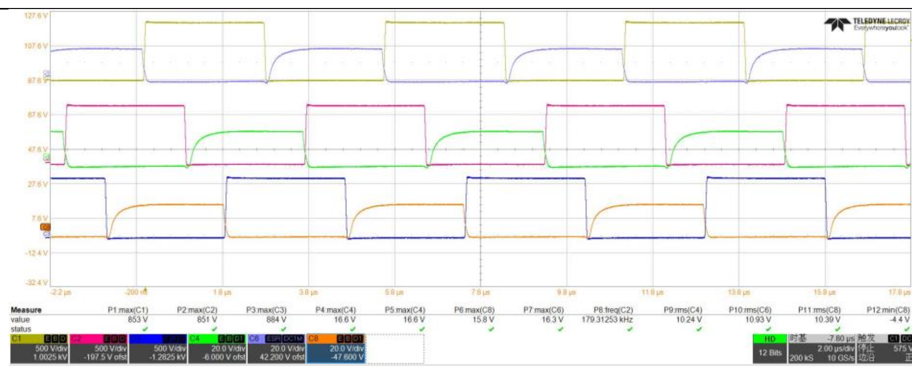
11. TYPICAL WAVEFORMS

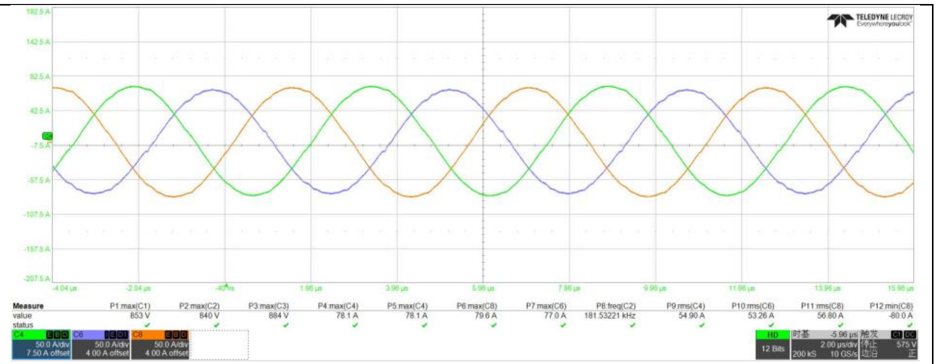
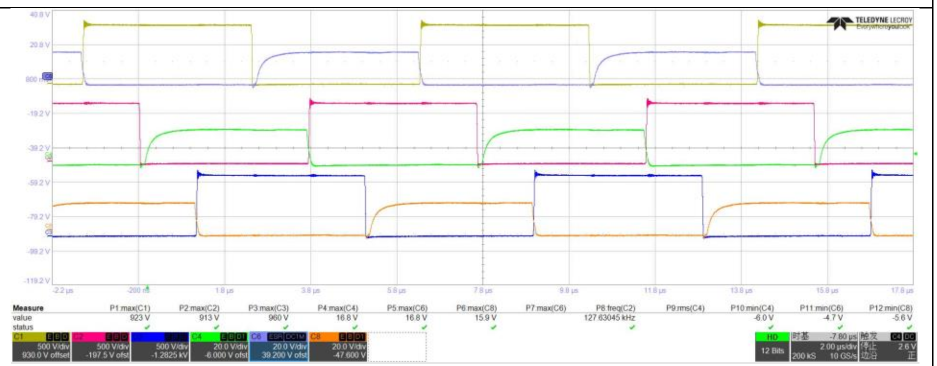
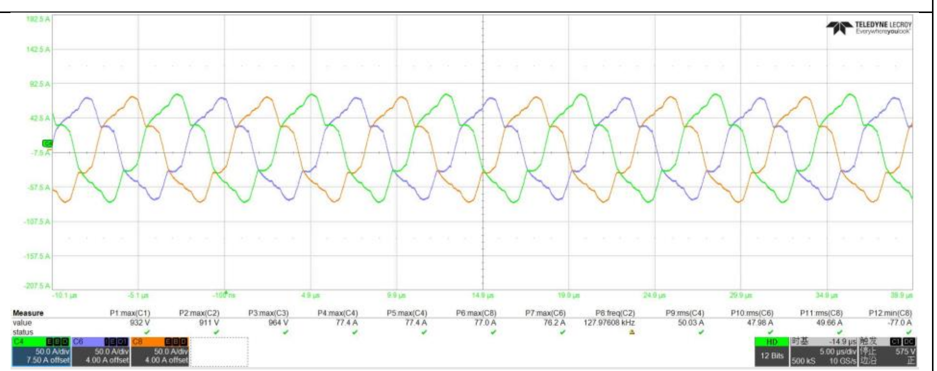
Operational waveforms are presented in Table 13 and Table 14. Current sharing waveforms between parallel MOSFETs are presented in Table 15. All waveforms are measured from the cost-effective version based on C3M0040120K.

11.1. DC/DC SECONDARY PARALLEL MODE

Table 13: DC/DC Secondary Parallel Mode Waveforms

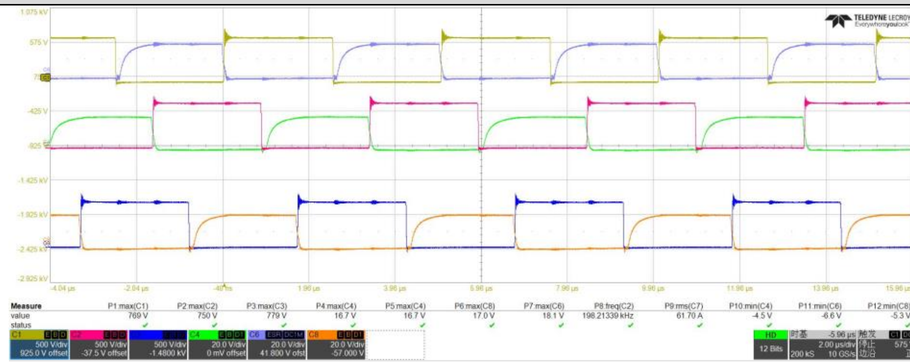
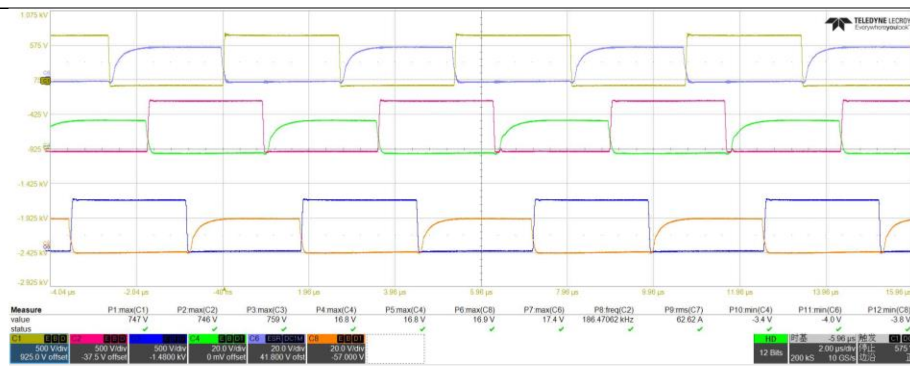
Condition	Waveform
DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 200Vdc/133A	 **CH1**: V_{DS} Q1 500V/div **CH3**: V_{DS} Q3 500V/div **CH4**: V_{GS} Q1 20V/div **CH6**: V_{GS} Q3 20V/div
DC/DC Secondary Parallel Mode Bus Side Input: 650Vdc Battery Side Output: 200Vdc/60A	 **CH7**: I_{LA} 50A/div **CH8**: I_{LB} 50A/div

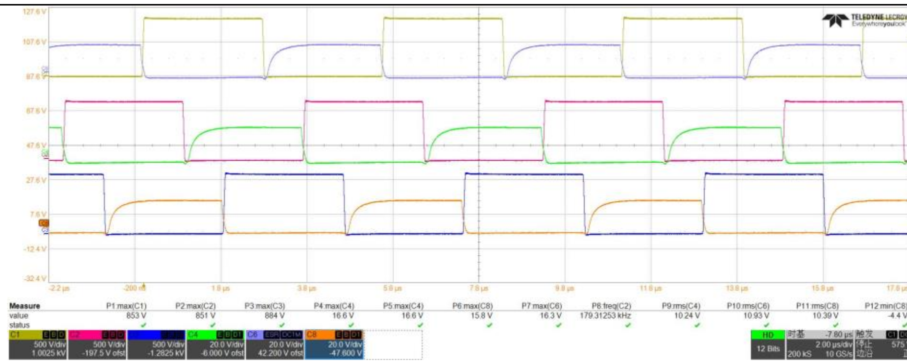
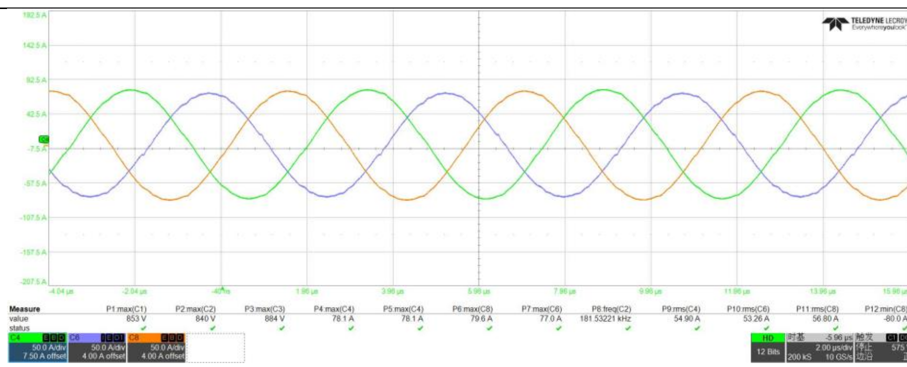
DC/DC Secondary Parallel Mode Bus Side Input: 730Vdc Battery Side Output: 300Vdc/200A	 **CH1**: V_{DS} Q1 500V/div **CH2**: V_{DS} Q2 500V/div **CH3**: V_{DS} Q19 500V/div **CH6**: V_{GS} Q1 20V/div **CH7**: V_{GS} Q2 20V/div **CH8**: V_{GS} Q19 20V/div
DC/DC Secondary Parallel Mode Bus Side Input: 730Vdc Battery Side Output: 300Vdc/200A	 **CH4**: I_{LA} 50A/div **CH5**: I_{LB} 50A/div **CH7**: I_{LC} 50A/div
DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 354Vdc/170A	 **CH1**: V_{DS} Q3 500V/div **CH2**: V_{DS} Q4 500V/div **CH3**: V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div

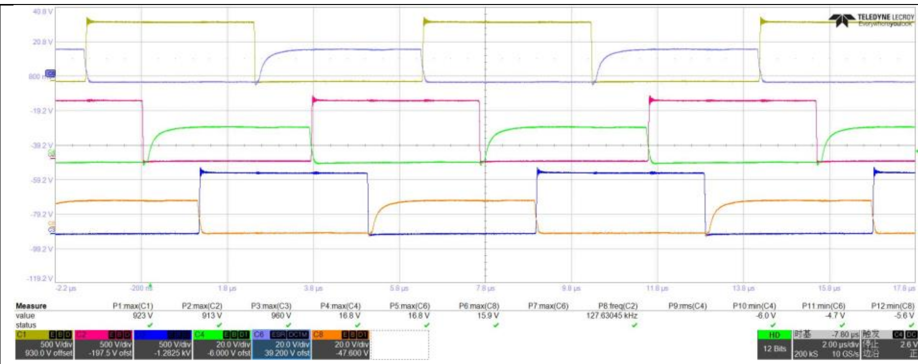
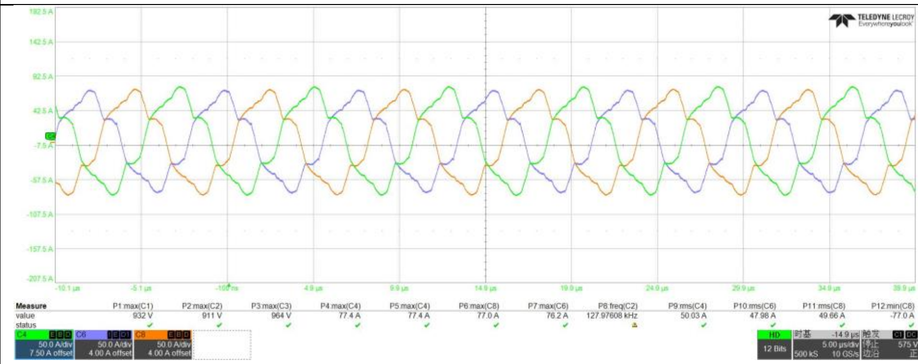
DC/DC Secondary Parallel Mode Bus Side Input: 850Vdc Battery Side Output: 354Vdc/170A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**
DC/DC Secondary Parallel Mode Bus Side Input: 870Vdc Battery Side Output: 500Vdc/110A	 **CH1**: V_{DS} Q3 500V/div **CH2:** V_{DS} Q4 500V/div **CH3:** V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div
DC/DC Secondary Parallel Mode Bus Side Input: 870Vdc Battery Side Output: 500Vdc/110A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**

11.2. DC/DC SECONDARY SERIES MODE

Table 14. DC/DC Secondary Series Mode Waveforms

Condition	Waveform
DC/DC Secondary Series Mode Bus Side Input: 650Vdc Battery Side Output: 500Vdc/100A	 **CH1**: V_{DS} Q3 500V/div **CH2**: V_{DS} Q4 500V/div **CH3**: V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div
DC/DC Secondary Series Mode Bus Side Input: 650Vdc Battery Side Output: 500Vdc/100A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**
DC/DC Secondary Series Mode Bus Side Input: 730Vdc Battery Side Output: 600Vdc/100A	 **CH1**: V_{DS} Q3 500V/div **CH2**: V_{DS} Q4 500V/div **CH3**: V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div

DC/DC Secondary Series Mode Bus Side Input: 730Vdc Battery Side Output: 600Vdc/100A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**
DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 708Vdc/85A	 **CH1**: V_{DS} Q3 500V/div **CH2**: V_{DS} Q4 500V/div **CH3**: V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div
DC/DC Secondary Series Mode Bus Side Input: 850Vdc Battery Side Output: 708Vdc/85A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**

DC/DC Secondary series Mode Bus Side Input: 870Vdc Battery Side Output: 1000Vdc/55A	 **CH1**: V_{DS} Q3 500V/div **CH2**: V_{DS} Q4 500V/div **CH3**: V_{DS} Q20 500V/div **CH6**: V_{GS} Q4 20V/div **CH4**: V_{GS} Q3 20V/div **CH8**: V_{GS} Q20 20V/div
DC/DC Secondary series Mode Bus Side Input: 870Vdc Battery Side Output: 1000Vdc/55A	 **CH4**: I_{L3} 50A/div **CH6: I_{L2} 50A/div** **CH8: I_{L4} 50A/div**

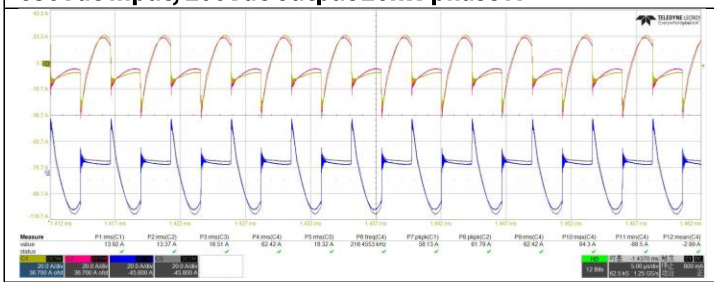
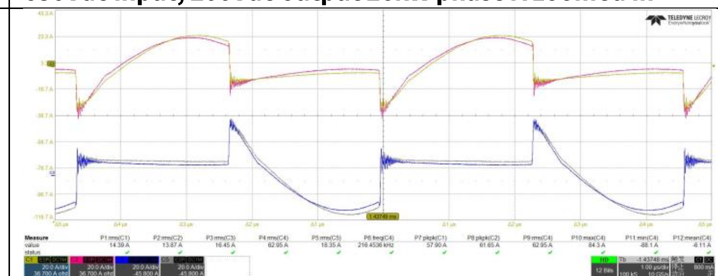
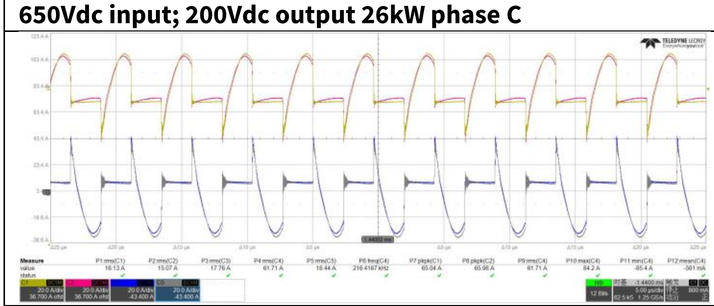
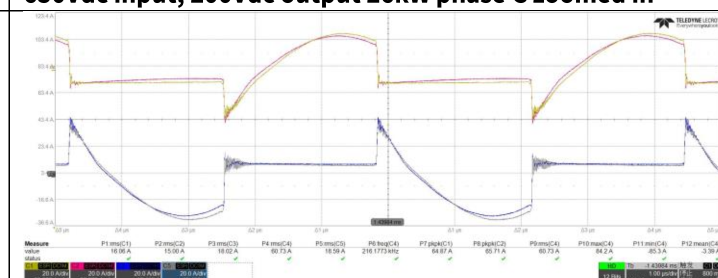
11.3. CURRENT SHARING BETWEEN PARALLEL MOSFETS

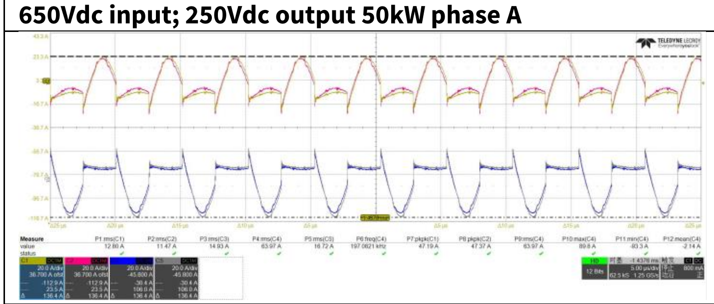
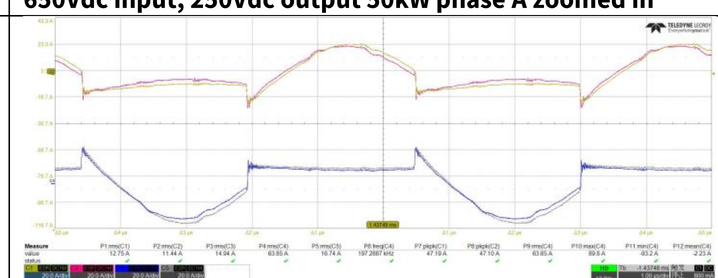
Note:
The current unbalance rate δ is calculated as:

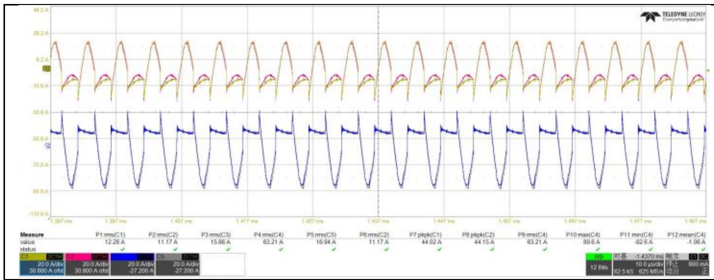
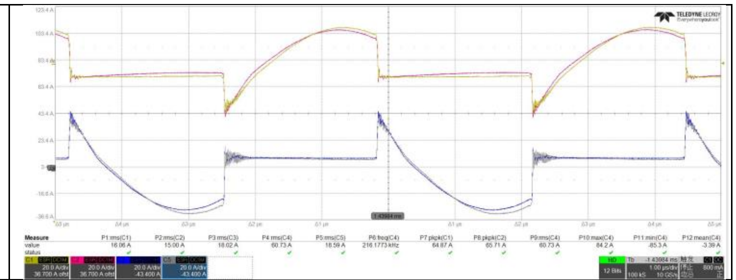
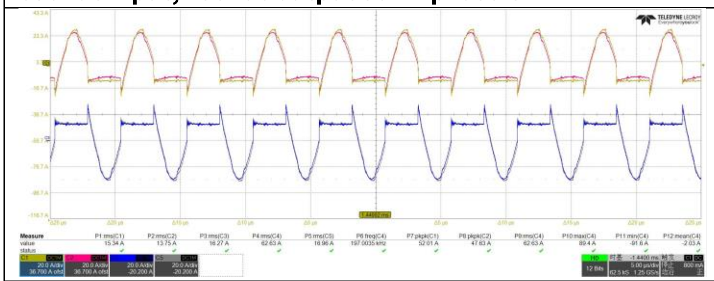
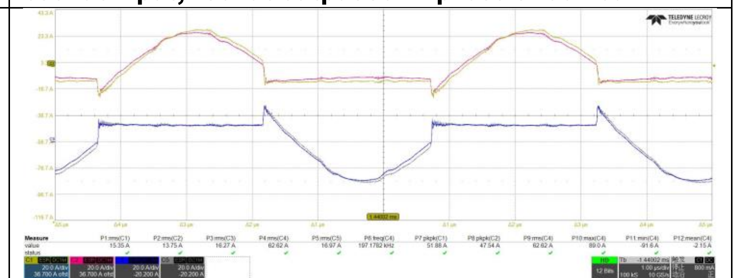
$$\delta = \frac{\Delta I}{I_{avg}} \times 100\%$$

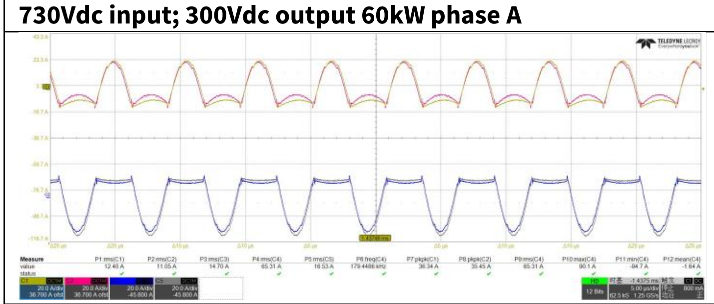
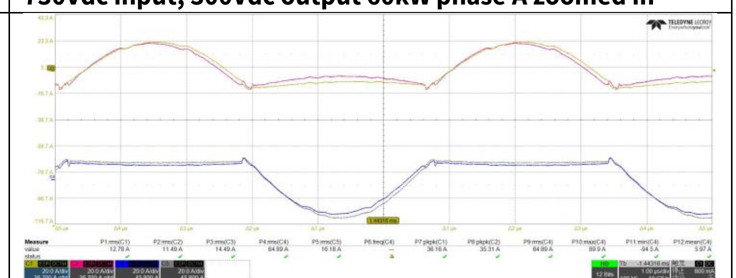
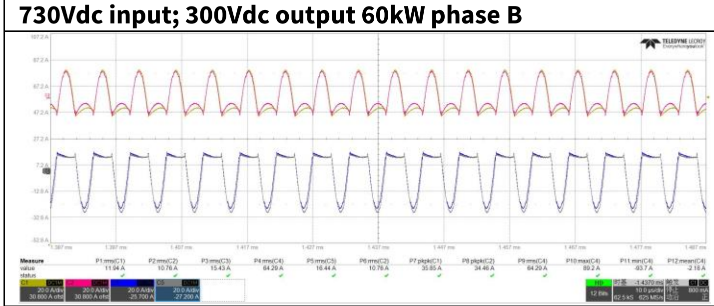
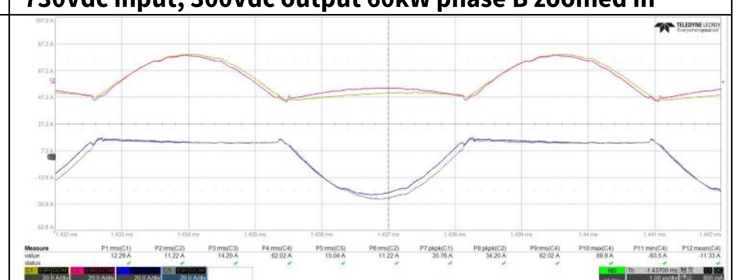
Where:
ΔI —— Current difference between the two parallel MOSFETs
I_{avg} —— Average current of the two parallel MOSFETs

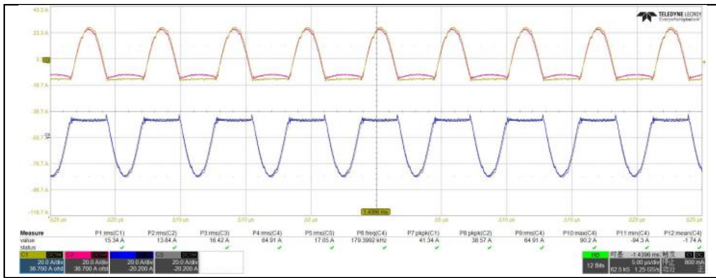
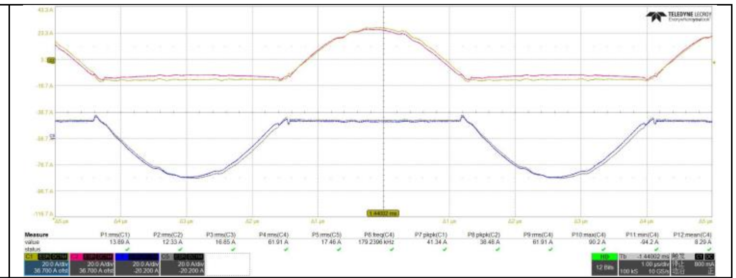
Table 15. Current sharing waveforms between parallel MOSFETs

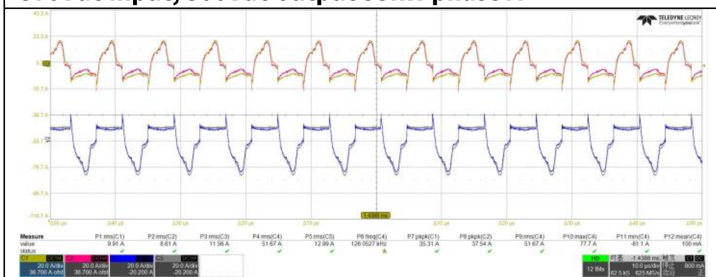
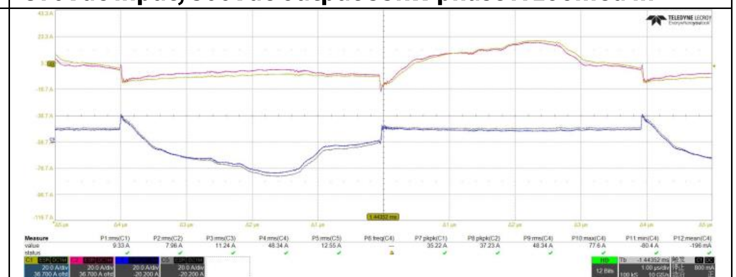
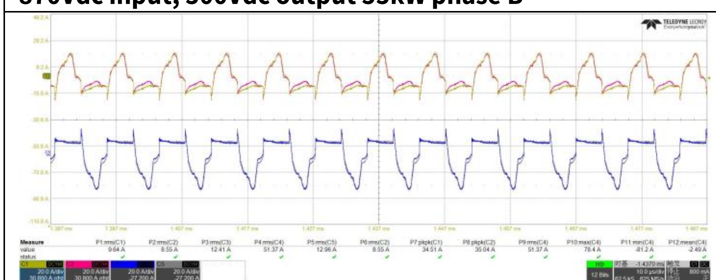
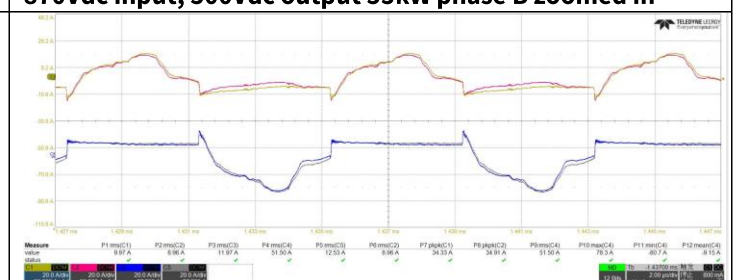
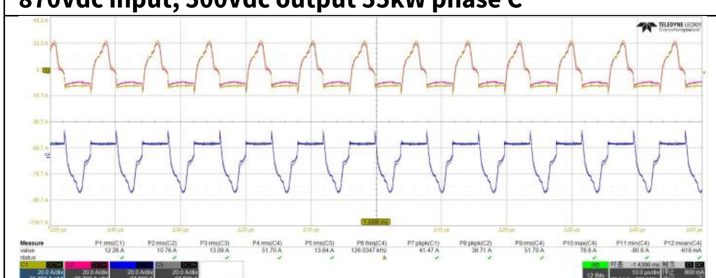
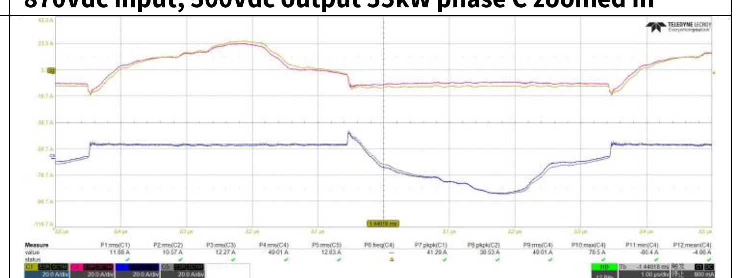
650Vdc input; 200Vdc output 26kW phase A	**650Vdc input; 200Vdc output 26kW phase A zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 2.02%, δ_{HIGH} = 5.2%	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
650Vdc input; 200Vdc output 26kW phase C	**650Vdc input; 200Vdc output 26kW phase C zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 3.4%, δ_{HIGH} = 1.88%	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}

650Vdc input; 250Vdc output 50kW phase A	**650Vdc input; 250Vdc output 50kW phase A zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 5.48%, δ_{HIGH} = 5.66%	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
650Vdc input; 250Vdc output 50kW phase B	**650Vdc input; 250Vdc output 50kW phase B zoomed in**

	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} $\delta_{LOW} = 5.2\%$, $\delta_{HIGH} = 3.17\%$	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
650Vdc input; 250Vdc output 50kW phase C	**650Vdc input; 250Vdc output 50kW phase C zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} $\delta_{LOW} = 5.47\%$, $\delta_{HIGH} = 2.08\%$	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}

730Vdc input; 300Vdc output 60kW phase A	**730Vdc input; 300Vdc output 60kW phase A zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} $\delta_{LOW} = 5.76\%$, $\delta_{HIGH} = 5.86\%$	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
730Vdc input; 300Vdc output 60kW phase B	**730Vdc input; 300Vdc output 60kW phase B zoomed in**
	
CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} $\delta_{LOW} = 5.21\%$, $\delta_{HIGH} = 3.15\%$	CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
730Vdc input; 300Vdc output 60kW c phase	**730Vdc input; 300Vdc output 60kW c phase zoom in**

 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 5.14%, δ_{HIGH} = 1.88%	 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}

870Vdc input; 500Vdc output 55kW phase A	**870Vdc input; 500Vdc output 55kW phase A zoomed in**
 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 7.02%, δ_{HIGH} = 5.82%	 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
870Vdc input; 500Vdc output 55kW phase B	**870Vdc input; 500Vdc output 55kW phase B zoomed in**
 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 5.99%, δ_{HIGH} = 2.17%	 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}
870Vdc input; 500Vdc output 55kW phase C	**870Vdc input; 500Vdc output 55kW phase C zoomed in**
 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2} δ_{LOW} = 6.6%, δ_{HIGH} = 2.06%	 CH1: I_{LOW1} CH2: I_{LOW2} CH3: I_{HIGH1} CH5: I_{HIGH2}

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 under full load (60kW or output 200A for three-phase operation and 130A for full-bridge operation) 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 16 and Table 17. The highest junction temperature of any MOSFET in the design was determined to be 103°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	725	870	650	728	870			
Vout (V)	200	250	300	500	500	600	1000			
Power (kW)	26	50	60	55	50	60	57			
Resonant Choke L2 (°C)	94.7	89.2	86.5	50.8	89.5	83.1	50.6	155	130	Pass
Resonant Choke L3 (°C)	-	104.8	96.2	51.4	99.6	92.9	52.6	155	130	Pass
Resonant Choke L4 (°C)	80.9	109.6	83.7	49.8	106.9	94.2	53.5	155	130	Pass
Transformer T11-1 Coil (°C)	60.1	64.3	63.8	50	57.9	59.7	60.6 (core)	180	160	Pass
Transformer T11-2 Coil (°C)	70.6	75.1	73.6	57.9	69.9	70.4	72.5 (core)	180	160	Pass
Transformer T12-1 Coil (°C)	-	72.3	70.7	56.6	68	66.5	71.8 (core)	180	160	Pass
Transformer T12-2 Coil (°C)	-	74.5	72.5	58.7	70.8	68.6	75 (core)	180	160	Pass
Transformer T13-1 Coil (°C)	67.2	72.5	72.6	57.8	69.8	69	70 (core)	180	160	Pass
Transformer T13-2 Coil (°C)	67.1	71.9	71.9	56.9	68.6	68.4	75.9 (core)	180	160	

Table 16: 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 26KW						
LC MOSFET Q1	0.46	44.5	80.5	101	175	Pass
LLC MOSFET Q21	0.46	44.5	77.7	98.2	175	Pass
LLC MOSFET Q2	0.46	44.5	-	-	175	Pass
LLC MOSFET Q23	0.46	44.5	-	-	175	Pass
LLC MOSFET Q19	0.46	44.5	80.2	100.7	175	Pass
LLC MOSFET Q25	0.46	44.5	77.8	98.3	175	Pass
LLC Diode D74	0.64	35	61.8	84.2	175	Pass
LLC Diode D75	0.64	35	63.9	86.3	175	Pass
LLC Diode D80	0.64	35	67.9	90.3	175	Pass
LLC Diode D81	0.64	35	66.9	89.3	175	Pass
LLC Diode D114	0.64	35	56.4	78.8	175	Pass
LLC Diode D115	0.64	35	51.5	73.9	175	Pass
Vin=730Vdc Vout= 300Vdc 60KW						
LC MOSFET Q1	0.46	30.3	72.4	86.4	175	Pass
LLC MOSFET Q21	0.46	30.3	71.6	85.6	175	Pass
LLC MOSFET Q2	0.46	30.3	66.7	80.7	175	Pass
LLC MOSFET Q23	0.46	30.3	75.1	89.1	175	Pass
LLC MOSFET Q19	0.46	30.3	68.9	82.9	175	Pass
LLC MOSFET Q25	0.46	30.3	67.9	81.9	175	Pass
LLC Diode D74	0.64	35.9	86.7	109.7	175	Pass
LLC Diode D75	0.64	35.9	84.6	107.6	175	Pass
LLC Diode D80	0.64	35.9	87.8	110.8	175	Pass
LLC Diode D81	0.64	35.9	86.4	109.4	175	Pass
LLC Diode D114	0.64	35.9	90.2	113.2	175	Pass
LLC Diode D115	0.64	35.9	83.1	106.1	175	Pass
Vin=870Vdc Vout= 500Vdc 55kW						
LC MOSFET Q1	0.46	29.5	51.3	64.9	175	Pass
LLC MOSFET Q21	0.46	29.5	50.8	64.4	175	Pass
LLC MOSFET Q2	0.46	29.5	48.2	61.8	175	Pass
LLC MOSFET Q23	0.46	29.5	52.6	66.2	175	Pass

LLC MOSFET Q19	0.46	29.5	50.2	63.8	175	Pass
LLC MOSFET Q25	0.46	29.5	49.6	63.2	175	Pass
LLC Diode D74	0.64	19.7	54.6	67.2	175	Pass
LLC Diode D75	0.64	19.7	53.3	65.9	175	Pass
LLC Diode D80	0.64	19.7	55.9	69.5	175	Pass
LLC Diode D81	0.64	19.7	55.5	69.1	175	Pass
LLC Diode D114	0.64	19.7	57	70.6	175	Pass
LLC Diode D115	0.64	19.7	54.1	67.7	175	Pass

Table 17: Thermal Test Results of SiC power MOSFETs and diodes

13. APPENDIX

13.1. PWM TIMING

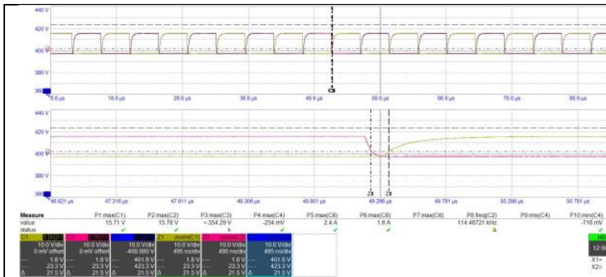
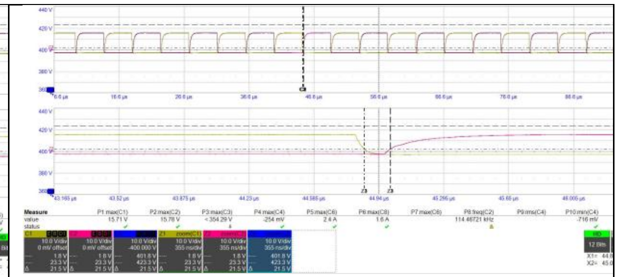
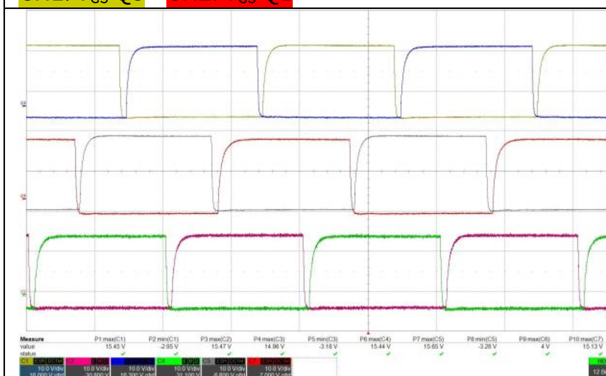
	
Td1 dead time=137ns CH1: V_{GS} Q3 CH2: V_{GS} Q1	Td2 dead time =153ns CH1: V_{GS} Q3 CH2: V_{GS} Q1
	
CH1: V_{GS} Q3 CH3: V_{GS} Q1 CH5: Vgs Q4 CH7: Vgs Q2 CH2: Vgs Q20 CH4: Vgs Q19	

Table 18: 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 19: 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 20: 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 21a: 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 21b: 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 22: 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 23: 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 24: 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 25: Command for querying DC/DC Specification

14. Revision History

Date	Revision	Changes
March 2023	1	First issue

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.

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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.
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● 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.

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