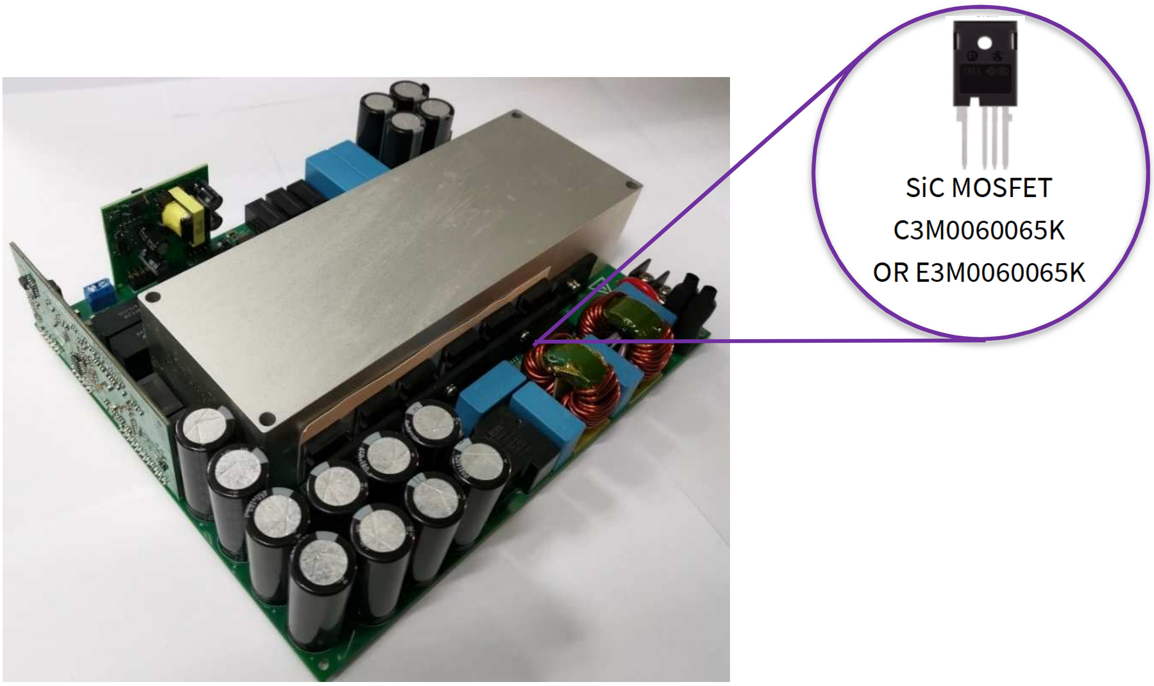
USER GUIDE PRD-02490

CRD-06600FF065N-K
6.6 KW HIGH POWER DENSITY BI-DIRECTIONAL EV ON-BOARD CHARGER

CRD-06600FF065N-K
6.6KW 高功率密度双向电动汽车车载充电机

CRD-06600FF065N-K
6.6KW 双方向電気自動車車載充電器



Wolfspeed® Power Applications

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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。

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, 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, to avoid any damage to electronic components. 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-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 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 PAGES, AS THEY CONTAIN IMPORTANT INFORMATION REGARDING THE HAZARDS AND SAFE OPERATING REQUIREMENTS RELATED TO THE HANDLING AND USE OF THIS BOARD

警告

请认真阅读以下内容，因为其中包含了处理和使用本板子有关的危险和安全操作要求方面的重要信息。

警告

ボードの使用、危険の対応、そして安全に操作する要求などの大切な情報を含むので、以下の内容をよく読んでください。

CAUTION

DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD. THERE CAN BE VERY HIGH VOLTAGES PRESENT ON THIS EVALUATION BOARD WHEN CONNECTED TO AN ELECTRICAL SOURCE, AND SOME COMPONENTS ON THIS BOARD CAN REACH TEMPERATURES ABOVE 50˚ CELSIUS. FURTHER, THESE CONDITIONS WILL CONTINUE FOR A SHORT TIME AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED.

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

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

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

警告

请勿在通电情况下接触板子，在操作板子前应使大容量电容器的电荷完全释放。接通电源后，该评估板上通常会存在危险的高电压，板子上一些组件的温度可能超过 50 摄氏度。此外，移除电源后，上述情况可能会短时持续，直至大容量电容器电量完全释放。

操作板子时应确保遵守正确的安全规程，否则可能会出现下列危险：

- 死亡
- 严重伤害
- 触电
- 电击
- 电灼伤
- 严重的热烧伤

请在操作本板子前完整阅读本文件。通电时禁止接触板子。所有测试与测量探针或附件必须在板子通电前连接。通电时，禁止使板子处于无人看护状态，且禁止操作板子。必须确保在操作板子前，大容量电容器已释放了所有电量。只有在切断板子电源，且大容量电容器完全放电后，才可更换待测试器件。

警告

通電している時、ボードに接触するのは禁止です。ボードを処分する前に、大容量のコンデンサーで電力を完全に釈放すべきです。通電してから、ボードにひどく高い電圧が存在している可能性があります。ボードのモジュールの温度は 50 度以上になるかもしれません。また、電源を切った後、上記の状況がしばらく持続する可能性がありますので、大容量のコンデンサーで電力を完全に釈放するまで待ってください。

ボードを操作するとき、正確な安全ルールを守るのを確保すべきです。さもないと、以下の危険がある可能性があります:

- 死亡
- 重症
- 感電
- 電撃
- 電気の火傷
- 厳しい火傷

当ボードを操作する前に、完全に当書類をよく読んでください。通電している時にボードに接触する必要がありません。通電する前に必ずすべての試験用のプローブあるいはアクセサリーをつないでください。通電している時に無人監視やボードを操作するのは禁止です。ボードを操作する前に、大容量のコンデンサーで電力を完全に釈放するのを必ず確保してください。ボードの電源を切った後、また大容量のコンデンサーで電力を完全に釈放した後、試験設備を取り換えることができます。

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1. INTRODUCTION

This User Guide provides the schematic, artwork, and test setup necessary to evaluate Wolfspeed's CRD-06600FF065N-K, 6.6KW Bi-Directional EV On-Board Charger (OBC).

The design of Wolfspeed's 6.6KW Bi-Directional OBC for electric vehicles (P/N CRD-06600FF065N-K) is based upon Wolfspeed's SiC MOSFETs - the C3M0060065K or E3M0060065K (650V, 60mΩ, TO-247). The OBC is designed to operate from a universal, single-phase input and provide an output voltage in the range of 250 VDC to 450 VDC. It can operate in constant-current, constant-voltage or constant power mode. Its output current, voltage and power can all be set through a CAN (Controller Area Network) interface.

The front-end AC/DC PFC (Power Factor Correction) stage uses a CCM (Continuous Conduction Mode) Totem-Pole Bi-Directional topology and operates at 67KHz. It creates a DC link voltage that is followed by a Bi-Directional Isolated DC/DC CLLC resonant converter that operates in a 148-300KHz range. The DC link voltage varies between 385Vdc and 425Vdc in order to optimize the OBC's efficiency as the charging battery voltage varies between 250Vdc and 450Vdc. This allows the peak efficiency of the OBC to reach 96.5% in both charging and discharging modes. Both the input and output sides of the Bi-Directional Isolated DC/DC stage use a full bridge switch arrangement isolated by a high frequency transformer. A unique tooled heatsink was designed to dissipate the heat generated by all of the power MOSFETs and power magnetics. This integrated heatsink approach allows the design to reach a power density of 54 W/in^3. A block diagram is shown in Figure 1.

Even though this unit is designed for electric vehicle (EV) applications, there is no battery charging algorithm built in. It must be tested with a resistive load when it is in DC/AC mode (discharging mode). However, an electronic load or a resistive load may be used in AC/DC mode (charging mode). The unit's output current in charging mode is limited to 18A.

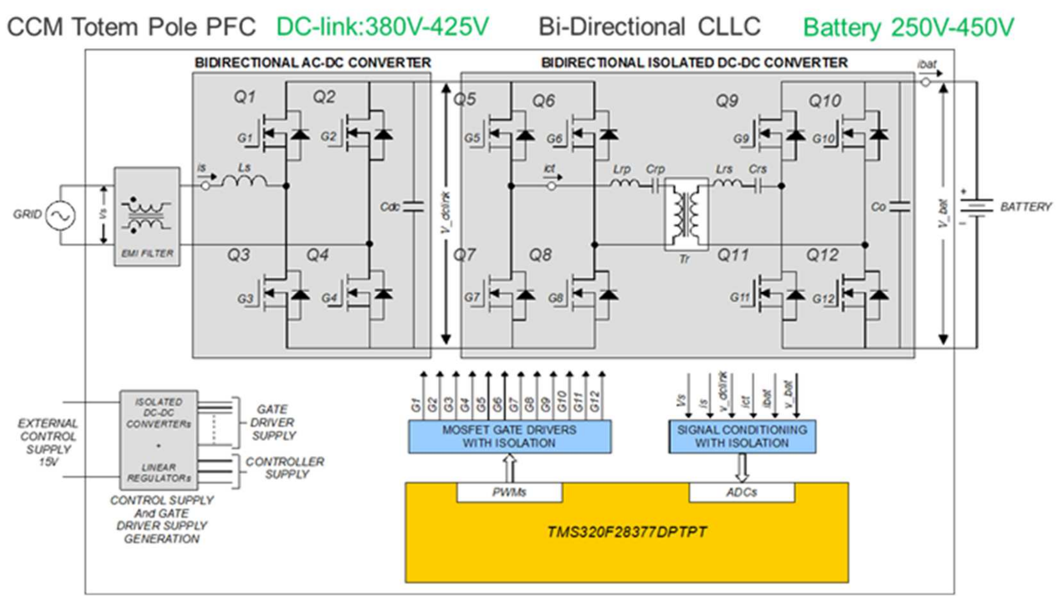


Figure 1: Block Diagram of CRD-06600FF065N-K, 6.6kW Bi-Directional EV On-board Charger.

2. DESCRIPTION

This reference design board uses Wolfspeed's C3M0060065K or E3M0060065K, 60mΩ, 650V, SiC MOSFETs (TO-247) in both the AC/DC and DC/DC stages. Two parallel MOSFETs are used in the high frequency half-bridge of the Totem-Pole PFC converter. A single MOSFET is used for the low frequency portion of the half bridge. The DC/DC stage uses a single MOSFET in both the primary (DC link) and secondary (battery) sides.

The unit's input accepts a universal input, single-phase voltage between 90Vac and 265Vac and its output provides an isolated voltage between 250Vdc and 450Vdc. Both the input and output of the unit are protected by fuses. The input's under-voltage and over-voltage protection and the output's over-voltage protection are controlled by the digital controller (refer to Section 7 of this User Guide). External power supplies for the Auxiliary Power Board and the heatsinks' cooling fans must be supplied separately.

The unit must be started with less than 1000W of load. The load may be increased incrementally after the output voltage has reached steady-state regulation. A graphical user interface (GUI) communicates to the unit via a CAN communication bus. It is used to display operational information and to provide related user controls.

3. ELECTRICAL PERFORMANCE SPECIFICATIONS

PARAMETER		TEST CONDITIONS	MIN	NOM	MAX	UNITS
Input Characteristics						
$V_{IN(AC)}$	Input voltage		90	230	265	V_{rms}
f_{grid}	Frequency*1		48	50/60	62	Hz
$V_{IN(AC)}$	Brownout voltage			85		V_{rms}
$V_{IN(AC)}$	Brownout recovery voltage			100		V_{rms}
$I_{IN(AC)}$	Input current	V_{IN} = 215V			32	A_{rms}
Output Characteristics						
V_{OUT}	Output voltage	V_{IN} = V_{MIN} to V_{MAX}, I_{OUT} = 0 to I_{NOM}	250	366	450	V
I_{OUT}	output current	V_{IN} = 215V_{AC} to V_{MAX}		18	18	A
V_{ripple}	Output voltage ripple	V_{IN} = V_{MIN} to V_{MAX}, I_{OUT} = 0 to I_{NOM}		15		V
$P_{OUT\ max}$	Output power	V_{IN} = 215Vac to 265Vac V_{IN} = 90Vac			6600 2000	W
System Characteristics						
η_{peak}	Peak efficiency	V_{IN} = V_{NOM}, V_{OUT} = 366V, I_{OUT} = 50% of $I_{OUT\ (nom)}$	96.5%	96.7%		
$\eta_{full\ load}$	Full load efficiency	V_{IN} = V_{NOM}, V_{OUT} = 366V I_{OUT} = 100% of $I_{OUT\ (nom)}$	94.8%	95.1%		
		V_{IN} = V_{NOM}, V_{OUT} = 450V, I_{OUT} = 100% of $I_{OUT\ (nom)}$	95%	95.3%		
		V_{IN} = V_{NOM}, V_{OUT} = 250V I_{OUT} = 100% of $I_{OUT\ (nom)}$	92%	92.5%		
Mechanical						
	Dimensions	Width Length Component height		180 220 50		mm

Table 1: Specifications of Wolfspeed's CRD-06600FF065N-K, 6.6 kW Bi-Directional EV On-Board Charger (AC/DC Mode).

***1**: The AC input voltage should be applied directly without any external ramp control. The user should remove power to the reference design, including the control board, by following the instructions in Section 7 before reapplying power using an AC input voltage with a different frequency.

PARAMETER		TEST CONDITIONS	MIN	NOM	MAX	UNITS
Input Characteristics						
$V_{IN(DC)}$	Input voltage (DC)		320	366	450	V
V_{DC}	Brownout voltage	$I_{OUT} = I_{NOM}$		295		V
$V_{IN(DC)}$	Brownout recovery voltage		310	330		V
$I_{IN(DC)}$	Input current	$V_{IN} = 320V$		-	11	A
Output Characteristics						
V_{OUT}	Output voltage (standalone)	$V_{IN} = V_{MIN}$ to V_{MAX}, $I_{OUT} = 0$ to I_{NOM}		220		V_{rms}
f_{AC}	Frequency (standalone mode)			50		Hz
$I_{OUT\ (nom)}$	output current	$V_{IN} = V_{MIN}$ to V_{MAX}		15		A_{rms}
$P_{OUT\ max}$	Output power	$V_{IN} = V_{MIN}$ to V_{MAX}		3300		W
System Characteristics						
η_{avg}	Average efficiency	V_{IN} = 320Vdc, 366Vdc, 450Vdc, V_{OUT} = 220Vac, I_{OUT} = 100% of $I_{OUT\ (nom)}$	95.6%	95.9%		
η_{peak}	Peak efficiency	V_{IN} = 366V, V_{OUT} = 220Vac, I_{OUT} = 60% of $I_{OUT\ (nom)}$	96.3%	96.6%		

Table 2: Specifications of Wolfspeed's CRD-06600FF065N-K, 6.6 kW Bi-Directional EV On-Board Charger (DC/AC Mode).

3.1. APPLICATIONS

The primary application for Wolfspeed's CRD-06600FF065N-K reference design board is isolated Bi-Directional EV charging systems. Using a single-phase AC input, it provides an isolated adjustable DC output suitable for charging batteries. This output must be connected to a resistive load or electronic load (CC mode recommended) since a battery charging algorithm has not been implemented in the design.

The CRD-06600FF065N-K reference design board is capable of supplying power into a resistive load when in DC/AC mode (discharge mode) when the output is connected to a DC voltage source.

3.2. FEATURES

Some of the features and the limitations of Wolfspeed's CRD-06600FF065N-K reference design board are given below:

- Universal AC input voltage range.
- Isolated 250Vdc – 450Vdc output in AC/DC mode.
- Maximum output current is limited to 18A in AC/DC mode whenever the output voltage is between 250Vdc and 366Vdc and the input voltage exceeds 215 VAC.

- Maximum output power is limited to 6.6KW in AC/DC mode whenever the output voltage is between 366Vdc and 430Vdc. It is linearly derated from 6.6 KW to 5KW when the output voltage is between 430Vdc and 450Vdc and the input voltage exceeds 215 VAC.
- Maximum power with a 90 Vac input is limited to 2 KW.
- Output power derating is shown in Figure 2 when the input voltage is between 90Vac and 215Vac. It is linearly derated from 6.6 kW to 2kW based on the input voltage while operating in AC/DC mode.
- Power is limited to 3.3 KW in DC/AC mode.
- Output voltage is targeted at 220Vac/50Hz in DC/AC mode.
- Peak efficiency > 96.5%.
- Various protections as shown in Table 4.
- Auto-selection between AC/DC mode and DC/AC mode on every start-up.
- Synchronous rectification (SR) is automatically controlled with load. SR is typically enabled when the load current exceeds 5A. When it is below 2A, SR is disabled.
- Easy to test using a GUI communicating via CAN. See Section 6.6 for details.

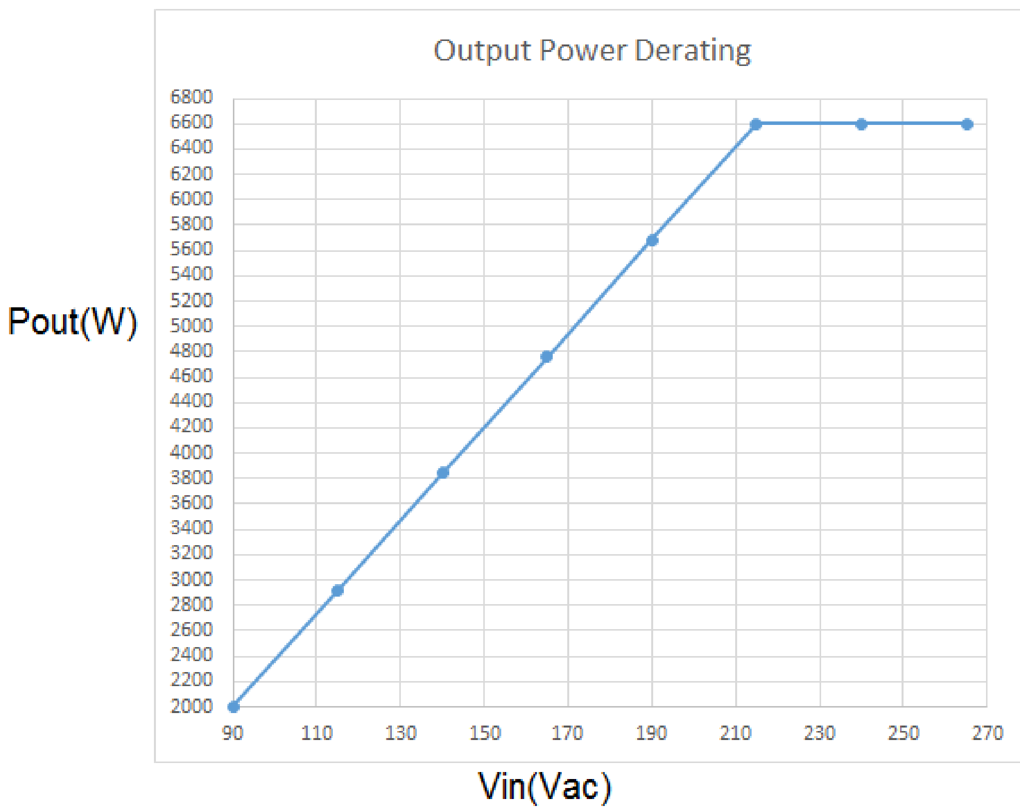


Figure 2: Power derating of Wolfspeed's CRD-06600FF065N-K, 6.6kW Bi-Directional EV On-board Charger.

4. SCHEMATICS OF POWER BOARD AND CONTROL BOARD

Note: The full schematics are available for download at https://www.wolfspeed.com/products/power/reference-designs/crd-06600ff065n-k/

Schematics of the power, control, and auxiliary-power boards are shown in Figures 3 through 6.

4.1. POWER BOARD SCHEMATIC:

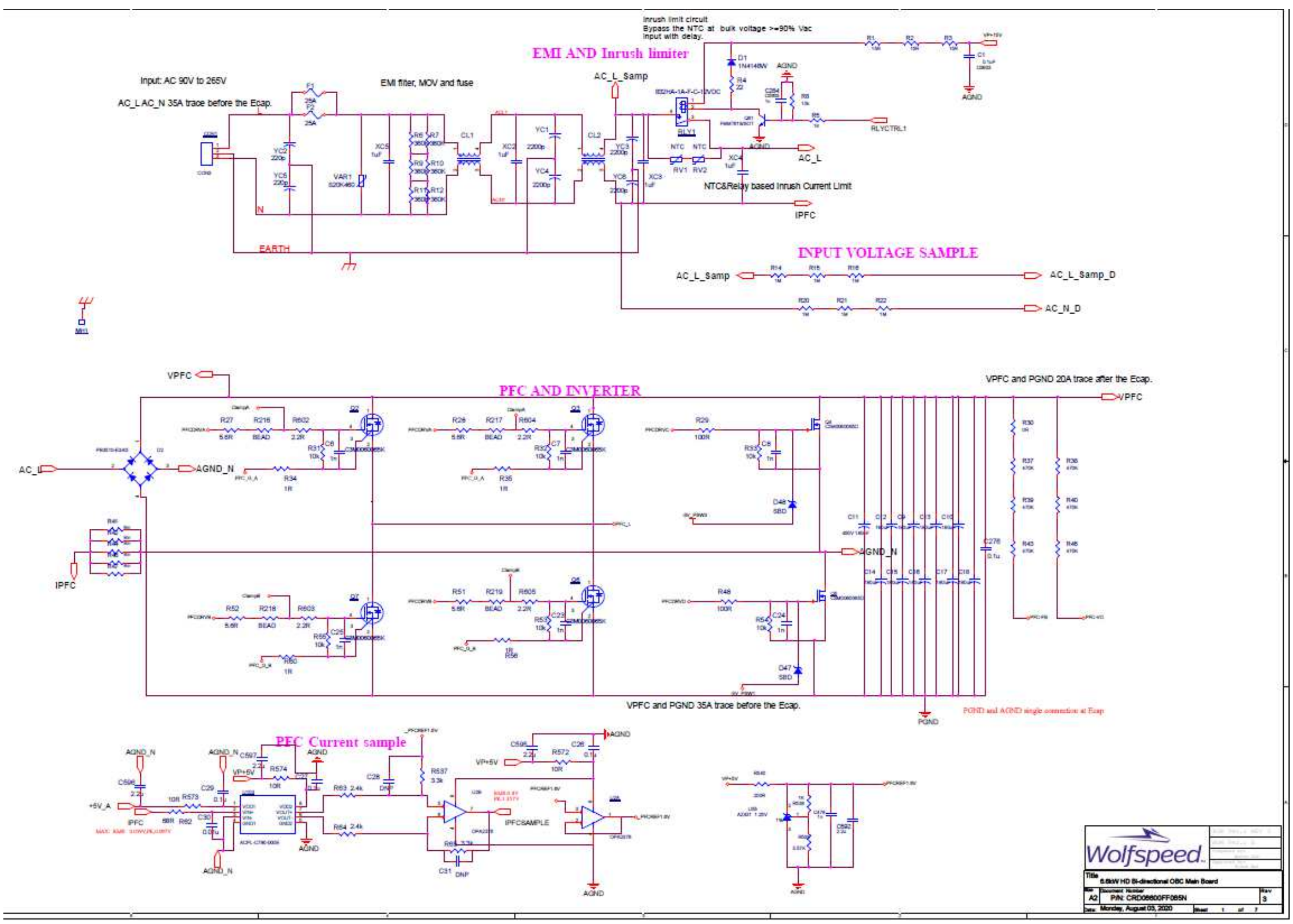


Figure 3 a: Schematic of Power Board: Totem-Pole Main Power

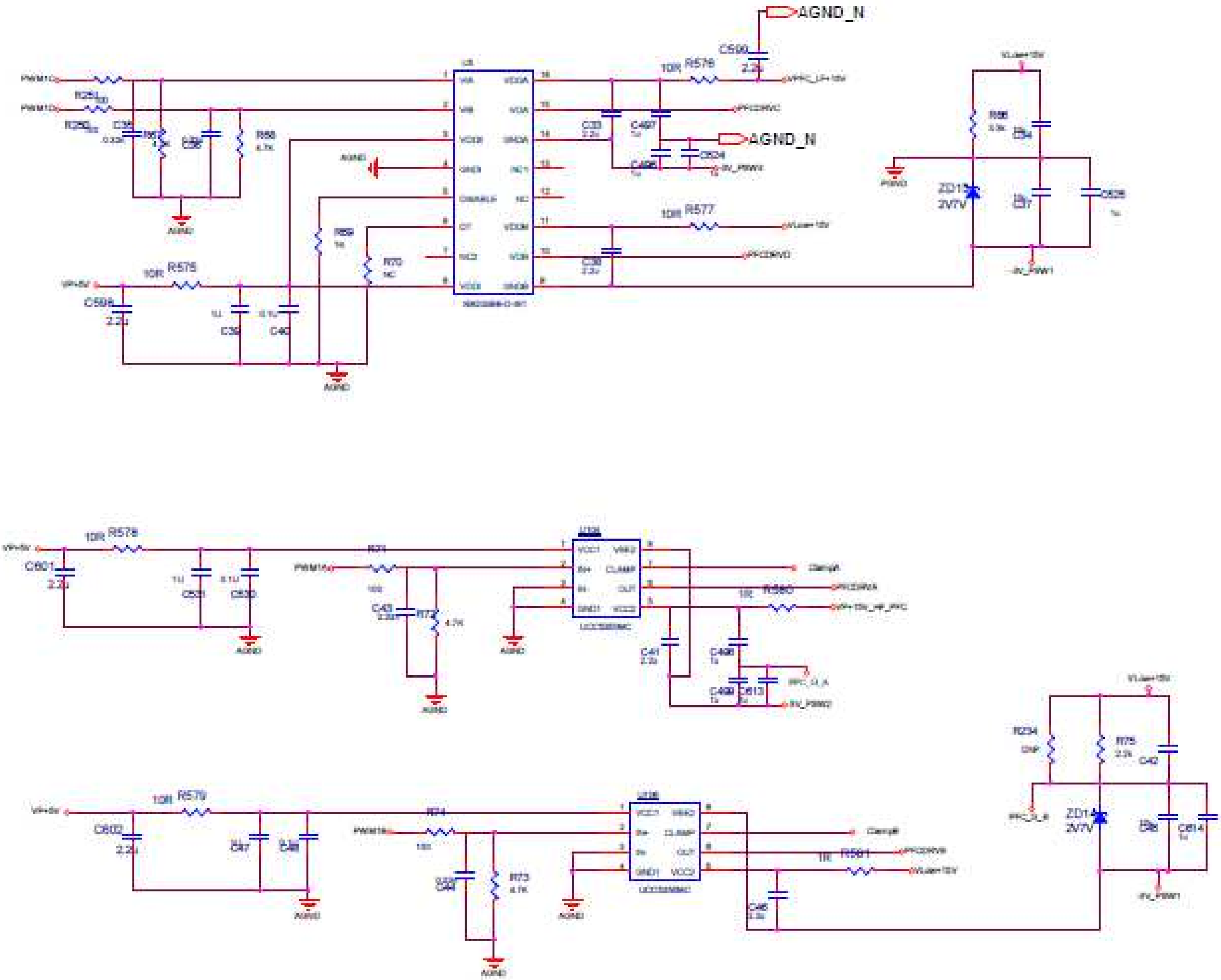


Figure 3 b: Schematic of Power Board: Totem-Pole Gate Drives.

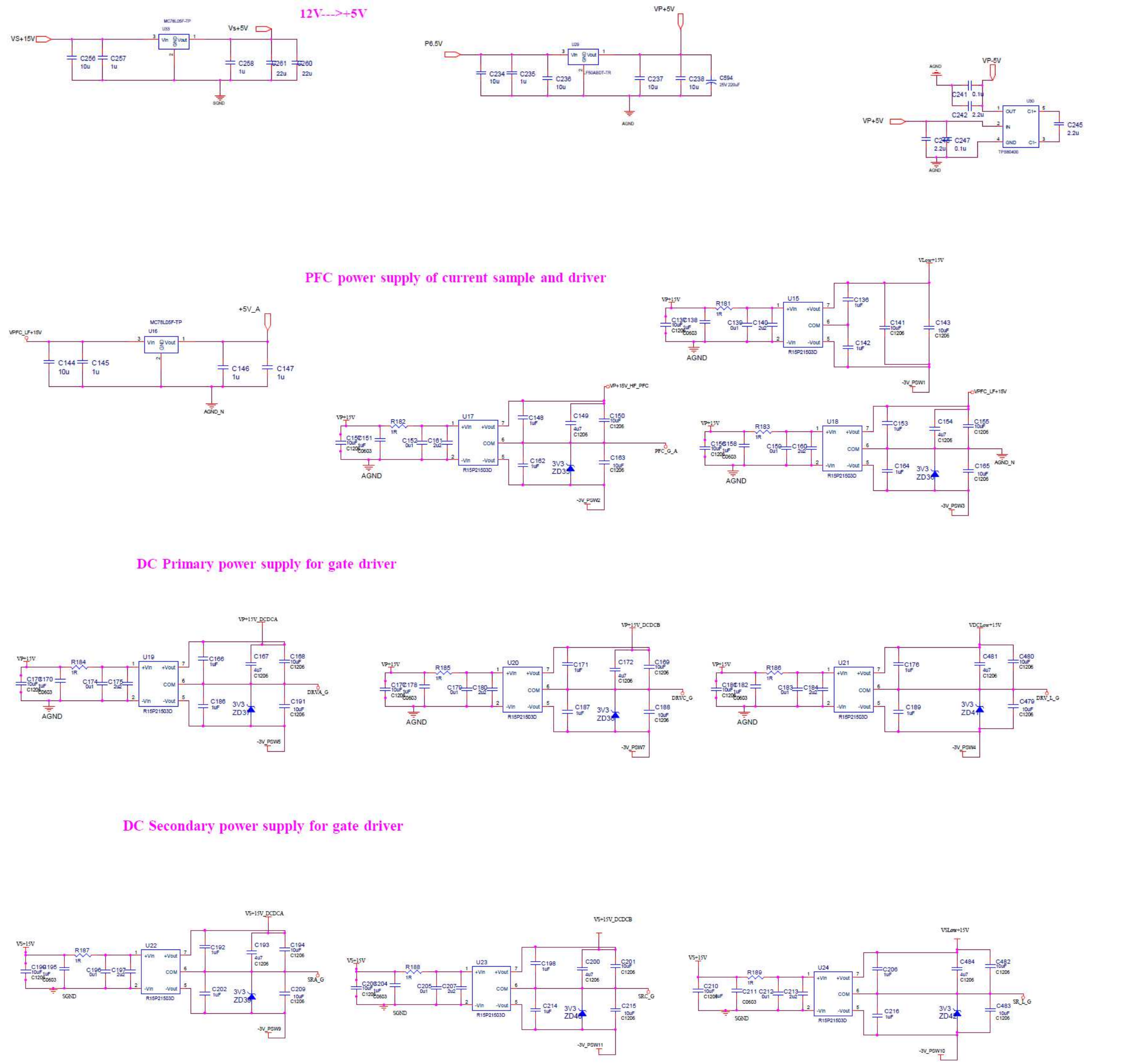
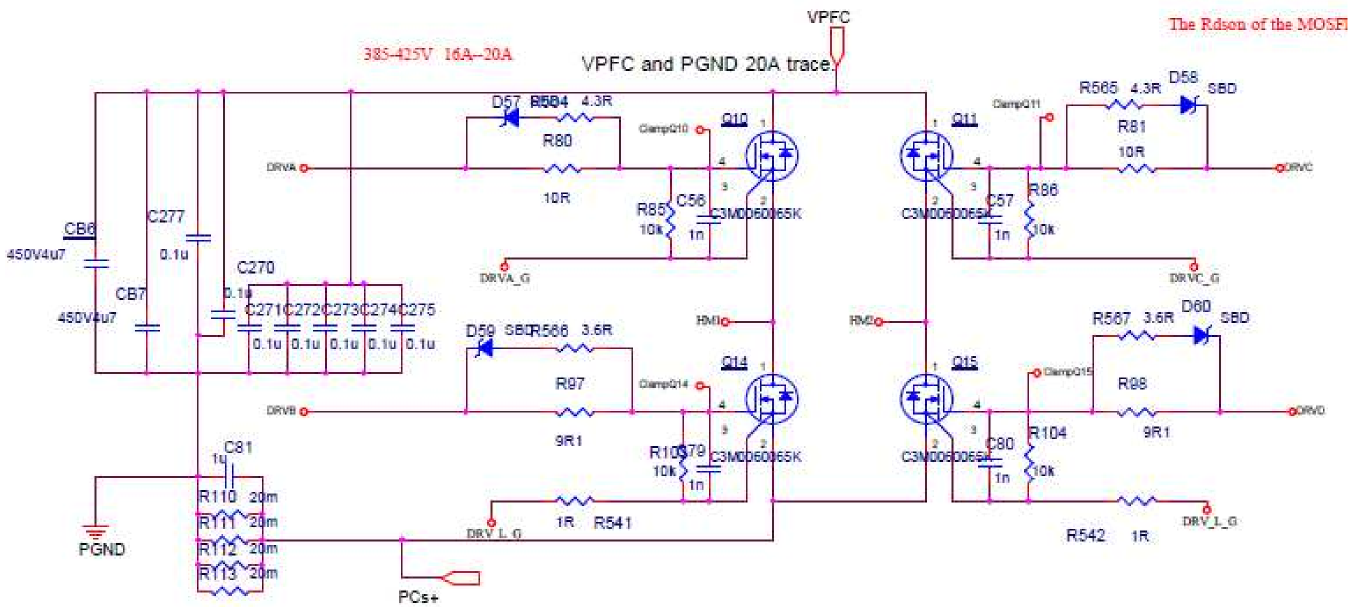
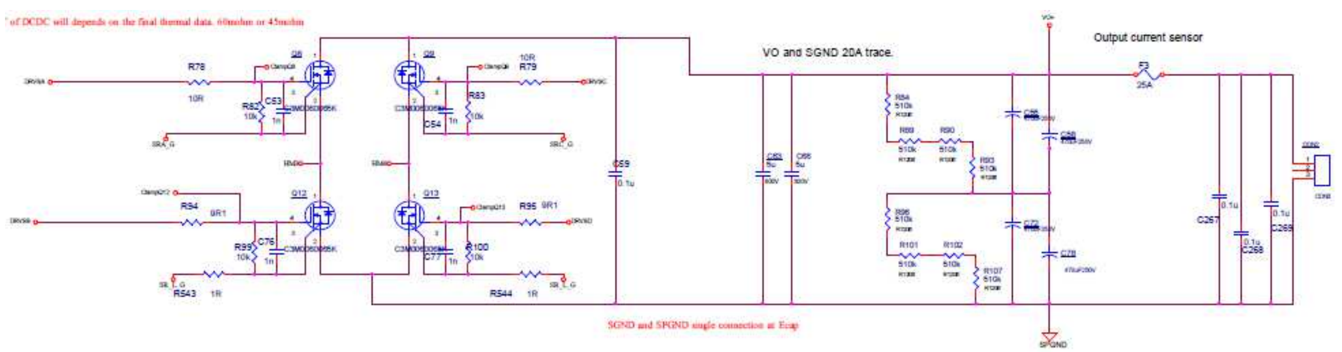
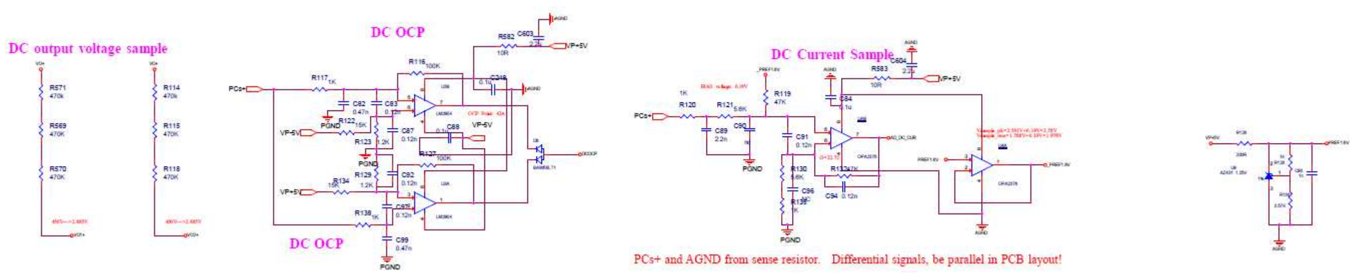


Figure 3 c: Schematic of Power Board: Power Supply and Connectors.


VPFC
VPFC and PGND 20A trace.
385-425V 16A--20A
The Rdson of the MOSFI
D57
R584 4.3R
R80
10R
ClampQ10
Q10
DRVA
R85
10k
C56
1n
C3M0060065K
DRVA_G
CB6
450V4u7
CB7
450V4u7
C277
0.1u
C270
0.1u
C271 C272 C273 C274 C275
0.1u 0.1u 0.1u 0.1u 0.1u
HM1
HM2
D59 SBD
R566 3.6R
R97
9R1
ClampQ14
Q14
DRVB
R103
C79
10k
1n
C81
1u
R110 20m
R111 20m
R112 20m
R113 20m
PGND
R541
1R
DRV_L_G
PCs+
Q11
ClampQ11
R565 4.3R
D58 SBD
R81
10R
DRVC
C57
1n
R86
10k
DRVC_G
R567 3.6R
D60 SBD
Q15
ClampQ15
R98
9R1
DRVD
C80
1n
R104
10k
R542 1R
DRV_L_G

VO and SGND 20A trace.
Output current sensor
SGND and SPGND single connection at Ecap
SPGND

DC output voltage sample
DC OCP
DC OCP
DC Current Sample
PCs+ and AGND from sense resistor. Differential signals, be parallel in PCB layout!

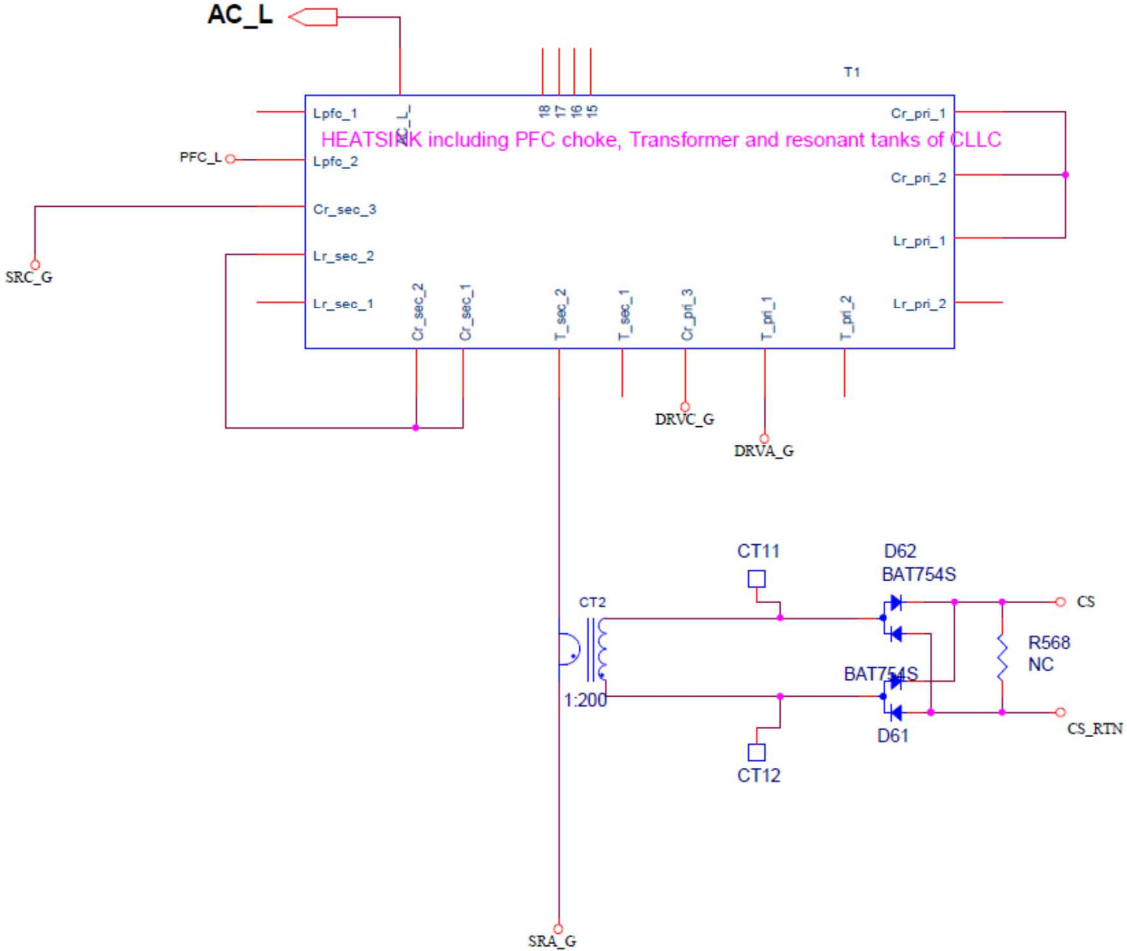


Figure 3 d: Schematic of Power Board: DC/DC Main Power.

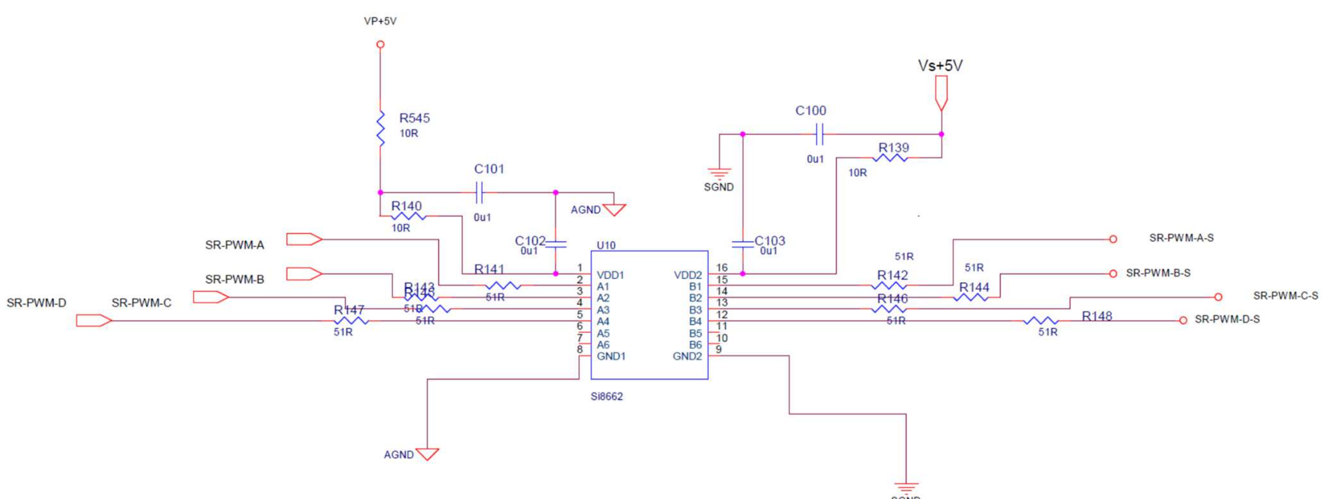


Figure 3 e: Schematic of Power Board: Signal Isolation.

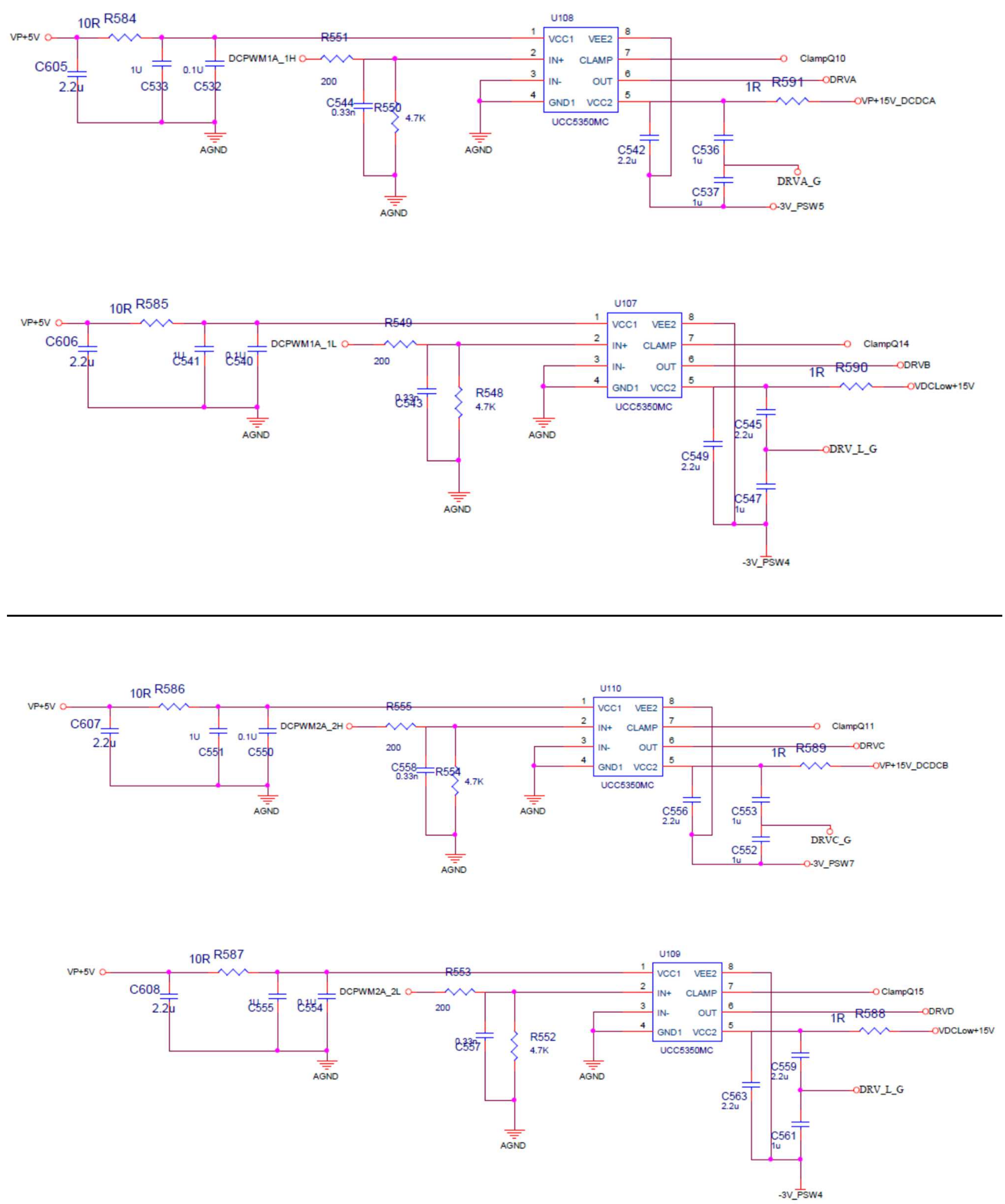


Figure 3 f: Schematic of Power Board: DC/DC Bus-Side Drives.

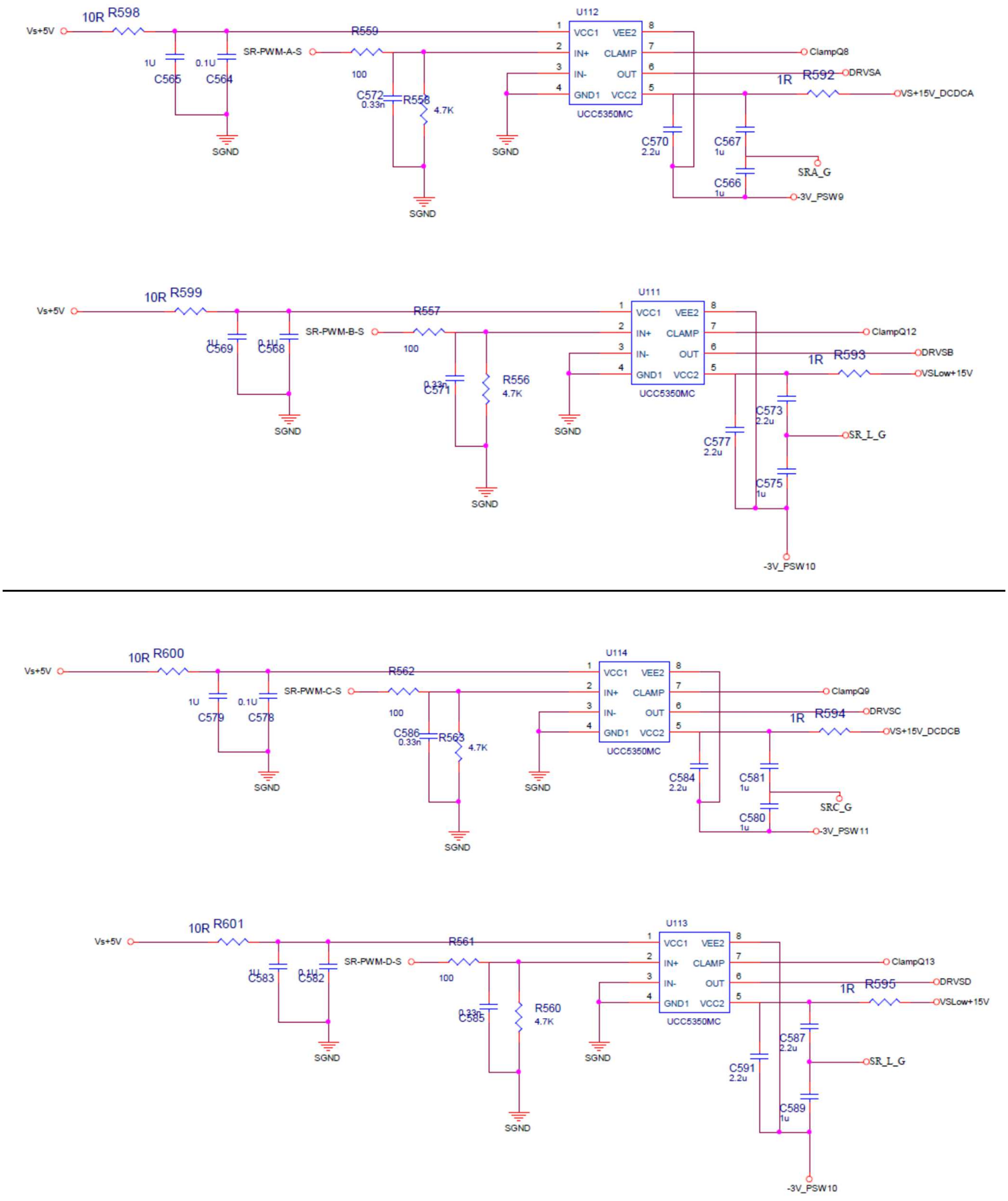


Figure 3 g: Schematic of Power Board: DC/DC Battery-Side Drives.

4.2. CONTROL BOARD SCHEMATIC:

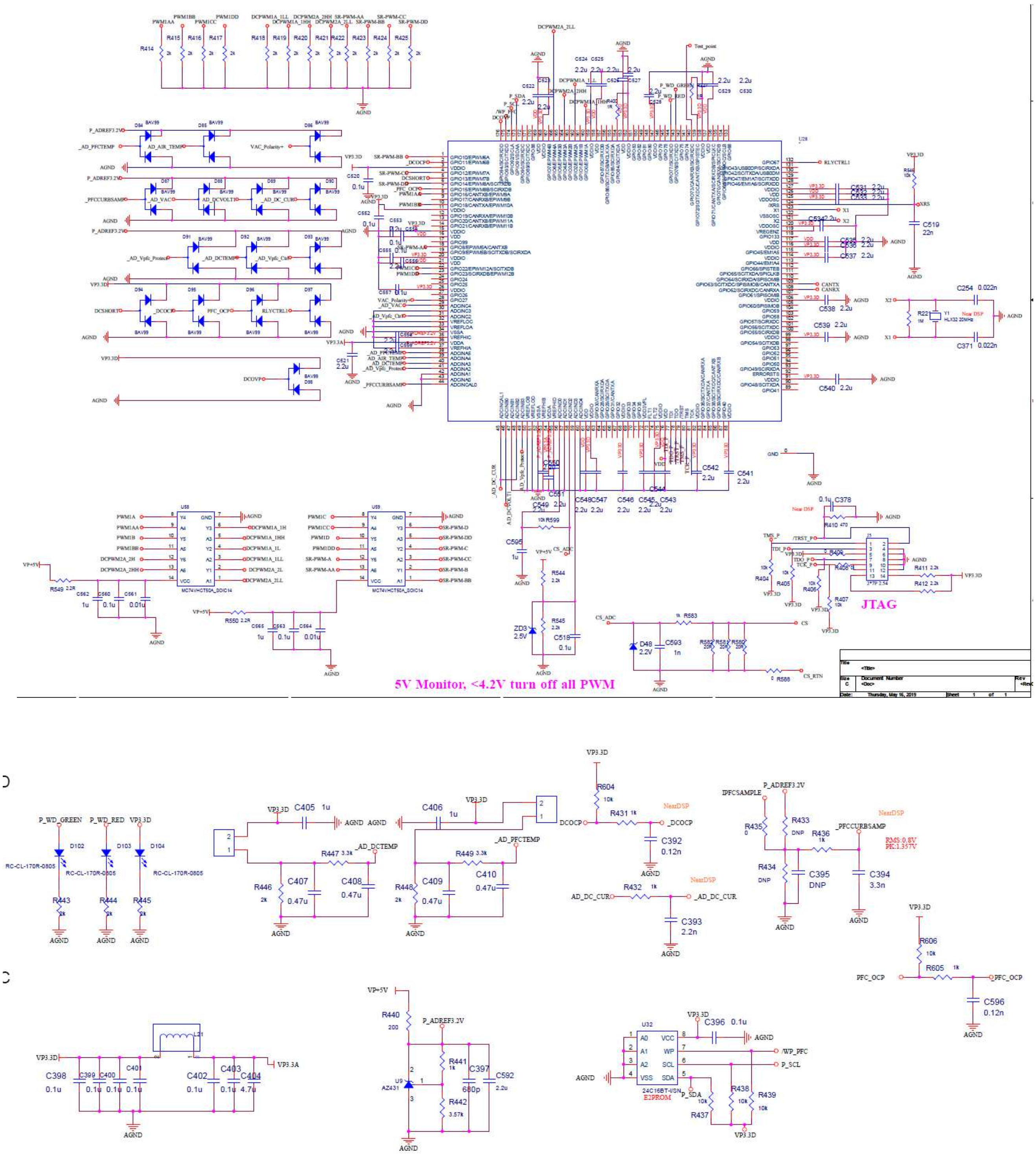


Figure 4 a: Schematic of Control Board: DSP.

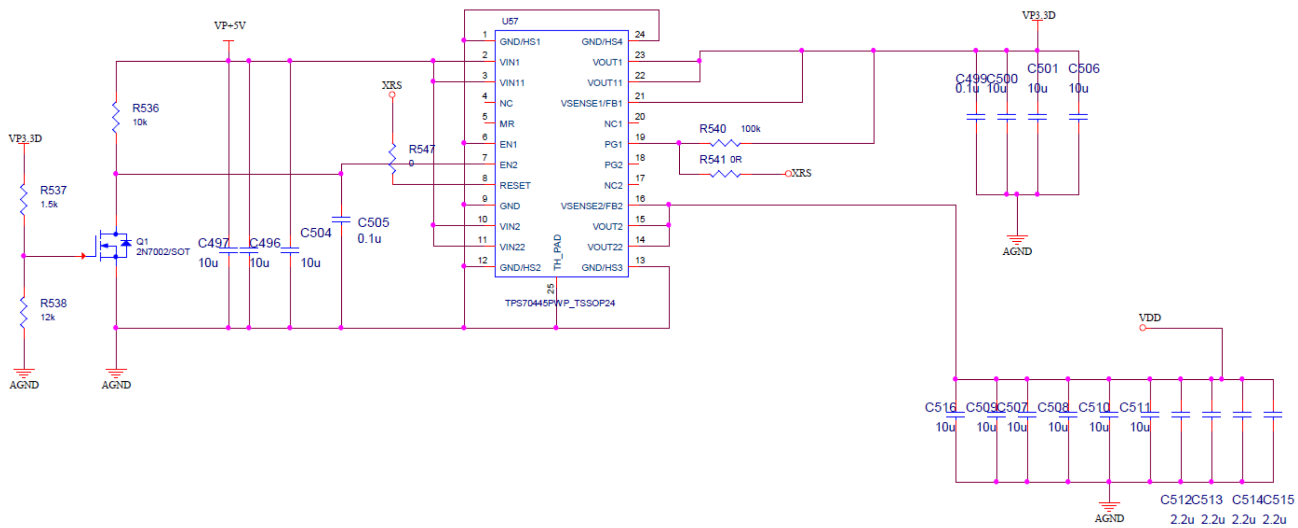


Figure 4 b: Schematic of Control Board: DSP Power Supply and Connectors.

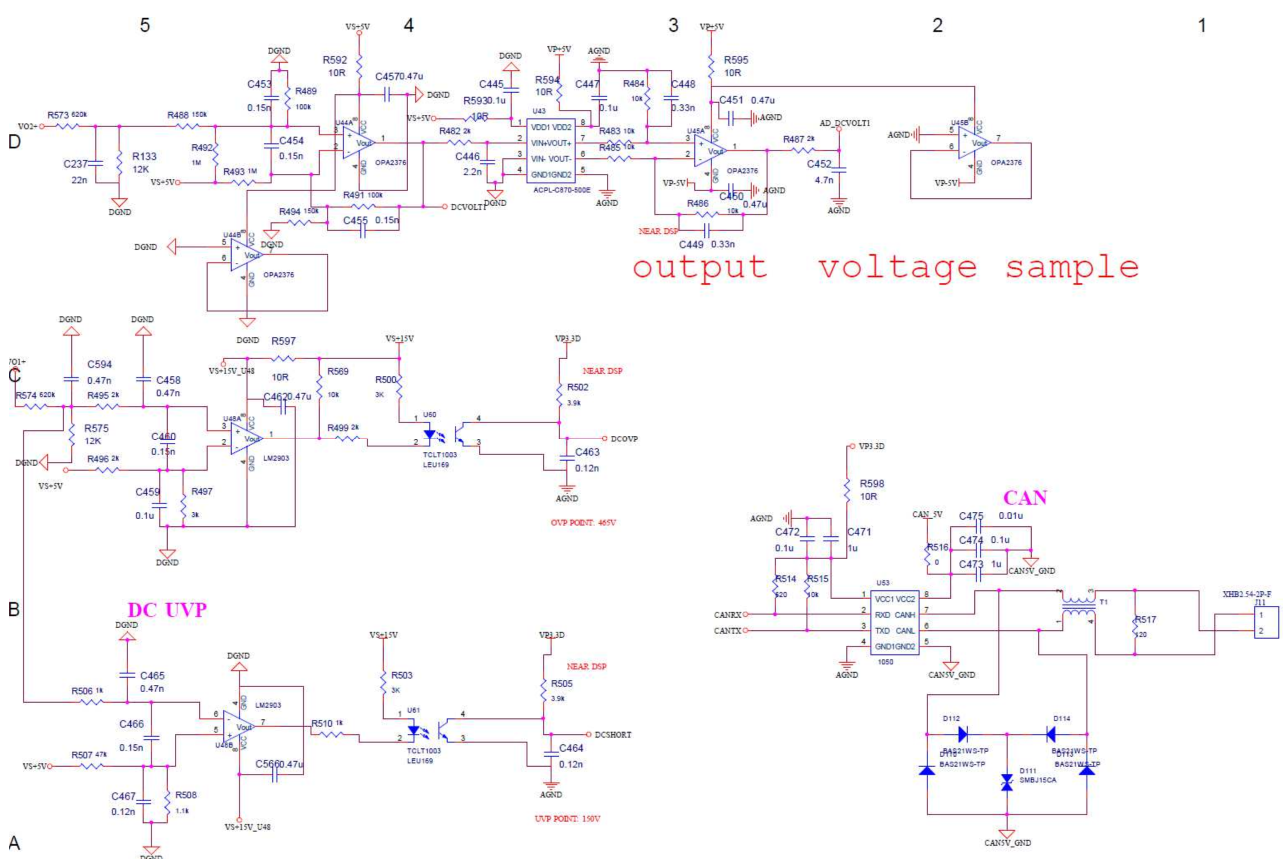


Figure 4 c: Schematic of Control Board: Output Voltage Sample and CAN Interface

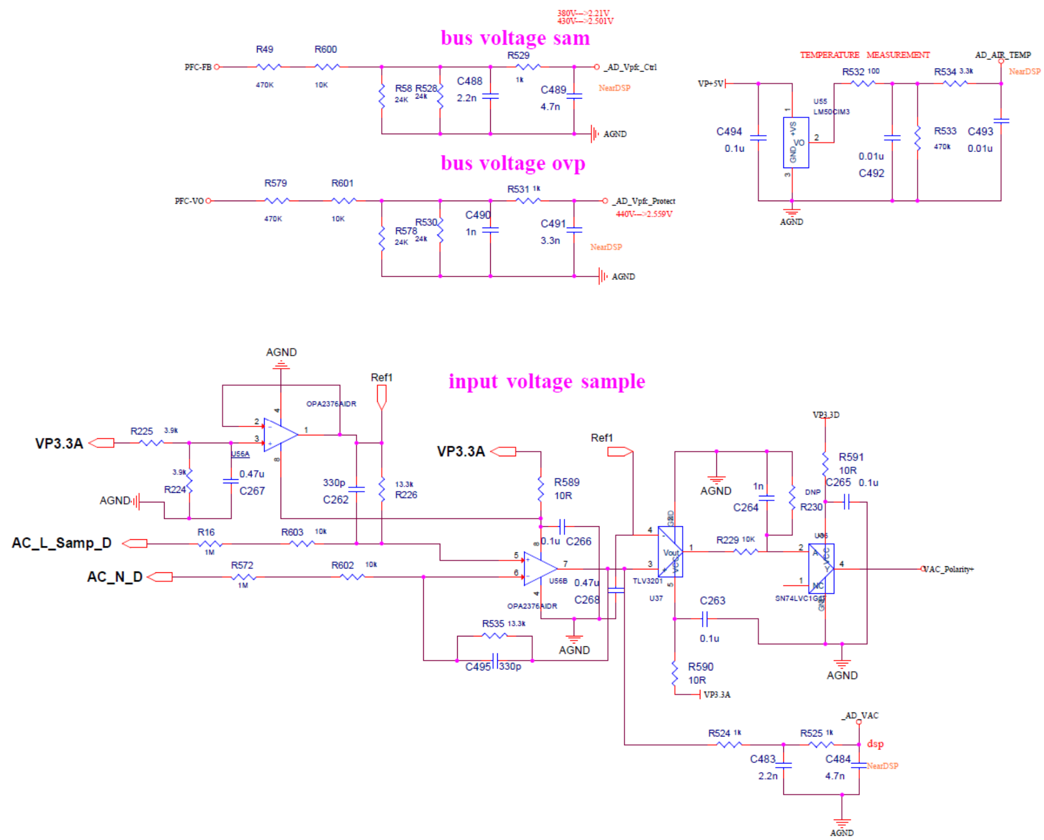
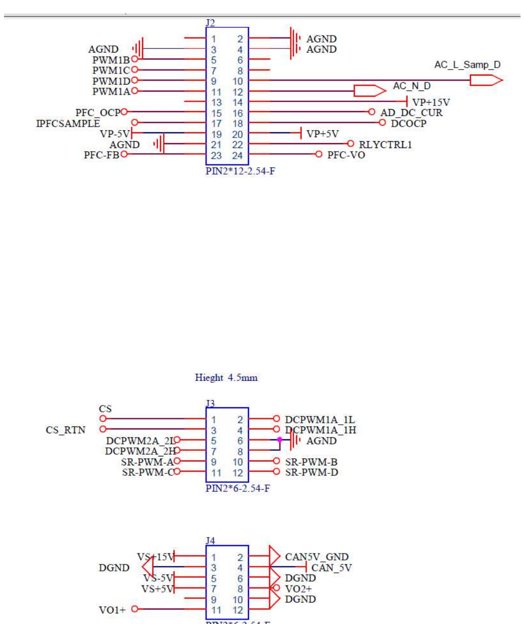


Figure 4 d: Schematic of Control Board: Input Voltage Sampling

4.3. CONNECTIONS OF CONTROL BOARD AND MAIN BOARD:



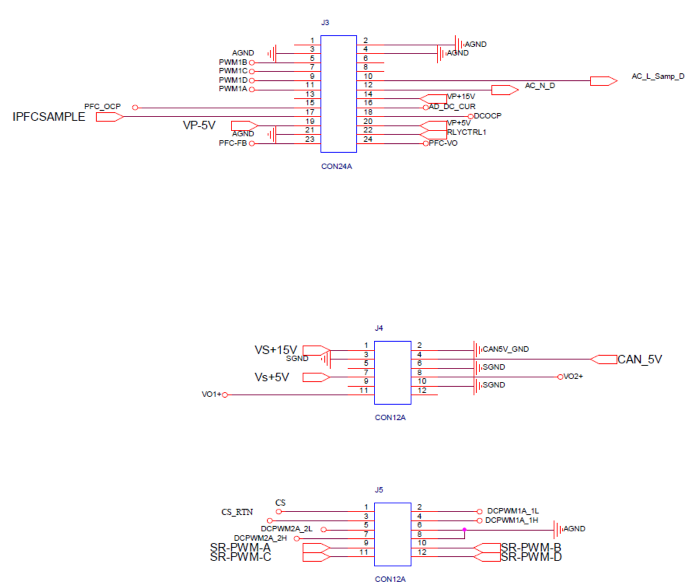


Figure 5 a: Connectors of Control Board.

Figure 5 b: Connectors of Main Board.

4.4. AUXILIARY POWER BOARD SCHEMATIC:

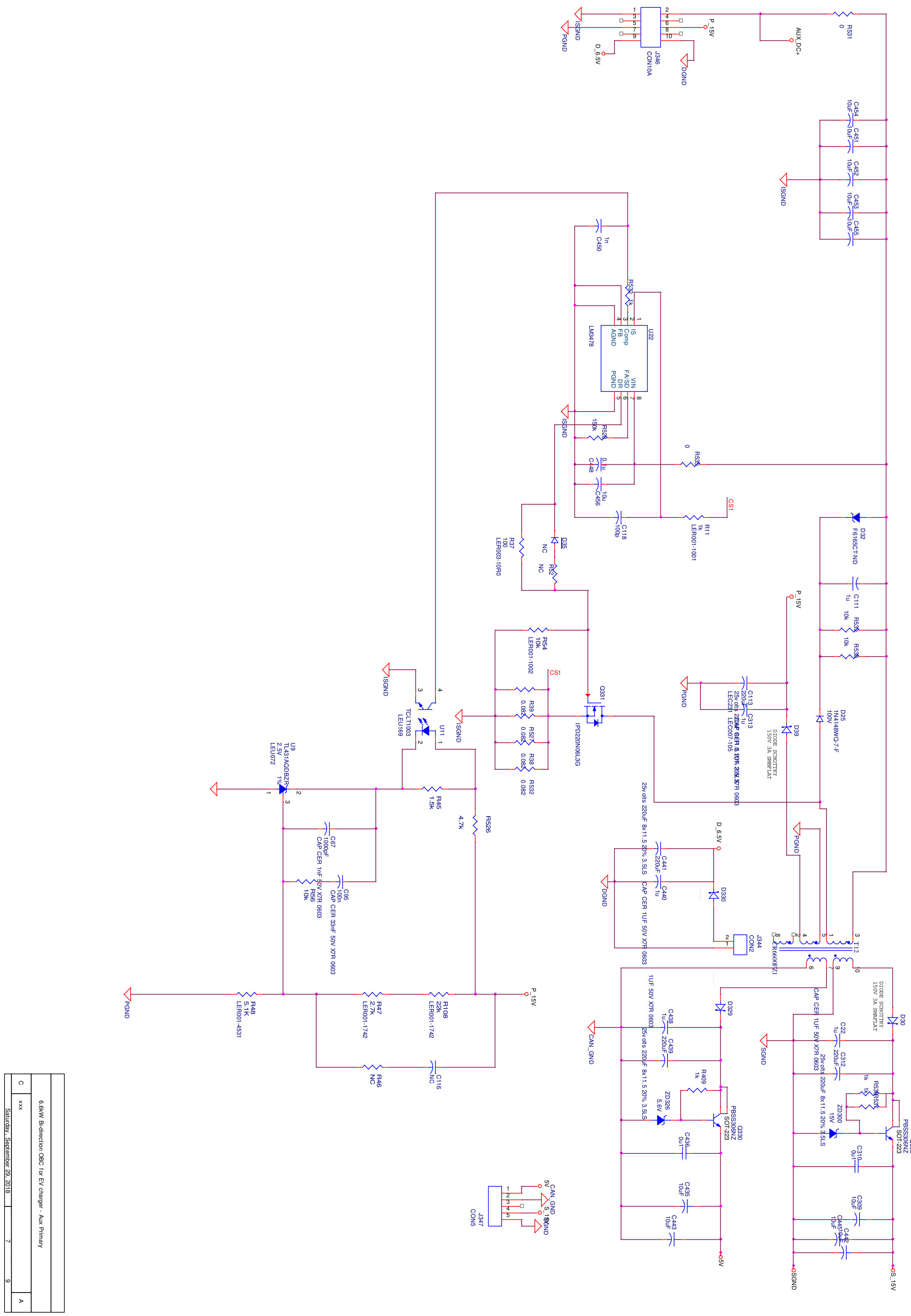


Figure 3: Schematic of Auxiliary Power Board.

5. HARDWARE DESCRIPTION OF POWER BOARD AND CONTROL BOARD

5.1. DESCRIPTION OF POWER BOARD:

As illustrated by Figure 3a, the input AC voltage is connected to terminals 1 and 3 of CON1 followed (in order) by fuses F1, and F2 and MOV VAR1 and common mode EMI filters CL1 and CL2. This is followed by bridge rectifier D2 and NTC resistors RV1 and RV2 through which the DC link capacitors are charged. Both RV1 and RV2 are short-circuited by relay RLY1 when the DC link voltage is charged. The PFC choke is connected after relay RLY1 between net “AC_L”, and net “PFC_L” which is the midpoint of the high-frequency half-bridge consisting of Totem-Pole MOSFETs Q2, Q3, Q6 and Q7. After passing through the EMI filters, the neutral of the AC power grid is connected to the low-frequency half-bridge Q4 and Q5.

The DC link capacitor bank consists of ten capacitors in parallel (180µF/450V). Also, in parallel are several film and ceramic capacitors. These absorb the high frequency ripple on the DC-link and input. The DC link is connected to MOSFETs Q10, Q11, Q14 and Q15 which form an H-bridge on the primary side (DC link side) of the bi-directional CLLC converter. The primary side contains a resonant tank composed of a 9µH inductor and a resonant capacitor bank consisting of ten parallel 6.8nF film capacitors. The secondary side resonant tank (battery side) is identical to the primary side tank. The secondary side H-bridge is composed of MOSFETs Q8, Q9, Q12 and Q13 followed by film capacitors C63, C66 and four electrolytic capacitors. The CLLC powertrain’s transformer isolates the secondary and primary sides from each other. It is constructed with a PQ5040 ferrite core and has a turns ratio of 15:14. The ferrite core’s center leg was gapped in order to obtain a primary inductance of 60 µH.

As illustrated by Figure 3b to Figure 3g, the gate drive signals for the MOSFETs in both the AC/DC and DC/DC stages are generated by a DSP controller. All gate drivers are separately powered by isolated, DC/DC power supplies (V_{IN} = +15V, V_{OUT} = +15V/-3V). A current sensing resistor is used for the H-bridge current at primary while a current transformer is used for the secondary tank current. The input AC current, output voltage signal and OVP/UVP protection signals are isolated by optocouplers before they are fed into the DSP controller for further processing.

5.2. DESCRIPTION OF CONTROL BOARD:

As illustrated by Figure 4a and 4b, the control board which carries out the control algorithm of the entire system is designed around a Texas Instruments Inc. DSP (P/N: TMS320F28377D). The power supply for the control board is an isolated, 7V@1A, power supply whose output is then tightly regulated to +5.0V by a linear regulator. This 5.0V voltage rail then supplies another precision linear regulator IC, U57, from Texas Instruments Inc. (P/N: TPS70445) which provides both a 3.3V and a 1.2V voltage rail. All output PWM signals are buffered and shifted to a +5V level by a Fairchild Semiconductor International Inc. (P/N: MC74HCT50A) level-shifter and buffer ICs (U58, U59) before they are fed to their respective gate drivers. The reference voltage for the DSP’s ADC is 3.2V. This reference is created by a reference IC, U9, (P/N: AZ431-2.5V) from the +5.0V rail.

5.3. DESCRIPTION OF AUXILIARY POWER BOARD:

They typical input voltage of the auxiliary power board is 14 V (J6, net “Aux_DC+” and net “ISGND” in Figure 6). It provides 4 isolated output voltages as shown in Table 3.

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

Table 3: Input and Outputs of Auxiliary Power Board.

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 MUCH BE FULLY DISCHARGED.

SOME COMPONENTS ON THE BOARD REACH TEMPERATURES ABOVE 50^{o} CELSIUS. THESE CONDITIONS WILL CONTINUE AFTER THE ELECTRICAL SOURCE IS DISCONNECTED UNTIL THE BULK CAPACITORS ARE FULLY DISCHARGED. DO NOT TOUCH THE BOARD WHEN IT IS ENERGIZED AND ALLOW THE BULK CAPACITORS TO COMPLETELY DISCHARGE PRIOR TO HANDLING THE BOARD.

PLEASE ENSURE THAT APPROPRIATE SAFETY PROCEDURES ARE FOLLOWED WHEN OPERATING THIS BOARD AS SERIOUS INJURY, INCLUDING DEATH BY ELECTROCUTION OR SERIOUS INJURY BY ELECTRICAL SHOCK OR ELECTRICAL BURNS, CAN OCCUR IF YOU DO NOT FOLLOW PROPER SAFETY PRECAUTIONS.

警告

通电时不必接触板子。连接器件进行测试时，必须切断板子电源，且大容量电容器必须释放完所有电荷。

板子上一些组件的温度可能超过 50 摄氏度。移除电源后，上述情况可能会短暂持续，直至大容量电容器完全释放电荷。通电时禁止触摸板子，应在大容量电容器完全释放电荷后，再操作电路板。

请确保在操作电路板时已经遵守了正确的安全规程，否则可能会造成严重伤害，包括触电死亡、电击伤害、或电灼伤。

警告

通電している時にボードに接触する必要がありません。設備をつないで試験する時、必ずボードの電源を切ってください。また、大容量のコンデンサーで電力を完全に釈放してください。

ボードのモジュールの温度は 50 度以上になるかもしれません。電源を切った後、上記の状況がしばらく持続する可能性がありますので、大容量のコンデンサーで電力を完全に釈放するまで待ってください。通電している時にボードに接触するのは禁止です。大容量のコンデンサーで電力をまだ完全に釈放していない時、ボードを操作しないでください。

ボードを操作している時、正確な安全ルールを守っているのを確保してください。さもなければ、感電、電撃、厳しい火傷などの死傷が出る可能性があります。

6.1. HARDWARE:

AC Input Source: The input source shall be a variable AC source whose output can be adjusted between 90Vac and 265Vac. It must be capable of supplying at least 7000W.

Output Load: A programmable electronic load or a resistor bank may be used. Each must be capable of sinking 20A of load current supplied from a source whose output ranges between 250Vdc and 450Vdc.

Power Meter: A YOKOGAWA® WT 1800 power analyzer or any other equivalent power analyzer should be used (a minimum rating of 32A required for 6.6kW).

MCB: Single phase MCB (Miniature Circuit Breaker) rated for 415 V, 32 A.

Multimeters: Two digital multimeters (DMMs) are used to measure the regulated output voltage and the input RMS voltage.

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

Power Supplies: Power supplies with isolated grounds should be used.

1) 14V @ 1.5A capability is required to supply the auxiliary power board.
2) 12VDC @ 6A capability is required to power the cooling fans.

External Fan: At least two cooling fans (PFR0612XHE-CV52 DC12V/3.30A from Delta Electronics or equivalent) must be used, and three cooling fans should be used, for cooling the heatsinks as shown in Figure 7. The red wire of the fan is the positive terminal while the black wire is the negative terminal.

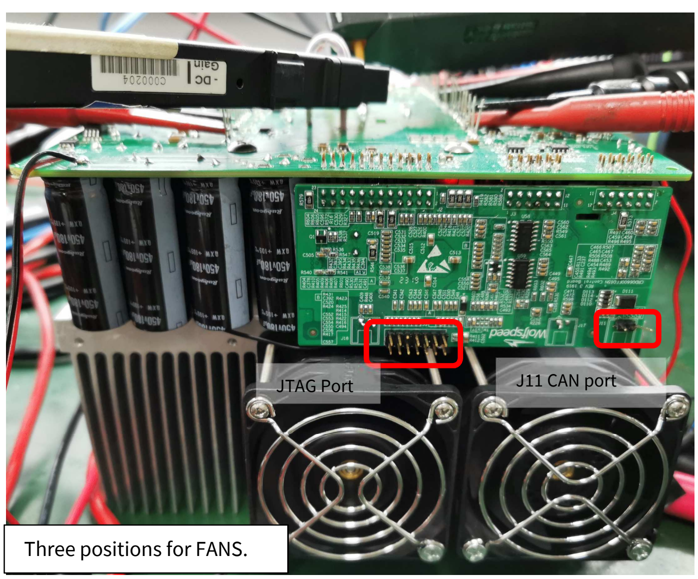


Figure 4: Setup of the Reference Design.

Recommended Wire Gauge: Cable with a minimum AWG #10 wire gauge is recommended to carry the input and output currents. The wire length between the reference design board and its AC source and DC load must be less than two feet long.

6.2. GUI:

The reference design can support CAN communications. The detailed CAN data format is shown in Section 6.6. 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 7.

The over/under voltage-protection and PLL faults are indicated by the back color of the voltage value and PLL frequency respectively as shown in Figure 8. “Green” indicates “Normal State” while “Red” means “Warning Issued”.

The ambient temperature is sensed by an IC and the two heatsink temperatures by negative temperature coefficient thermistor (NTC) resistors. These are displayed in the panel as well. Refer to Table 4 for protections.

The bus capacitor has been discharged as expected and shown in Figure 8e and Figure 8l. The bus capacitor has not discharged due to the source supply at the AC input as shown in Figure 8g.
To conduct an efficiency test with the output lightly loaded shown in Figure 8j, it is recommended that the SR be enabled. This is done by increasing the load sufficiently as shown in Figure 8k and then decreasing the load to the required test load.

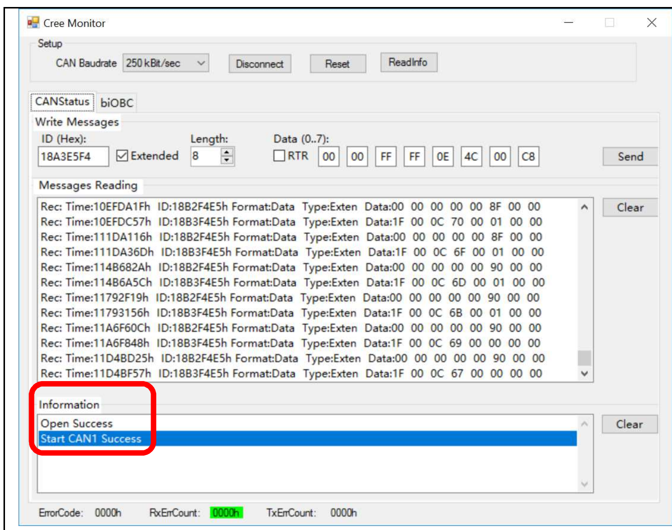


Figure 8 a: CAN Status Tab After Connection.

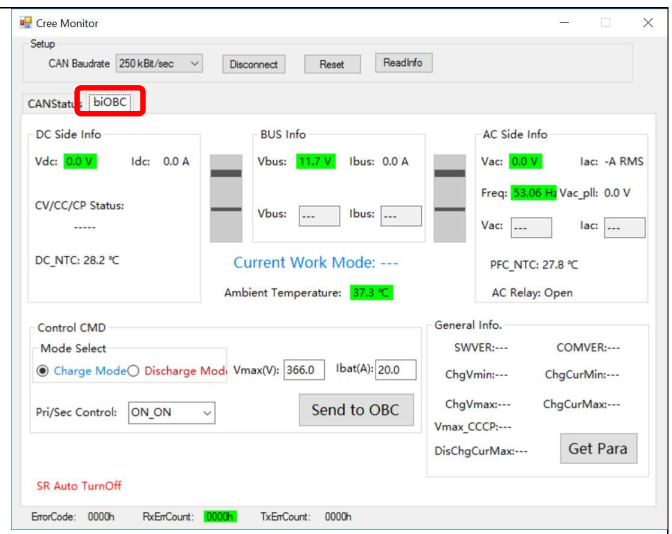


Figure 8 b: Connected to Control Board.

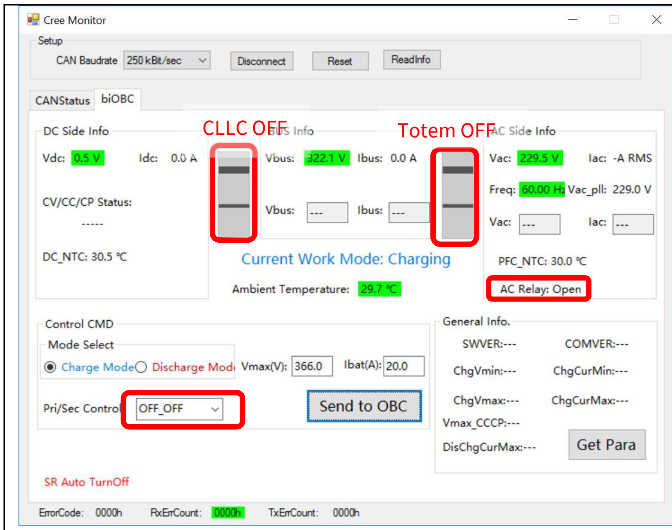


Figure 8 c: Power-on with OFF Control.

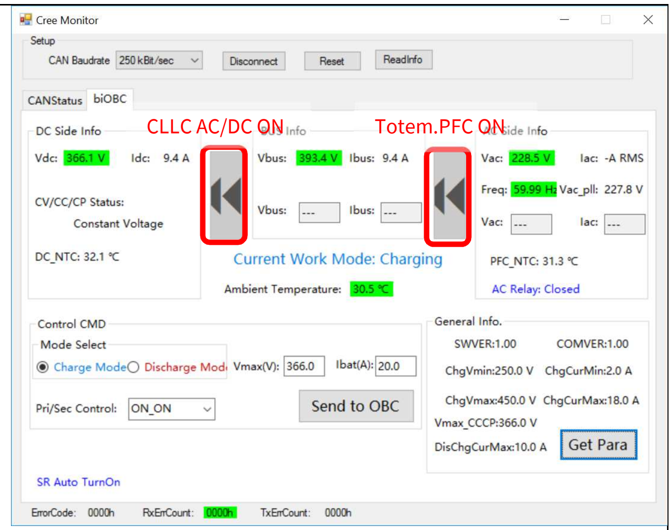


Figure 8 d: Normal Operation at Half-Load.

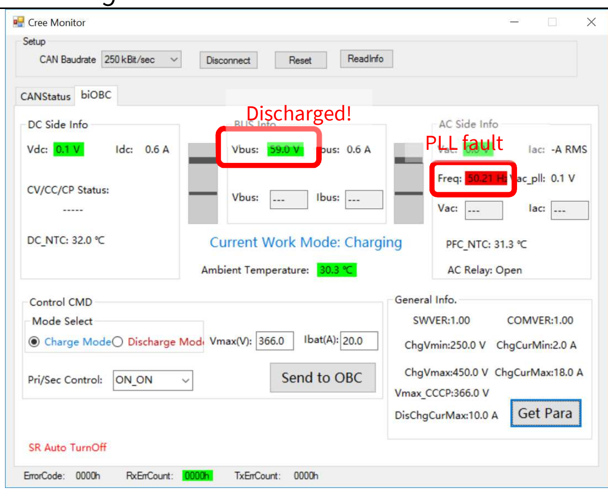


Figure 8 e: Power-off AC with About 200Ω Load. (PLL Fault)

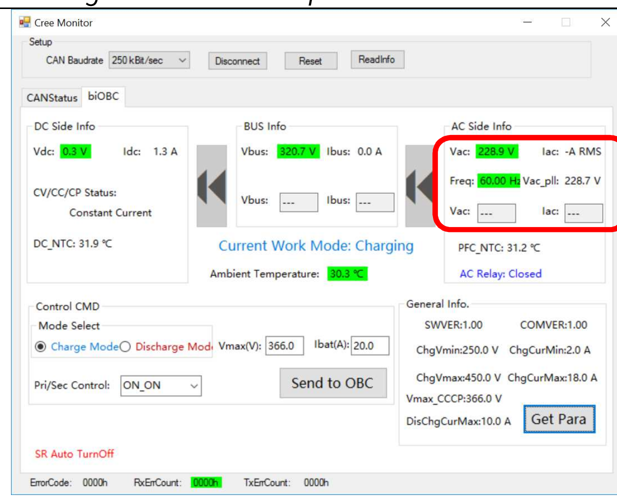


Figure 8 f: Power-on Again (Starting).

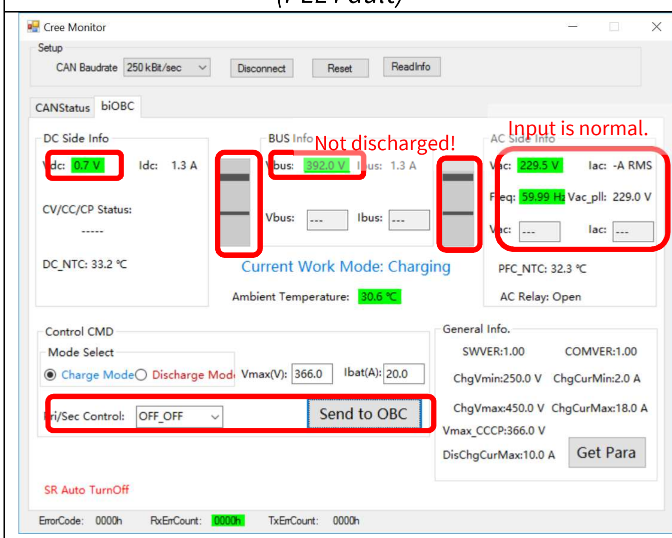


Figure 8 g: Shut-down Via CAN.

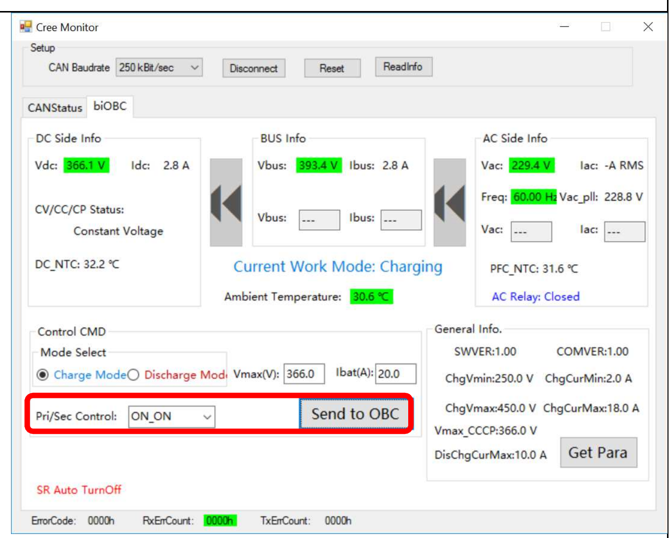


Figure 8 h: Start-up Via CAN.

Power-off of the board and bus discharge for the DC/AC test is shown below.

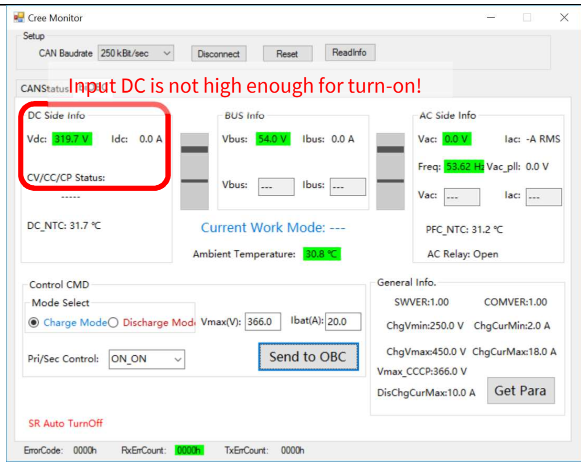


Figure 8 i: Power-on with DC Input at DC Terminal.

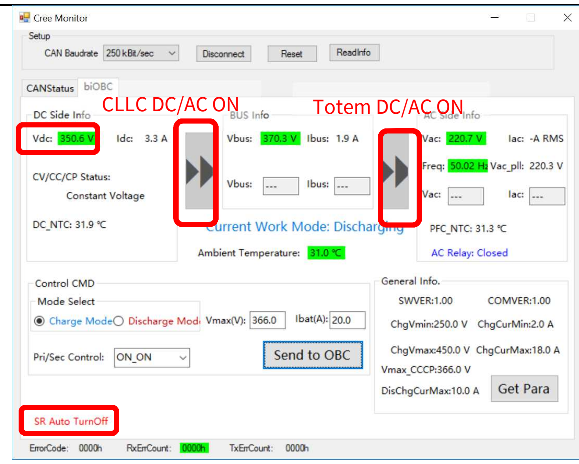


Figure 8 j: DC/AC without SR.

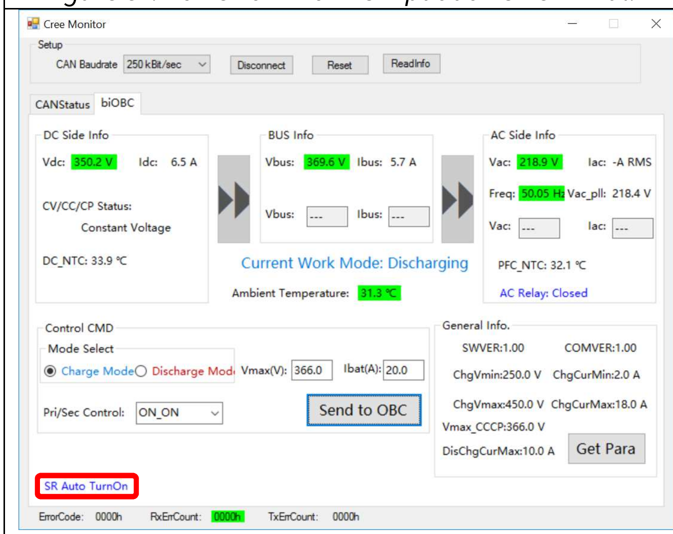


Figure 8 k: DC/AC with SR.

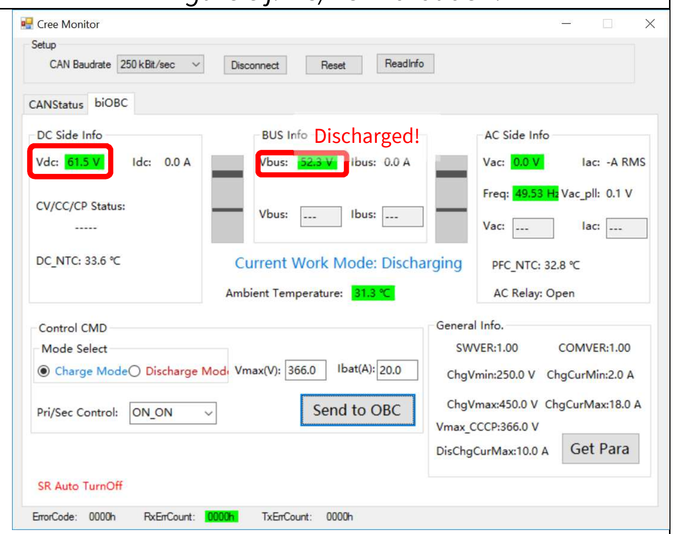


Figure 8 l: Shutdown Due to Loss of DC Input with Load.

6.3. RECOMMENDED TEST SETUP (AC/DC MODE)

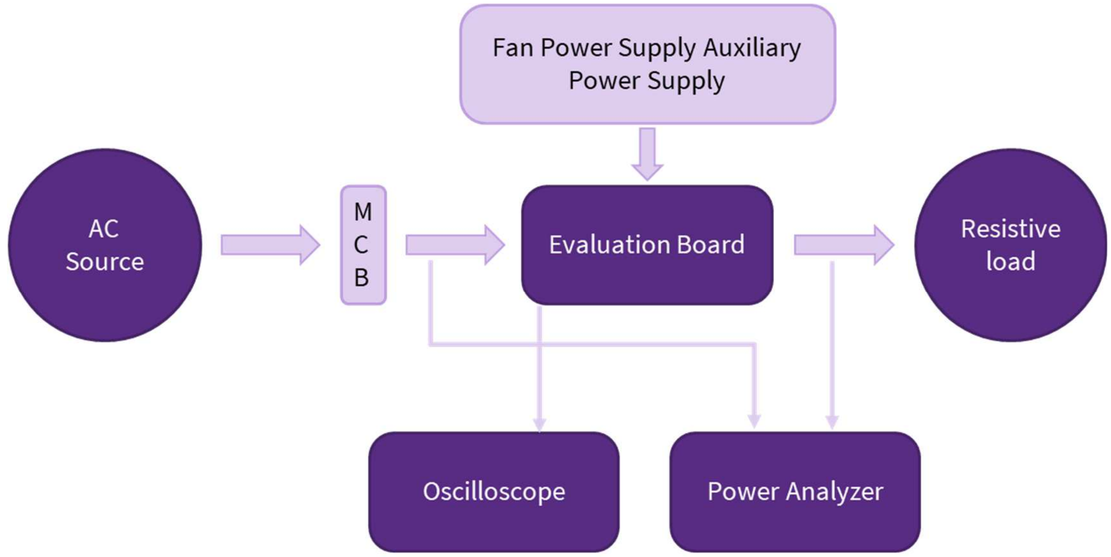


Figure 5: AC-DC Mode Test Setup.

- Connect single phase AC source to the AC terminal (input) of the EVM through MCB.
- Connect the resistive load bank to the DC terminal (output).
- 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.

6.4. RECOMMENDED TEST SET UP (DC/AC OFF-GRID MODE)

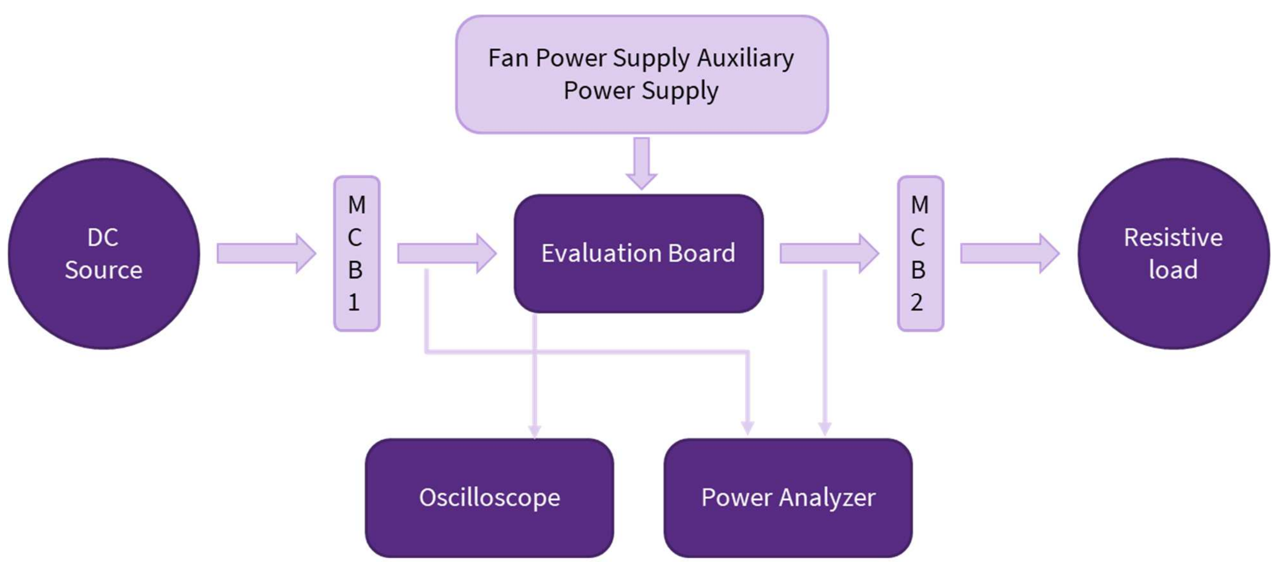


Figure 6: DC-AC OFF Grid Mode with Resistive Load Test Setup.

- Connect AC terminals (output) of EVM to resistive load through MCB2.
- Connect DC source to the EVM DC terminals (input) 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.

6.5. PROTECTIONS

Table 4 describes various protection functions in the reference design.

Work Mode	Power signal	Protection	Trip Point
AC/DC	AC input voltage	OVP/UVP	>270V, <80V
	DC-link voltage	OVP/UVP	>450V, <300V
	DC output voltage	OVP/ Short protection	>480V, <15V
DC/AC	DC input voltage	UVP	<295V

Table 4: Protection Details.

6.6. ISOLATED POWER SUPPLIES – VOLTAGE AND CURRENT SETTINGS

The requirements for the isolated power supplies are shown in Table 5. A single power supply connected to J6 is used to power the on-board auxiliary power board.

Control board Connector Designator	Power Supply	Voltage (V)	Current 1 (A) (Relay Open + PWM Off)	Current 2 (A) (Relay Closed + PWM Off)	Current 3 (A) Normal operation
J6	+14V for AUX power	+14V +/-5%	0.5	0.58	0.72

Table 5: Auxiliary Power Supply Requirements.

6.7. 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.

NAME	DESCRIPTION
AC Current	AC current at AC terminal
AC Voltage	High voltage AC at AC terminal
DC link voltage/Bus voltage	DC voltage across dc bulk capacitor
DC Voltage	DC voltage at DC terminal
DC Current	DC current at DC terminal
3.3V DSP Supply	+3.3V supply for DSP I/O

1.2V DSP Supply	+1.2V supply for DSP core
PWM pulses	MOSFET drives
Efficiency	Measured with power analyzer
PFC inductor current	Current of PFC inductor
CLLC primary current	CLLC tank current at DC link side
CLLC secondary current	CLLC tank current at DC output side

Table 6: Parameters Which Can be Measured.

6.8. CAN COMMUNICATION DATA FORMAT

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

When adjusting the output voltage in AC/DC mode, the user should use a reference current over 18A. When adjusting the output current, the user should use a voltage reference larger than the current operating voltage be used. Setting the output to 20A or/and 450V each time should be acceptable. The digital controller will check the value range each time.

In DC/AC mode the reference values above are ignored because the output AC voltage is not adjustable. Instead, it is fixed at 220VAC/50Hz. The only valid function is the On/Off command.

Example: “0x18A3E5F4” is sent as the message identifier and “0x0000FFFF0E4C00C8” as the CAN data. The OBC is placed in AC/DC mode, its output voltage is set to 366V and it will supply its maximum rated current. 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 or that instruction will be ignored by the reference board.

Message Identifier: 0x18A3E5F4					
Data	Byte0 = 00	Byte1= 00	Byte2+Byte3	Byte4+Byte5 = 0x0E4C	Byte6+Byte7 = 0x00C8
Property	AC/DC Mode	On	Reserved 0xFFFF	DC Voltage: 0x0E4C*0.1V = 366V	DC Current: 0x00C8*0.1A = 20A

Table 7: Example of Control Command.

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. Load of about 1KW should remain connected whenever the input source is removed regardless of the operating mode. Although the reference design has a feature to automatically discharge the DC link bus, it only provides a supplementary protection function and should not be relied upon.
2. In AC/DC mode, the DC link capacitor will discharge to about 50 Volts when the AC input is lost. During this discharge period the inrush relay is closed, and no inrush protection will be active. Reapplication of power to the AC input will result in a large inrush current which may result in damage to the reference design or the AC source.
3. If the GUI is used to disable the reference design while valid AC power is available, the DC link capacitors' discharge feature will not activate. As a result, no safety delay is required before the reference design is reenabled.
4. The DC link capacitors are always discharged to about 50Volts when the module is shut down in DC/AC mode. However, there is no control over the discharge of the output capacitors (battery side).
5. The reference design can automatically choose the proper operating mode under the following conditions:
    a. In AC/DC mode, if the AC input is normal and the DC link voltage is equal to or larger than the peak input voltage, the reference design will start regardless of the battery side status.
    b. In DC/AC mode, if the DC link voltage is below 60Vdc and the battery side DC voltage is equal to its programmed value, the reference design will start. A resistive load is permitted while in DC/AC mode.
6. In AC/DC mode, the AC supply should be applied without the use of soft-start because doing so may interfere with the PLL's frequency detection. However, in DC/AC mode, there is no current inrush limiter (battery side) and the DC input voltage must be increased slowly (soft-start).
7. Always remember to connect the cooling fans to their power supplies and operate the cooling fans when operating the board.

7.1. STARTUP PROCEDURE: DC/AC OFF-GRID MODE WITH RESISTIVE LOAD

This mode is used to generate 220Vrms/50Hz sinusoidal AC voltage. The setup is as shown in Figure 10. Please take the following steps in order when starting the unit in this mode:

1. Keep MCB1 (DC supply) in open position and the DC source output disabled.
2. Ensure the load is under 1KW at 220Vac and the DC link capacitor is fully discharged.
3. Apply 14Vdc to J6 on the power board. Check the output voltage of the Auxiliary Power Supply at J7 (P6.5V, VP+15V) and J8 (VS+15V, CAN_5V). Check that the current draw is approximately the same as shown in Table 5. Check the +3.3V LED (on) and watchdog led (blinking) on the control board.
4. Connect the GUI to the system.
5. Apply power to the cooling fans.
6. Put MCB1 in the ON position. Because there is no inrush limiter, turn on the DC supply and increase it slowly from 0V to the required voltage (320Vdc – 450Vdc). On the initial powerup, the GUI information should be checked with about a 100V~200V input voltage. The reference design will start in DC/AC

mode when the input voltage is at or above its setpoint.

7. Verify that the measured values in the GUI were reported correctly.
8. After startup, increase the load up to 3.3KW. The step-load change should not exceed 1KW for each step when increasing the load.
9. Check the efficiency and power-factor under load conditions of interest. Check if SR is turned on automatically when DC input current is above 5A. SR should be enabled by increasing load to greater than 5A; the load can then be decreased to the target load if you would like to apply a lighter load.

`

7.2. TURNOFF PROCEDURE: DC/AC OFF-GRID MODE WITH RESISTIVE LOAD

1. Decrease the load to 1KW in less than 1KW steps.
2. Disable the output of the DC power supply. Open MCB1, disconnecting the DC power supply from the DC terminals.
3. **The DC link capacitors remain charged for up to 30 minutes after the circuit is turned OFF. They must be allowed to fully discharge before handling the board. You may decrease the time that it takes for the board to be fully discharged by adding a discharge circuit to the DC link to discharge the DC link capacitors. Please check the DC link voltage with a multimeter to ensure that the board has fully discharged and is therefore safe to handle.**
4. Turn OFF resistive load MCB2 after “relay is open” is shown in the GUI.
5. Turn OFF the 14Vdc power supply on J6. The unit should be fully discharged before the auxiliary power supply is disabled.

7.3. STARTUP PROCEDURE: AC/DC MODE

The board should be connected as shown in Figure 9.
Please take the following steps in order when starting the unit in this mode:

1. Keep MCB1 (AC supply) in the open position and the AC source output disabled.
2. Apply a load of no more than 1KW to the DC terminals.
3. Apply 14Vdc to J6 on the power board. Check the output voltage of the Auxiliary Power Supply at J7 (P6.5V, VP+15V) and J8 (VS+15V, CAN_5V). Check that the current draw is approximately the same as shown in Table 5. Check the +3.3V LED (on) and watchdog led (blinking) on the control board.
4. Connect the GUI to the system.
5. Apply power to the cooling fans.
6. Set the AC input voltage within the universal range (nominally 230Vac). It must be greater than 90Vac before the inrush relay can close. Turn ON the miniature circuit breaker (MCB). The reference design will start in AC/DC mode.
7. Verify the measured values in the GUI were reported correctly. The reference design should issue a fault (PLL fault, OCP, OVP, UVP, etc.) if it fails to start.
8. The output voltage can be regulated using the GUI. Keep the current reference as default before start-up.
9. Apply a load to the output in no more than 2KW steps. The maximum load should not exceed 4.5KW

with a 250Vdc output or 5KW with a 450Vdc output. Exceeding these power levels may cause the output voltage to droop until it reaches a stable operating point. Permanent damage may occur during sustained operation if a heavy load causes voltage droop below 250Vdc.

10. Check the efficiency and power-factor under load conditions of interest. Check if SR is turned on automatically when DC output current is above 5A. SR should be enabled by increasing load to greater than 5A; the load can then be decreased to the target load if you would like to apply a lighter load.

7.4. TURNOFF PROCEDURE: AC/DC MODE

1. Decrease the load to 1KW. The step of load change should be less than 2KW for each step.
2. Turn OFF the AC source. Open MCB, disconnecting the AC supply from the AC terminals.
3. **The DC link capacitors remain charged for up to 30 minutes after the circuit is turned OFF. They must be allowed to fully discharge before handling the board. You may decrease the time that it takes for the board to be fully discharged by adding a discharge circuit to the DC link to discharge the DC link capacitors. Please check the DC link voltage with a multimeter to ensure that the board has fully discharged and is therefore safe to handle.**
4. Turn OFF resistive load MCB2 after “relay is open” is shown in the GUI.
5. Turn off the 14Vdc power supply on J6. The unit should be fully discharged before the auxiliary power supply is disabled.

8. PHOTOS OF THE REFERENCE DESIGN

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

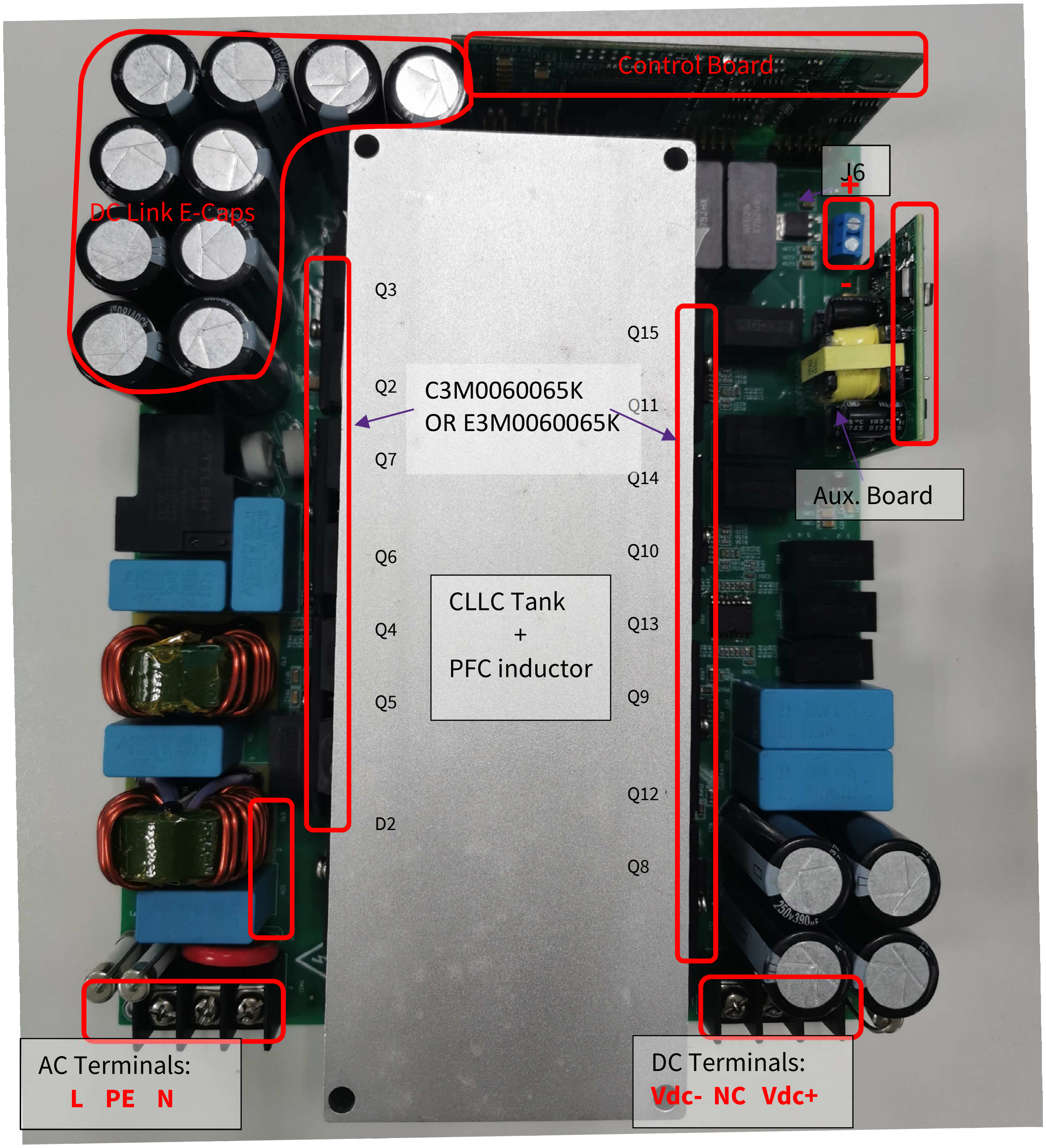


*Figure 7: Top View of PCBA (270mm*180mm*50mm).*

Figure 12 shows a detailed view of the tooled aluminum heatsink with power semiconductors mounted. The magnetics are to be potted with a thermal compound.

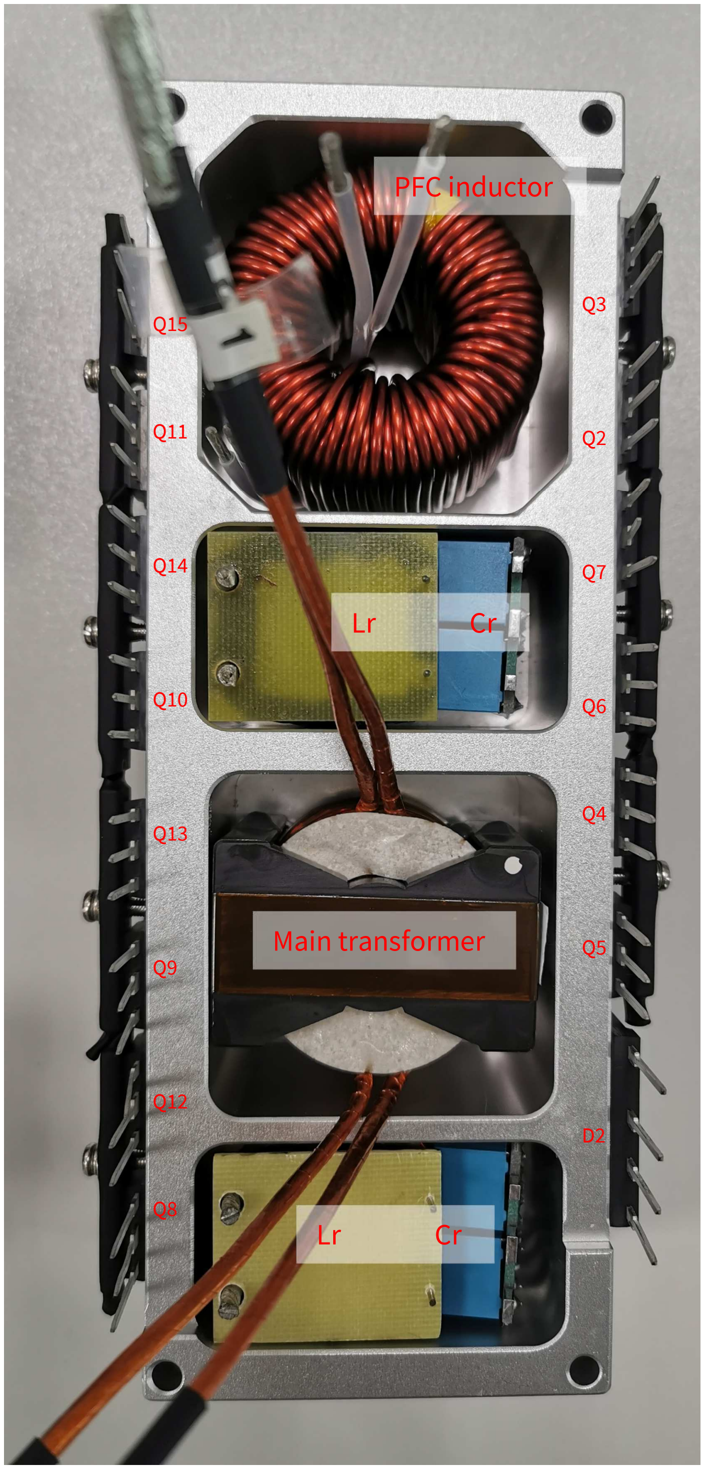


Figure 8: Heatsink Interior.

9. PERFORMANCE DATA

The performance data of Wolfspeed's CRD-06600FF065N-K reference design board is taken in both AC/DC and DC/AC modes. Table 8 to Table 11 indicates the performance data.

Input Voltage (Vac)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)	PF
265	526.82	10%	250.103	494.39	93.823	0.88309
265	1034.5	20%	250.077	984.42	95.155	0.96569
265	1607.5	30%	250.063	1532.6	95.337	0.98624
265	2091.7	40%	250.06	1991.8	95.221	0.99303
265	2610.1	50%	250.023	2479.8	95.005	0.996
265	3161	60%	249.954	2996	94.765	0.99718
265	3683.6	70%	249.906	3479.1	94.45	0.99781
265	4274.9	80%	249.871	4020.8	94.031	0.99821
265	4773.88	90%	249.823	4472.9	93.697	0.99843
265	701.96	10%	366.367	670.09	95.459	0.92906
265	1376.1	20%	366.313	1332.5	96.836	0.9791
265	2056.5	40%	366.323	1996.2	97.071	0.99102
265	2740.5	40%	366.307	2658.4	97.003	0.9949
265	3423.8	50%	366.28	3317.4	96.893	0.99662
265	4112.8	60%	366.27	3978.6	96.744	0.99751
265	4802.8	70%	366.268	4637.2	96.553	0.99805
265	5498.4	80%	366.236	5292.6	96.263	0.99835
265	6198	90%	366.209	5949.9	95.997	0.99856
265	6836.5	100%	366.225	6543.1	95.71	0.99866
265	560.93	10%	449.96	505.36	90.093	0.88512
265	1070.1	20%	449.962	1014.7	94.83	0.96544
265	1582.7	30%	449.961	1519.1	95.978	0.98421
265	2095.6	40%	449.951	2021	96.438	0.99108
265	2610.7	50%	449.95	2522.7	96.617	0.99415
265	3127.8	60%	449.91	3024.7	96.703	0.99578
265	3651.1	70%	449.899	3529.4	96.666	0.99678
265	4171.6	80%	449.905	4029.8	96.607	0.9974
265	4696.3	90%	449.869	4530	96.459	0.99781
265	5222.5	100%	449.123	5030.2	96.317	0.99806

Table 8: Efficiency Data (AC/DC mode), VIN = 265VAC/50Hz.

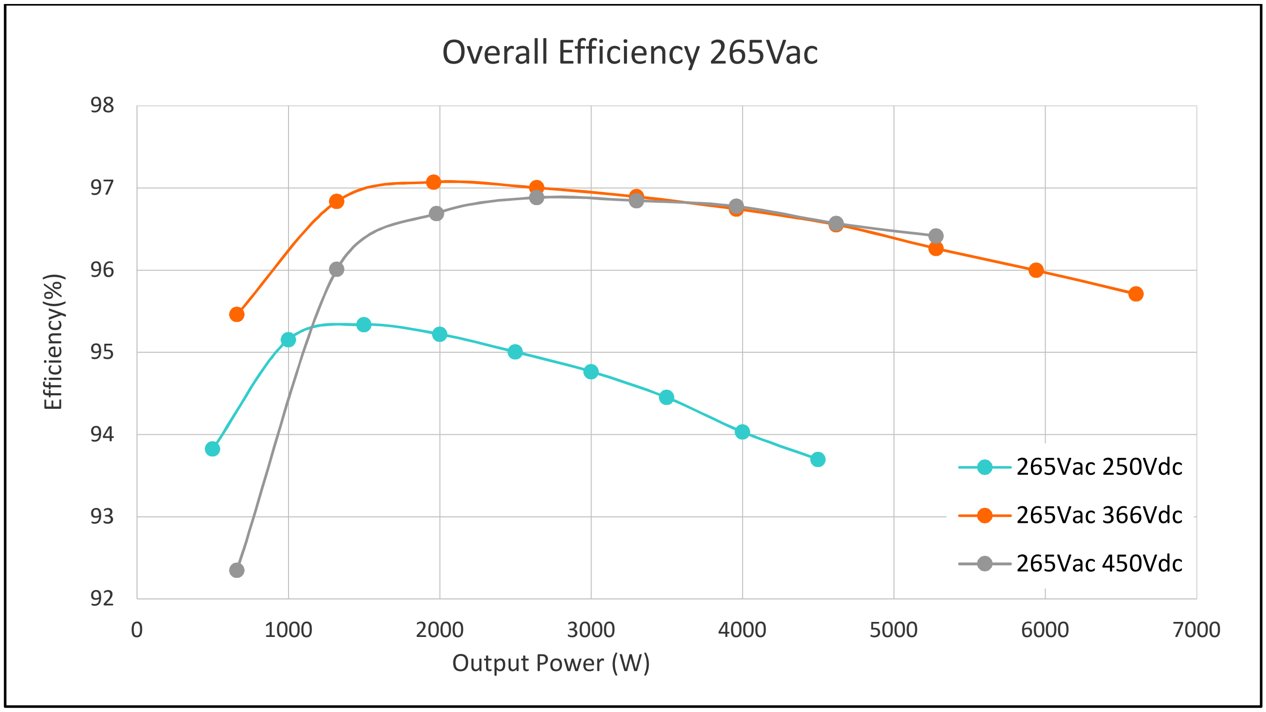


Figure 9: Efficiency Data (AC/DC mode), VIN = 265 VAC/50Hz.

Input Voltage (Vac)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)	PF
230	532.13	10%	250.111	499.48	93.865	0.91583
230	1046	20%	250.073	994.47	95.071	0.97545
230	1561.8	30%	250.056	1487.5	95.247	0.98938
230	2112	40%	250.068	2007.1	95.033	0.99437
230	2634	50%	250.018	2498.8	94.866	0.99662
230	3157.7	60%	249.962	2986.2	94.569	0.9975
230	3721.3	70%	249.896	3508.5	94.229	0.99795
230	4250.4	80%	249.858	3990.2	93.88	0.99822
230	4475.6	90%	249.493	4788.4	93.467	0.99841
230	702.08	10%	366.363	668.88	95.272	0.9426
230	1381.8	20%	366.324	1335.2	96.626	0.98422
230	2063	30%	366.322	1999.7	96.932	0.99282
230	2748	40%	366.298	2662.6	96.876	0.99574
230	3438	50%	366.279	3324.2	96.692	0.99702
230	4129.7	60%	366.27	3985.8	96.515	0.99768
230	4826.5	70%	366.259	4645.1	96.24	0.99804
230	5527.9	80%	366.233	5303.9	95.948	0.99826
230	6238.3	90%	366.215	5965.5	95.626	0.99836
230	6857.8	100%	366.193	6539.8	95.364	0.99837
230	558.88	10%	449.946	502.09	89.838	0.91603
230	1068.3	20%	449.951	1010.6	94.601	0.97366
230	1587.5	30%	449.935	1519.5	95.718	0.98787
230	2103.2	40%	449.915	2024.1	96.24	0.99279
230	2622.3	50%	449.888	2528.1	96.409	0.99508
230	3134.8	60%	449.864	3023.8	96.46	0.99632
230	3656	70%	449.884	3525.5	96.431	0.99705
230	4180.9	80%	449.854	4027.7	96.336	0.99751
230	4708.2	90%	449.84	4529.8	96.211	0.99781
230	5245.4	100%	448.857	5037.6	96.038	0.99798

Table 9: Efficiency Data (AC/DC mode), VIN = 230 VAC/50Hz.

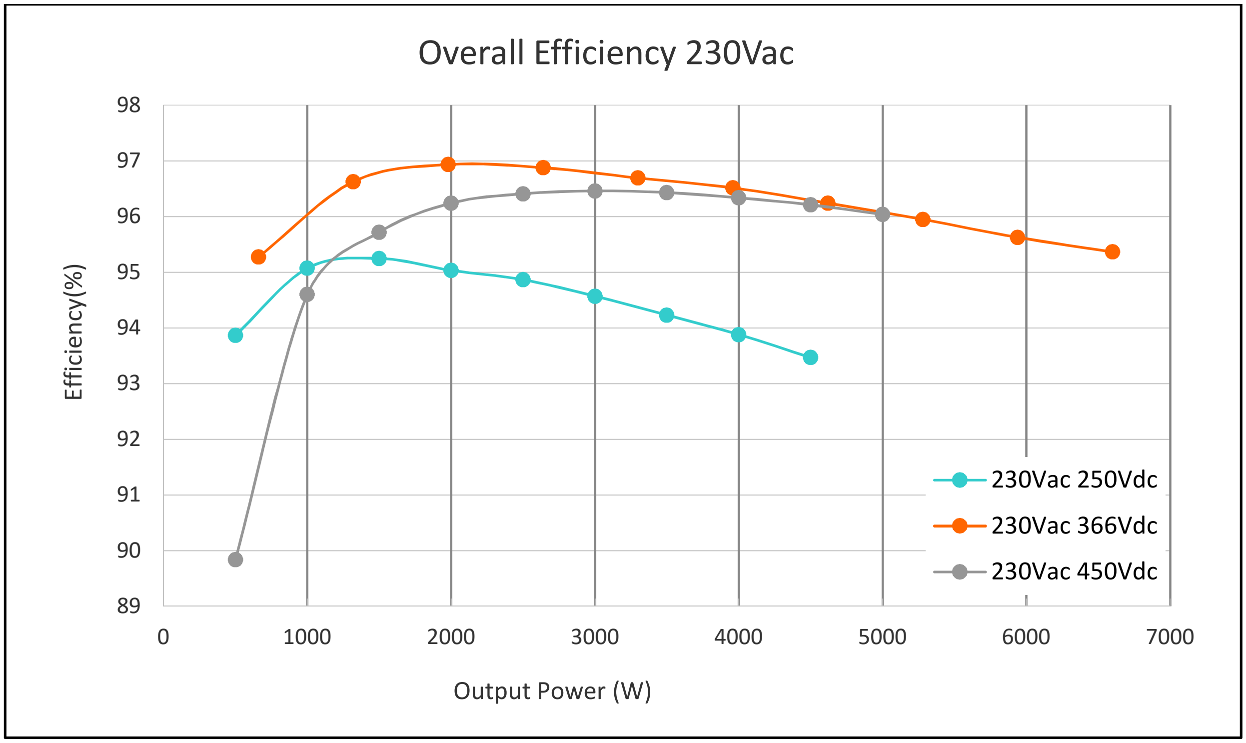


Figure 10: Efficiency Data (AC/DC mode), VIN = 230 VAC/50Hz.

Input Voltage (Vac)	Input Power (W)	Load (%)	Output Voltage (Vdc)	Output Power (W)	Overall Efficiency (%)	PF
90	536.46	25%	250.146	496.29	92.512	0.98397
90	1056.6	50%	250.105	985.55	93.272	0.99533
90	1619.9	75%	250.068	1506.2	92.983	0.99709
90	1856.5	100%	250.083	1721	92.701	0.99753
90	572.05	25%	366.406	532.86	93.15	0.98575
90	1057.8	50%	366.358	998.75	94.427	0.99491
90	1623.4	75%	366.346	1534.2	94.508	0.99698
90	2121.9	100%	366.327	1998.8	94.198	0.99744
90	568.58	25%	449.941	504.06	88.653	0.98561
90	1100.8	50%	449.995	1008.7	91.64	0.9952
90	1638.6	75%	449.968	1510.7	92.198	0.99699
90	2194	100%	449.957	2020.6	92.097	0.99738

Table 10: Efficiency Data (AC/DC mode), VIN = 90 VAC/50Hz.

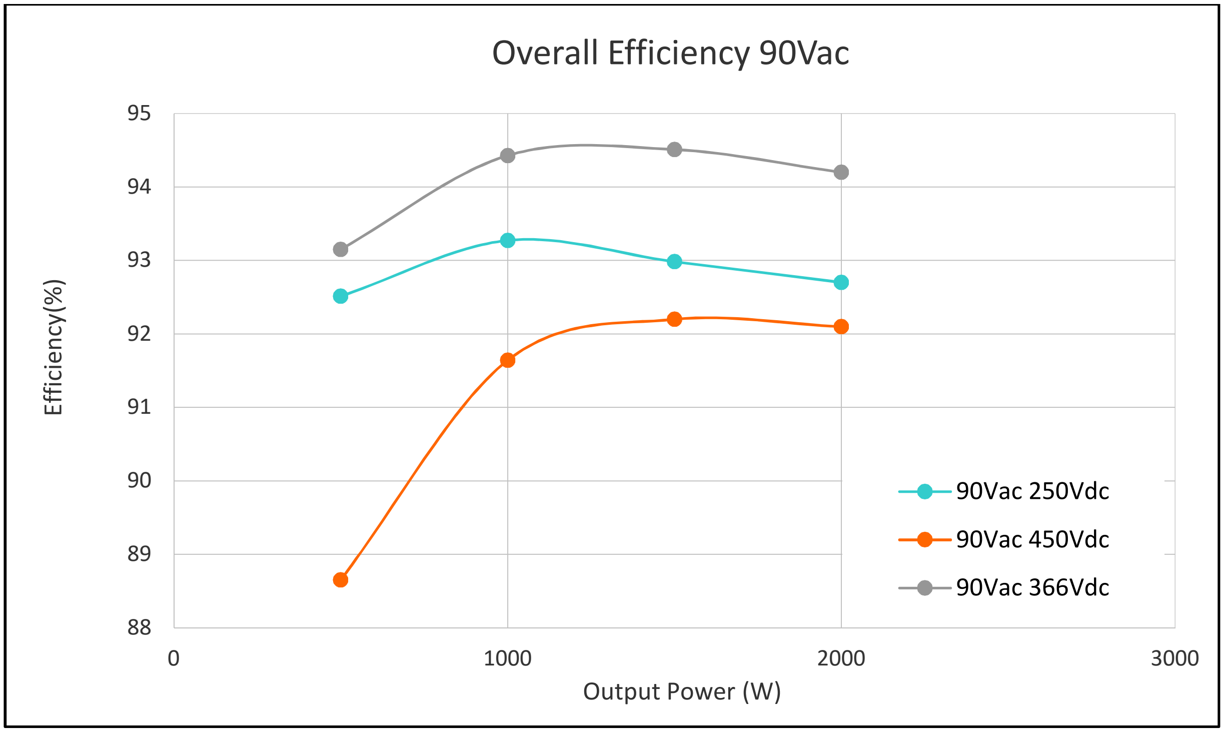


Figure 11: Efficiency Data (AC/DC mode), VIN = 90 VAC/50Hz.

Input Voltage (Vdc)	Input Power (W)	Load (%)	Output voltage (Vac)	Output Power (W)	Overall Efficiency (%)	PF
320	360.22	10%	220	328.54	91.206	0.99995
320	731.88	20%	220	687.66	93.958	0.99998
320	1035.5	30%	220	997.35	96.306	0.99998
320	1377.7	40%	220	1331.3	96.636	0.99999
320	1692.7	50%	220	1636.5	96.675	0.99999
320	2055.9	60%	220	1987.7	96.68	0.99999
320	2390.9	70%	220	2310.2	96.625	0.99999
320	2727.2	80%	220	2630.6	96.46	0.99999
320	3084.6	90%	220	2971.5	96.334	0.99998
320	3415.9	100%	220	3284.1	96.142	0.99998
366	366.83	10%	220	330.06	89.978	0.99994
366	707.96	20%	220	660.52	93.298	0.99996
366	1037.3	30%	220	992.74	95.704	0.99998
366	1378	40%	220	1326.4	96.254	0.99998
366	1719.5	50%	220	1659.1	96.49	0.99998
366	2060	60%	220	1988.8	96.571	0.99998
366	2400.4	70%	220	2318.8	96.6	0.99998

366	2741.7	80%	220	2648.4	96.595	0.99998
366	3081.3	90%	220	2973.9	96.513	0.99998
366	3423.2	100%	220	3299.2	96.38	0.99998
450	377.24	10%	220	334.12	88.57	0.9988
450	723.52	20%	220	662.03	91.501	0.99964
450	1059.5	30%	220	990.31	93.47	0.99986
450	1387.3	40%	220	1318.5	95.046	0.99988
450	1748.1	50%	220	1669.1	95.483	0.99992
450	2063.5	60%	220	1976.3	95.776	0.99995
450	2405.6	70%	220	2304.4	95.794	0.99996
450	2767.1	80%	220	2651.4	95.819	0.99996
450	3124.4	90%	220	2995	95.857	0.99996
450	3439.3	100%	220	3294	95.775	0.99996

Table 11: Efficiency Data (DC/AC mode), VIN = 320V/366V/450 VDC.

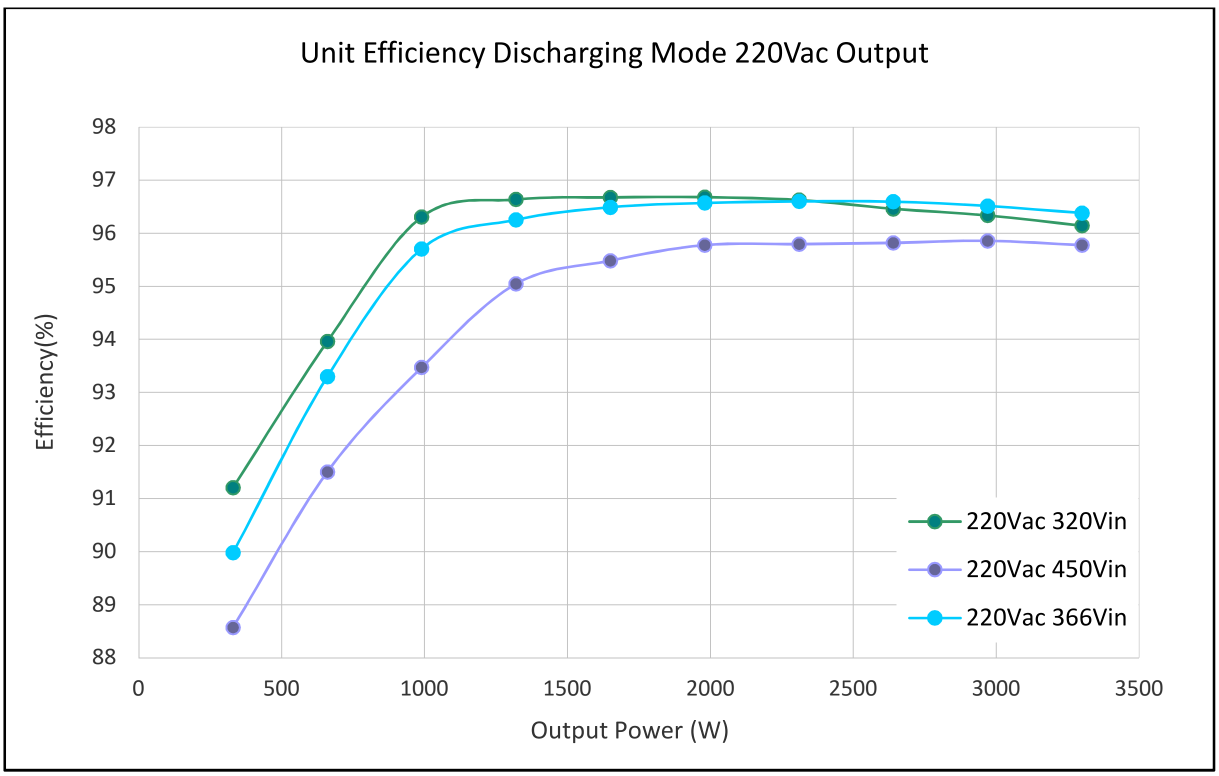
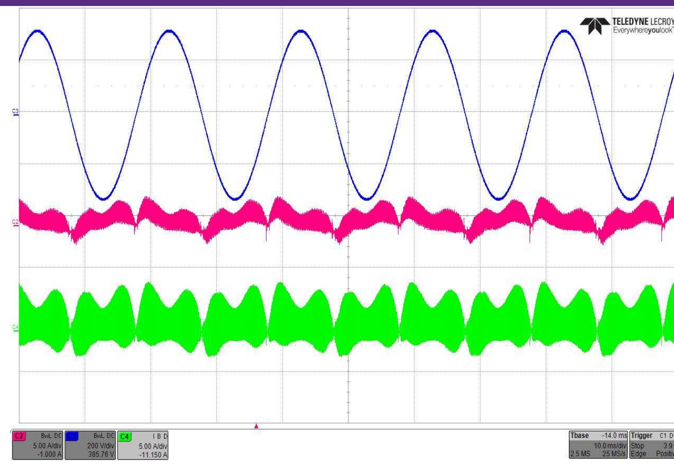
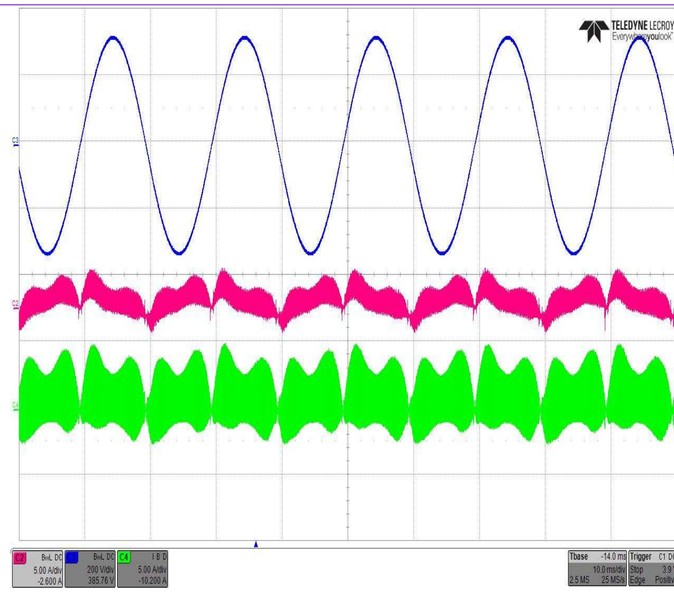


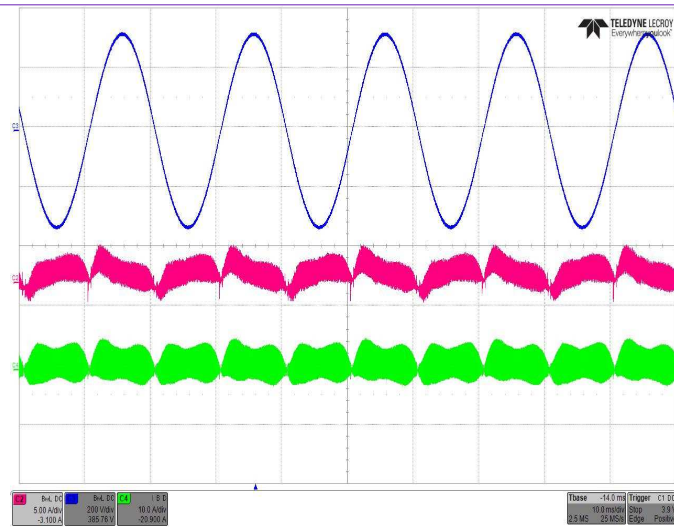
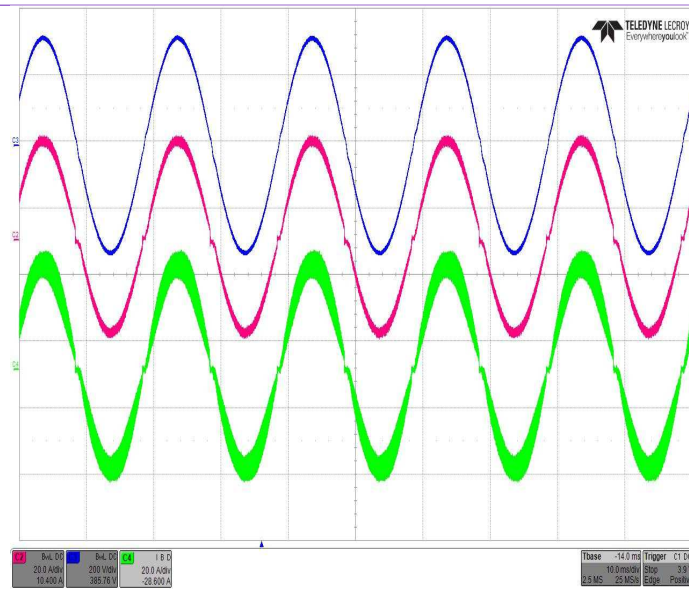
Figure 12: Efficiency Data (DC/AC mode).

10. TYPICAL WAVEFORMS

Operational waveforms are presented in Table 12 and Table 13.

10.1. AC/DC MODE:

Condition	Comments	Waveform
AC/DC Mode **AC Input:** **230Vac grid voltage** **DC Output:** **250Vdc** **No load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 5A/div Green trace : inductor current, 5A/div	
AC/DC Mode **AC Input:** **230Vac grid voltage** **DC Output:** **366Vdc** **No load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 5A/div Green trace: inductor current, 5A/div	

AC/DC Mode **AC Input: 230Vac grid voltage** **DC Output: 450Vdc** **No load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 5A/div Green trace: inductor current, 10A/div	
AC/DC Mode **AC Input: 230Vac grid voltage** **DC Output: 250Vdc** **Full load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 20A/div Green trace: inductor current, 20A/div	

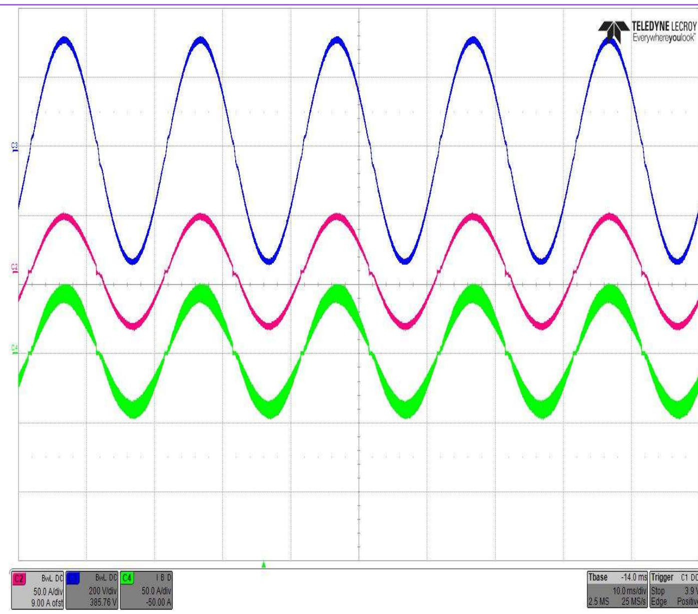
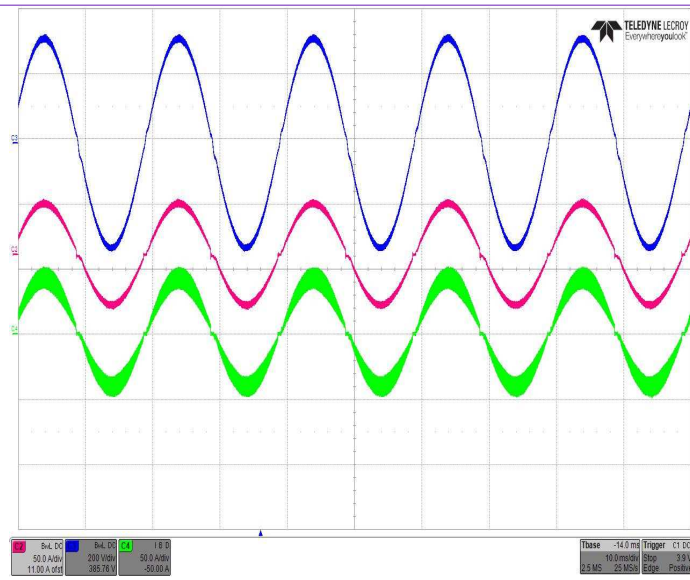
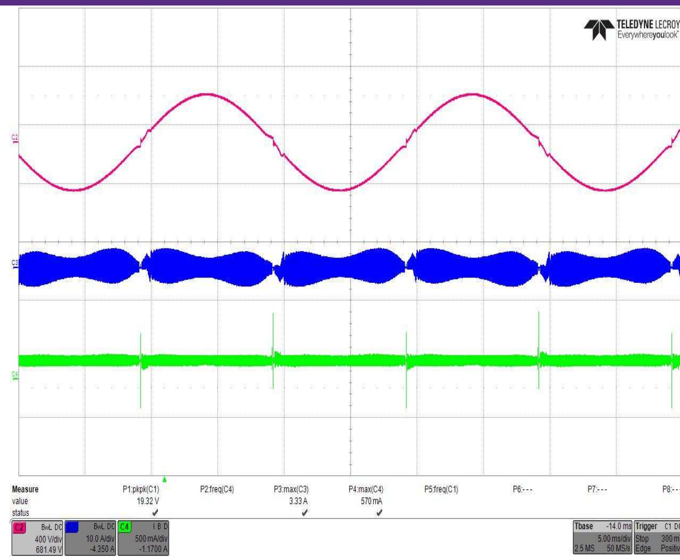
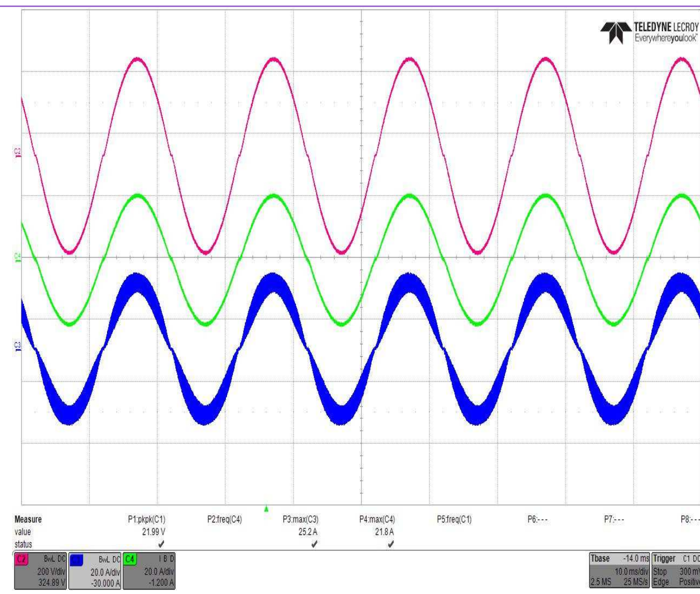
AC/DC Mode **AC Input:** **230Vac grid voltage** **DC Output:** **366Vdc** **Full load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 50A/div Green trace: inductor current, 50A/div	
AC/DC Mode **AC Input:** **230Vac grid voltage** **DC Output:** **450Vdc** **Full load**	Blue trace: grid voltage, 200V/div Pink trace: input current, 50A/div Green trace: inductor current, 50A/div	

Table 12: AC/DC Waveforms.

10.2. DC/AC MODE:

DC/AC Stand Alone Mode (Resistive load).

Condition	Comments	Waveform
DC Input: **366Vdc** **AC Output:** **220Vac** **No load**	Pink trace: AC voltage, 400V/div Blue trace: Inductor current, 10A/div Green trace: output current, 0.5A/div	
DC Input: **366V** **AC Output:** **220Vac** **Full load**	Pink trace: AC voltage, 200V/div Green trace: output current, 20A/div Blue trace: inductor current, 20A/div	

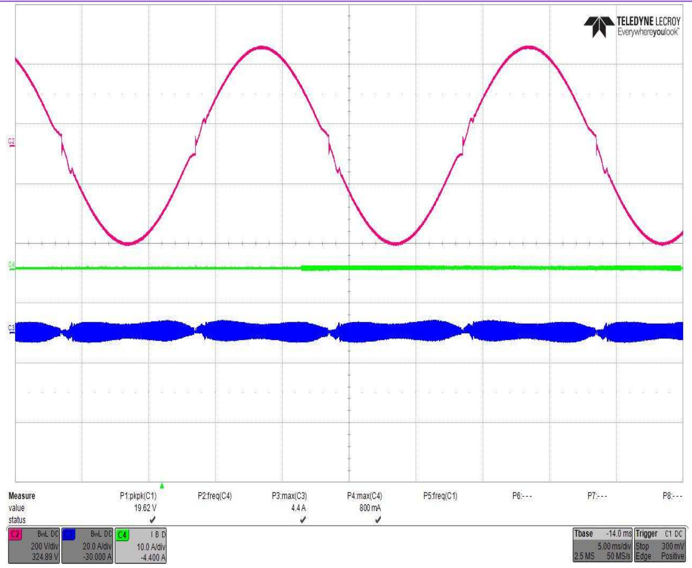
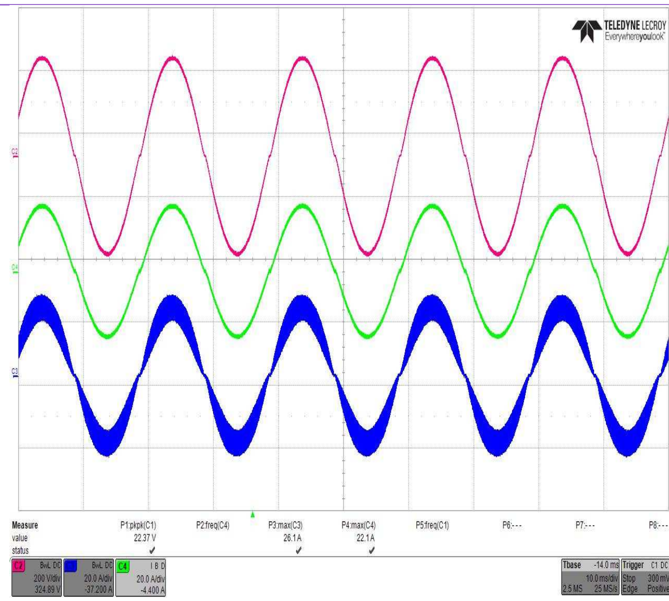
DC Input: **450Vdc** **AC Output:** **220Vac** **no load**	Pink trace: AC voltage, 200V/div Green trace: output current, 10A/div Blue trace: inductor current, 20A/div	
DC Input: **450Vdc** **AC Output:** **220Vac** **Full load**	Pink trace: AC voltage, 200V/div Green trace: output current, 20A/div Blue trace: inductor current, 20A/div	

Table 13: DC/AC Waveforms.

11. THERMAL DESIGN AND TEST RESULTS

In order to achieve both a high power density and bi-directional control, single-phase CCM totem pole PFC and CLLC topologies were selected. TO-247 packages are used exclusively for the power semiconductors. They lend themselves to a high-density design with cooling heatsinks.

In OBC applications, the MOSFETs in TO-247 packages are usually reverse assembled on the PCB. Their leads are bent at 90 degrees and they are installed with their bodies flush against the PCB and then soldered. A flat, cooling baseplate is then attached to their bodies. While this technique is effective, a large amount of PCB area is required. This negatively impacts the power density of the system. Figure 12 shows the proposed method for attaching the power MOSFETs. A tooled aluminum heatsink was designed that integrates the heatsinks needed to cool both the power semiconductors and magnetics. The power semiconductors are mounted on the outer side of the heatsink while the magnetics are placed within the heatsink slots and then potted with a thermally conductive epoxy compound. The required footprint is smaller since the MOSFETs remain vertically oriented. The thermal resistance from the tooled aluminum heatsink to the system cooling baseplate is low as well.

Description	Rth_{j-c} (°C /W)	Calculated Power loss (W)	Measured Case Temp. (°C)	Calculated Junction Temp. (°C)
Output = 366Vdc 6.6KW				
PFC MOSFET	1.58	18	97.9	126.3
CLLC MOSFET	1.58	18.7	95.8	125.4
CLLC SR MOSFET	1.58	16.8	87.8	114.4
PFC Inductor	NA	13.9	89.2	NA
CLLC Transformer	NA	13.8	114.9	NA
Output = 450Vdc 6.6KW				
PFC MOSFET	1.58	18.3	100.5	129.4
CLLC MOSFET	1.58	17.8	92.5	120.6
CLLC SR MOSFET	1.58	11	86.8	104.2
L_PFC	NA	15.1	91.4	NA
T_DCDC	NA	19.5	123.1	NA
Output = 250Vdc 4.5KW				
PFC MOSFET	1.58	12.6	78	97.9
CLLC MOSFET	1.58	21.5	95	128.97
CLLC SR MOSFET	1.58	16.8	79.2	105.74
L_PFC	NA		83.6	NA
T_DCDC	NA		107.5	NA

Table 14: Thermal Test Results.

During thermal testing of the prototype, forced-air cooling was applied to the bottom side of the baseplate assembly and adjusted as necessary so that it remained at 65^{0}C. This simulates the thermal condition in an OBC application. There is no direct air flow to the power MOSFETs.

In AC/DC mode, the most extreme thermal condition for the MOSFETs in this CLLC converter should occur when the output is loaded to 18A while at 366V. The most extreme thermal condition for the MOSFETs in the totem-pole PFC converter should occur when the output is loaded to 14.67A at 450V. The thermal test was performed with a low-line AC input of 215Vac. The full-load (6.6KW) output conditions were 366V@18A and 450V@14.67A. T-type thermal couplers and a KEYSIGHT® 34972A acquisition unit are used to measure the case temperature of various components.

The test results under these conditions are shown in Table 14. The highest junction temperature of any MOSFET in the design was determined to be 129.4°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 C3M0060065K and E3M0060065K is 175°C, the integrated heat sink design has allowed the MOSFETs to remain within their thermal derating guidelines. Note that this testing was done by overriding the reference design's software which would normally limit the output power to 5KW in AC/DC mode when the output voltage is 450Vdc.

12. APPENDIX

12.1. PWM TIMING

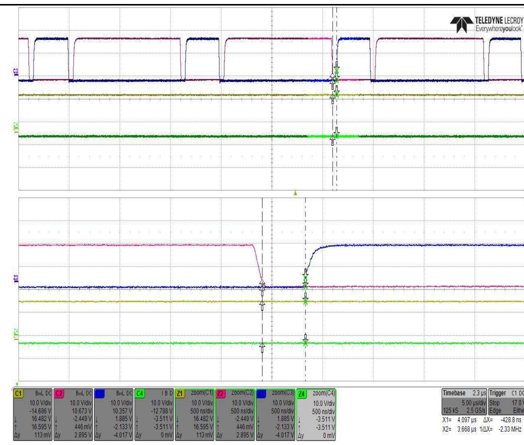
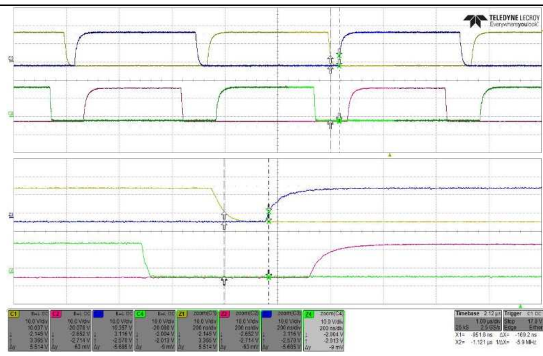
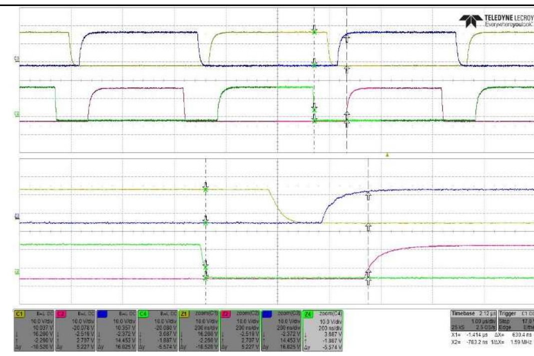
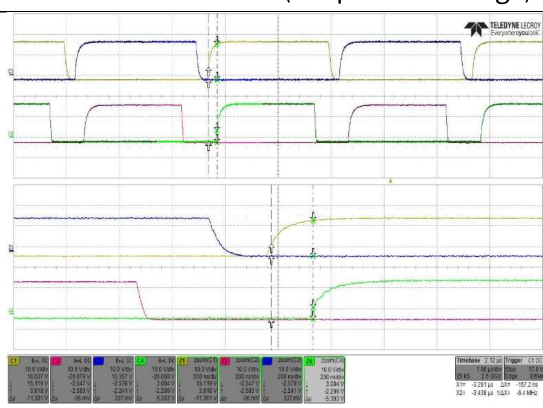
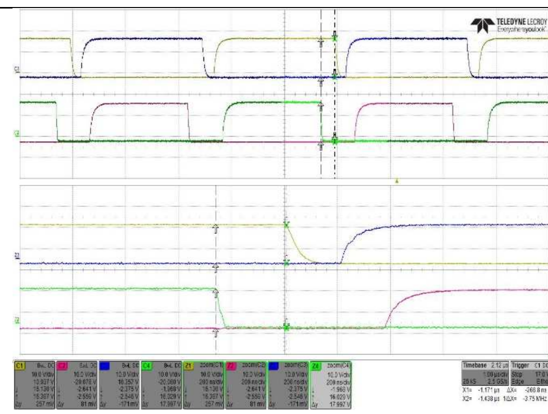
 Td_Low Frequency Half Bridge=104us	 Td_ High Frequency Half Bridge =429ns
CH1: Vgs Low-Frequency Low Side CH3: Vgs High-Frequency High Side	CH2: Vgs High-Frequency Low Side CH4: Vgs Low-Frequency High Side
 Td Dead Time=169ns (Output Side Bridge)	 Td Dead Time=630ns (Bus Side Bridge)
 Td_Output_Bus_on_delay =157ns	 Td_Output_Bus_off_delay=267ns
CH1: High Side Vgs of Output Side Bridge CH3: Low Side Vgs of Output Side Bridge	CH2: Low Side Vgs of Bus Side Bridge CH4: High Side Vgs of Bus Side Bridge

Table 15: Gate Signals and Timings in DC/AC Mode.

12.2. CAN MESSAGES FROM OBC

Message Identifier	0x18B2F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	DC voltage	DC Current	Bus Voltage	AC Voltage
Unit	0.1V	0.1A	0.1V	
Bias	0			
Data Format	integer			
Time interval	3 seconds			

Table 16: Overall Charge Status.

Message Identifier	0x18B0F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	Ambient Temperature	PFC Temperature	DC Temperature	Charge state 0: Constant Voltage 1: Constant Power 2: Constant Current
Unit	0.1 °C			NA
Bias	50 °C			NA
Data Format	integer			
Time interval	30 seconds			

Table 17: Temperature and Charge Mode.

Message dentifier	0x18B3F4E5			
Data	Byte0+Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	OBC status. See Table 18a for details.	AC Frequency	Voltage Amplitude from PLL	CLLC Current
Unit	NA	0.1Hz	0.1V	0.1A
Bias	0			
Data Format	integer			
Time interval	3 seconds max.			

Table 18: Charge Status, AC and CLLC Information.

OBC Status	Comments	OBC Status	Comments
Bit15	1: DC/AC mode 0: AC/DC mode (default)	Bit7	1: DC port OVP 0: normal (default)
Bit14	1: PLL Error 0: normal (default)	Bit6	1: PFC abnormal 0: normal (default)
Bit13	1: CLLC Tank OCP 0: normal(default)	Bit5	1: AC abnormal 0: normal (default)
Bit12	1: SR OFF 0: SR ON (default)	Bit4	1: OTP 0: normal (default)
Bit11	1: Output OFF 0: normal (default)	Bit3	1: Power limited by AC voltage 0: normal (default)
Bit10	1: totem drive OFF 0: normal (default)	Bit2	1: Power limited by Temperature 0: normal (default)
Bit9	1: Mode Status Invalid (Bit15) 0: Mode Status Valid (default)	Bit1	1: derating output 0: normal (default)
Bit8	1: Relay Open 0: Relay Closed (default)	Bit0	1: CAN error 0: normal (default)

Table 18. a: Bit Definition for OBC Status.

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

Table 19: Part I of OBC Specification.

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

Table 20: Part II of OBC Specification.

12.3. CAN MESSAGES TO OBC

Message Identifier	0x18A3E5F4				
Data	Byte0	Byte1	Byte2+Byte3	Byte4+Byte5	Byte6+Byte7
Property	0: AC/DC 1: DC/AC	0: On 1: OFF	Reserved 0xFFFF	DC Voltage	DC Current
Unit	NA			0.1V	0.1A
Bias	0				
Data Format	integer				

Table 21: Control Command.

13. REVISION HISTORY

Date	Revision	Changes
March 11 2021	1	First issue
June 2023	3	Formatting & branding updates. Added E3M automotive qualified parts.

14. IMPORTANT NOTES

14.1. PURPOSES AND USE

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

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

14.2. OPERATION OF BOARD

It is important to operate the board within Wolfspeed's recommended specifications and environmental considerations as described in the Documentation. Exceeding specified ratings (such as input and output voltage, current, power, or environmental ranges) may cause property damage. If you have questions about these ratings, please contact Wolfspeed at forum.wolfspeed.com prior to connecting interface electronics (including input power and intended loads). Any loads applied outside of a specified output range may result in adverse consequences, including unintended or inaccurate evaluations or possible permanent damage to the board or its interfaced electronics. Please consult the Documentation prior to connecting any load to the board. If you have any questions about load specifications for the board, please contact Wolfspeed at forum.wolfspeed.com for assistance.

Users should ensure that appropriate safety procedures are followed when working with the board as serious injury, including death by electrocution or serious injury by electrical shock or electrical burns can occur if you do not follow proper safety precautions. It is not necessary in proper operation for the user to touch the board while it is energized. When devices are being attached to the board for testing, the board must be disconnected from the electrical source and any bulk capacitors must be fully discharged. When the board is connected to an electrical source and for a short time thereafter until board components are fully discharged, some board components will be electrically charged and/or have temperatures greater than 50˚ Celsius. These components may include bulk capacitors, connectors, linear regulators, switching transistors, heatsinks, resistors and SiC diodes that can be identified using board schematic. Users should contact Wolfspeed at forum.wolfspeed.com for assistance if a board schematic is not included in the Documentation or if users have questions about a board's components. When operating the board, users should be aware that these components will be hot and could electrocute or electrically shock the user. As with all electronic evaluation tools, only qualified personnel knowledgeable in handling electronic performance evaluation, measurement, and diagnostic tools should use the board.

14.3. USER RESPONSIBILITY FOR SAFE HANDLING AND COMPLIANCE WITH LAWS

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

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

In addition, users are responsible for:

- Compliance with all international, national, state, and local laws, rules, and regulations that apply to the handling or use of the board by a user or the user's employees, affiliates, contractors, representatives, agents, or designees.
- Taking necessary measures, at the user's expense, to correct radio interference if operation of the board causes interference with radio communications. The board may generate, use, and/or radiate radio frequency energy, but it has not been tested for compliance within the limits of computing

devices pursuant to Federal Communications Commission or Industry Canada rules, which are designed to provide protection against radio frequency interference.

- Compliance with applicable regulatory or safety compliance or certification standards that may normally be associated with other products, such as those established by EU Directive 2011/65/EU of the European Parliament and of the Council on 8 June 2011 about the Restriction of Use of Hazardous Substances (or the RoHS 2 Directive) and EU Directive 2002/96/EC on Waste Electrical and Electronic Equipment (or WEEE). The board is not a finished product and therefore may not meet such standards. Users are also responsible for properly disposing of a board's components and materials.

14.4. NO WARRANTY

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

14.5. LIMITATION OF LIABILITY

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

14.6. INDEMNIFICATION

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

