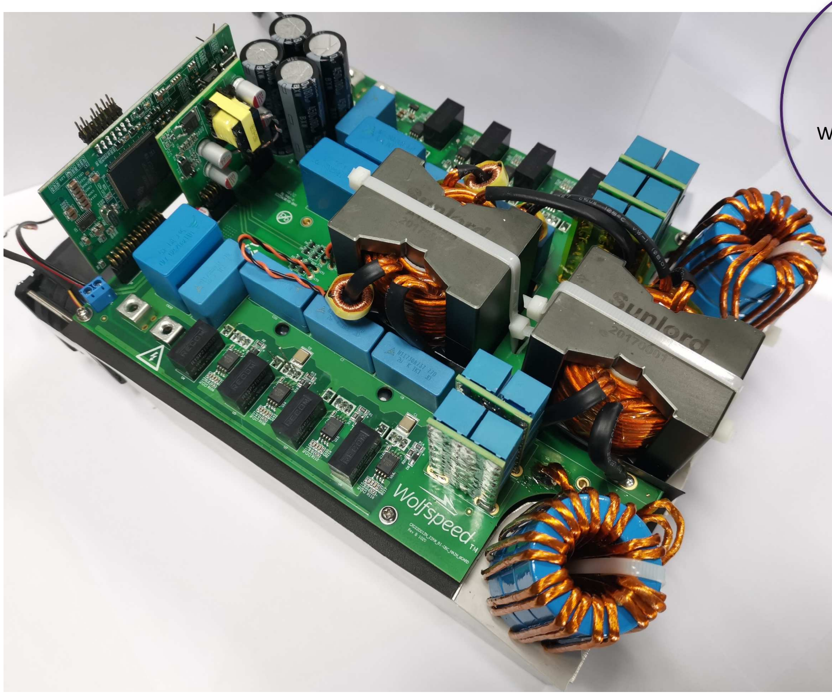
**USER GUIDE** **PRD-01218**

# CRD-22DD12N 22kW Bi-Directional

# High Efficiency DC/DC Converter

# 22 kW 双向高效直流—直流变换器

# 22 kW 双方向高効率 DC/DC 変換器




# CRD-22DD12N 22kW Bi-Directional High Efficiency DC/DC Converter User Guide

This User Guide provides the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-22DD12N, 22 kW Bi-Directional DC/DC converter for an electric vehicle (EV) on-board charger (OBC) and similar applications. The design achieves high power density (8 kW/L) and high efficiency (> 98.5%) and supports a wide battery voltage range from 200 VDC – 800 VDC.

## CONTENTS

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

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

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

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

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

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

**CAUTION**
**PLEASE CAREFULLY REVIEW THE FOLLOWING PAGES, AS THEY 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˚ 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。

# 1. Introduction

The design of Wolfspeed's 22 kW, Bi-Directional DC/DC converter is based upon one of Wolfspeed's latest generation of SiC MOSFETs - C3M0032120K or E3M0032120K (1200 V, 32 mΩ, TO-247-4). The converter is the DC/DC stage of a bi-directional OBC converter. Referring to 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 full bridge CLLC resonant topology is selected for the converter to achieve both high efficiency and wide voltage regulation. A block diagram in Figure 1 shows both the bus side and the battery side of the converter use a full bridge switch arrangement isolated by two high frequency transformers. The converter operates in a 135-250 kHz switching frequency range. A tooled heatsink was designed to simulate the cooling plate in an OBC application. It dissipates the heat generated by all the power MOSFETs. The power density is up to 8 kW/L.

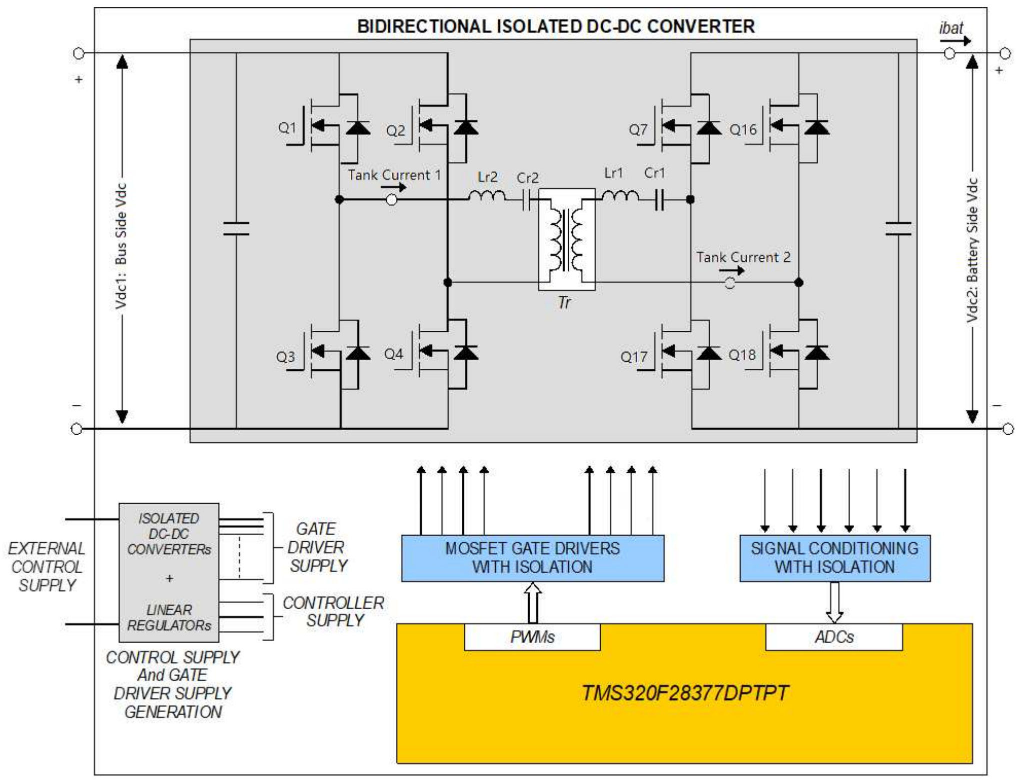



*Figure 1: Block Diagram of Wolfspeed's CRD-22DD12N, 22 kW Bi-directional high efficiency DC/DC.*

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 component, 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 a proposed control method. The peak efficiency of the DC/DC CLLC resonant can be above 98.5% in both charging and discharging modes.

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. Therefore, there is neither a battery charging nor discharging algorithm built in. It must not be connected with any battery directly. An electronic load or a resistive load should be used in both charging and discharging modes.

## 2. Description

This reference design board uses Wolfspeed's C3M0032120K or E3M0032120K, 1200 V, 32 mΩ, SiC MOSFETs (TO-247-4) in both primary-side and battery-side full bridges. A single SiC MOSFET is used for each position.

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 wide output range in both directions. When the required voltage gain is lower, it is out of the high efficiency range of the hybrid control (variable frequency and phase shift) in both charging and discharging mode at full bridge configuration, the primary-side full bridge will be reconfigured as a half bridge. 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 as shown in Table 1. The evaluation board is designed to support the DC bus voltage of a Power Factor Correction (PFC) 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 Figure 2 and Figure 3. This is to simulate the real conditions in the application. Equation (1) is for a full bridge and Equation (2) is for a half bridge configuration.

$$V_{DC2} = (V_{DC1} - 30) \times \frac{19}{24} \tag{1}$$

$$V_{DC2} = (V_{DC1} - 44) \times \frac{19}{24} \times \frac{1}{2} \tag{2}$$

The start-up 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.

*Table 1: Overall charging operation*

| 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 | | |

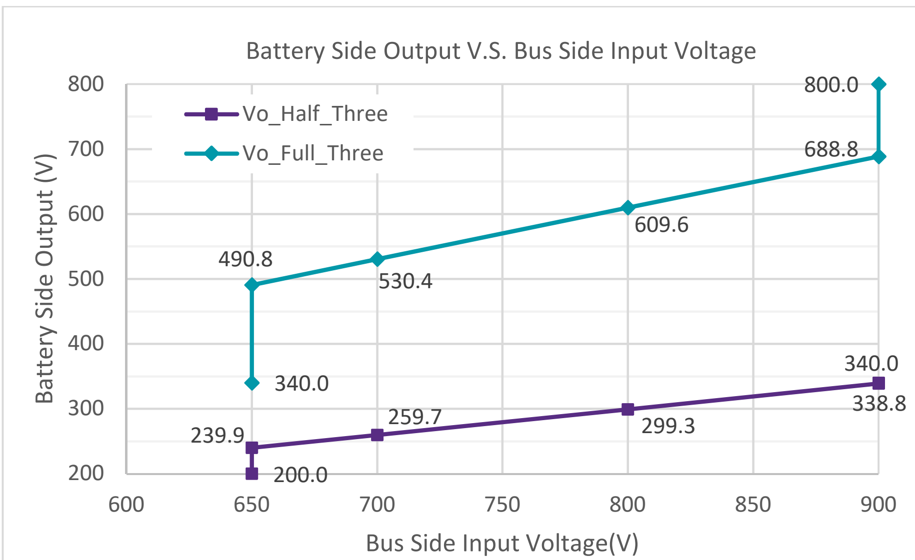



*Figure 2: Battery voltage vs. bus voltage in charging mode for three-phase application*

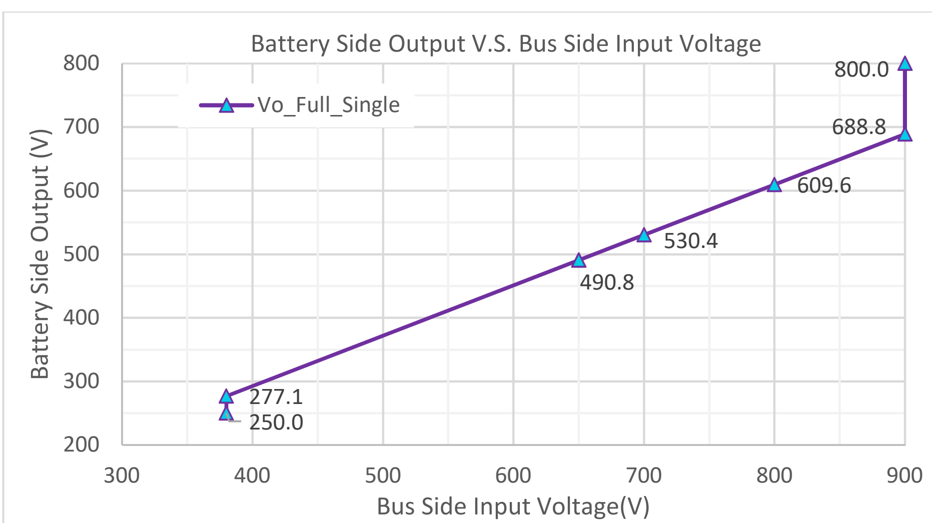



*Figure 3: Battery voltage vs. bus voltage in charging mode for single-phase application*

For discharging mode, the overall discharging operations are shown in Table 2. The output bus voltage is regulated, as shown in Figure 4, to enable high efficiency for both CLLC stage and DC/AC stages. Equation (3) is for full bridge and Equation (4) for half bridge. The start-up voltage is also calculated using the same equations.

$$V_{DC1} = V_{DC2}\frac{24}{19} - 10 \tag{3}$$

$$V_{DC1} = V_{DC2}\frac{24}{19} \times \frac{1}{2} - 10 \tag{4}$$

*Table 2: Overall discharging operation*

<table>
<tr><th>Bus side Volt.<br><input></th><th>Battery side Volt.<br><output></th><th>Max. output Power/<br>Max. output Current</th><th>Topology</th></tr>
<tr><td>300 V-600 V</td><td>360 V-750 V</td><td rowspan="2">6.6 kW</td><td>Full Bridge</td></tr>
<tr><td>600 V-800 V</td><td>360 V-500 V</td><td>Half Bridge</td></tr>
</table>

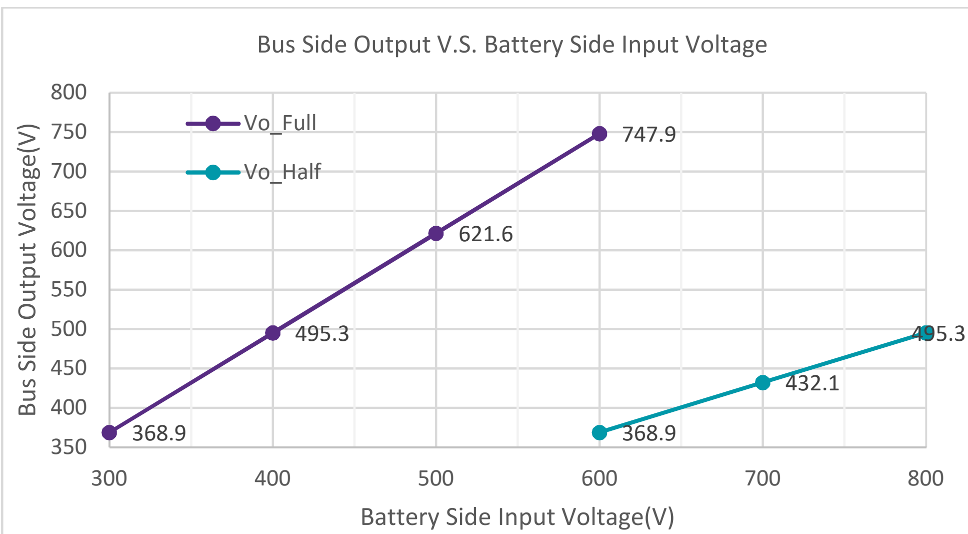



*Figure 4: Bus voltage vs. battery voltage in discharging mode*

**A user should follow the operations as shown in Figure 2, Figure 3 and Figure 4 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 to the unit via a controller area network (CAN) communication bus. It is used to display operational information and provide related user controls, such as 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 2 and Figure 3 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

*Table 3: Characteristics of Wolfspeed's CRD-22DD12N, 22 kW bi-directional DC/DC in charging modes*

| 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*2** | | | | | | |
| $\eta_{peak}$ | Peak efficiency | $V_{IN}$ = 800 V, $V_{OUT}$ = 610 V, $I_{OUT}$ = 11 A, Full Bridge | | | $\eta_{peak}$ | Peak efficiency |
| $\eta_{full\ load}$ | Full load efficiency | $V_{IN}$ = 900 V, $V_{OUT}$ = 800 V, $I_{OUT}$ = 20 A, Full Bridge | 97.0 % | 97.2% | | |
| | | $V_{IN}$ = 800 V, $V_{OUT}$ = 610 V, $I_{OUT}$ = 32 A, Full Bridge | 97.6 % | 97.8% | | |
| | | $V_{IN}$ = 650 V, $V_{OUT}$ = 480 V, $I_{OUT}$ = 32 A, Full Bridge | 95.9 % | 96.1% | | |
| | | $V_{IN}$ = 650 V, $V_{OUT}$ = 240 V, $I_{OUT}$ = 30 A, Half Bridge | 95.2 % | 95.4% | | |

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

*2: Maximum load current is about 32 A for the efficiency test due to the limitation of the power analyzer.

*Table 4: Characteristics of Wolfspeed's CRD-22DD12N, 22 kW bi-directional DC/DC in discharging mode*

| 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<br>$V_{IN}$ = 300 VDC~600 VDC Full Bridge | | | 6600 | W |
| $I_{OUT}$ | Output current | | | | 19 | A |
| $V_{ripple}$ | Output voltage ripple | | | | ±2% | |
| **System Characteristics** | | | | | | |
| $\eta_{peak}$ | Peak efficiency | $V_{IN}$ = 480 V, $V_{OUT}$ = 600 V, $P_O$ = 6.6 kW Full Bridge | 98.2% | 98.4% | | |
| $\eta_{full\ load}$ | Full load efficiency (PO = 6.6 KW) | $V_{IN}$ = 300 V, $V_{OUT}$ = 366 V Full Bridge | 97.0% | 97.2% | | |
| | | $V_{IN}$ = 600 V, $V_{OUT}$ = 755 V Full Bridge | 98.2% | 98.4% | | |
| | | $V_{IN}$ = 600 V, $V_{OUT}$ = 365 V Half Bridge | 96.8% | 97.0% | | |
| | | $V_{IN}$ = 800 V, $V_{OUT}$ = 495 V Half Bridge | 97.6% | 97.8% | | |

## 3.1 Applications

The primary application for Wolfspeed's CRD-22DD12N reference design board is isolated Bi-Directional EV charging systems, but the output must be connected to a resistive load or electronic load (CR (Constant Resistor) mode recommended). 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-22DD12N 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.
- 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 derating from 22 kW to 16 kW when the output voltage is between 770 VDC and 800 VDC under 900 V input.

- Maximum output power is 6.6 kW at the input voltage range of 380 VDC – 650 VDC in charging mode. Without AC input info, the controller cannot identify the operation mode, so the 6.6 kW power limit function is not accurate in this input range.
- Maximum output power is 6.6 kW in discharging mode.
- Peak efficiency > 98.5% 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.

Easy to test using a GUI communicating via CAN. See Section 5 and Section 0 for details.

# 4. Hardware Description of Main Board, Control Board and Auxilary 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 the main board, control board, and auxiliary-power board are shown in Figure 5 to Figure 15.

## 4.1 Description of Main Board

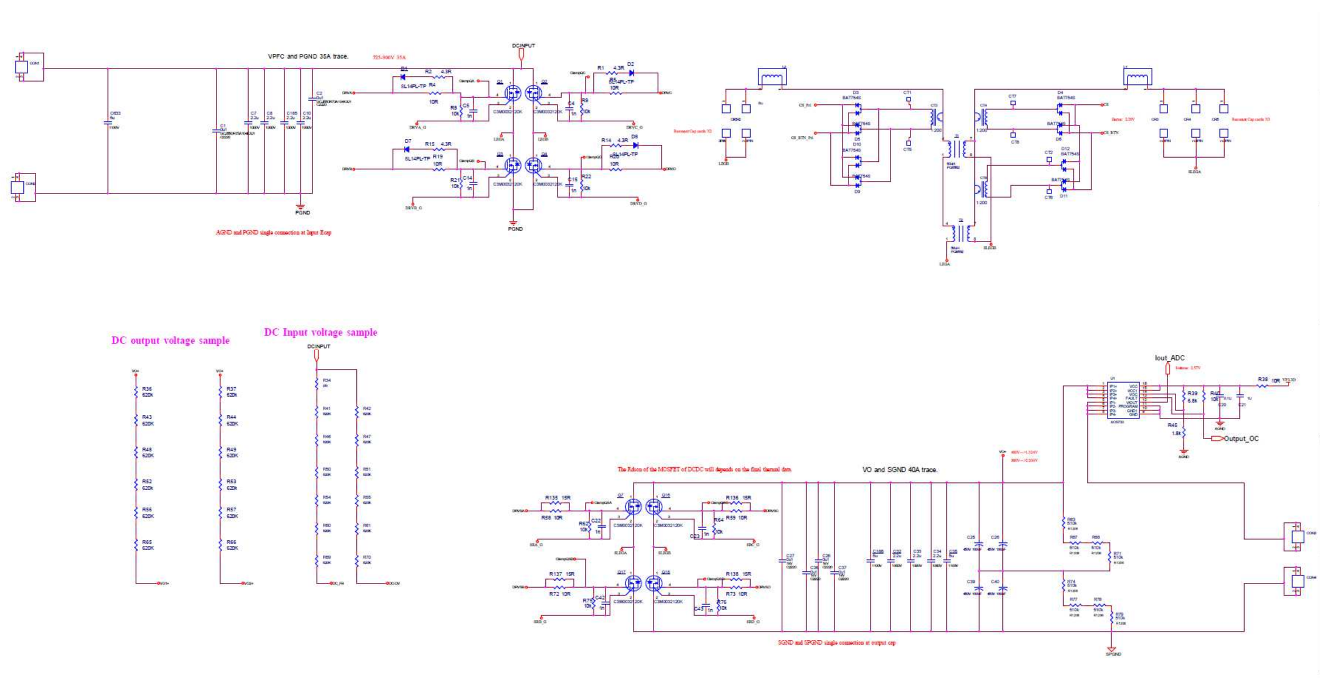



*Figure 5: Schematic of DC/DC main board*

As illustrated by Figure 5, a full bridge CLLC topology is selected for the converter. The bus side DC terminals are CON1(+) and CON2(-) followed by five film capacitors which absorb the high-frequency ripple on the DC port. The battery side DC terminals are CON3(+) and CON4(-). The H-bridge at DC bus side is composed of SiC

MOSFETs Q1, Q3, Q2 and Q4. The battery side H-bridge is composed of SiC MOSFETs Q7, Q17, Q16 and Q18 followed by five film capacitors and four electrolytic capacitors. 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 in series for the bus side and in parallel for the battery side. The final turns ratio is 24:19. One current transformer is used to sense tank current at bus side. Two current transformers, one for each main transformer that are paralleled after bridge diodes, are used to sense battery side tank current.

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

*Table 5: Key parameters of resonant tanks*

| | **Resonant Inductor** | **Resonant Capacitor** |
|---|---|---|
| **Bus Side Tank** | 12.8 µH | $\frac{6.8nF}{2} \times 8 \times 2 = 54.4nF$ |
| **Battery Side Tank** | 9.9 µH | $\frac{6.8nF}{2} \times 7 \times 3 = 71.4nF$ |

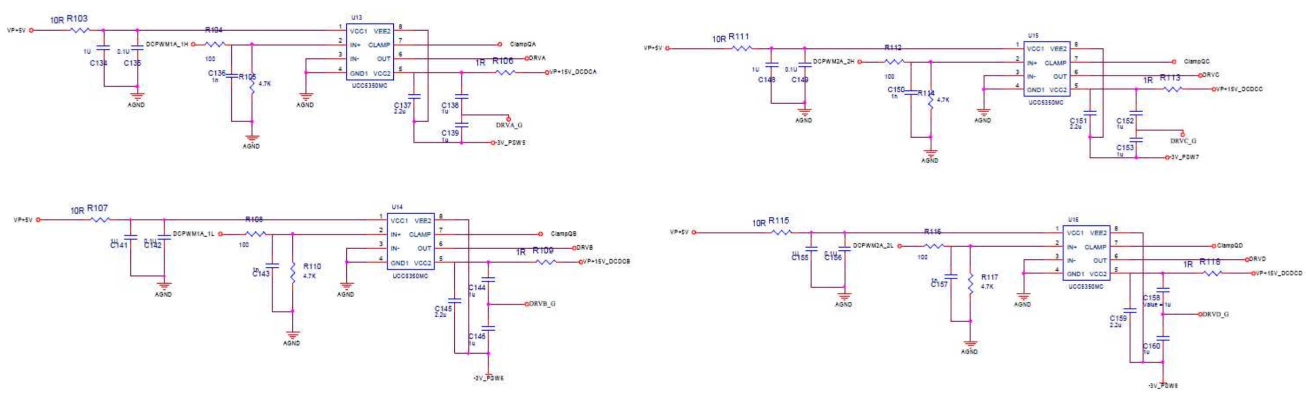


*Figure 6: Schematic of DC/DC main board: bus-side gate drives*

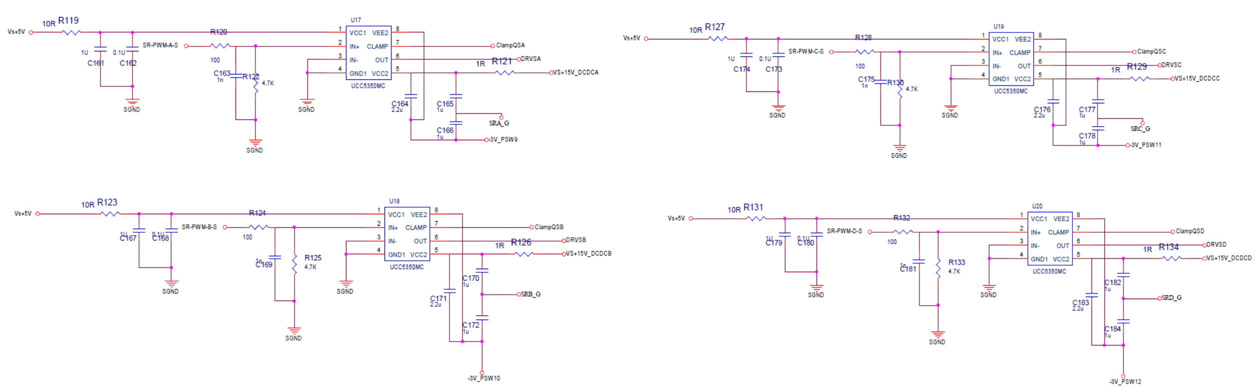


*Figure 7: Schematic of DC/DC main board: battery-side gate drives*

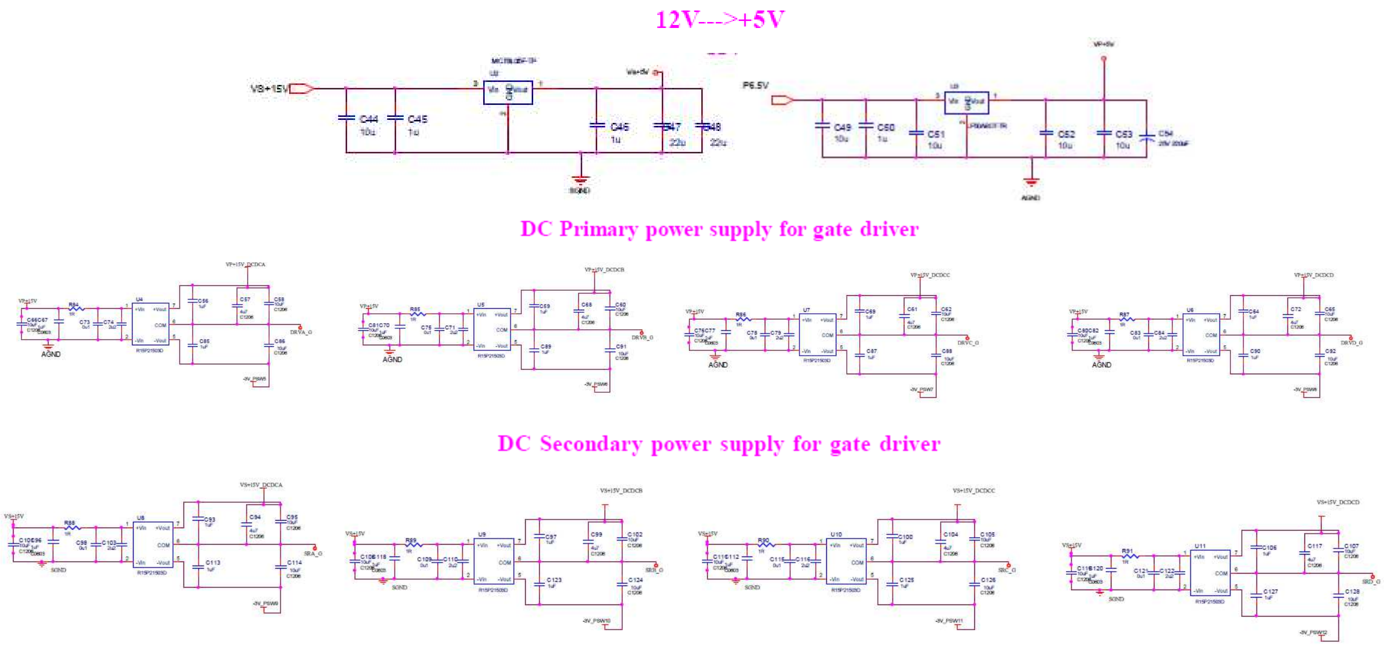



*Figure 8: Schematic of DC/DC main board: power supply*

As illustrated by Figure 6 to Figure 8, all Texas Instruments, Inc. gate drivers (P/N: UCC5350MCQDQ1) are separately powered by isolated, DC/DC power supplies with $V_{IN}$ = +15 V and $V_{OUT}$ = +15 V/-3 V from RECOM Power GmbH (P/N: R15P21503D). Gate drives at battery side are isolated from the control board by digital isolator U12 from Analog Devices, Inc. (P/N: ADUM262N0BRIZ) as illustrated by Figure 9.

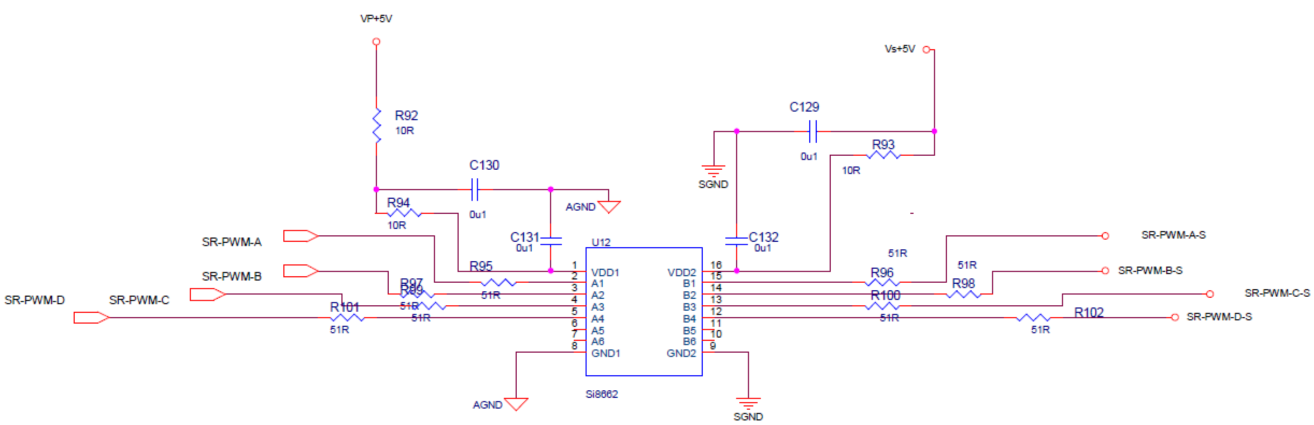



*Figure 9: Schematic of DC/DC main board: signal isolation*

## 4.2 Description of Control Board

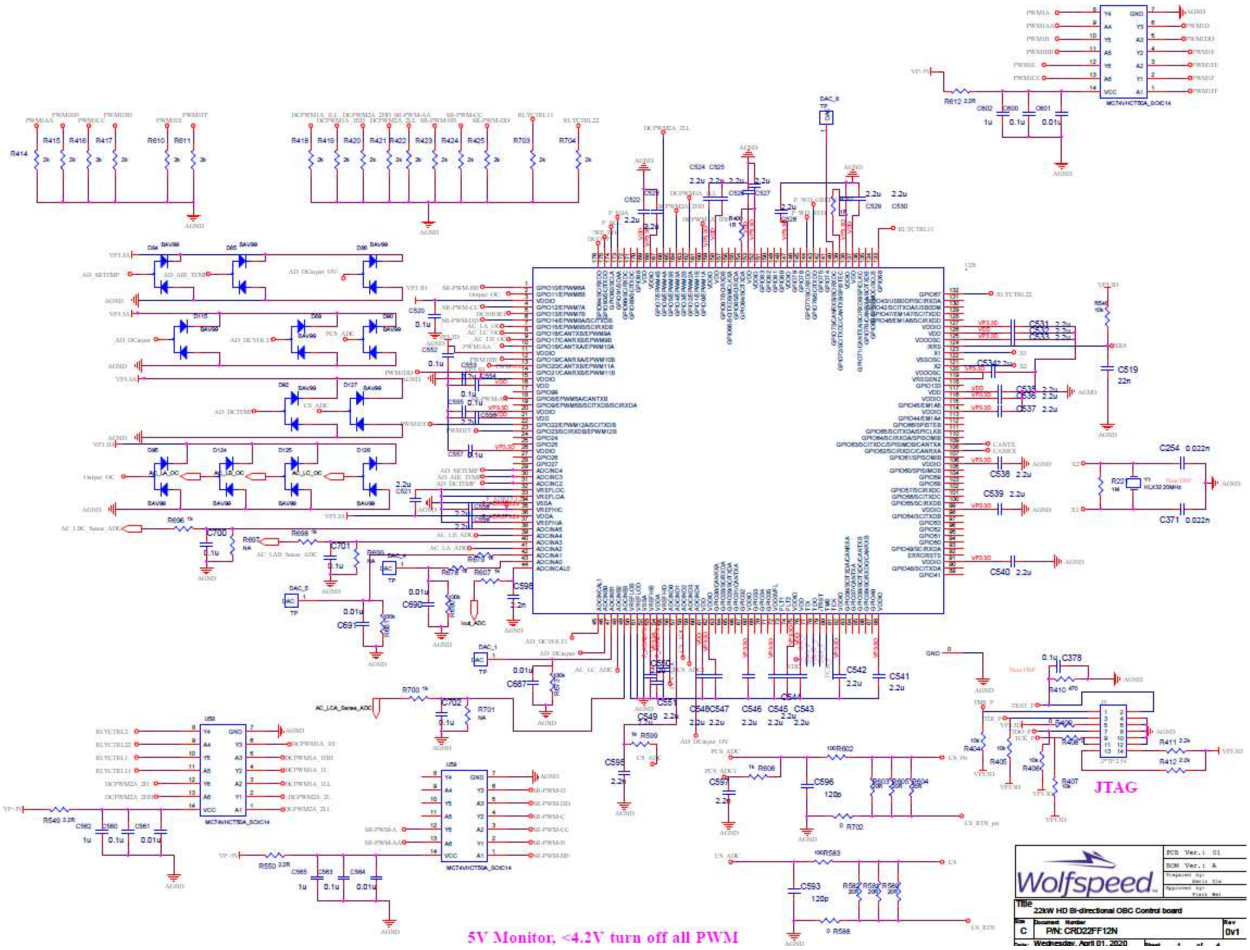



*Figure 10: Schematic of control board: controller*

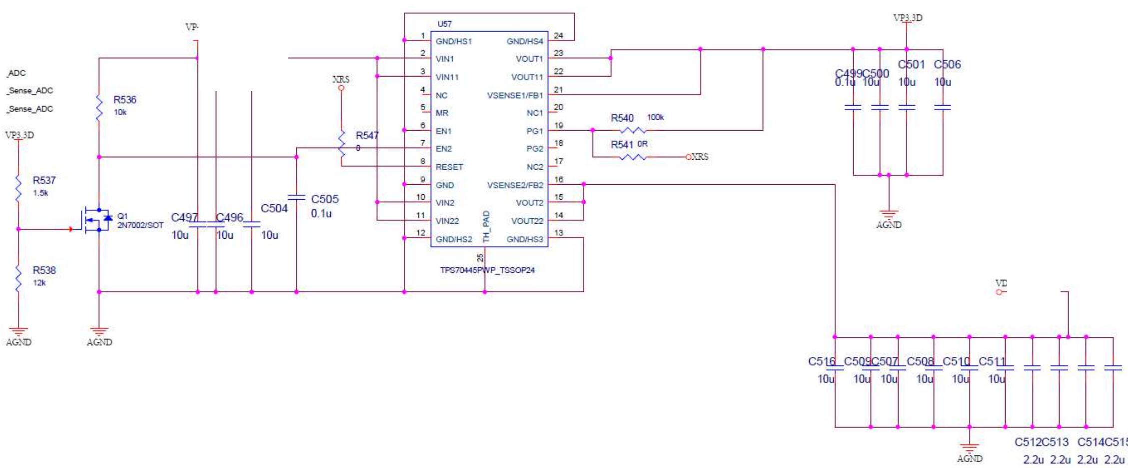



*Figure 11: Schematic of control board: controller power supply*

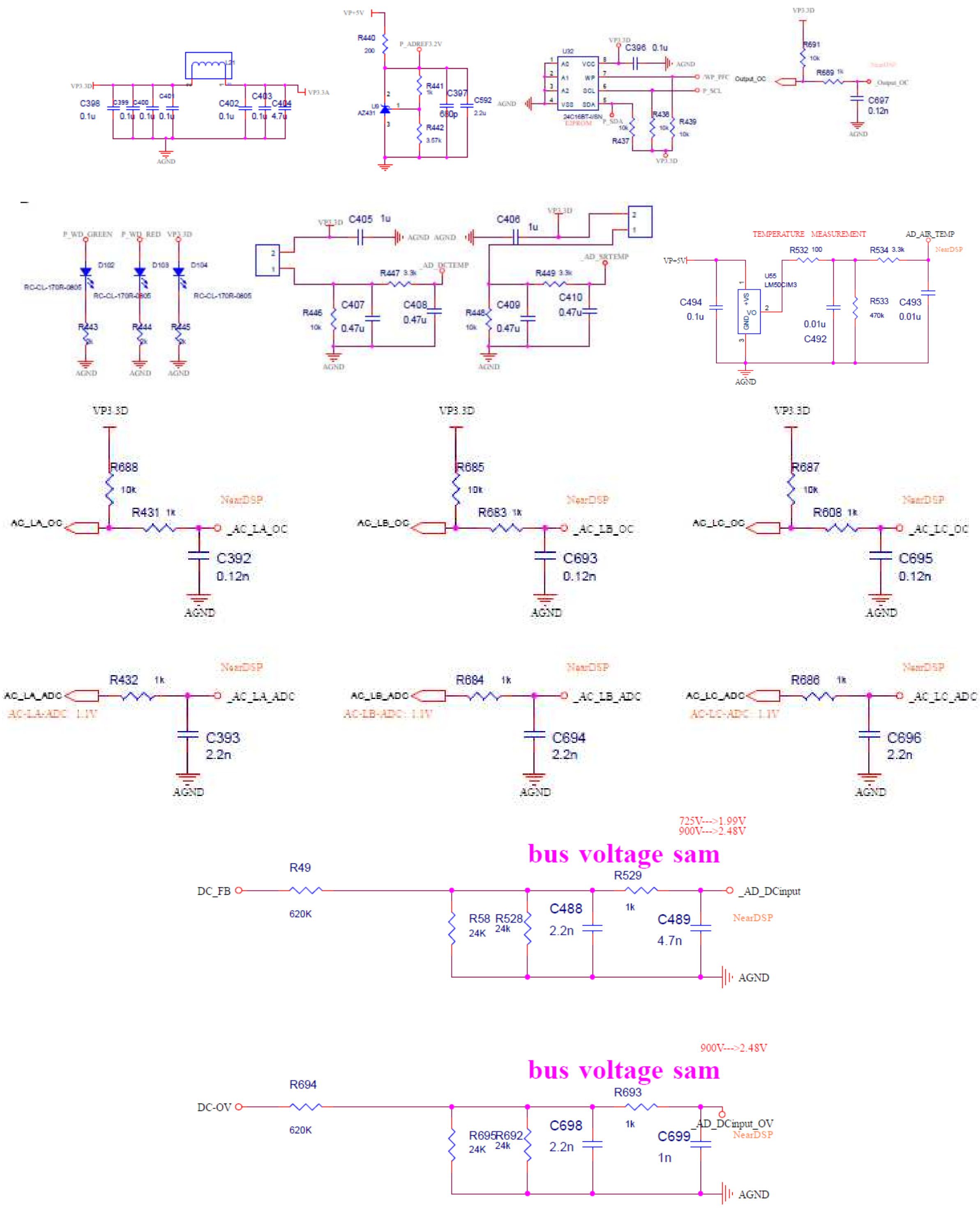



*Figure 12: Schematic of control board: bus voltage sample*

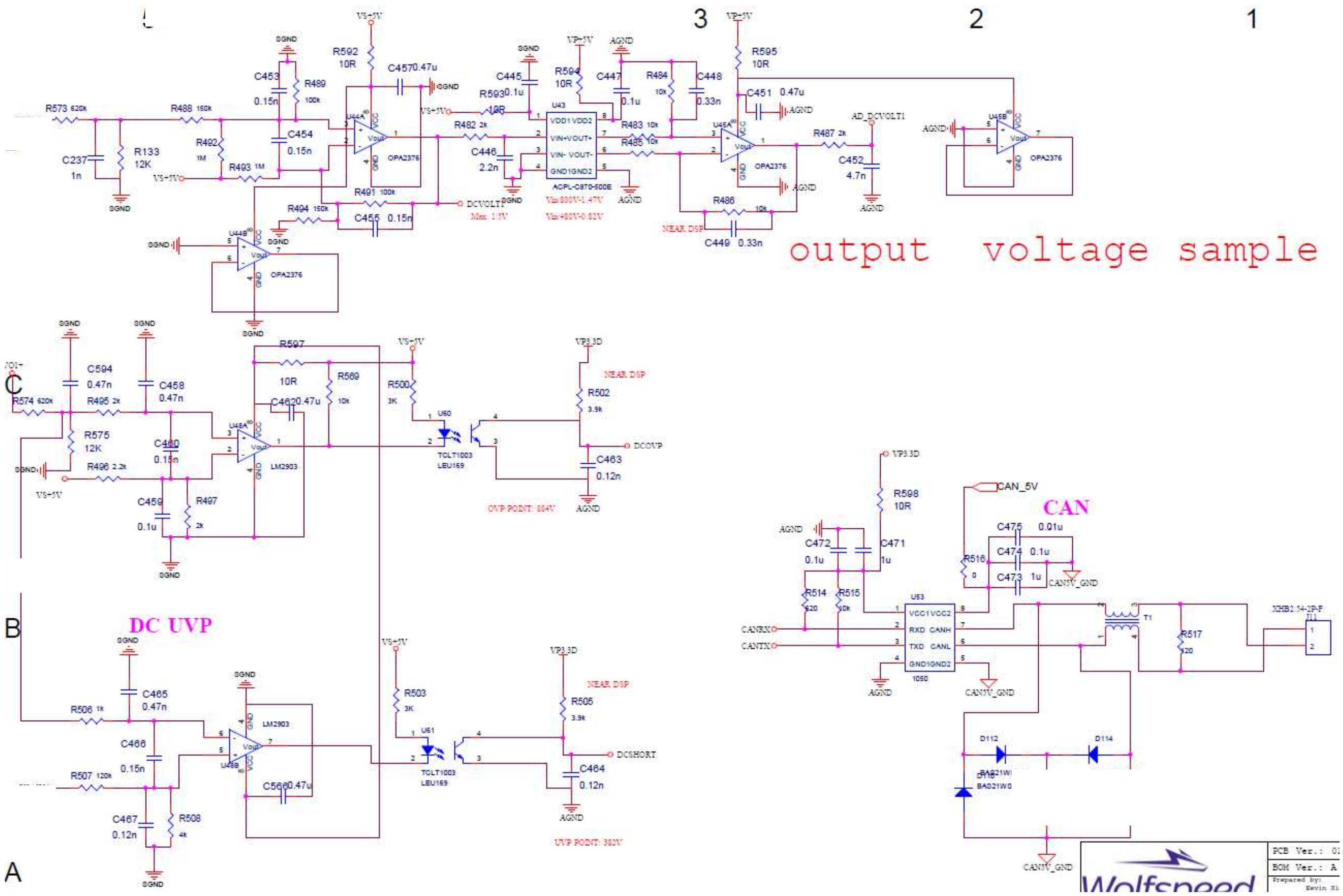



*Figure 13: Schematic of control board: battery voltage sample and CAN interface*

As illustrated by Figure 10 to Figure 13, 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 control board is the negative terminal of 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.

## 4.3 Connections of Control Board and Auxiliary Power Board to Main Board

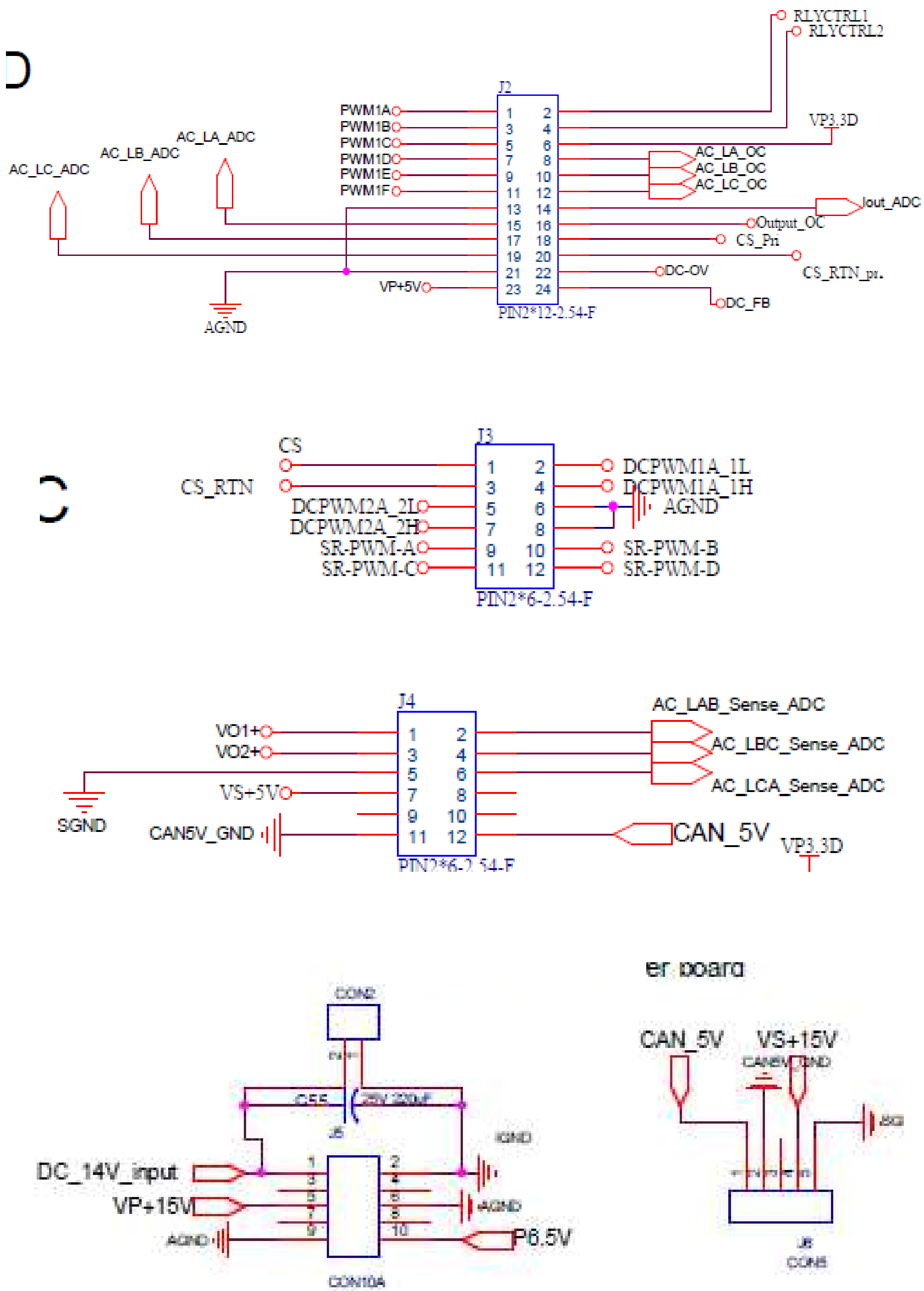



*Figure 14: Schematic of connectors of auxiliary power board and main board*

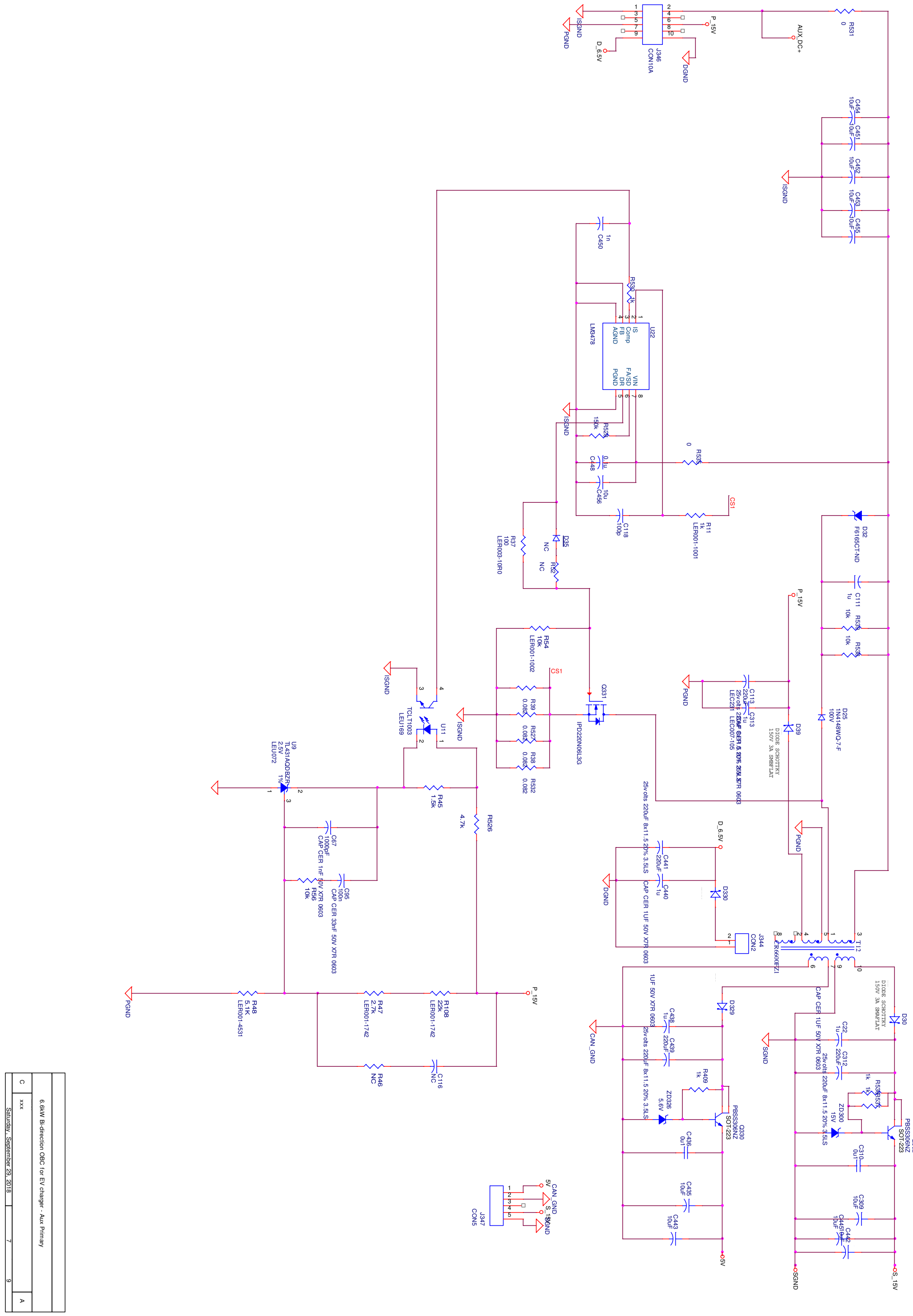



*Figure 15: Schematic of auxiliary power board*

The typical input voltage of the auxiliary power board is 14 V (J6, net ' Aux_DC+' and net 'ISGND' in Figure 15). It provides four isolated output voltages, as shown in Table 6.

*Table 6: Input and outputs of auxiliary power board*

| 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 MOSFET gate drivers |
| **Output 2** | S_15 V | 15 V Power supply for MOSFET gate drivers |
| **Output 3** | 5 V | 5 V output for CAN communication |
| **Output 4** | D_6.5 V | Controller power supply |

# 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 16, at least two 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 baseplate. Another two fans are used for the magnetics. They can be placed to let the air flow go to the two resonant inductors and the transformers. The red wire of the fan is the positive terminal and the black wire is the negative terminal. The temperature of the magnetics should be monitored by an infrared scanner to verify the cooling fan setup during first-time testing.

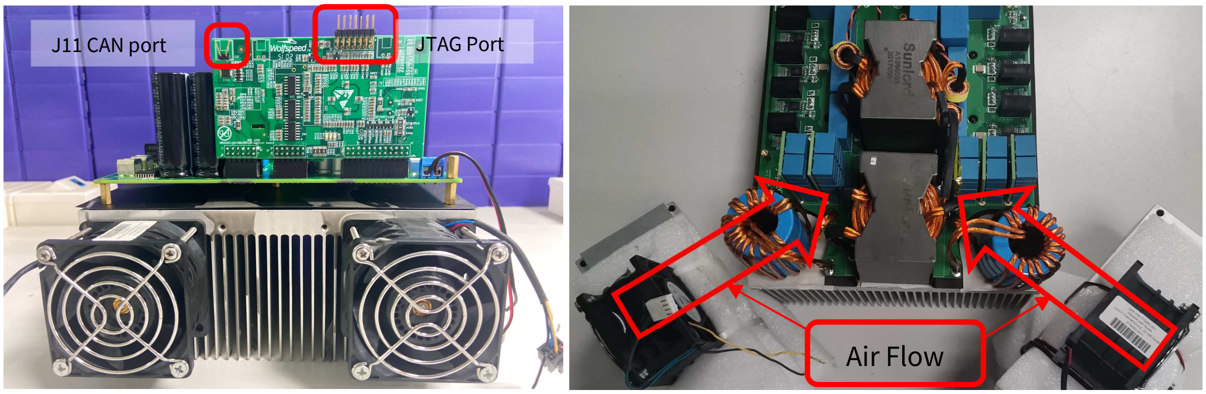



*Figure 16: Setup of the reference design*

**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 16. 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 17. "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 Figure 18 (a), Figure 19 (a) and (b). 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.

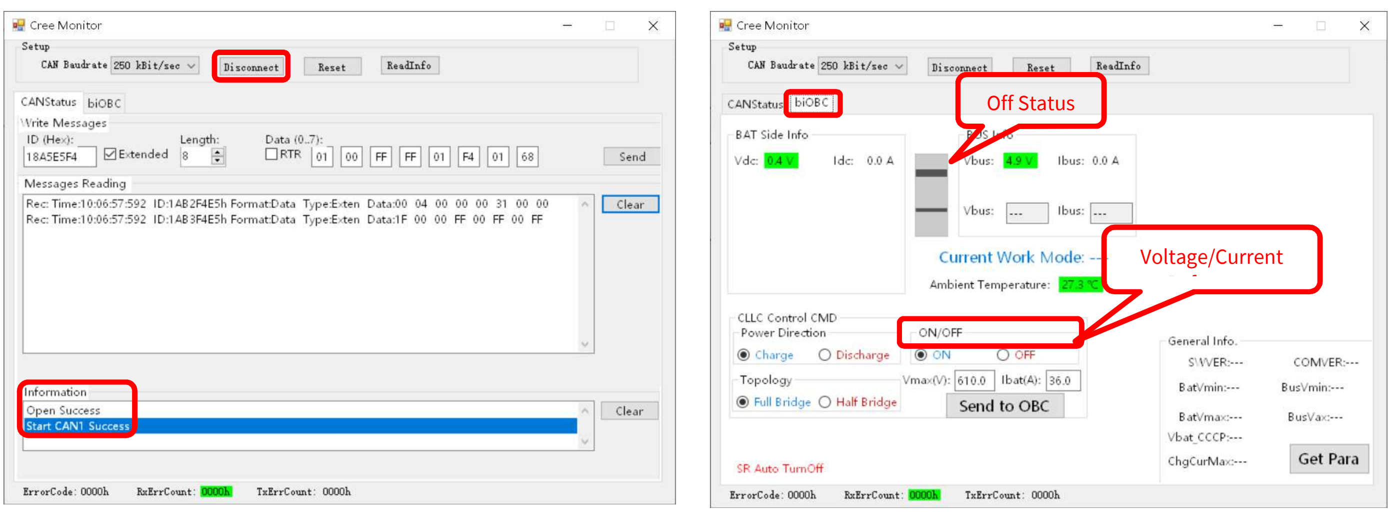



*Figure 17: (a) CAN status tab after connection, (b) connected to control board <Off Mode>*

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 display 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. Start-up voltage will always be calculated by controller based on the equation mentioned in Section 2, and thus don’t rely upon the input voltage reference.

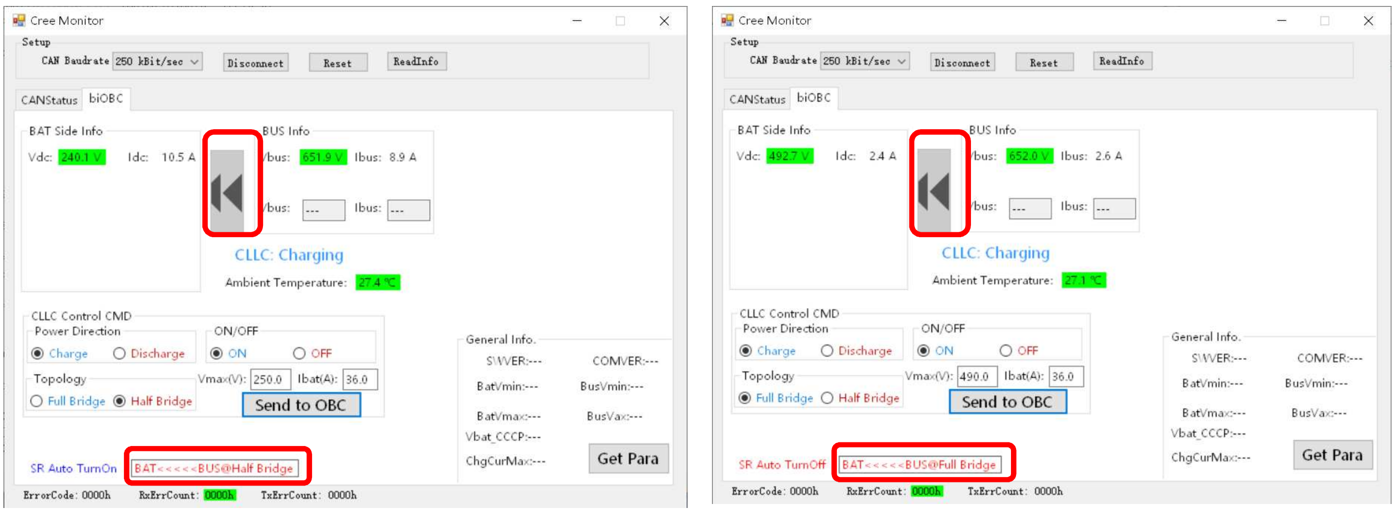



*Figure 18: (a) Charging operation in half bridge, (b) charging operation in full bridge*

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 start-up.

In discharging mode, these reference values have no impact.

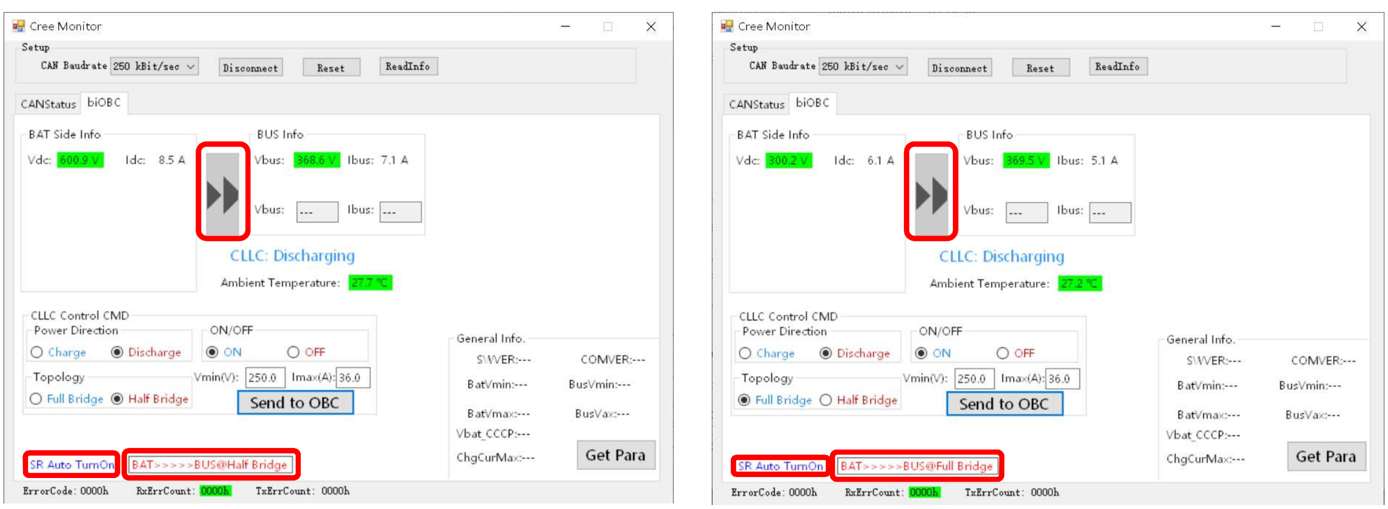



*Figure 19: (a) Discharging operation in half bridge, (b) discharging operation in full bridge*

## 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.

*Table 7: Example of control command*

| 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 |

## 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

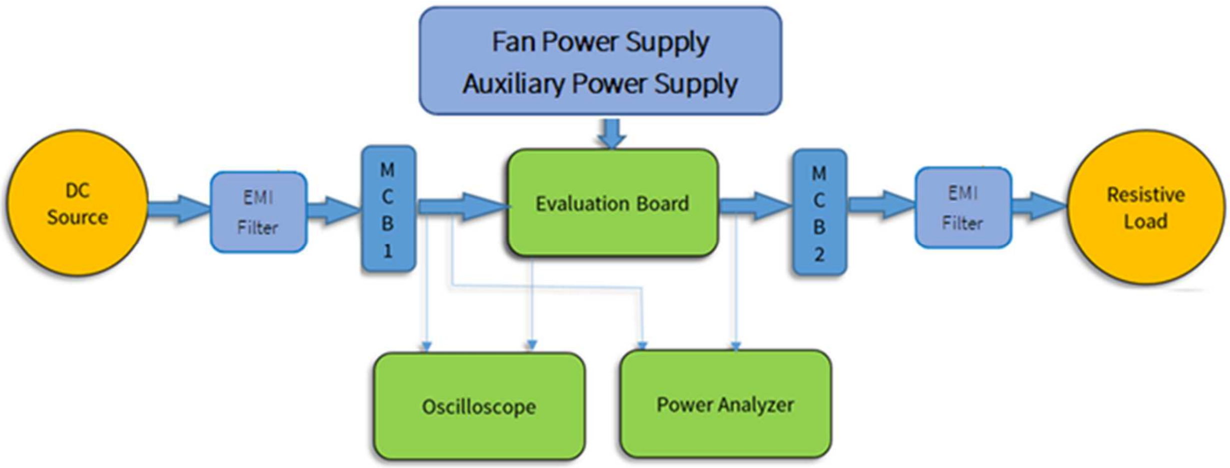



*Figure 20: Converter test setup*

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. Over Current Protection (OCP) 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 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.

*Table 8: Protection details*

| 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 |
| **Start-up Voltage** | | >350 V | >280 V |
| **Output Power Limitation** | | 22 kW±1.5 kW | |
| **Output Current Limitation** | | 30 A±1.5 A @ <240 V, 36 A±1.5 A others | |

## 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 J6 is used to power the on-board auxiliary power board.

*Table 9: Auxiliary power supply requirements*

| Control Board Connector Designator | Power Supply | Voltage (V) | Current 1 (A) (PWM Off) | Current 2 (A) (Single Phase Normal Operation) | Current 3 (A) (Three Phase Normal Operation) |
|---|---|---|---|---|---|
| **J6** | +14 V for AUX power | +14 V +/- 5% | 0.45 | 0.57 | 0.61 |

## 6.4 Measured Parameters

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

*Table 10: Parameters which can be measured*

| 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 sides |
| **VGS /VDS Signals** | voltage across gate to source or drain to source of SiC MOSFETs |
| **Auxiliary Power Board Outputs** | Please refer to Figure 6 and Table 3 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 |

# 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 start-up.
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 with Resistive Load

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 J6 on the main board. Check the output voltage of the Auxiliary Power Supply at J7 (P6.5 V, VP+15 V) and J8 (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 start-up. Start-up voltage is calculated according to Figure 4.
10. After the output voltage has reached steady-state regulation, increase the load up to desired value within 6.6 kW. The step-load change should not be larger than 1 kW for each step.
11. Check the efficiency under load conditions of interest. Check if SR is turned on automatically when DC input current is above 5 A. SR should be enabled by increasing load to >5 A. The load may be decreased to a lighter target load.

## 7.2 Turnoff Procedure: Discharging Mode with Resistive Load

1. Decrease the load to 1 kW in less than 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 J6. 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 right, 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 J6 on the main board. Check the output voltage of the Auxiliary Power Supply at J7 (P6.5 V, VP+15 V) and J8 (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 (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 and Figure 3.

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 and Figure 3.

11 After the output voltage has reached steady-state regulation, 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 enabled by increasing load to >5 A. The load may be decreased to a lighter target load.

## 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 J6.

## 8. Photo of the Reference Design

Figure 21 shows the locations of the terminals, key components and daughter-boards on the main board.

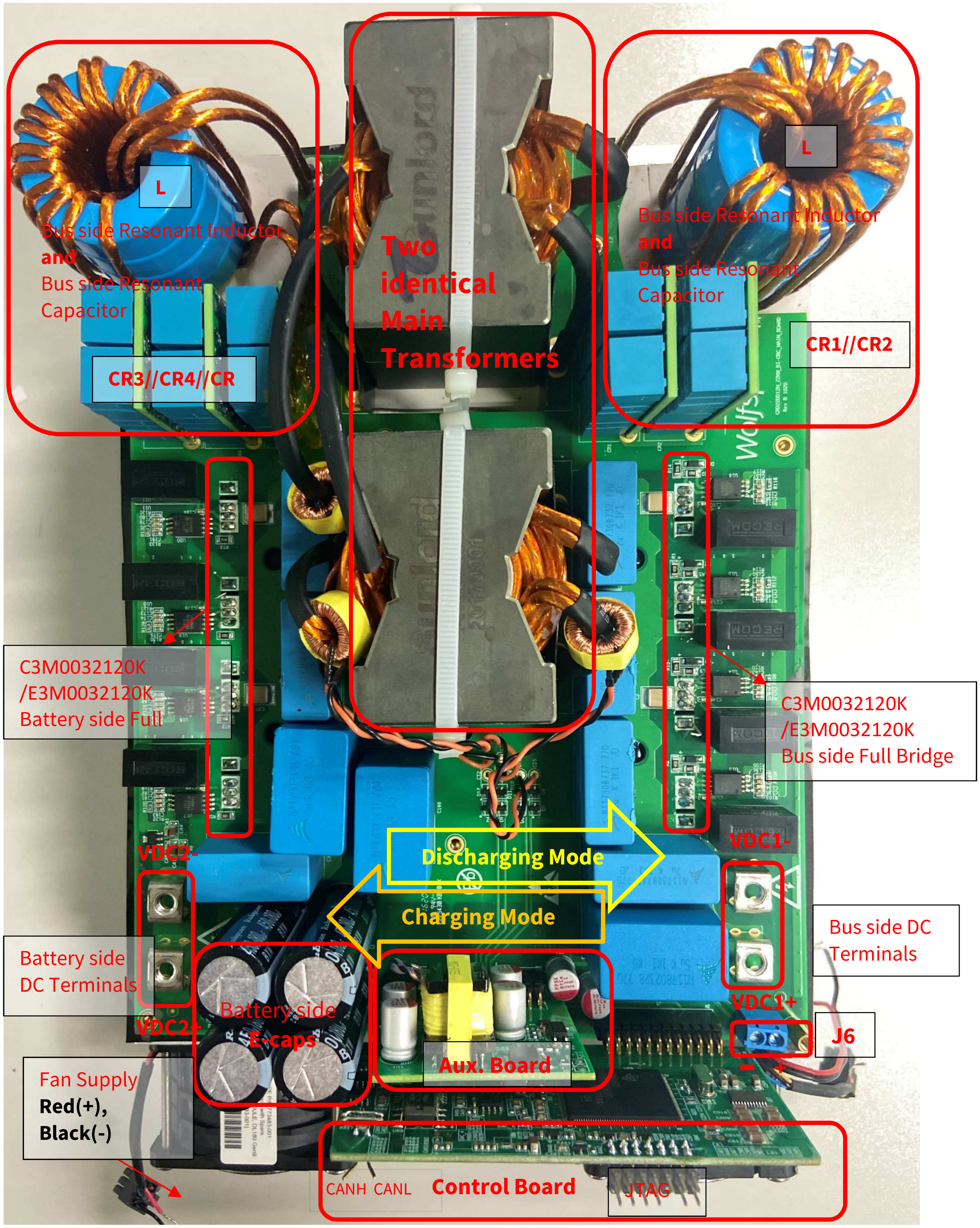



*Figure 21: Top view of PCBA (250 mm * 190 mm * 55 mm)*

# 9. Performance Data

The performance data of Wolfspeed's CRD-22DD12N reference design board is taken in both DC/DC Charging and DC/DC Discharging modes. Table 11 to Table 14 indicates the performance data.

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

| Input Voltage (VAC) | Input Power (W) | Load (%) | Output Voltage (VDC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **650** | 905.9 | 10 | 240 | 871.5 | 96.204 |
| **650** | 1783 | 20 | 240 | 1734.3 | 97.269 |
| **650** | 2666.3 | 30 | 240 | 2597.1 | 97.405 |
| **650** | 3555.8 | 40 | 240 | 3458.4 | 97.261 |
| **650** | 4451.3 | 50 | 240 | 4319.2 | 97.032 |
| **650** | 5356.4 | 60 | 240 | 5179 | 96.688 |
| **650** | 6277.6 | 70 | 240 | 6046.9 | 96.325 |
| **650** | 7197.9 | 80 | 240 | 6905.8 | 95.942 |
| **650** | 8130.5 | 90 | 240 | 7766.7 | 95.525 |
| **650** | 1323.3 | 10 | 340 | 1245.2 | 94.097 |
| **650** | 2585.5 | 20 | 340 | 2471.1 | 95.577 |
| **650** | 3841.1 | 30 | 340 | 3665.1 | 95.417 |
| **650** | 5085.3 | 40 | 340 | 4863.5 | 95.638 |
| **650** | 6364 | 50 | 340 | 6109.7 | 96.005 |
| **650** | 7668.7 | 60 | 340 | 7385.8 | 96.31 |
| **650** | 8957.6 | 70 | 340 | 8622.6 | 96.26 |
| **650** | 10218.3 | 80 | 340 | 9803.5 | 95.941 |
| **650** | 11518.8 | 90 | 340 | 11012.4 | 95.604 |
| **650** | 1517 | 10 | 400 | 1440.4 | 94.952 |
| **650** | 2951.2 | 20 | 400 | 2847.5 | 96.487 |
| **650** | 4441.1 | 30 | 400 | 4291.1 | 96.623 |
| **650** | 5887.5 | 40 | 400 | 5707.7 | 96.946 |
| **650** | 7383.9 | 50 | 400 | 7199.6 | 97.504 |
| **650** | 8827 | 60 | 400 | 8592.9 | 97.349 |
| **650** | 10365.3 | 70 | 400 | 10067.5 | 97.127 |
| **650** | 11780.6 | 80 | 400 | 11415.2 | 96.898 |
| **650** | 13344.1 | 90 | 400 | 12901.1 | 96.68 |
| **650** | 1793.2 | 10 | 480 | 1735.2 | 96.766 |
| **650** | 3501.6 | 20 | 480 | 3421.9 | 97.725 |
| **650** | 5202.5 | 30 | 480 | 5120.5 | 98.423 |
| **650** | 6916.7 | 40 | 480 | 6806.9 | 98.413 |

| Input Voltage (VAC) | Input Power (W) | Load (%) | Output Voltage (VDC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **650** | 8767.1 | 50 | 480 | 8620.3 | 98.326 |
| **650** | 10506.4 | 60 | 480 | 10317.8 | 98.205 |
| **650** | 12352.2 | 70 | 480 | 12111 | 98.047 |
| **650** | 14085.6 | 80 | 480 | 13785.4 | 97.869 |
| **650** | 15875.8 | 90 | 480 | 15506.9 | 97.677 |

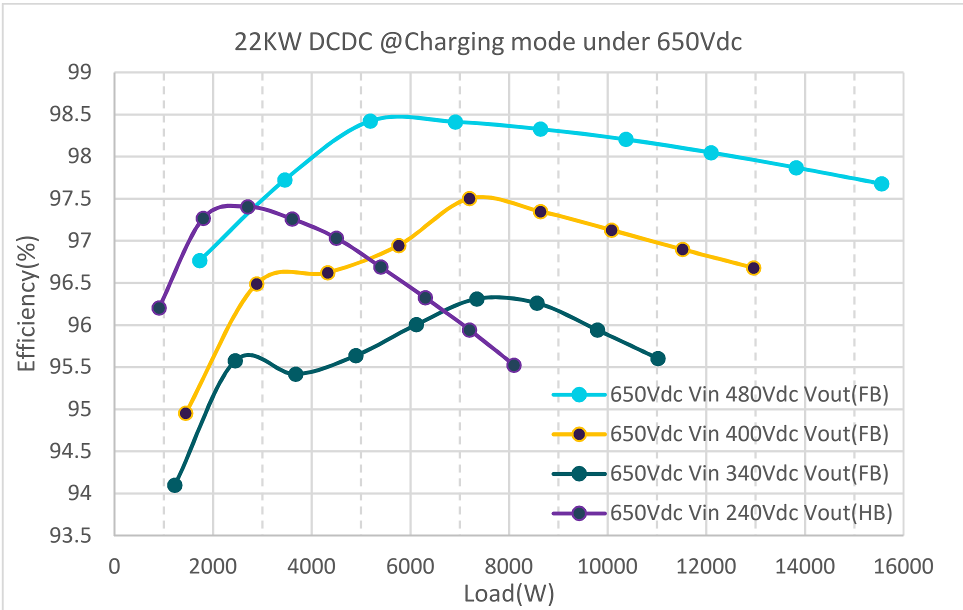



*Figure 22: Efficiency data (DC/DC charging mode), $V_{IN}$ = 650 VDC*

*Table 12: Efficiency data (DC/DC charging mode), $V_{IN}$ = 900 VDC*

| Input Voltage (VAC) | Input Power (W) | Load (%) | Output Voltage (VDC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **900** | 1231.1 | 10 | 340 | 1186.6 | 96.387 |
| **900** | 2483.3 | 20 | 340 | 2416.8 | 97.324 |
| **900** | 3749.3 | 30 | 340 | 3662 | 97.673 |
| **900** | 5040.3 | 40 | 340 | 4920.8 | 97.629 |
| **900** | 6239.4 | 50 | 340 | 6085.7 | 97.537 |
| **900** | 7532.1 | 60 | 340 | 7332.2 | 97.347 |
| **900** | 8829 | 70 | 340 | 8582.7 | 97.21 |
| **900** | 10136.8 | 80 | 340 | 9826.1 | 96.934 |
| **900** | 11413.9 | 90 | 340 | 11031.6 | 96.651 |
| **900** | 2114.2 | 10 | 770 | 2050.1 | 96.968 |
| **900** | 4457.7 | 20 | 770 | 4381.5 | 98.291 |

| Input Voltage (VAC) | Input Power (W) | Load (%) | Output Voltage (VDC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **900** | 6784 | 30 | 770 | 6692.8 | 98.656 |
| **900** | 8835.6 | 40 | 770 | 8723 | 98.725 |
| **900** | 11188 | 50 | 770 | 11042.6 | 98.701 |
| **900** | 13536.9 | 60 | 770 | 13355.9 | 98.663 |
| **900** | 15593.4 | 70 | 770 | 15375.7 | 98.604 |
| **900** | 17912.8 | 80 | 770 | 17646.2 | 98.512 |
| **900** | 19989.3 | 90 | 770 | 19671.1 | 98.408 |
| **900** | 22049.7 | 100 | 770 | 21665.2 | 98.256 |
| **900** | 1651.4 | 10 | 800 | 1580.6 | 95.714 |
| **900** | 3255.6 | 20 | 800 | 3179.7 | 97.669 |
| **900** | 4830.1 | 30 | 800 | 4748 | 98.299 |
| **900** | 6416.3 | 40 | 800 | 6322.6 | 98.54 |
| **900** | 8308.7 | 50 | 800 | 8197.6 | 98.664 |
| **900** | 9838.1 | 60 | 800 | 9707.3 | 98.671 |
| **900** | 11422.9 | 70 | 800 | 11268.4 | 98.647 |
| **900** | 13009.9 | 80 | 800 | 12830.3 | 98.619 |
| **900** | 14596.9 | 90 | 800 | 14386.6 | 98.56 |
| **900** | 16424.8 | 100 | 800 | 16180.1 | 98.511 |

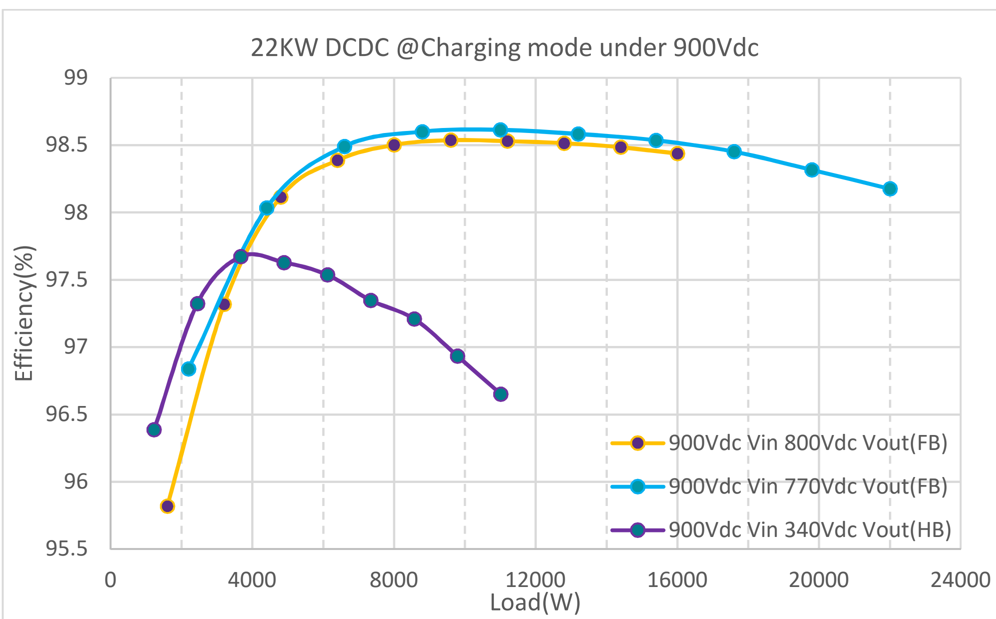



*Figure 23: Efficiency data (DC/Dc charging mode), $V_{IN}$ = 900 VDC*

*Table 13: Efficiency data (DC/DC discharging mode), $V_{IN}$ = 300 V/480 V/600 VDC full bridge*

| Input Voltage (VDC) | Input Power (W) | Load (%) | Output Voltage (VAC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **300** | 690.3 | 10% | 370 | 679.3 | 98.395 |
| **300** | 1363.5 | 20% | 370 | 1346.5 | 98.755 |
| **300** | 1970.1 | 30% | 368.6 | 1944.6 | 98.706 |
| **300** | 2642.1 | 40% | 367.6 | 2605.1 | 98.6 |
| **300** | 3303.3 | 50% | 367.2 | 3251.2 | 98.425 |
| **300** | 4049.9 | 60% | 367 | 3978.3 | 98.234 |
| **300** | 4725.1 | 70% | 366.4 | 4632.8 | 98.047 |
| **300** | 5409.1 | 80% | 366.3 | 5291.9 | 97.833 |
| **300** | 6084.3 | 90% | 366.1 | 5939.6 | 97.623 |
| **300** | 6773 | 100% | 365 | 6596.7 | 97.398 |
| **480** | 763.4 | 10% | 600 | 733.5 | 96.081 |
| **480** | 1465.9 | 20% | 600 | 1441.1 | 98.305 |
| **480** | 1977 | 30% | 600 | 1948.2 | 98.539 |
| **480** | 2687.7 | 40% | 600 | 2652.5 | 98.69 |
| **480** | 3260.9 | 50% | 600 | 3221.1 | 98.779 |
| **480** | 3959.5 | 60% | 600 | 3913.4 | 98.834 |
| **480** | 4672.7 | 70% | 600 | 4618 | 98.828 |
| **480** | 5388.9 | 80% | 600 | 5325.2 | 98.818 |
| **480** | 6084.3 | 90% | 600 | 6009.9 | 98.777 |
| **480** | 6608.7 | 100% | 600 | 6525.5 | 98.742 |
| **600** | 629.6 | 10% | 755 | 585 | 89.764 |
| **600** | 1474.9 | 20% | 755 | 1436.4 | 93.011 |
| **600** | 2037.1 | 30% | 755 | 1995.3 | 95.739 |
| **600** | 2604.2 | 40% | 755 | 2559.2 | 96.296 |
| **600** | 3441.2 | 50% | 755 | 3389.6 | 96.565 |
| **600** | 4017.3 | 60% | 755 | 3962.3 | 96.675 |
| **600** | 4580.7 | 70% | 755 | 4522.3 | 96.715 |
| **600** | 5431.1 | 80% | 755 | 5364.5 | 96.67 |
| **600** | 6036.7 | 90% | 755 | 5962.1 | 96.595 |
| **600** | 6608 | 100% | 755 | 6528.1 | 96.478 |

*Table 14: Efficiency data (DC/DC discharging mode), $V_{IN}$ = 600 V/800 VDC half bridge*

| Input Voltage (VDC) | Input Power (W) | Load (%) | Output Voltage (VAC) | Output Power (W) | Overall Efficiency (%) |
|---|---|---|---|---|---|
| **600** | 683.7 | 10% | 365 | 666.8 | 97.534 |
| **600** | 1361.1 | 20% | 365 | 1333.1 | 97.949 |
| **600** | 2013.6 | 30% | 365 | 1979.3 | 98.296 |
| **600** | 2662.7 | 40% | 365 | 2615.6 | 98.23 |
| **600** | 3345.2 | 50% | 365 | 3281.5 | 98.094 |
| **600** | 4082 | 60% | 365 | 3995.5 | 97.882 |
| **600** | 4730.7 | 70% | 365 | 4623.4 | 97.731 |
| **600** | 5458.3 | 80% | 365 | 5325.5 | 97.567 |
| **600** | 6133.8 | 90% | 365 | 5972.5 | 97.371 |
| **600** | 6800.4 | 100% | 365 | 6607.7 | 97.166 |
| **802** | 768.5 | 10% | 495 | 735.1 | 95.653 |
| **802** | 1376.8 | 20% | 495 | 1346.4 | 97.797 |
| **801.8** | 1988 | 30% | 495 | 1953.4 | 98.259 |
| **801.8** | 2602.4 | 40% | 495 | 2559.7 | 98.36 |
| **801.7** | 3326.7 | 50% | 495 | 3274.3 | 98.423 |
| **801.5** | 4068.8 | 60% | 495 | 4004.2 | 98.411 |
| **801.5** | 4673.9 | 70% | 495 | 4597.8 | 98.372 |
| **801.4** | 5408.9 | 80% | 495 | 5317.9 | 98.319 |
| **801.3** | 6011.3 | 90% | 495 | 5906.5 | 98.256 |
| **801.2** | 6765.3 | 100% | 495 | 6640.3 | 98.153 |

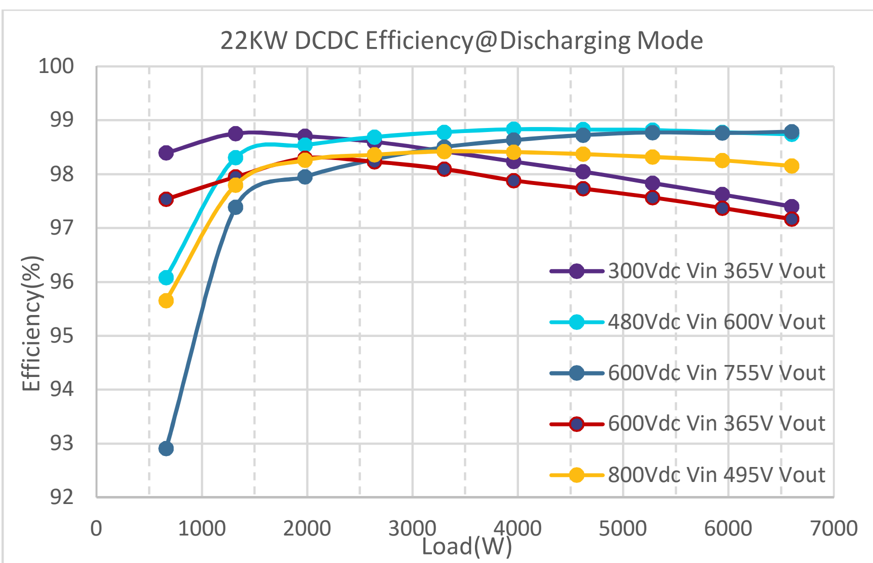


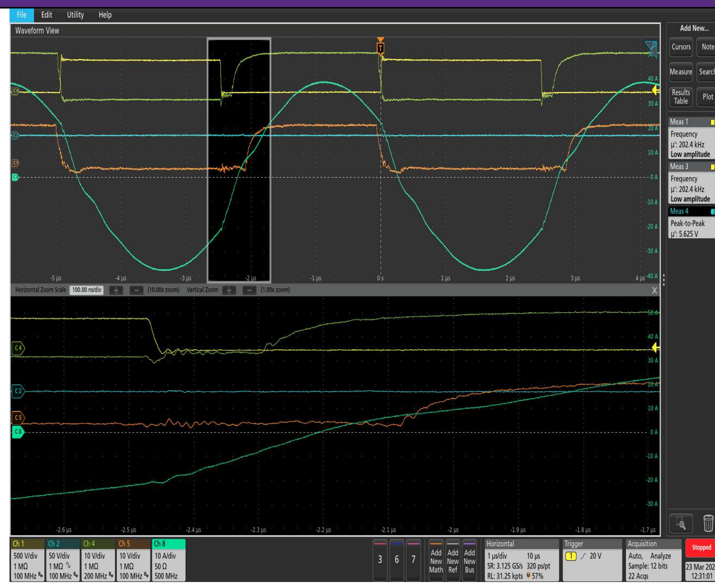
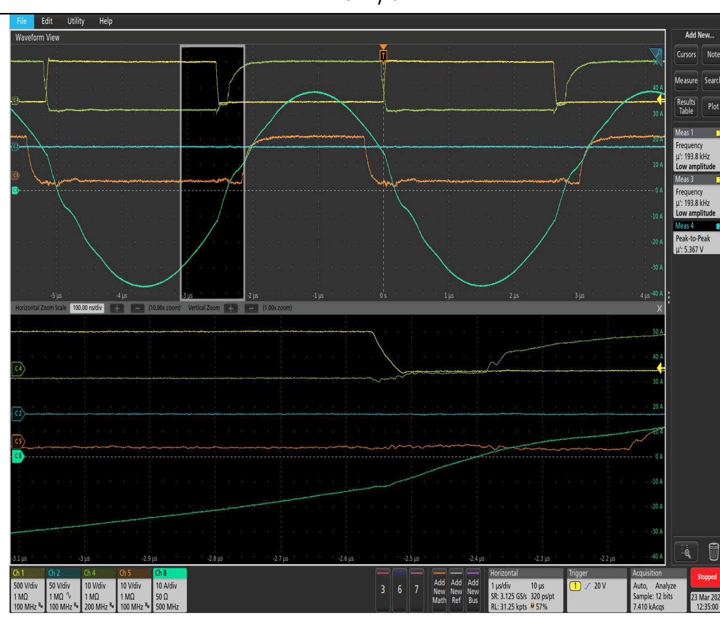

*Figure 24: Efficiency data (DC/DC discharging mode)*

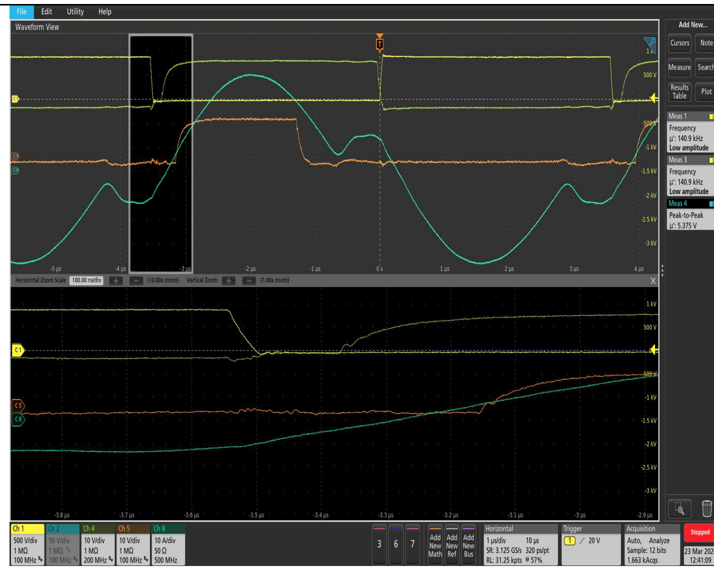
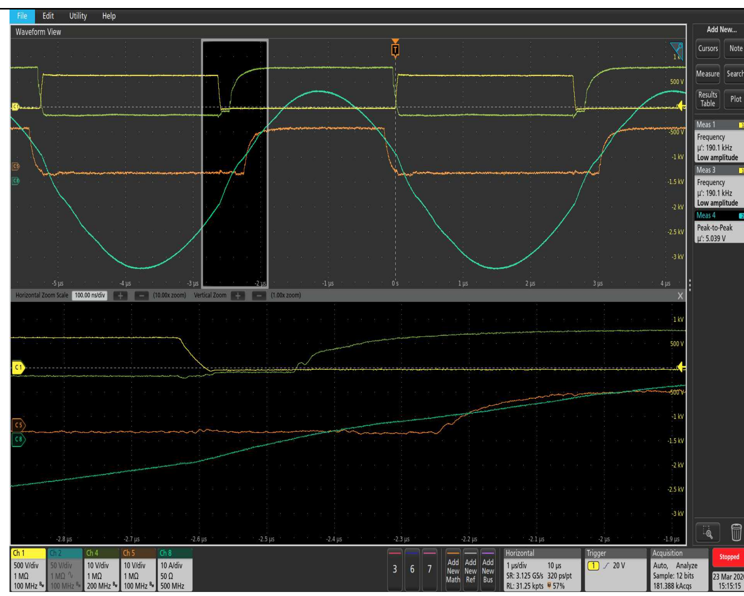
# 10. Typical Waveforms

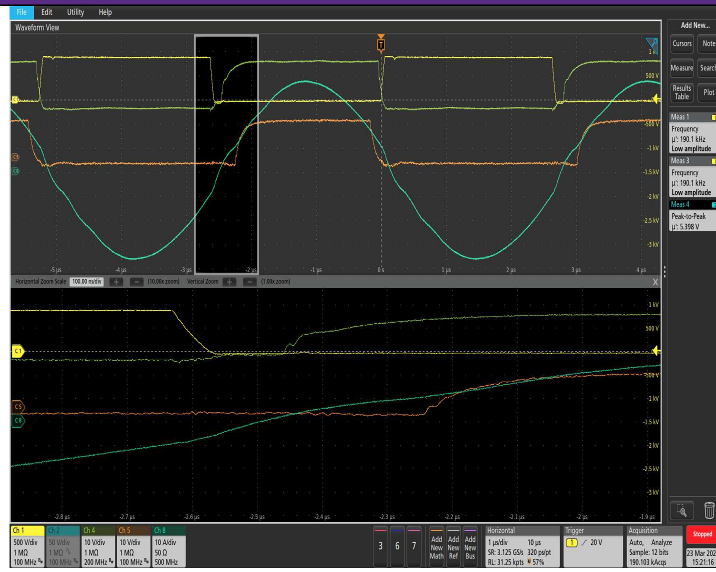
Operational waveforms are presented in Table 15 and Table 16.

## 10.1 DC/DC Charging Mode

*Table 15: DC/DC charging mode waveforms*

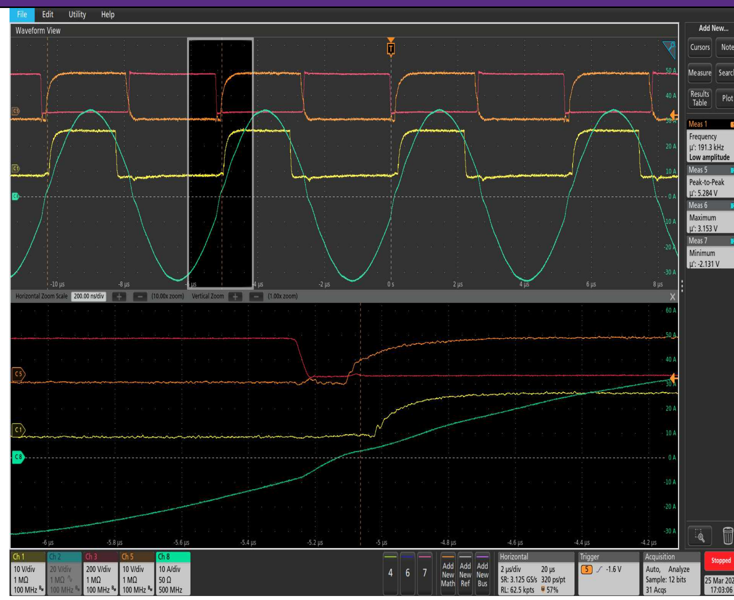
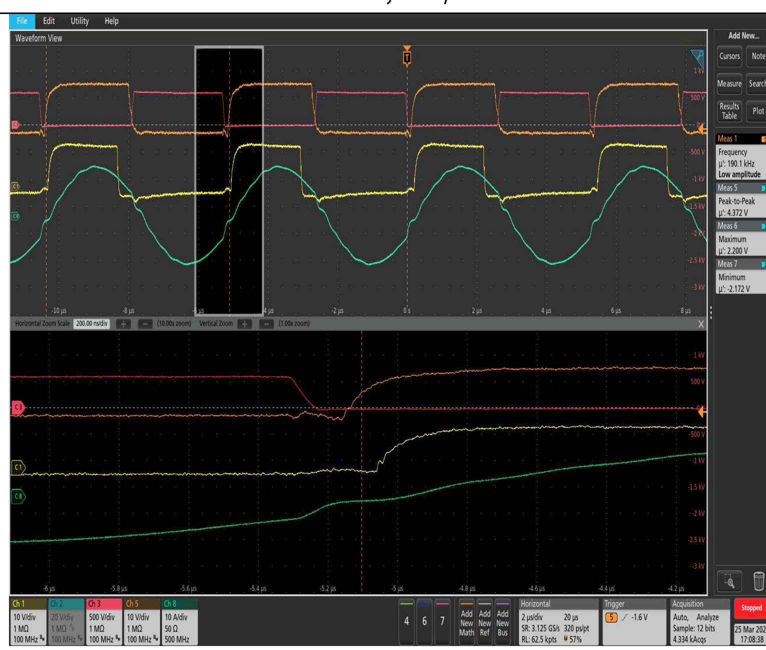
| Condition | Waveform |
|---|---|
| **DC/DC Charging Mode (Full Bridge)**<br><br>**Bus Side Input: 650 VDC**<br><br>**Battery Side Output: 480 VDC**<br><br>**Full Load** | <br>CH1: VDS Primary Low Side, 500 V/div CH4: VGS Primary Low Side, 10 V/div<br>CH5: VGS Secondary Low Side,10 V/div CH8: Primary Resonant Choke Current, 10 A/div |
| **DC/DC Charging Mode (Full Bridge)**<br><br>**Bus Side Input: 780 VDC**<br><br>**Battery Side Output: 610 VDC**<br><br>**Full Load** | <br>CH1: VDC Primary Low Side, 500 V/div CH4: VGS Primary Low Side, 10 V/div |

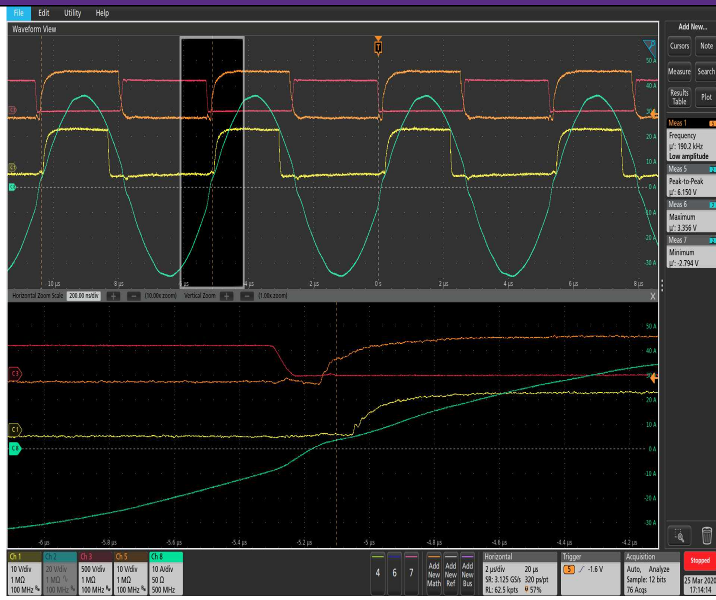
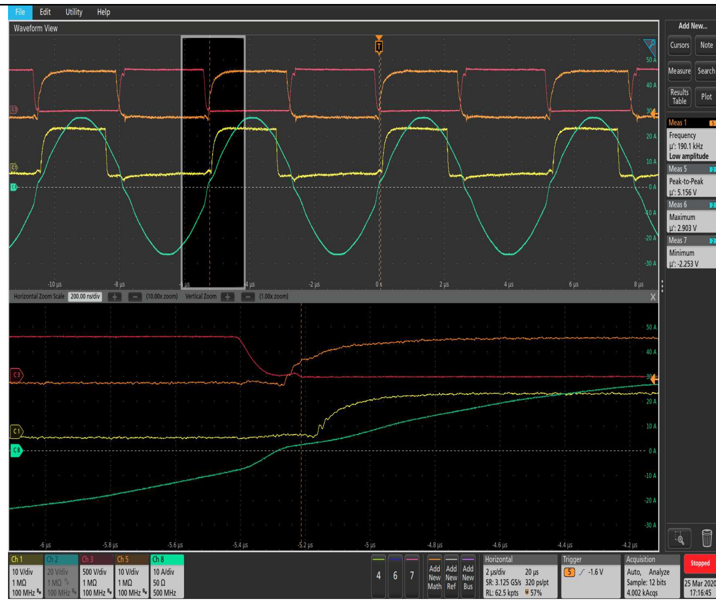
| Condition | Waveform |
|---|---|
| | CH5: VGS Secondary Low Side,10 V/div CH8: Primary Resonant Choke Current, 10 A/div |
| **DC/DC Charging Mode (Full Bridge)**<br><br>**Bus Side Input: 900 VDC**<br><br>**Battery Side Output: 800 VDC**<br><br>**Full Load** | <br>CH1: VDC Primary Low Side, 500 V/div CH4: VGS Primary Low Side, 10 V/div CH5: VGS Secondary Low Side,10 V/div CH8: Primary Resonant Choke Current, 10 A/div |
| **DC/DC Charging Mode (Half Bridge)**<br><br>**Bus Side Input: 650 VDC**<br><br>**Battery Side Output: 200 VDC**<br><br>**Full Load** | <br>CH1: VDC Primary Low Side, 500 V/div CH4: VGS Primary Low Side, 10 V/div CH5: VGS Secondary Low Side,10 V/div CH8: Primary Resonant Choke Current, 10 A/div |

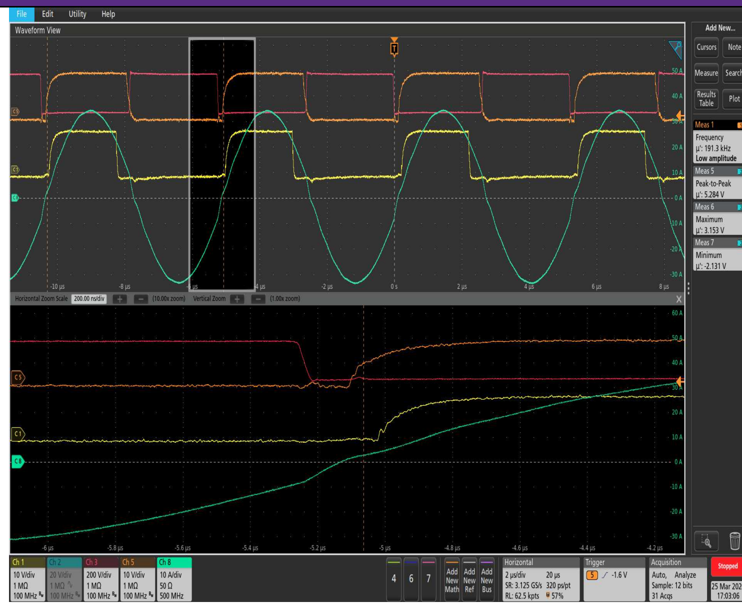
| Condition | Waveform |
| --- | --- |
| **DC/DC Charging Mode (Half Bridge)**<br><br>**Bus Side Input: 900 VDC**<br><br>**Battery Side Output: 360 VDC**<br><br>**Full Load** | <br>CH1: VDS Primary Low Side, 500 V/div CH4: VGS Primary Low Side, 10 V/div CH5: VGS Secondary Low Side,10 V/div CH8: Primary Resonant Choke Current, 10 A/div |

## 10.2 DC/DC Discharging Mode: Resistive load

*Table 16: DC/DC discharging mode waveforms*

| Condition | Waveform |
| --- | --- |
| **DC/DC Discharging Mode (Full Bridge)**<br><br>**Battery Side Input: 300 VDC**<br><br>**Bus Side Output: 365 VDC**<br><br>**Full Load** | <br>CH1: VGS Secondary Low Side,10 V/div CH3: VDC Primary Low Side, 200 V/div CH5: VGS Primary Low Side, 10 V/div CH8: Primary Resonant Choke Current,10 A/div |
| **DC/DC Discharging Mode (Full Bridge)**<br><br>**Battery Side Input: 600 VDC**<br><br>**Bus Side Output: 750 V VDC dc**<br><br>**Full Load** | <br>CH1: VGS Secondary Low Side,10 V/div CH3: VDC Primary Low Side, 500 V/div CH5: VGS Primary Low Side, 10 V/div CH8: Primary Resonant Choke Current,10 A/div |

| Condition | Waveform |
| --- | --- |
| **DC/DC Discharging Mode (Half Bridge)**<br><br>**Battery Side Input: 600 VDC**<br><br>**Bus Side Output: 360 VDC**<br><br>**Full Load** | <br>CH1: VGS Secondary Low Side,10 V/div CH3: **VDC** Primary Low Side, 500 V/div CH5: VGS Primary Low Side, 10 V/div CH8: Primary Resonant Choke Current, 10 A/div |
| **DC/DC Discharging Mode (Half Bridge)**<br><br>**Battery Side Input: 800 VDC**<br><br>**Bus Side Output: 490 VDC**<br><br>**Full Load** | <br>CH1: VGS Secondary Low Side,10 V/div CH3: **VDC** Primary Low Side, 500 V/div CH5: VGS Primary Low Side, 10 V/div CH8: Primary Resonant Choke Current, 10 A/div |

| Condition | Waveform |
|---|---|
| **DC/DC Discharging Mode (Full Bridge)**<br><br>**Battery Side Input: 300 VDC**<br><br>**Bus Side Output: 365 VDC**<br><br>**Full Load** | <br>CH1: VGS Secondary Low Side,10 V/div CH3: **VDC** Primary Low Side, 200 V/div<br>CH5: VGS Primary Low Side, 10 V/div CH8: Primary Resonant Choke Current,10 A/div |

## 11. Thermal Design and Test Results

In a thermal test of the unit, forced air cooling is applied to the cooling base plate at the bottom side to achieve a 65°C cooling plate in order to simulate the thermal condition in an OBC application. There is no air flow to the power MOSFETs. MOSFETs in the CLLC resonant converter operate in full load thermal condition with a 611 V/36 A load. So, the thermal test was performed at 800V DC input and full load 22 kW with 611 V/36 A load in charging mode. T-type thermal couplers 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 17 and Table 18. The highest junction temperature of any MOSFET in the design was determined to be 113.9°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 C3M0032120K and E3M0032120K is 175°C, the integrated heat sink design has allowed the MOSFETs to remain within their thermal derating guidelines.

*Table 17: Thermal test results of magnetic components*

| Description | Scenario 1. 480 V/36 A charging | Scenario 2. 610 V/36 A charging | Scenario 3. 400 V/36 A charging | Rated Temperature | Derating Requirement | Comments |
|---|---|---|---|---|---|---|
| **Base Plate** | 65°C | 65°C | 65°C | NA | NA | NA |
| **Resonant Choke1** | 98.7°C | 80.2°C | 105.6°C | 155 °C | 130 °C | Pass |
| **Resonant Choke2** | 92°C | 76.9°C | 102.5°C | 155 °C | 130 °C | Pass |
| **Main-Tx** | 99.1°C | 92°C | 93.6°C | 155 °C | 130 °C | Pass |

Temperature of semiconductors is shown in the table below.

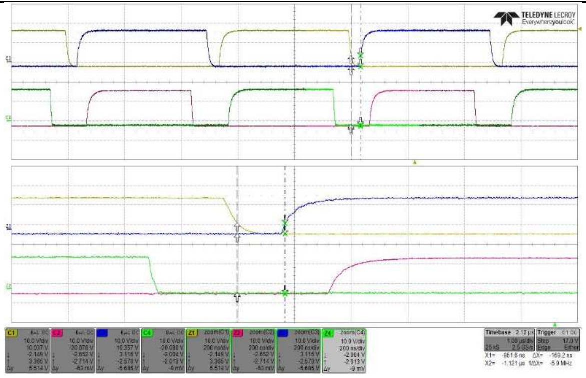
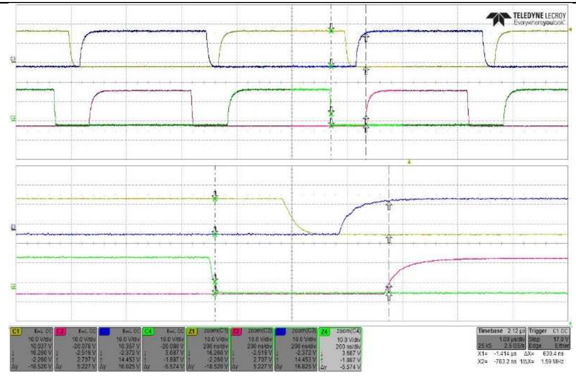
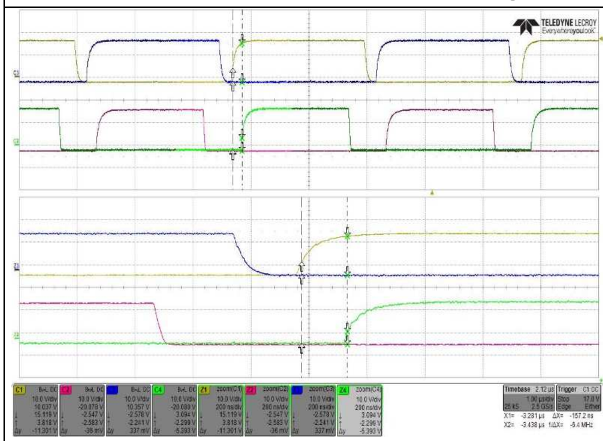
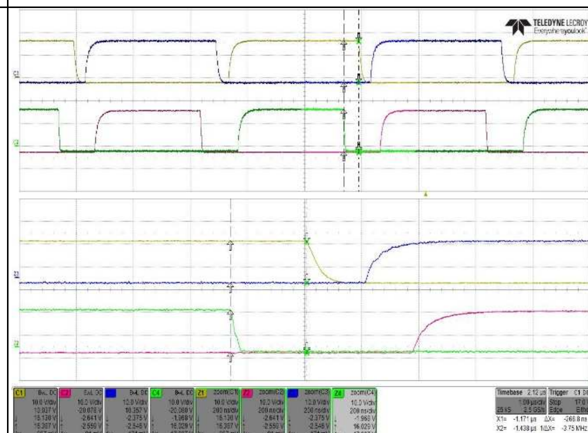
*Table 18: Thermal test results of SiC power MOSFETs*

| Description | Rth (j-c) (°C/W) | Calculated Power Loss | Measured Case Temperature | Calculated Junction Temperature | Max. Operating Junction Temperature | Derating Require-ment | Comment |
|---|---|---|---|---|---|---|---|
| **Charging Output = 480 VDC 36 A** | | | | | | | |
| **CLLC MOSFET** | 0.45 | 42 W | 86.9°C | 105.8°C | 175°C | 140°C | Pass |
| **CLLC SR MOSFET** | 0.45 | 38 W | 83.6°C | 100.7°C | 175°C | 140°C | Pass |
| **Charging Output = 610 VDC 36 A** | | | | | | | |
| **CLLC MOSFET** | 0.45 | 32.5 W | 81.7°C | 96.4°C | 175°C | 140°C | Pass |
| **CLLC SR MOSFET** | 0.45 | 38 W | 83.3°C | 100.4°C | 175°C | 140°C | Pass |
| **Charging Output = 400 VDC 36 A** | | | | | | | |
| **CLLC MOSFET** | 0.45 | 53 W | 90.1°C | 113.9°C | 175°C | 140°C | Pass |
| **CLLC SR MOSFET** | 0.45 | 38 W | 83.7°C | 100.8°C | 175°C | 140°C | Pass |

# 12. Appendix

## 12.1 PWM Timing

*Table 19: Gate signals and timings in discharging mode*

| | |
|---|---|
|  Dead time=169 ns (battery side bridge) |  SR off time=630 ns (bus side bridge) |
|  Time Delay from Primary to Secondary = 157 ns |  Time Ahead from Secondary to Primary = 267 ns |
| CH1: High Side VGS of Battery Side Bridge<br>CH3: Low Side VGS of Battery Side Bridge | CH2: Low Side VGS of Bus Side Bridge<br>CH4: High Side VGS of Bus Side Bridge |

## 12.2 CAN Messages from OBC

*Table 20: Overall charge status*

| 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 21: Temperature and charge mode*

| 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 22: Charge status, AC and CLLC information*

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

*Table 23: Bit definition for OBC status*

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

*Table 24: Part I of OBC specification*

| 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 25: Part II 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 | | | |

## 12.3 CAN Messages to OBC

*Table 26: Control command*

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

## Revision History

| Date | Revision | Changes |
|---|---|---|
| **July 2020** | 1 | Initial Release |
| **November 2023** | 2 | Reformatted document and included Automotive grade E3M0032120K device. |

## References

None

## Important Notes

## Purposes and Use

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

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

## Operation of Board

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

## 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.

## No Warranty

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

## Limitation of Liability

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