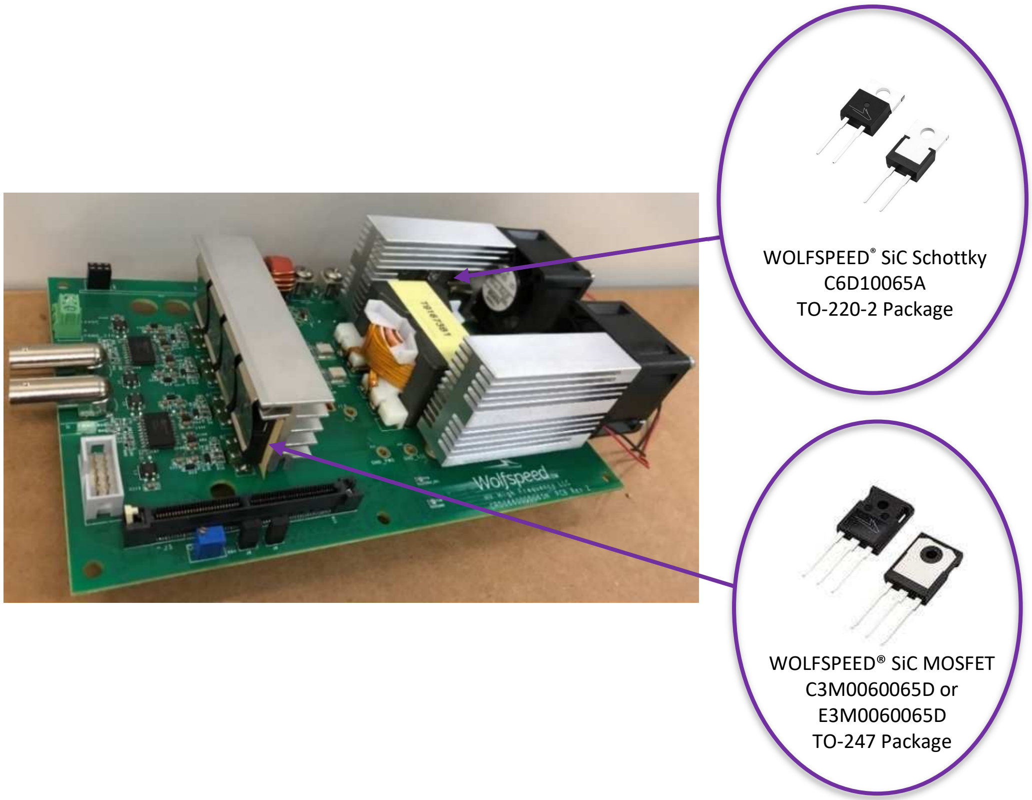
CRD-06600DD065N
6.6 kW High-Frequency LLC DC-DC Converter



User Guide PRD-06981

CRD-06600DD065N
6.6 kW High-Frequency LLC DC-DC Converter

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以及安全操作条件。

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 within the storage temperature range identified in the product documentation. 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.*

本工具（一种易碎、高压、高温电力电子系统）是由科锐为其组件设计的评估硬件，旨在用作实验室环境下的评估工具，并由够格的技术人员或工程师处理和操作。当此硬件未使用时，应将其存储在温度在产品文档中规定的范围内的存储区域；如需运输本硬件，运输过程中应该特别小心，避免损坏电路板或其易碎组件。电路板应放置在静电放电（ESD）袋中谨慎运输，或用与 Wolfspeed 运输此硬件时使用的相同或相似的ESD 或短路保护方法，以避免损坏电子组件。如果您对运输过程中此硬件的保护有任何疑问，请用Email地址forum.wolfspeed.com联系Wolfspeed。本硬件不含任何有害物质，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、製品ドキュメントで温度が指定されている保管領域に保管する必要があります。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、またはWolfspeedがこのハードウェアを輸送するときに使用される同じまたは類似のESDまたは短絡保護方法を使用します。輸送中のこのハードウェアの保護についてご質問がある場合は、Email アドレスforum.wolfspeed.comまでお問い合わせください。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**时持续，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

High efficiency and high –power density are two key demands for switching mode power supplies. The technology development and applications of wide bandgap (WBG) power devices, such as silicon carbide (SiC) devices, have enabled WBG power devices to emerge as promising substitutions for traditional silicon (Si) devices in a variety of applications [1-5]. Because of the superior switching speed and lower switching loss along with lower temperature dependency of turn-on resistance found in SiC devices, SiC devices provide higher efficiency, higher power density, and greater robustness and reliability than traditional Si devices.

Wolfspeed's CRD06600DD06N Demo Board as shown in Figures 1 and 2 is used to demonstrate the benefits of SiC devices described above through the performance of the Wolfspeed® E3M0060065D (or) C3M0060065D (60mΩ/650V, TO-247-3) SiC MOSFET and the Wolfspeed C6D10065A (10A/650V, TO-220-2) SiC diode in a 6.6 kW high-frequency DC/DC LLC converter with an output voltage of 400 VDC and with a maximum output current of 16.5 A DC. Thanks to the low switching loss of these Wolfspeed SiC devices, the converter can be operated at high frequencies. The main benefits of high-frequency converter operation are smaller transformer and EMI filters, integrated resonant inductors into the transformer, and further size reduction of the converter.

Measuring approximately 190 mm X 125 mm X 35 mm, the Demo Board allows an input voltage range of 380 VDC to 420 VDC and can operate in either open-loop or closed-loop mode, depending on the operation mode selection of the user. In closed-loop operation, the converter regulates the output voltage to 400 V_{DC}.

Four Wolfspeed SiC MOSFETs (P/N E3M0060065D (or) C3M0060065D) are used for the primary switches which are turned on at zero-voltage (ZVS) which results in high efficiency and low EMI. Four Wolfspeed SiC diodes (P/N C6D10065A) are used for secondary-side rectifiers.

The Demo Board accepts an optional daughter card (a Wolfspeed CRD-15DD17P 15W Flyback, which must be purchased separately) for the bias power needed for the control circuit including the optional Texas Instruments® (TI) control card (P/N TMDSCNCD280049C, which must also be purchased separately for the closed loop operation) and the primary-side bias needed for the four isolated DC/DC modules for the two gate drivers. With the Wolfspeed daughter card, the Demo Board doesn't need an external 12V DC power supply for the control circuit. The optional TI® control card can generate the desired control signals to turn on or turn off the four SiC MOSFETs, and therefore no external signal generator is needed if it is installed.

This user guide includes a description of the circuit operation and design of the Demo Board and the measured efficiency, key waveforms, regulation of the output voltage, and thermal measurement of the converter with a maximum output power of 6.6 kW.

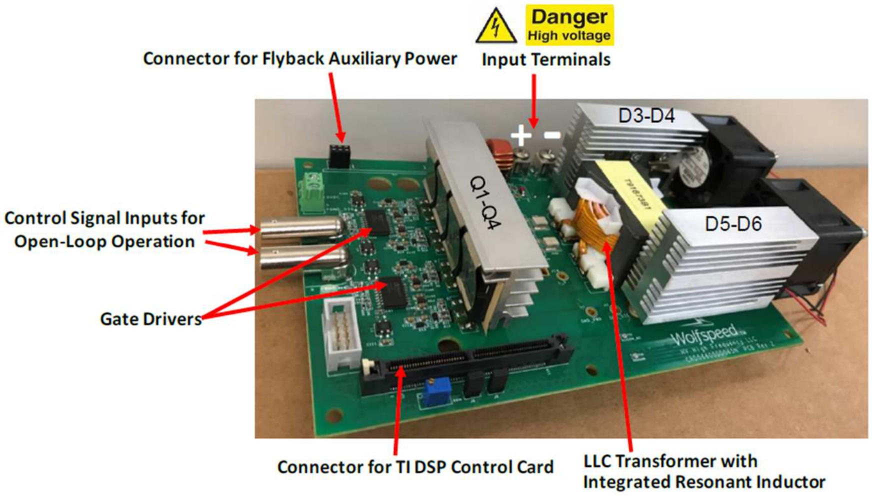


Figure 1: Top view of high-frequency LLC DC/DC converter with high-voltage output

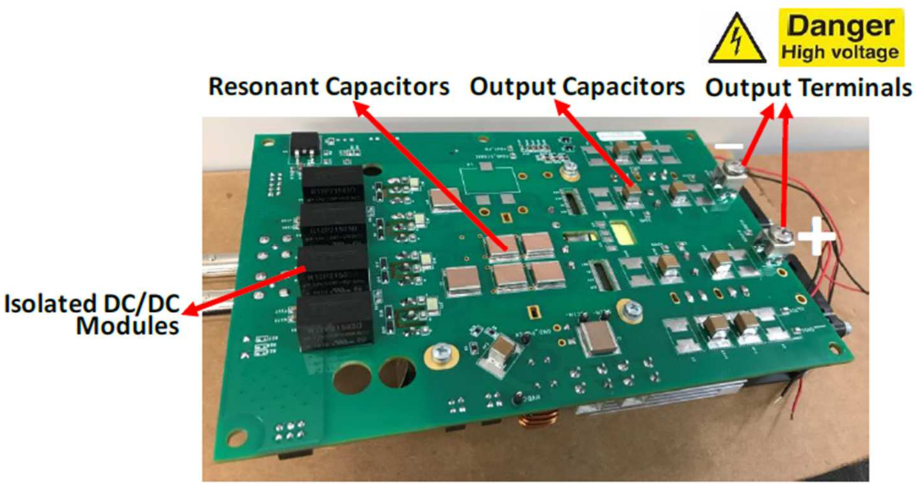


Figure 2: Bottom view of high-frequency LLC DC/DC converter with high-voltage output

2. High-Frequency Full-Bridge LLC DC/DC Converter

A basic full-bridge LLC converter consists of an input capacitor, four MOSFETs (Q_1 – Q_4), one resonant inductor L_r, one resonant capacitor Cr, one transformer T_1, four output rectifiers (D_1– D_4) and an output capacitor as shown in Figure 3. The resonant frequency of the converter is determined by resonant inductor Lr and capacitor C_r ($f_r = 1/(2\pi\sqrt{L_rC_r})$). The circuit operation is briefly described as follows. When Q_1 and Q_4 are turned on, D1 and D_4 conduct, and the resonant current charges the output capacitor and delivers power to the output. During the deadtime, the resonant current on the primary side discharges the drain-source capacitors of switch Q_2 and Q_3. When the drain-source voltage of switches Q_2 and Q_3 reaches zero and the set deadtime td elapses, Q_2 and Q_3 are turned on for a period of T_{ON}, then turned off. The resonant current now discharges the drain-source capacitors of switches Q_1 and Q_4 to zero, Q_1 and Q_4 are turned on after the deadtime elapses, and another switching cycle begins. A detailed description of the operation and design of the LLC circuit along with waveforms can be found in [6-9].

The specifications of the converter are shown in Table 1.

Table 1: DC/DC Converter Specifications

Parameter	Value	Note
Input Voltage	380 - 420 V_{DC}	
Output Voltage	400 V_{DC}	
Output Power	6.6 kW Max.	
Switching Frequency	500 kHz – 1 MHz	Soft startup at 1.5 MHz 625 kHz at 400V input and full load
Operating Ambient Temperature	-40°C – +55°C	

The magnetizing inductance of the transformer, L_m, is a key design parameter for achieving zero-voltage switching (ZVS) in a high-frequency LLC converter. To understand its effect on ZVS of SiC MOSFETs and converter efficiency, simulations using LTspice® Simulation Software were done, and the simulation results are shown below.

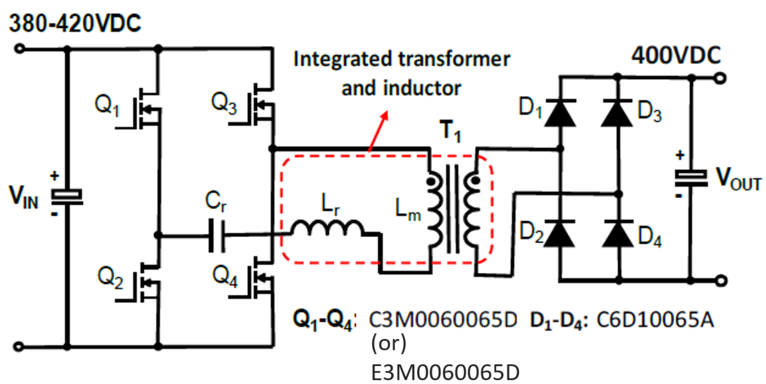
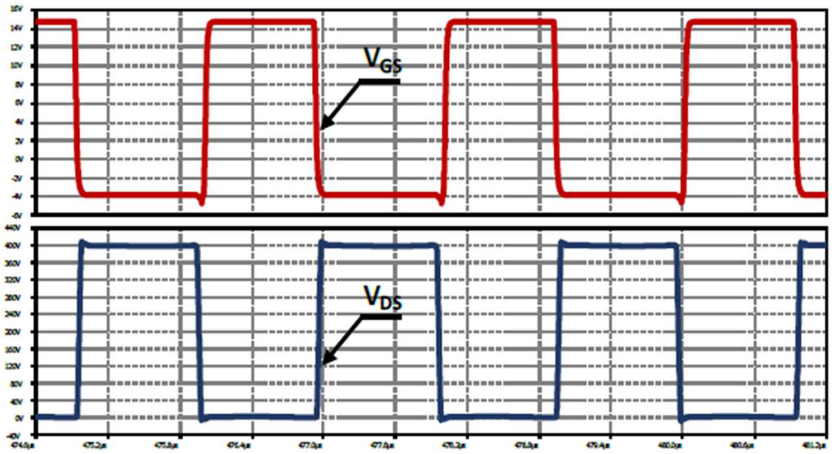
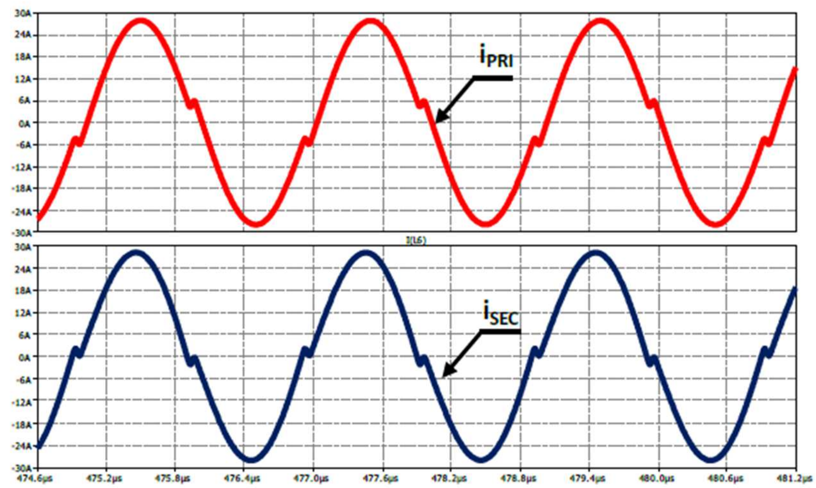


Figure 3: Simplified LLC DC/DC resonant converter with diodes for output rectifiers

Figure 4 shows the simulated waveforms at 500 kHz switching frequency with a magnetizing inductance L_m = 30 µH. The simulated total power loss of the four primary switches is 80.24 W (20.06 W for each) and the overall efficiency reaches 98.11% with diodes for output rectifiers thanks to ZVS turn-on of all the primary switches.



(a)



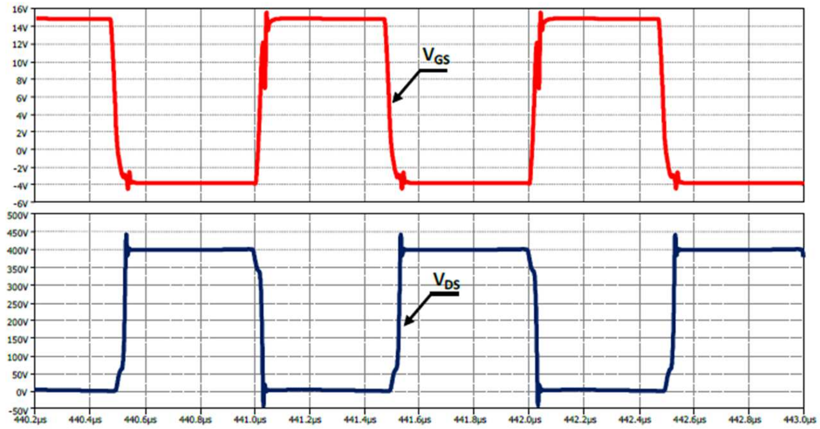
(b)

Figure 4: Simulated waveforms at 500 kHz and 6.6 kW output power:
(A) Gate drive and drain source voltage of primary switch, (B) Primary and secondary resonant currents

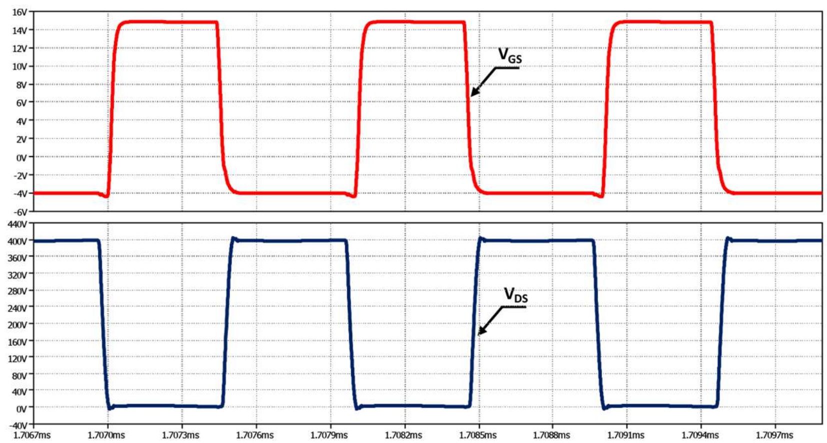
A large magnetizing inductance L_m can reduce the magnetizing current and lower the conduction and turn-off loss of the primary switches. However, the value of L_m also needs to provide sufficient magnetizing current to totally discharge the drain-source capacitors and ensure primary switch ZVS turn-on during the dead-time td. Therefore, L_m should satisfy Equation (1) [6-7].

$$\mathrm{Lm} \leq \frac{t_d}{16 f_s c_{Total}}$$

Where, td is the dead-time between the two gate drive signals for the upper and lower switches, fs is the switching frequency, and C_{Total} is the total capacitance including the drain-source capacitance of the primary switch and parasitic capacitance of the PCB. For a given dead-time td, L_m can be optimally designed based on Equation (1) and high efficiency at normal operation can be achieved.



(a)



(b)

Figure 5: Simulated waveforms of gate drive and drain-source voltage of primary switch at 1 MHz with magnetizing inductance: (a) Lm = 30 µh; (b) Lm = 10 µh

An improperly chosen magnetizing inductance can result in undesired high switching losses of the switches and efficiency drop, especially at high frequencies. Simulated results show more than 1.5% efficiency drop at 1 MHz for L_m = 30 µH (η = 96.5%) compared to L_m = 10 µH (η = 98.08%) since ZVS turn-on condition is lost and the total switching loss increases by 104.28 W for 6.6 kW output power. Figure 5 shows the simulated waveforms of gate drive and drain-source voltage of the primary switch at 1 MHz with L_m = 30 µH and Lm = 10 µH, respectively. As can be seen from Figure 5 (a), the primary switch is not turned on at zero voltage because of the high L_m. However, with L_m = 10 µH, there is a 0.3% efficiency drop at 500 kHz due to increased conduction loss resulting from the increased magnetizing current. The magnetizing inductance, therefore, needs to be carefully designed for the desired switching frequency range.

3. Design and Hardware Descriptions

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

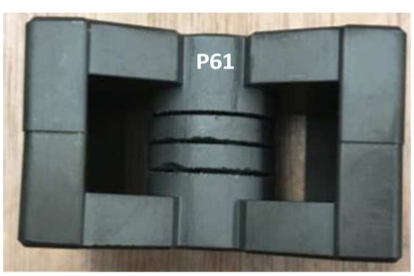
通電している時にボードに接触する必要がありません。設備をつないで試験する時、必ずボードの電源を切ってください。また、大容量のコンデンサーで電力を完全に釈放してください。

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。

3.1 Design of LLC Transformer

After the maximum magnetizing inductance is calculated using Equation (1), the magnetic core material, airgap, and wire sizes need to be carefully considered for high-frequency operation, otherwise extreme power loss will result, causing undesired failure of the transformer. Among the core materials suitable for high frequencies, ferrite core material (P/N P61 from ACME Electronics Corporation) is chosen for its low power loss and easy availability of core shapes for high power applications with a switching frequency range from 500 kHz to 1 MHz. Thanks to the high switching frequency, a pair of magnetic cores (P/N PQ50/28 from ACME Electronics Corporation) made of P61 core material can be used for the transformer which delivers 6.6 kW output power. Both the primary (P/N MW 79/80 ϕ0.05 mm × 360 × 4 from Rubadue Wire) and secondary windings (P/N ϕ0.05 mm × 400 × 2 TIW from Rubadue Wire) of the transformer employ served Litz wires of 9 turns. To reduce the copper loss induced by the fringing magnetic flux near the airgap, three distributed airgaps on the center leg instead of one large airgap are used as shown in Figure 6 (a). The magnetizing inductance of the transformer is designed to be 22.5 µH, which causes ZVS at 1 MHz for a t_d = 100 ns and C_{Total} = 250 pF according to Equation (1). Figure 6 (b) shows the photo of the transformer prototype.



(a)

(b)

Figure 6: Low-profile transformer (PQ50/28 with material P61 from acme) with leakage inductance used for resonant inductor: (a) Magnetic core with distributed airgaps; (b) Experimental transformer prototype

3.2 PCB Layout

PCB layout plays a critical role in EMI, signal integrity, and circuit efficiency and operation, and especially so with high-frequency LLC converters. Figure 7 shows the parasitic capacitances present within the two PCBs with 2 layers (Ver. 2) and 6 layers (Ver. 1) for an LLC converter. The 6-layer PCB was done with large overlapping copper area intended for the reduction in power loss of the PCB traces and cancellation of the magnetic fields of the current loops to reduce parasitic inductances and EMI. However, large parasitic capacitances as shown in Table 2 were created because of the big overlapping area between different copper layers. The copper traces for the 2-layer PCB (Ver. 2) have much smaller overlapping areas, which results in significantly lower parasitic capacitances. In an LLC circuit, large parasitic capacitances C_{P1}-C_{P4} across the switches, C_{P8}-C_{P10} across transformer windings and C_{P11} across the two mid-points A and B of the primary full-bridge circuit will cause undesired power loss and efficiency drop because of the loss of the ZVS condition, and the charging and discharging of these parasitic capacitances. As can be seen from Table 2, there is a 0.79% efficiency drop and 26.07 W increase in power loss at the same test conditions (400V input, 48 V/3.3 kW output). Therefore, extra care is needed during the PCB layout to reduce the adverse effects of parasitic capacitances.

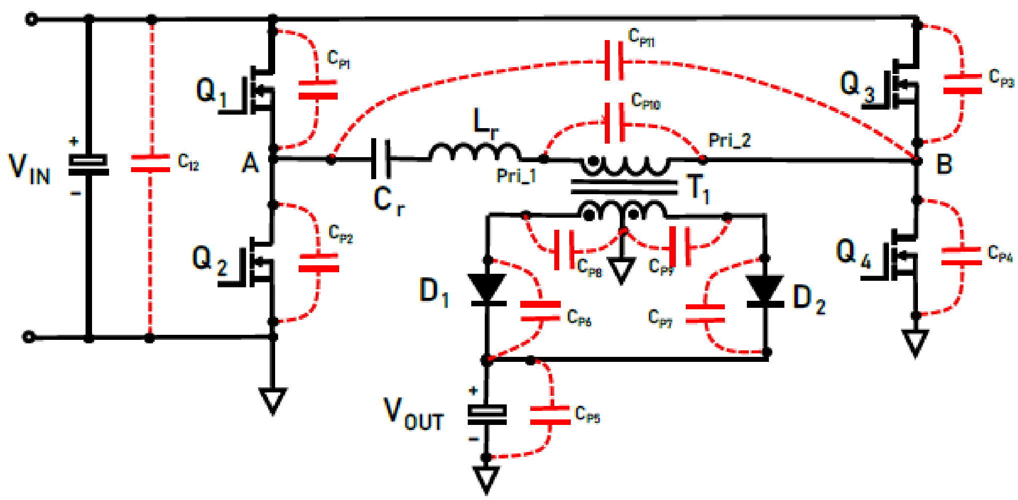


Figure 7: Parasitic capacitances present in PCB for LLC circuit

Table 2: Comparison of Measured Parasitic Capacitances for 6-Layer (Ver. 1) and 2-Layer (Ver. 2) PCBs (Unit: pF)

PCB Version	C_{P1}	C_{P2}	C_{P3}	C_{P4}	C_{P5}	C_{P6}	C_{P7}	C_{P8}	C_{P9}	C_{P10}	C_{P11}	C_{P12}	Efficiency (%)	Power Loss (W)
Ver. 1	315	390	343	420	4860	534	535	620	598	508	896	1385	95.71	141.57
Ver. 2	17	22	25	28	4731	528	516	589	575	11	13	308	96.50	115.50

Another parasitic capacitance resulting from the PCB layout is the stray inductance of copper traces. The undesired parasitic inductance can cause ringing of the gate drive signals, voltage spikes across the power switches, and severe EMI. There are a few ways of minimizing the stray inductance:

- Shortening the trace length for critical signals, such as gate drive control signals.

- Making the equivalent loop area covered by traces as small as possible.
- Overlapping or placing traces with opposite current flows as close as possible to cancel the magnetic field.

In the Demo Board design, the traces for the gate drive signals generated by the gate drivers U1 and U2 are placed on the first layer of the PCB shown in Figure 36, and a large plane on the second layer shown in Figure 37 for the return paths to the gate drivers. In this way, the parasitic inductances in the gate drive loop are significantly reduced because of the effective cancellation of the magnetic field generated by the driving and return path currents.

3.3 Resonant Capacitors

The leakage inductance of the transformer measured from the primary side when the secondary winding is shorted is about 1 µH, a resonant capacitance of 79.8 nF (P/N C2225X392JGGAC2 × 2/2 kV from KEMET Corporation, paralleled with surface mount capacitors (P/N C3640C183JFGACAUTO × 4 /1.5 kV also from KEMET Corporation) is used to have a resonant frequency (= $1/(2\pi\sqrt{LrCr}$) of around 560 kHz. Thanks to their low ESR at high frequencies, these ceramic capacitors have low power loss and temperature rise. Moreover, compared to film capacitors, they have dramatic size reduction

3.4 Gate Drivers

High switching-frequency poses great challenges to gate drivers. Among the switching parameters, the propagation delay and delay matching time are critical to ensure safe operation of the bridge circuits. A gate driver from Analog Devices, Inc. (ADI) (P/N ADuM4221), or from Texas Instruments Incorporated (TI) (P/N UCC21530), or from Skyworks (P/N Si823H2BD) can be used. Each of them has low propagation delay (< 50 ns), low delay mismatching (~ 5 ns), greater than 100 V/ns common-mode transient immunity (CMTI), and a minimum of 2 A peak source and sink currents. These gate drivers have the same package and pinouts and have been tested on the Demo Board. The diagrams for the three drivers are shown in Figure 8. The main differences between these drivers are the bias voltage and enabling voltage at the input/control side, deadtime programming, and isolation barriers. ADuM4221 and Si823H2BD can only accept +5 V logic level voltage at VDD1/VDDI while UCC21530 can accept 3 V - 18 V at VCCI so that it can interface with both digital and analog controllers. The enabling control voltage is logic LOW for ADuM4221 but logic HIGH (up to VCCI) for UCC21530 and Si823H2BD.

The default gate drivers populated on the Demo Board are ADuM4221 from ADI, and resistors R30 and R32 (0 Ω) are populated (Pin 5 connected to ground) while resistors R29 and R31 are not. If the user wants to test gate driver UCC21530 from TI or Si823H2BD from Skyworks, resistors R29 and R31 (0 Ω) need to be populated (Pin 5 tied to +5V, which is generated by U6/MC7805) and R30 and R32 are left open. The circuit schematic for the gate drivers is shown in Figure 9. A small RC filter (a 4.7 Ω resistor with a 10pF capacitor) is used at each of the control signal inputs (INA and INB) to improve noise immunity. At the output side, a 4.7 µF ceramic capacitor is placed across PIN 16 and PIN 14, PIN 11 and PIN 9 to bias the drive output circuit. Capacitors C170 and C171 are charged when the drive output OUTA or OUTB is HIGH and their voltage is clamped to 3.3 V by Zener diode D57 and D60. A negative voltage is then provided when power switches Q3 and Q4 need to be turned off. This negative bias voltage is needed to prevent overshoot when there is a severe cross-talk between the upper and lower switches and both switches can be simultaneously turned on.

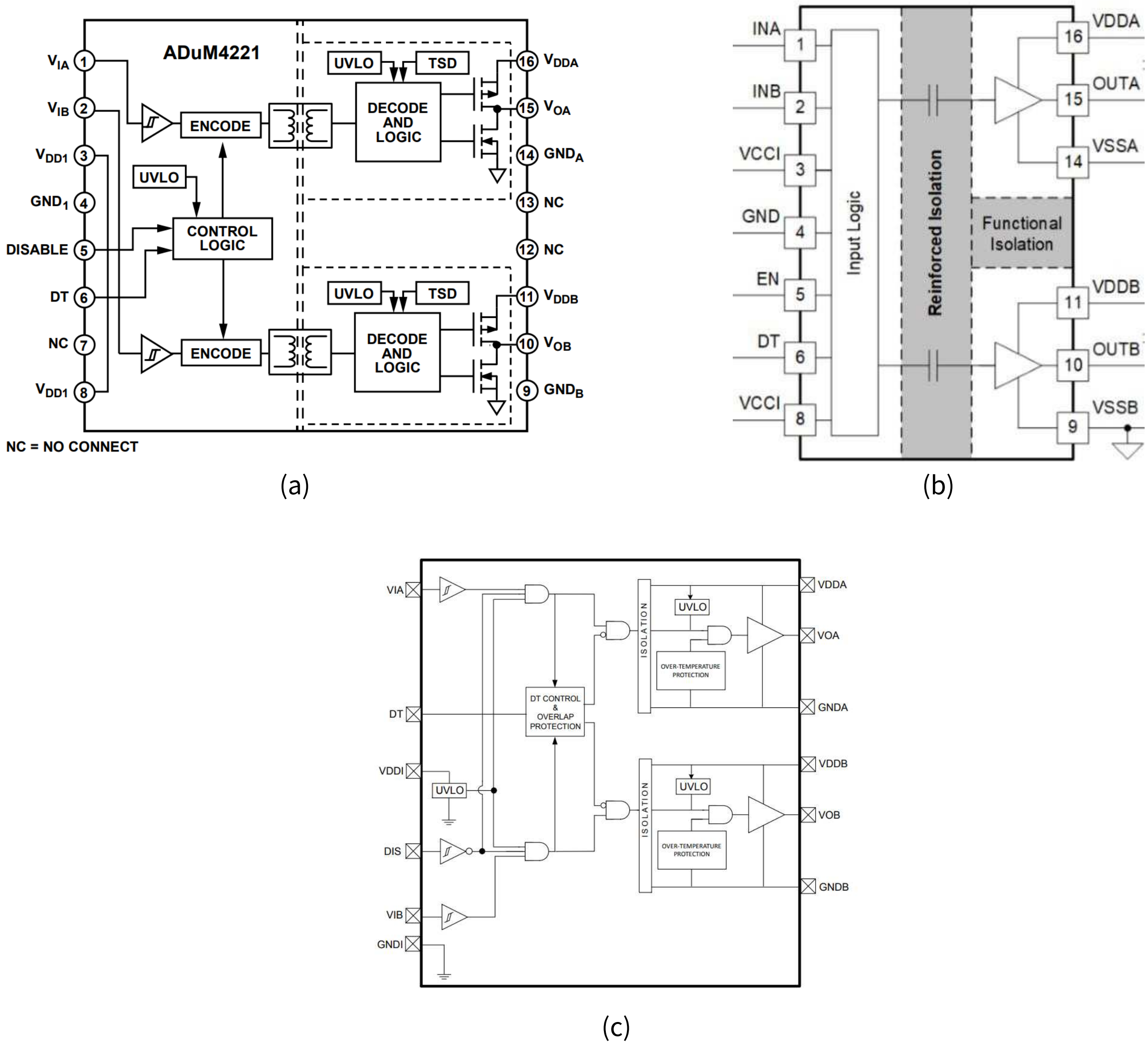


Figure 8: Pinouts and block diagram of gate drivers:
(a) ADuM4221 (ADI), (b) UCC21530 (TI), (c) Si823H2BD (silicon lab)

The deadtime, td, between the two outputs OUTA and OUTB of the gate drivers, is programmed by resistors R88 and R93 located at Pin 6 of gate drivers U1 and U2, as shown in Equation (2).

$$t_d(\text{ns}) \approx \begin{cases} 5R_{88}(R_{93})\ (\text{k}\Omega)\ \text{for ADI} \\ 1.8R_{88}(R_{93})\ (\text{k}\Omega) + 12\ \text{for Silicon Lab} \\ 10R_{88}(R_{93})\ (\text{k}\Omega)\ \text{for TI} \end{cases} \tag{2}$$

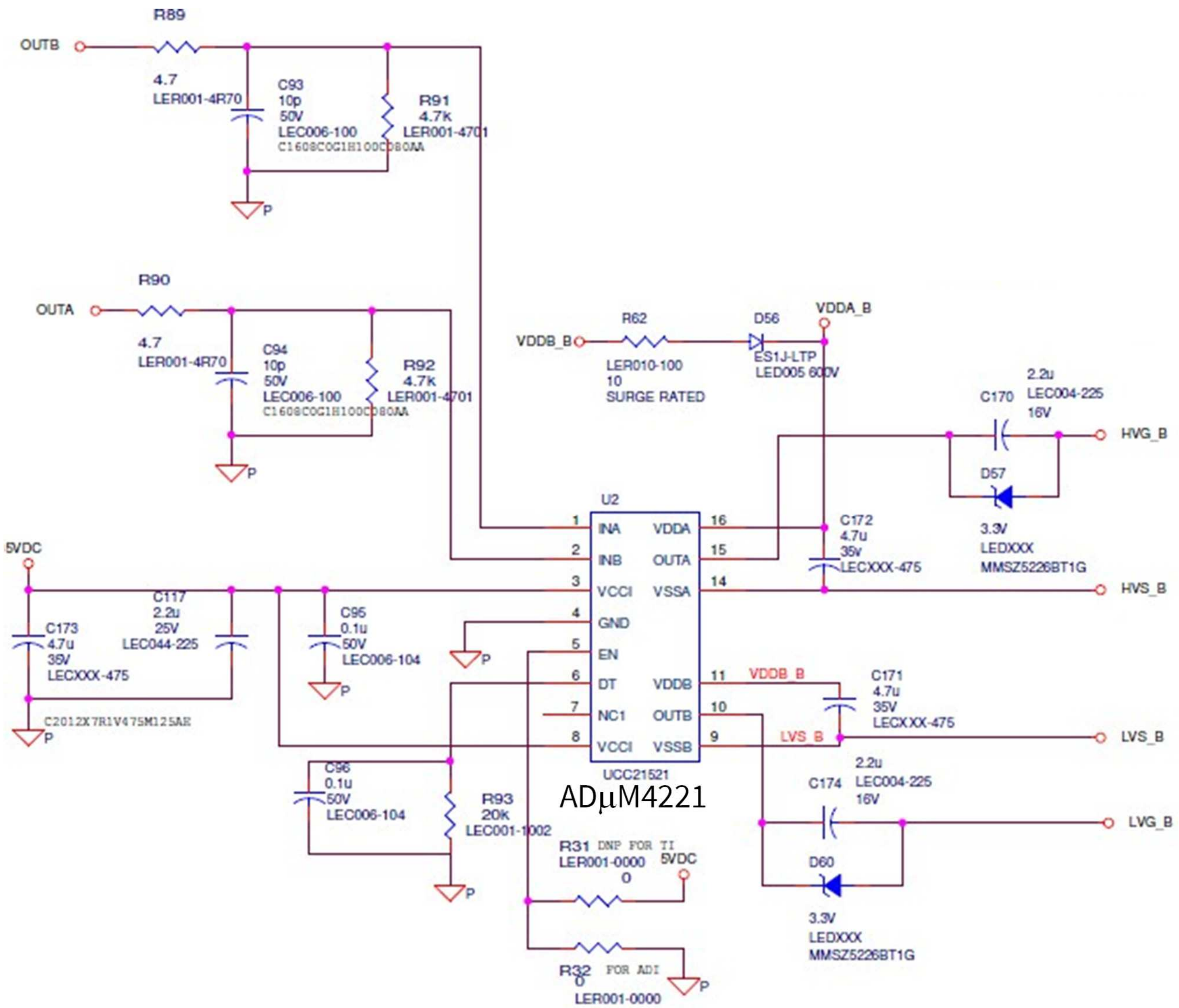


Figure 9: Circuit schematic for gate driver ADuM4221 (ADI)

Four 2-W isolated DC/DC modules (X1 - X4, P/N MEJ2D1209SC from Murata Power Solutions Inc.) are used to provide bias power for the gate drivers U1 and U2. Featuring an isolation voltage of 5.2 kV DC and an isolation capacitance of 4 pF, these modules accept 12V DC input and generate ± 9 V DC dual outputs, which are connected to VDDA and VSSA, and VDDB and VSSB of the gate drivers, as shown in Figure 10. Alternate 2-W DC/DC modules (P/N QA15115R2 from Mornsun Power), which are pin to pin compatible, can also be used. The dual outputs of QA15115R2 are +15 V and -2.5 V with an input voltage of 15 VDC. Therefore, it can provide the negative drive voltage (-2.5 V) directly to the SiC MOSFETs without the need for a Zener diode in parallel with a capacitor as shown in Figure 9.

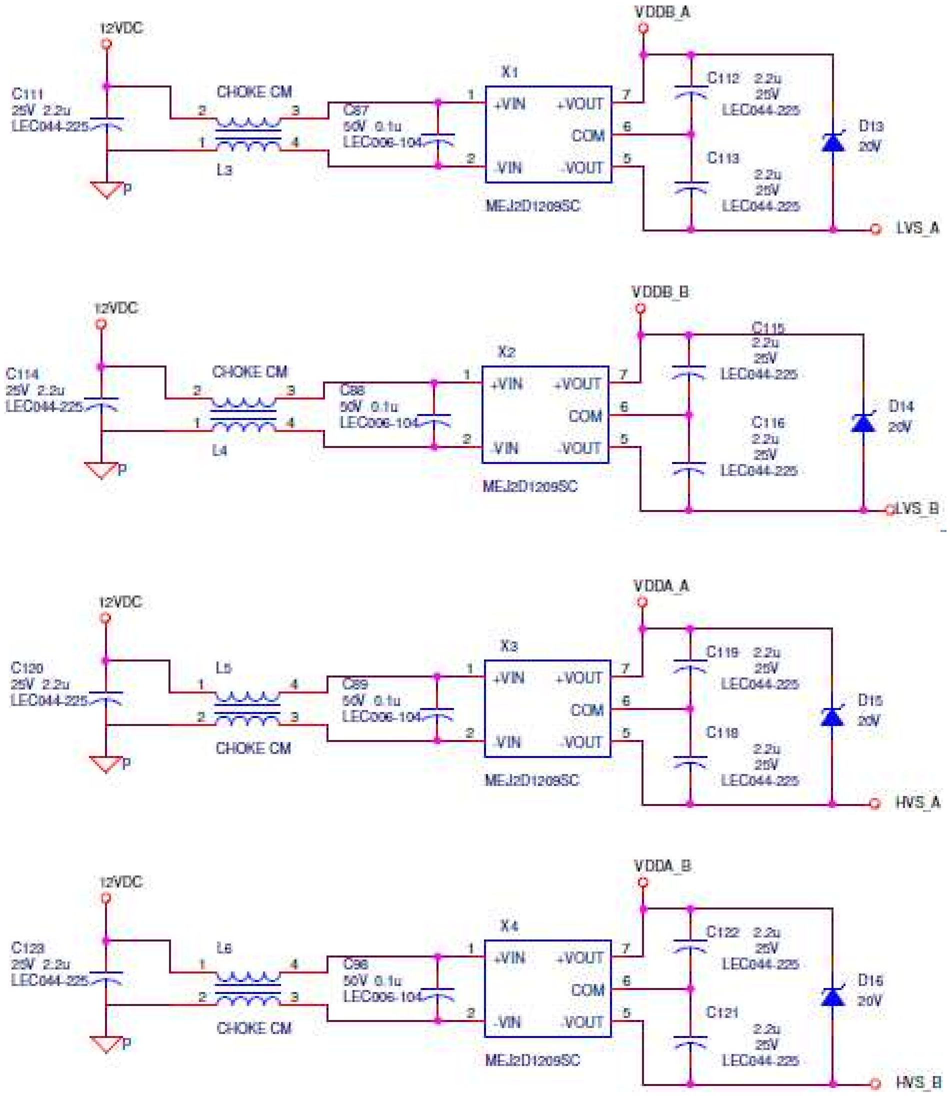


Figure 10: Bias powers with four DC/DC modules - MEJ2D1209SC from Murata

3.5 Input and Output Filters

High-voltage rated ceramic capacitors with low equivalent serial inductance (ESL) and low equivalent serial resistance (ESR) are used for filtering the high-frequency ripple current at the input and output. Referring to the schematic of the converter circuit, C1, C2, and C39 at the primary side are 0.22 µF/500 V C0G-type caps (P/N CKC33C224KCGACTU from KEMET Corporation), and capacitors C7, C9, C10, C40, C187, C196, C197, C199, C201 are 1 µF/500 V CeraLink® series caps (P/N B58031I5105M062 from EPCOS/TDK), which are optimized for high frequencies up to several MHz.

A common-mode filtering choke L1 (175 µH/10 A from Wurth Electronics Inc.) along with capacitors C1 and C40, as shown in Figure 11, is used to form a π-filter at the input. Capacitors C2 and C39 are placed right across the drain-terminals of power switches Q1 and Q3 and the power ground to suppress voltage spikes and absorb high-frequency currents.

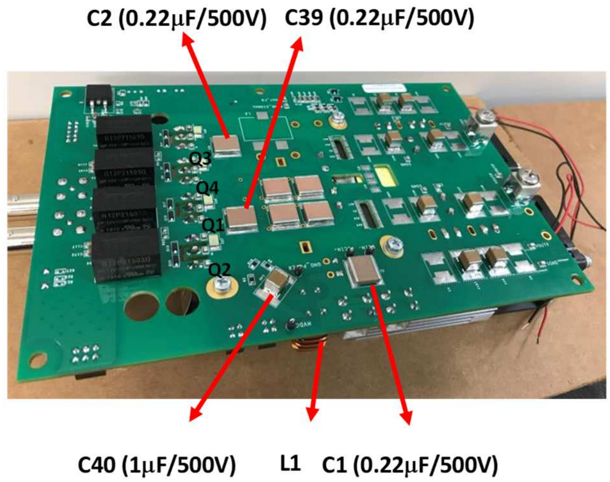


Figure 11: Placement of ceramic capacitors on bottom side of circuit board for input ripple current and noise filtering

3.6 Operation Mode Selection

There is a jumper connector J6 shown in Figure 12 on the Demo Board. With J6 shorted, the converter enters a closed-loop operation if the TI DSP control card with a working feedback control firmware is installed. The TI digital control card senses a signal VOUT_FB which is obtained through a voltage divider and generates two complementary control signals for the full- bridge LLC to regulate the output voltage VOUT. If J6 is left open but with the TI DSP card installed, the converter operates in an open-loop mode, and the user can vary the switching frequency with a POT (R94) located on the bottom left corner. After the operation mode is selected and a load (a light load is recommended for startup) is connected, the Demo Board can be powered up and tested with a specified input voltage (380 - 420 VDC). Placing a sheet of insulation material underneath the board is recommended to avoid unintended short circuits before turning on the power. With 380V – 420V input voltage, the output voltage with closed-loop operation should measure around 400 VDC on a digital multimeter or an oscilloscope. It is always recommended that the user start with a low input voltage and gradually increase the input voltage to the specified range to prevent huge inrush current from damaging the power switches Q1-Q4.

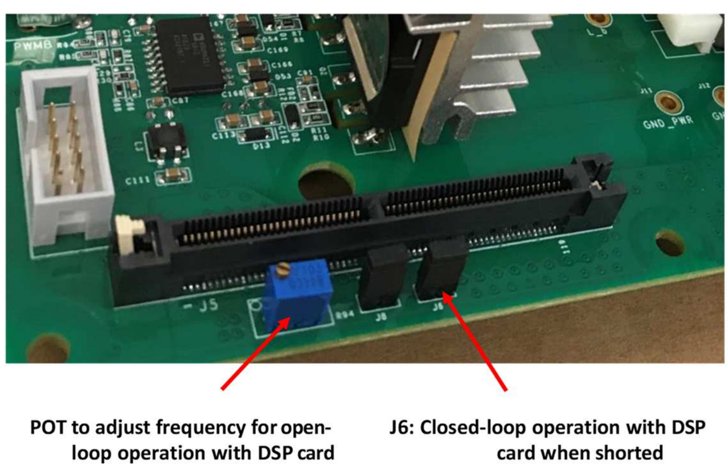


Figure 12: Jumper (J6) for operation mode selection and POT (R94) for frequency adjustment

The user can also evaluate the circuit in an open-loop mode without the TI control card by using the two BNC connectors (please refer to Figure 1) on the left side of the Demo Board. Two complementary control signals (3 V to 5 V in amplitude) with a recommended deadtime of 100 ns are needed for the two inputs of the two gate drivers U1 and U2 to turn on or off corresponding switches of the full-bridge LLC circuit. In this mode operation, a minimum switching frequency of 400 kHz is recommended to avoid operating the resonant circuit in a capacitive mode, and the user should monitor the output voltage carefully when varying the switching frequency and/or input voltage to avoid over voltage or part damage of the Demo Board. When varying the switching frequency, turn off the input power. Turn the main power back on when the two control signals measured at the gate to source of the upper and lower switches have the expected frequency and right dead time (at least 100 ns).

A 5×2 header connector J7 with pins for OUTA, OUTB, +12V, VOUT_FB, and GND is also populated on the Demo Board. If the user has another digital control card available, this connector can be used for the input of the two gate drive control signals and output voltage feedback with a ribbon cable.

3.7 Primary and Secondary Current Sensing

The primary resonant current can be sensed by soldering a wire (~AWG20 size, not supplied) between vias J13 and J14 with a current probe, such as a probe from Tektronix (P/N TCP30), as shown in Figure 13. The secondary current is sensed via a 20A, 50kHz -1MHz current transformer (P/N PA1005.100NLT from Pulse Electronics). The sensed current signal can be detected between the two test points TP29 and TP30 (shown in Figure 14) and monitored on the oscilloscope. The user can also use this signal as the feedback signal to achieve output current regulation (instead of the default voltage regulation) when resistor R110 (4.7k) is populated, and resistors R99 and R100 (1M), R101 and R102 (1M), or R103 and R104 (1M) are depopulated. However, the user needs to develop a corresponding control firmware to fulfil output current regulation.

3.8 Resonant Inductor

The Demo Board uses the leakage inductance (Lk ≈ 1 µH) of the power transformer (T3 in the complete schematic shown in Figure 25 in Section 5) as the resonant inductor. Because of the much lower resonant inductance compared to the magnetizing inductance (22.5 µH), there is a wide switching-frequency range depending on the load and input/output voltages. If the user wants to narrow the switching frequency of the converter in the closed-loop operation, an external resonant inductor (~20 A with inductance of a few µHs) can be added between these two vias J13 and J14, shown in Figure 13.

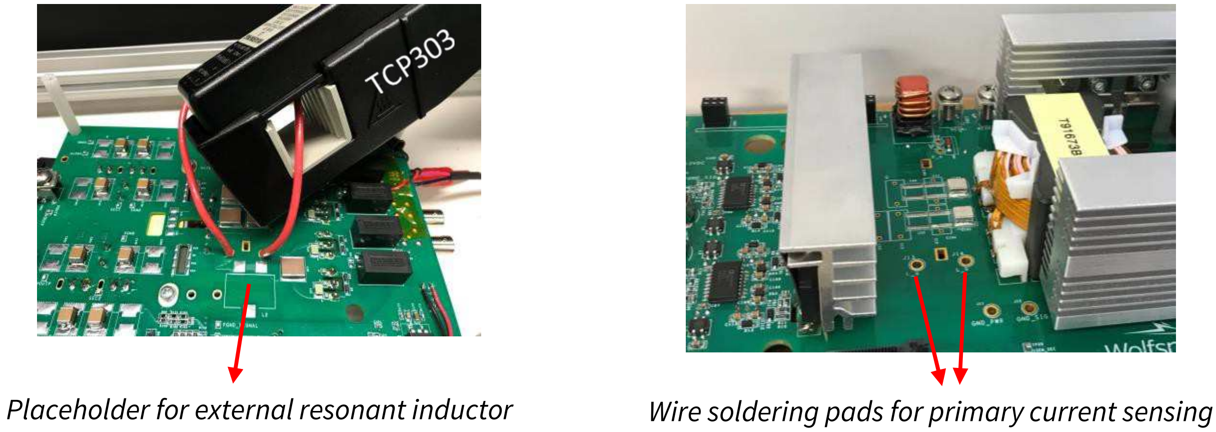


Figure 13: Primary resonant current sensing using current probe from Tektronix (P/N TCP303)

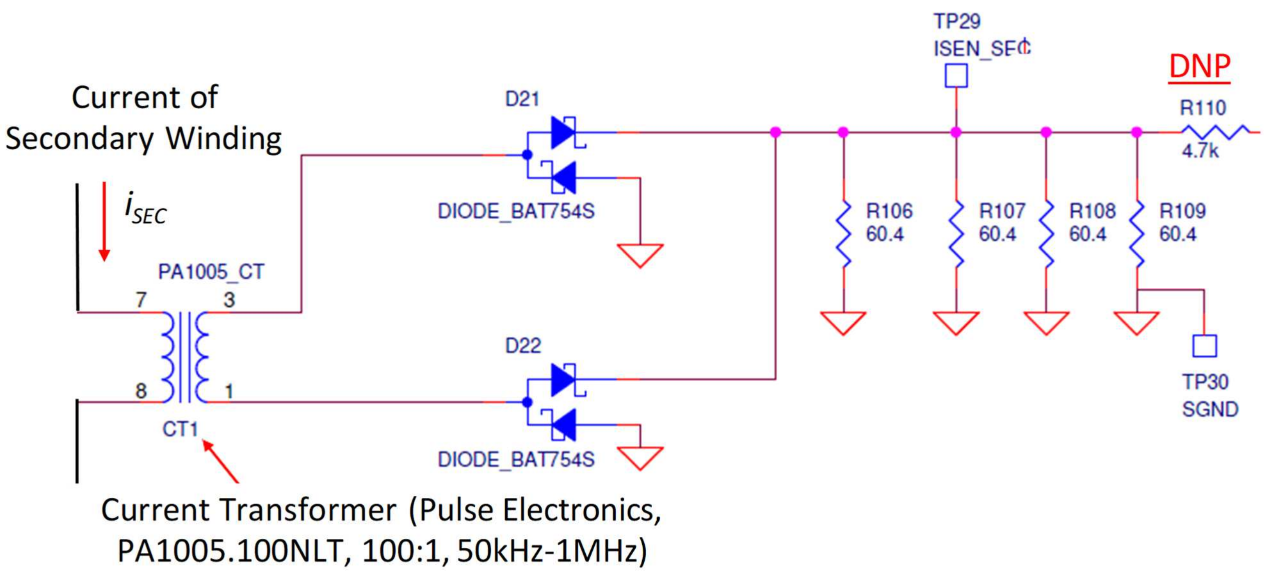


Figure 14: Secondary resonant current sensing using current transformer PA1005.100NLT from pulse electronics (100:1)

4. Experimental Results

A typical test setup for the Demo Board is shown in Figure 15. A 2.5GS/s 350MHz oscilloscope (P/N DLM2034 from Yokogawa) is used to capture the switching waveforms. A FLIR® T420 IR camera is used to monitor the temperature of the key parts, such as transformer and MOSFETs. Two DC fans (NMB, 04028DA-12Q-AAF, 12V/0.35A) are mounted on two heatsinks to cool the output diodes D3-D6, the main transformer T3, and the primary power MOSFETs Q1- Q4. For continuous testing at high power, an extra DC fan (Sunon, PMD1206PMB1-A, 12V/10.6W) mounted above the transformer, as shown in Figure 15, is needed to ensure there is no overheating of the transformer. Airflow is also needed to cool the heatsink of the MOSFETs at heavy load to prevent the power devices from entering thermal runaway. In the following test, a fan (P/N 4715FS-12T-B50-D00 from NMB TECHNOLOGIES) is used. Figure 16 shows other equipment needed for testing the Demo Board. The user can use equipment of other brands with similar functions.

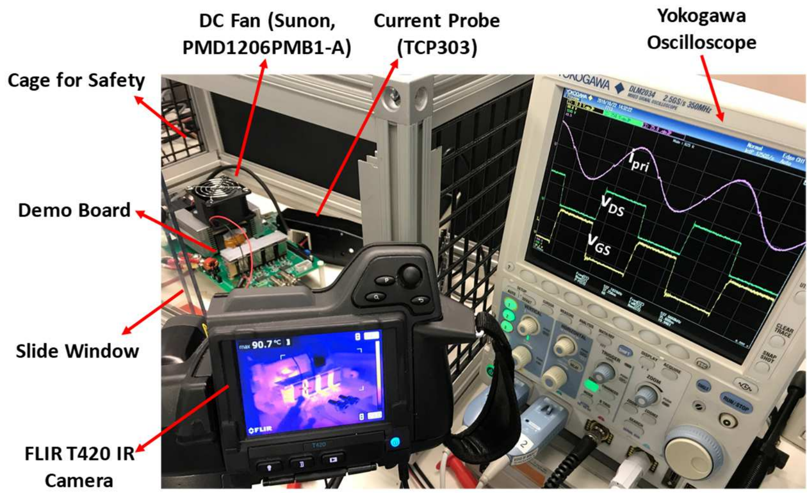


Figure 15: Test setup for evaluating demo board

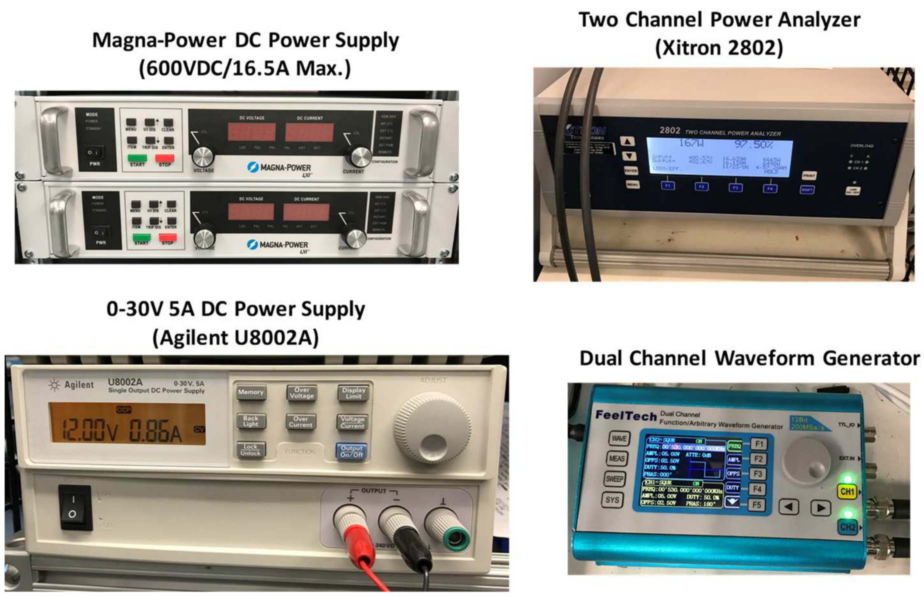


Figure 16: DC power supplies, power analyzer and signal generator used for tests

4.1 Measured Efficiency, Switching Frequency and Output Voltage

The LLC DC/DC converter has the highest efficiency when the switching frequency is near the resonant frequency (= $1/(2\pi\sqrt{LrCr}$) since the power switches are turned on at ZVS and turned off at zero current (ZCS) resulting in low switching losses. This operation mode is best suited for bus converters, which have a fixed voltage conversion ratio and don't need a tightly regulated output voltage. Figure 17 shows the measured efficiency vs. output power in open-loop operation at 500 kHz. A peak efficiency of 98.45% can be achieved at 500 kHz and medium load (~3.2 kW). As the input voltage drops, the efficiency decreases because of higher conduction loss resulting from higher current.

Figure 18 shows the measured efficiency vs. output power in closed-loop operation. A peak efficiency of over 98% can be achieved at lower input voltages (< 400 V) and medium load. As the input voltage increases and/or the load decreases, the efficiency decreases resulting from high switching frequency, as shown in Figure 19. The frequency range can be narrowed by introducing more leakage inductance of the transformer or adding an external resonant inductor. The regulation of output voltage is shown in Figure 20. **For a safe and stable closed-loop operation, power derating (≤ 4kW is recommended) is needed for input voltage over 400V, otherwise, the transformer winding gets extremely hot due to high power loss resulting from high switching frequency (> 600kHz) and high current, and the transformer fails finally and the unit gets damaged**.

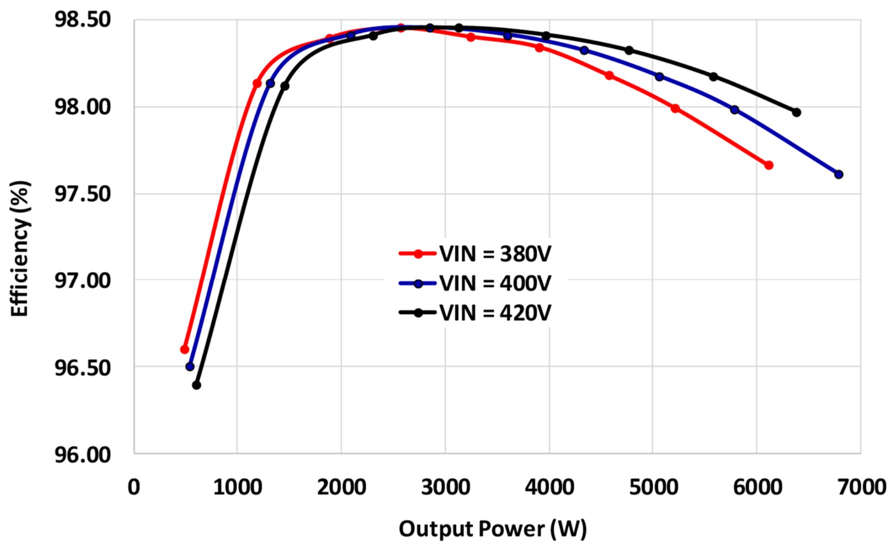


Figure 17: Measured efficiency vs. output power in open-loop operation at fixed switching frequency (500 kHz)

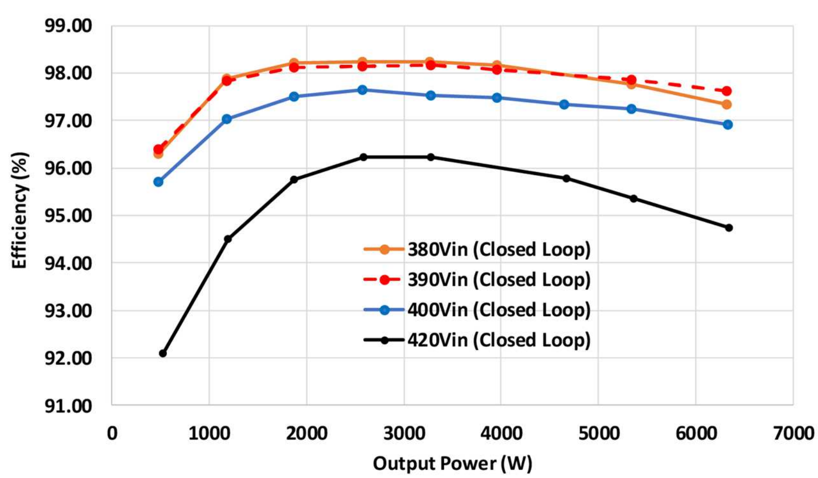


Figure 18: Measured efficiency vs. output power in closed-loop operation

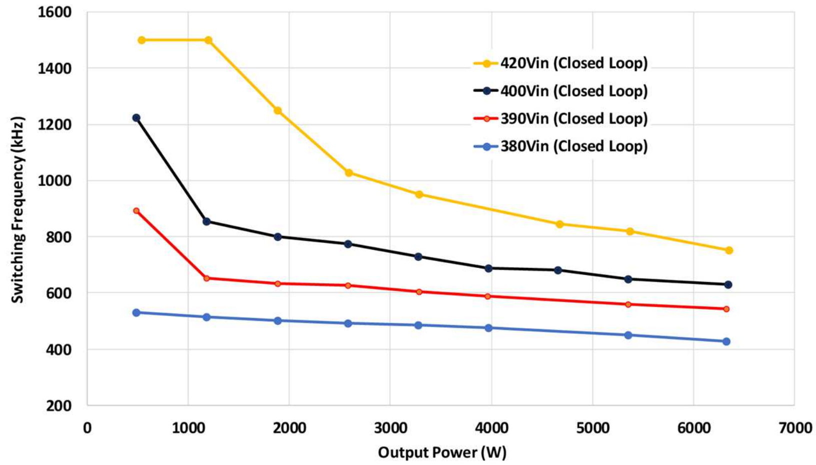


Figure 19: Measured switching frequency vs. output power in closed-loop operation

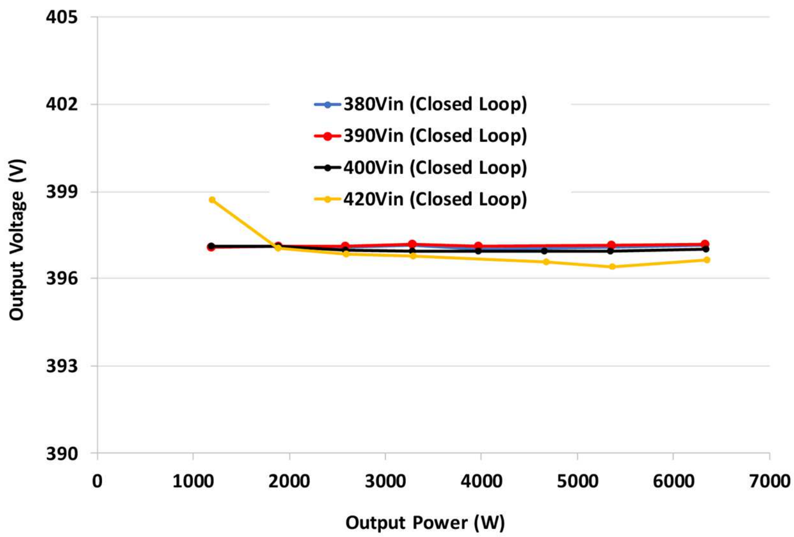
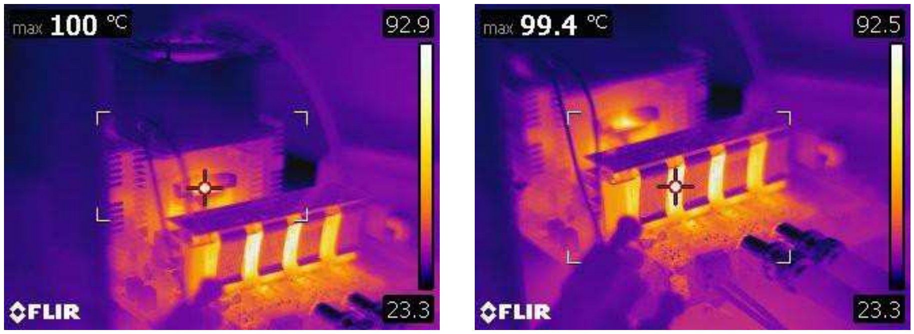


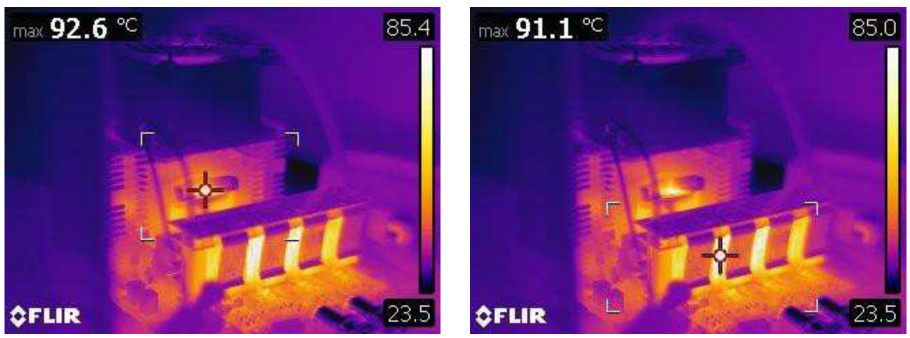
Figure 20: Measured output voltage Vs. output power in closed-loop operation

4.2 Thermal Images

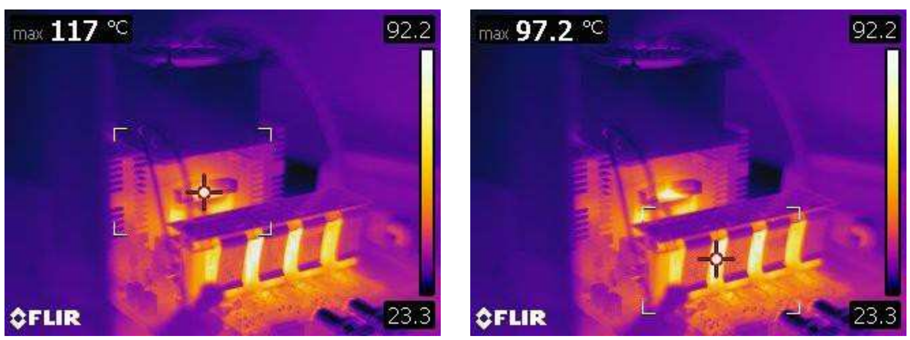
Thermal images captured with the FLIR® T420 IR camera at full load in closed-loop operation are shown in Figure 21. At V_{IN} = 390V, the switching frequency (538 kHz) is close to the resonant frequency (~560 kHz), and the efficiency reaches its highest percentage (~98.25%), resulting in lowest transformer and MOSFET temperatures. As can be seen from the thermal images, the maximum MOSFETs' case temperature remains below 100°C from 380 V to 400 V input voltage at full load. The hot spot is the transformer winding with a temperature of 117°C (still below safe limit: 155°C) at 400V input.



(a)



(b)



(c)

Figure 21: Thermal images captured with FLIR® T420 IR camera: (a) V_{IN} = 380V; (b) V_{IN} = 390V; (c) V_{IN} = 400V

4.3 Captured Waveforms

The captured switching waveforms for different input voltages at 500 kHz and full load are shown in Figure 22. The screenshots in the middle show that the power switches are turned on at zero voltage and turned off near zero-crossing of the primary resonant current. The waveforms of the output diode voltage, output voltage, and the sensed current signal are shown in Figures 23 and 24.

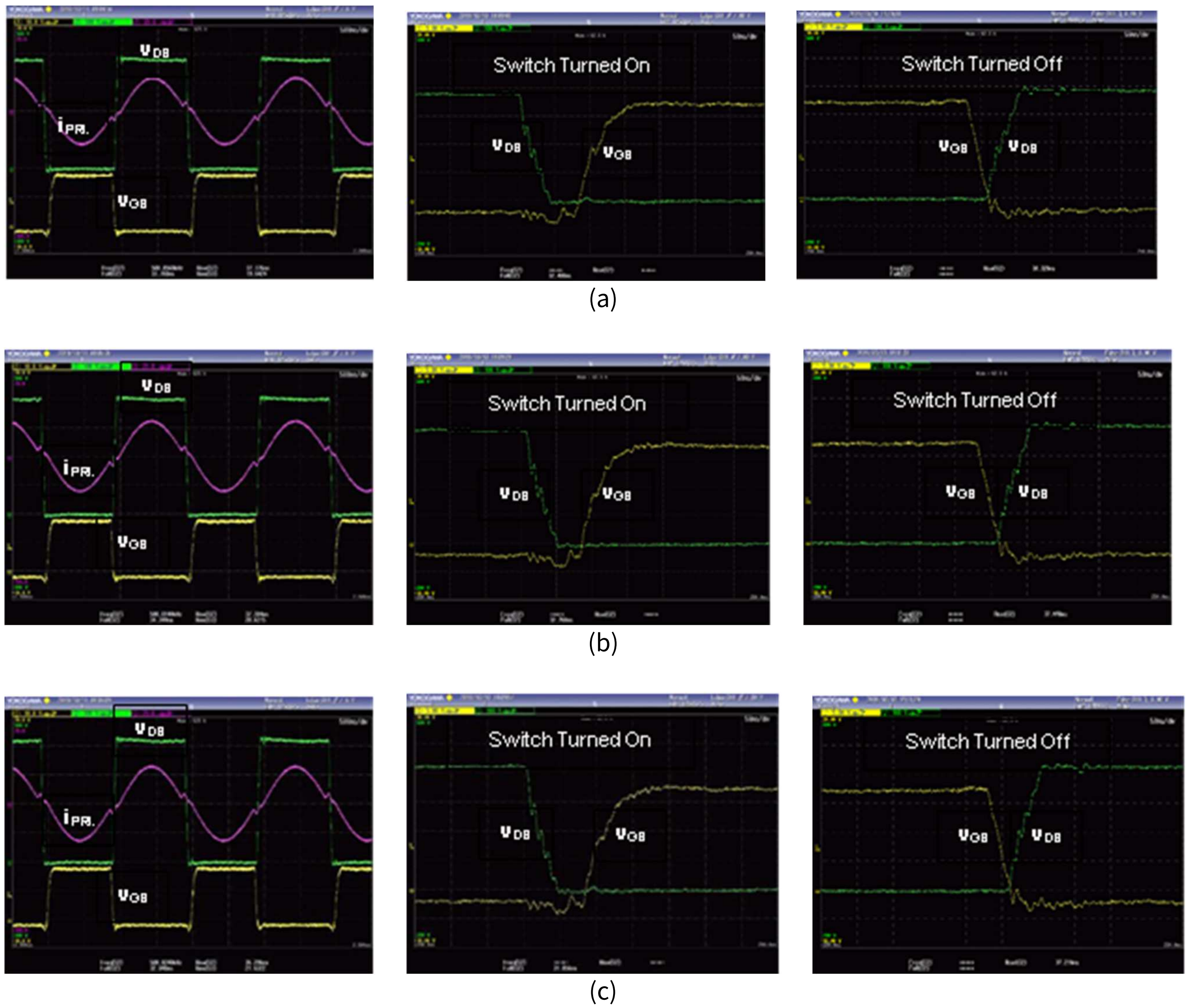


Figure 22: Captured switching waveforms at 500 kHz:
(a) V_{IN} = 380V; (b) V_{IN} = 400V; (c) V_{IN} = 420V. yellow trace: gate-source voltage;
green trace: drain-source voltage; purple trace: primary current

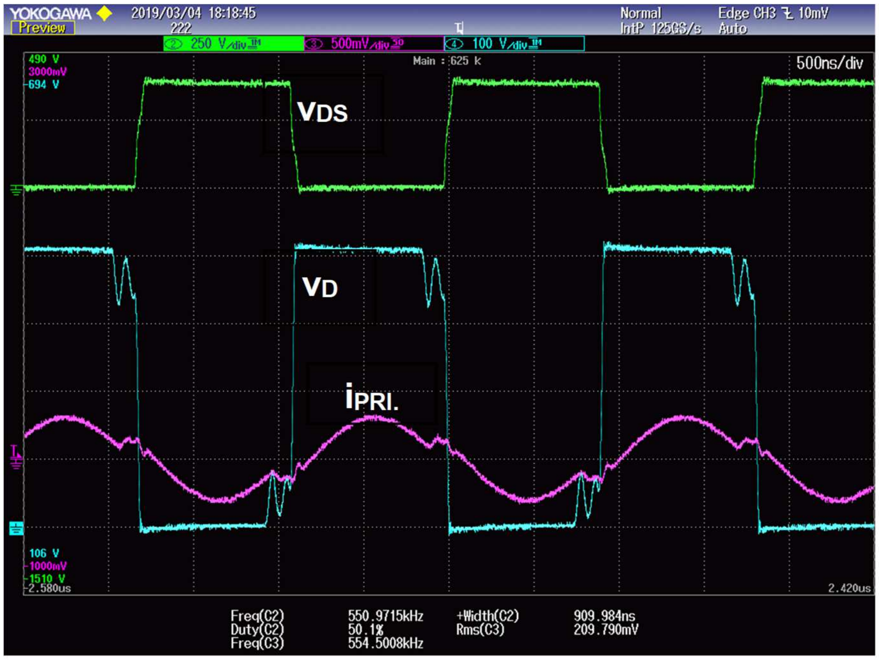


Figure 23: Captured waveforms of drain-source voltage, output diode voltage and primary current at V_{IN} = 390V and full load

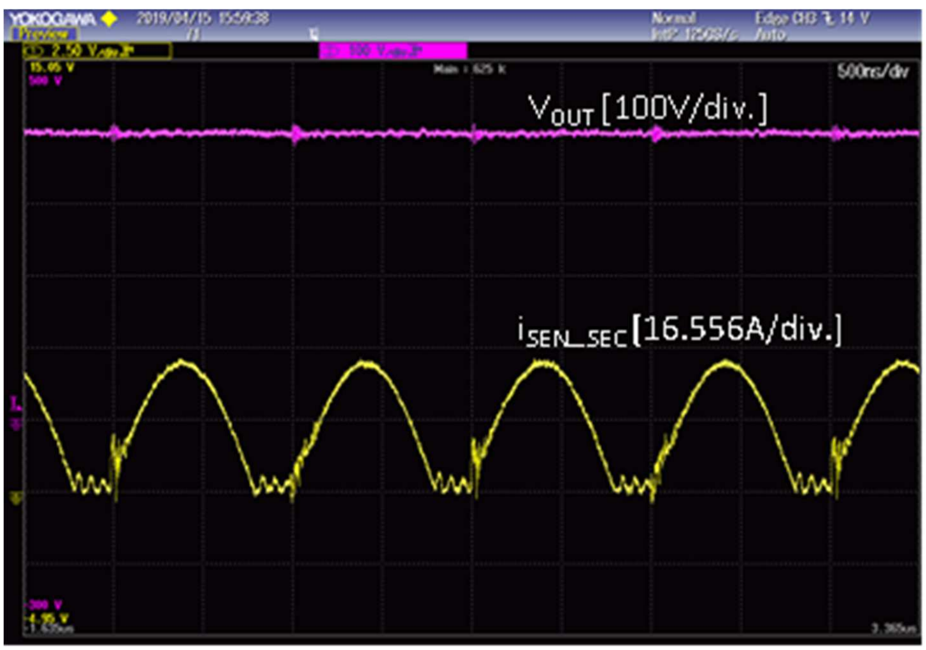


Figure 24: Captured waveforms of output voltage and sensed current signal (across TP29 And TP30) Via CT1 at V_{IN} = 390V and full load

5. Schematic Drawings, Layout and BOM

Note: A larger copy of any schematic in this Section 5, or any other schematic included in this user guide, may be obtained upon request by contacting Wolfspeed at forum.wolfspeed.com

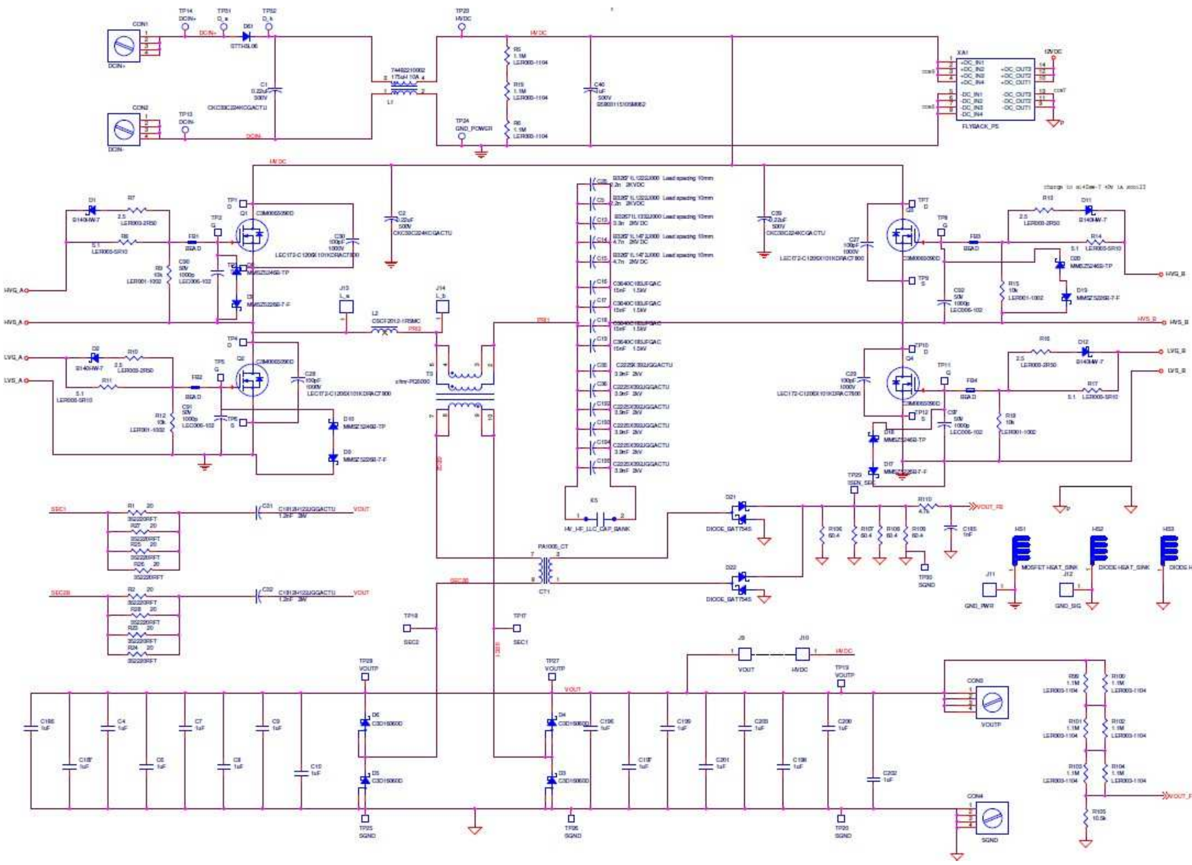


Figure 25: Complete schematic of power stage of LLC converter

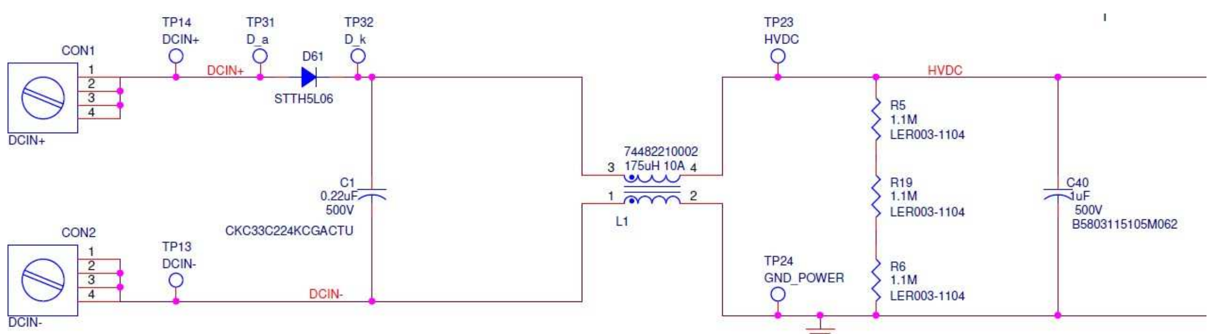


Figure 26: Input stage

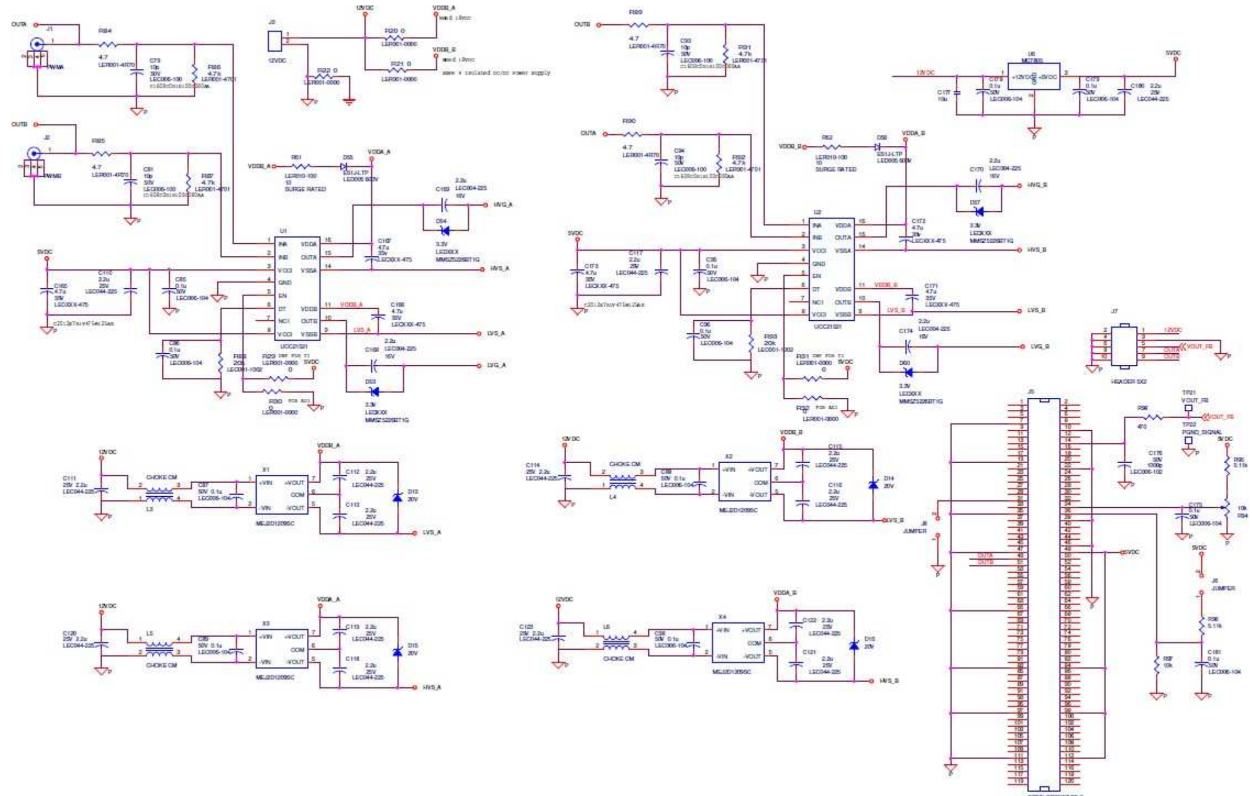


Figure 27: Complete schematic of gate drive and control stage of LLC converter

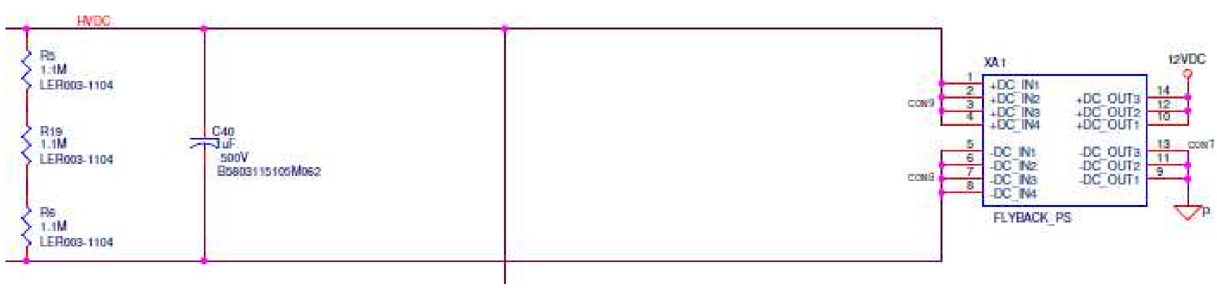


Figure 28: Daughter card of flyback auxiliary power supply

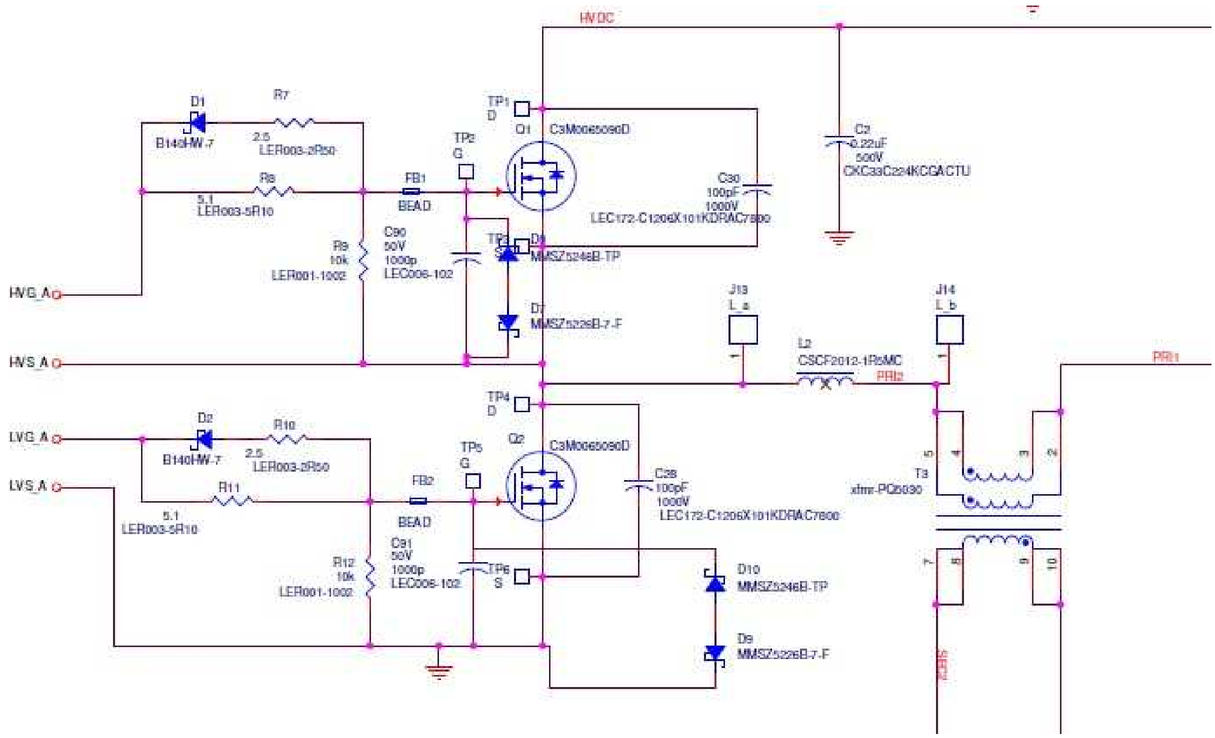


Figure 29: Half-bridge A of LLC converter

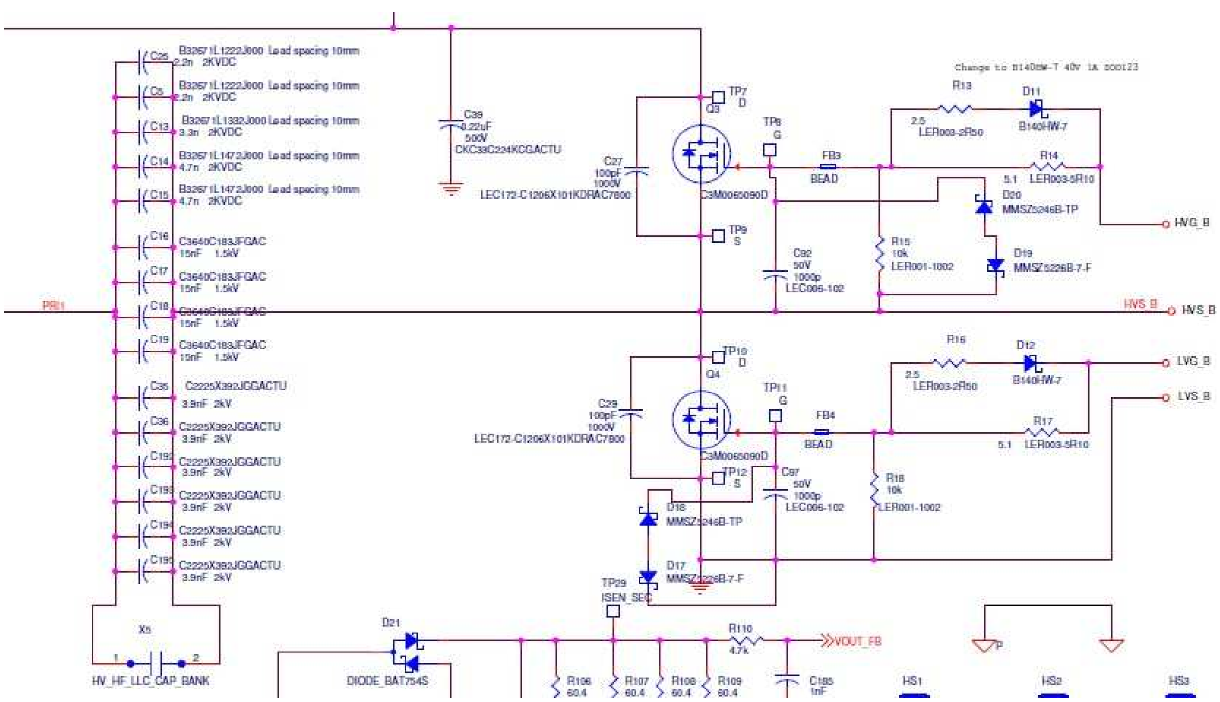


Figure 30: Half-bridge B of LLC converter

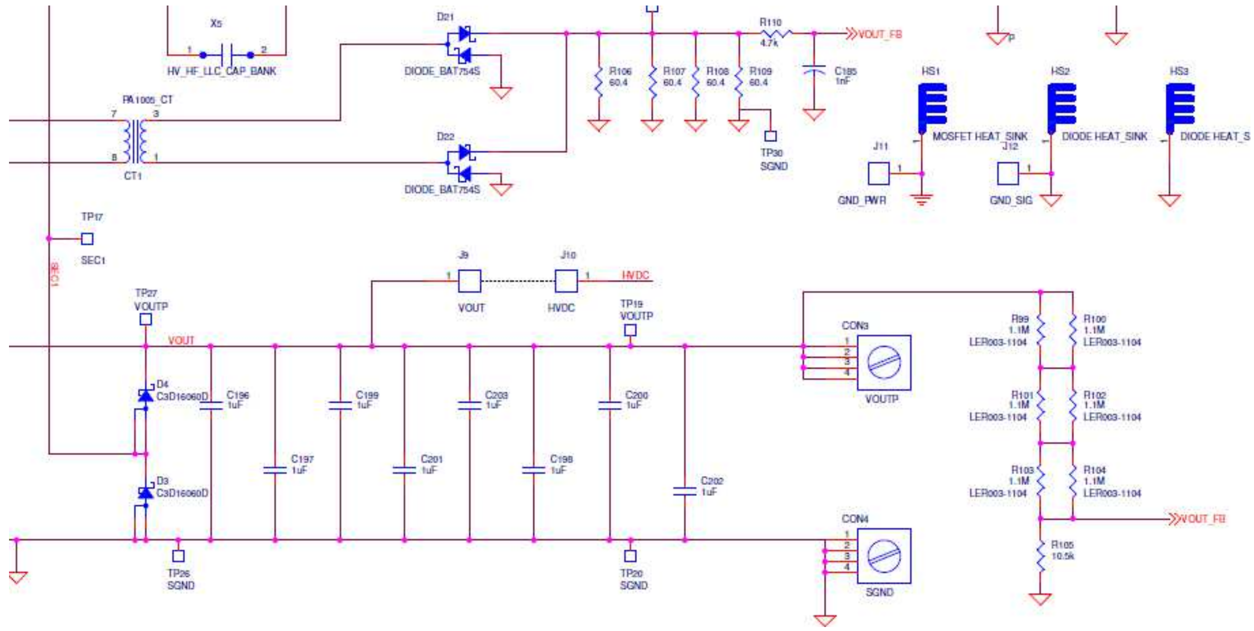


Figure 31: Output stage with current transformer CT1

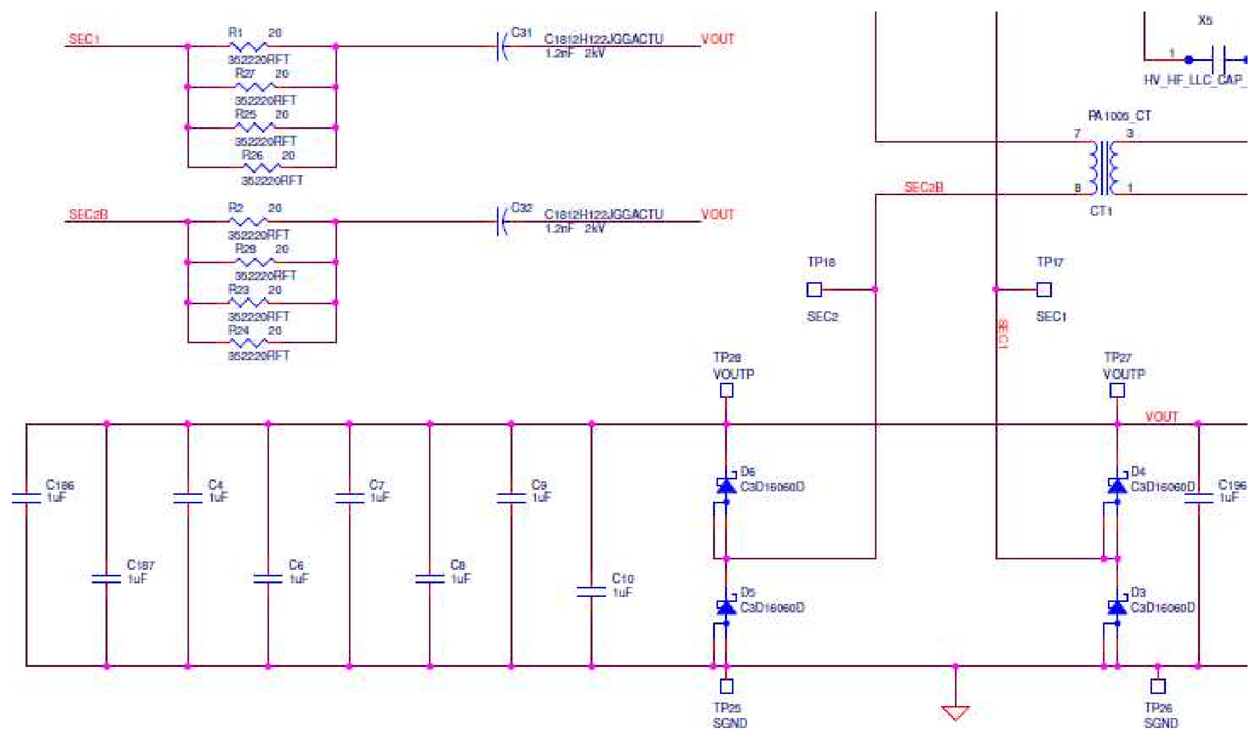


Figure 32: Output stage with snubber (not populated)

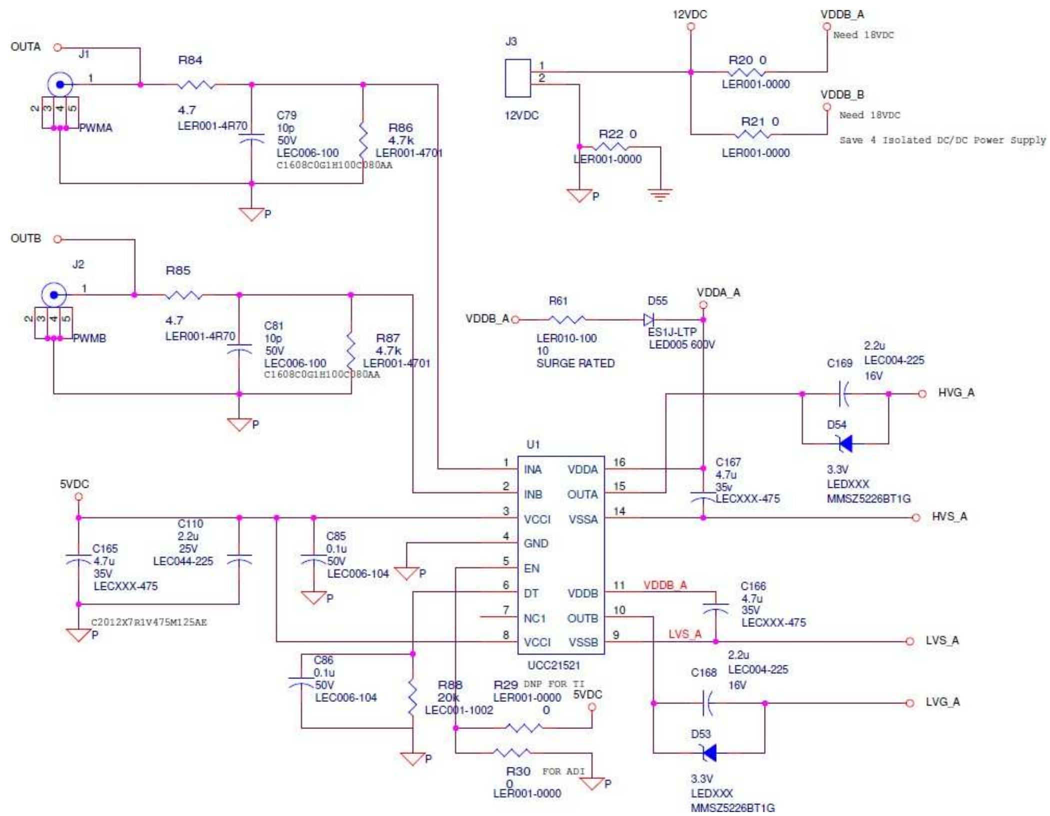


Figure 33: Gate drive circuit for half bridge A

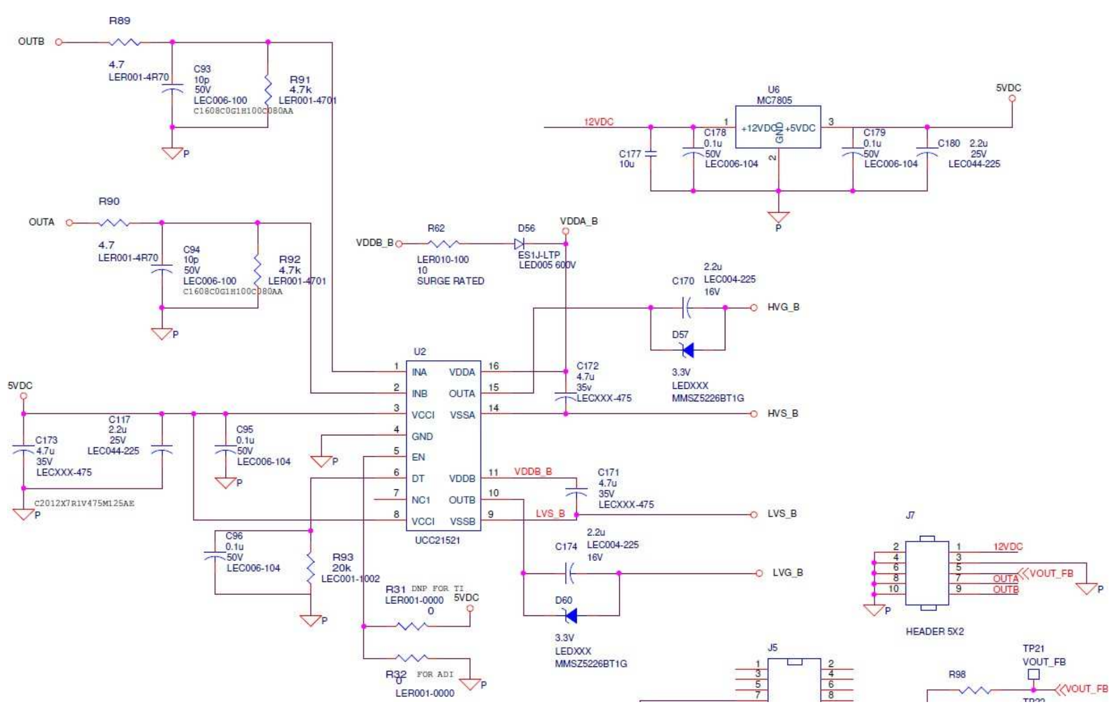


Figure 34: Gate drive circuit for half bridge B

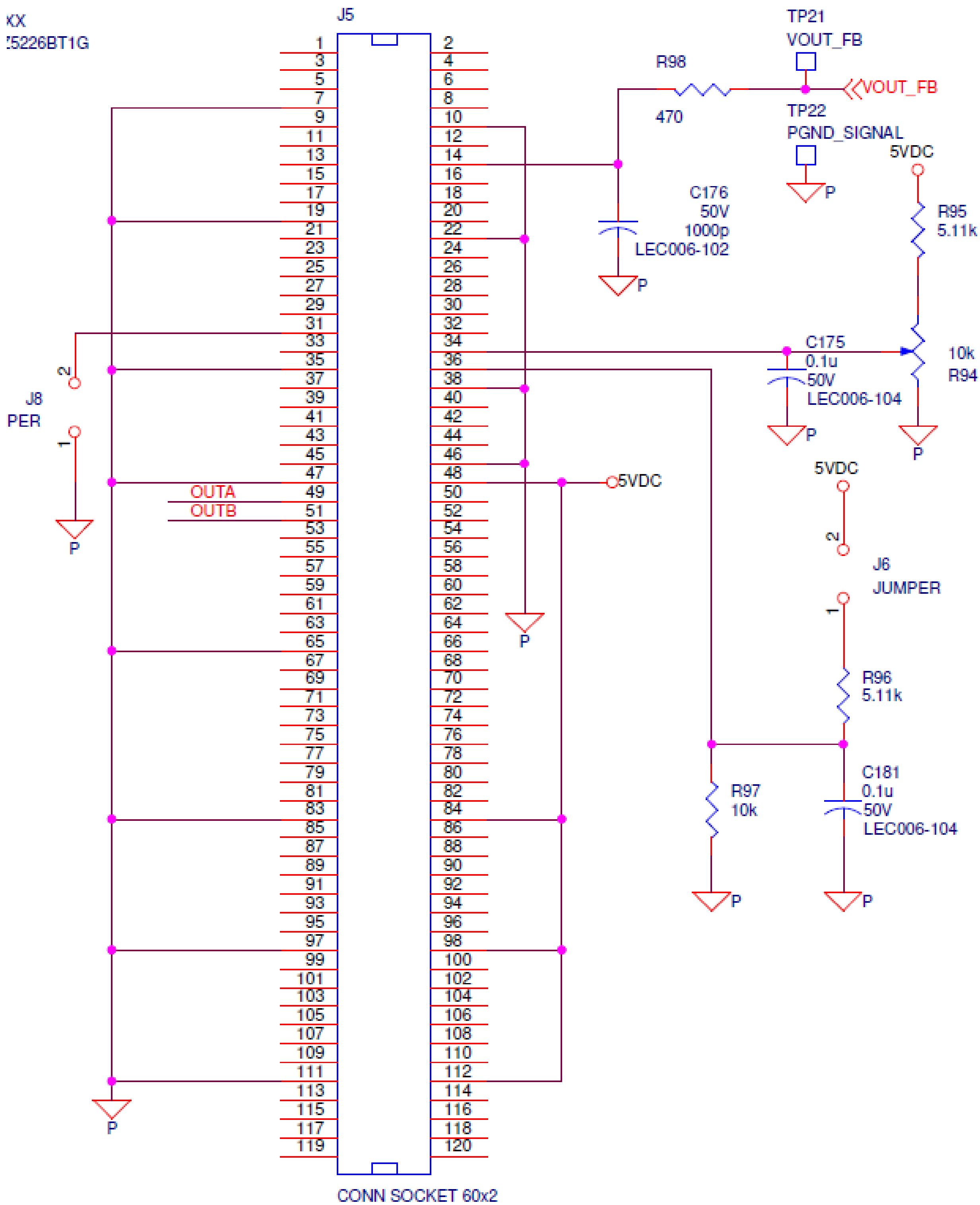


Figure 35: Connector socket for TI® DSP control card

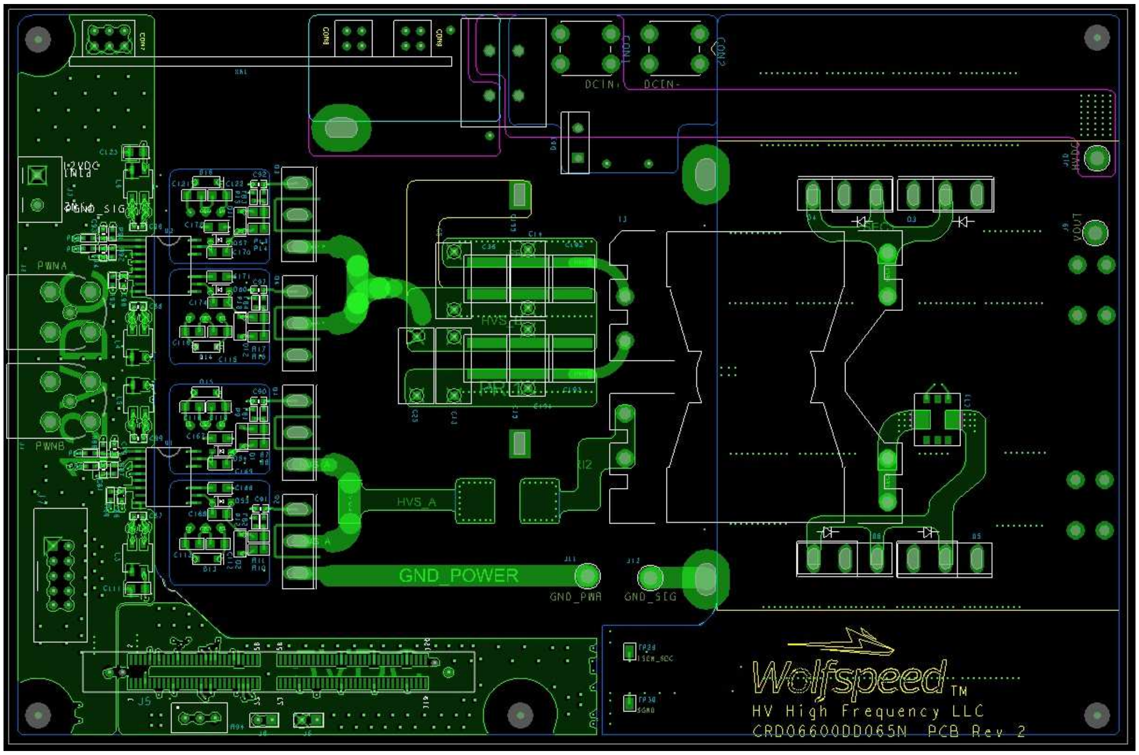


Figure 36: Top layer of PCB

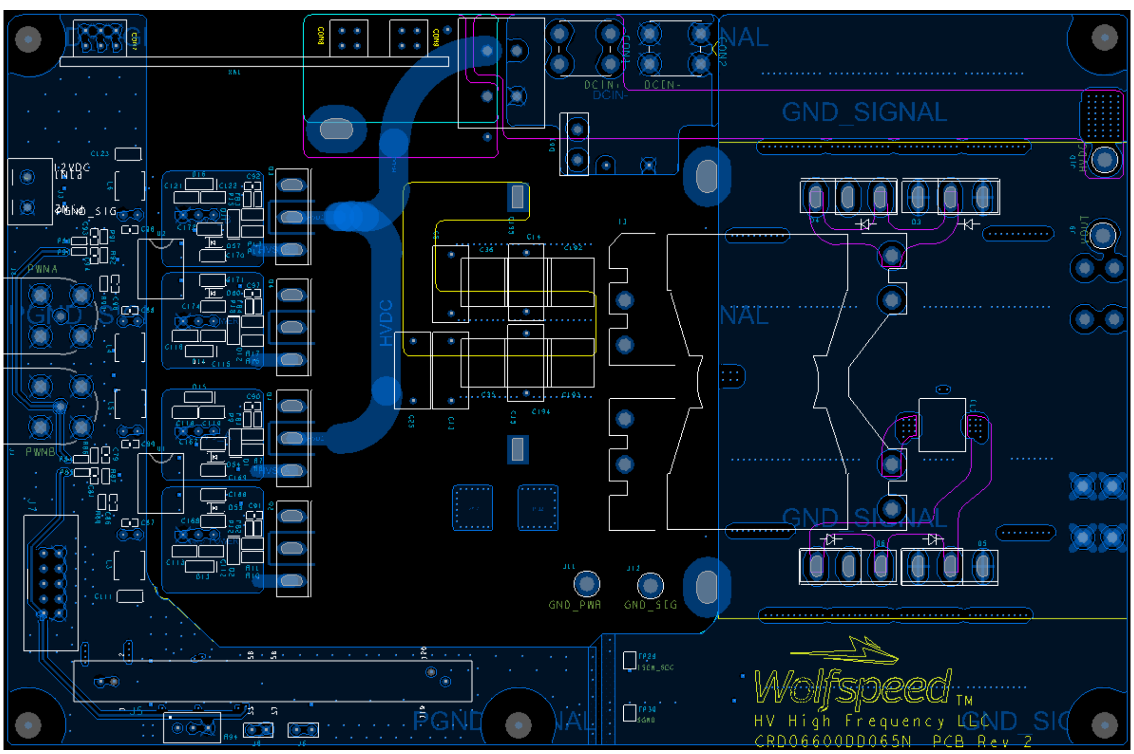


Figure 37: Layer two of PCB

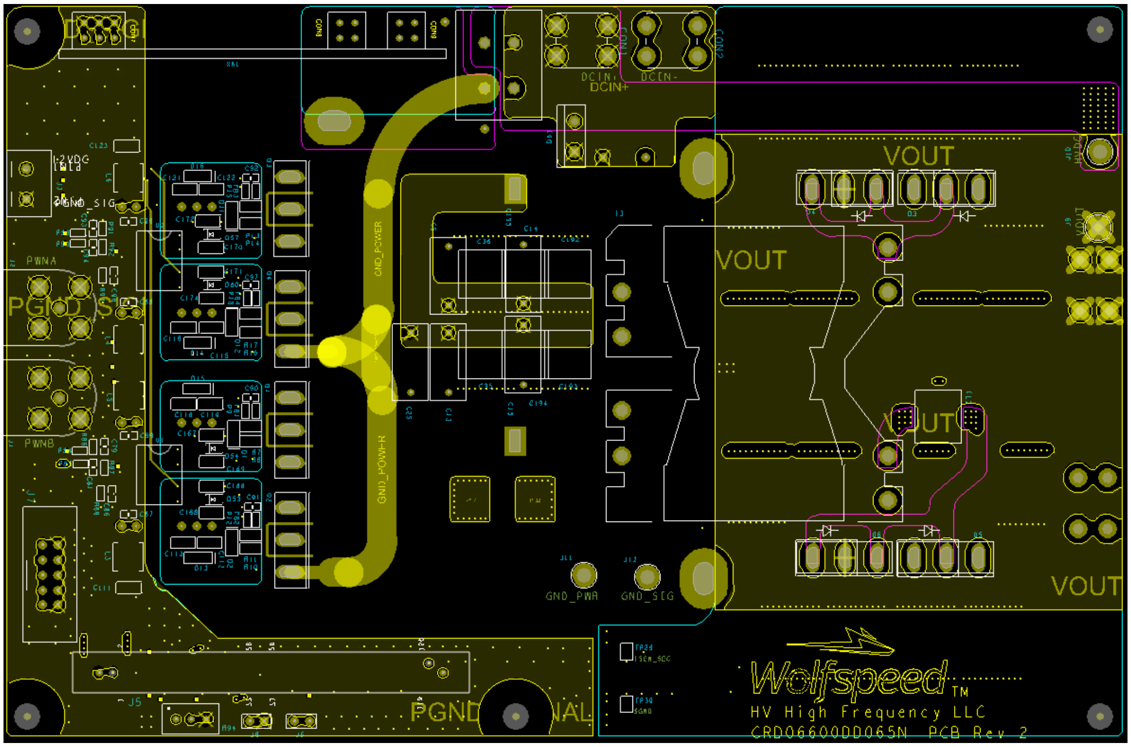


Figure 38: Layer three of PCB

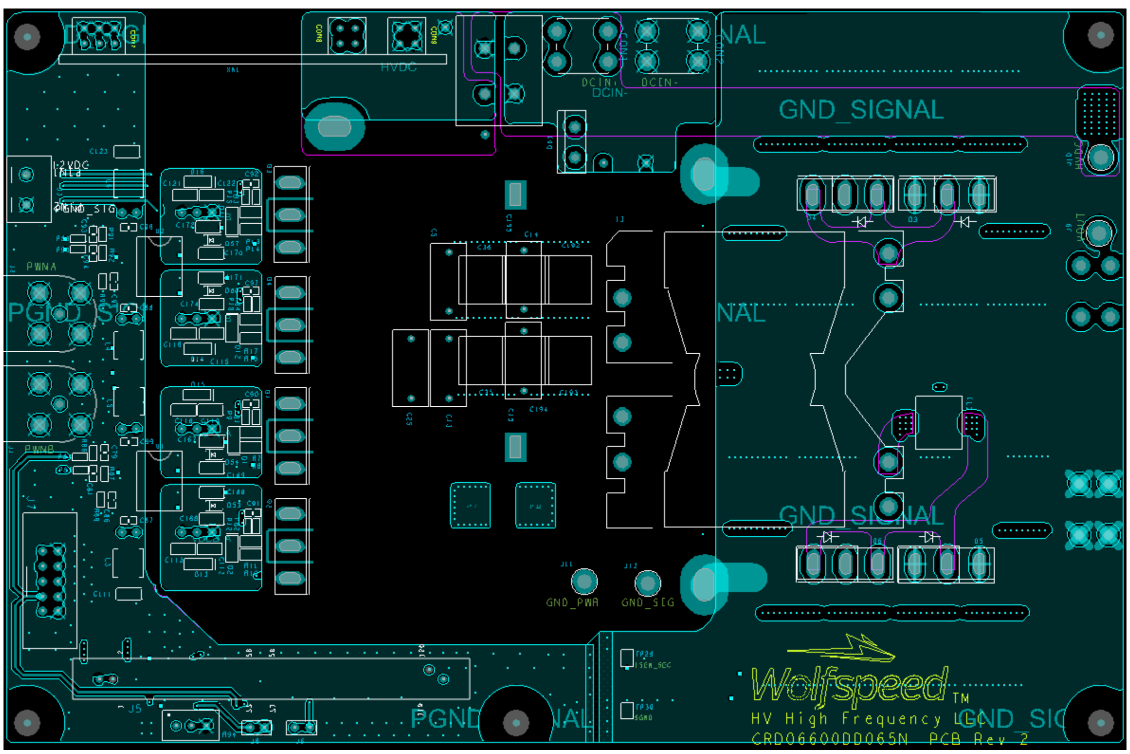


Figure 39: Layer four of PCB

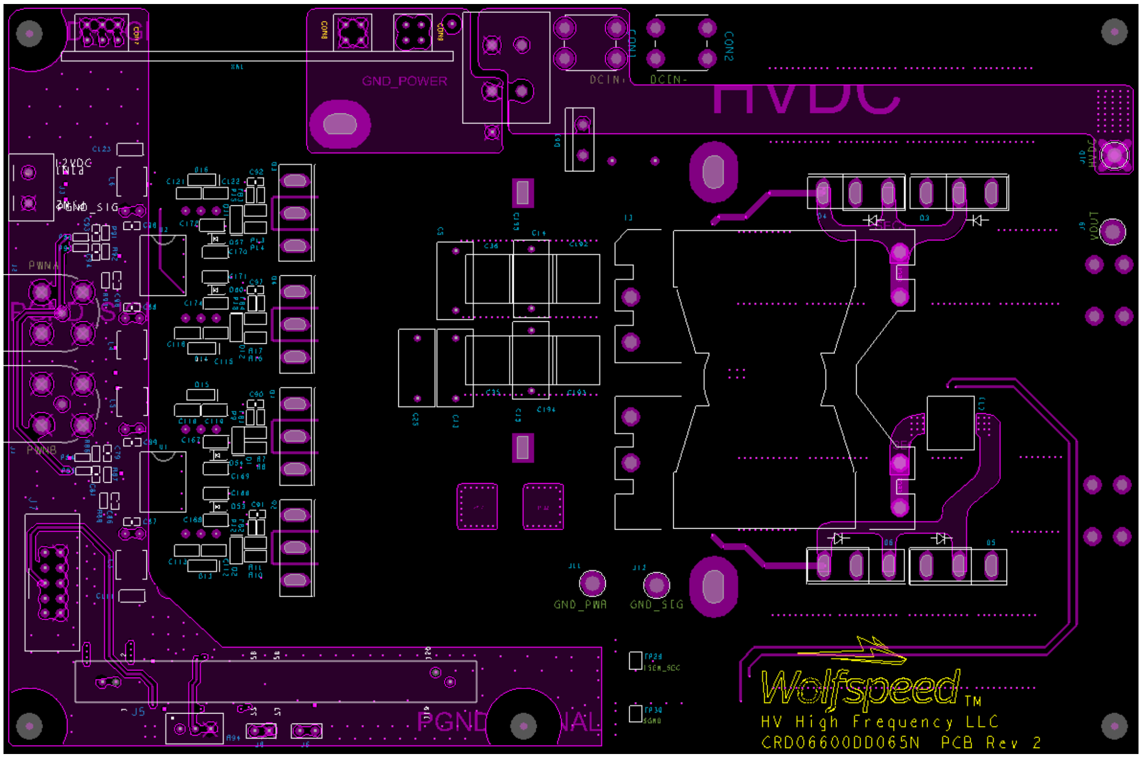


Figure 40: Layer five of PCB

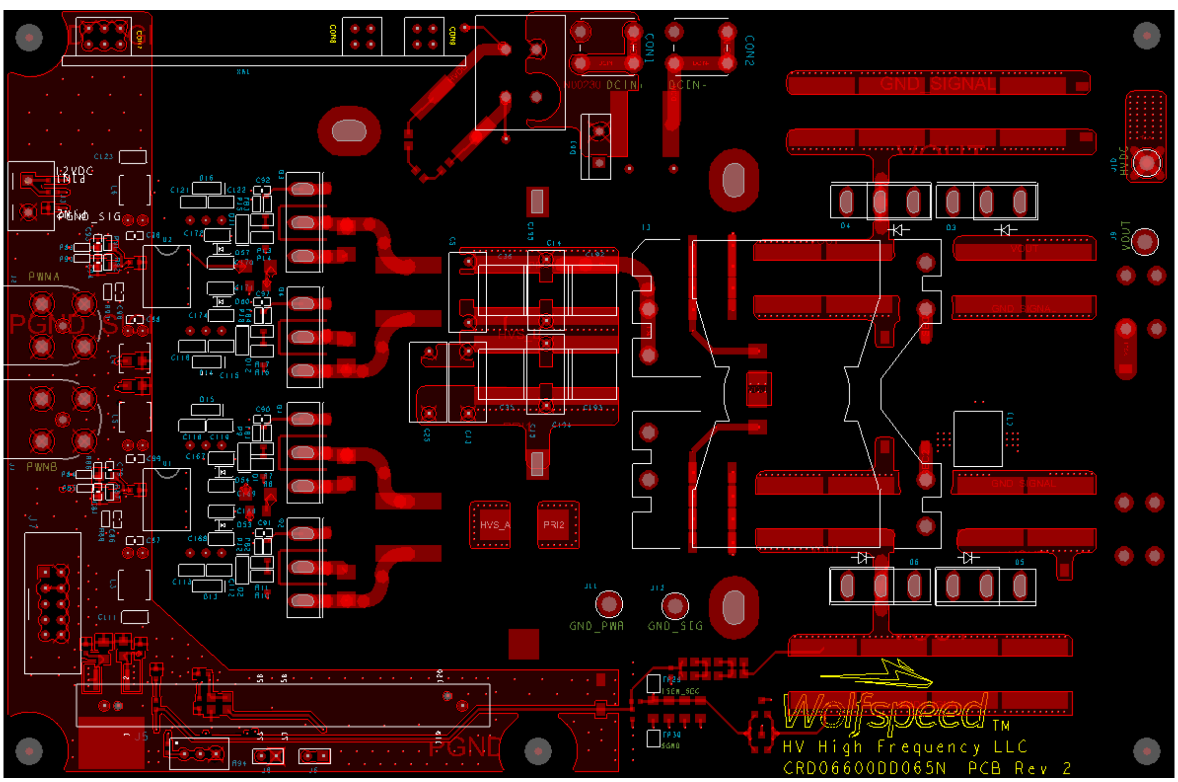


Figure 41: Bottom layer of PCB

Table 3: BOM of LLC Converter

Item	Qty Per	Reference	Description	Manufacturer Name	Manufacturer P/N
1	4	CON1, CON2, CON3, CON4	TERM SCREW 10-32 4 PIN PCB	Keystone Electronics	8174
2	1	CON7	CONN HDR 6POS 0.1 GOLD PCB	PPPC032LFBN-RC	Sullins
3	2	CON8, CON9	CONN HEADER FMAL 4PS .1" DL GOLD	PPPC022LFBN-RC	Sullins
4	3	C1, C2, C39	KC-LINK 3640 220NF 500V C0G	KEMET	CKC33C224KCG ACTU
5	9	C7, C9, C10, C40, C187, C196, C197, C199, C201	CAP CER 1UF 500V SMD	TDK Corporation	B58031I5105M0 62
6	4	C192, C193, C194, C195	CAP CER 3900PF 2KV C0G/NP0 2225	Kemet	C2225X392JGGA CTU
7	4	C16, C17, C18, C19	CAP CER 0.015u 2KV C0G 3640	Kemet	C3640C153JGG ACAUTO
8	4	C27, C28, C29, C30	CAP CER 100PF 1KV C0G/NP0 1812	Vishay Vitramon	VJ1812A101JXG AT
9	4	C79, C81, C93, C94	CAP CER 10PF 50V C0G/NPO 0603	Yageo	CC0603JRNPO9 BN100
10	12	C85, C86, C87, C88, C89, C95, C96, C98, C175, C178, C179, C181	CAP CER 0.1UF 50V X8R SMD	TDK Corporation	C1608X8R1H104 M080AB
11	6	C90, C91, C92, C97, C176, C185	CAP CER 1000PF 50V X7R 0603	Murata	GRM188R71H10 2KA01D
12	19	C110, C111, C112, C113, C114, C115, C116, C117, C118, C119, C120, C121, C122, C123, C168, C169, C170, C174,	CAP CER 2.2UF 25V X7R 0805	Yageo	CC0805KKX7R8 BB225

Item	Qty Per	Reference	Description	Manufacturer Name	Manufacturer P/N
		C180			
13	6	C165,C166,C167,C171,C172,C173	CAP CER 4.7UF 35V X7R 0805	TDK Corporation	CGA4J1X7R1V475K125AC
14	1	C177	CAP CER 10UF 25V X7R 1206	TDK Corporation	C3216X7R1E106K160AB
15	1	CT1	CURRENT SENSE XFMR 1:100 20A SMD	Pulse Electronics Power	PA1005.100NLT
16	4	D1, D2, D11, D12	DIODE SCHOTTKY 40V 1A SOD123	Diodes Incorporated	B140HW-7
17	4	D3, D4, D5, D6	DIODE SCHOTTKY 650V 10A TO220-2	Wolfspeed	C6D10065A
18	4	D13, D14, D15, D16	DIODE ZENER 20V 500MW SOD123	Diodes Incorporated	MMSZ5250B-7-F
19				ON Semiconductor	MMSZ20T1G
20	8	D53, D54, D57, D60, D7, D9, D17, D19	DIODE ZENER 3.3V 500MW SOD123	Diodes Incorporated	MMSZ5226B-7-F
21	4	D8, D10, D18, D20	DIODE ZENER 16V 500MW SOD123	Micro Commercial Components (MCC)	MMSZ5246B-TP
22	2	D21, D22	DIODE ARRAY SCHOTTKY 30V SOT23	Nexperia USA Inc.	BAT754S,215
23	4	FB1, FB2, FB3, FB4	FERRITE BEAD 22 OHM 0603	Taiyo Yuden	FBMJ1608HS220NTR
24	2	J1, J2	CONN BNC JACK R/A 50 OHM PCB	TE Connectivity	5-1634513-1
25	1	J3	TERM BLOCK PCB 2POS 5.0MM GREEN	Phoenix Contact	1935161

Item	Qty Per	Reference	Description	Manufacturer Name	Manufacturer P/N
26	1	J5	CONN EDGE DUAL FMALE 120POS .031	3M	SPD08-120-L-RB-TR
27	2	J6, J8	CONN HEADER .100" SNGL STR 2POS	Sullins Connector Solutions	PRPC002SAAN-RC
28	1	J7	CONN HEADER LOW-PRO 10POS GOLD	Assmann WSW Components	AWHW 10G-0202-T
29	1	L1	CMC 175UH 10A 2LN TH	Wurth Electronics Inc.	74482210002
30	4	L3, L4, L5, L6	CMC 1.7A 2LN 1.4 KOHM SMD	TDK Corporation	ACM4520-142-2P-T000
31	4	Q1, Q2, Q3, Q4	MOSFET N-CH 650V 30A TO247-3	Wolfspeed	C3M0060065D (or) E3M0060065D
32	2	R30, R32	RES SMD 0 OHM JUMPER 1/10W 0603	Samsung Electro-Mechanics	RC1608J000CS
33	9	R5, R6, R19, R99, R100, R101, R102, R103, R104	RES SMD 1.1M OHM 1% 1/8W 0805	Vishay Dale	CRCW08051M10FKEA
34	4	R7, R10, R13, R16	RES SMD 2.55 OHM 1% 1/8W 0805	Yageo	RC0805FR-072R55L
35	4	R8, R11, R14, R17	RES SMD 5.1 OHM 1% 1/2W 0805	Vishay Dale	CRCW08055R10FKEAHP
36	4	R9, R12, R15, R18	RES SMD 10K OHM 1% 1/10W 0603	Vishay Dale	CRCW060310K0FKEA
37	2	R88, R93	RES SMD 20K OHM 1% 1/10W 0603	Vishay Dale	CRCW060320K0FKEA
38	4	R84, R85, R89, R90	RES SMD 4.7 OHM 1% 1/10W	Panasonic Electronic Components	ERJ-3RQF4R7V

Item	Qty Per	Reference	Description	Manufacturer Name	Manufacturer P/N
			0603		
39	4	R86, R87, R91, R92	RES SMD 4.7K OHM 1% 1/10W 0603	Panasonic Electronic Components	ERJ-3EKF4701V
40	1	R94	TRIMMER 10K OHM 0.25W PC PIN TOP	Bourns Inc	3266Y-1-103LF
41	2	R95, R96	RES SMD 5.11K OHM 1% 1/8W 0805	Vishay Dale	CRCW08055K11 FKEAC
42	1	R97	RES SMD 10K OHM 1% 1/8W 0805	Vishay Dale	CRCW080510K0 FKEA
43	1	R105	RES SMD 10.5K OHM 1% 1/8W 0603	Panasonic Electronic Components	ERJ-3EKF1052V
44	4	R106, R107, R108, R109	RES SMD 60.4 OHM 1% 1/2W 1206	Rohm Semiconductor	ESR18EZPF60R4
45	1	R98	RES SMD 470 OHM 1% 1/10W 0603	Vishay Dale	CRCW0603470 RFKEAC
46	1	T3	Transformer PQ5030 26.5uH	Sumida	T91673B or T91673B1?
47	1	U6	IC REG LINEAR 5V 1A D2PAK	ON Semiconductor	NCV7805ABD2T R4G
48	2	U1, U2	Gate Driver Magnetic Coupling 5.7kV 2 Channel 16-SOIC	ADI	ADuM4221
49	4	X1, X2, X3, X4	DC/DC CONV 5.2KV ISO SIP7 TH 2W	Murata Power Solutions Inc.	MEJ2D1209SC
50	24	TP1-TP12, TP17-TP22, TP25-TP30	PC TEST POINT TIN SMD	Harwin	S2751-46R
51	4	TP13, TP14, TP23,	PC TEST POINT	Keystone	5001

Item	Qty Per	Reference	Description	Manufacturer Name	Manufacturer P/N
		TP24	MINIATURE BLACK		
52	2	JUMPER0	CONN JUMPER SHORTING GOLD FLASH	Sullins Connector Solutions	SPC02SYAN

6. References

[1] M. Paolucci, "Improving Power Density and Efficiency in Servers and Telecom," Power Systems Design, Nov. 2015.

[2] R. Wang, P. Ning, Z. Wang, et al., "A High-Temperature SiC Three Phase AC-DC Converter Design for > 100°C Ambient Temperature," IEEE Trans. Power Electronics, vol. 28, no. 1, pp 555-572, Jan. 2013.

[3] L. Zhang, S. Guo, X. Li, et al., "Integrated SiC MOSFET Module with Ultralow Parasitic Inductance for Noise Free Ultrahigh Speed Switching," in Wide Bandgap Power Devices and Applications (WiPDA), 2015 IEEE 3rd Workshop, pp.224-229, 2-4 Nov. 2015.

[4] J. W. Palmour, L. Cheng, V. Pala, et al., "Silicon Carbide Power MOSFETs: Breakthrough Performance from 900 V up to 15 kV," in Power Semiconductor, pp.79–82, 15–19 June 2014.

[5] G. Wang, F. Wang, G. Magai, et al., "Performance Comparison of 1200V 100A SiC MOSFET and 1200V 100A Silicon IGBT," in 2013 IEEE ECCE, pp.3230-3234, 15–19 Sept. 2013.

[6] Ya Liu, "High Efficiency Optimization of LLC Resonant Converter for Wide Load Range," Master's thesis, Center for Power Electronics System, Virginia Tech, 2007.

[7] B. Lu, W. Liu, Y. Liang, et al., "Optimal Design Methodology for LLC Resonant Converter," IEEE-APEC Proc., 2006, pp. 533-538.

[8] Z. U. Zahid, Z. M. Dalala, R. Chen, et al., "Design of Bidirectional DC–DC Resonant Converter for Vehicle-to-Grid (V2G) Applications," IEEE Trans. Transportation Electrification, vol. 1, no. 3, pp. 232-244, Oct. 2015.

[9] On Semiconductors, "Basic Principles of LLC Resonant Half Bridge Converter and DC/Dynamic Circuit Simulation Examples," AND9408/D, https://www.onsemi.com/pub/Collateral/ AND9408-D.PDF, April 2016.

7. Revision History

Date	Revision	Changes
January 2019	V1.0	1st Issue
January 2024	2	Branding and formatting updates

8. 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.