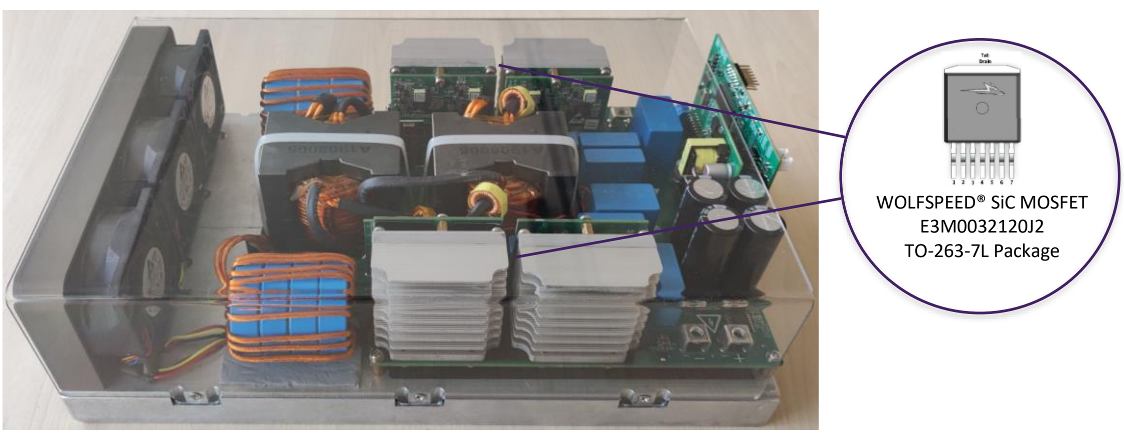
User Guide **PRD-08423**

CRD-22DD12N-J2

22 kW Bi-Directional CLLC Utilizing IMS Board



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CAUTION

PLEASE CAREFULLY REVIEW THE FOLLOWING PAGES, AS THEY CONTAINS 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んでいるため、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˚ C 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，在处理板子前应使大容量电容**器**完全释放电**力。**接**通**电源后，该评估**板上**可能**存在非常**高**的**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**会短暂持续，直至大容量电容**器**完全释放电**量**。

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。**通电时不必接触板子。在为板子通电**前必**须连接**所有**测试与测量探针或附件。通电时，禁止使板子处于无人看护状态，或操作板子。必须确保在操作板**子**前，大容量电容**器**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る必要があります。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's Guide provides the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-22DD12N-J2, 22 kW Bi-Directional DC/DC converter for an electric vehicle (EV) on-board charger (OBC) and similar applications. Wolfspeed's latest bottom-side cooled SiC MOSFETs – E3M0032120J2 (1200V, 32mΩ, TO-263-7L package) are used in this design, which offers easier manufacturing and lower parasitic parameters. Insulated metal substrate (IMS) PCB is used for super thermal management. The design achieves high power density (9.4 kW/L), high peak efficiency (> 98.6%), and supports a wide battery voltage range from 200 VDC to 800 VDC.

This converter is the DC/DC stage of a bi-directional OBC converter. A block diagram is shown in Figure 1. It operates from a rectified DC voltage at bus-side DC terminals and provides an isolated output voltage at the battery-side DC terminals (referred to as charging mode) or vice versa (referred to as discharging mode).

The bidirectional full-bridge CLLC resonant topology is selected for the converter to achieve both high efficiency and wide voltage regulation. Both the bus side and the battery side of the converter use a full-bridge topology that is isolated by a high-frequency transformer. The converter operates at 135 kHz-250 kHz switching frequency range. A daughter card IMS PCB with heatsink is designed to simulate the cooling plate in an OBC application. It dissipates the heat generated by the power MOSFETs.

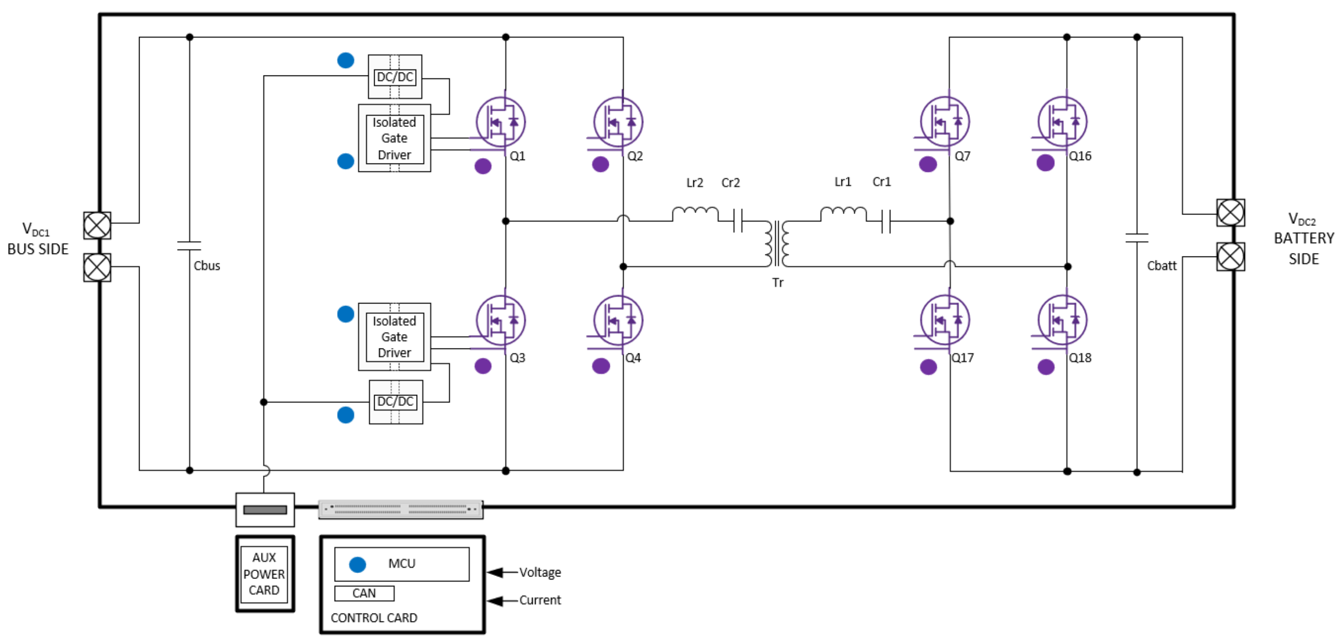


Figure 1: Block Diagram of Wolfspeed's CRD-22DD12N-J2, 22 kW bi-directional high-efficiency DC/DC.

In charging mode, the bus voltage varies between 650 VDC and 900 VDC for three-phase input or between 380 VDC and 900 VDC in a single-phase input. This varied bus voltage, along with the reconfiguration of half-bridge and full-bridge operation without any additional power components, makes it possible to realize wide output voltage range between 200 VDC and 800 VDC with high efficiency and high density. The same technique is applied to discharging mode and thus the bus voltage can be designed between 360 V and 750 V to support single phase output with high efficiency. A 480 VDC - 800 VDC is the typical OBC output range for a high-voltage battery. The operation at an output range of 200 VDC - 480 VDC will result in lower efficiency, but it demonstrates the effectiveness of the proposed control method. The peak efficiency of the DC/DC stage can be above 98.6% in both charging and discharging modes.

Since the main purpose of the reference design is to show the performance of SiC devices in the power converter for EV applications, it does not focus on battery charging technique. Therefore, there is neither a battery charging nor discharging algorithm built in. It must not be connected to any battery directly. An electronic load or a resistive load should be used in both charging mode and discharging mode.

2. DESCRIPTION

This reference design board uses Wolfspeed's E3M0032120J2 (1200 V, 32 mΩ, TO-263-7L package) SiC MOSFETs on both primary side and battery side. A single SiC MOSFET is used for each position as shown in Figure 1.

Flexible gain control methods include the conventional variable frequency control, phase shift control, and reconfigured structure between half bridge and full bridge. The flexible control method plus the high-performance of 1200 V SiC MOSFETs enable high-efficiency operation for a wide output range in both directions. The primary-side full bridge will be reconfigured as half bridge when the required voltage gain is low, which is out of the high-efficiency range of the hybrid control (variable frequency and phase shift) in both charging mode and discharging mode at full-bridge configuration. Thus, the power direction and converter configuration should be selected properly via the graphical user interface (GUI) before turning on the unit.

The operation range of the evaluation board in charging mode is shown in Table 1. The evaluation board is designed to support the DC bus voltage of a PFC (Power Factor Correction) with both single-phase input and three-phase input. In a typical application, the bus voltage (V_{DC1}) is regulated by the PFC stage according to the battery-side voltage. However, with a controlled PFC output, the output voltage at battery side (V_{DC2}) is regulated to maintain the same relation curve as shown in Figures 2a and 2b. This is to simulate real conditions in OBC application.

The battery voltage can be expressed as follows:

$$V_{DC2} = (V_{DC1} - 30V) \times \frac{19}{24} \qquad \text{for full bridge}$$

$$V_{DC2} = (V_{DC1} - 44V) \times \frac{19}{24} \times \frac{1}{2} \qquad \text{for half bridge}$$

The startup voltage is calculated by using the same equations.

The output power at 650 VDC - 900 VDC input is 22 kW maximum, and the output current is up to 36 A. When the output voltage is above 770 V, the output power is limited by its lowest operation frequency. Output power at 800 V output is 16 kW.

Bus side Volt. <input>	Battery side Volt. <output>	Max. Output Power/ Max. Output Current	Topology	Comments
380 V-900 V	250 V-800 V	6.6 kW	Full Bridge	Single Phase Input
650 V-900 V	340 V-770 V	22 kW/36 A	Full Bridge	Three Phase Input
	770 V-800 V	22 kW to 16 kW		
650 V-900 V	240 V-340 V	30 A to 36 A	Half Bridge	
	200 V-240 V	30 A		

Table 1: Overall charging operation.

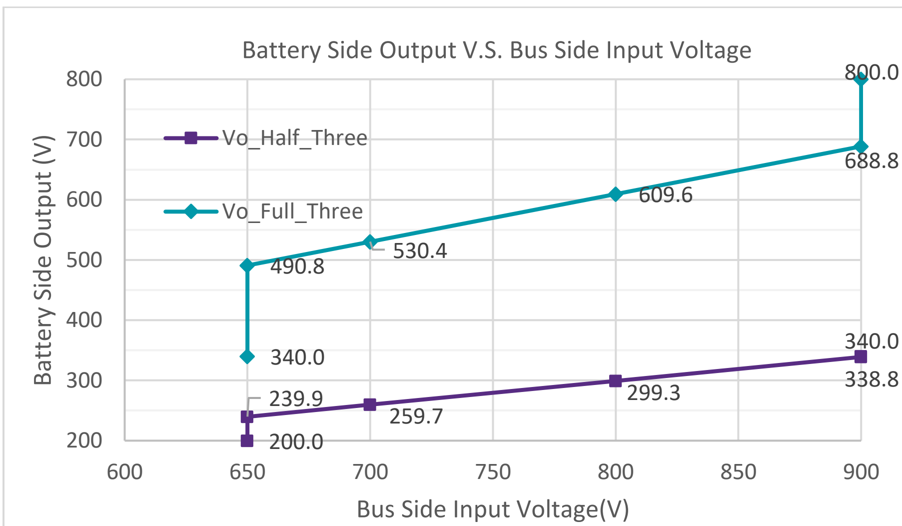


Figure 2a. Battery voltage vs. bus voltage in charging mode for three-phase application.

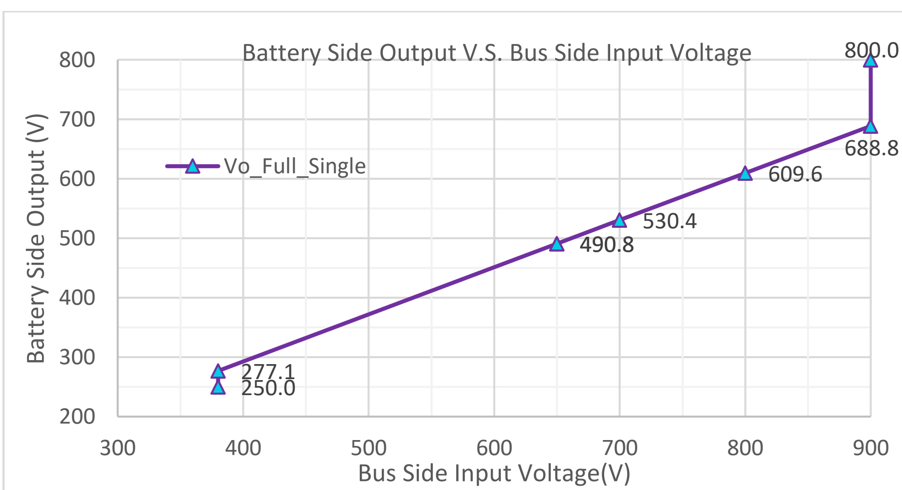


Figure 2b. Battery voltage vs. bus voltage in charging mode for single-phase application.

For discharging mode, the overall discharging operations are shown in Table 2. The output bus voltage is regulated, as shown in Figure 3, to enable high efficiency for both DC/DC stage and DC/AC stages.
The bus voltage can be expressed as follows:

$$V_{DC1} = V_{DC2} \times \frac{24}{19} - 10V \qquad \text{for full bridge}$$

$$V_{DC1} = V_{DC2} \times \frac{24}{19} \times \frac{1}{2} - 10V \qquad \text{for half bridge}$$

The startup voltage is also calculated using the same equations.

Bus side Volt. <input>	Battery side Volt. <output>	Max. Output Power/ Max. Output Current	Topology
300 V-600 V	360 V-750 V	6.6 kW	Full Bridge
600 V-800 V	360 V-500 V		Half Bridge

Table 2: Overall discharging operation.

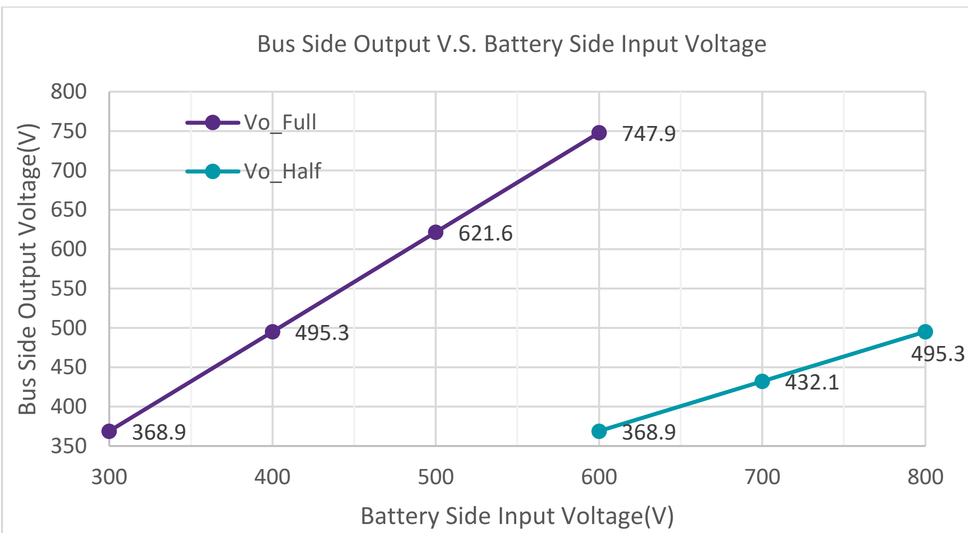


Figure 3: Bus voltage vs. battery voltage in discharging mode.

A user should follow the operations as shown in Figure 2a, Figure 2b and Figure 3 and not overload the converter out of the SOA (Safe Operation Area). Please refer to Table 8 in Section 6.2 of this User's 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 the selection of power direction and topology. The output voltage and/or current with 380 VDC, 650 VDC and 900 VDC input can all be set according to Figure 2a and Figure 2b through CAN interface in charging mode. The output voltage is calculated based on the input DC voltage to enable high efficiency for other inputs in charging mode, or any inputs in discharging mode.

3. ELECTRICAL PERFORMANCE CHARACTERISTICS

Parameter		Test Conditions	Min	Nom	Max	Units
Input Characteristics						
V_{in}	Input voltage		380	800	900	V
I_{in}	Input current				35	A
Output Characteristics						
V_{OUT1}	Output voltage	V_{IN} = 650 VDC~900 VDC Full / Half Bridge	200*1	611	800	V
$P_{OUT1\ max}$	Output power				22000	W
I_{OUT1}	Output current				36	A
V_{OUT2}	Output voltage	V_{IN} = 380 VDC ~900 VDC Full Bridge	250		800	V
$P_{OUT2\ max}$	Output power				6600	W
I_{OUT2}	Output current				26.4	A
V_{ripple}	Output voltage ripple				±2	%
System Characteristics						
η_{peak}	Peak efficiency	V_{IN} = 800 V, V_{OUT} = 610 V, I_{OUT} = 11 A, Full Bridge		98.67		%
$\eta_{full\ load}$	Full load efficiency	V_{IN} = 900 V, V_{OUT} = 800 V, I_{OUT} = 20 A, Full Bridge		98.3		%
		V_{IN} = 800 V, V_{OUT} = 610 V, I_{OUT} = 36 A, Full Bridge		98.0		%
		V_{IN} = 650 V, V_{OUT} = 490 V, I_{OUT} = 36 A, Full Bridge		97.5		%
		V_{IN} = 650 V, V_{OUT} = 240 V, I_{OUT} = 30 A, Half Bridge		95.2		%

Table 2: Characteristics of Wolfspeed's CRD-22DD12N-J2, 22 kW bi-directional DC/DC in charging modes.

*1: 480 V-800 V is the preferred output range. 200 V-480 V is the extended output range for study.

Parameter		Test Conditions	Min	Nom	Max	Units
Input Characteristics						
V_{in}	Input voltage		300		800	V
I_{in}	Input current				25	A
Output Characteristics						
V_{OUT}	Output voltage		360		750	V
P_{OUT} max	Output power	V_{IN} = 600 VDC~800 VDC Half Bridge V_{IN} = 300 VDC~600 VDC Full Bridge			6600	W
I_{OUT}	Output current				19	A
V_{ripple}	Output voltage ripple				±2	%
System Characteristics						
η_{peak}	Peak efficiency	V_{IN} = 600 V, V_{OUT} = 748 V, P_O = 6.6 kW Full Bridge		98.7		%
$\eta_{full\ load}$	Full load efficiency (PO = 6.6 KW)	V_{IN} = 300 V, V_{OUT} = 369 V Full Bridge		97.15		%
		V_{IN} = 600 V, V_{OUT} = 748 V Full Bridge		98.6		%
		V_{IN} = 600 V, V_{OUT} = 369 V Half Bridge		97.0		%
		V_{IN} = 800 V, V_{OUT} = 495 V Half Bridge		97.9		%

Table 3: Characteristics of Wolfspeed's CRD-22DD12N-J2, 22 kW bi-directional DC/DC in discharging mode.

3.1 APPLICATIONS

The main application for Wolfspeed's CRD-22DD12N-J2 reference design board is isolated bidirectional EV charging systems, but the output must be connected to a resistive load or electronic load (Constant Resistor mode is recommended). A test with battery 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-22DD12N-J2 reference design board are listed below:

- Wide voltage range. 380 VDC -900 VDC voltage range for bus-side terminals and 200 VDC -800 VDC voltage range for battery-side terminals.
- Bi-directional operation with flexible control. However, please operate the evaluation board within the safe operation area as described in Section 2.
- The maximum output current is limited to 36 A and maximum output power is limited to 22 kW at the input voltage range of 650 VDC -900 VDC in charging mode. Note: output power is linearly derated from 22 kW to 16 kW when the output voltage is between 770 VDC and 800 VDC under 900 V input.

- The maximum output power is 6.6 kW at the input voltage range of 380 VDC -650 VDC in charging mode. Without AC input information, the controller cannot identify the operation mode, so the 6.6kW power limit function is not accurate in this input range.
- The maximum output power is 6.6 kW in discharging mode.
- Peak efficiency > 98.6% in both charging and discharging mode.
- Protection functions are shown in Table 8.
- Synchronous rectification (SR) is automatically controlled based on operation conditions. SR is typically enabled when the load current exceeds 5 A, and it is disabled when the load current is lower than 2.5 A.
- Half-bridge Insulated Metal Substrate (HBIMS) boards for mounting J2 package device.
- Easy to test using a GUI communicating via CAN. See Section 5 and Section 12 for more details.

4. HARDWARE DESCRIPTION OF MAIN BOARD, DRIVER BOARD, HBIMS BOARD, CONTROL BOARD AND AUXILIARY POWER BOARD

Note: A larger copy of any diagram in Section 4 may be downloaded from the Wolfspeed® reference design website (https://www.wolfspeed.com/power/products/reference-designs/) or obtained upon request by contacting Wolfspeed at forum.wolfspeed.com.

Schematics of Main Board, Driver Board, HBIMS Board, Control Board, and Auxiliary Power Board are shown in Figure 4 to Figure 11.

4.1 DESCRIPTION OF MAIN BOARD

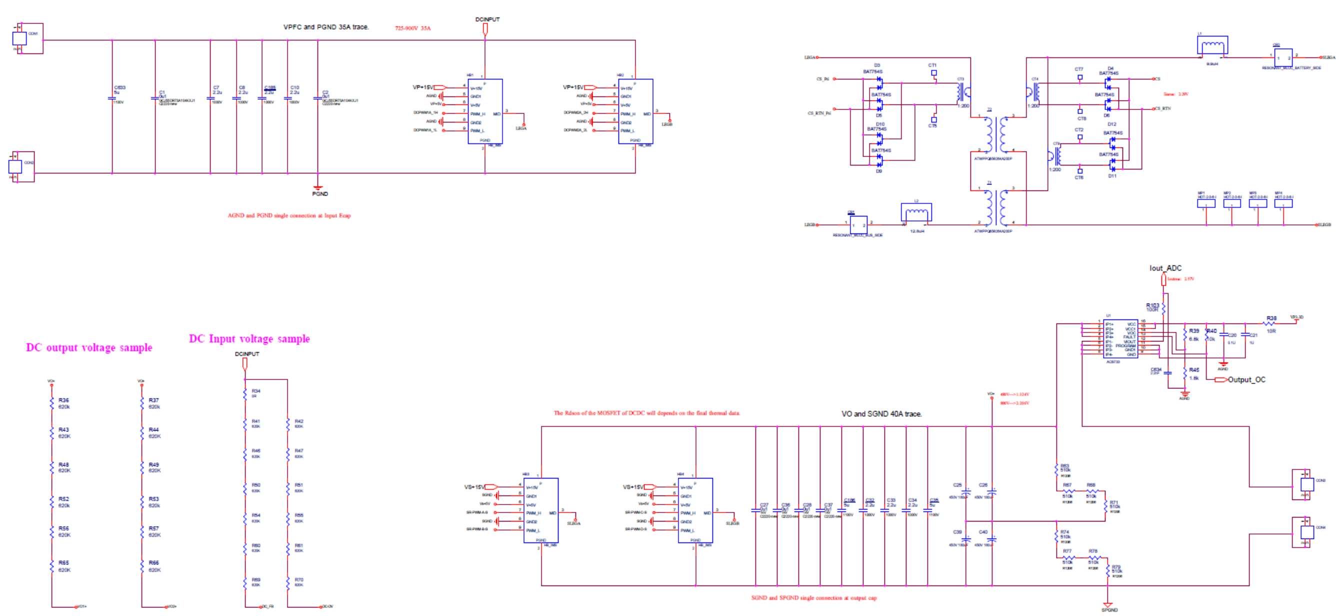


Figure 4a. Schematic of DC/DC main board.

As illustrated by Figure 4a, a full-bridge CLLC topology is selected for the converter. The bus-side DC terminals are CON1(+) and CON2(-) followed by five film capacitors that absorb the high-frequency ripple on the DC port. The battery-side DC terminals are CON3(+) and CON4(-). The full bridge at DC bus side is composed of two half-bridge daughter cards HB1 and HB2. The battery-side full bridge is composed of another two half-bridge daughter cards HB3 and HB4. Two identical transformers isolate these two sides from each other. The main transformer is constructed with a center-leg gapped PQ6562 ferrite core and has a turns ratio of 12:19. The windings of these two transformers are connected in series on the primary side and in parallel on the battery side. The final turns ratio is 24:19. One current transformer is used to sense resonant tank current on the primary side. Two current transformers are used to sense resonant tank currents on the battery side, and these two current signals are paralleled after full-bridge rectification diodes.

The key parameters for these two resonant tanks are shown as below:

	Resonant Inductor	Resonant Capacitor
Bus Side Tank	12.8 µH	$\frac{12nF}{2} \times 9 = 54nF$
Battery Side Tank	9.9 µH	$\frac{12nF}{2} \times 12 = 72nF$

Table 5: Key parameters of resonant tanks.

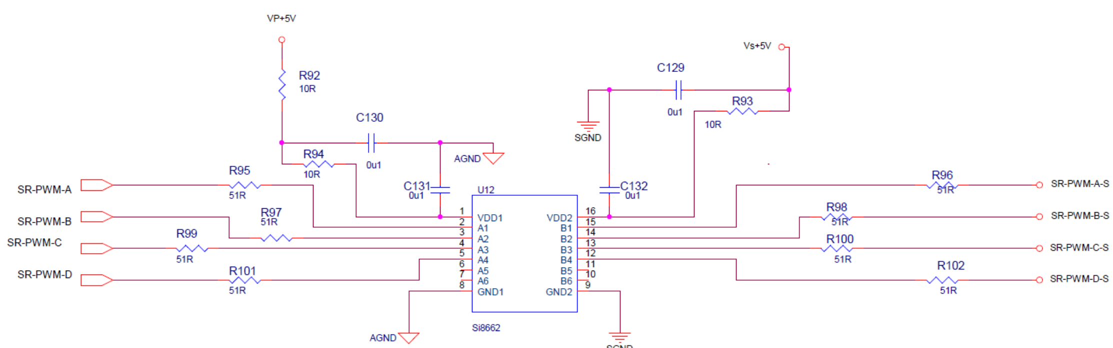


Figure 4b. Schematic of DC/DC main board: signal isolation.

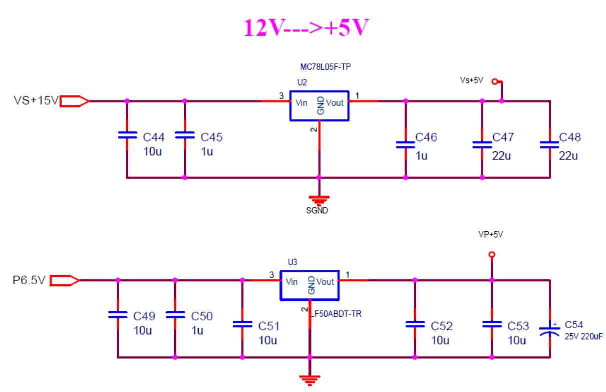


Figure 4c. Schematic of DC/DC main board: power supply.

4.2 DESCRIPTION OF DRIVER BOARD

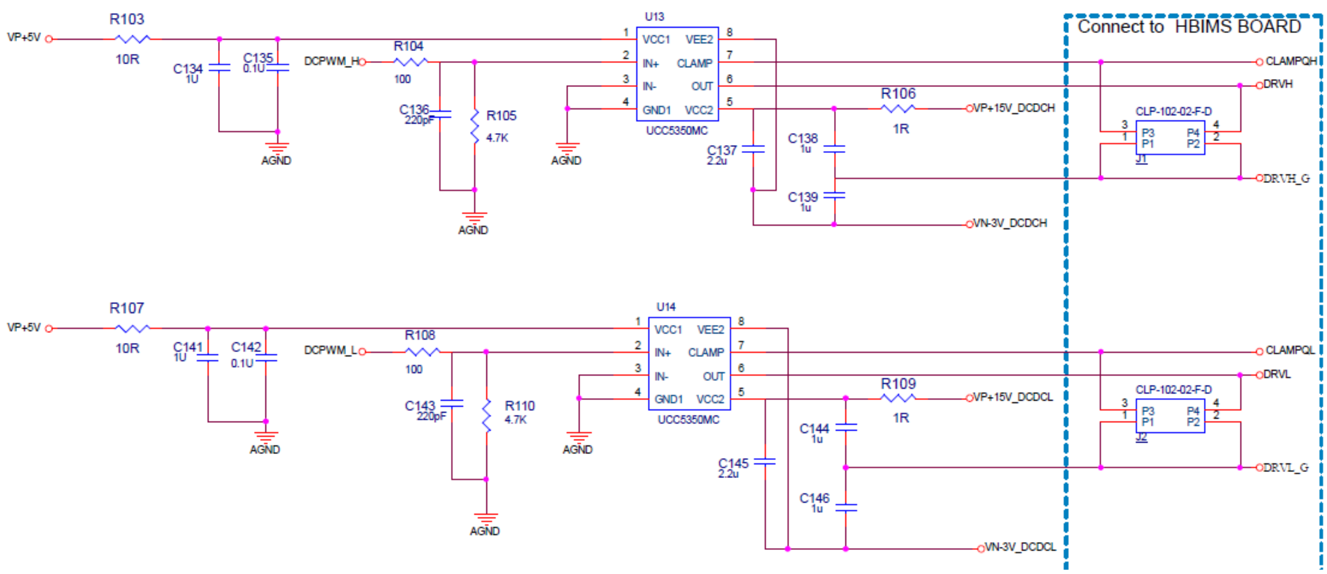


Figure 5a. Schematic of driver board: gate drives.

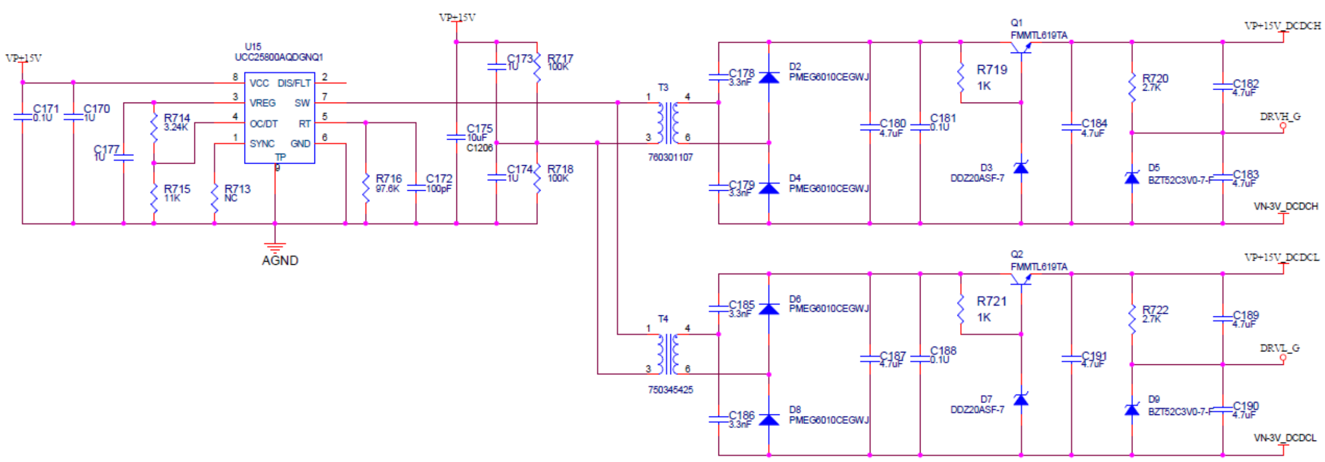


Figure 5b. Schematic of driver board: bias power supply.

As illustrated in Figures 5a and 5b, the driver board is a daughter card, including two separated and insulated gate drivers. Single-channel isolated gate drivers (P/N: UCC5350MC) are used to drive the MOSFETs. A low-cost bias power supply with push-pull transformer is used, and the output is divided to +15 V/-3 V to power the gate driver. The power flow and gate driver signals are connected from main board to HBIMS board through driver board.

4.3 DESCRIPTION OF HBIMS DAUGHTER CARD

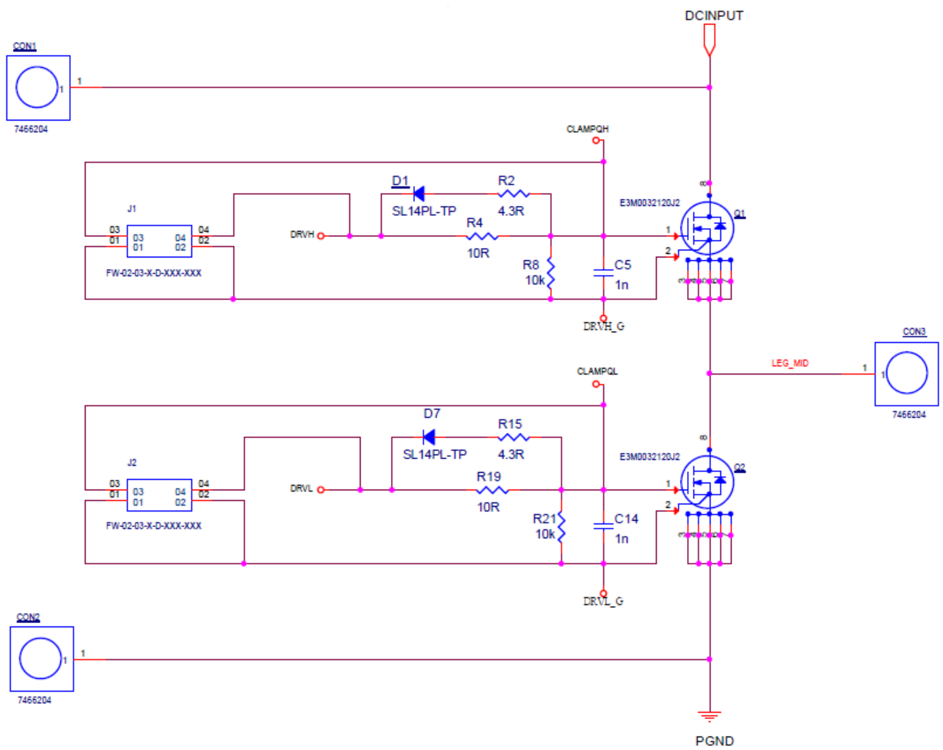


Figure 6. Schematic of HBIMS board: half-bridge switches.

As shown in Figure 6, the HBIMS board is designed in a half-bridge configuration. This design allows users to easily integrate two HBIMS boards into a full-bridge configuration. The HBIMS board is populated with Wolfspeed's E3M0032120J2 (bottom-side cooled SiC MOSFET) and peripheral devices. Thermal management of surface mount (SMT) devices is different from through-hole devices. There are many types of mounting options that can be used to mount SMT power devices. While thermal vias is the traditional solution, insulated metal substrate (IMS) PCB is another popular SMT solution used in high-power and high-power-density applications.

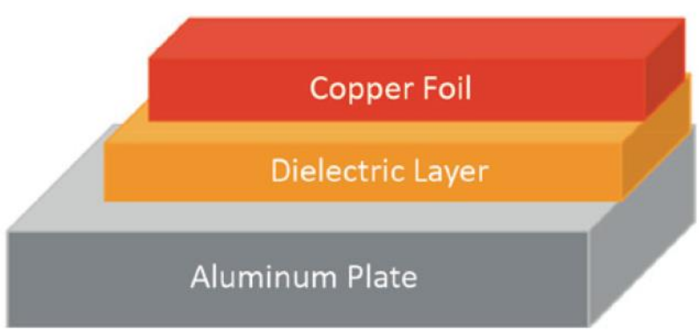


Figure 7. Cross-section view of standard single layer IMS board.

IMS are metal base plates with a thin dielectric layer and copper layer. IMS PCBs can provide much lower thermal impedance at an appropriate cost. Mostly, they are single-layer PCBs. The structure of a standard single-layer IMS PCB is schematically shown in Figure 7. The metal baseplate is often aluminum due to low cost and density, but copper is offered as an alternative in certain applications. The copper foil layer is generally a standard HTE (high-temperature elongation) ED (electro-deposited) foil as used in regular copper-clad PCB laminates. The copper foil is etched to form electrical interconnections for all electrical components on the PCB. The dielectric layer is resin-based and serves to bond to the metal layers as well as provide electrical insulation between the copper foil and the aluminum plate. The dielectric thickness should be as small as practicable to provide the shortest thermal path consistent while maintaining acceptable electrical insulation and maximizing the thermal conductivity of the dielectric.

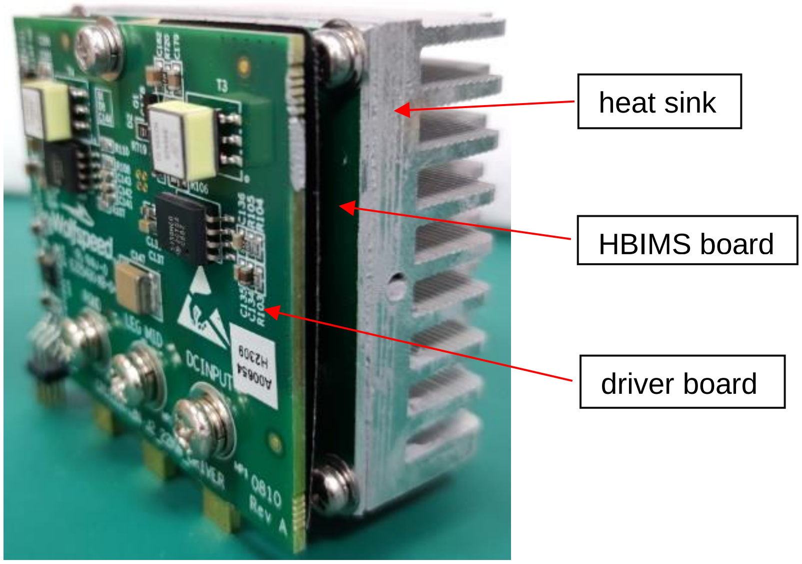


Figure 8. Half bridge IMS daughter card with surface mount SiC MOSFETs.

HBIMS daughter card assembly is shown in Figure 8 with a size of 50 mm (W) × 56 mm (D). A gate drive card is mounted on the top of the HBIMS board, and a heatsink is mounted on the bottom of the HBIMS board with an appropriate TIM. Screws and nuts are used to secure all the boards together.

4.4 DESCRIPTION OF CONTROL BOARD

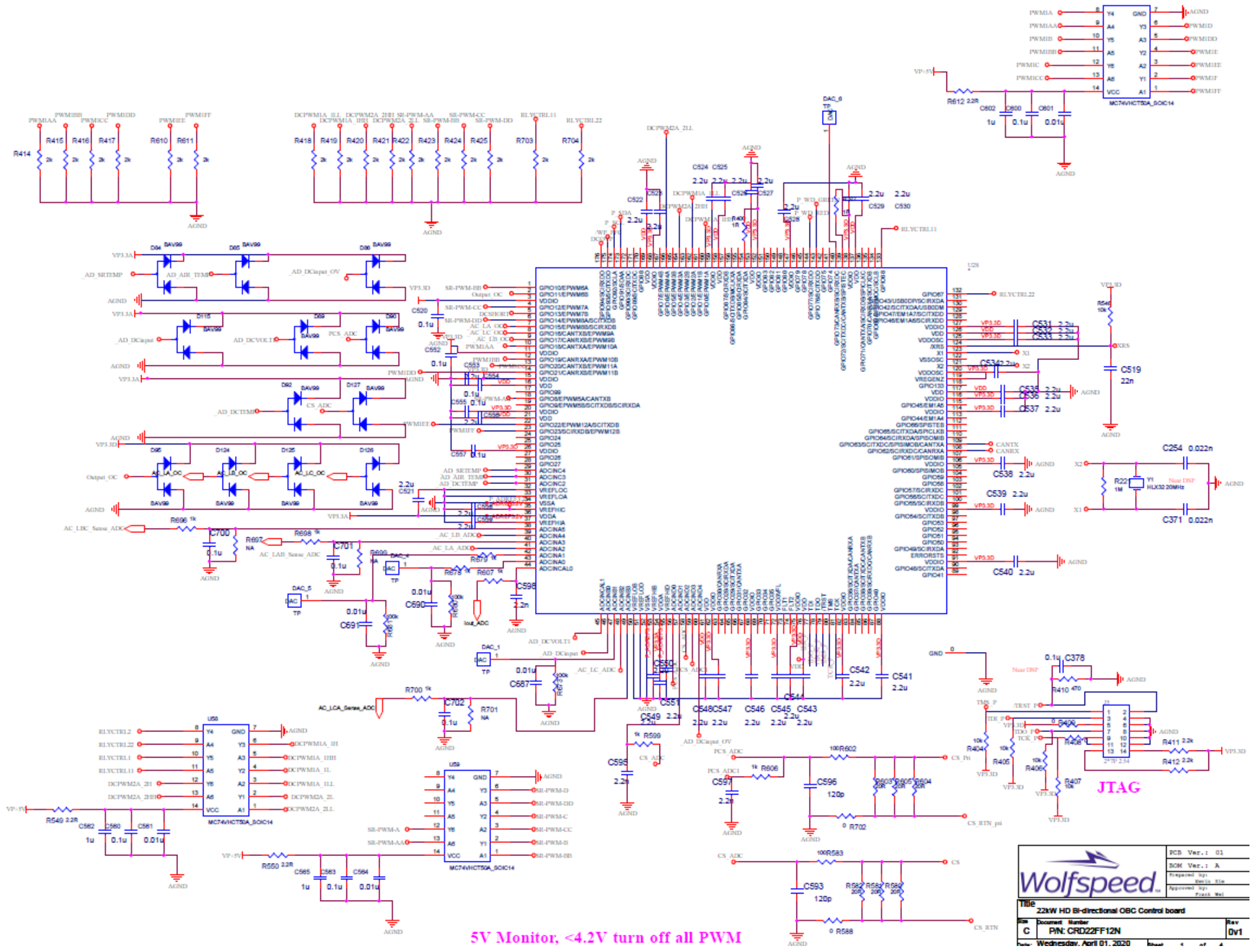


Figure 9a. Schematic of control board: Controller.

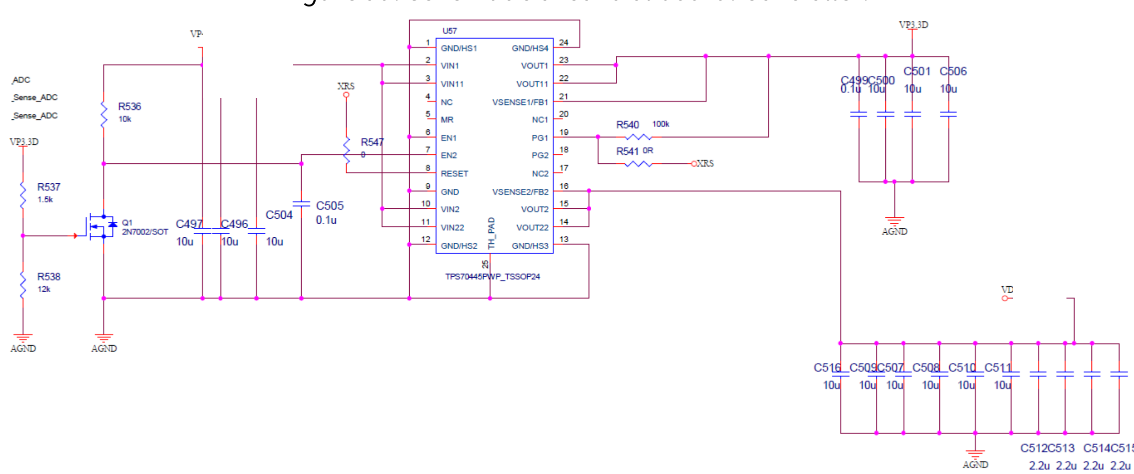


Figure 9b. Schematic of control board: Controller power supply.

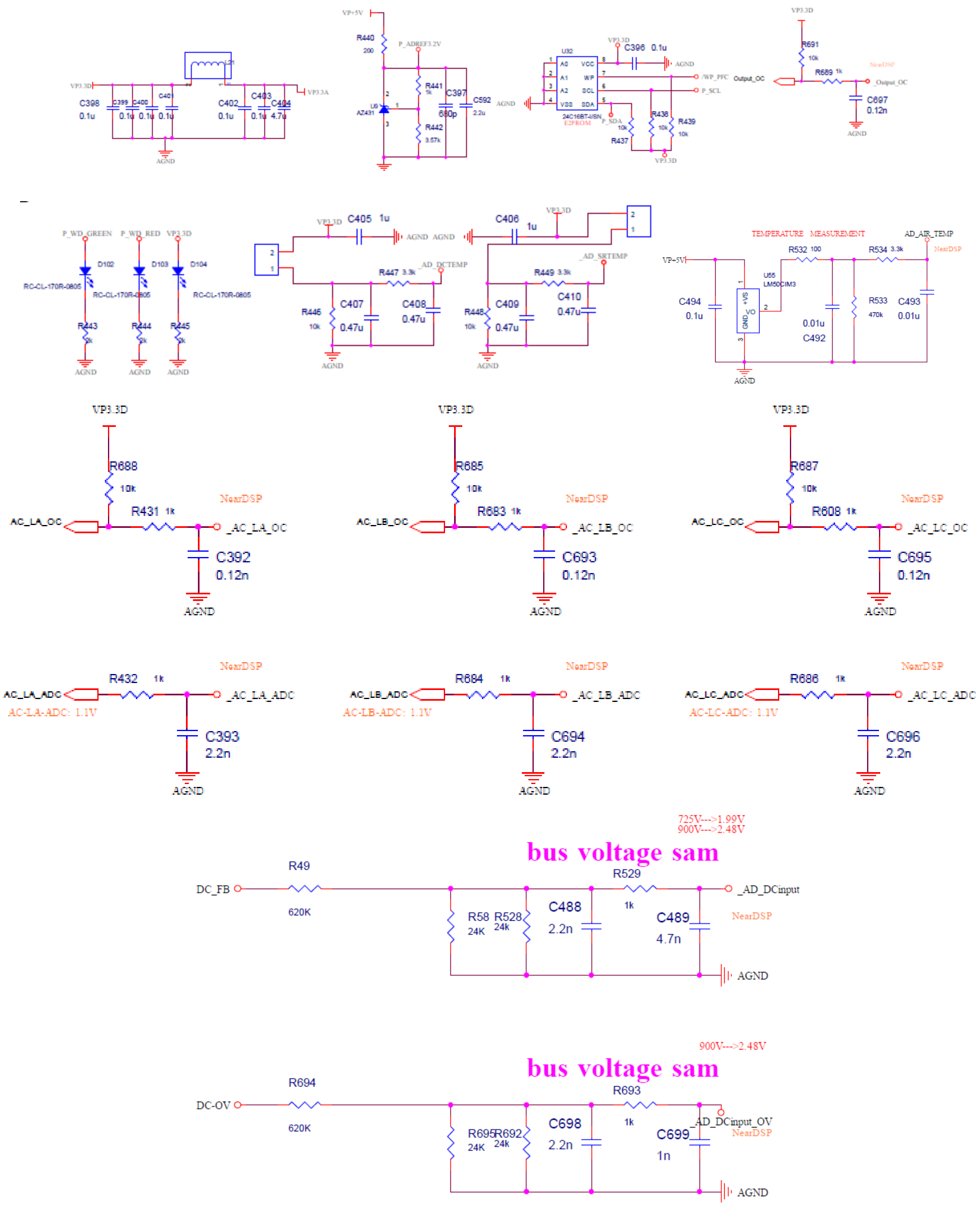


Figure 9c. Schematic of control board: Bus voltage sample.

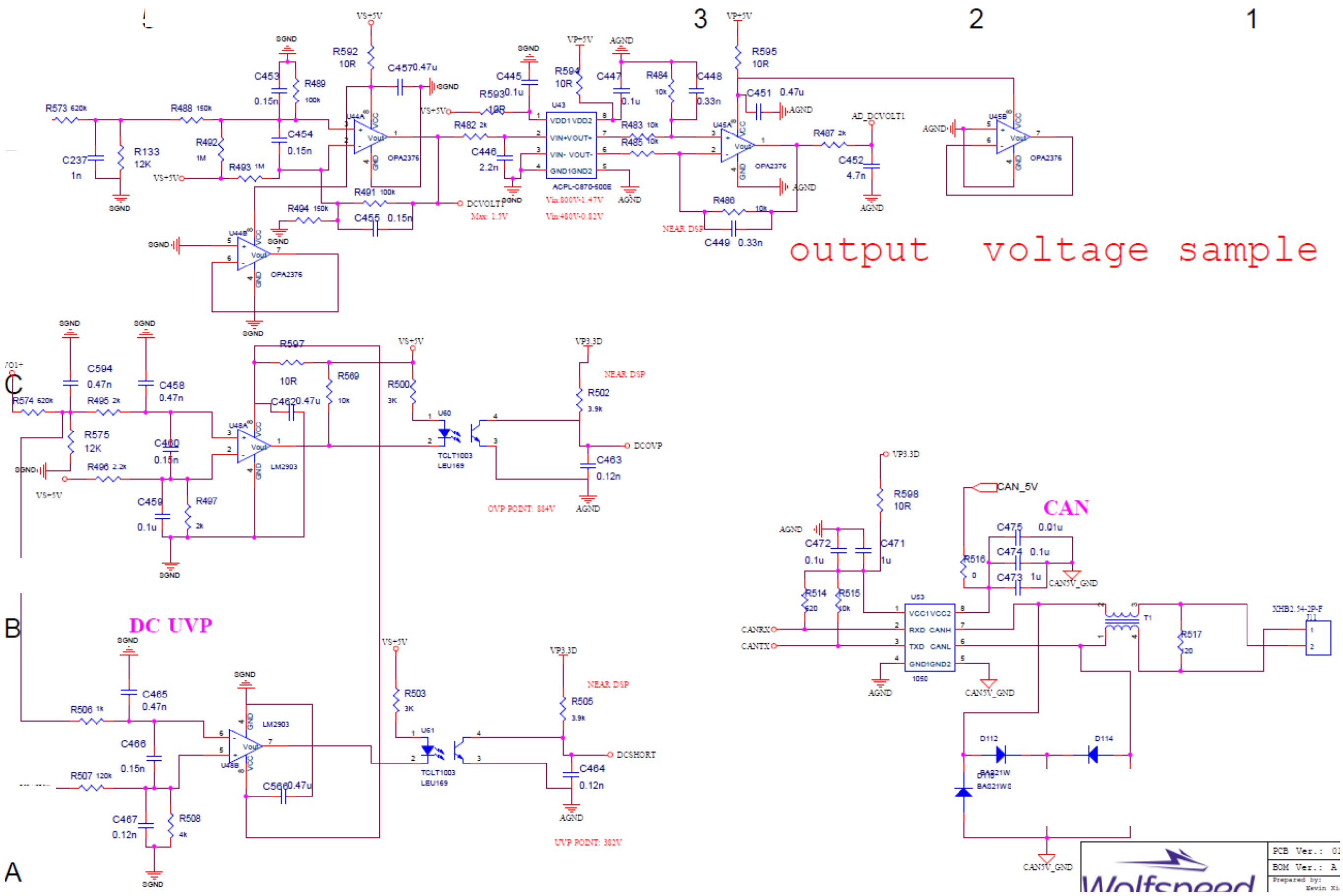


Figure 9d. Schematic of control board: Battery voltage sample and CAN interface.

As illustrated by Figure 9a to 9d, 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, 7 V @ 1 A, power supply whose output is then tightly regulated to +5.0 V by a linear regulator. This 5.0 V voltage rail then supplies another precision linear regulator IC, U57, from Texas Instruments Inc. (P/N: TPS70445), which provides both a 3.3 V and a 1.2 V voltage rail. All output drive signals are buffered and shifted to a +5 V 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 3.3 V. This reference is created by a reference IC U9, (P/N: AZ431-2.5 V) from the +5.0 V 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) 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 after voltage divider.

4.5 CONNECTIONS OF CONTROL BOARD AND AUXILIARY POWER BOARD TO MAIN BOARD

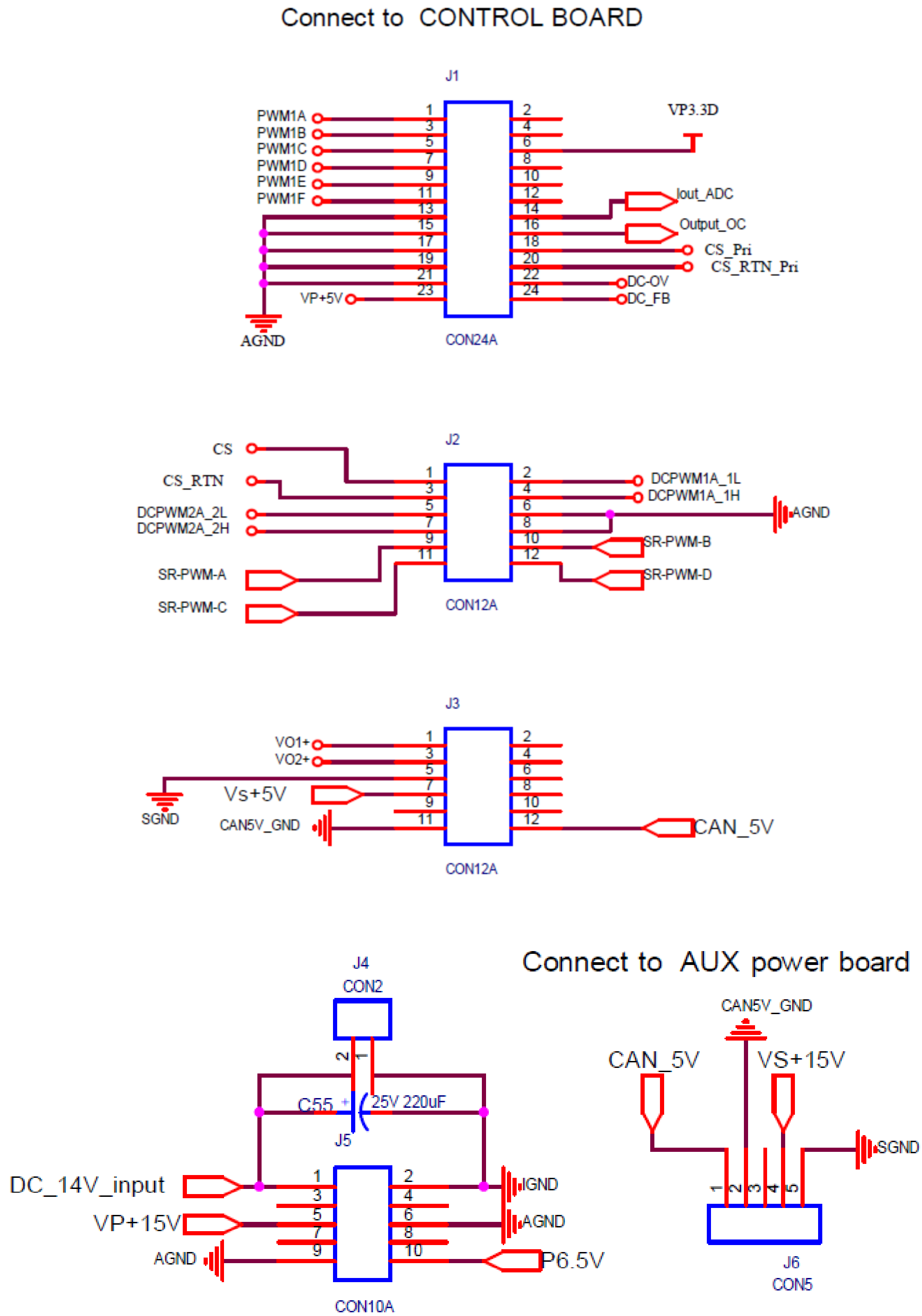


Figure 10. Schematic of connectors on Main Board.

4.6 DESCRIPTION OF AUXILIARY POWER BOARD

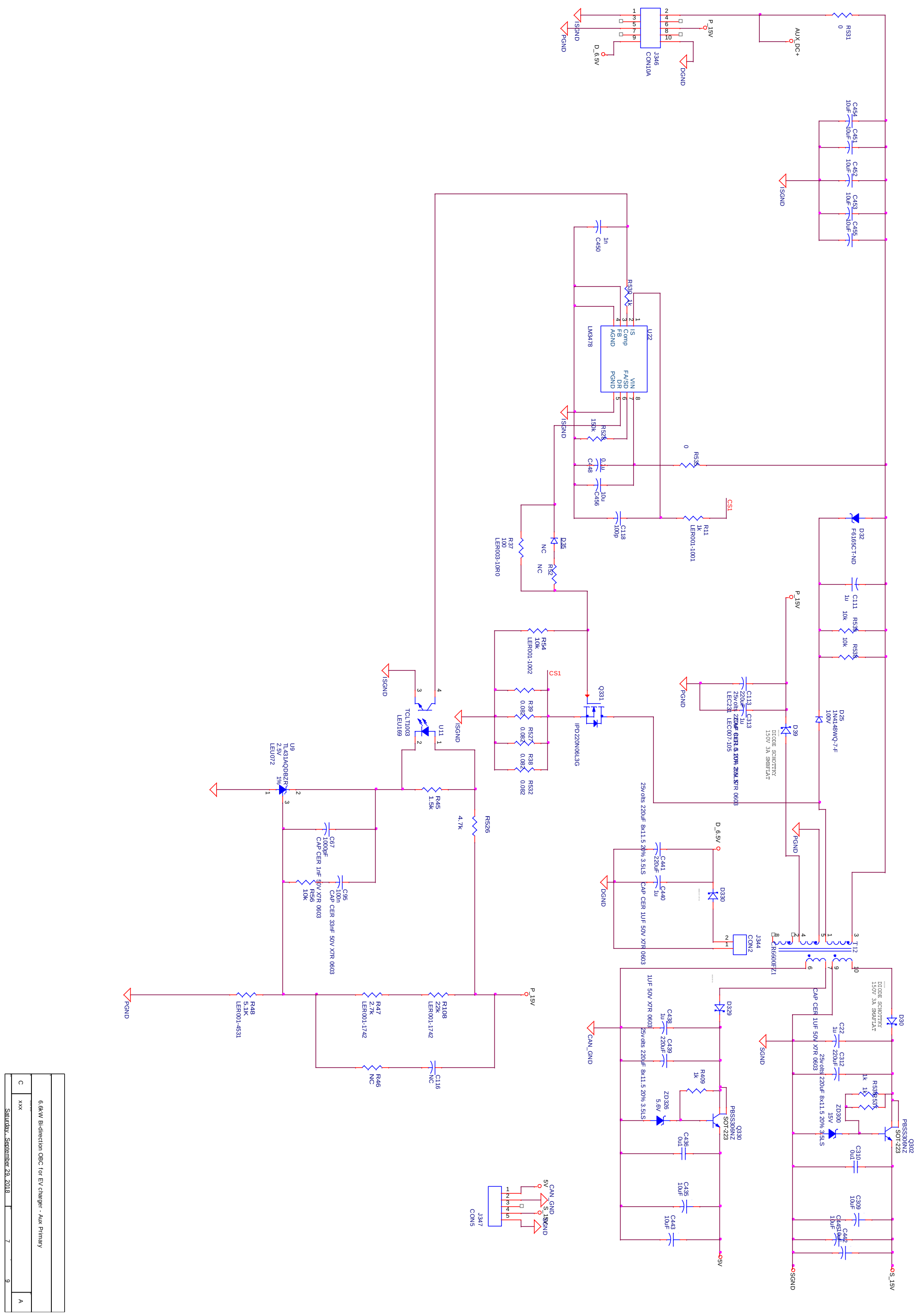


Figure 11. Schematic of Auxiliary Power Board.

The typical input voltage of the Auxiliary Power Board is 14 V (J346, net 'Aux_DC+' and net 'ISGND' in Figure 11). It provides four isolated output voltages, as shown in Table 6.

Input/Outputs	Net Name	Comments
Input	14 V	14 V Typical input of the auxiliary power board
Output 1	P_15 V	15 V Power supply for primary side MOSFET gate drivers
Output 2	S_15 V	15 V Power supply for Battery side MOSFET gate drivers
Output 3	5 V	5 V output for CAN communication
Output 4	D_6.5 V	Controller power supply

Table 6: Input and outputs of Auxiliary Power Board.

5. INTERFACE OF HARDWARE AND SOFTWARE

5.1 HARDWARE INTERFACE

DC Input Source: The input source must be an adjustable DC source whose output can be adjusted between 300 VDC and 900 VDC. It must be capable of supplying at least 25000 W.

Output Load: A programmable high-voltage electronic load or a high-voltage resistor bank may be used. Each must be capable of sinking 36 A of load current supplied from the evaluation board whose output can be 1000 VDC/22 kW.

Power Meter: A power analyzer from Yokogawa Test and Measurement Corporation (P/N: WT 3000) or any other equivalent power analyzer should be used. An external shunt resistor should be used when the output current exceeds the rating of the internal shunt resistor.

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

Power Supplies: The following power supplies with isolated grounds should be used and must be obtained separately:

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

External Fans: Cooling fans should be used and must be obtained separately. As shown in Figure 12, at least three cooling fans, such as the Delta Electronics Inc. ® DC12 V/3.30 A fan (P/N: PFR0612XHE-CV52) or an equivalent must be used for cooling the system. The red wire of the fan is the positive terminal, and the black wire is the negative terminal. The temperature of the magnetics and heatsinks should be monitored by an infrared scanner to verify the cooling fan setup during first-time testing.

Figure 12. Setup of the reference design.

Recommended Wire Gauge: Cable with a minimum AWG #10 wire gauge is recommended to carry the DC input and output currents.

5.2 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 12. The detailed CAN data format is shown in Section 5.3 and Section 12.2.

The over/under voltage-protection is indicated by the back color of the voltage value, as shown in Figure 13. “Green” indicates “Normal Operation” while “Red” means “Warning Issued.” The ambient temperature sensed by the IC is displayed in the panel as well.

To conduct an efficiency test with the output lightly loaded, it is recommended that the SR be enabled as shown in Figures 13c, 13e, and 13f. This can be done by increasing the load sufficiently and then decreasing the load to the required test load. The SR status is shown in the left bottom of the GUI window.

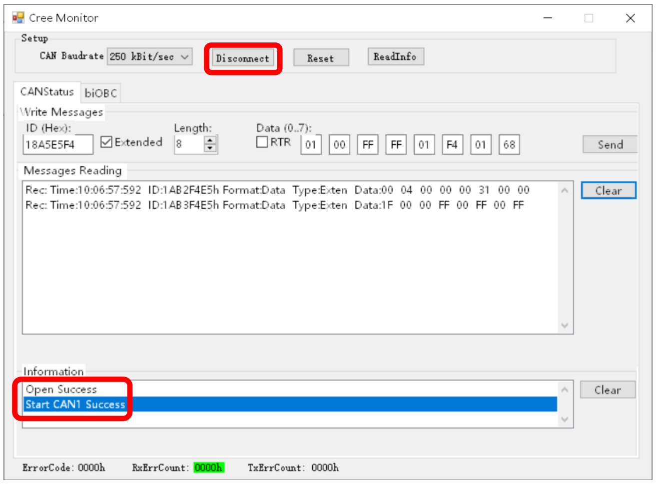


Figure 13a. CAN status tab after connection.

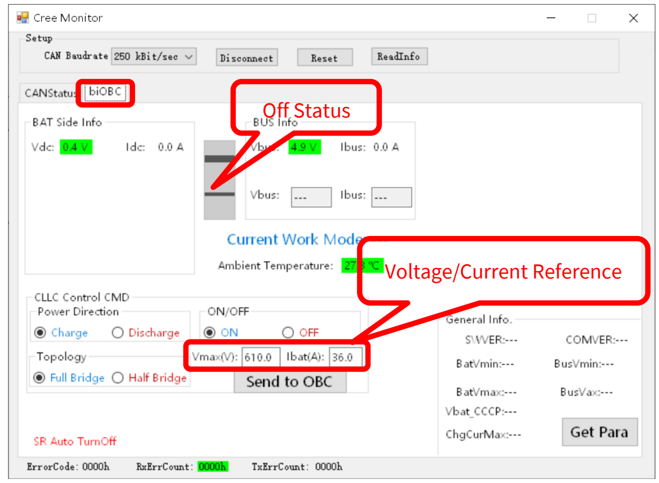


Figure 13b. Connected to control board <Off Mode>.

The power direction and topology can only be changed when the rectifier is shut down. This can be done in two steps: first send an “OFF” command to shut down the converter, then send an “ON” command with desired power direction and topology. The converter will shut down and ignore any other configuration bits once it receives the CAN frame with the “OFF” configuration. If the converter is shut down, it will start, as configured, once it receives the CAN frame with the “ON” configuration. The power direction and topology will also be displayed in the left bottom area.

Voltage reference is the desired output voltage while current reference is the desired output current. The current reference is recommended to be 36 A. The digital controller will check the value range each time. Startup voltage will always be calculated by the controller based on the equation mentioned in Section 2, and thus does not rely upon the input voltage reference.

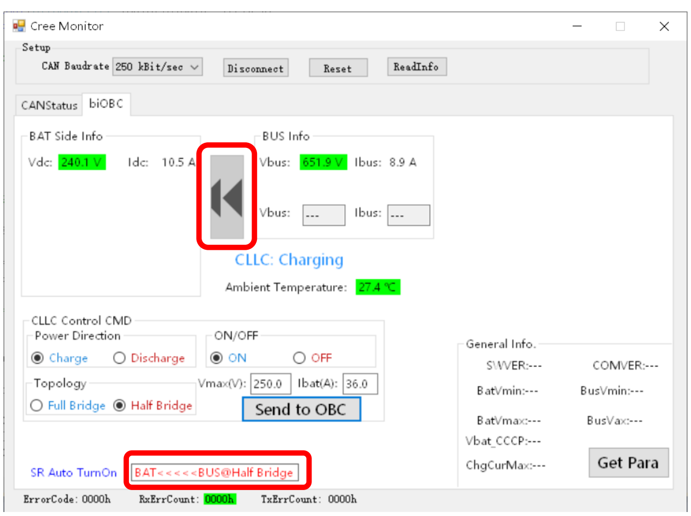


Figure 13c. Charging operation in half bridge.

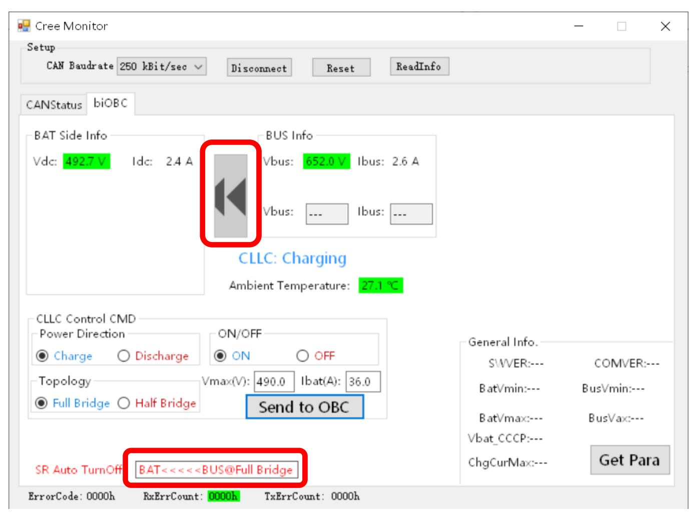


Figure 13d. Charging operation in full bridge.

In charging mode, the output voltage is calculated by the digital controller when the input voltage is between 650 V and 900 V, and the output voltage setting is disabled when the input voltage is between 650 V+3 V or 900 V-3 V after startup.

In discharging mode, these reference values have no impact.

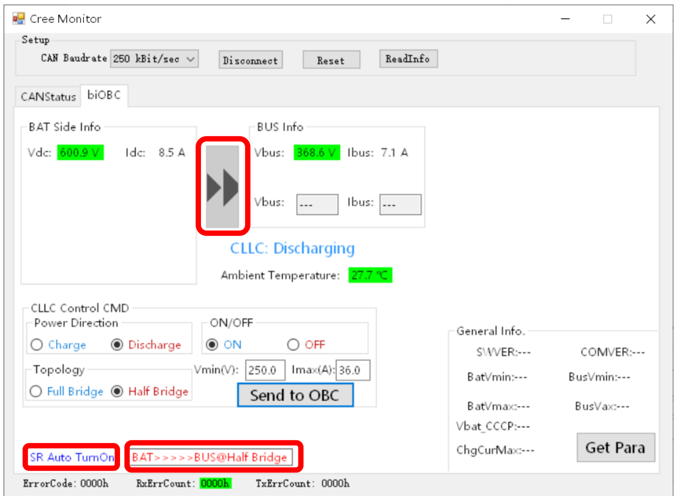


Figure 13e. Discharging operation in half bridge.

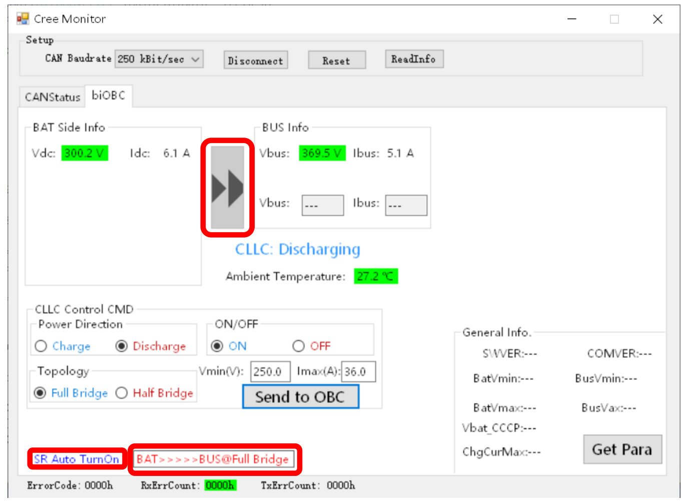


Figure 13f. Discharging operation in full bridge.

5.3 CAN COMMUNICATION DATA FORMAT

The reference design communicates over a CAN V2.0 B bus at 250 K 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 12.2 and 12.3.

Table 7 below provides an example when "0x18A5E5F4" is sent as the message identifier and "0x0100FFFF12C00168" as the CAN data. When the OBC is placed in charging mode, its output voltage is set to 650 V and care must be taken to ensure that the first byte in the CAN instruction matches the correct operating mode when the second byte is zero. Otherwise, that instruction will be ignored by the reference board.

Message Identifier: 0x18A5E5F4					
Data	Byte0 = 01	Byte1= 00	Byte2+Byte3	Byte4+Byte5 = 0x12C0	Byte6+Byte7 = 0x0168
Property	Charging Mode; Full Bridge	On	Reserved 0xFFFF	DC Voltage: 0x12C0*0.1 V = 480 V	DC Current: 0x0168*0.1 A = 36 A

Table 7: Example of control command.

6. TEST EQUIPMENT

CAUTION

IT IS NOT NECESSARY FOR YOU TO TOUCH THE BOARD WHILE IT IS ENERGIZED. WHEN DEVICES ARE BEING ATTACHED FOR TESTING, THE BOARD MUST BE DISCONNECTED FROM THE ELECTRICAL SOURCE AND ALL BULK CAPACITORS MUST BE FULLY DISCHARGED.
SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50° CELSIUS. THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED. DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD.
PLEASE ENSURE THAT APPROPRIATE SAFETY PROCEDURES ARE FOLLOWED WHEN OPERATING THIS BOARD AS SERIOUS INJURY, INCLUDING DEATH BY ELECTROCUTION OR SERIOUS INJURY BY ELECTRICAL SHOCK OR ELECTRICAL BURNS, CAN OCCUR IF YOU DO NOT FOLLOW PROPER SAFETY PRECAUTIONS.

警告

通电时不必接触板子。连接器件进行测试时，必须切断板子电源，且大容量电容器必须释放完所有电量。
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量。通电时禁止触摸板子，应在大容量电容器完全释放电量后，再操作板子。请确保在操作板子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。

6.1 RECOMMENDED TEST SETUP

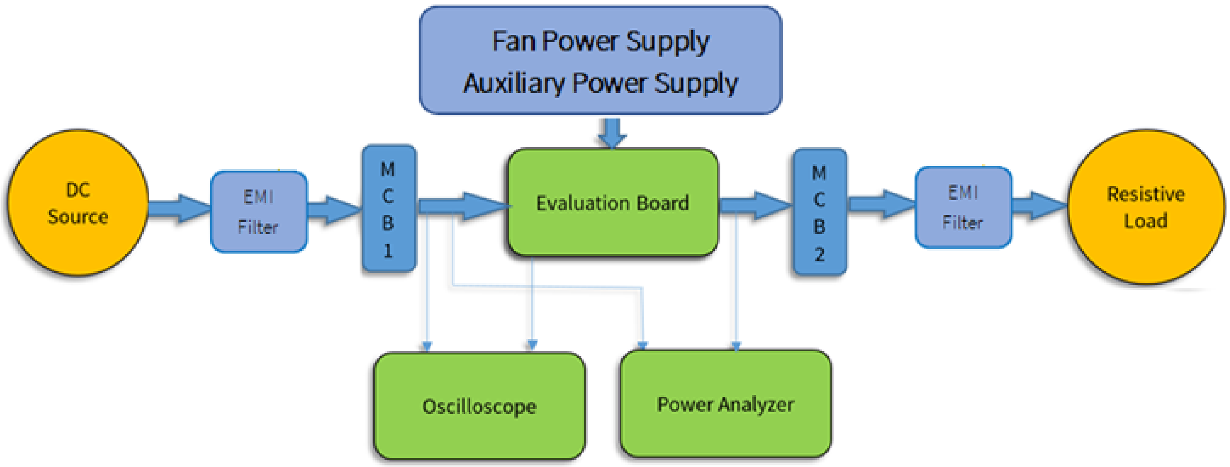


Figure 14: Converter test setup.

Charging mode means the DC source is connected to **bus**-side terminals and the load is connected to the **battery-**side terminals. Discharging mode means the DC source is connected to **battery**-side terminals and the load is connected to the **bus**-side terminals.

- Connect resistive load to the evaluation board through MCB2.
- Connect DC source to the evaluation board through MCB1.
- Connect power analyzer to measure input and output power.
- Use appropriately rated voltage and current probes and connect to the oscilloscope.
- Place and operate the external fans.

6.2 PROTECTIONS

Table 8 describes various protection functions in the reference design. OCP (Over Current Protection) for the CLLC resonant tank and short 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. In both charging mode and discharging mode, the power/current limitation function based on resonant tank current 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/UVP	>950 V, <370 V	>880 V, <195 V
Short Protection	short	---	<60 V
CLLC Tank Current	OCP	40 A	40 A
Startup Voltage		>350 V	>280 V

Power Signal	Protection	Trip Point for Battery Side	Trip Point for Bus Side
Output Power Limitation		22 kW±1.5 kW	
Output Current Limitation		30 A±1.5 A @ <240 V, 36 A±1.5 A others	

Table 8: Protection details.

6.3 ISOLATED POWER SUPPLY: VOLTAGE AND CURRENT SETTINGS

The requirements for the isolated power supplies are shown in Table 9. A single power supply connected to J4 on the Main Board is used to power the Auxiliary Power Board.

Main Board Connector Designator	Power Supply	Voltage (V)	Current 1 (A) (PWM Off)	Current 2 (A) (Normal Operation)
J4	+14 V for AUX power	+14 V +/-5%	0.46	0.86

Table 9: Auxiliary power supply requirements.

6.4 MEASURED PARAMETERS

No power MOSFET pins are reachable directly, as they are covered by the driver board. To test the stress of V_{GS} or V_{DS}, one option is to use twisted wires to bring the voltage signal out. Make sure the length of the twisted pair cabling is as short as possible for the purpose of reducing crosstalk and noise. 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 fully discharged.

Name	Description
Efficiency	Measured with power analyzer
Input/Output Current	DC current at DC terminal
Input/Output Voltage	High voltage at DC terminal
CLLC Tank Current	CLLC tank current at both BUS side and battery side
VGS /VDS Signals	Voltage across gate to source or drain to source of SiC MOSFETs
Auxiliary Power Board Outputs	Please refer to Figure 10 and Table 6 for details
3.3 V /1.2 V Controller Supply	+3.3 V supply for Controller's I/O; +1.2 V supply for Controller's core

Table 10: Parameters which can be measured.

7. 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.

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. Power direction and topology can't be changed via CAN communication after startup.
2. Please choose the appropriate power direction matched with the setup.
3. Please choose the appropriate topology according to the desired output voltage in charging mode at given input bus voltage or according to the input voltage in discharging mode.
   a. In charging mode, the converter should operate as full-bridge topology when the battery-side output voltage is targeted in the range of 340-800 VDC and as half-bridge topology for 200-340 VDC when the input DC voltage is above 650 V.
   b. In discharging mode, the converter should operate as full-bridge topology when the battery-side input voltage is in the range of 300-600 VDC and as half-bridge topology for 600-800 VDC.
4. Please do not overload the converter. Please refer to Table 1, Table 2, and Section 3.2.
5. There is no current inrush limiter for either port. The DC input voltage must be increased slowly (soft start) for either power direction.
6. Always remember to connect the cooling fans to their power supplies and operate the cooling fans when operating the board.

7.1 STARTUP PROCEDURE: DISCHARGING MODE

1. Double check the setup: Make sure the polarity is correct, the source is connected to the **battery-side** terminals, and the load is connected to the **bus-side** terminals.
2. Keep MCB1 (DC supply) in open position and the DC source output disabled.
3. Ensure that the load is less than 1 kW, and then close MCB2.
4. Apply 14 VDC to J4 on the main board. Check the output voltage of the Auxiliary Power Supply at J5 (P6.5 V, VP+15 V) and J6 (VS+15 V, CAN_5 V). Check that the current draw is approximately the same as shown in Table 9. Check the +3.3 V 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 0 V to the required voltage (300 VDC – 800 VDC).
8. Verify that the measured values in the GUI were reported correctly.
9. Send ON command with settings of "**Discharge**" and "Full Bridge" or "Half Bridge" according to the input voltage. Voltage reference and current reference have no impact for startup. Startup voltage is calculated according to Figure 3.
10. After the output voltage has reached steady-state target value, increase the load up to desired value within 6.6 kW. The step-load change should not be more than 1 kW for each step.
11. Check the efficiency under load conditions of interest. Check if SR is turned on automatically when DC output current is above 5 A. SR should be active by increasing output current to >5A.

7.2 TURNOFF PROCEDURE: DISCHARGING MODE

1. Decrease the load to 1 kW within 1 kW steps.
2. Use GUI to send OFF command.
3. Disable the output of the DC power supply.
4. Wait until the DC source has fully discharged its output.
5. Turn OFF load after the bus-side capacitors are fully discharged.
6. **Capacitors may remain charged for up to 30 minutes after the circuit is turned OFF if step 4 or step 5 are skipped or compromised. They must be allowed to fully discharge before handling the board. Please check the terminal voltages with a multimeter to ensure that the board has fully discharged and is therefore safe to handle.**
7. Turn OFF the 14 VDC power supply on J4. The unit should be fully discharged before the auxiliary power supply is disabled.

7.3 STARTUP PROCEDURE: CHARGING MODE

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

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

3 Apply a load of no more than 1 kW to the DC terminals, and then close MCB2.

4 Apply 14 VDC to J4 on the main board. Check the output voltage of the Auxiliary Power Supply at J5 (P6.5 V, VP+15 V) and J6 (VS+15 V, CAN_5 V). Check that the current draw is approximately the same as shown in Table 9. Check the +3.3 V 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 (380 VDC – 900 VDC).

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

9 Send ON command with settings of “**Charge**” and “Full Bridge” or “Half Bridge,” according to desired output voltage. Use 36 A as current reference for start-up. The converter will start up with voltage calculated according to Figure 2.

10 The output voltage can be regulated using GUI only when the input voltage is 380 V, 650 V and 900 V. Otherwise, the output voltage is calculated according to Figure 2.

11 After the output voltage has reached steady-state target value, apply a load to the output in no more than 2 kW steps. Permanent overload damage may occur during sustained operation with unmatched input and output relation.

12 Check the efficiency under load conditions of interest. Check if SR is turned on automatically when DC output current is above 5 A. SR should be active by increasing output current to >5 A.

7.4 TURNOFF PROCEDURE: CHARGING MODE

1. Decrease the load to 1 kW. The step of load change should be less than 2 KW for each step.
2. Use GUI to send OFF command.
3. Turn OFF the DC source.
4. Open MCB1 after the DC source has fully discharged its output.
5. Turn OFF load and MCB2 after the battery 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 both the terminal voltages with a multimeter to ensure that the board has fully discharged and is therefore safe to handle.**
7. Turn OFF the 14 Vdc power supply on J4.

8. PHOTOS OF THE REFERENCE DESIGN

Figure 15 shows the locations of the terminals, key components and daughterboards on the main board.

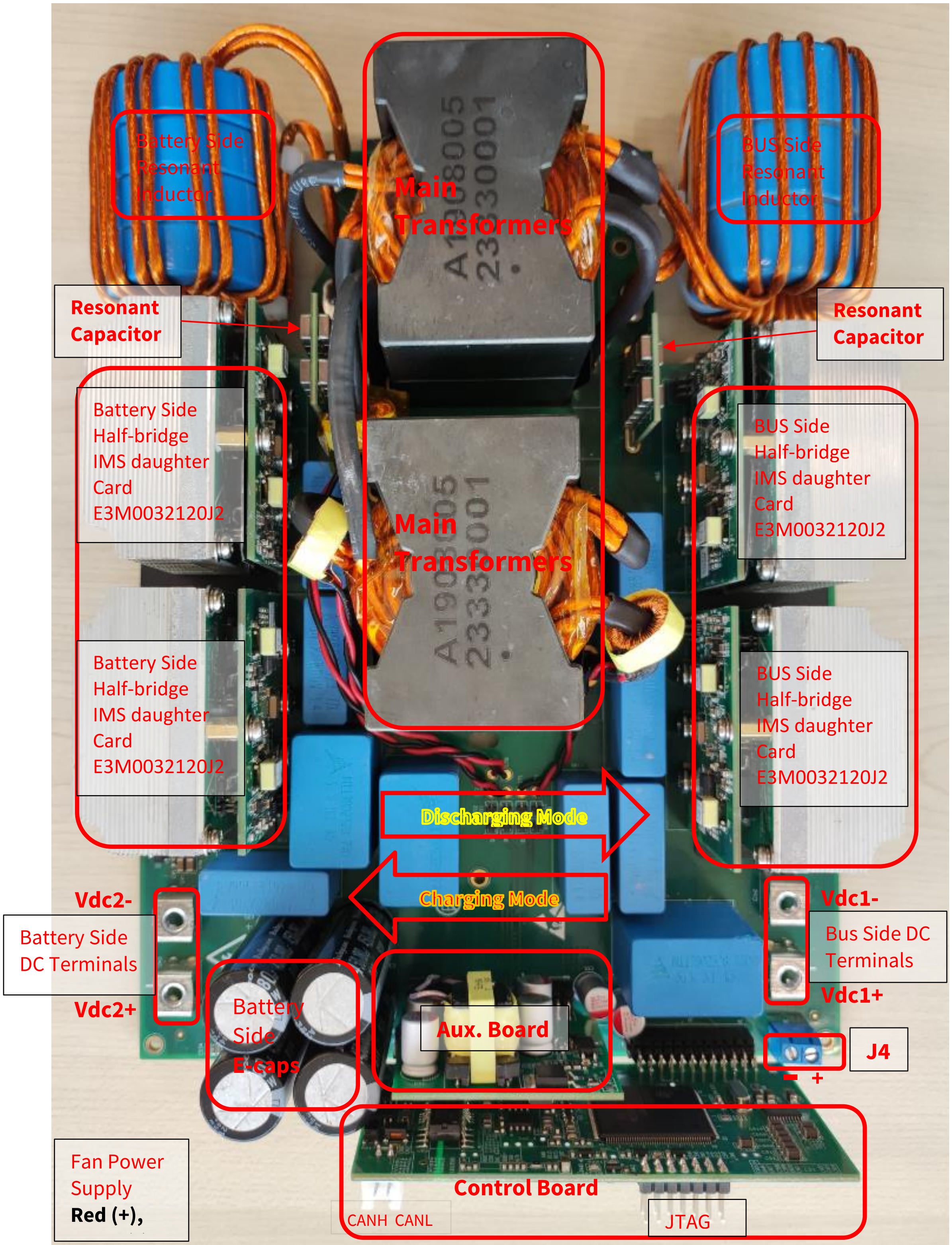


*Figure 15. Top view of PCBAs (236 mm*180 mm*55 mm).*

9. PERFORMANCE DATA

The performance data of Wolfspeed's CRD-22DD12N-J2 reference design board is taken in both DC/DC Charging Mode and Discharging Mode. Table 11 to Table 14 show the performance data. All tests are done at room temperature unless otherwise specified.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
650	2284.66	10	240	2222.37	97.274
650	4554.00	20	240	4411.45	96.870
650	6875.87	30	240	6594.74	95.911
650	2338.11	10	340	2176.96	93.108
650	4798.35	20	340	4473.39	93.228
650	7036.68	30	340	6650.97	94.519
650	9111.80	40	340	8762.11	96.162
650	11567.39	50	340	11073.69	95.732
650	12668.71	60	340	12072.69	95.295
650	2356.71	10	400	2255.61	95.710
650	4668.62	20	400	4468.98	95.724
650	6899.81	30	400	6683.55	96.866
650	9075.40	40	400	8834.55	97.346
650	11465.96	50	400	11128.76	97.059
650	13783.50	60	400	13314.74	96.599
650	2314.85	10	490	2251.72	97.273
650	4515.47	20	490	4454.40	98.648
650	6739.24	30	490	6647.77	98.643
650	8977.75	40	490	8845.45	98.526
650	11224.22	50	490	11038.45	98.345
650	13506.45	60	490	13255.71	98.144
650	15742.84	70	490	15412.88	97.904
650	18005.76	80	490	17581.19	97.642

Table 11: Efficiency data (DC/DC charging mode), V_{IN} = 650 VDC.

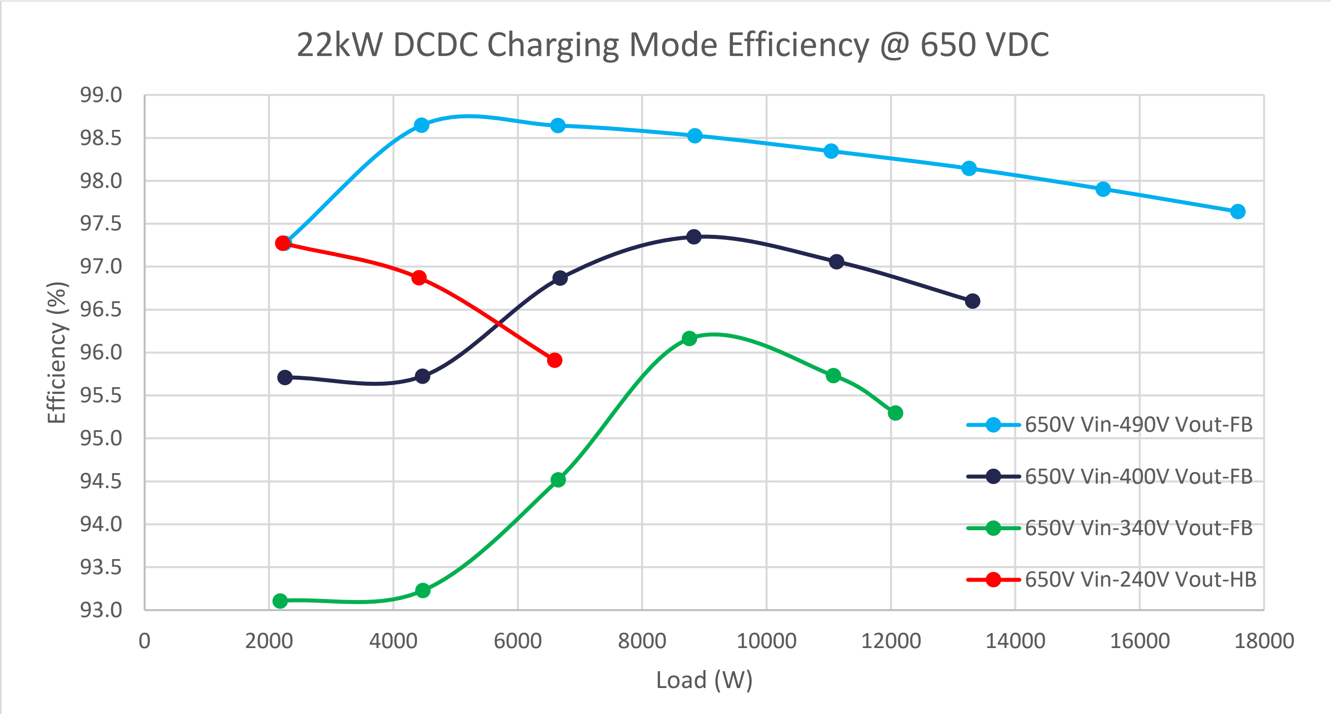


Figure 16: Efficiency data (DC/DC Charging Mode), V_{IN} = 650 VDC.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
900	2285.66	10	340	2231.20	97.618
900	4539.92	20	340	4436.46	97.721
900	6807.82	30	340	6640.67	97.545
900	9127.98	40	340	8858.23	97.045
900	11401.14	50	340	10977.50	96.284
900	12365.61	60	340	11846.75	95.804
900	2341.48	10	685	2267.69	96.848
900	4542.83	20	685	4467.97	98.352
900	6762.19	30	685	6663.59	98.542
900	8995.64	40	685	8871.92	98.625
900	11232.96	50	685	11079.21	98.631
900	13456.16	60	685	13268.34	98.604
900	15690.59	70	685	15464.92	98.562
900	17909.34	80	685	17636.39	98.476
900	20188.35	90	685	19860.74	98.377
900	22367.78	100	685	21982.58	98.278

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
900	2401.68	10	800	2284.21	95.109
900	4609.43	20	800	4484.85	97.297
900	6816.44	30	800	6683.10	98.044
900	9037.69	40	800	8880.80	98.264
900	11263.61	50	800	11075.07	98.326
900	13505.42	60	800	13279.72	98.329
900	15742.21	70	800	15480.80	98.339
900	18051.64	80	800	17762.83	98.400
900	20253.41	90	800	19921.74	98.362
900	22629.66	100	800	22215.32	98.169

Table 12: Efficiency data (DC/DC Charging Mode), V_{IN} = 900 VDC.

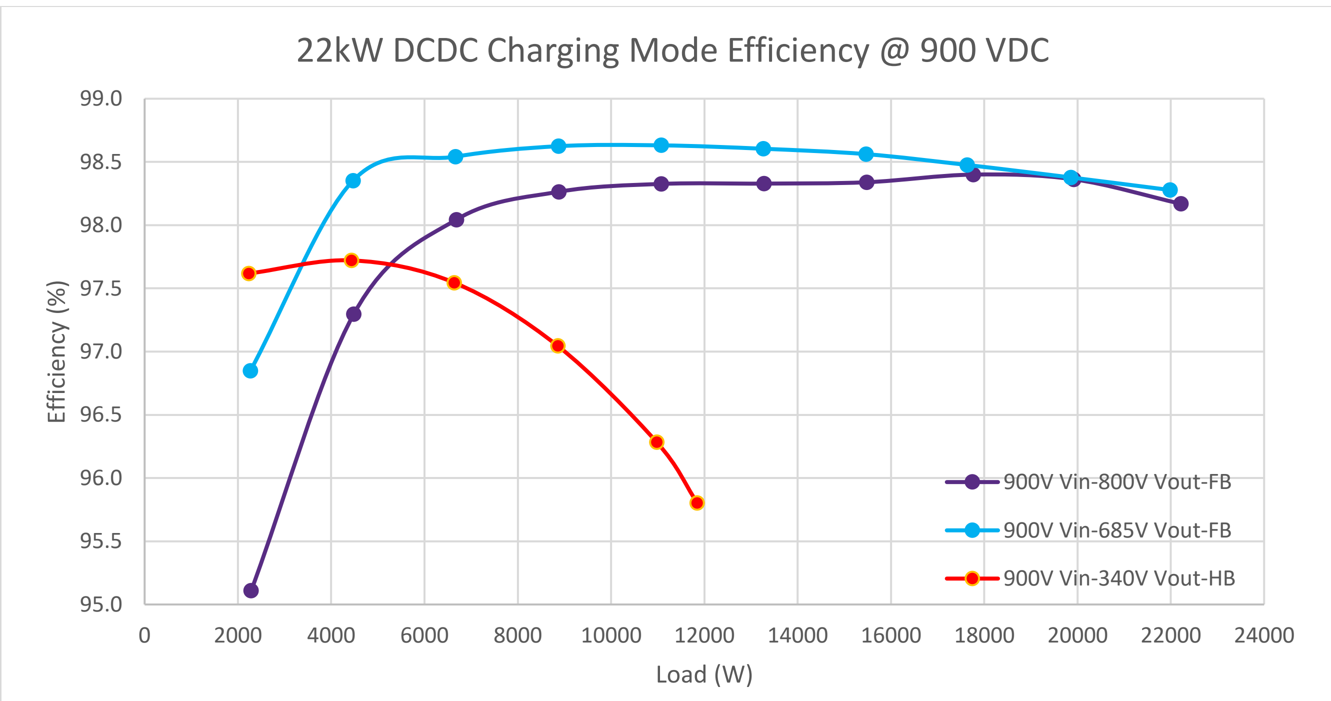


Figure 17: Efficiency data (DC/DC Charging Mode), V_{IN} = 900 VDC.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
300	717.94	10%	369	693.23	96.558
300	1390.71	20%	369	1347.99	96.929
300	2036.85	30%	369	2003.70	98.372

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
300	2715.22	40%	369	2669.43	98.313
300	3386.09	50%	369	3324.43	98.179
300	4045.83	60%	369	3964.26	97.984
300	4732.74	70%	369	4625.80	97.740
300	5417.89	80%	369	5289.26	97.626
300	6123.99	90%	369	5966.22	97.424
300	6766.87	100%	369	6574.27	97.154
500	852.56	10%	622	818.76	96.034
500	1427.00	20%	622	1382.16	96.858
500	2097.94	30%	622	2041.54	97.312
500	2774.56	40%	622	2708.26	97.611
500	3410.78	50%	622	3361.53	98.556
500	4075.95	60%	622	4019.85	98.624
500	4743.42	70%	622	4679.39	98.650
500	5407.48	80%	622	5332.20	98.608
500	6085.93	90%	622	5999.80	98.585
500	6754.35	100%	622	6656.00	98.544
600	878.81	10%	745	844.57	96.103
600	1440.13	20%	745	1390.26	96.537
600	2109.50	30%	745	2050.53	97.205
600	2782.39	40%	745	2712.46	97.487
600	3442.82	50%	745	3364.04	97.712
600	4105.33	60%	745	4041.71	98.450
600	4747.38	70%	745	4682.63	98.636
600	5418.01	80%	745	5346.08	98.672
600	6079.87	90%	745	6001.05	98.704
600	6758.32	100%	745	6669.63	98.688

Table 13: Efficiency data (DC/DC Discharging Mode), V_{IN} = 300 V/500 V/600 VDC full bridge.

Input Voltage (VDC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
600	723.76	10%	369	691.45	95.536
600	1398.96	20%	369	1349.82	96.487
600	2049.67	30%	369	2009.96	98.062
600	2724.92	40%	369	2671.88	98.053
600	3396.76	50%	369	3326.60	97.935
600	4070.01	60%	369	3980.72	97.806
600	4767.14	70%	369	4654.69	97.641
600	5456.72	80%	369	5317.15	97.442
600	6141.55	90%	369	5973.24	97.260
600	6836.42	100%	369	6634.43	97.045
800	747.72	10%	495	707.37	94.604
800	1420.30	20%	495	1364.58	96.077
800	2092.47	30%	495	2024.64	96.759
800	2737.00	40%	495	2683.67	98.051
800	3410.65	50%	495	3348.49	98.177
800	4086.96	60%	495	4012.57	98.180
800	4756.57	70%	495	4669.05	98.160
800	5423.90	80%	495	5319.59	98.077
800	6108.87	90%	495	5983.63	97.950
800	6784.49	100%	495	6644.01	97.929

Table 14: Efficiency data (DC/DC Discharging Mode), V_{IN} = 600 V/800 VDC half bridge.

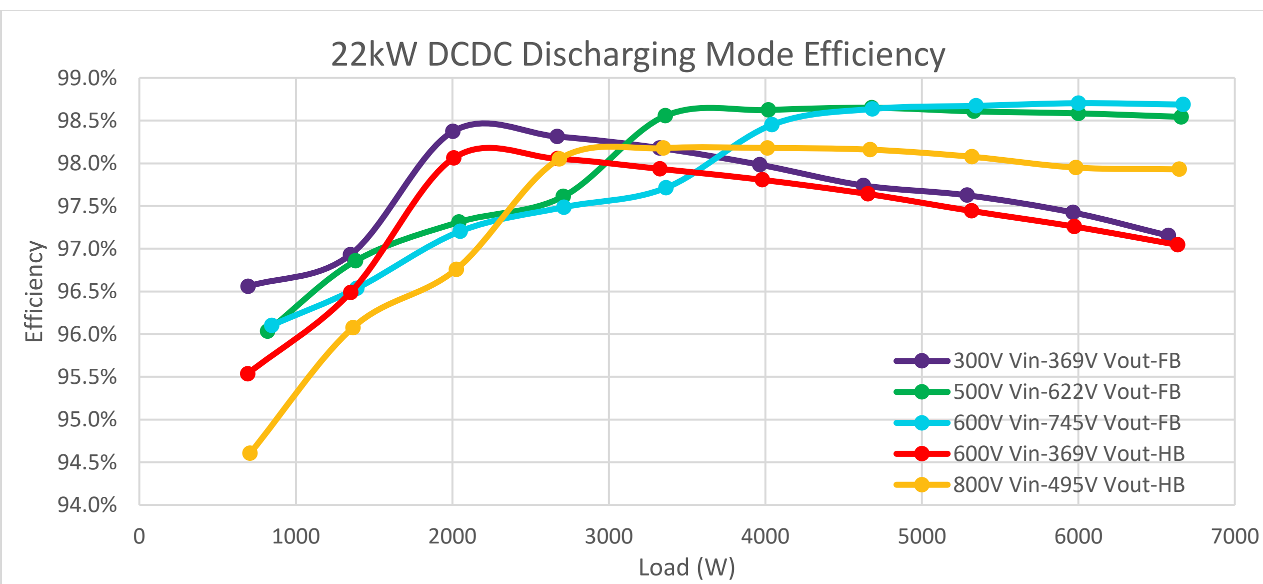
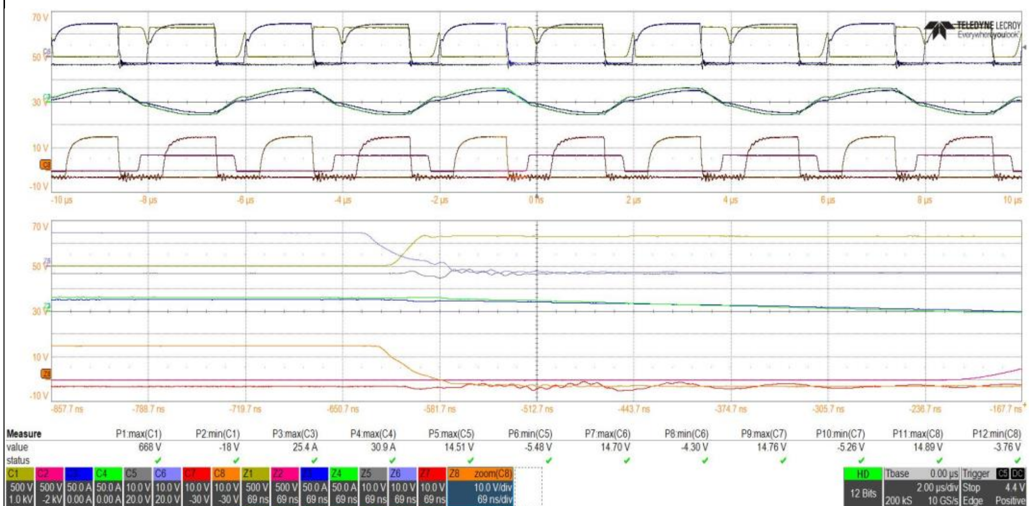
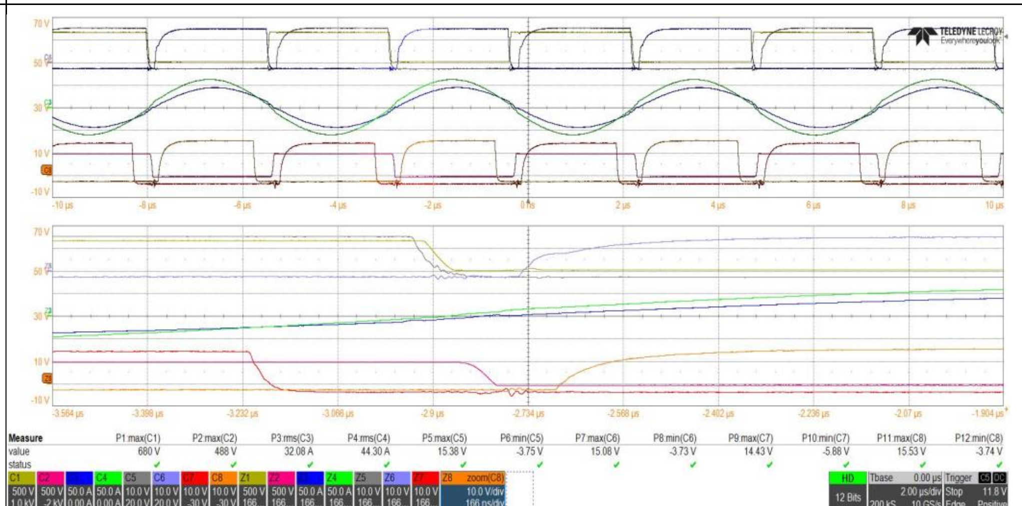


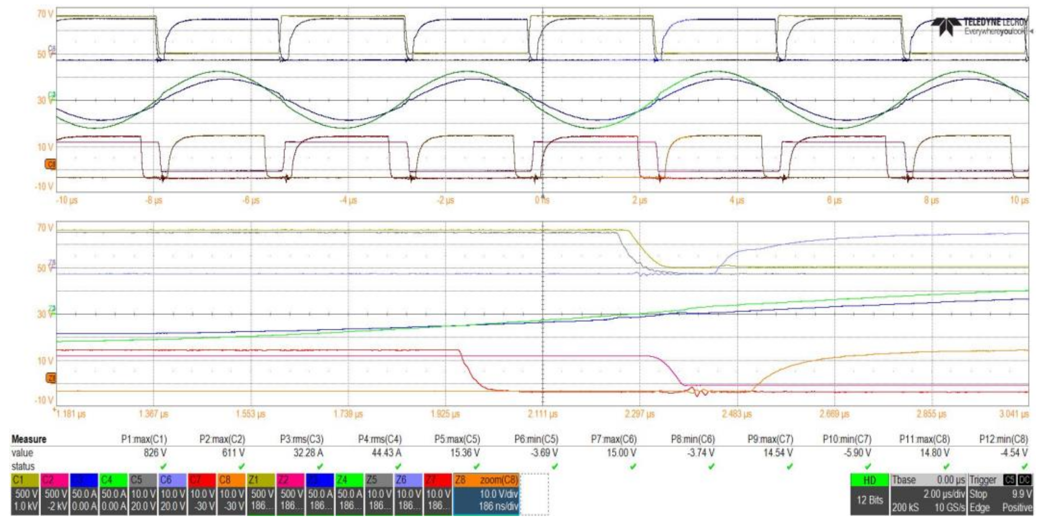
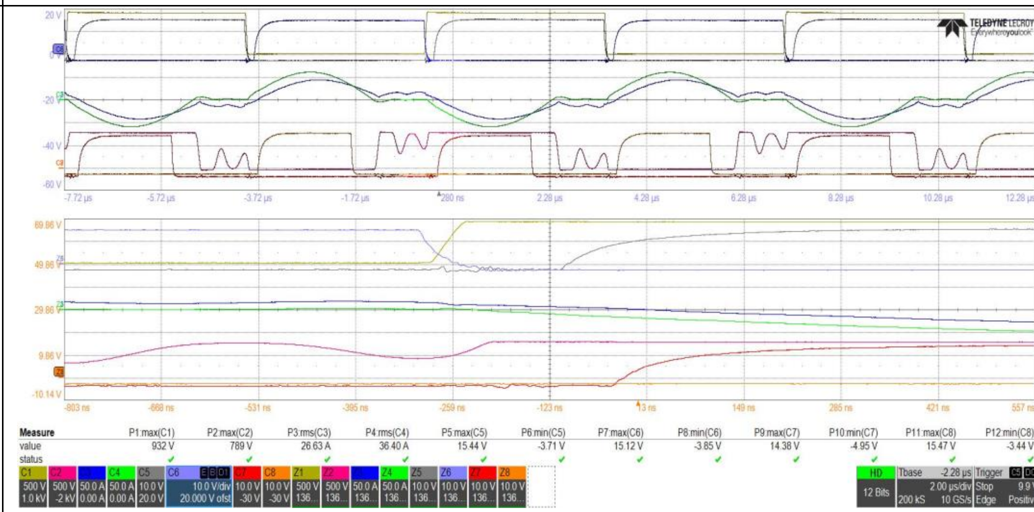
Figure 18: Efficiency data (DC/DC Discharging Mode).

10. TYPICAL WAVEFORMS

Operational waveforms are presented in Table 15 and Table 16.

10.1 DC/DC CHARGING MODE

Condition	Waveform
DC/DC Charging Mode (Full Bridge) **Bus Side Input: 650 VDC** **Battery Side Output: 340 VDC** **Half Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge
DC/DC Charging Mode (Full Bridge) **Bus Side Input: 650 VDC** **Battery Side Output: 490 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

Condition	Waveform
DC/DC Charging Mode (Full Bridge) **Bus Side Input: 800 VDC** **Battery Side Output: 610 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge
DC/DC Charging Mode (Full Bridge) **Bus Side Input: 900 VDC** **Battery Side Output: 800 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

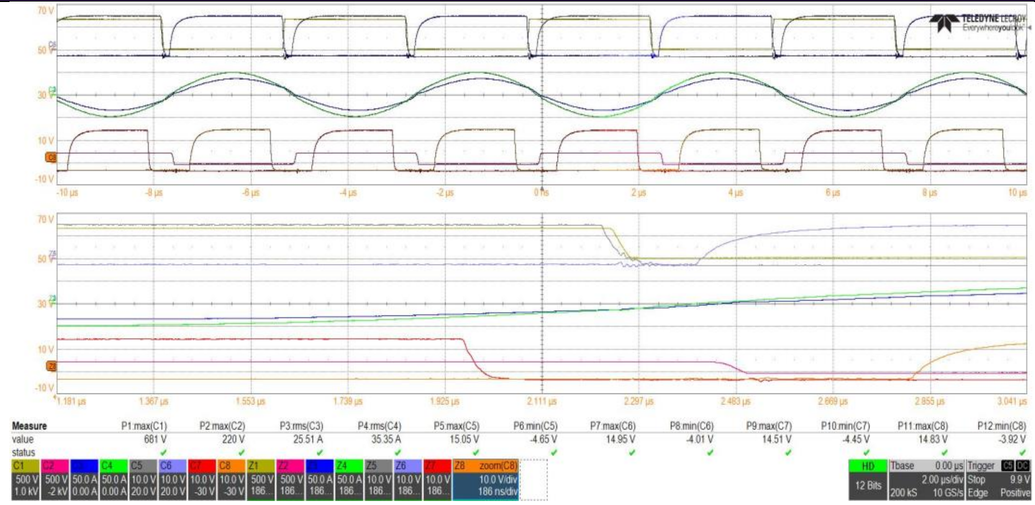
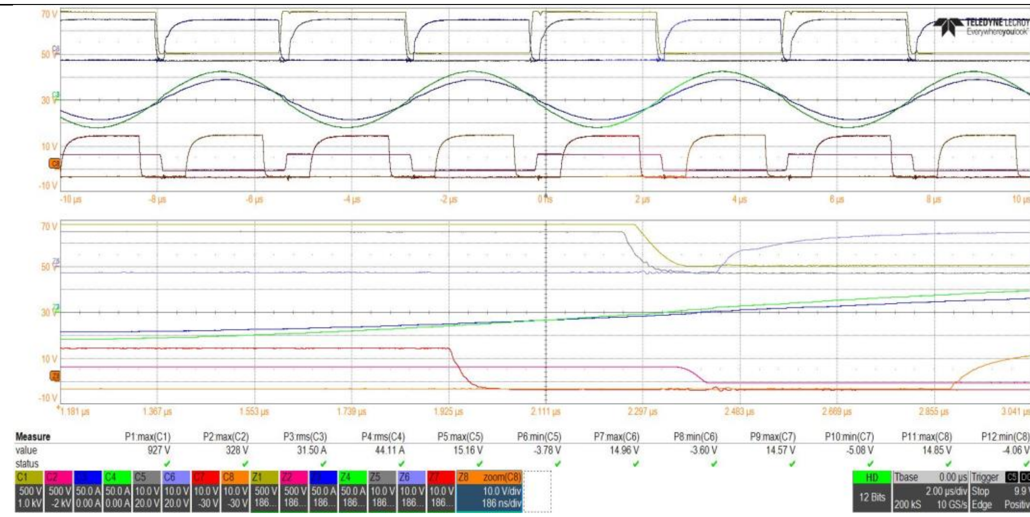
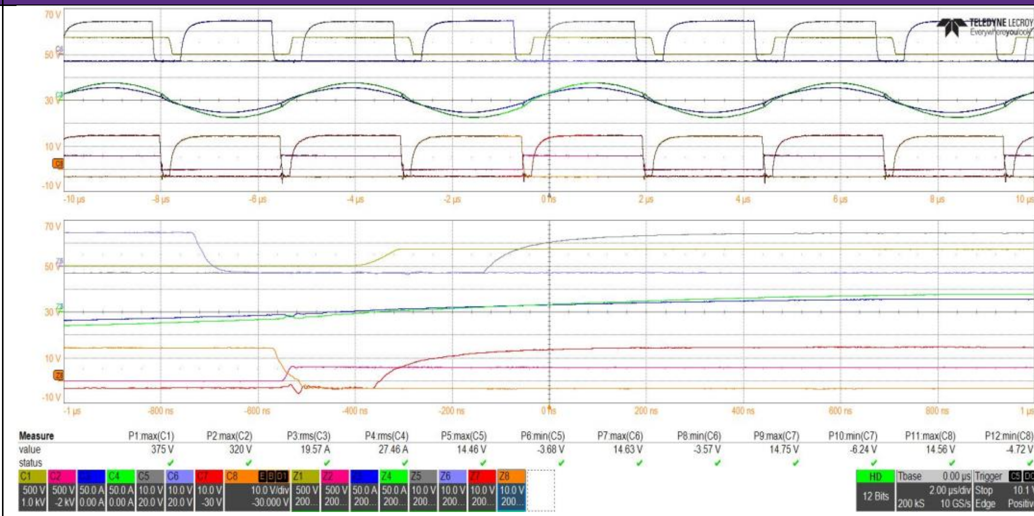
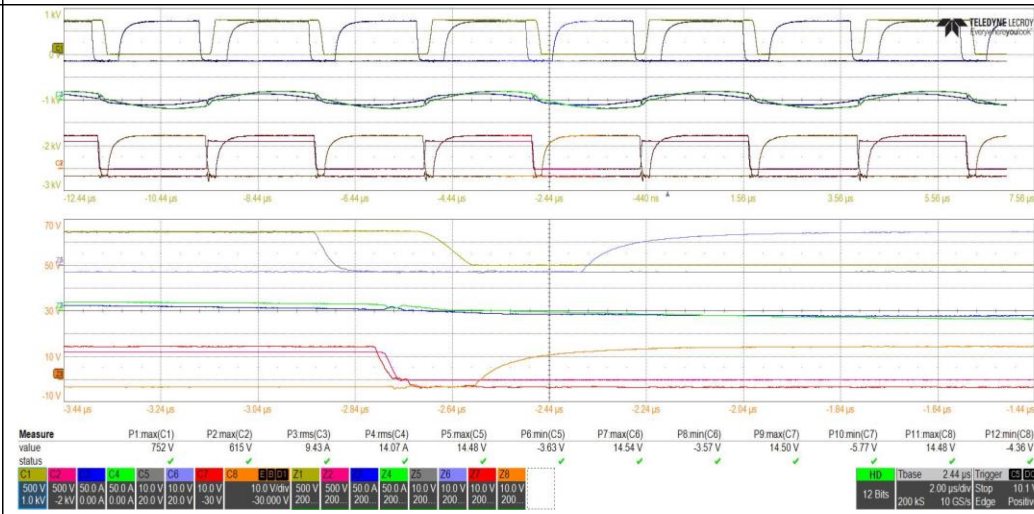
Condition	Waveform
DC/DC Charging Mode (Half Bridge) **Bus Side Input: 650 VDC** **Battery Side Output: 240 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge
DC/DC Charging Mode (Half Bridge) **Bus Side Input: 900 VDC** **Battery Side Output: 340 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

Table 15: DC/DC Charging Mode waveforms.

10.2 DC/DC DISCHARGING MODE

Condition	Waveform
DC/DC Discharging Mode (Full Bridge) **Battery Side Input: 300 VDC** **Bus Side Output: 369 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge
DC/DC Discharging Mode (Full Bridge) **Battery Side Input: 600 VDC** **Bus Side Output: 750 V VDC dc** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

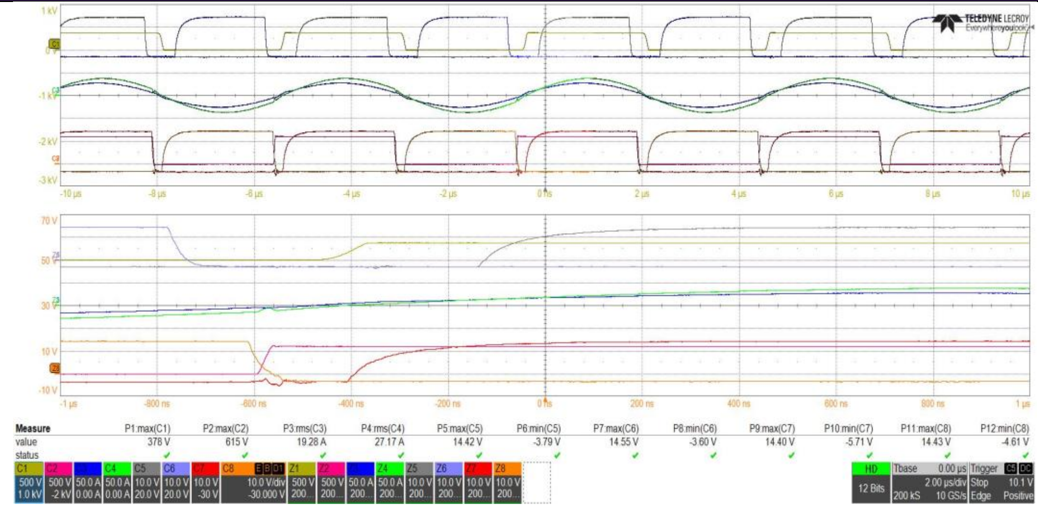
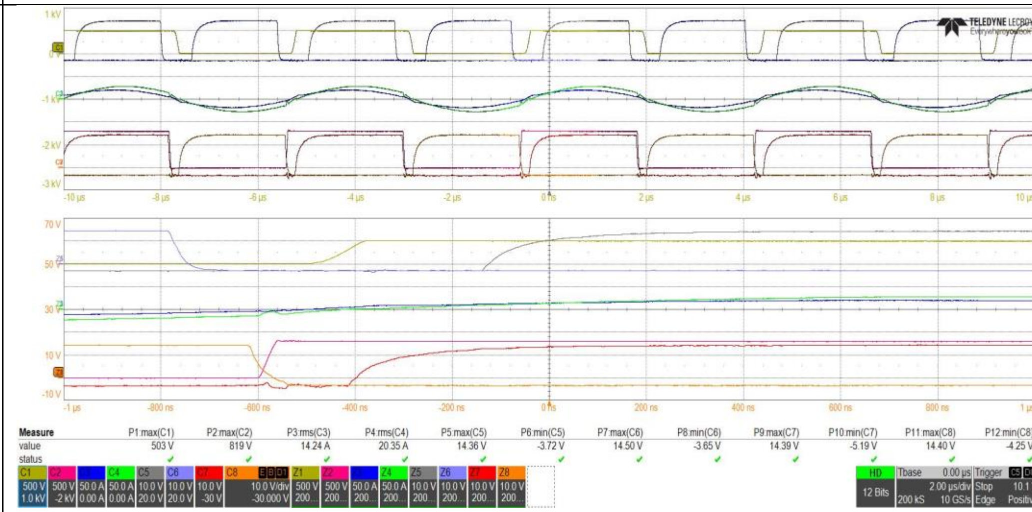
Condition	Waveform
DC/DC Discharging Mode (Half Bridge) **Battery Side Input: 600 VDC** **Bus Side Output: 369 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge
DC/DC Discharging Mode (Half Bridge) **Battery Side Input: 800 VDC** **Bus Side Output: 495 VDC** **Full Load**	 CH1: Low Side V_{DS} of BUS Side Bridge CH2: Low Side V_{DS} of Battery Side Bridge CH3: Resonant Current of BUS Side CH4: Resonant Current of Battery Side CH5: High Side V_{GS} of BUS Side Bridge CH6: Low Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

Table 16: DC/DC Discharging Mode waveforms.

11. THERMAL DESIGN AND TEST RESULTS

In a thermal test of the unit, forced air cooling is used, and the temperature of heatsink is kept as 65˚C to simulate the liquid cooling system in an automotive application. There is no air flow to the SiC MOSFETs because a mylar sheet is used to block the airflow through the surface of the MOSFETs.

The thermal test was performed at 650 VDC input and 340 VDC output with 36A current in charging mode, which is the worst operating condition for a thermal test. K-type thermal couplers and a 34970A data acquisition unit from Keysight Technologies Inc. are used during the thermal test.

The test results are shown in Table 17 and Table 18. The highest junction temperature among all MOSFETs in this design is around 104°C. This value was calculated based on the measured case temperature, the thermal resistance, and the calculated power loss. Because the maximum junction temperature of E3M0032120J2 is 175°C, there is a large margin of T_J.

Description	Scenario 1. Input: 650 V Output:480 V/36 A Charging Mode	Scenario 2. Input: 900 V Output:800 V/20 A Charging Mode	Rated Temperature	Derating Requirement	Comments
Base Plate	25	25	NA	NA	NA
Resonant Choke of BUS Side	70.4	40.8	155 °C	130 °C	PASS
Resonant Choke of Battery Side	83.3	44.2	155 °C	130 °C	PASS
Core of Main Transformer	83.9	104.3	155 °C	130 °C	PASS

Table 17: Thermal test results of magnetic components.

Temperature of semiconductors is shown in the table below.

Description	R_{TH_J-C} (°C/W)	Calculated Power Loss (W)	Measured Case Temperature (°C)	Calculated Junction Temperature (°C)	Max. Operating Junction Temperature (°C)	Derating Requirement (°C)	Comments
Charging Mode; Input: 650VDC; Output: 340VDC * 36A; Temperature of heatsink is 65˚C							
High Side MOSFET of BUS Side	0.44	33.6	88.6	103.4	175	140	PASS
Low Side MOSFET of BUS Side	0.44	33.6	89	104.0	175	140	PASS

Description	R_{TH_J-C} (°C/W)	Calculated Power Loss (W)	Measured Case Temperature (°C)	Calculated Junction Temperature (°C)	Max. Operating Junction Temperature (°C)	Derating Requirement (°C)	Comments
High Side MOSFET of BAT Side	0.44	32.9	87.6	102.1	175	140	PASS
Low Side MOSFET of BAT Side	0.44	32.9	89.7	104.2	175	140	PASS

Table 18: Thermal test results of SiC power MOSFETS.

12. APPENDIX

12.1 PWM TIMING

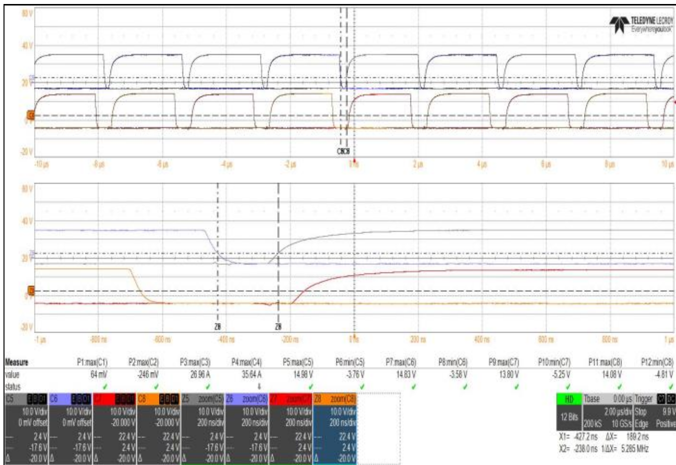
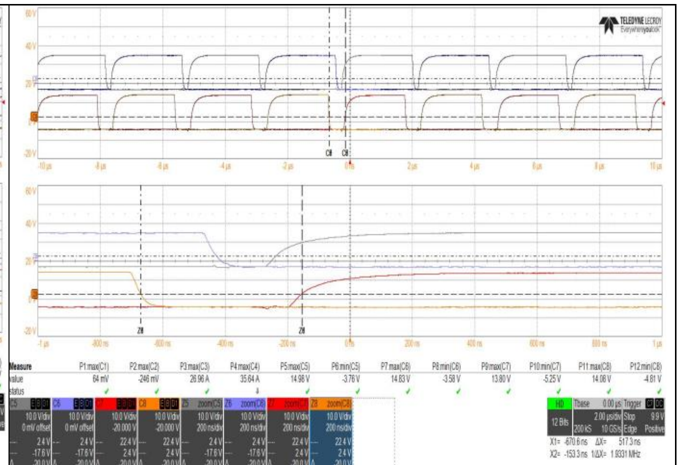
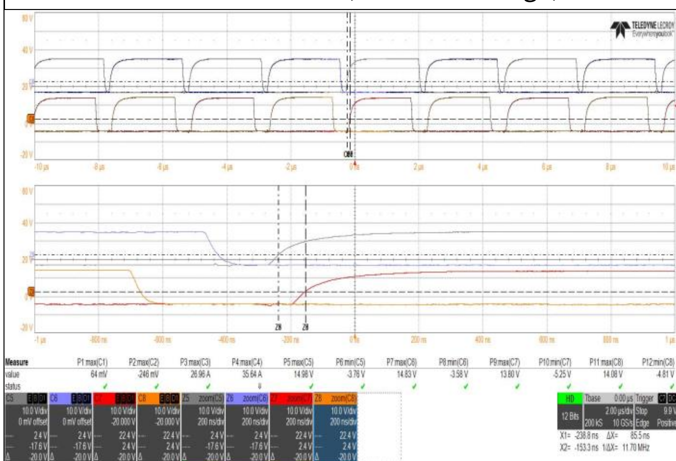
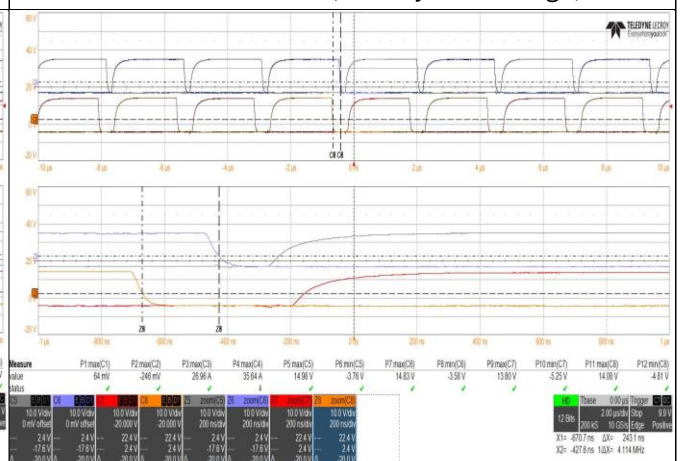
 Dead time = 189 ns (BUS Side Bridge)	 SR off time = 517 ns (Battery Side Bridge)
 Time Delay from Primary to Secondary = 86 ns	 Time Ahead from Secondary to Primary = 243 ns
CH5: High Side V_{GS} of BUS Side Bridge CH7: High Side V_{GS} of Battery Side Bridge	CH6: Low Side V_{GS} of BUS Side Bridge CH8: Low Side V_{GS} of Battery Side Bridge

Table 19: Gate signals and timings in Charging Mode.

12.2 CAN MESSAGES FROM OBC

Message Identifier: 0x1AB2F4E5				
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	DC Voltage at Battery Side	Tank Current at Battery Side	DC Voltage at Bus Side	Tank Current at Bus Side
Unit	0.1 V	0.1 A	0.1 V	0.1 A
Bias	0			
Data Format	Integer			
Time Interval	3 seconds			

Table 20: Overall charge status.

Message Identifier: 0x18B0F4E5				
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Ambient Temperature	Reserved		Reserved
Unit	0.1°C			NA
Bias	50°C			NA
Data Format	Integer			
Time Interval	30 seconds			

Table 21: Temperature and charge mode.

Message Identifier: 0x1AB3F4E5				
Data	Byte0+Byte 1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	OBC status. See Table 23 for details.	Work Mode 0xFF: Invalid, default 0x0: Charge, Half bridge 0x1: Charge, Full bridge 0x2: Discharge, Half bridge 0x3: Discharge, Full bridge	Reserved 0x00FF	Reserved 0x00FF
Unit	NA			
Bias	0			
Data Format	Integer			
Time Interval	3 seconds max.			

Table 22: Charge status, AC and CLLC information.

OBC Status	Comments	OBC Status	Comments
Bit15	1: Discharging mode 0: Charging mode (default)	Bit7	1: DC OVP at Battery Side 0: Normal (default)
Bit14	1: Output shorted 0: Normal (default)	Bit6	1: Abnormal Bus Side Voltage 0: Normal (default)
Bit13	1: CLLC Tank1/Tank2 OCP 0: Normal(default)	Bit5~1	Reserved
Bit12	1: SR OFF 0: SR ON (default)		
Bit11	Reserved		
Bit10	1: OFF 0: ON (default)		
Bit8	Reserved	Bit0	1: CAN error 0: Normal (default)

Table 23: Bit definition for OBC status.

Message Identifier: 0x1AB8F4E5				
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Com. Software Version	Min. Bus Voltage	Max. Bus Voltage	Max. Charge Current
Unit	0.01	0.1 V	0.1 V	0.1 A
Bias	0			
Data Format	Integer			
Time Interval	Reply to 0x18A8E5F4			

Table 24: Part I of OBC specification.

Message Identifier: 0x1AB9F4E5				
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	OBC Software Version	Min. Battery Voltage	Max. Battery Voltage	Max. Voltage with max. Current
Unit	0.01	0.1 V		
Bias	0			
Data Format	Integer			
Time Interval	Reply to 0x18A8E5F4			

Table 25: Part II of OBC specification.

12.3 CAN MESSAGES TO OBC

Message Identifier: 0x18A5E5F4					
Data	Byte0	Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	0x0: Charge, Half bridge 0x1: Charge, Full bridge 0x2: Discharge, Half bridge 0x3: Discharge, Full bridge	0: On 1: OFF	Reserved 0xFFFF	DC Voltage	DC Current
Unit	NA			0.1 V	0.1 A
Bias	0				
Data Format	Integer				

Table 26: Control command.

13. REVISION HISTORY

Date	Revision	Changes
January 2024	1	Initial Release

14. REFERENCE

None

15. IMPORTANT NOTES

15.1 PURPOSES AND USE

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

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

15.2 OPERATION OF BOARD

It is important to operate the board within Wolfspeed’s recommended specifications and environmental considerations as described in the Documentation. Exceeding specified ratings (such as input and output voltage, current, power, or environmental ranges) may cause property damage. If you have questions about these ratings, please contact Wolfspeed at forum.wolfspeed.com 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 at forum.wolfspeed.com 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.

15.3 USER RESPONSIBILITY FOR SAFE HANDLING AND COMPLIANCE WITH LAWS

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

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

In addition, users are responsible for:

- Compliance with all international, national, state, and local laws, rules, and regulations that apply to the handling or use of the board by a user or the user's employees, affiliates, contractors, representatives, agents, or designees.

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

15.4 NO WARRANTY

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

15.5 LIMITATION OF LIABILITY

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

15.6 INDEMNIFICATION

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