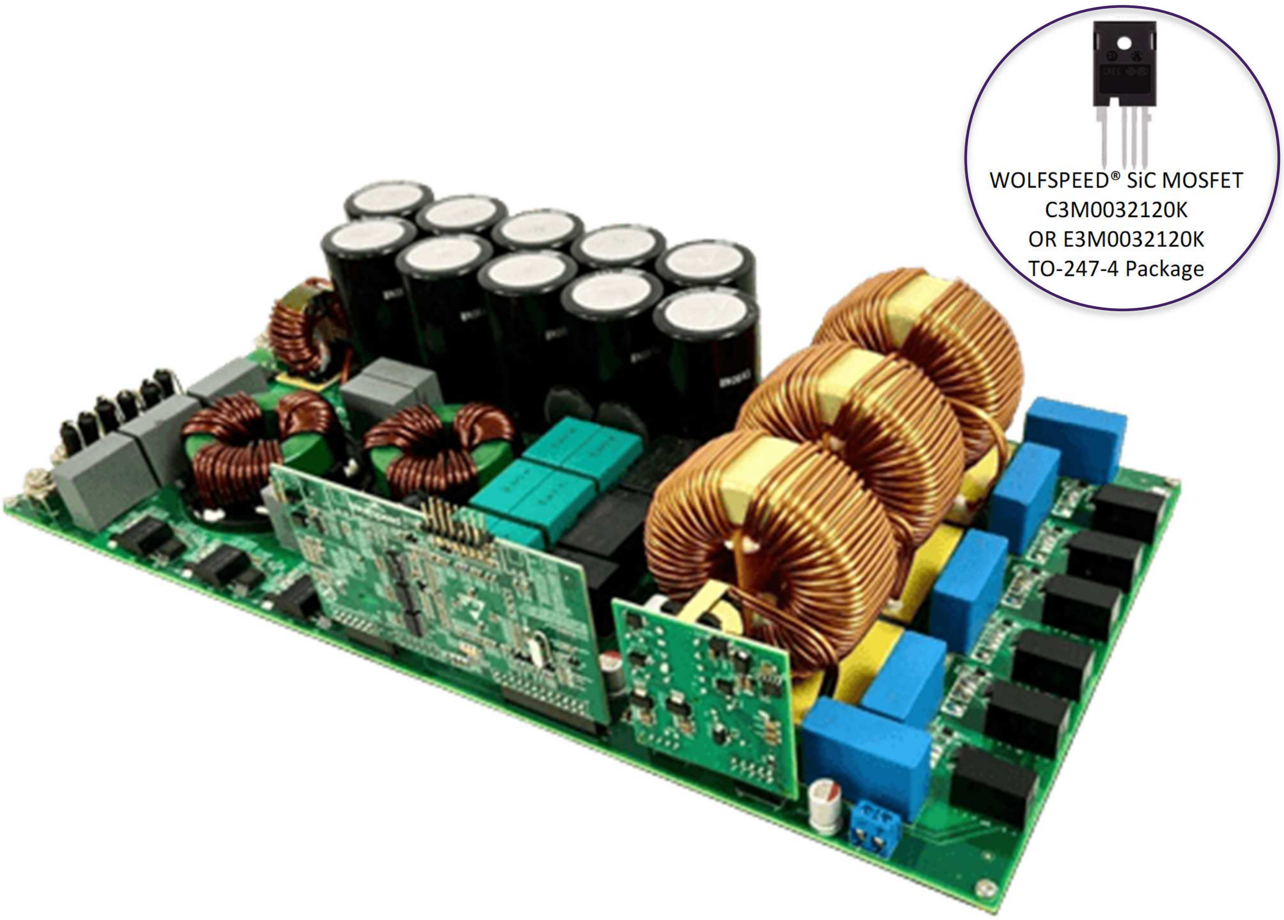
User Guide **PRD-02282**

CRD-22AD12N
22 kW Bi-Directional Active Front End (AFE)



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Contents

This document is prepared as a user guide to install and operate Wolfspeed® evaluation hardware. All parts of this user guide are provided in English, and the cautions are provided in English, Mandarin, and Japanese. If the end user of this board is not fluent in any of these languages, it is your responsibility to ensure that they understand the terms and conditions described in this document, including without limitation the hazards of and safe operating conditions for this board.

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

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本样机（易碎、高压、高温电力电子系统）由科锐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-40°C~105°C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 https://forum.wolfspeed.com/ に連絡してください。ハードウェアには危険物質が含まれていないが、工業的、技術的、安全性の基準または分類に適合するように設計されておらず、生産適格組立品でもない。

CAUTION

PLEASE CAREFULLY REVIEW THE FOLLOWING PAGE, AS IT 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˚ CELSIUS. FURTHER, THESE CONDITIONS WILL CONTINUE FOR A SHORT TIME AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED.

Please ensure that appropriate safety procedures are followed when operating this board, as any of the following can occur if you handle or use this board without following proper safety precautions:

- Death
- Serious injury
- Electrocution
- Electrical shock
- Electrical burns
- Severe heat burns

You must read this document in its entirety before operating this board. It is not necessary for you to touch the board while it is energized. All test and measurement probes or attachments must be attached before the board is energized. You must never leave this board unattended or handle it when energized, and you must always ensure that all bulk capacitors have completely discharged prior to handling the board. Do not change the devices to be tested until the board is disconnected from the electrical source and the bulk capacitors have fully discharged.

警告

请勿在通电情况下接触板子，在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

This User's Guide provides the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-22AD12N, 22 kW Bi-Directional Active Front End (AFE) converter for an electric vehicle (EV) on-board charger (OBC) and similar applications.

A block diagram of 22 kW OBC based on SiC is shown in Figure 1. This design of Wolfspeed's 22 kW, Bi-Directional AFE converter (P/N CRD-22AD12N) is based upon one of Wolfspeed's latest generation of SiC MOSFETs - C3M0032120K of E3M0032120K (1200 V, 32m Ω, TO-247-4). This reference design is the grid connected stage of a bi-directional OBC converter. As shown in Figure 1, it operates from grid supply at AC terminals and provides a non-isolated DC output voltage at the DC terminals (referred to as rectifier mode) or vice versa (referred to as inverter mode). Please refer to Wolfspeed's 22 kW isolated DC/DC converter (P/N CRD-22DD12N) for the DC/DC stage.

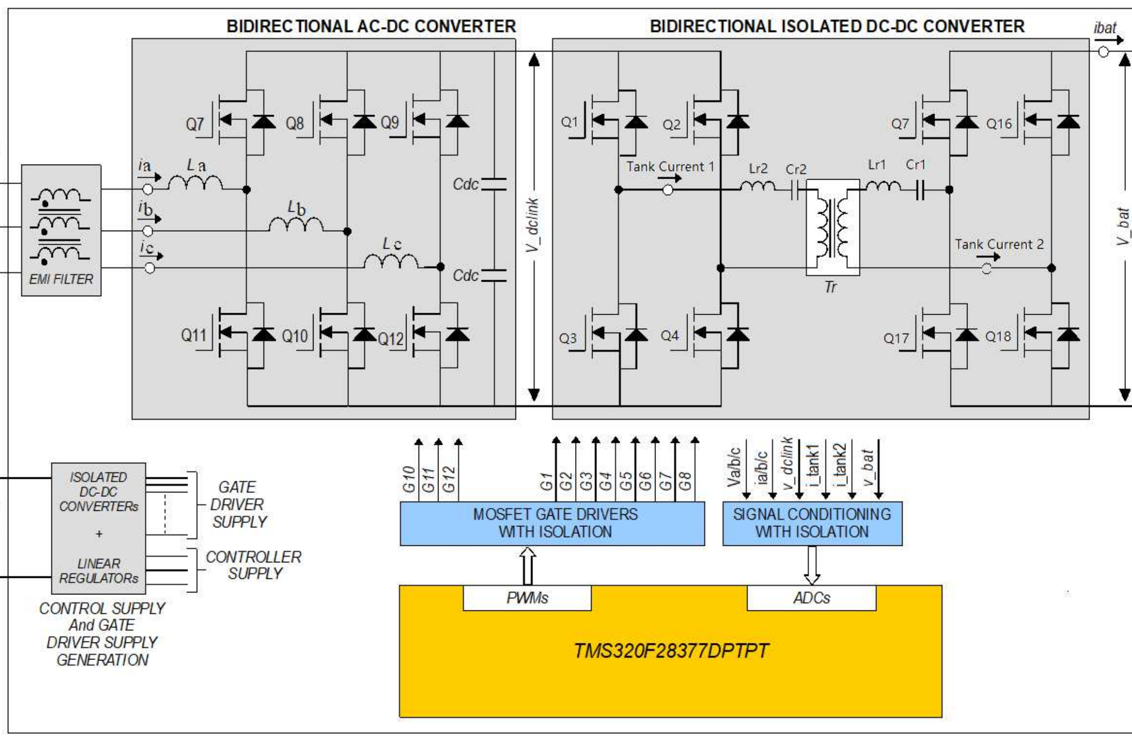


Figure 1: Block diagram of Wolfspeed's CRD-22DD12N and CRD-22AD12N, 22 kW bi-directional EV on-board charger

The classic AFE topology using a six-switch, two-level converter, is chosen to meet high efficiency, high power density and bi-directional operation requirements. The converter operates at a fixed 45 kHz switching frequency for both charging and discharging modes. An extruded heatsink and fan are used to cool the MOSFETs to simplify bench testing in place of a cooling plate in an OBC application.

In charging mode, the DC output voltage is adjustable between 650 VDC and 900 VDC for three-phase AC input or between 380 VDC and 900 VDC for a single-phase AC input. This variable bus voltage helps to realize a wide output voltage range for the DC/DC stage. In an OBC application, a single-phase AC output is required in discharging mode, therefore, a single-phase inverter is demonstrated.

Since the main purpose of the reference design is to demonstrate the performance of SiC in the power converter for OBC applications, only standalone load is supported. Thus, this reference design doesn't focus on techniques related to a grid-connected inverter and there is no grid-connected inverter algorithm built in. A resistive load connected to the single-phase AC output is recommended when operating in inverter mode. An electronic load or a resistive load may be used on the DC output when operating in rectifier mode.

2. Description

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

This AFE evaluation board is compatible for both single-phase and three-phase application. In inverter mode, the three-phase application is only used for gate driver signal verification, not for power test. Thus, the power direction and converter configuration should be selected properly via the graphical user interface (GUI) before turning on the unit.

The operational range of the evaluation board in charging mode is as shown in Table 1. The output power should not exceed 22 kW for three-phase application and 6.6 kW for single-phase application. The Root Mean Square (RMS) value of the input line current should not exceed 32 A in any condition.

Table 1: Overall Charging Operation

Operation Mode	Input AC RMS Range	Input Line Current	Output DC Range	Output Power
Three-Phase Charging	176 V_{phase} ~ 264 V_{phase}	32 A RMS Max.	650 VDC~900 VDC	22 kW Max.
Single-Phase Charging	180 VAC ~ 264 VAC		380 VDC~900 VDC	6.6 kW Max.

Table 2: Overall Discharging Operation (Open Loop)

Operation Mode	Max. Input DC	Max. Output AC RMS	Max. Output Power
Single-Phase Inverter Mode	760 VDC	220 V RMS	6.6 kW

The hardware can support 480 VAC three-phase input, but the software is not designed to be compatible for it. **A user should not overload the converter out of the SOA (Safe Operation Area)**. Please refer to Table 7 in Section 6.3 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 is configurable through the CAN interface in rectifier mode. The output voltage is fixed at about 220 V RMS max for a single-phase inverter operation. No load is allowed for three-phase application in inverter mode.

3. Electrical Performance Characteristics

3.1 Rectifier/Charging Mode

Table 3: Characteristics of Wolfspeed's CRD-22AD12N, 22 kW Bi-Directional AFE in Charging Modes

Parameter		Test Conditions	Min.	Nom	Max.	Units
Input Characteristics (AC Terminals)						
$\mathbf{V_{in}}$	Input Phase RMS voltage	Three-phase inputs	176	230	264	V
$\mathbf{V_{in}}$	Input RMS voltage	Single-phase input	180	230	264	V
$\mathbf{V_{in}}$	Input line frequency			50/60		Hz
$\mathbf{I_{in}}$	Input current				32	A
Output Characteristics (DC Terminals)						
$\mathbf{V_{OUT1}}$	Output voltage	Three-phase inputs	650	800	900	V
$\mathbf{P_{OUT1\ max.}}$	Output power				22000	W
$\mathbf{I_{OUT\ 1}}$	Output current				32	A
$\mathbf{V_{OUT2}}$	Output voltage	Single-phase input	380		900	V
$\mathbf{P_{OUT2\ max.}}$	Output power				6600	W
$\mathbf{I_{OUT\ 2}}$	Output current				18	A
System Characteristics*1						
$\mathbf{\eta_{peak1}}$	Peak efficiency (Single Phase)	V_{IN} = 230 VAC, V_{OUT} = 385 VDC, P_{OUT} = 2 kW	98.3%	98.5%		
$\mathbf{\eta_{full\ load}}$	Full load efficiency (Single Phase)	V_{IN} = 215 VAC, V_{OUT} = 385 VDC, P_{OUT} = 6.6 kW	97.0%	97.2%		
		V_{IN} = 230 VAC, V_{OUT} = 385 VDC, P_{OUT} = 6.6 kW	97.3%	97.5%		
		V_{IN} = 264 VAC, V_{OUT} = 385 VDC, P_{OUT} = 6.6 kW	97.6%	97.8%		
		V_{IN} = 215 VAC, V_{OUT} = 900 VDC, P_{OUT} = 6.08 kW	95.9%	96.1%		
		V_{IN} = 230 VAC, V_{OUT} = 900 VDC, P_{OUT} = 6.4 kW	96.2%	96.4%		
		V_{IN} = 264 VAC, V_{OUT} = 900 VDC, P_{OUT} = 6.5 kW	96.6%	96.8%		

Parameter		Test Conditions	Min.	Nom	Max.	Units
η_{peak2}	Peak efficiency	V_{IN} = 230 V Phase RMS, V_{OUT} = 650 V, P_{OUT} = 11 kW	98.2%	98.4%		
$\eta_{full\ load}$	Full load efficiency	V_{IN} = 176 V Phase RMS, V_{OUT} = 650 V, P_{OUT} = 15.1 kW	97.3%	97.5%		
		V_{IN} = 230 V Phase RMS, V_{OUT} = 650 V, P_{OUT} = 19.3 kW	98.0%	98.2%		
		V_{IN} = 264 V Phase RMS, V_{OUT} = 650 V, P_{OUT} = 19.5 kW	98.3%	98.5%		
		V_{IN} = 176 V Phase RMS, V_{OUT} = 900 V, P_{OUT} = 14.9 kW	96.6%	96.8%		
		V_{IN} = 230 V Phase RMS, V_{OUT} = 900 V, P_{OUT} = 22.1 kW	97.3%	97.5%		
		V_{IN} = 264 V Phase RMS, V_{OUT} = 900 V, P_{OUT} = 22.1 kW	97.7%	97.9%		

*1: Maximum current is about 30A for the efficiency test due to the limitation of the power analyzer. Output power is not exactly the same as target at high voltage because resistive load is used.

3.2 Inverter/Discharging Mode

Table 4: Characteristics of Wolfspeed's CRD22AD12N, 22 kW Bi-Directional AFE in Single-Phase Discharging Mode

Parameter		Test Conditions	Min.	Nom	Max.	Units
Input Characteristics (DC Terminals)						
V_{in}	Input voltage				760	V
I_{in}	Input current				20	A
Output Characteristics (AC Terminals)						
V_{OUT}	Output RMS voltage				230	V
Frequency	Output Frequency			50		Hz
$P_{OUT\ max.}$	Output power				6600	W
I_{OUT}	output current				32	A
System Characteristics						
η_{peak}	Peak Efficiency	V_{IN} = 350 V DC, V_{OUT} = 220 V AC, P_O = 2.6 kW	98.3%	98.5%		
$\eta_{full\ load}$	Full Load Efficiency	V_{IN} = 350 V DC, V_{OUT} = 220 V AC, P_O = 6.5 kW	97.4%	97.6%		
		V_{IN} = 500 V DC, V_{OUT} = 220 V AC, P_O = 6.3 kW	97.05%	97.25%		

Parameter		Test Conditions	Min.	Nom	Max.	Units
		V_{IN} = 760 V DC, V_{OUT} = 210 V AC, P_O = 6.2 kW	96.45%	96.65%		

3.3 Applications

The primary application for Wolfspeed's CRD-22AD12N 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.**

3.4 Features

Some of the features and limitations of Wolfspeed's CRD-22AD12N reference design board are listed below:

- Bi-directional operation: DC output range is 380 VDC-900 VDC for single-phase and 650 VDC-900 VDC for three-phase inputs.
- Maximum allowed AC line current is 32 A and maximum affordable output DC power is 22 kW. Only rectifier mode is allowed for three-phase application.
- Maximum output power is 6.6 kW for single-phase application.
- Maximum output power is 6.6 kW in discharging mode.
- Peak efficiency > 98.3%.
- Protection functions are shown in Table 7.
- Easy to test using a GUI communicating via CAN. See Section 5 and Section 12 for details.

4. Schematics of Power Board and Control 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 power, control, and auxiliary-power boards are shown in Figures 3 through 10.

4.1 Power Board Schematic:

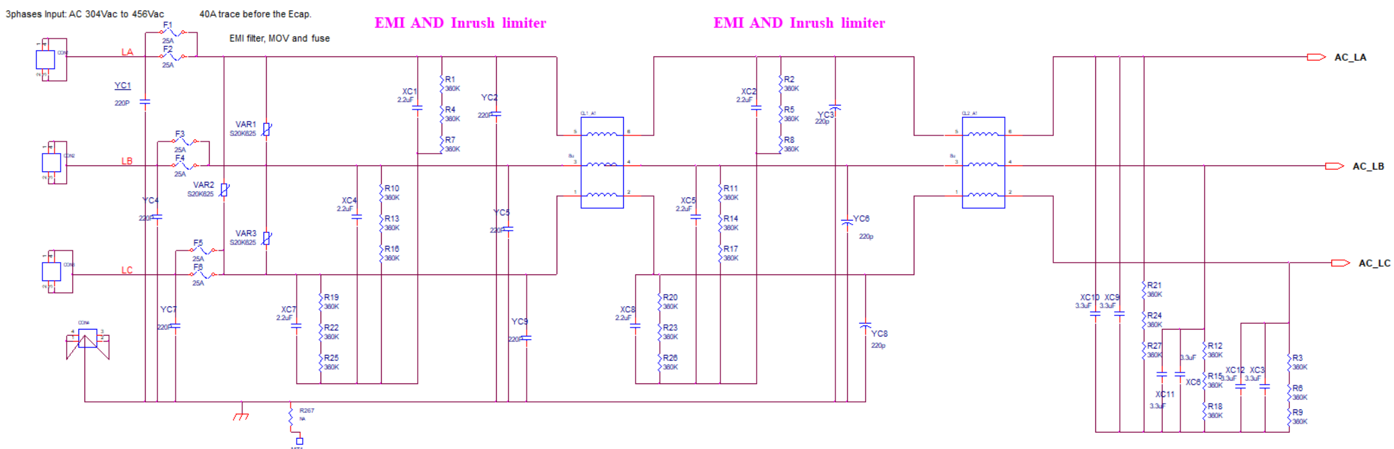


Figure 2 (a): Schematic of power board: Input EMI filtering

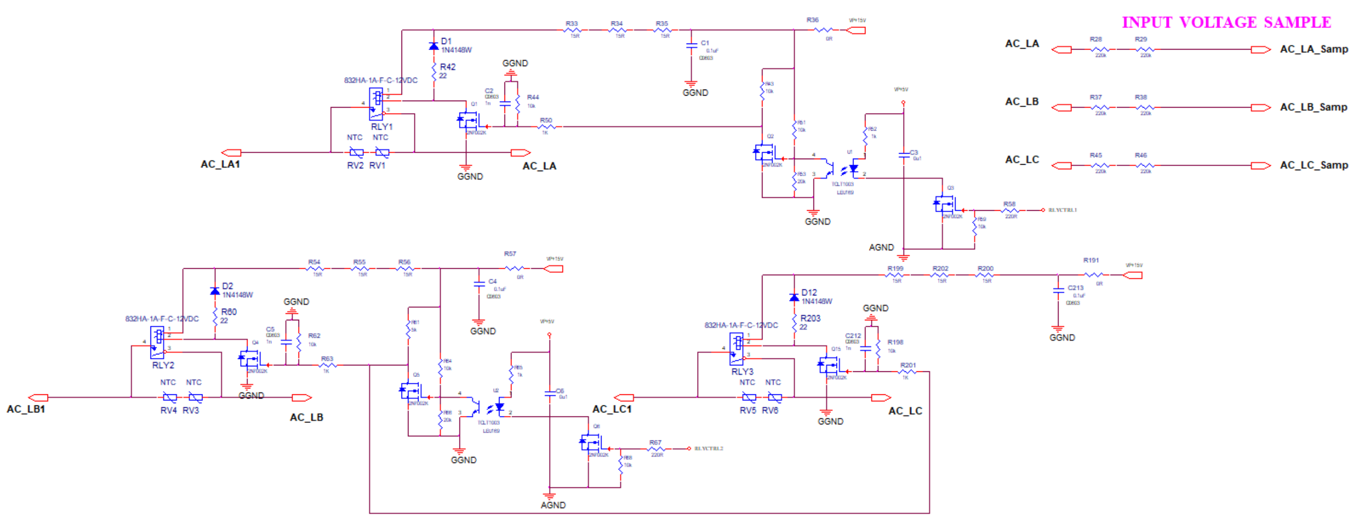


Figure 2 (b): Schematic of power board: Inrush limiting pre-charge circuit

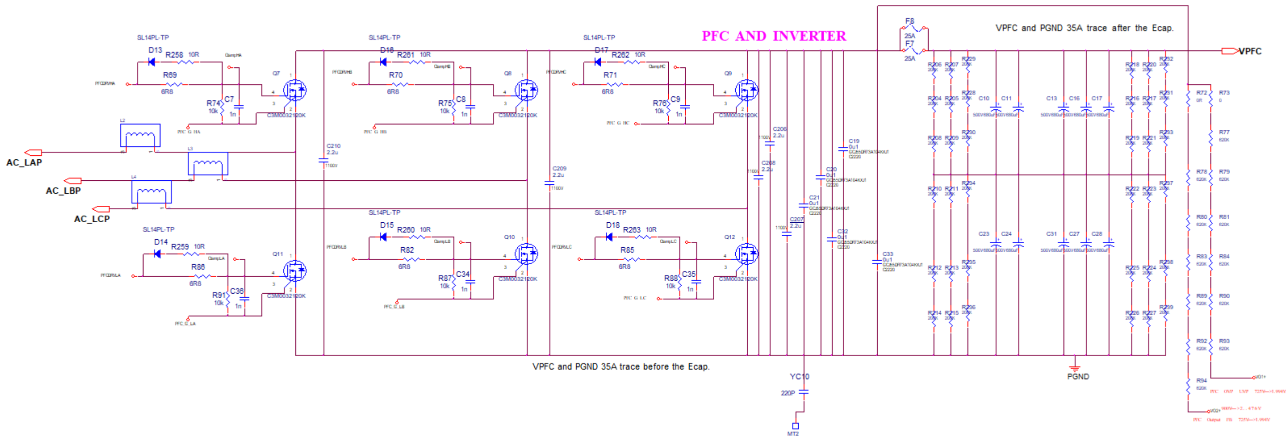


Figure 2 (c): Schematic of power board: Main inverter MOSFETs and DC bus

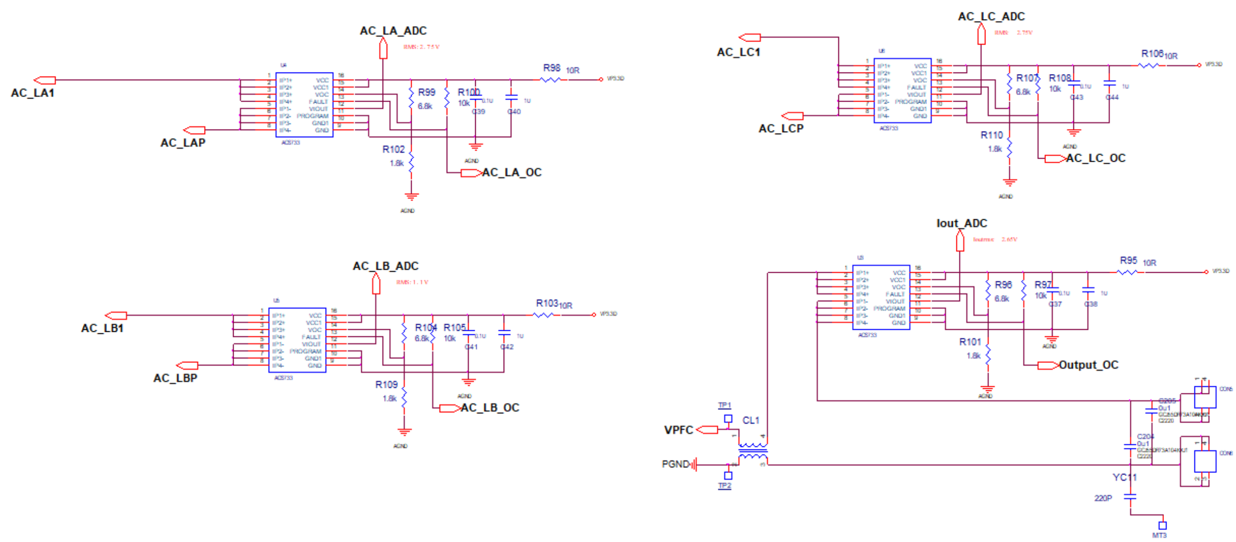


Figure 2 (d): Schematic of power board: Current sensing

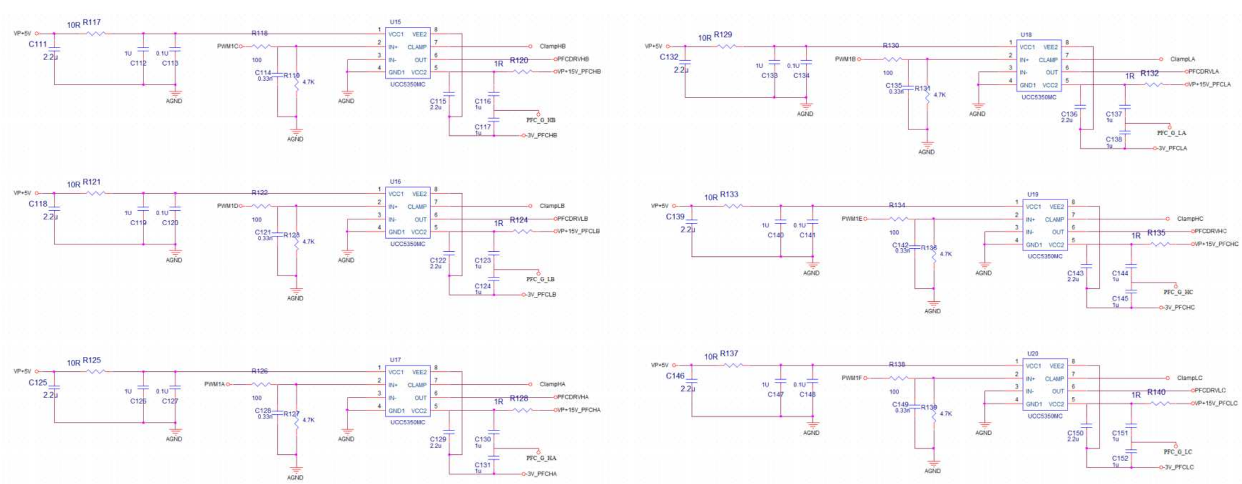


Figure 3 (a): Schematic of power board: AFE gate drives

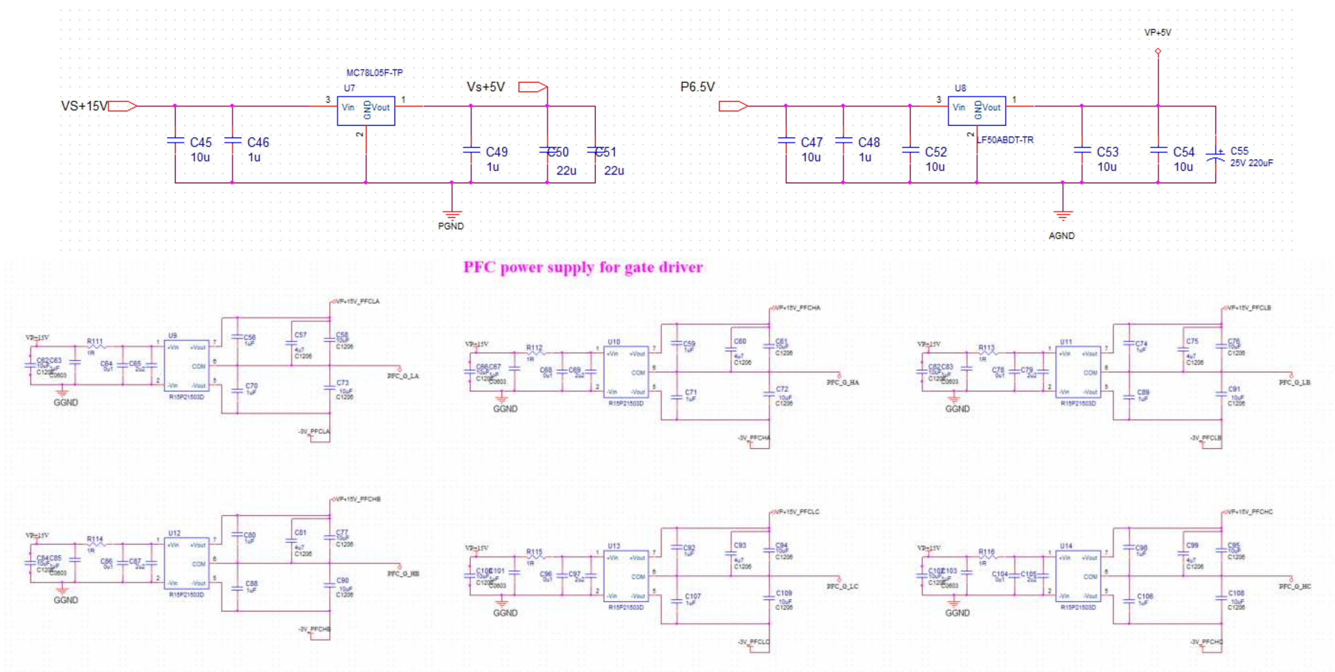


Figure 3 (b): Schematic of power board: Linear regulators and isolated gate power supplies

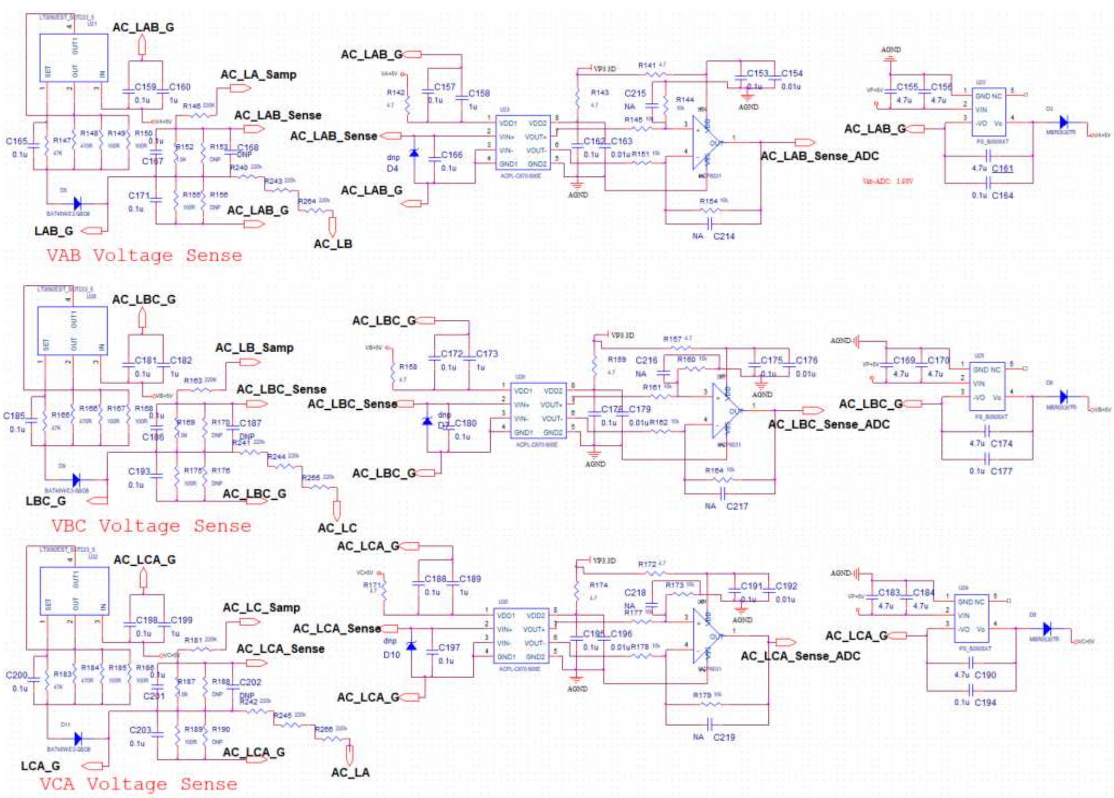


Figure 4: Schematic of power board: Signal conditioning circuit

4.2 Control Board Schematic:

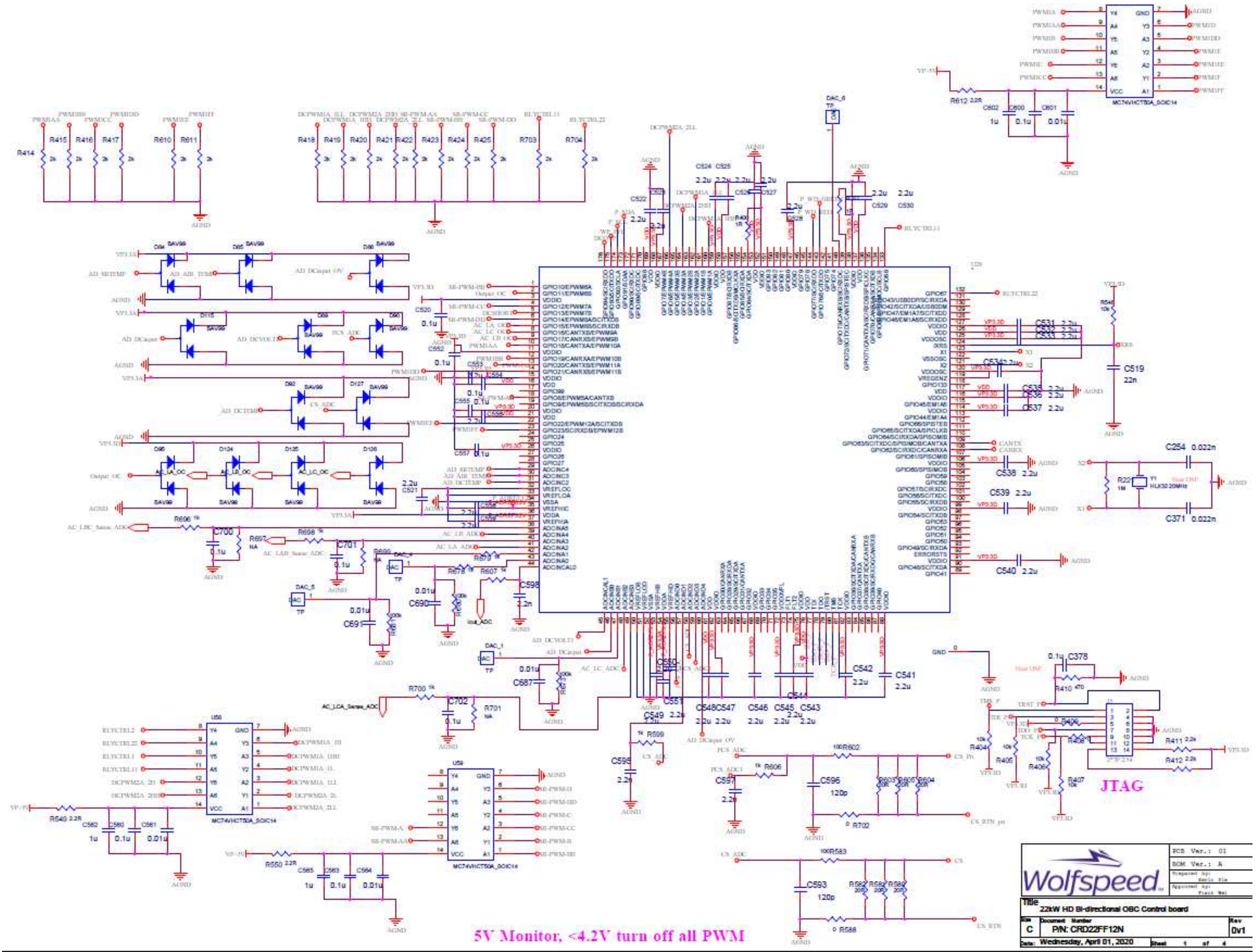


Figure 5: Schematic of control board: Controller

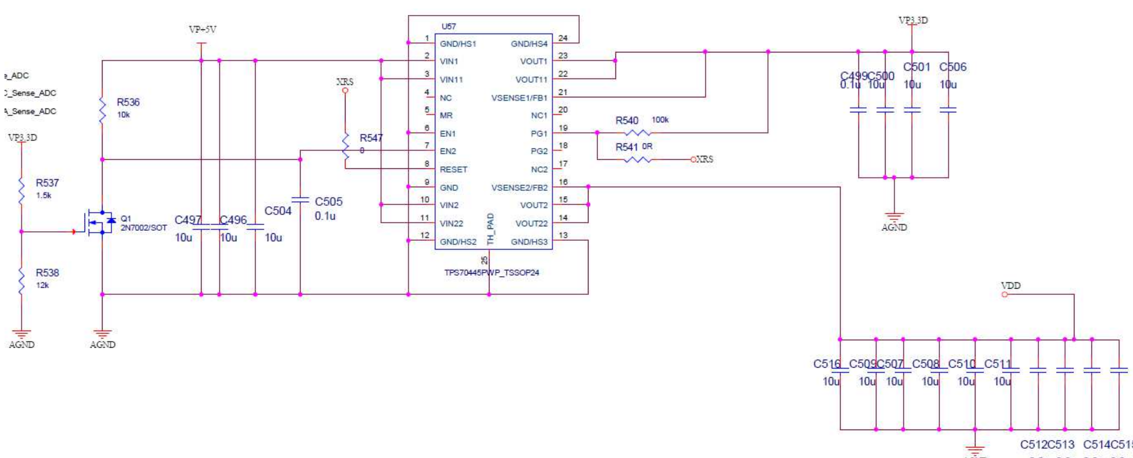


Figure 6: Schematic of control board: Controller power supply

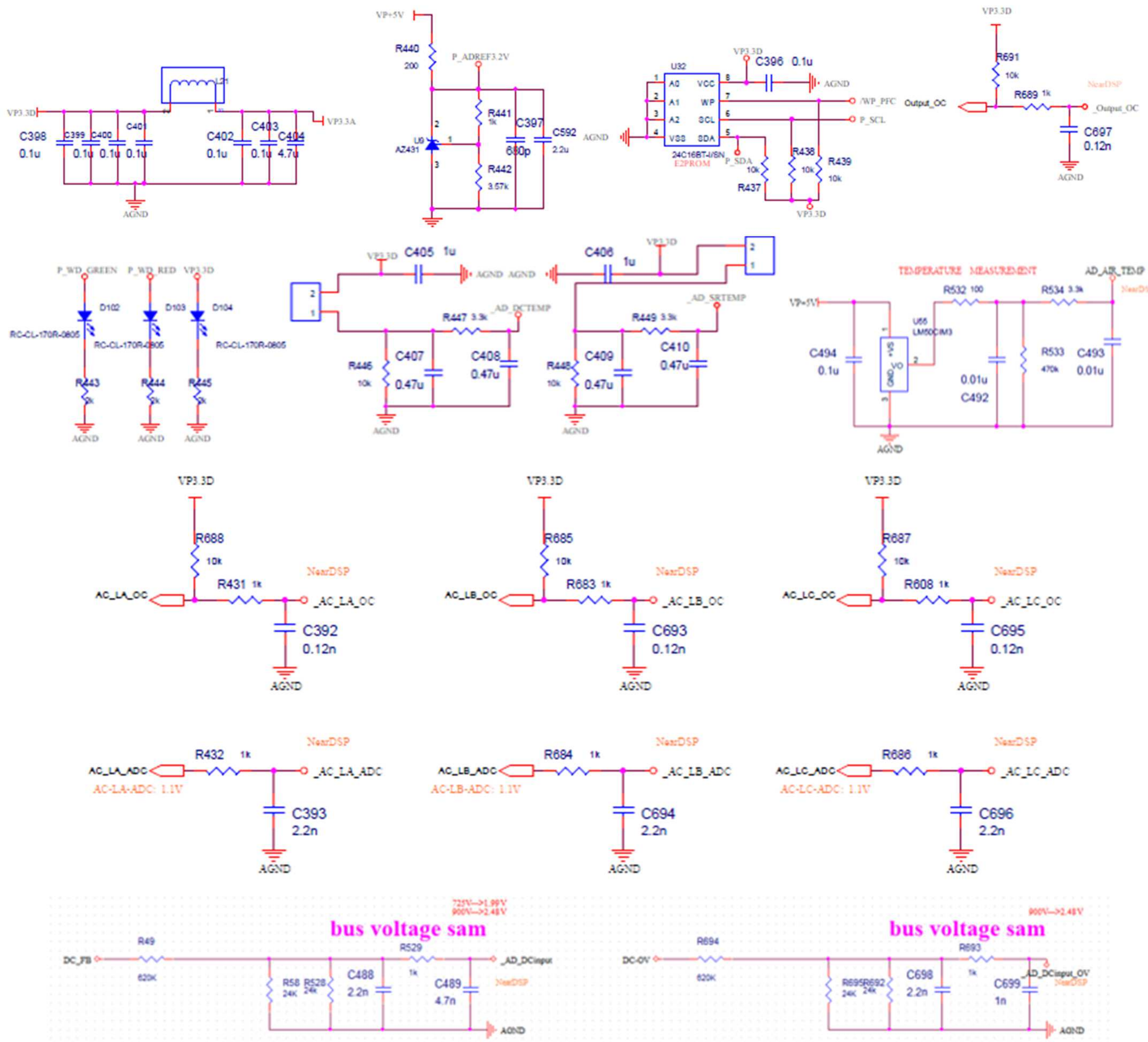


Figure 7 (a): Schematic of control board: Sample circuit

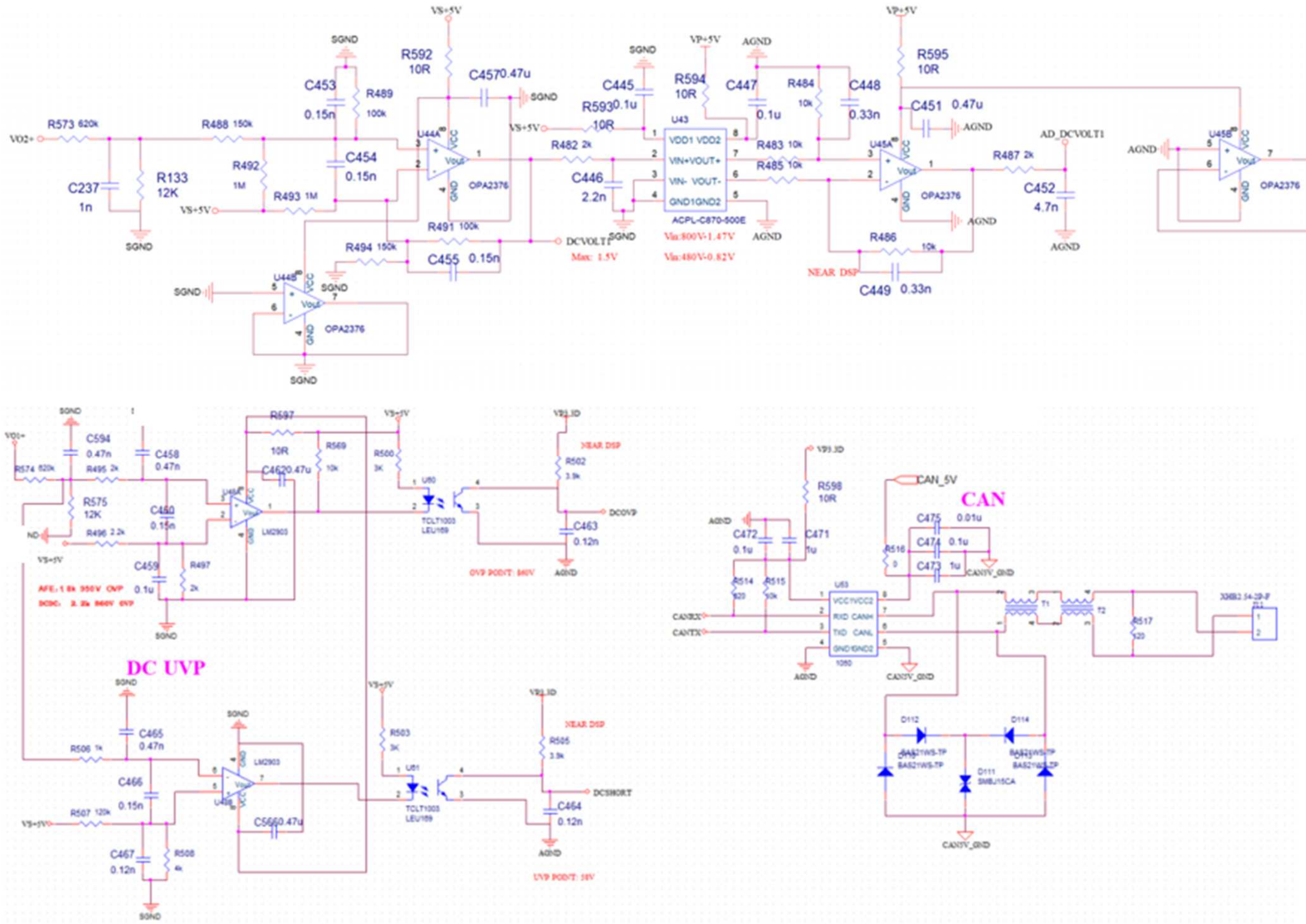


Figure 7 (b): Schematic of control board: Sample and CAN interface

4.3 Auxiliary Power Board Schematic:

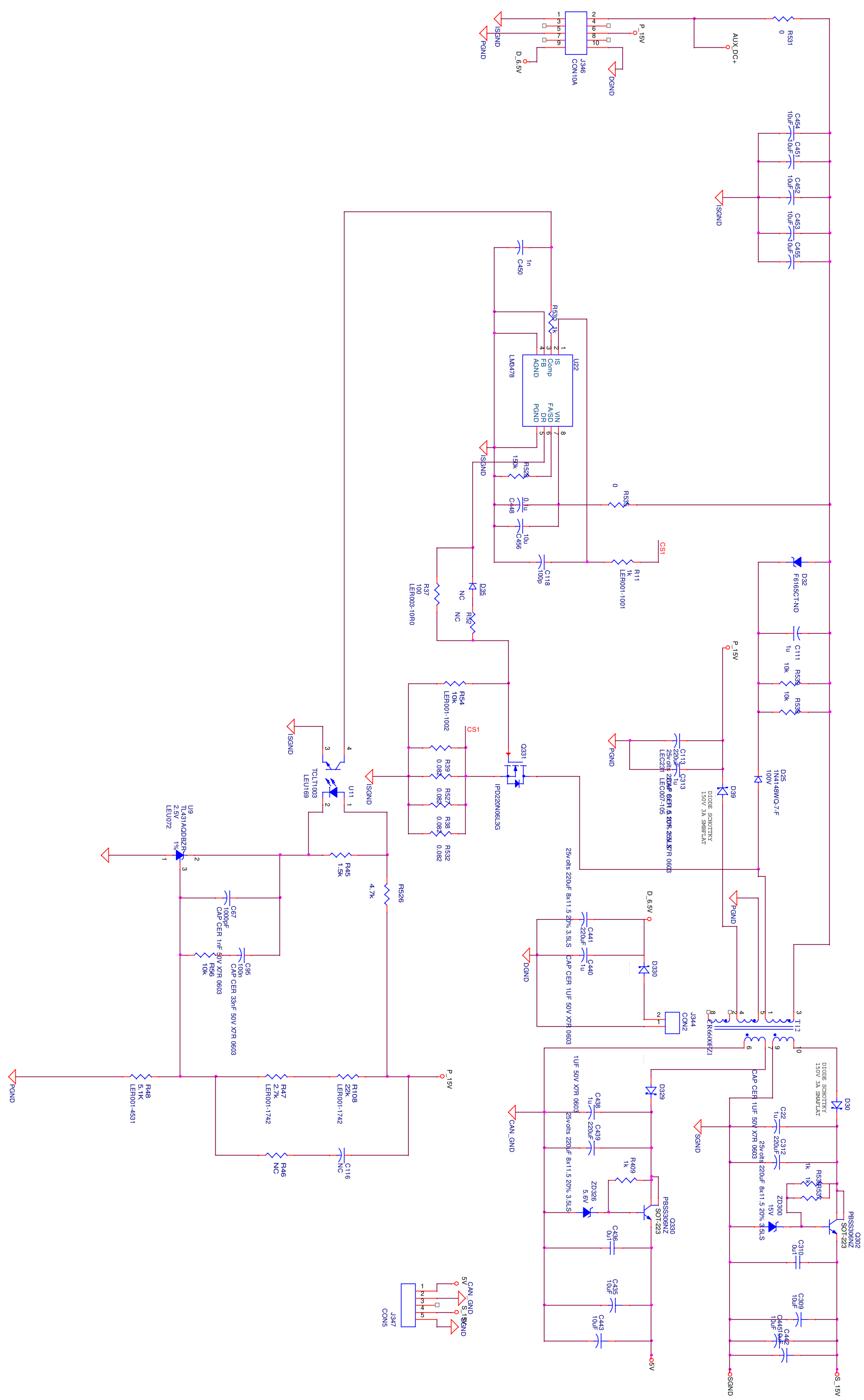


Figure 8: Schematic of auxiliary power board

4.4 Connections of Control and Auxiliary Power Board to Main Board:

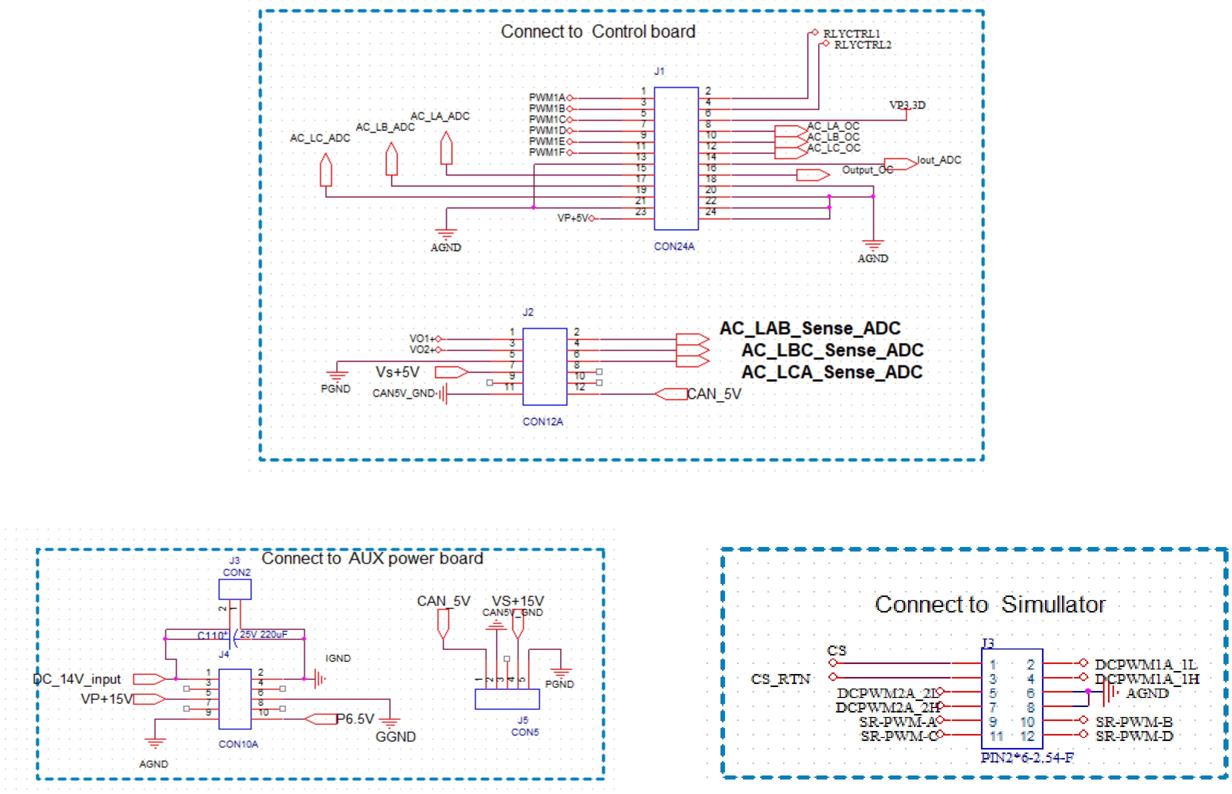


Figure 9: Schematic of connectors of auxiliary power board and main board

5. Hardware Description of Power Board and Control Board

5.1 Description of Power Board:

As illustrated by Figure 2a to 2d, a six-switch, two-level topology is selected for the converter. Three-phase AC line supply in positive sequence is connected to terminals “A,” “B,” and “C” of CON1, 2, and 3 respectively, followed by three-phase fuses (F1~F6) and MOVs (VAR1~VAR3). Electro-magnetic interference (EMI) filters CL1_A1 and CL2_A1 and X/Y capacitors are connected next. This is followed by relays (RLY1, RLY2 and RLY3) and Negative temperature coefficient (NTC) resistors (RV1~RV6) through which the DC link capacitors are charged. NTC resistors will be short-circuited by relays when the DC link voltage is charged. Three Power factor correction (PFC) chokes are connected between relays and midpoints of a three-phase bridge consisting of Wolfspeed SiC MOSFETs (Q7~Q12). The bus-side DC terminals are CON5(+) and CON6(-), followed by ten electrolytic capacitors (five parallel sets of two in a series) which absorb the high-frequency ripple on the DC port. Several film and ceramic capacitors are also arranged in parallel.

For compatible single-phase application, terminals “B” and “C” are used as inputs for L and N. In this situation, relay in phase “A” is always open and terminal “A” should remain unconnected.

As illustrated by Figures 3a to 3b, 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). Input voltage sensing circuits are illustrated in Figure 4.

5.2 Description of Control Board:

As illustrated by Figure 5 to 7, 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, 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 voltage 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 DC bus. The voltage sample signal and OVP/UVP (Over/Under Voltage Protection) signals of the DC bus are isolated by optocouplers before they are fed into the controller for further processing.

5.3 Description of Auxiliary Power Board:

The typical input voltage of the auxiliary power board is 14V (J3-2 = +14 V, J3-1=14 V Return). It provides four isolated output voltages, as shown in Table 5.

Table 5: Input and Outputs of Auxiliary Power Board

Input/Outputs	Net Name	Comments
Input	Aux_DC+/ISGND	14 V Typical Input of the Auxiliary Power Board
Output 1	P_15 V/PGND	15 V Power Supply for MOSFET Gate Drivers
Output 2	S_15 V/SGND	15 V Power Supply for MOSFET Gate Drivers
Output 3	5 V/CAN_GND	5 V Output for CAN Communication
Output 4	D_6.5 V/DGND	Controller Power Supply

5.4 Hardware

AC Input Source: The input source must be an adjustable AC source whose output can be adjusted between 90 VAC and 300 VAC. 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 10, at least two cooling fans, such as the Delta Electronics Inc. DC12 V/3.30 A fan (P/N: PFR0612XHE) or an equivalent fan, must be used for cooling the baseplate. Another fan is used to cool the magnetics. The fans can be placed to let the air flow go to the three PFC inductors and the CM inductors. 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.

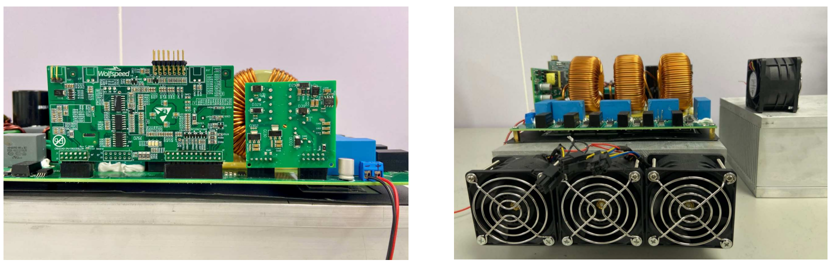


Figure 10: Setup of the reference design

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

5.5 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 10.

The over/under voltage-protection is indicated by the back color of the voltage value, as shown in Figure 11a to Figure11e. "Green" indicates "Normal Operation" while "Red" indicates "Warning Issued." The ambient temperature sensed by the IC is displayed in the panel as well.

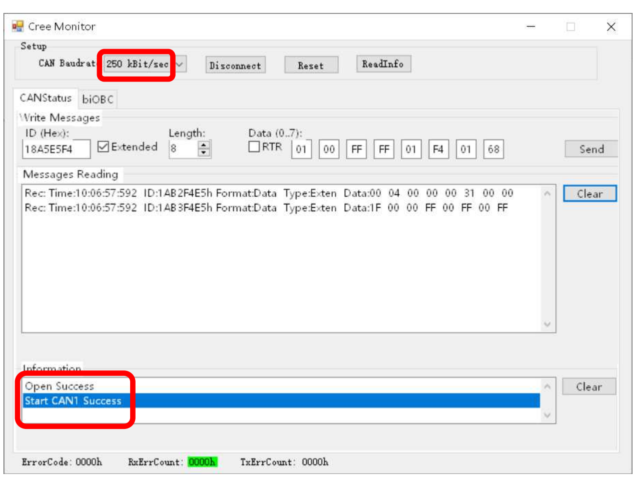


Figure 11 (a): CAN status tab after connection

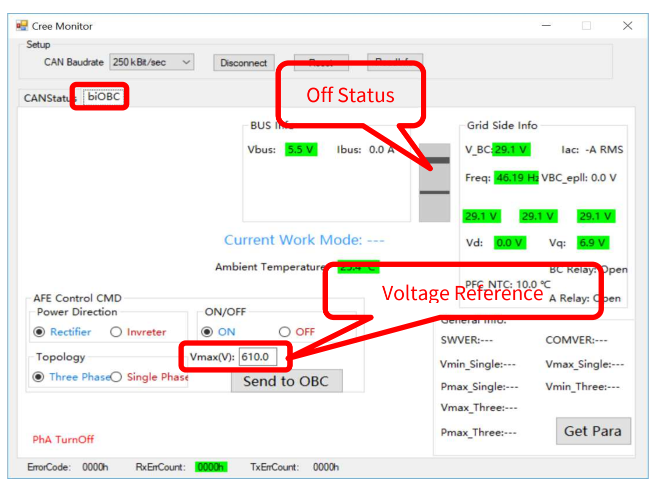


Figure 11 (b): Connected to control board <off mode>

The power direction and topology can only be changed when the rectifier is shut down. This can be accomplished in two steps: first send an “OFF” command to shut down the converter, then send an “ON” command with correct 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 current power direction and topology will also display in the left bottom area.

Voltage reference is the desired output DC voltage in charging mode. The digital controller will check the value range each time. In discharging mode, these reference values have no impact.

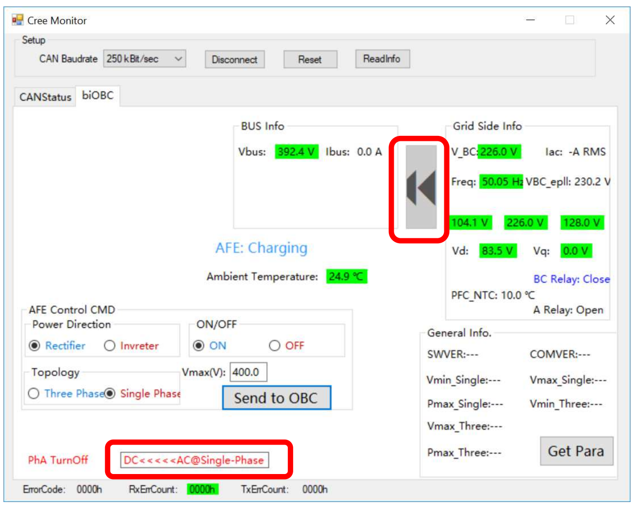


Figure 11 (c): Charging operation in single phase

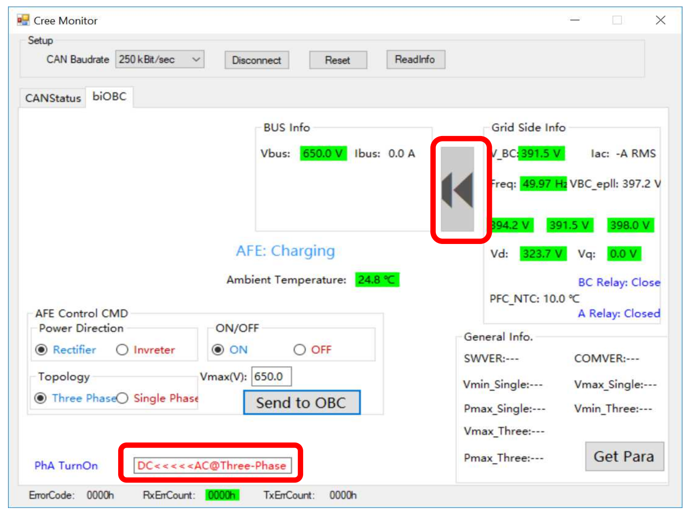


Figure 11 (d): Charging operation in three phase

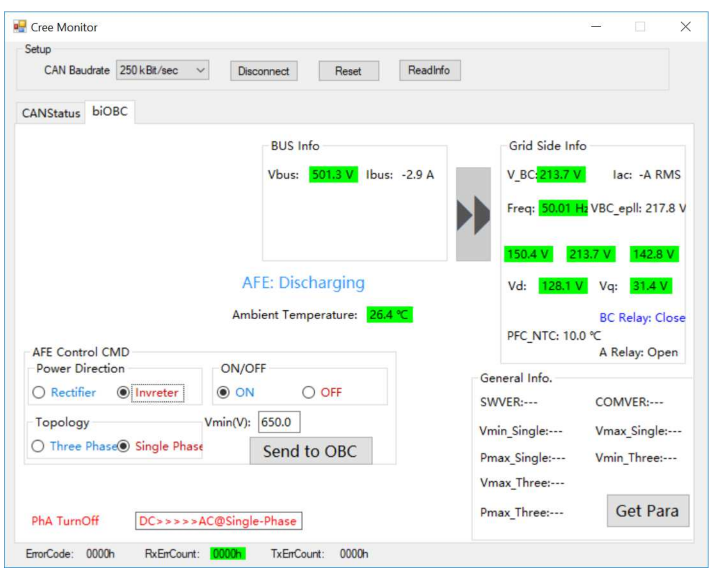


Figure 11 (e): Discharging operation in single phase

OVP fault will be generated if a user connects three-phase power when the software is configured for single phase. To correct this issue, turn the unit off and change the setting to match the correct input.

5.6 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 6 below provides an example when "0x18A5E5F4" is sent as the message identifier and "0x0100FFFF19640168" is sent 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.

There is no current limit function for AFE, so the current reference has no impact at all. User should take precautions to prevent overloading.

Table 6: Example of Control Command

Message Identifier: 0x18A5E5F4					
Data	Byte0 = 01	Byte1= 00	Byte2+Byte3	Byte4+Byte5 = 0x1964	Byte6+Byte7 = 0x0168
Property	0x01: Charging, Three Phase	On	Reserved (0xFFFF)	DC Voltage: 0x1964*0.1 V = 650 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 for Rectifier Mode

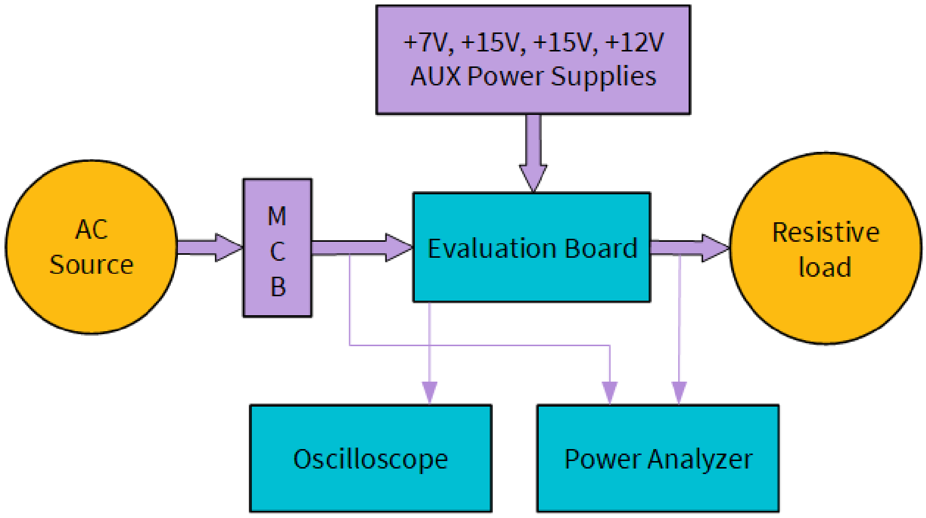


Figure 12: Converter test setup

Miniature circuit breaker (MCB) is optional for the testing setup. Charging mode includes the three-phase AC/DC operation and single-phase AC/DC operation using AC terminal “B” and “C”.

- Connect resistive load to the DC port of the evaluation board.
- Connect AC source to the AC terminals of the evaluation board. AC terminal “A” should be kept floating for single-phase operation.
- 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 Recommended Test Setup for Inverter Mode

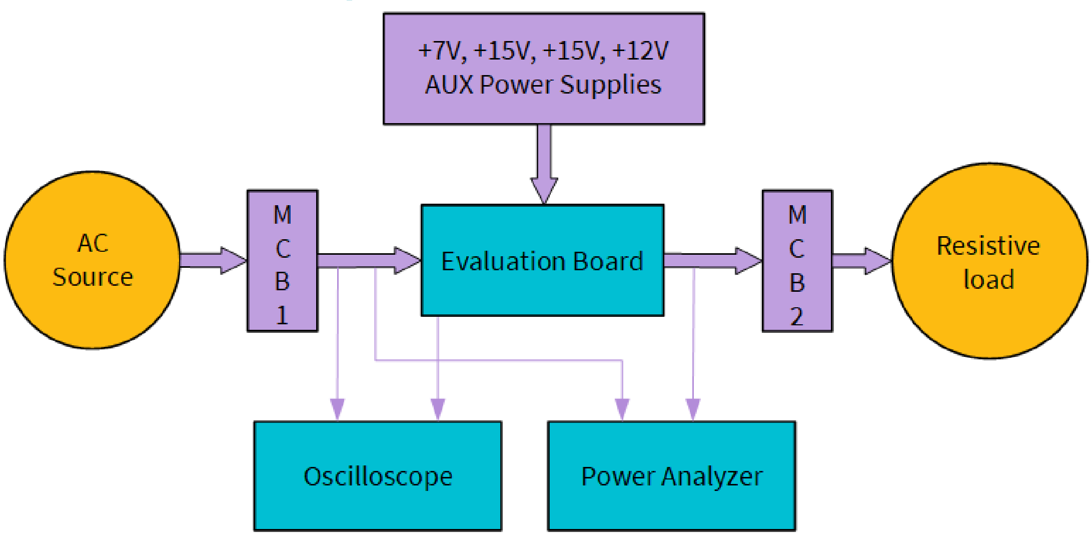


Figure 13: Converter test setup

MCB1 and MCB2 are optional for the testing setup. Discharging mode refers to single-phase DC/AC operation only using AC terminals "B" and "C." Three-phase inverter mode is only used for three-phase drive check.

- Connect resistive load to the AC terminals "B" and "C" of the evaluation board.
- Connect DC source to the DC port of the evaluation board.
- 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.

6.3 Protections

Table 7 describes over/under voltage protection (OVP/UVP) and over current protection (OCP) functions in the reference design.

Do not overload the converter outside the operating specs.

Table 7: Protection Details

Power Signal	Protection Point
DC OVP/UVP	>950 V, <370 V
Line Current OCP	32 A RMS (charging: AC/ DC)

6.4 Isolated Power Supply – Voltage and Current Settings

The requirements for the isolated power supply are shown in Table 8. A single power supply connected to J3 is used to power the on-board auxiliary power board. The cooling fans (DC12 V/3.30 A) are independently powered.

Table 8: 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)
J3	+14 V for AUX power	+14 V +/- 5%	0.45	0.7	0.8

6.5 Measured Parameters

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

Table 9: 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
V_{GS} /V_{DS} Signals	Voltage across gate to source or drain to source of SiC MOSFETs
Auxiliary Power Board Outputs	Please refer to Figure 9 and Table 5 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

Notes:

1. Power direction (rectifier mode or inverter mode) and topology (single-phase or three-phase) cannot be changed after start-up.
2. Choose the appropriate power direction and topology matched with the setup. Phase AC terminal "A" should be left floating if the converter operates as single-phase rectifier or inverter.
3. Make sure the sequence between AC source and terminals of converter. The terminal "A" "B" "C" should connect with phase "U" "V" "W" of AC source if the converter operates as three phases rectifier.
4. Do not overload the converter. The AC line RMS current should not exceed 32 A and the DC output power should not exceed 6.6 kW for single-phase rectifier and 22 kW for three-phase rectifier.
5. There is no current inrush limiter for DC port. The DC input voltage must be increased slowly (soft-start) for inverter mode.
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

Please take the following steps in order when starting the unit in this mode:

1. Double check the setup: Make sure the polarity is correct, the DC source is connected to the DC terminals, and the load is connected to the AC terminals "B" and "C" (terminal "A" unconnected).
2. DC source output disabled.
3. Ensure that the load is less than 1 kW.
4. Apply 14 VDC to J3 on the power board. Check the output voltage of the Auxiliary Power Supply at J4 (P6.5 V, VP+15 V) and J5 (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. Turn on the DC supply and increase it slowly from 0 V to the required voltage (380 VDC – 760 VDC).
8. Verify that the measured values in the GUI are reported correctly.
9. Send ON command with settings of "Inverter" and "Single Phase." Voltage reference has no impact for inverter mode.
10. After the output voltage has reached steady-state regulation, increase the load up to desired value with a maximum of 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.

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: Rectifier Mode

Please take the following steps in order when starting the unit in this mode:

1. Double check the setup: Make sure the AC source is connected to the AC terminals, and the load is connected to the DC terminals. For single-phase operation the AC source should be connected to terminals "B" and "C." Terminal "A" should be left floating.
2. Check the input status and make sure the AC source output is disabled.
3. Make sure no load is applied to the DC terminals until step 11.
4. Apply 14 VDC to J3 on the power board. Check the output voltage of the Auxiliary Power Supply at J4 (P6.5 V, VP+15 V) and J5 (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. Turn on the AC supply (215 V~264 V RMS line-to-neutral).
8. Verify that the measured values in the GUI were reported correctly.
9. Send ON command with settings of "Rectifier" and "Three Phase" or "Single Phase," according to desired output voltage. The converter will start up with the voltage according to Table 1.
10. The output voltage can be regulated using the GUI.
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.

12. Check the efficiency under load conditions of interest.

7.4 Turnoff Procedure: Charging Mode

1. Decrease the load to 1 kW. Do not remove all load or the output capacitors will remain charged for at least 30 minutes after power down. 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 AC source.
4. Wait until the AC source has fully discharged its output.
5. Turn OFF load after the battery side capacitors are fully discharged.
6. **Capacitors may remain charged for up to 30 minutes after the circuit is turned OFF if steps 1, 4, or 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 J3.

8. Photos of the Reference Design

Figure 14 shows the locations of the terminals, key components, and daughter-boards on the Power Board.

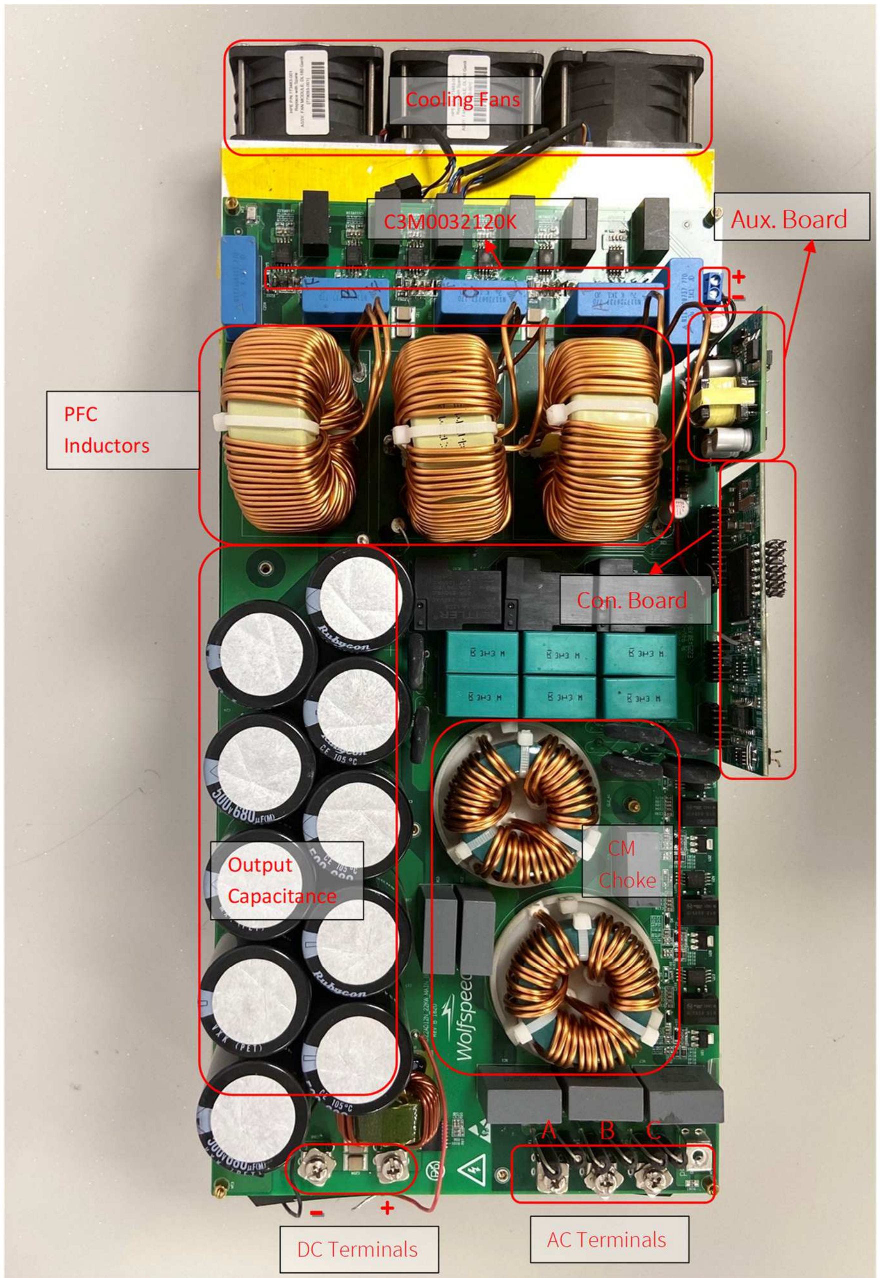


*Figure 15. Top view of PCBA (430 mm*180 mm*150 mm)*

9. Performance Data

The performance data of Wolfspeed's CRD-22AD12N reference design board is taken in AC/DC single-phase and three-phase charging modes, and DC/AC single-phase discharging. Table 10 to Table 17 indicates the performance data.

Table 10: Efficiency Data (AC/DC Single-Phase Mode), V_{IN} = 230 V_{AC}

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
230	681	10	385	663	97.38
230	1348	20	385	1329	98.55
230	2026	30	385	1999	98.70
230	2701	40	385	2666	98.68
230	3332	50	385	3286	98.62
230	4012	60	385	3950	98.46
230	4697	70	385	4616	98.28
230	5300	80	385	5202	98.14
230	6062	90	385	5937	97.93
230	6597	100	385	6451	97.78
230	684	10	650	648	94.77
230	1333	20	650	1292	96.94
230	1987	30	650	1939	97.59
230	2710	40	650	2651	97.82
230	3368	50	650	3295	97.83
230	4031	60	650	3943	97.83
230	4663	70	650	4556	97.72
230	5331	80	650	5203	97.60
230	6007	90	650	5854	97.45
230	6691	100	650	6509	97.27
230	870	10	900	802	92.14
230	1275	20	900	1203	94.33
230	2084	30	900-	2001	96.00
230	2487	40	900	2398	96.40
230	3302	50	900	3195	96.78
230	4125	60	900	3996	96.87
230	4896	70	900	4743	96.88
230	5314	80	900	5146	96.84
230	6150	90	900	5948	96.72
230	6585	100	900	6366	96.67

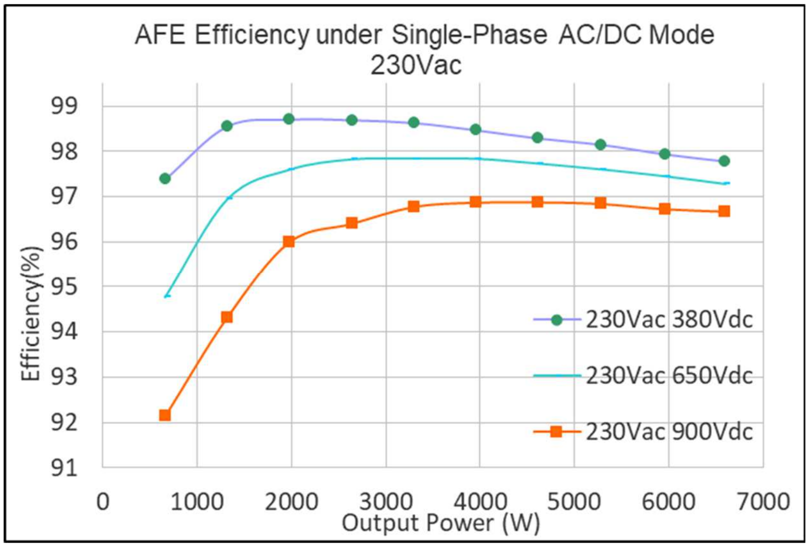


Figure 16: Efficiency data (AC/DC single-phase mode), V_{IN} = 230 V_{AC}

Table 11: Efficiency Data (AC/DC Single-Phase Mode), V_{IN} = 180 V_{AC}

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
180	682	10	385	661	96.81
180	1338	20	385	1312	98.03
180	2017	30	385	1979	98.08
180	2732	40	385	2675	97.93
180	3347	50	385	3270	97.71
180	4064	60	385	3933	97.42
180	4711	70	385	4575	97.11
180	5175	80	385	5014	96.88
180	677	10	650	637	94.10
180	1310	20	650	1262	96.36
180	2144	30	650	2080	97.01
180	2576	40	650	2500	97.06
180	3445	50	650	3340	96.94
180	4105	60	650	3972	96.76
180	4569	70	650	4414	96.61
180	5237	80	650	5045	96.35
180	875	10	900	808	92.35
180	1287	20	900	1214	94.36
180	2104	30	900	2013	95.70
180	2511	40	900	2490	95.96
180	3342	50	900	3214	96.17

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
180	4205	60	900	4034	95.93
180	5055	70	900	4841	95.78
180	5489	80	900	5255	95.73

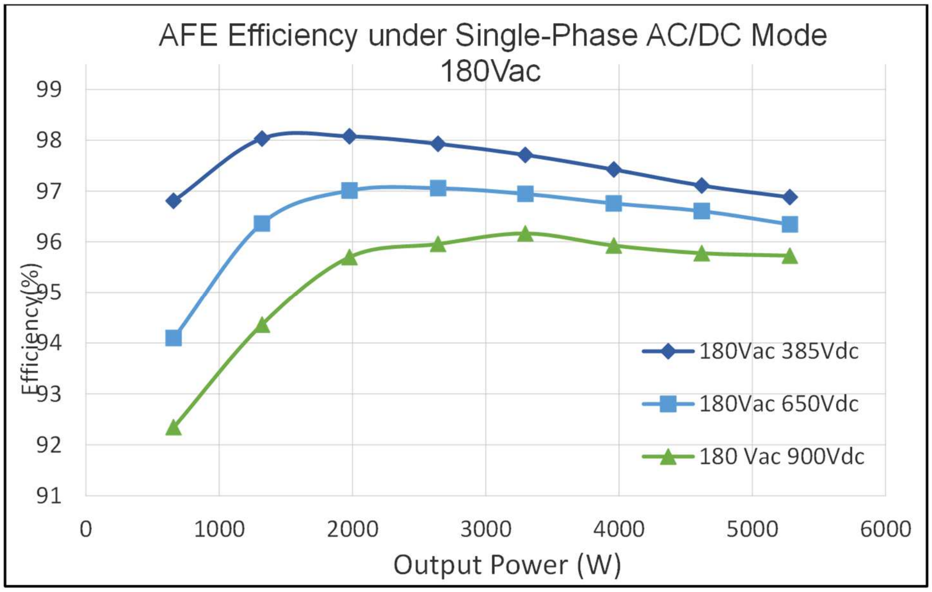


Figure 17: Efficiency data (AC/DC single-phase mode), V_{IN} = 180 V_{AC}

Table 12: Efficiency Data (AC/DC Single-Phase Mode), V_{IN} = 215 V_{AC}

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
215	683	10	385	661	96.77
215	1346	20	385	1323	98.26
215	2021	30	385	1989	98.45
215	2693	40	385	2652	98.45
215	3369	50	385	3312	98.32
215	4042	60	385	3968	98.15
215	4676	70	385	4582	98.01
215	5361	80	385	5245	97.83
215	6049	90	385	5902	97.58
215	6202	100	385	6050	97.54
215	1311	10	650	1264	96.42
215	1952	20	650	1896	97.15
215	2659	30	650	2591	97.45

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
215	3521	40	650	3434	97.54
215	4172	50	650	4065	97.43
215	4827	60	650	4698	97.32
215	5266	70	650	5122	97.27
215	5492	80	650	5339	97.21
215	6154	90	650	5973	97.05
215	870	10	900	803	92.22
215	1277	20	900	1205	94.33
215	2087	30	900	2004	95.98
215	2494	40	900	2403	96.35
215	3310	50	900	3199	96.64
215	4102	60	900	3969	96.77
215	4936	70	900	4773	96.70
215	5363	80	900	5181	96.61
215	6213	90	900	5990	96.42

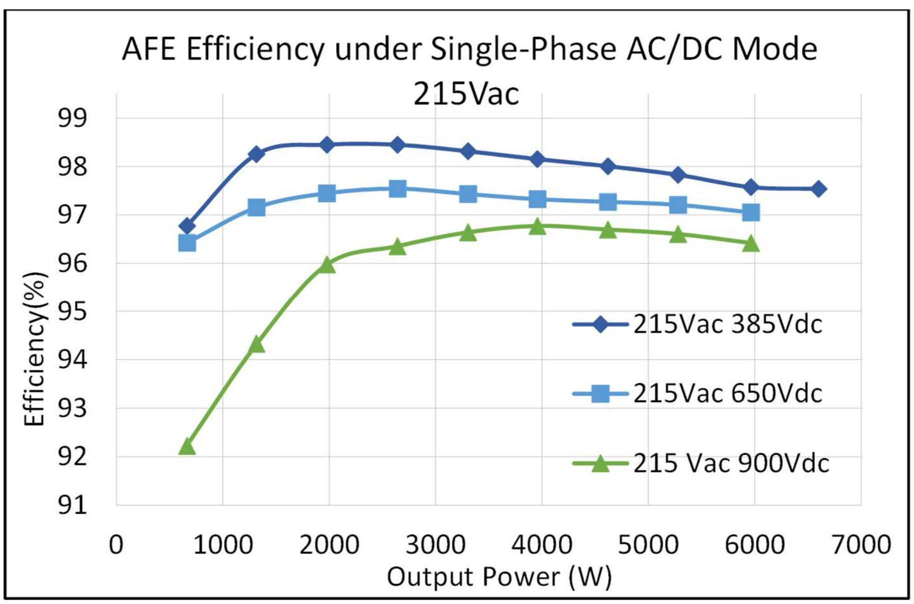


Figure 18: Efficiency data (AC/DC single-phase mode), $V_{IN} = 215\ V_{AC}$

Table 13: Efficiency Data (AC/DC Single-Phase Mode), V_{IN} = 264 V_{AC}

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
264	680	10	385	660	97.10
264	1349	20	385	1329	98.51
264	2016	30	385	1991	98.78
264	2639	40	385	2607	98.80
264	3312	50	385	3272	98.78
264	3979	60	385	3927	98.70
264	4727	70	385	4661	98.60
264	5327	80	385	5246	98.46
264	6079	90	385	5978	98.33
264	6756	100	385	6633	98.18
264	676	10	650	635	93.97
264	1311	20	650	1265	96.47
264	1950	30	650	1899	97.38
264	2595	40	650	2536	97.71
264	3448	50	650	3377	97.93
264	4092	60	650	4008	97.95
264	4724	70	650	4627	97.94
264	5368	80	650	5255	97.90
264	6234	90	650	6094	97.75
264	6895	100	650	6737	97.71
264	875	10	900	806	92.13
264	1283	20	900	1209	94.19
264	2089	30	900	2006	96.01
264	2903	40	900	2808	96.72
264	3304	50	900	3203	96.94
264	4062	60	900	3947	97.17
264	4888	70	900	4753	97.22
264	5309	80	900	5163	97.27
264	6135	90	900	5966	97.24
264	6966	100	900	6768	97.16

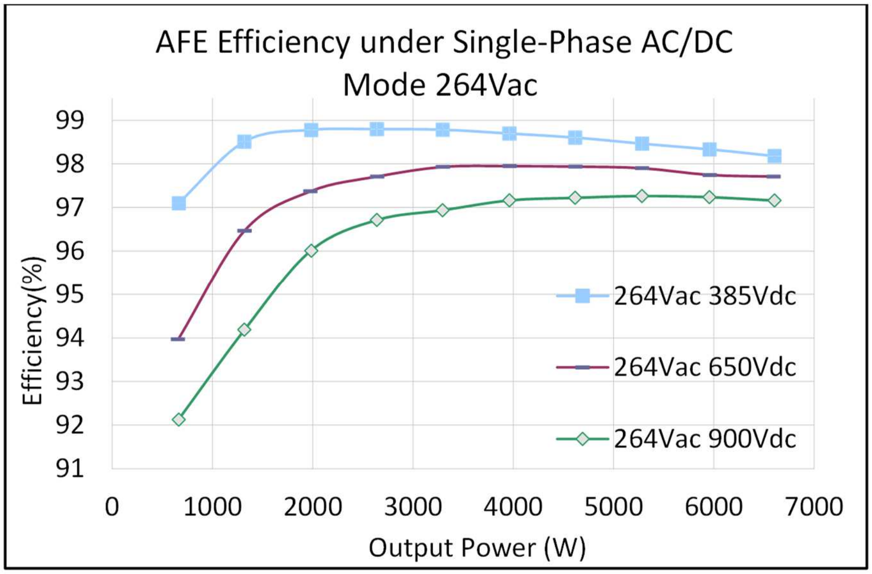


Figure 19: Efficiency data (AC/DC single-phase mode), V_{IN} = 264 V_{AC}

Table 14: Efficiency Data (AC/DC Three-Phase Mode) 230 V_{AC}

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
230	788	779	788	10	650	2292	97.32
230	1495	1467	1499	20	650	4385	98.30
230	2262	2225	2261	30	650	6653	98.60
230	2967	2924	2965	40	650	8741	98.70
230	3750	3697	3740	50	650	11041	98.70
230	4482	4415	4466	60	650	13184	98.67
230	5190	5115	5167	70	650	15257	98.62
230	5882	5800	5856	80	650	17283	98.54
230	6574	6514	6584	90	650	19370	98.46
230	840	815	848	10	780	2409	96.29
230	1558	1525	1561	20	780	4533	97.63
230	2249	2207	2247	30	780	6572	98.07
230	3064	3013	3058	40	780	8977	98.28
230	3800	3740	3788	50	780	11139	98.34
230	4509	4438	4493	60	780	13216	98.33
230	5232	5153	5211	70	780	15330	98.29
230	5849	5762	5823	80	780	17130	98.25
230	6784	6682	6752	90	780	19845	98.16
230	849	821	857	10	900	2678	95.19
230	1527	1491	1529	20	900	4905	96.96

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
230	2201	2159	2200	30	900	6402	97.59
230	2994	2942	2988	40	900	8737	97.90
230	3808	3746	3798	50	900	11128	98.02
230	4597	4523	4581	60	900	13434	98.05
230	5419	5336	5400	70	900	15836	98.03
230	5971	5878	5951	80	900	17441	97.99
230	6801	6696	6778	90	900	19852	97.92

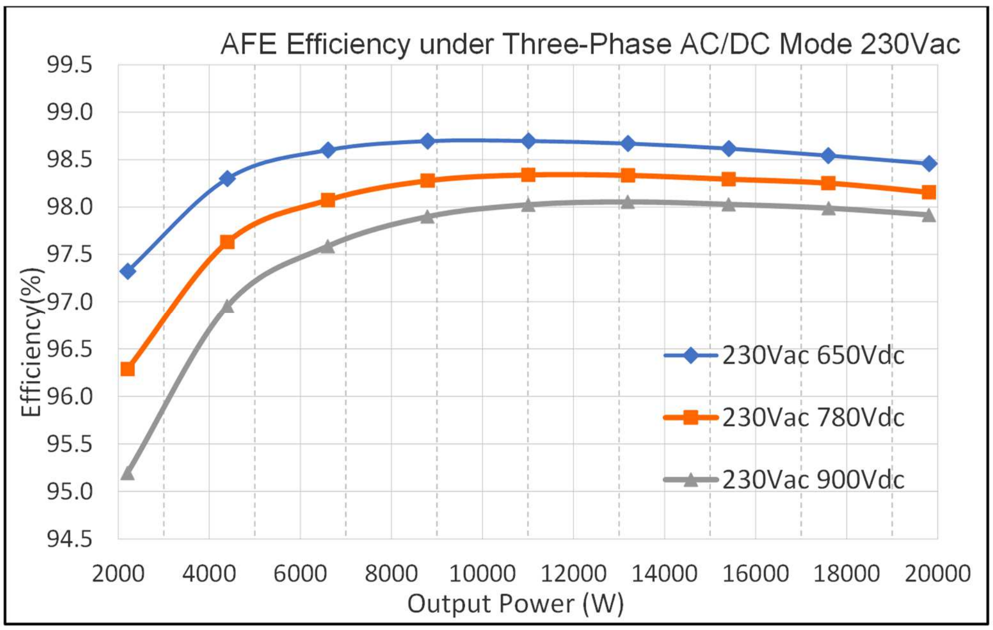


Figure 20: Efficiency data (AC/DC three-phase mode) 230 V_{AC}

Table 15: Efficiency Data (AC/DC Three-Phase Mode) 176 V_{AC}

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
176	803	784	807	10	650	2318	96.86
176	1512	1485	1511	20	650	4413	97.88
176	2242	2206	2237	30	650	6560	98.13
176	3018	2972	3007	40	650	8831	98.17
176	3796	3739	3779	50	650	11097	98.10
176	4514	4446	4493	60	650	13182	97.99
176	5161	5083	5141	70	650	15055	97.85
176	844	823	846	10	780	2410	95.89

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
176	1581	1551	1579	20	780	4583	97.27
176	2287	2248	2280	30	780	6656	97.66
176	3007	2959	2996	40	780	8761	97.76
176	3718	3660	3702	50	780	10831	97.75
176	4553	4484	4522	60	780	13250	97.65
176	5180	5101	5156	70	780	15058	97.54
176	851	829	853	10	900	2400	94.76
176	1497	1469	1495	20	900	4304	96.47
176	2176	2140	2170	30	900	6299	97.11
176	2998	2951	2986	40	900	8698	97.36
176	3819	3762	3804	50	900	11090	97.41
176	4509	4445	4493	60	900	13091	97.35
176	5204	5126	5186	70	900	15089	97.24

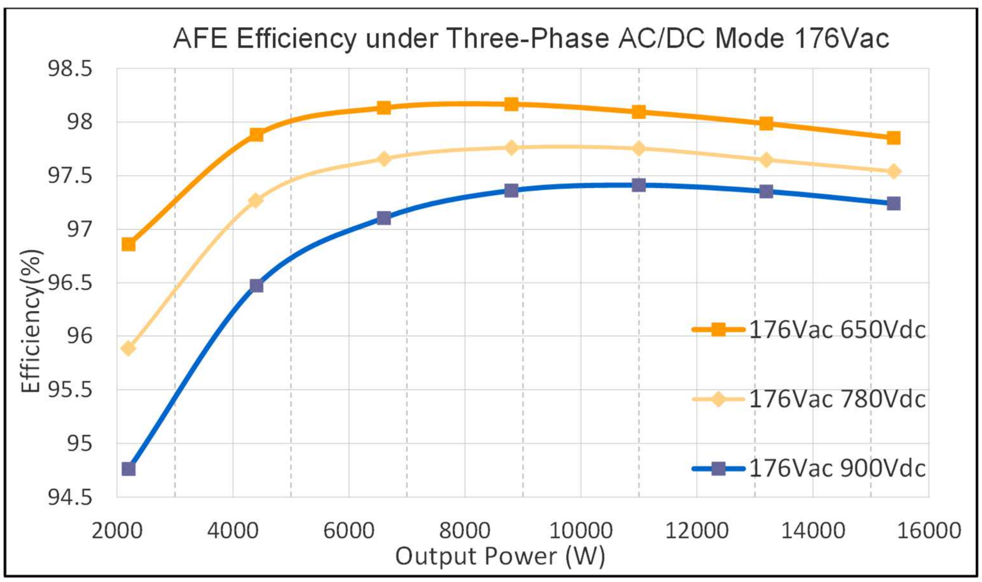


Figure 21: Efficiency data (AC/DC three-phase mode) 176 V_{AC}

Table 16: Efficiency Data (AC/DC Three-Phase Mode) 264 V_{AC}

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
264	857	845	869	10	650	2519	97.98
264	1566	1543	1571	20	650	4618	98.65
264	2268	2237	2270	30	650	6696	98.85
264	2972	2931	2969	40	650	8778	98.94

Input Voltage (VAC)	Input Power A (W)	Input Power B (W)	Input Power C (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
264	3770	3720	3762	50	650	11134	98.96
264	4481	4422	4467	60	650	13227	98.95
264	5262	5194	5245	70	650	15528	98.90
264	5967	5895	5947	80	650	17603	98.84
264	6519	6442	6496	90	650	19223	98.80
264	847	815	856	10	780	2414	96.66
264	1528	1489	1532	20	780	4579	97.90
264	2203	2156	2204	30	780	6637	98.32
264	2985	2929	2982	40	780	8742	98.51
264	3796	3730	3789	50	780	11383	98.59
264	4592	4517	4580	60	780	13197	98.61
264	5272	5191	5259	70	780	15544	98.60
264	5957	5871	5943	80	780	17657	98.57
264	6777	6687	6761	90	780	19776	98.52
264	7604	7511	7588	100	780	22188	98.45
264	837	812	849	10	900	2401	95.33
264	1569	1535	1574	20	900	4417	97.10
264	2264	2222	2265	30	900	6414	97.75
264	2976	2925	2974	40	900	8726	98.09
264	3872	3810	3863	50	900	11115	98.24
264	4489	4419	4475	60	900	13457	98.31
264	5288	5208	5270	70	900	15457	98.32
264	6008	5920	5920	80	900	17471	98.31
264	6732	6636	6705	90	900	19876	98.28
264	7556	7454	7528	100	900	22300	98.23

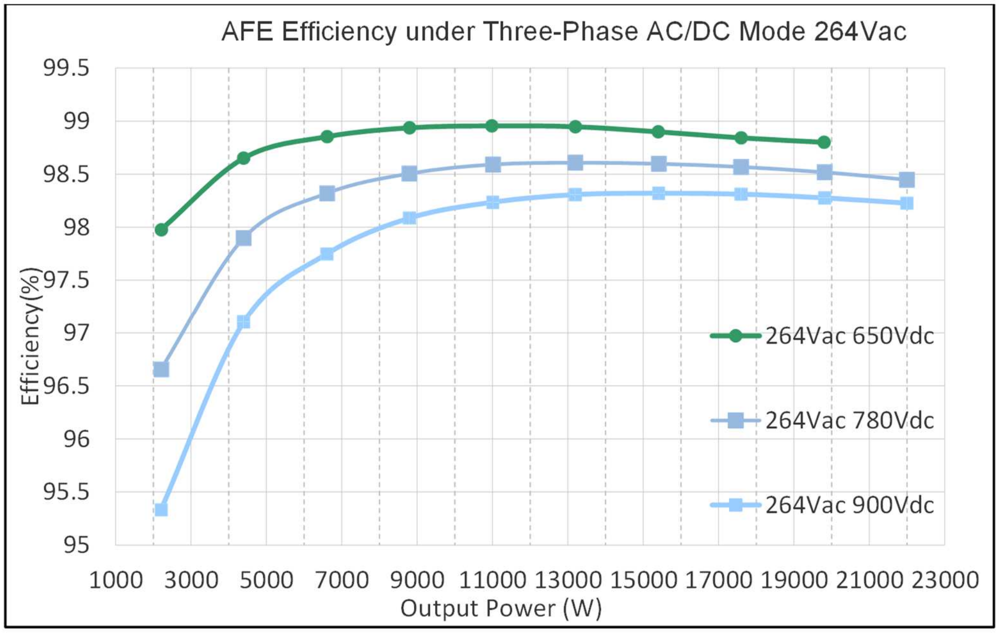


Figure 22: Efficiency data (AC/DC three-phase mode) 264 V_{AC}

Table 17: Efficiency Data (DC/AC Single-Phase Mode)

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
350	680	10	224	669	98.53
350	1341	20	223	1325	98.77
350	1999	30	222	1973	98.70
350	2716	40	222	2681	98.69
350	3441	50	222	3389	98.49
350	4034	60	222	3968	98.36
350	4723	70	221	4636	98.17
350	5365	80	220	5257	97.98
350	5547	90	220	5435	97.98
350	6616	100	220	6470	97.80
500	691	10	220	673	97.31
500	1347	20	219	1321	98.10
500	2011	30	218	1975	98.24
500	2692	40	218	2644	98.19
500	3374	50	218	3313	98.18
500	4058	60	217	3978	98.03
500	4740	70	216	4639	97.87
500	5381	80	216	5255	97.67
500	6131	90	215	5981	97.56
500	6475	100	215	6311	97.47

Input Voltage (VAC)	Input Power (W)	Load (%)	Output Voltage (VDC)	Output Power (W)	Overall Efficiency (%)
610	704	10	217	679	96.40
610	1349	20	216	1311	97.51
610	2031	30	215	1988	97.90
610	2707	40	215	2651	97.94
610	3377	50	215	3307	97.89
610	4050	60	214	3960	97.76
610	4739	70	214	4627	97.64
610	5263	80	213	5131	97.49
610	6129	90	213	5975	97.49
610	6462	100	212	6295	97.41
760	722	10	215	687	95.05
760	1371	20	214	1326	96.73
760	2017	30	213	1961	97.26
760	2720	40	212	2650	97.44
760	3400	50	211	3310	97.36
760	4058	60	211	3950	97.34
760	4786	70	210	4650	97.19
760	5099	80	210	4955	97.17
760	6156	90	209	5970	96.98
760	6381	100	209	6182	96.88

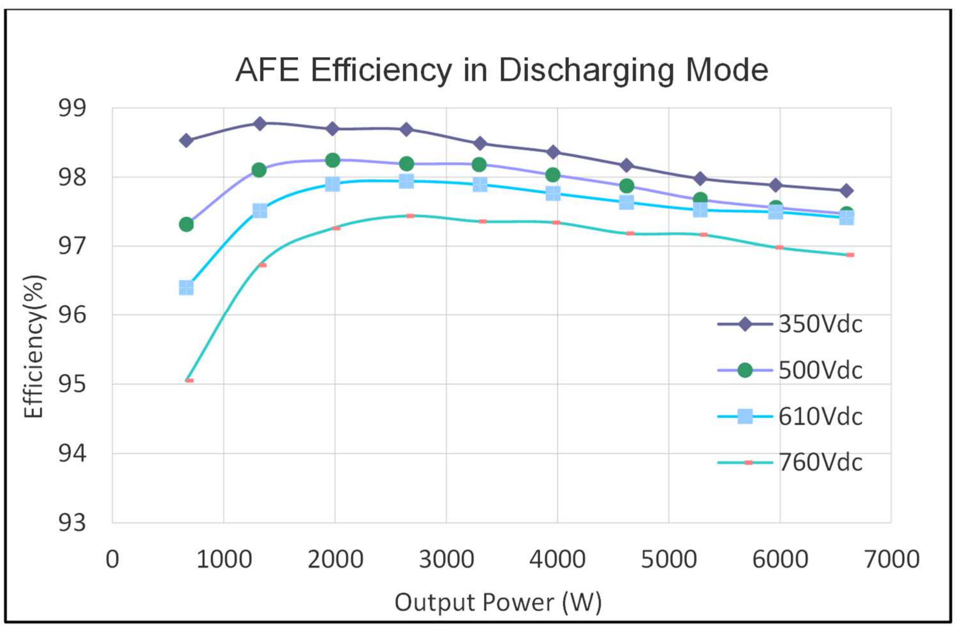


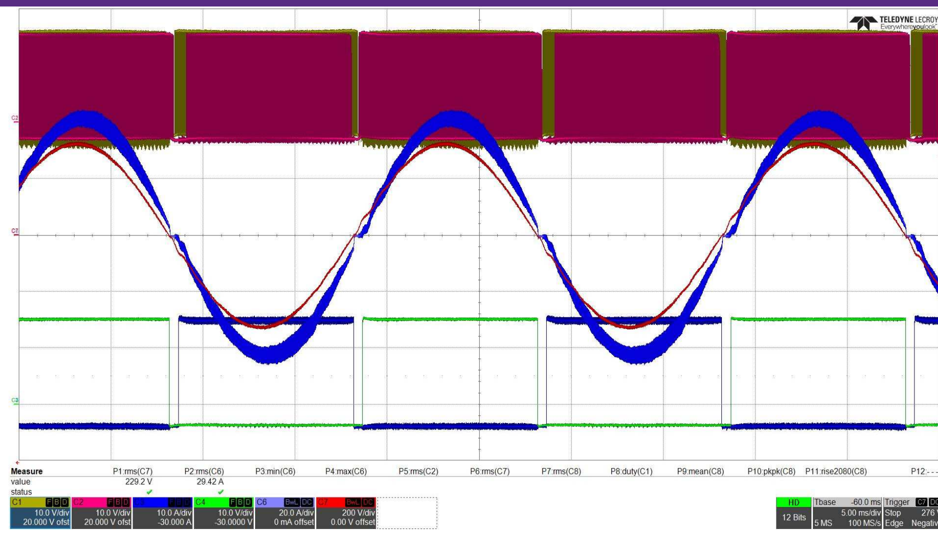
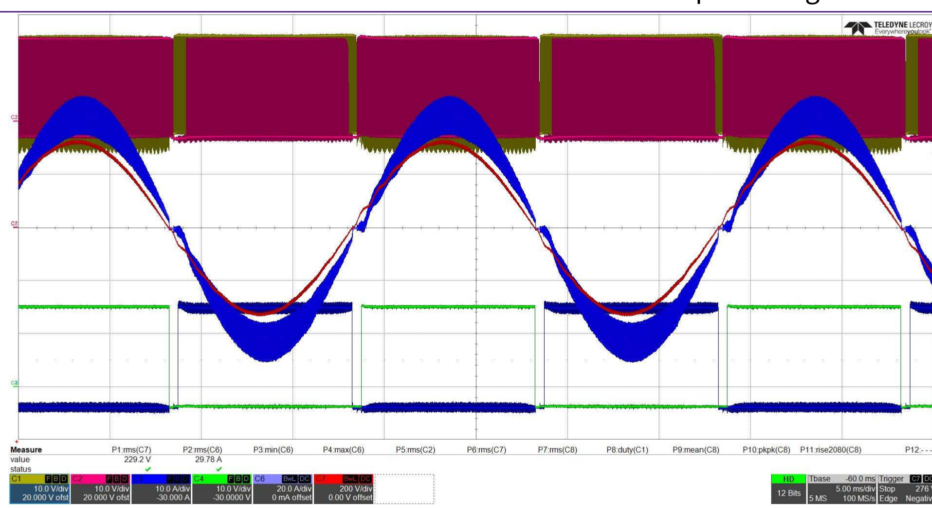
Figure 23: Efficiency data (AC/DC single-phase mode)

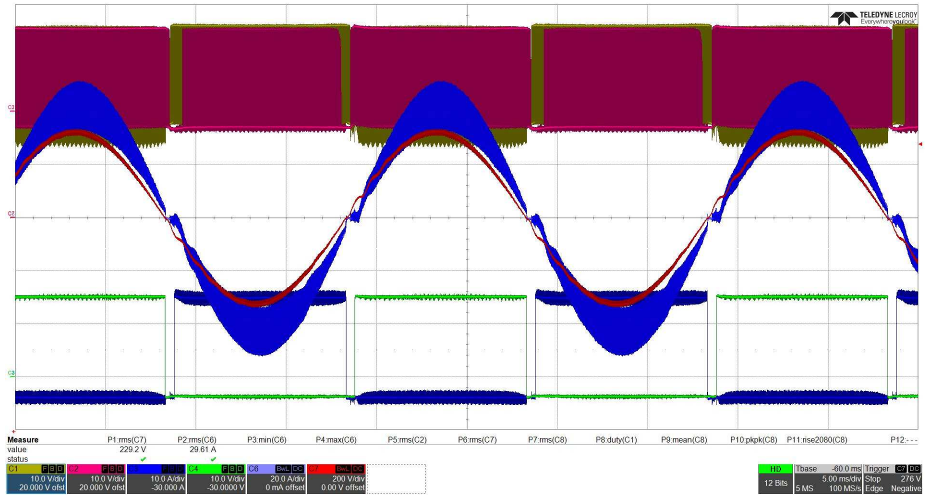
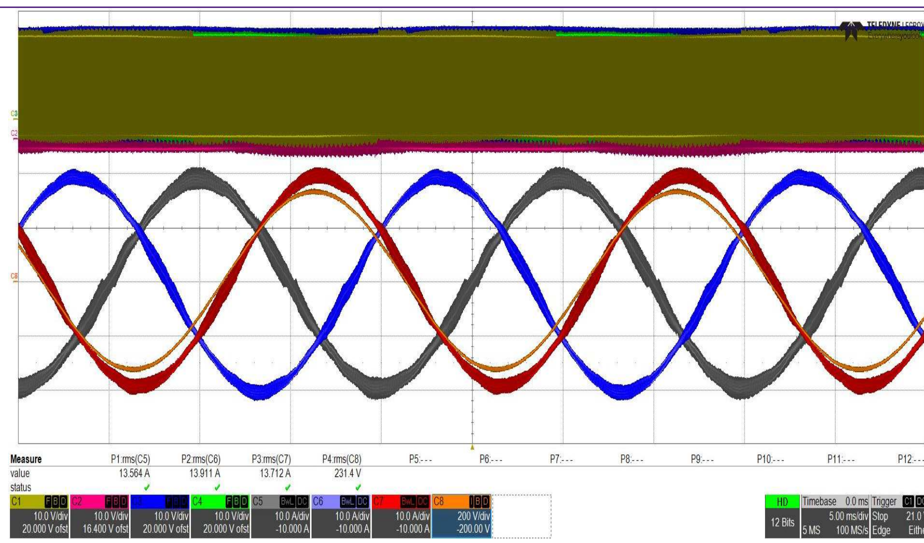
10. Typical Waveforms

Operational waveforms are presented in Table 18 and Table 19.

10.1 AC/DC Charging Mode:

Table 18: AC/DC Charging Mode Waveforms

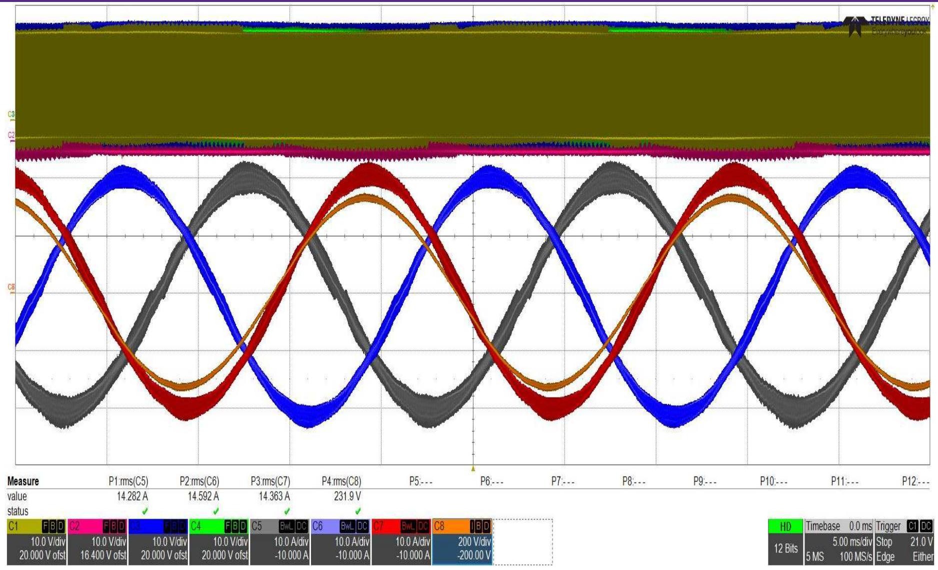
Condition	Waveform
AC/DC Single-Phase Charging Mode **Input: 230 V_{AC}** **Output: 380 VDC** **Full Load**	 CH1: VGS high frequency, high side CH2: VGS high frequency, low side CH3: VGS low frequency, high side CH4: VGS low frequency, low side CH6: Choke current of LB CH7: Input voltage
AC/DC Single-Phase Charging Mode **Input: 230 V_{DC}** **Output: 650 V_{DC}** **Full Load**	 CH1: VGS high frequency, high side CH2: VGS high frequency, low side CH3: VGS low frequency, high side CH4: VGS low frequency, low side CH6: Choke current of LB CH7: Input voltage

Condition	Waveform
AC/DC Single-Phase Charging Mode **Input: 230 V_{DC}** **Output: 900 VDC** **Full Load**	 CH1: VGS high frequency, high side CH2: VGS high frequency, low side CH3: VGS low frequency, high side CH4: VGS low frequency, low side CH6: Choke current of LB CH7: Input voltage
AC/DC Three-Phase Charging Mode **Input: 230 V_{DC}** **Output: 650 V_{DC}** **Full Load**	 CH1/3/4: VGS low side of phase C/B/A CH2: VGS high side of phase B CH5-7: Choke current of LA、LC、LB CH8: Input voltage of phase B

<table>
<tr><th>Condition</th><th>Waveform</th></tr>
<tr><td>AC/DC Three-Phase Charging Mode

Input: 230 V_{DC}

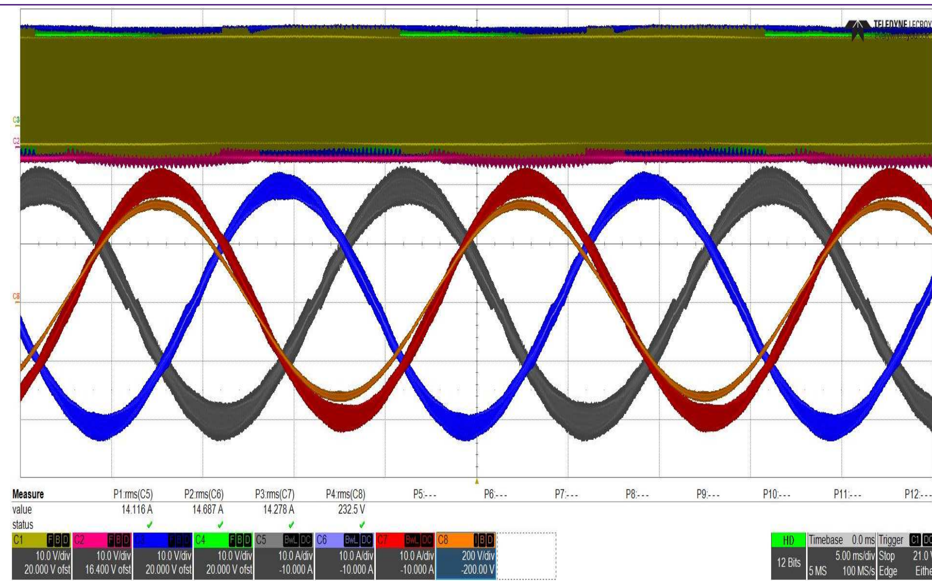
Output: 780 V_{DC}

Full Load</td><td>

CH1/3/4: VGS low side of phase C/B/A CH2: VGS high side of phase B
CH5-7: Choke current of LA、LC、LB CH8: Input voltage of phase B</td></tr>
<tr><td>AC/DC Three-Phase Charging Mode

Input: 230 V_{DC}

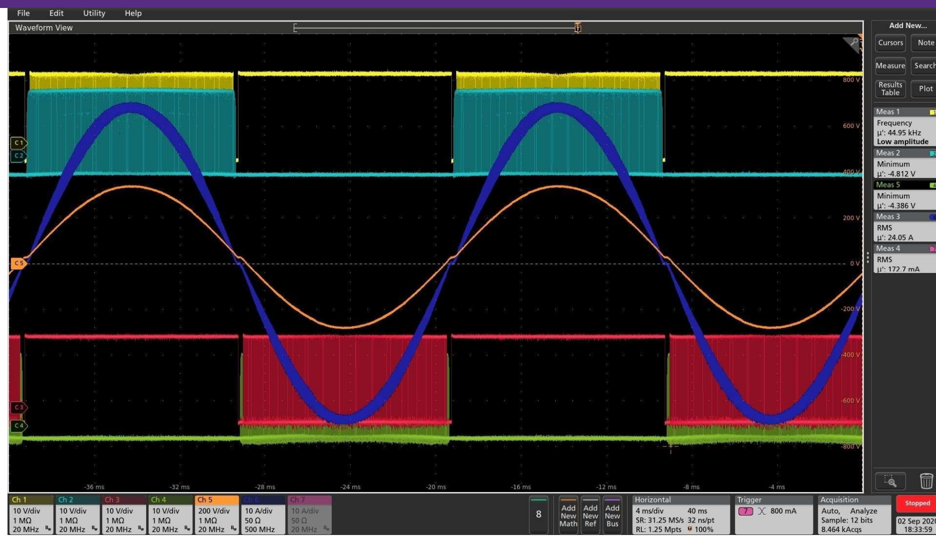
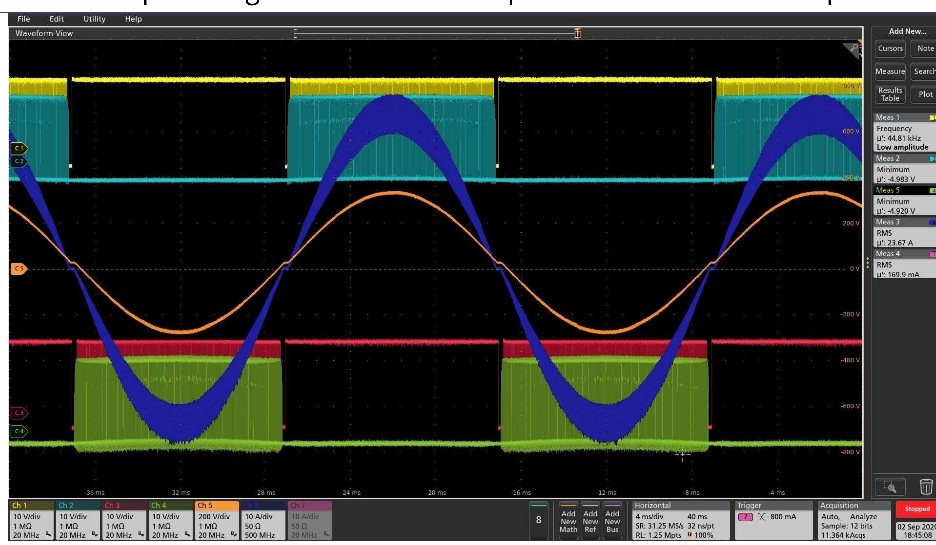
Output: 900 V_{DC}

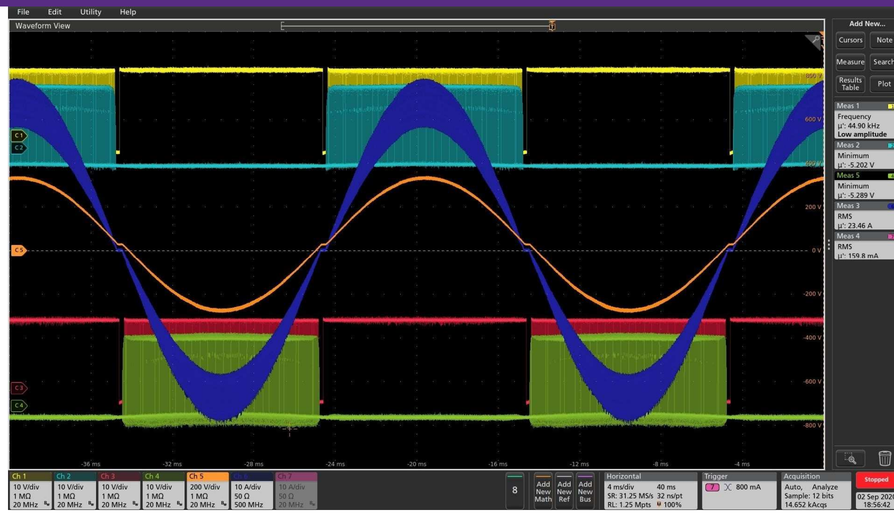
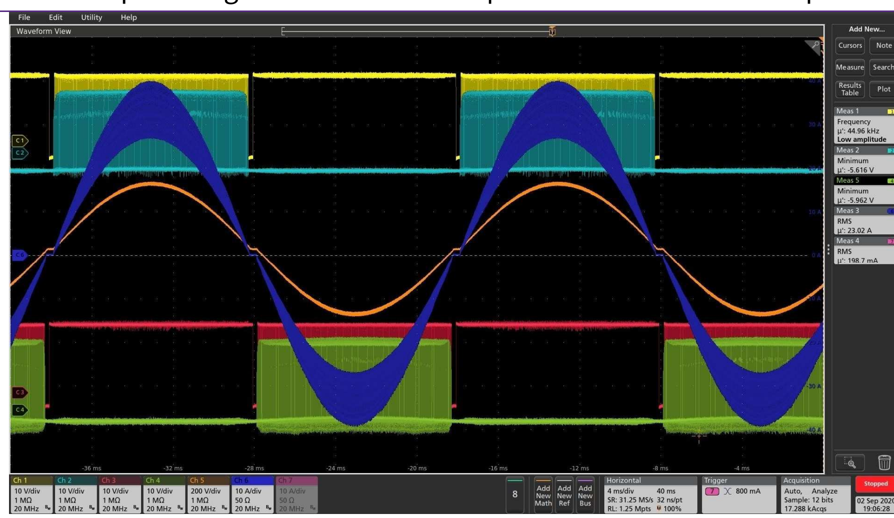
Full Load</td><td>

CH1/3/4: VGS low side of phase C/B/A CH2: VGS high side of phase B
CH5-7: Choke current of LA、LC、LB CH8: Input voltage of phase B</td></tr>
</table>

10.2 DC/AC Single-Phase Discharging Mode: (Resistive Load)

Table 19: DC/AC Single-Phase Discharging Mode Waveforms

Condition	Waveform
DC/AC Discharging Mode **Input: 350 V_{DC}** **Output: 220 V_{AC}** **Full Load**	 CH1: VGS B phase low side CH2: VGS B phase high side CH6: PFC choke current CH3: VGS C phase high side CH4: VGS C phase low side CH7: Output Voltage
DC/AC Discharging Mode **Input: 500 V_{DC}** **Output: 220 V_{AC}** **Full Load**	 CH1: VGS B phase low side CH2: VGS B phase high side CH6: PFC choke current CH3: VGS C phase high side CH4: VGS C phase low side CH7: Output Voltage

Condition	Waveform
DC/AC Discharging Mode Input: 610 V_{DC} Output: 220 V_{AC} Full Load	 CH1: VGS B phase low side CH2: VGS B phase high side CH6: PFC choke current CH3: VGS C phase high side CH4: VGS C phase low side CH7: Output Voltage
DC/AC Discharging Mode Input: 760 V_{DC} Output: 220 V_{AC} Full Load	 CH1: VGS B phase low side CH2: VGS B phase high side CH6: PFC choke current CH3: VGS C phase high side CH4: VGS C phase low side CH7: Output Voltage

11. Thermal Design and Test Results

In a thermal test of the unit, forced-air cooling is applied to the bottom side of the cooling baseplate to achieve and maintain a 65^{0}C cooling plate. This simulates the thermal condition in an OBC application. There is no direct air flow to the power MOSFETs. MOSFETs in the AFE converter operate in full load thermal condition with a 32 A load. The thermal test was performed at 220 VAC input and full load 22 kW with 900 V/32 A load in three-phase AC/DC mode, 230 VAC input and full load 6.6 kW with 900 V/32 A load in single-phase AC/DC mode, and 760 VDC input and full load 6.6 kW with 220 VAC/32 A load in single-phase AC/DC mode. K-type thermal couples and an acquisition unit from Keysight Technologies Inc. (P/N:34972A) are used to measure the case temperature of components.

The test results under these conditions are shown in Table 20 and Table 21. 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 or E3M0032120K is 175°C, the integrated heat sink design has allowed the MOSFETs to remain within their thermal derating guidelines.

Table 20: Thermal Test Results of Magnetic Components

Description	Base Plate (°C)	PFC choke A (°C)	PFC choke B (°C)	PFC choke C (°C)	CM choke1 (°C)	CM choke2 (°C)
Single-Phase AC/DC Mode 215 VAC 900 V 6.6 kW 32 A	65	NA	58.1	61.5	50	61.8
Single-Phase DC/AC Mode 760 VDC 220 VAC 6.6 kW	65	NA	56.7	58.1	49.7	56.4
Three-Phase AC/DC Mode 230 VAC 900 VDC 22 kW 32 A	65	58.3	59.8	68.5	61.1	84.3
Rated Temperature	NA	155	155	155	155	155
Derating Requirement	NA	130	130	130	130	130
Result	NA	Pass	Pass	Pass	Pass	Pass

Temperature of semiconductors is shown in the table below.

Table 21: Thermal Test Results of SiC Power MOSFETS

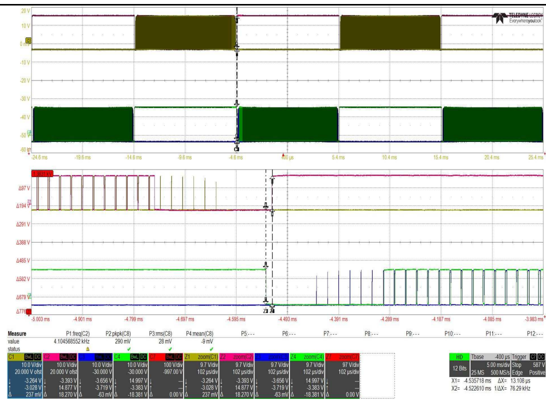
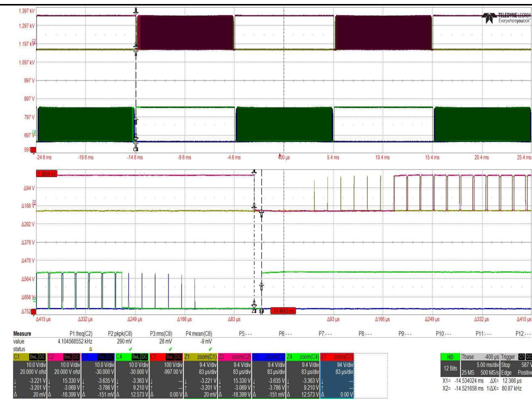
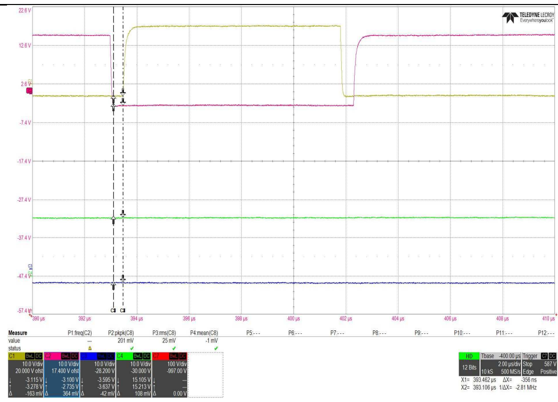
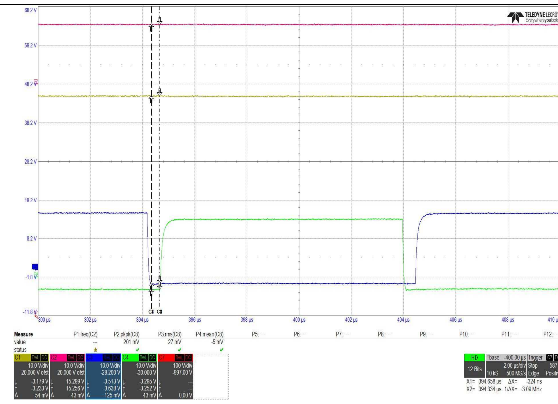
Description	Rth (j-c) (C/W)	Calculated Power Loss (W)	Measured Case Temp (°C)	Calculated Junction Temp (°C)	Max Operating Junction Temp (°C)	Derating Requirement (°C)	Result
		Single-Phase Charging Mode		**215 VAC 900 VDC 6.6 kW**			
PFC MOS HF	0.45	42	84.9	103.9	175	135	Pass
PFC MOS LF	0.45	20	69.1	78.1	175	135	Pass
		Single-Phase Discharging Mode		**760 VDC 220 VAC 6.6 kW**			
PFC MOS B	0.45	36	79.8	96.1	175	135	Pass
PFC MOS C	0.45	36	76.5	92.8	175	135	Pass
		Three-Phase Charging Mode		**398 VAC 900 VDC 22 kW**			
PFC MOS A	0.45	48	79.9	102.5	175	135	Pass
PFC MOS B	0.45	48	81.4	103	175	135	Pass
PFC MOS C	0.45	48	79.5	102.1	175	135	Pass

12. Appendix

12.1 PWM Timing

It is optional to verify the blanking time and timing of gate signals in discharging mode.

Table 22: Gate Signals and Timings in Discharging Mode

	
Drive signals	Drive signals
	
Td_ B bridge =356 ns	Td_ C bridge =324 ns
CH1: VGS B phase bridge high side CH2: VGS B phase bridge low side	CH3: VGS C phase bridge high side CH4: VGS C phase bridge low side

12.2 CAN Messages from OBC

Table 23: Overall Charge Status

Message Identifier	0x19B2F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Vab	Vca	Vac_D	Vac_Q
Unit	0.1 V	0.1 V	0.1 V	0.1 V
Bias	0			
Data Format	Integer			
Time Interval	3 seconds			

Table 24: Overall Charge Status

Message Identifier	0x19B1F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	NA	Ibus	Vpfc	VBC
Unit		0.1 A	0.1 V	0.1 V
Bias	0			
Data Format	Integer			
Time Interval	3 seconds			

Table 25: Temperature and Charge Mode

Message Identifier	0x19B0F4E5			
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 26: Charge Status, AC and AFE Information

Message Identifier	0x19B3F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	OBC status. See Table 27 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 27: Bit Definition for OBC Status

OBC Status	Comments	OBC Status	Comments
Bit15	1: Inverter mode 0: Rectifier mode (default)	Bit7	1: Phase A Relay Open 0: Phase A Relay Closed
Bit14	1: PLL Error 0: Normal (default)	Bit6	1: PFC abnormal 0: Normal (default)
Bit13	Reserved	Bit5	1: AC abnormal 0: Normal (default)
Bit12	1: Phase A Drive OFF 0: Phase A Drive ON (default)	Bit4	1: OTP 0: Normal (default)
Bit11	Reserved	Bit3	Reserved
Bit10	1: OFF, 0: ON (default)	Bit2	Reserved
Bit9	Reserved	Bit1	Reserved
Bit8	1: BC Relay Open 0: BC Relay Closed	Bit0	1: CAN error 0: Normal (default)

Table 28: 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 29: 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 30: Control Command

Message Identifier	0x18A5E5F4				
Data	Byte0	Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	0x0: Charging, Single Phase 0x1: Charging, Three Phase 0x2: Discharging, Single Phase 0x3: Discharging, Three Phase	0: On 1: OFF	Reserved 0xFFFF	DC Voltage	Reserved 0xFFFF
Unit	NA			0.1 V	NA
Bias	0				
Data Format	Integer				

13. Revision History

Date	Revision	Changes
December, 2020	0	First issue
March, 2021	1	Correct connector number in the main board. Update the test note.
January 2024	2	Branding and formatting updates

14. Reference

NA

15. 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.

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.