User Guide **PRD-06982**

CRD-02AD065N
2.2 kW, High Efficiency (80+ Titanium) Bridgeless Totem-Pole PFC with SiC MOSFET

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Contents

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CAUTION

PLEASE CAREFULLY REVIEW THE FOLLOWING PAGE, AS IT CONTAINS IMPORTANT INFORMATION REGARDING THE HAZARDS AND SAFE OPERATING REQUIREMENTS RELATED TO THE HANDLING AND USE OF THIS BOARD.

警告

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

警告

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

CAUTION

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

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

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

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

警告

请勿在通电情况下接触板子，在处理板子前应使大容量电容**器**完全释放电**力。**接**通**电源后，该评估**板上**可能**存在非常**高**的**电压，**板子上一些**组件的**温度**可能**超**过 50 摄氏度。此外，**移除**电源后，上述情况**可能**会短暂持续，直至大容量电容**器**完全释放电**量**。

操作板子时应确保遵守正确的安全规程，**否**则可能**会出**现下列**危**险：

- **死亡**
- 严**重**伤害
- **触**电
- 电击
- 电**灼**伤
- 严重的热烧伤

请在操作本**板子**前完整阅读本**文件。**通电时不必接触板子。在为板子通电**前必**须连接**所有**测试与测量探针或附件。通电时，禁止使板子处于无人看护状态，或操作板子。必须确保在操作板**子**前，大容量电容**器**释放**了所有**电**量**。只有在**切**断**板子电源**，且大容量电容**器**完全放电后，**才**可更换待测试器件

警告

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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-power efficiency is an important concern in the design of a switch mode power supply, especially for energy saving and environmental protection. The importance of this concern is illustrated in the 80 PLUS® efficiency specifications (as shown in Table 1), which since 2007 have awarded high efficiency to AC/DC rectifiers ranging from Gold to Platinum and continuing to Titanium.

Table 1: 80 PLUS® Efficiency Specifications

80 Plus® Test Type	115 V Internal Non-Redundant				230 V Internal Redundant			
Fraction of rated load	10%	20%	50%	100%	10%	20%	50%	100%
80 Plus		80%	80%	80%				
80 Plus Bronze		82%	85%	82%		81%	85%	81%
80 Plus Silver		85%	88%	85%		85%	89%	85%
80 Plus Gold		87%	90%	87%		88%	92%	88%
80 Plus Platinum		90%	92%	89%		90%	94%	91%
80 Plus Titanium	90%	92%	94%	90%	90%	94%	96%	91%

To get 96% Titanium peak efficiency, the budgetary efficiency of a power factor correction (PFC) circuit should be 98.5% or above for high lines and 96.4% or above for low lines. It becomes very challenging with a traditional PFC design to get efficiency higher than 97.5%.

2. Traditional PFC Design Vs Bridgeless Totem-Pole PFC Design

PFC control scheme is widely adopted for AC-DC power conversion applications. The main advantage of adding a PFC stage in an AC-DC power converter is to achieve better efficiency, low total harmonic distortion (THD) and better power factor (PF). Figure 1 shows the traditional PFC topology that can give 97.5% efficiency (which helps to achieve 80 Plus Platinum level efficiency). Disadvantages of using traditional PFC design include high conduction losses in the fixed diode bridge, low power density, more components and high cost.

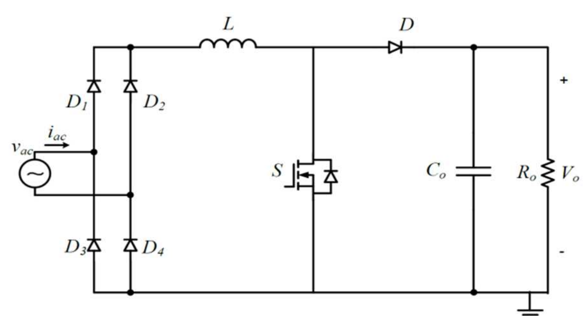


Figure 1: Traditional PFC design

The most promising PFC topology is the bridgeless totem-Pole PFC design (as shown in Figure 2). This configuration doesn't have a full-wave AC rectifier bridge which reduces related conduction losses. Moreover, this topology gives high power density, high efficiency, low THD and low common mode noise.

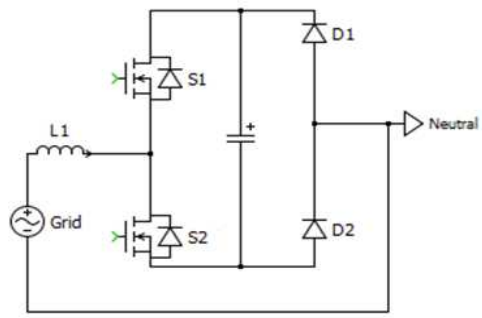


Figure 2: Bridgeless totem-pole PFC design

3. SiC MOSFETs Based Totem-Pole PFC Topology

The main limitation of bridgeless totem-pole PFC topology is the use of conventional silicon (Si) devices. The large reverse recovery charge of Si devices limits the totem-pole PFC circuit to critical conduction mode (CRM). During CRM, bridgeless totem-pole topology suffers from large electromagnetic interference (EMI) noise, which restricts the use of this topology to low power levels. These issues can be mitigated by using silicon carbide (SiC) Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs). Their fast-switching speed, low on-state resistance (Rds_{on}), low reverse recovery charge (Qrr) and low capacitance makes them an ideal choice to enable a continuous conduction mode (CCM) bridgeless totem-pole PFC configuration.

This user guide for Wolfspeed's CRD-02AD065N reference design board explains the design procedure of implementing a SiC MOSFET based bridgeless totem-pole PFC topology with a standard analog PFC controller.

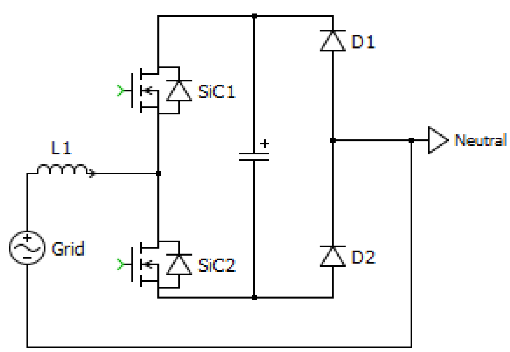


Figure 3: Wolfspeed's SiC MOSFET based bridgeless totem-pole PFC topology

Figure 3 shows the selected totem pole PFC circuit that includes two Wolfspeed SiC MOSFETs S1 and S2 (C3M0060065D for TO-247 vision, C3M0060065K for TO-247-4 vision, C3M0060065J for TO-263-7 vision) and the two-line rectification fast recovery epitaxial diodes (FRED) (D1 and D2) from ST Microelectronics (P/N: STTH30L06C). In order to boost efficiency, line rectification diodes can be replaced with two low R_{dson} MOSFETs. However, this adds extra cost and requires 2 extra gate drives. In addition, one of the major problems of totem-pole PFC topology is the inductor current spike at input voltage zero crossing. This problem is less severe with FRED diode line rectification than with a MOSFET solution because of the FRED's low output capacitance and low Qrr compared to those of the body diode of a MOSFET.

3.1 Basic Operating Principle: Positive Half Line Cycle Operation

The positive half line cycle operation of the totem-pole PFC circuit is shown in Figure 4. There are only two semiconductors in the current path. When the SiC MOSFET S2 is turned ON, the alternating current (AC) source charges the inductor (L1) and the output capacitor (C0) supplies energy to the load (R0). The diode D2 also conducts current and connects the AC source to the output ground.

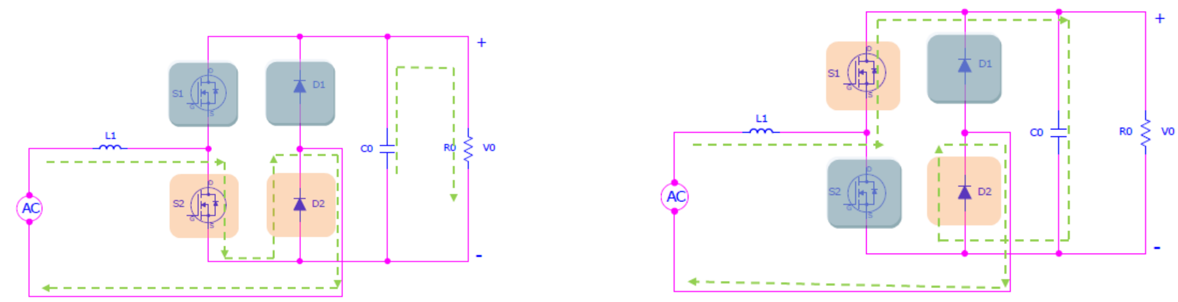


Figure 4a Figure 4b

Figure 4: Totem-pole PFC positive line cycle.
a. when switch is turned ON (or) b. when switch is turned OFF

When the SiC MOSFET S2 is turned OFF, the inductor (L1) discharges energy to the output. The diode D2 still conducts current and connects the AC source to the output ground.

3.2 Basic Operating Principle: Negative Half Line Cycle Operation

The negative half line cycle operation of the totem-pole PFC topology is shown in Figure 5. There are only two semiconductor devices in the current path. When the SiC MOSFET S1 is turned ON, the AC source charges the inductor (L1) and the output capacitor (C0) supplies energy to the load(R0). The diode D1 conducts current and connects the AC source to the positive terminal output.

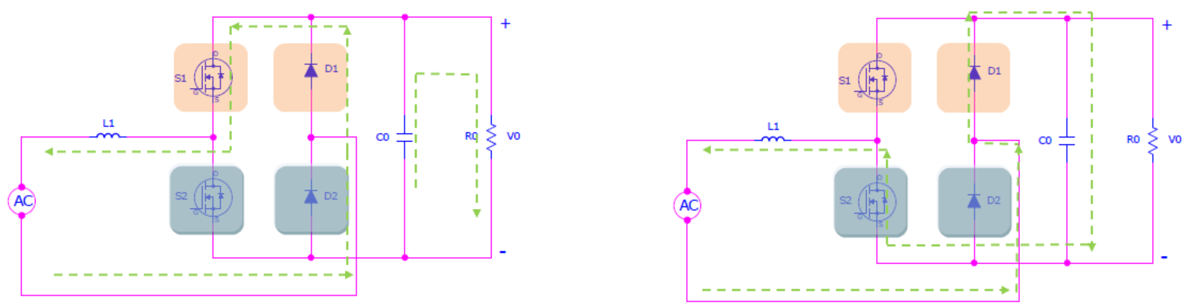


Figure 5a Figure 5b

Figure 5: Totem-pole PFC negative line cycle.
a. when switch is turned ON (or) b. when switch is turned OFF

When the SiC MOSFET S1 is turned OFF, the inductor (L1) discharges energy to the output. The diode D1 still conducts current and connects the AC source to the positive terminal output.

4. Design Specifications

The design specifications of Wolfspeed's CRD-02AD065N reference design board are listed in Table 2.

Table 2: Design Specifications of Wolfspeed's CRD-02AD065N Reference Design Board

Parameters	Values	Note
Input voltage range, 47-63 Hz	180-264 V (rms)	
Output voltage	385 V nominal	+/- 5%
Output power	2,200 W	At 230 V AC
	1,500 W (Limited by thermal)	At 180 V AC
Input power factor	>.98	
Input THD at full load	<5% (of fundamental)	
Switching frequency	64 KHz	
Efficiency at 50% load	>98.5%	
Max ambient operating temperature	50 ^{0}C	
Cooling	Forced air, 15x40 mm Fan	
Topology	Totem pole	Diode as LF switch
Power devices package	TO-247-3、TO-247-4、TO-263-7	

5. Power Board

CAUTION

IT IS NOT NECESSARY FOR YOU TO TOUCH THE BOARD WHILE IT IS ENERGIZED. WHEN DEVICES ARE BEING ATTACHED FOR TESTING, THE BOARD MUST BE DISCONNECTED FROM THE ELECTRICAL SOURCE AND ALL BULK CAPACITORS MUST BE FULLY DISCHARGED.

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

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

警告

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

板子上一些组件的温度可能超过 50 摄氏度。移除电源后，上述情况可能会短暂持续，**直至大容量**电容器完全释放电量。通电时禁止触摸板子，应在大容量电容器完全释放电量后，再操作板子。请确保在操作板子时已经遵守了正确的安全规程，否则可能会造成严重伤害，包括触电死亡、电击伤害、**或**电灼伤。

警告

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

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

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

In Wolfspeed's CRD-02AD065N reference design board, the main power board carrying PFC circuit has been implemented on a 4-layer printed circuit board (PCB). Wolfspeed's C3M0065065D of TO-247-3, C3M0065065K of TO-247-4, C3M0065065J of TO-263-7, 650V, 65mohm, SiC MOSFETs has been used in Wolfspeed's

CRD-02AD065N reference design board (as shown in Figure 3). And Wolfspeed's C3M0065065J SiC MOSFET consists of a fast intrinsic diode with low Qrr and a very low output capacitance (60pF). Wolfspeed's SiC MOSFET also comes in a compact surface mount package with extended leads for higher voltage capability with low source inductance (< 2nH).

Low voltage drop diodes from ST Microelectronics (P/N: STTH30L06C) in a D2PAK have been used for low frequency diodes D1 and D2 (as shown in Figure 3). A heat sink from Aavid Engineering (P/N: 7109DG) is used for the MOSFETs (S1 & S2) and diodes (D1 & D2). The heat sink is directly soldered on to the drain tab of the MOSFET.

The input inductor (L1) is designed to keep the current ripples under 20% of the maximum peak input current (IPK_pk). The maximum peak input current occurs during the condition of low line voltage at full load. Equation (1) gives the minimum value of inductor (L1) to operate in CCM at full load. D is the duty ratio of the active switches (S1 or S2). V_{out} is the 400 V DC output voltage and F_{sw} is the switching frequency. By using equation (1), the minimum value of inductor L1 value has been calculated as 317 µH.

$$L \geq \frac{D(1-D)}{\Delta I_{pk\_pk} f_{sw}} . Vout \qquad (1)$$

The inductor is fabricated with 2 stacks of cores from Micrometals Inc. (P/N: OP-157075-2). The winding consists of 57 turns of AWG-15 magnetic wire. The inductance is 317 µH at full load and 690 µH at no load. The DC resistance of inductor L1 is 40 mΩ.

The value of output capacitance (C_{out}) is based on two constraints, load hold-up time (t_{holdup}) and output voltage ripple (V_{ripple}). In this design, the hold-up time has been set at one AC line cycle and the output voltage peak to peak ripple has been set at 10 V, while f_{line} is the AC line frequency, V_0 is the output voltage and P_0 is the output power.

$$C_{out} \geq \frac{2P_0 t_{holdup}}{V_0{}^2 - V_{0\_min}{}^2} \; ; C_{out} \geq \frac{P_0}{2V_0 \pi f_{line} V_{ripple}} \qquad (2)$$

Four capacitors with the rating of 450V, 390µF are used in parallel on the board to assist the user in determining the C_{out} value.

For the input side filter, a differential mode inductor with direct current resistance (DCR) of 2.8 mΩ from Coilcraft Inc. (P/N: AGP4233-473ME) and a common mode inductor with an impedance of 160 Ω @ 100 MHz, 75 A (DCR = 0.3 mΩ) from Laird Technologies (P/N: CM5441Z101B-10) have been used.

Estimated efficiency of Wolfspeed's CRD-02AD065N reference design board at 230 VAC is listed in Table 3.

Table 3: Estimated Efficiency of Wolfspeed's CRD-02AD065N Reference Design Board at 230 VAC

Components	Watts 100% Load	Watts 50% Load
MOSFET (conduction loss)	6.01	1.57
MOSFET (switching loss-Rg=10)	7.0	6.03
Diode	8	3.4
Main inductor (300 µH)	7	3.9

Components	Watts 100% Load	Watts 50% Load
Differential mode inductor	1.1	.856
Common mode inductor	1	.8
Sense resistor	74	.185
Total (Losses)	30.85	16.741
Efficiency	98.48%	98.35%

6. Totem-Pole PFC with Traditional Analog PFC Controller

A traditional analog PFC controller from Infineon Technologies AG (P/N: ICE3PCS01G) has been selected for Wolfspeed's CRD-02AD065N reference design board. ICE3PCS01G is a 14-pin wide input range controller for active PFC converters. If "D" is the duty cycle of traditional PFC design then the pulse width modulation (PWM) signal of the totem-pole PFC design is as shown in Table 4.

Table 4: Duty Cycle of PWM Signal During Positive and Negative Half Cycles

PWM	Top MOSFET (S1)	Bottom MOSFET(S2)
Positive Half Cycle	1-D	D
Negative Half Cycle	D	1-D

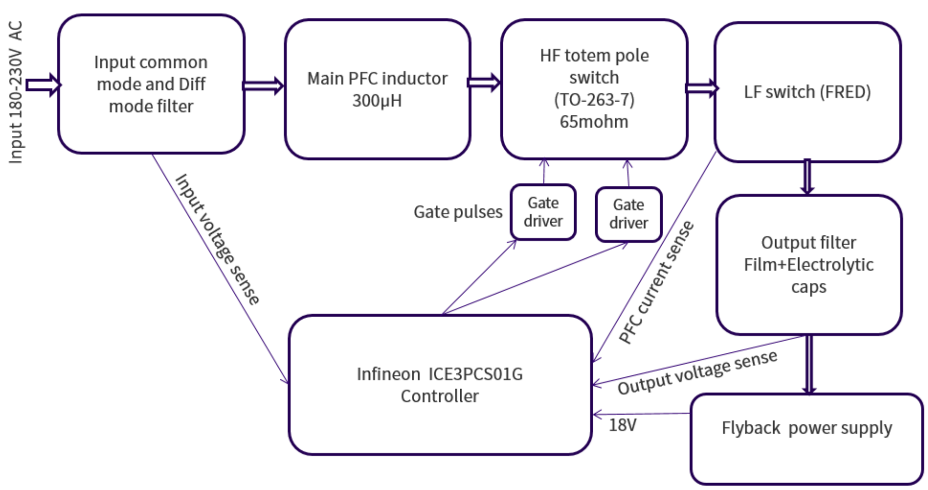


Figure 6: Block diagram Wolfspeed's CRD-02AD065N reference design board

6.1 Generating PWM for the Top and the Bottom MOSFET

An offset of 1.6V has been added to the grid AC voltage sense by using opamp U2 and then it is compared with 1.6V from opamp U3 to get the I_GRID_V_ZERO signal. To avoid false triggering of the comparator, a hysteresis has been added by using R39, R35, R36, R46, D4 and C20 as shown in Figure 7.

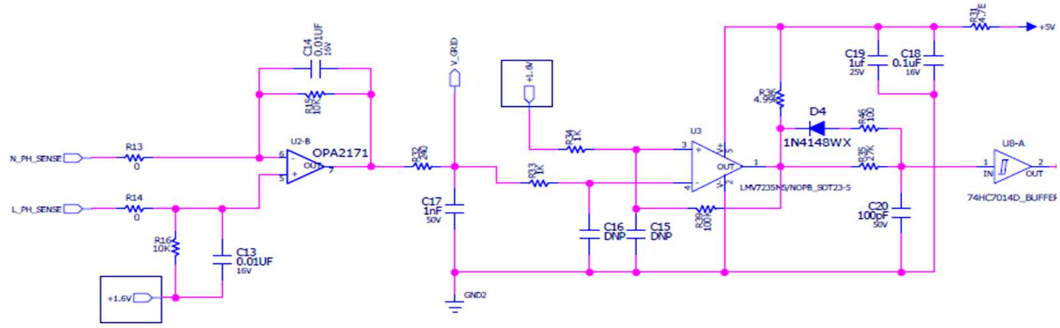


Figure 7: Schematic of AC voltage zero crossing detection circuit

The PWM output signal GATE from ST Microelectronics rectifier (P/N: STTH30L06C) and the I_GRID_V_ZERO signal are set to be inverted by using U5A and U5B respectively to generate the signal I_GATE and GRID_V_ZERO as shown in Figure 36.

Bottom MOSFET (S2): During the positive half cycle, the input signal GATE should be turned ON and for the negative half cycle, the input signal I_GATE should be turned ON. In this arrangement, input signals of GATE and GRID_V_ZERO are fed into AND gate U6B while input signals of I_GATE and I_GRID_V_ZERO are fed into AND gate U6C. Outputs of U6B and U6C are fed into XOR gate U4A to generate a PWM signal for Wolfspeed's SiC MOSFET S2. R30, C33 and D2 are used for generating the dead band as shown in Figure 8.

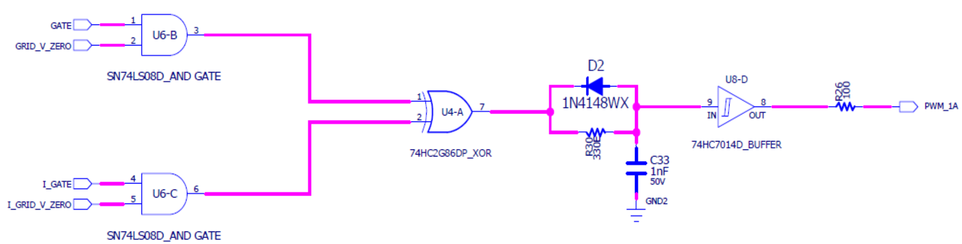


Figure 8: Schematic of PWM signal generator for the bottom MOSFET (S2)

Top MOSFET (S1): During the positive half cycle, the input signal I_GATE should be turned ON and for the negative half cycle, the input signal GATE should be turned ON. In this arrangement, input signals of I_GATE and GRID_V_ZERO are fed into AND gate U6D while input signals of GATE and I_GRID_V_ZERO are fed into AND gate U6E. Outputs of U6D and U6E are fed into XOR gate U4B to generate a PWM signal for Wolfspeed's SiC MOSFET S1. R19, C34 and D1 are used for generating dead band as shown in Figure 9.

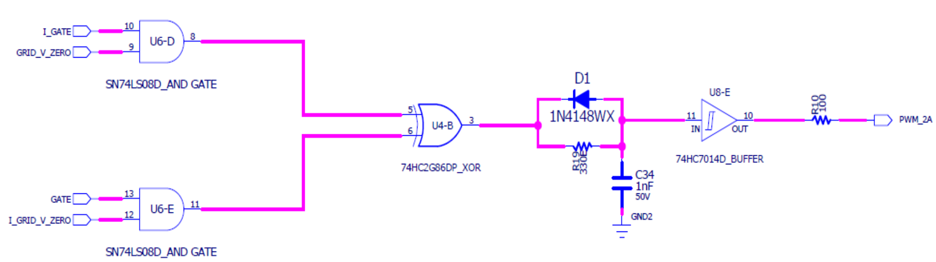


Figure 9: Schematic of PWM signal generator for the top MOSFET (S1)

6.2 Methods of Current Sensing:

For the average current mode control method, inductor average current is required for the current loop. For conventional PFC circuits, inductor current sensing can be achieved by using a shunt resistor at the return path of inductor current, as shown in Figure 10.

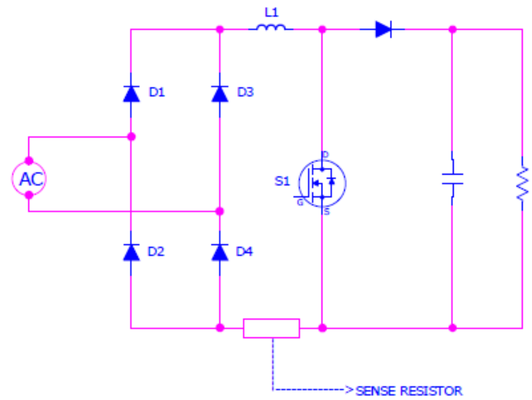


Figure 10: Current sensing method of traditional PFC design

Another method of current sensing is to use a differential mode amplifier (as shown in Figure 11a). However, the PF may be hurt because of the current sensing noise (since the current sensing voltage should be low to minimize the power loss), and the cost of parts for this method are higher than the costs for a shunt resistor current sensing solution.

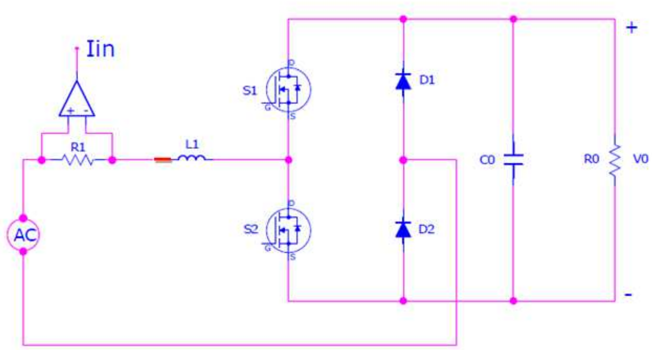


Figure 11. a: Differential current sensing

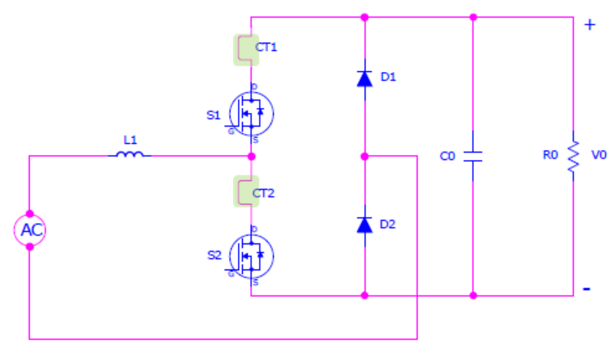


Figure 11. b: Current transformer sensing

Alternatively, the inductor current can be reconstructed by using a MOSFET current. Due to the different conduction path of the inductor current, a total of two current transformers (CT1 & CT2) are required for the current sensing. Figure 11b shows the position of the required current transformers. The input current can be reconstructed as the sum of the three sensed currents. Cost, effect of magnetizing current and size are limiting factors for this approach.

A better cost-effective approach is followed in Wolfspeed's CRD-02AD065N reference design board (as shown in Figure 12). During the positive half cycle, the voltage drop across the current sense resistor CS1 will give the current sense signal and during the negative half cycle, the voltage drop across the current sense resistor CS2 will give the current sense signal. In this approach (and unlike the current transformer (CT) approach), there is no need to rectify current sense signal. 8mΩ current sense resistors (CS1 and CS2) have been selected for this application.

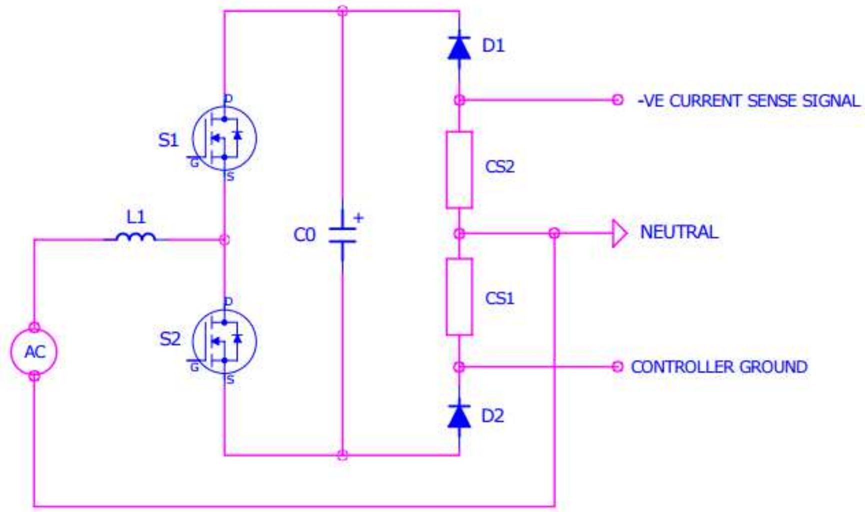


Figure 11: Proposed low cost current sensing method for Wolfspeed's CRD-02AD065N reference design board

7. Current Distortion Near Input Voltage Zero Crossing

The line current in single-phase PFC topology is distorted at the zero-crossing point of the input AC voltage. This distortion happens due to the bandwidth and the dynamic response of the general proportional integral (PI) current controller. This distortion degrades certain line current quality characteristics, such as the THD and the PF.

There are two primary reasons for this distortion. The first reason is the dynamic response of the PI controller. The bandwidth of the PI current controller causes a slow dynamic response, which further generates an error in the PI controller, especially at the zero-crossing point. The second reason is the discontinuous conduction mode (DCM) operation of the PFC converter near the zero-crossing point of the AC input voltage. During the DCM interval, line current cannot follow the reference current, which results in line current distortion.

To deal with line current distortion, a DC offset internal reference (Vref) of 8mV generated from the main output by using resistors R20 and R23 is added to the actual current signal (Isense). Figure 13a and Figure 13b show the waveforms of the input current signal before and after adding current reference offset. After adding current reference offset, the flat spot at the zero-crossing goes away and the THD is reduced to 3.3 % as compared to 9.18%.

The DC offset value also depends on the value of load and the inductance, so a proper value which will satisfy the THD requirement for all load conditions needs to be chosen.

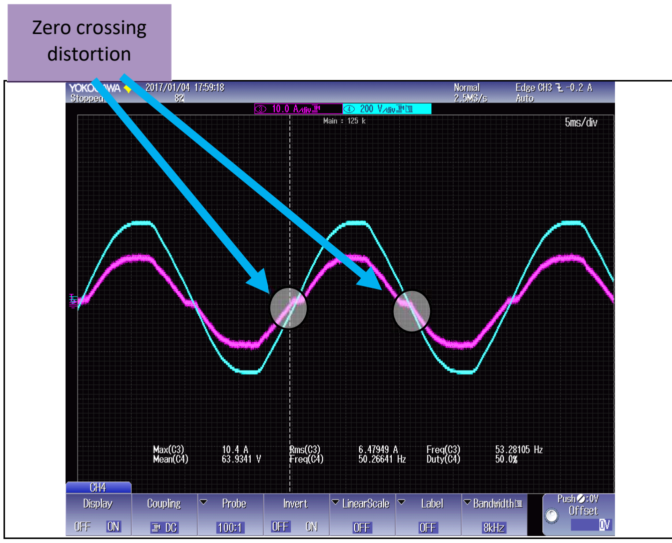


Figure 13. a: Zero crossing distortion in the current waveform before compensation

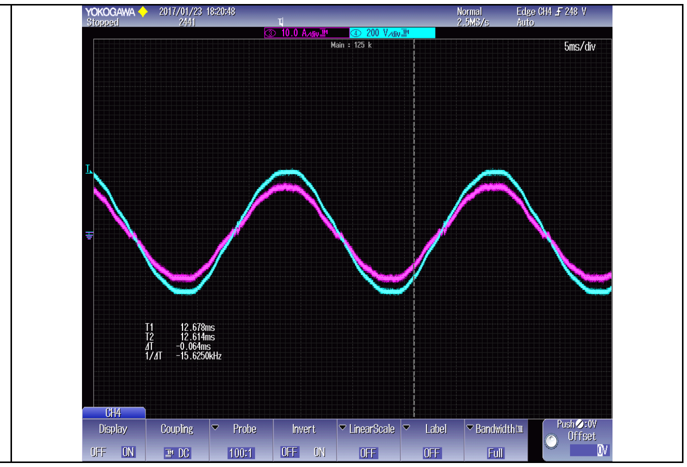


Figure 13. b: Zero crossing distortion in the current waveform after compensation

8. AUX Power Supply

The auxiliary (AUX) power supply is designed with an Infineon Technologies AG (P/N: ICE2QR2280Z) Quasi-Resonant PWM Controller with an integrated 800 V CoolMOS® MOSFET as shown in Figure 14.

AUX power supply generates two isolated output voltages, +18 V_1 and +18 V_2. The second output (+18 V_2) is used to power up the controller and the first output (+18 V_1) is used to drive the bottom MOSFET (S1). To drive the top MOSFET (S2), a separate dc-dc converter from MORNSUN Guangzhou Science & Technology Co. (P/N: QA1515R2) is used.

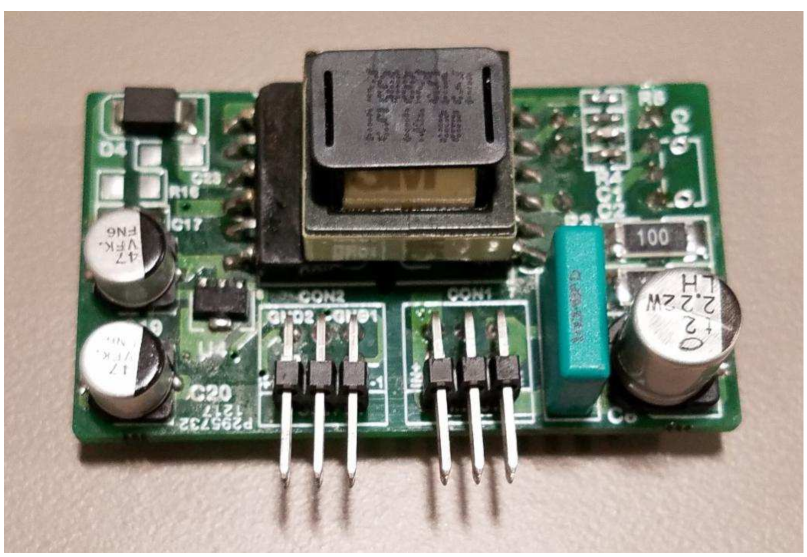


Figure 12: Auxiliary power supply board of Wolfspeed's CRD-02AD065N reference design board

9. Test Instructions

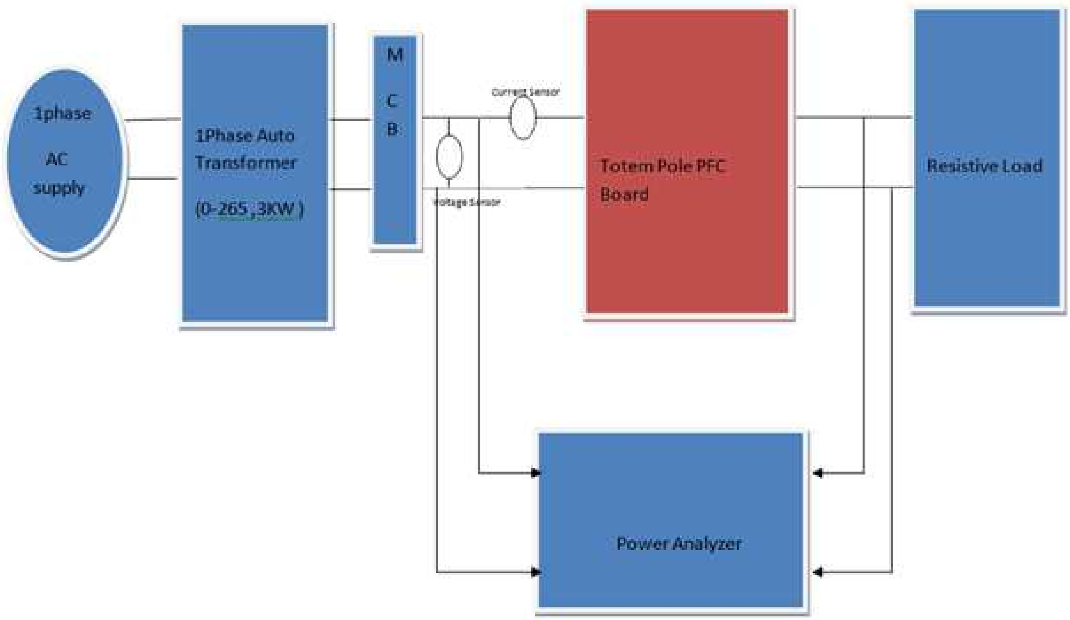


Figure 13: Test setup of Wolfspeed's CRD-02AD065N reference design board

1. Visually check the power board, controller board and fly back board for any damage of the components or board itself.
2. Insert the controller card into the connector (J2) of the power board. The connector of the controller card should face the power board as shown in Figure 16. The controller card should be on the top of the marking of "Controller Board".

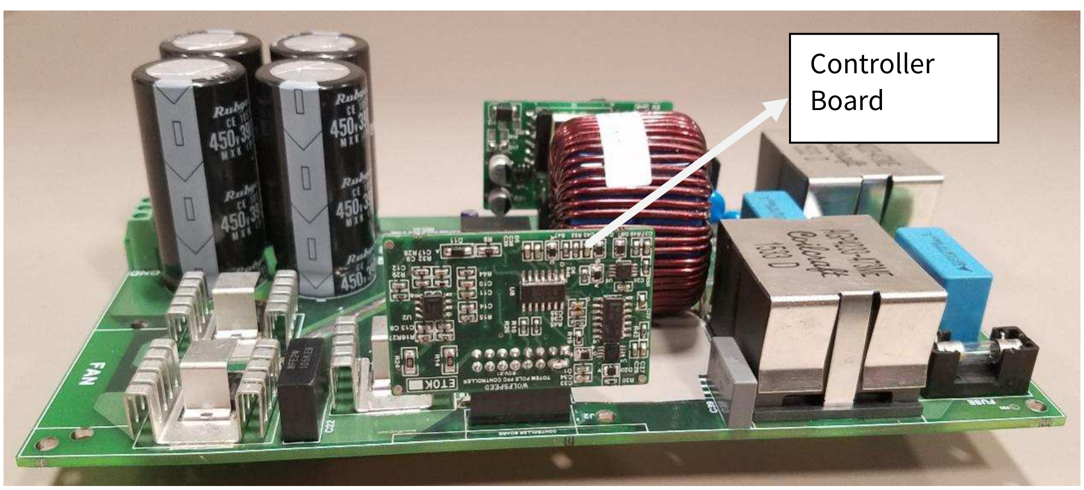


Figure 14: Controller board location on Wolfspeed's CRD-02AD065N reference design board

3. Insert the fly back board into the connector (J1 and J3) of the power board. The connector of the fly back board should face the power board as shown in Figure 17. The flyback card should be on the top of the marking of "AUX power supply".

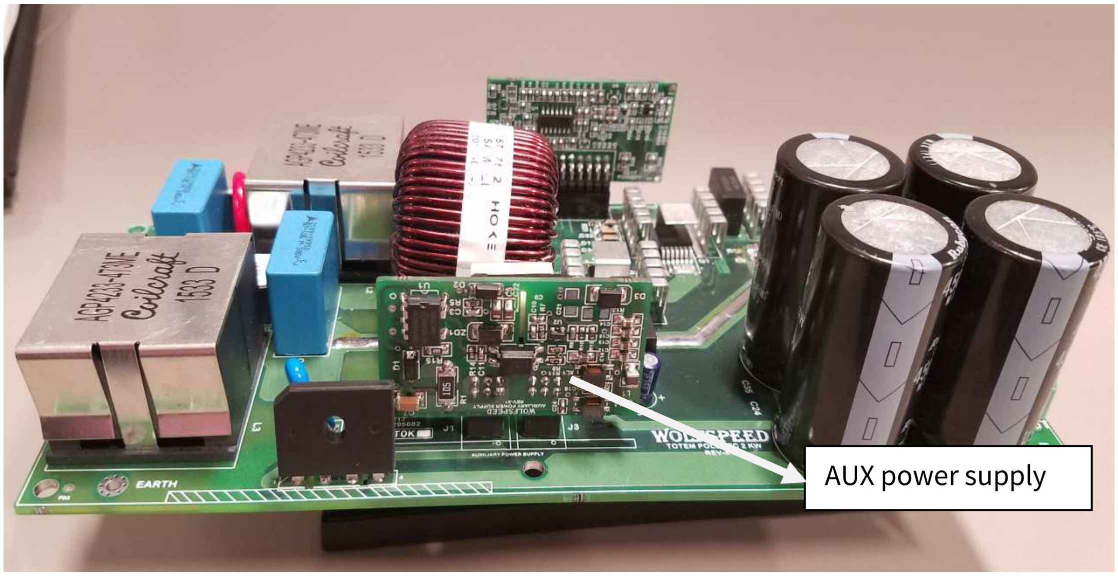


Figure 15: Auxiliary power supply board location on Wolfspeed's CRD-02AD065N reference design board

4. Check the fuse (F1) rating (min of 15 A)
5. Check if there is any shorting between the line and neutral connections of the power board with a multimeter.
6. Check if there is any shorting between the Vout and ground connections of the power board with a multimeter.
7. If step 1 to step 6 are successfully completed then connect the test set up as shown in Figure 15. Wolfspeed's CRD-02AD065N reference design board doesn't have inrush protection, so connect the input supply only with an auto transformer.
8. Make sure that the line is connected to the line terminal and the neutral is connected to the neutral terminal of Wolfspeed's CRD-02AD065N reference design board. Otherwise, the board will not work.
9. If a user is testing Wolfspeed's CRD-02AD065N reference design board for the first time, follow all sub-steps in this step number 9. If a user is testing Wolfspeed's CRD-02AD065N reference design board for a subsequent time, disregard the steps that are mentioned in step number 9 and move to step number 10.

A) Remove the gate resistors (R30 and R3) as shown in Figure 18.

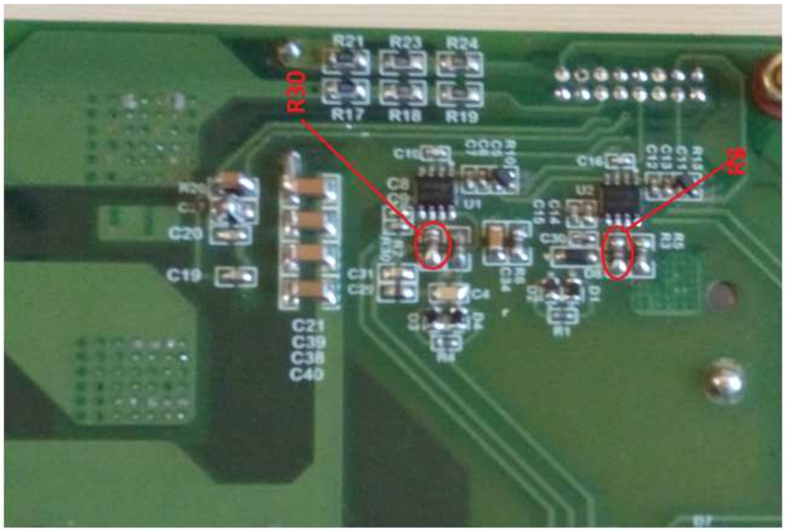


Figure 16: Location of R30 and R3 on the power board of Wolfspeed's CRD-02AD065N reference design board

B) Increase the input voltage (Vin) from zero to 100 VAC slowly and observe the input voltage and PWM bottom (PWM1A) by connecting the oscilloscope to Pin # 7 and either Pin # 2 or Pin # 4 of the power board. When input voltage is negative, the PWM should be high as shown in Figure 19.

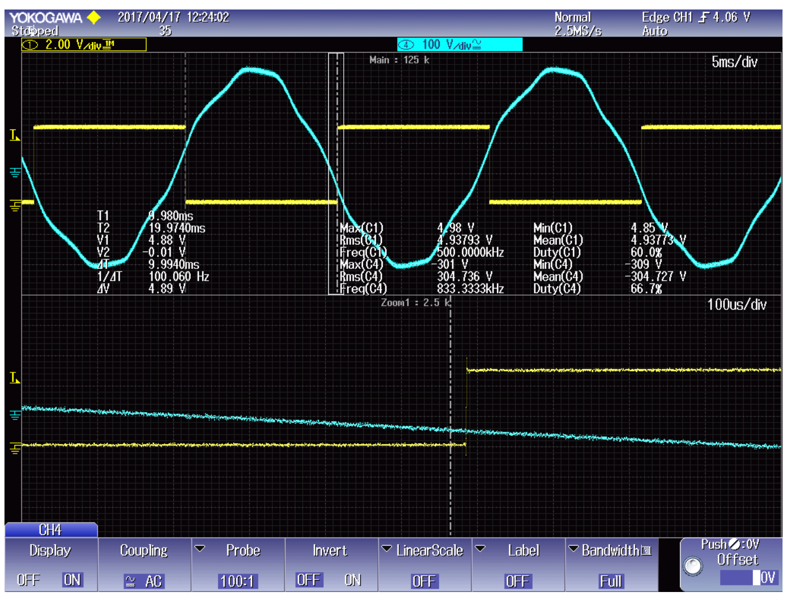


Figure 17: Input voltage (Vin) and (PWM1A) waveforms at Vin = 100 VAC

C) Observe the input voltage and PWM top (PWM2A) by connecting the oscilloscope to Pin # 5 and either Pin # 2 or Pin # 4 of the power board. When the input voltage (Vin) is positive, the PWM should be high as shown in Figure 20.

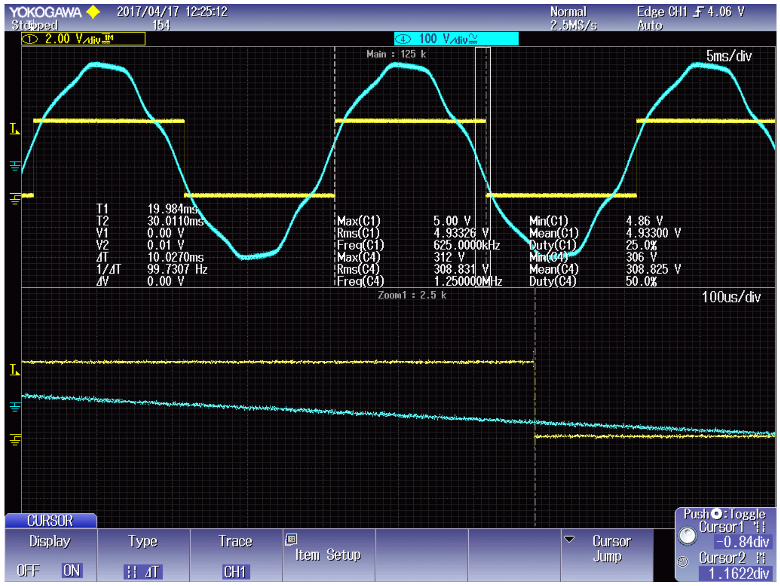


Figure 18: Input voltage (Vin) and (PWM2A) waveforms at Vin = 100 VAC

D) Observe the dead band between PWM bottom and PWM top, which should be 10 µs as shown in Figure 21.

Figure 19: Input voltage (Vin) and dead band waveforms at Vin = 100 VAC

E) If step (A) to step (D) are successfully completed then increase the input voltage (Vin) slowly to 170 VAC and observe the PWM bottom. High frequency PWM should start on or around 165 VAC (as shown in Figure 22).

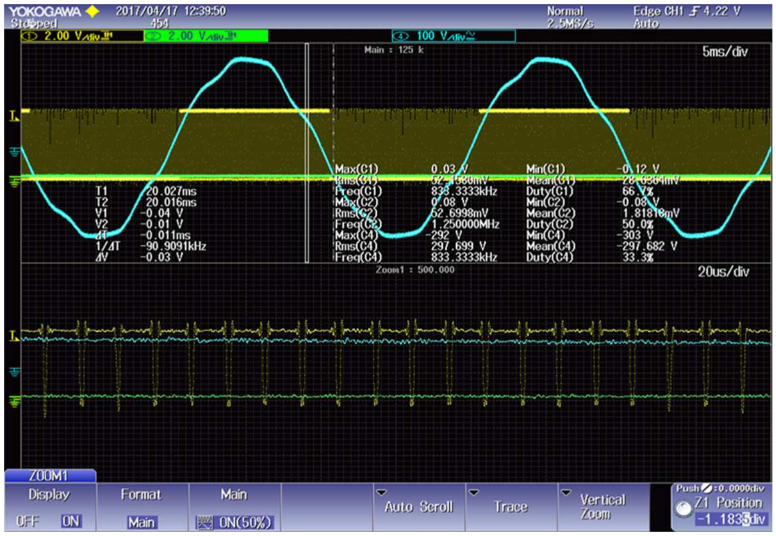


Figure 20: Input voltage (Vin) and the PWM bottom waveforms at Vin = 170 VAC

F) When the input voltage (Vin) is positive, the bottom PWM should look like a regular PFC PWM signal (i.e., when the input voltage (Vin) is near to zero, the PWM should have maximum duty cycle and at the input voltage (Vin) peak, the PWM should have a minimum duty cycle, as shown in Figure 22). The frequency of the PWM signal should be 65 kHz.

G) When the input voltage (Vin) is negative, the top PWM should look like a regular PFC PWM signal (i.e., when the input voltage (Vin) is near to zero, the PWM should have maximum duty cycle and at the negative peak of input voltage (Vin), the PWM should have a minimum duty cycle, as shown in Figure (23). The frequency of the PWM signal should be 65 kHz.

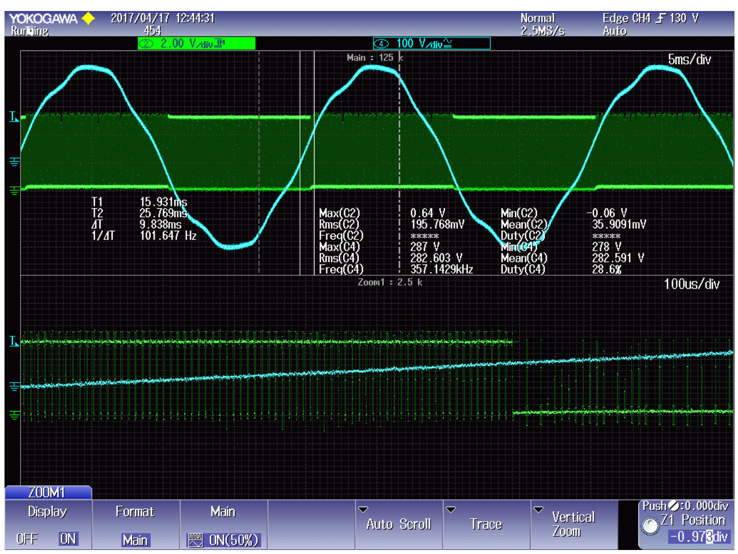


Figure 21: Input voltage (Vin) and the PWM top waveforms at Vin = 170 VAC

H) Observe the dead time between top and bottom PWM signals, which should be 270ns as shown in Figure 24.

I) Increase the input voltage to 230 VAC. If step (A) to step (H) are successfully completed then turn the main AC input power OFF. Solder back the gate resistors (R30 & R3) into their original positions.

J) Place a cooling fan with a minimum air flow of 30 cubic feet per minute (CFM) in a position facing Wolfspeed's SiC MOSFETs heat sink.

10. Connect a 400 W load to the output of Wolfspeed's CRD-02AD065N reference design board and increase the input voltage (Vin) up to 230 VAC. At 165 VAC, the high frequency gate pulse begins and the PFC circuit starts working. Increase the load up to 2.2 KW and observe the input current waveform and the temperature of Wolfspeed's SiC MOSFETs.

Figure 22: Deadtime between the top and the bottom PWM signals

11. To turn OFF Wolfspeed's CRD-02AD065N reference design board, reduce the input AC voltage (Vin) to zero and turn OFF any external switch or miniature circuit breaker that is used with this board. Next, disconnect the load and let capacitors C24, C25, C35 and C36 fully discharge.

10. Test Results

10.1 Efficiency

Efficiency of Wolfspeed's CRD-02AD065N reference design board was tested under various operating conditions. At (Vin) = 230 VAC and switching frequency (Fsw) = 64 kHz, peak efficiency achieved by the totem-pole topology was > 98.5 % as shown in Figure 25, Figure 26, and Figure 27**.**

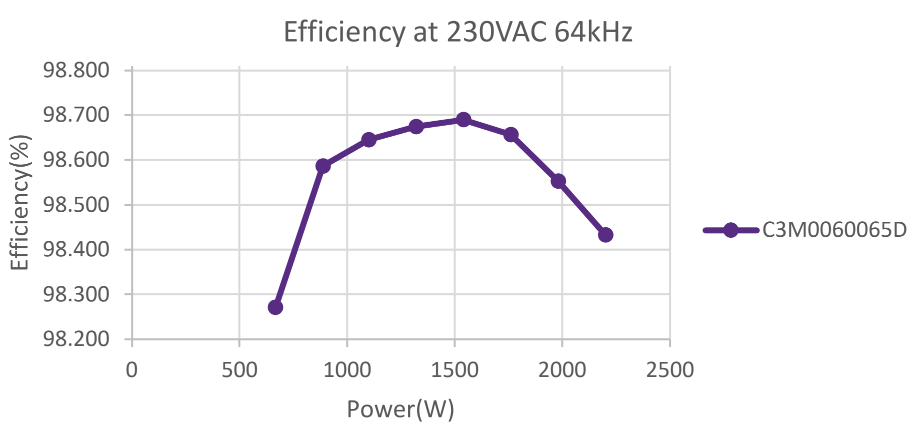


Figure 23: Efficiency data at 230 VAC, 64 kHz (TO-247-3 vision)

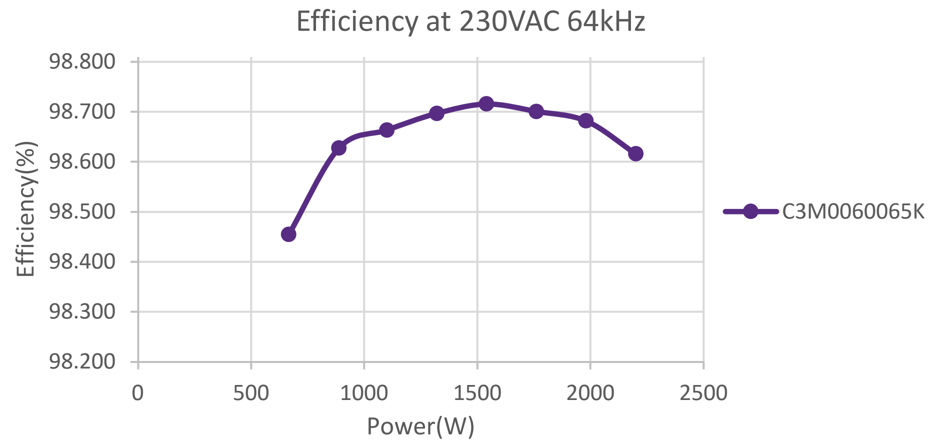


Figure 24: Efficiency data at 230 VAC, 64 kHz (TO-247-4 vision)

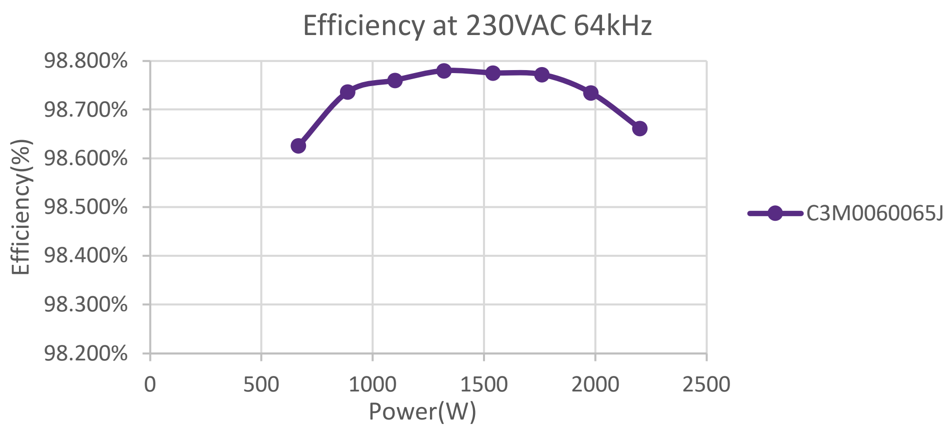


Figure 25: Efficiency data at 230 VAC, 64 kHz (TO-263-7 vision)

10.2 THD Measurements

THD performance data of Wolfspeed's CRD-02AD065N reference design board was taken at 230 VAC. During both operating conditions, THD was < 5% as shown in Figure 28, Figure 29 and Figure 30.

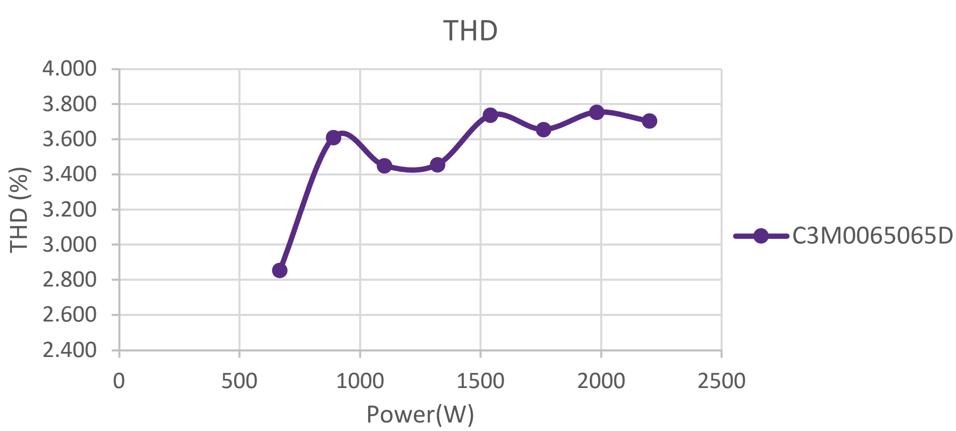


Figure 26: THD data at 230 VAC, 64 kHz (TO-247-3 vision)

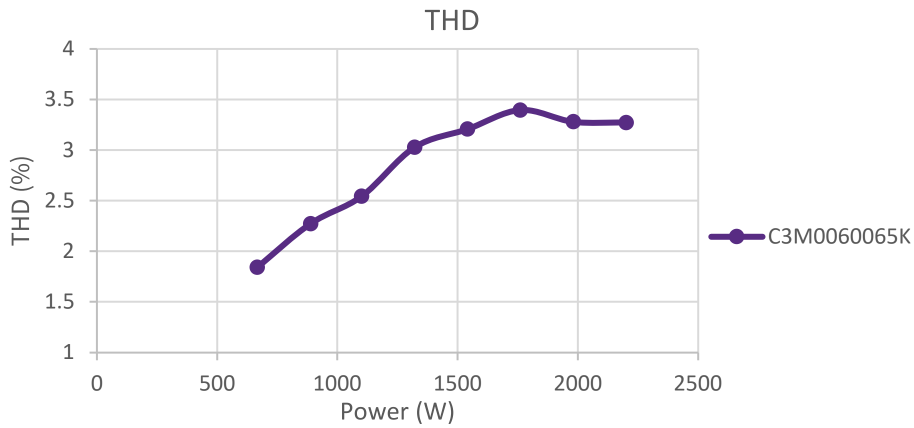


Figure 27: THD data at 230 VAC, 64 kHz (TO-247-4 vision)

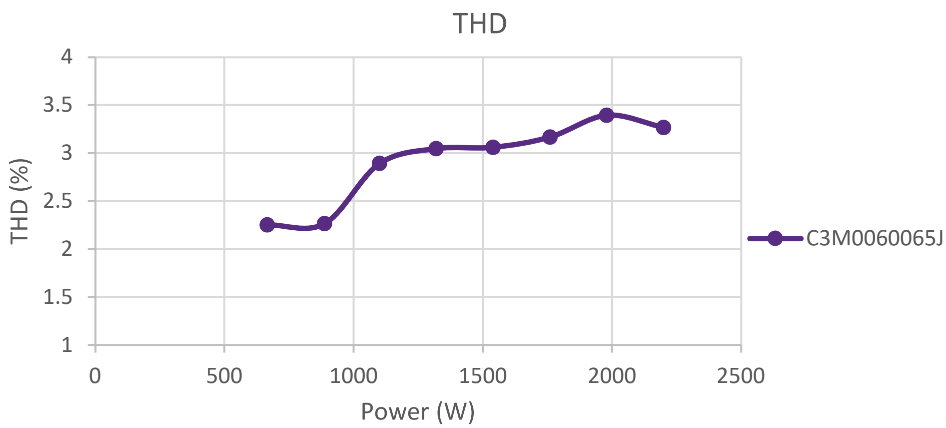
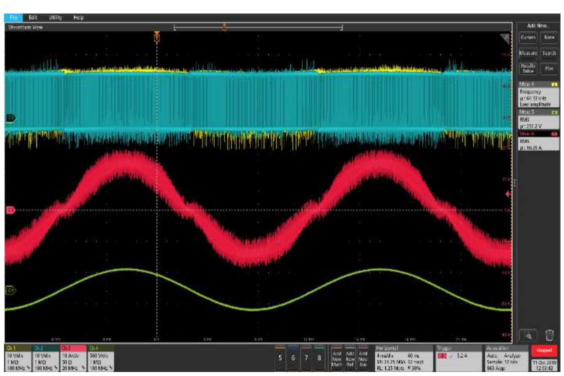


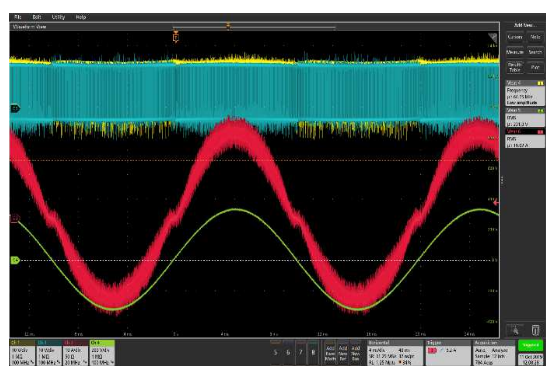
Figure 28: THD data at 230 VAC, 64 kHz (TO-263-7 vision)

10.3 Inductor Current and Input Voltage Waveforms

Performance of Wolfspeed's CRD-02AD065N reference design board based totem-pole PFC configuration can also be evaluated by observing the choke current (red color) and input voltage (green color) waveforms at various load conditions (as shown in Figure 31). Both waveforms are without any distortion and in phase with each other.



230 VAC 1100 W

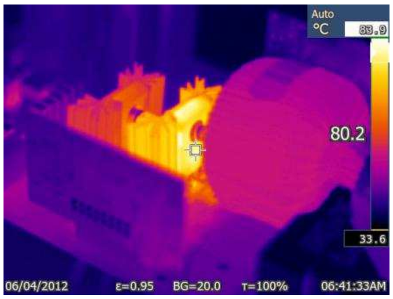


230 VAC 2200 W

Figure 29: Input current and input voltage waveform at various load conditions

10.4 Thermal Measurements

Thermal measurements of Wolfspeed’s SiC MOSFETs were taken at various line voltages and load conditions. These measurements were well below the rated temperature range as shown in Figure 32.



TO-247-3 vision

TO-247-4 vision

TO-263-7 vision

Figure 30: Thermal images of Wolfspeed’s SiC MOSFETs for three visions at 230 VAC, 2.2 kW

11. Schematic Drawings, BOM, and PCB Layout of 3Pins

For three visions, the Schematic, BOM and PCB layout are the same of AUX Power Supply Board and Control Board.

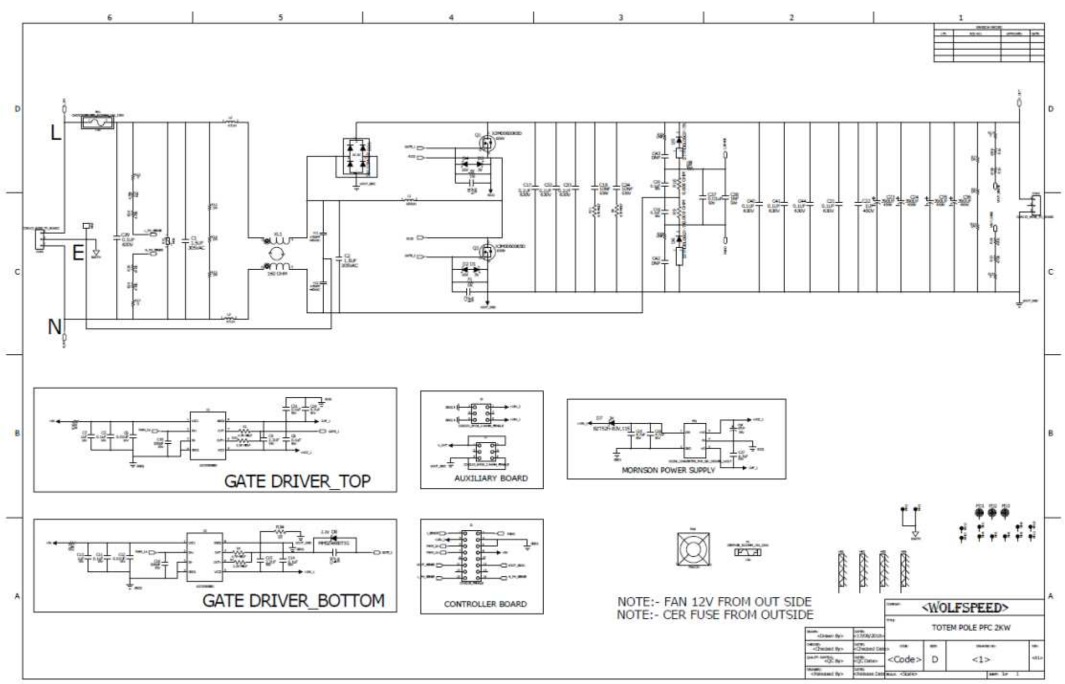


Figure 31: Power board schematic design board of TO-247 vision

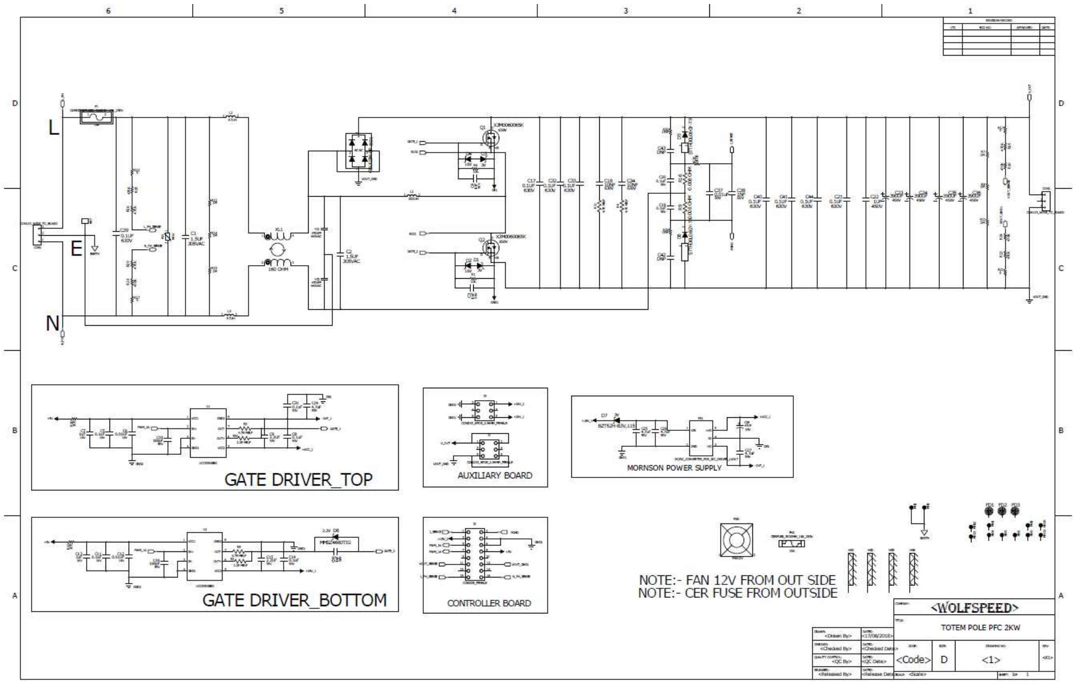


Figure 32: Power board schematic design board of TO-247-4 vision

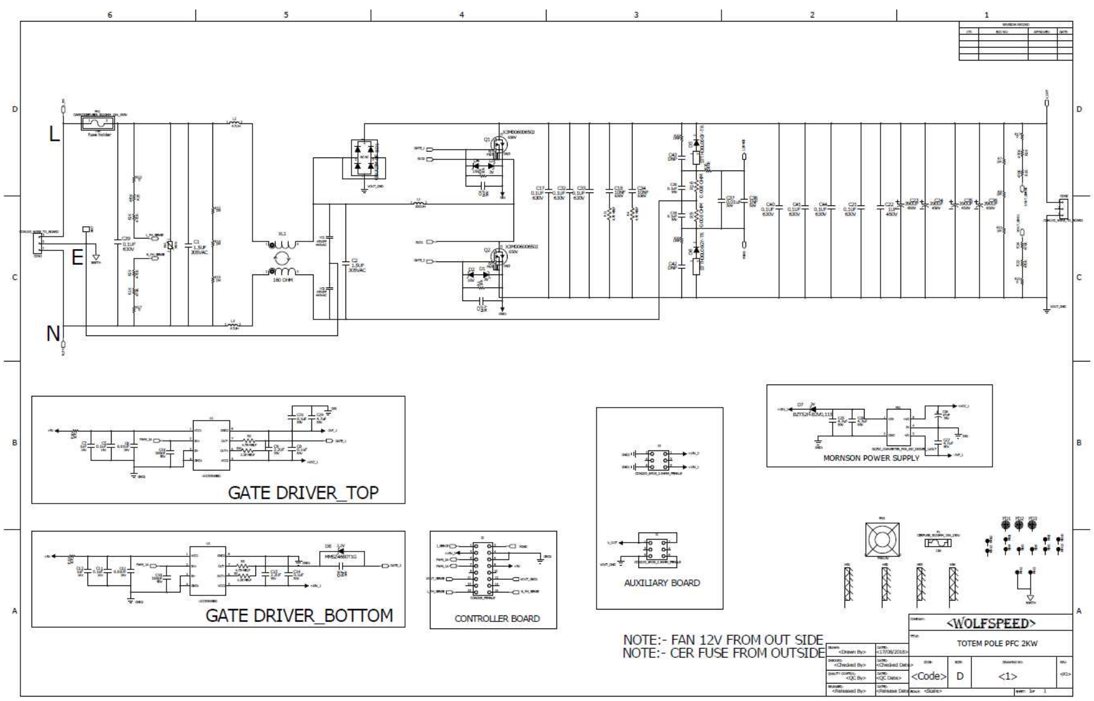


Figure 33: Power board schematic design board of TO-263-7 vision

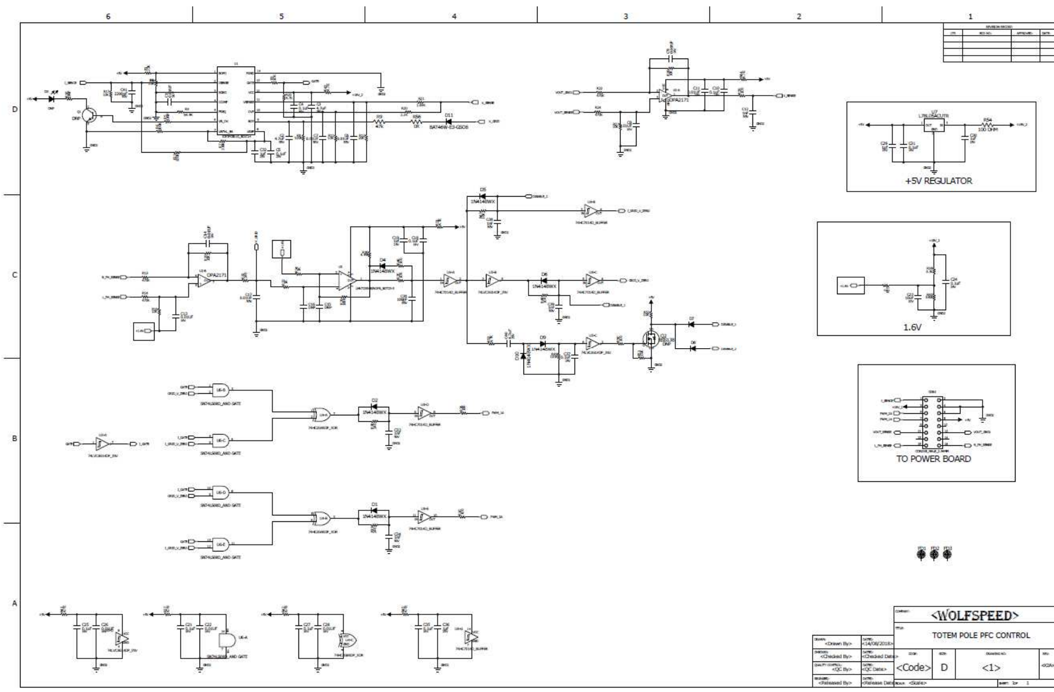


Figure 34: Controller board schematic design board of TO-247 vision

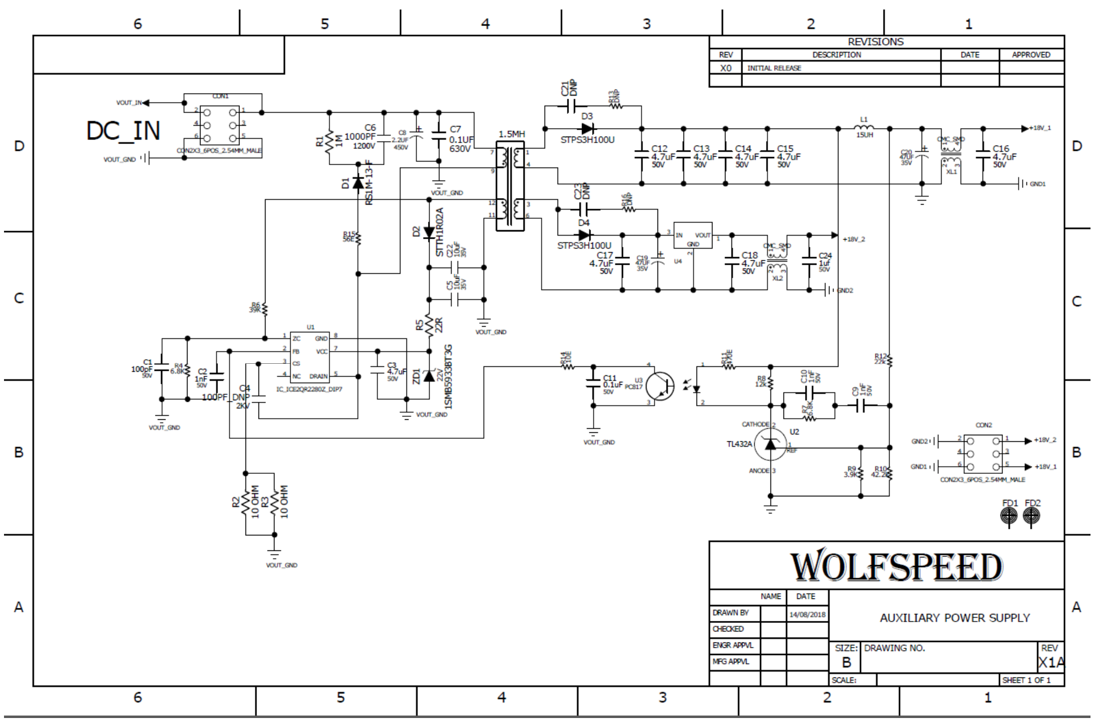


Figure 35: AUX power supply board schematic design board of TO-247 vision

Table 5: Power Board BOM of TO-247 Vision

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	BD1	BRIDGERECT SINGLE PHASE 1000 V 15 A TH	MICRO COMM.	GBU15M-BPMS	TH HOLE
2	C6 C12	CAP CER 0.01 UF 10% 16 V X7R 0603	TDK CORP.	C1608X7RIC103K	CAP0603
2	C5 C11	CAP 0.1 uF 10% 16 V X7R 0603	KEMET	C0603X104K4RACTU	CAP0603
2	C8 C14	CAP CER 0.1 uF 10% 50 V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
2	C7 C13	CAP CER 1.0 uF 10% 16 V X5R 0603	KEMET	C0603C105K4PACTU	CAP0603
1	C30	CAP CER 1 uf 10% 50 V X7R 0805	MURATA	GCM21BR71H105KA03L	CAP0805
2	C9 C15	CAP0603 2.2 UF 35 V X5R	MURATA	GRM188R6YA225KA12D	CAP0603
3	C19-20 C31	CAP CER 0.1 uF 10% 50 V X7R 0805	TDK	CEU4J2X7R1H104K125 AE	CAP0805
2	C3-4	CAP CER 1nF 10% 50 V X7R 0805	MURATA	C0805C102K5RACTU	CAP0805
4	C25-27 C29	CAP CER 4.7uF 10% 50 V X7R 0805	MURATA	GRM21BR61H475ME51 L	CAP0805
1	C37	CAP CER 0.01 uF 10% 50 V X7R 1206	TDK	C1206C103K5RACTU	CAP1206
2	C18 C34	CAP CER 10000PF 10% 630 V X7R 1206	MURATA	GRM31BR72J103KW01L	CAP1206
1	C38	CAP CER 1NF 10% 50 V X7R 1206	TDK	C1206C102K5RACTU	CAP1206
2	C42-43	CAP1206 DNP	KEMET	DNP	CAP1206
7	C17 C21 C32-33 C40-41 C44	CAP CER 1808 0.1 UF 630 V X7R	KEMET	C1808C104KBRACTU	CAP1808
4	C23-24 C35-36	CAP ELECT 390 uF 450 V DC RADIAL	RUBYCON	450MXK390MEFCSN25X 50	TH HOLE
1	C39	CAPFILM 0.1 UF 10% 630 V RADIAL	KEMET	R71P131004030K	CAPFILM_1 8 MMX5 MM P=15 MM

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
2	C1-2	FILM CAPACITOR 1.5 UF 305 VAC	EPCOS	B32923C3155M	CAPFILM_2 6.5X12 MM P-22.5 MM
1	C22	FILM CAPACITOR 1 UF 450 V 10% PP RADIAL	PANASONIC	ECW-FE2W105K	CAPFILM_1 7.5X7 MM P-7.5 MM
2	YC1-2	CAP CERMIC 4700PF 440 VAC RADIAL	KEMET	C947U472MZVDBA7317	DIA 11 MM P-7.50 MM
1	C28	CAP 47 UF 35 V ELECT PW RADIAL	PANASONIC	ECA-1VM470I	5/2.5 MM TH
1	F1	CARTRIDGE FUSES 5X 20 MM 250 V 15 A	LITTLEFUSE	0215015.MXP	CERAMIC FUSE 5X20 MM
2	CON1-2	3 POS. WIRE TO BOARD 10 A	AMPHENOL FCI	20020316-H031B01LF	TH HOLE
2	J1 J3	6 POS.FEMALE HEADER 2.54 MM TH	SULLINS	PPTC032LFBN	6POS FEMELE
1	J2	CON2X8 FEMALE 2.5 MM PITCH	SULLINS	PPTC082LFBN-RC	CON2X8
1	PS1	DC/DC Converter for SiC Driver low voltage	MORNSON	QA15115R2	SIP PACK
2	C10 C16	CAP CER 100pF 10% 50V X7R 0603	VISHAY/VITRAM ON	VJ0603Y101KXACW1BC	CAP0603
2	D2 D4	DIODE BZX-384-C16,115 ZENER 16 V	NXP Semiconductor	BZX384-C16,115	SOD-323
2	D1 D3	DIODE BZX-384-C3V0,115 ZENER 3 V	NXP SEMI	BZX-384-C3V0,115	SOD-323
2	D5-6	DIODE STANDARD 600 V 30 A SMD D2PAK	ST MICRO	STTH30L06GY-TR	D2PAK
1	D8	DIODE ZENER 2.2 V 500 MW SOD-123	ON Semiconductor	MMSZ4680T1G	SOD-123
1	D7	DIODE ZENER 3 V SOD-123	Nexperia USA Inc.	BZT52H-B3V0,115	SOD-123

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	XL1	EMI 2 LINE COOMON MODE CHOKE TH 160 OHM@100 MHZ 75 A	LAIRD	CM5441Z101B-10	TH HOLE
2	HS1-2	HEAT SINK SMD FOR D2PAK	AAVIID	7109DG	SMD_D2PAK
2	HS3-HS4	vert heat sink	fischer ele	FK 245 MI 247 H	vert heat sink
2	U1-2	Single Channel IGBT Gate Driver IC SOIC-8	texas ins.	UCC5350SBD	SOIC8
1	L1	INDUCTOR	INFANTRON	AOP-157075-2-219	TORROID
2	L2-3	INDUCTOR TOROID 47UH 16 A	COILCRAFT	AGP4233-473ME/CPQ4228-470M	TH HOLE
2	Q1-2	MOSFET N-CHAN 650 V TO-247-3	WOLFSPEED/ WOLFSPEED	C3M0060065D	TO-247-3
1	RV1	MOV VERISTOR510 V 10KA DISK 20MM	EPCOS	B72220S2321K101	TH HOLE
2	R10 R13	RES 10.0 OHM 0.1% 1/10 W 0603	Vishay/Dale	TNPW060310R0BEEA	RES_0603
1	R1	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R4	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R34	RES0805 1E 5% 1/10 W 0805	Yageo	RC0805FR-071RL	RES0805
4	R17 R21-22 R27	RES 0.0 OHM 1/10 W 5% 1206	PANASONIC	ERJ-8GEY0R00V	RES1206
6	R7-8 R11-12 R14-15	RES 1.0M 1% 1/4 W 1206	VISHAY/DALE	CRCW12061M00FKEA	RES1206
1	R20	RES1206 200E 1% 1/10 W	PANASONIC	ERJ-8GEYJ201V	RES1206
8	R18-19 R23-26 R28-29	RES1206 470 K 1%1/4 W	PANASONIC	ERJ-8ENF4703V	RES1206
2	R32-33	RES DNP 1% 1W 1206	DNP	DNP	RES1206
2	R9 R16	RES2512 0.008 OHM 3 W 1%	Panasonic	P17096CT	RES2512
4	R2 R5 R6 R31	SURFACE MOUNT RESISTOR 4.7E MELF	YAGEO	MMA02040C4708FB300	3.5X1.4 MM
2	R3 R30	RES MELF 2.2E 1/4W 1%	VISHAY	MMA02040C2208FB300	RES1206

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	FAN	DC12V FAN 40X20 MM 0.15 A	SANYO	109P0412D601	DC12V FAN
1	FH1	CARTRIDGE FUSES 5X20 MM 250 V 15 A HOLDER	MULTICOMP	MC000830	FUSE HOLDER 5X20 MM

Table 6: Power Board BOM of TO-247-4 Vision

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	BD1	BRIDGERECT SINGLE PHASE 1000 V 15 A TH	MICRO COMM.	GBU15M-BPMS	TH HOLE
2	C6 C12	CAP CER 0.01UF 10% 16 V X7R 0603	TDK CORP.	C1608X7RIC103K	CAP0603
2	C5 C11	CAP 0.1 uF 10% 16 V X7R 0603	KEMET	C0603X104K4RACTU	CAP0603
2	C8 C14	CAP CER 0.1 uF 10% 50 V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
2	C7 C13	CAP CER 1.0 uF 10% 16 V X5R 0603	KEMET	C0603C105K4PACTU	CAP0603
1	C30	CAP CER 1 uf 10% 50 V X7R 0805	MURATA	GCM21BR71H105KA03L	CAP0805
2	C9 C15	CAP0603 2.2 UF 35 V X5R	MURATA	GRM188R6YA225KA12D	CAP0603
3	C19-20 C31	CAP CER 0.1 uF 10% 50 V X7R 0805	TDK	CEU4J2X7R1H104K125AE	CAP0805
2	C3-4	CAP CER 1nF 10% 50 V X7R 0805	MURATA	C0805C102K5RACTU	CAP0805
4	C25-27 C29	CAP CER 4.7uF 10% 50 V X7R 0805	MURATA	GRM21BR61H475ME51L	CAP0805
1	C37	CAP CER 0.01uF 10% 50 V X7R 1206	TDK	C1206C103K5RACTU	CAP1206
2	C18 C34	CAP CER 10000PF 10% 630V X7R 1206	MURATA	GRM31BR72J103KW01L	CAP1206
1	C38	CAP CER 1NF 10% 50 V X7R 1206	TDK	C1206C102K5RACTU	CAP1206
2	C42-43	CAP1206 DNP	KEMET	DNP	CAP1206
7	C17 C21 C32-33 C40-41 C44	CAP CER 1808 0.1 UF 630 V X7R	KEMET	C1808C104KBRACTU	CAP1808

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
4	C23-24 C35-36	CAP ELECT 390 uF 450 V DC RADIAL	RUBYCON	450MXK390MEFCS N25X50	TH HOLE
1	C39	CAPFILM 0.1 UF 10% 630 V RADIAL	KEMET	R71P131004030K	CAPFILM_18MMX 5 MM P=15 MM
2	C1-2	FILM CAPACITOR 1.5 UF 305 VAC	EPCOS	B32923C3155M	CAPFILM_26.5X12 MM P-22.5 MM
1	C22	FILM CAPACITOR 1UF 450 V 10% PP RADIAL	PANASONIC	ECW-FE2W105K	CAPFILM_17.5X7 MM P-7.5 MM
2	YC1-2	CAP CERMIC 4700PF 440VAC RADIAL	KEMET	C947U472MZVDBA 7317	DIA 11MM P-7.50MM
1	C28	CAP 47UF 35V ELECT PW RADIAL	PANASONIC	ECA-1VM470I	5/2.5MM TH
1	F1	CARTRIDGE FUSES 5X20 MM 250 V 15 A	LITTLEFUSE	0215015.MXP	CERAMIC FUSE 5X20 MM
2	CON1-2	3 POS. WIRE TO BOARD 10 A	AMPHENOL FCI	20020316-H031B01LF	TH HOLE
2	J1 J3	6 POS.FEMALE HEADER 2.54 MM TH	SULLINS	PPTC032LFBN	6POS FEMELE
1	J2	CON2X8 FEMALE 2.5MM PITCH	SULLINS	PPTC082LFBN-RC	CON2X8
1	PS1	DC/DC Converter for SiC Driver low voltage	MORNSON	QA15115R2	SIP PACK
2	C10 C16	CAP CER 100pF 10% 50 V X7R 0603	VISHAY/VITRAM ON	VJ0603Y101KXACW 1BC	CAP0603
2	D2 D4	DIODE BZX-384-C16,115 ZENER 16 V	NXP Semiconductor	BZX384-C16,115	SOD-323
2	D1 D3	DIODE BZX-384-C3V0,115 ZENER 3 V	NXP SEMI	BZX-384-C3V0,115	SOD-323
2	D5-6	DIODE STANDARD 600V 30A SMD D2PAK	ST MICRO	STTH30L06GY-TR	D2PAK
1	D8	DIODE ZENER 2.2 V 500 MW SOD-123	ON Semiconductor	MMSZ4680T1G	SOD-123
1	D7	DIODE ZENER 3 V SOD-123	Nexperia USA Inc.	BZT52H-B3V0,115	SOD-123
1	XL1	EMI 2 LINE COOMON MODE CHOKE TH 160 OHM@100 MHZ 75 A	LAIRD	CM5441Z101B-10	TH HOLE
2	HS1-2	HEAT SINK SMD FOR D2PAK	AAVIID	7109DG	SMD_D2PAK

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
2	HS3-HS4	vert heat sink	fischer ele	FK 245 MI 247 H	vert heat sink
2	U1-2	Single Channel IGBT Gate Driver IC SOIC-8	texas ins.	UCC5350SBD	SOIC8
1	L1	INDUCTOR	INFANTRON	AOP-157075-2-219	TORROID
2	L2-3	INDUCTOR TOROID 47UH 16 A	COILCRAFT	AGP4233-473ME/CPQ4228-470M	TH HOLE
2	Q1-2	MOSFET N-CHAN 650V TO-247-4	WOLFSPEED/ WOLFSPEED	C3M0060065K	TO-247-4
1	RV1	MOV VERISTOR510 V 10 KA DISK 20 MM	EPCOS	B72220S2321K101	TH HOLE
2	R10 R13	RES 10.0 OHM 0.1% 1/10 W 0603	Vishay/Dale	TNPW060310R0BE EA	RES_0603
1	R1	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R4	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R34	RES0805 1E 5% 1/10 W 0805	Yageo	RC0805FR-071RL	RES0805
4	R17 R21-22 R27	RES 0.0 OHM 1/10 W 5% 1206	PANASONIC	ERJ-8GEY0R00V	RES1206
6	R7-8 R11-12 R14-15	RES 1.0M 1% 1/4 W 1206	VISHAY/DALE	CRCW12061M00FK EA	RES1206
1	R20	RES1206 200E 1% 1/10W	PANASONIC	ERJ-8GEYJ201V	RES1206
8	R18-19 R23-26 R28-29	RES1206 470K 1%1/4W	PANASONIC	ERJ-8ENF4703V	RES1206
2	R32-33	RES DNP 1% 1 W 1206	DNP	DNP	RES1206
2	R9 R16	RES2512 0.008 OHM 3 W 1%	Panasonic	P17096CT	RES2512
4	R2 R5 R6 R31	SURFACE MOUNT RESISTOR 4.7E MELF	YAGEO	MMA02040C4708F B300	3.5X1.4MM
2	R3 R30	RES MELF 2.2E 1/4 W 1%	VISHAY	MMA02040C2208F B300	RES1206
1	FAN	DC12 V FAN 40X20 MM 0.15 A	SANYO	109P0412D601	DC12V FAN
1	FH1	CARTRIDGE FUSES 5X20 MM 250 V 15 A HOLDER	MULTICOMP	MC000830	FUSE HOLDER 5X20 MM

Table 7: Power Board BOM of TO-263-7 Vision

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	BD1	BRIDGERECT SINGLE PHASE 1000 V 15 A TH	MICRO COMM.	GBU15M-BPMS	TH HOLE
2	C6 C12	CAP CER 0.01 UF 10% 16 V X7R 0603	TDK CORP.	C1608X7RIC103K	CAP0603
2	C5 C11	CAP 0.1 uF 10% 16 V X7R 0603	KEMET	C0603X104K4RACTU	CAP0603
2	C8 C14	CAP CER 0.1 uF 10% 50 V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
2	C7 C13	CAP CER 1.0 uF 10% 16 V X5R 0603	KEMET	C0603C105K4PACTU	CAP0603
1	C30	CAP CER 1uf 10% 50 V X7R 0805	MURATA	GCM21BR71H105KA03 L	CAP0805
2	C9 C15	CAP0603 2.2 UF 35 V X5R	MURATA	GRM188R6YA225KA12 D	CAP0603
3	C19-20 C31	CAP CER 0.1 uF 10% 50 V X7R 0805	TDK	CEU4J2X7R1H104K12 5AE	CAP0805
2	C3-4	CAP CER 1 nF 10% 50 V X7R 0805	MURATA	C0805C102K5RACTU	CAP0805
4	C25-27 C29	CAP CER 4.7 uF 10% 50 V X7R 0805	MURATA	GRM21BR61H475ME5 1L	CAP0805
1	C37	CAP CER 0.01 uF 10% 50 V X7R 1206	TDK	C1206C103K5RACTU	CAP1206
2	C18 C34	CAP CER 10000PF 10% 630 V X7R 1206	MURATA	GRM31BR72J103KW0 1L	CAP1206
1	C38	CAP CER 1NF 10% 50 V X7R 1206	TDK	C1206C102K5RACTU	CAP1206
2	C42-43	CAP1206 DNP	KEMET	DNP	CAP1206
7	C17 C21 C32-33 C40-41 C44	CAP CER 1808 0.1 UF 630 V X7R	KEMET	C1808C104KBRACTU	CAP1808
4	C23-24 C35-36	CAP ELECT 390 uF 450 V DC RADIAL	RUBYCON	450MXK390MEFCSN25 X50	TH HOLE
1	C39	CAPFILM 0.1 UF 10% 630 V RADIAL	KEMET	R71P131004030K	CAPFILM_18 MMX5 MM P=15 MM

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
2	C1-2	FILM CAPACITOR 1.5 UF 305 VAC	EPCOS	B32923C3155M	CAPFILM_26.5X12 MM P-22.5 MM
1	C22	FILM CAPACITOR 1 UF 450 V 10% PP RADIAL	PANASONIC	ECW-FE2W105K	CAPFILM_17.5X7 MM P-7.5 MM
2	YC1-2	CAP CERMIC 4700PF 440 VAC RADIAL	KEMET	C947U472MZVDBA7317	DIA 11 MM P-7.50 MM
1	C28	CAP 47 UF 35 V ELECT PW RADIAL	PANASONIC	ECA-1VM470I	5/2.5MM TH
1	F1	CARTRIDGE FUSES 5X20MM 250V 15A	LITTLEFUSE	0215015.MXP	CERAMIC FUSE 5X20MM
2	CON1-2	3 POS. WIRE TO BOARD 10 A	AMPHENOL FCI	20020316-H031B01LF	TH HOLE
2	J1 J3	6 POS.FEMALE HEADER 2.54 MM TH	SULLINS	PPTC032LFBN	6POS FEMELE
1	J2	CON2X8 FEMALE 2.5 MM PITCH	SULLINS	PPTC082LFBN-RC	CON2X8
1	PS1	DC/DC Converter for SiC Driver low voltage	MORNSON	QA15115R2	SIP PACK
2	C10 C16	CAP CER 100 pF 10% 50 V X7R 0603	VISHAY/VITRAMON	VJ0603Y101KXACW1BC	CAP0603
2	D2 D4	DIODE BZX-384-C16,115 ZENER 16 V	NXP Semiconductor	BZX384-C16,115	SOD-323
2	D1 D3	DIODE BZX-384-C3V0,115 ZENER 3 V	NXP SEMI	BZX-384-C3V0,115	SOD-323
2	D5-6	DIODE STANDARD 600 V 30 A SMD D2PAK	ST MICRO	STTH30L06GY-TR	D2PAK
1	D8	DIODE ZENER 2.2 V 500 MW SOD-123	ON Semiconductor	MMSZ4680T1G	SOD-123
1	D7	DIODE ZENER 3 V SOD-123	Nexperia USA Inc.	BZT52H-B3V0,115	SOD-123
1	XL1	EMI 2 LINE COOMON MODE CHOKE TH	LAIRD	CM5441Z101B-10	TH HOLE

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
		160 OHM@100 MHZ 75 A			
2	HS1-2	HEAT SINK SMD FOR D2PAK	AAVIID	7109DG	SMD_D2PAK
2	HS3-HS4	vert heat sink	fischer ele	FK 245 MI 247 H	vert heat sink
2	U1-2	Single Channel IGBT Gate Driver IC SOIC-8	texas ins.	UCC5350SBD	SOIC8
1	L1	INDUCTOR	INFANTRON	AOP-157075-2-219	TORROID
2	L2-3	INDUCTOR TOROID 47UH 16 A	COILCRAFT	AGP4233-473ME/CPQ4228-470M	TH HOLE
2	Q1-2	MOSFET N-CHAN 650 V TO-263-7	WOLFSPEED/ WOLFSPEED	C3M0060065J	TO-263-7
1	RV1	MOV VERISTOR510 V 10KA DISK 20 MM	EPCOS	B72220S2321K101	TH HOLE
2	R10 R13	RES 10.0 OHM 0.1% 1/10 W 0603	Vishay/Dale	TNPW060310R0BEEA	RES_0603
1	R1	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R4	RES 10 k 1% 1/10 W 0603	PANASONIC	ERJ-3GEYJ103V	RES0603
1	R34	RES0805 1E 5% 1/10 W 0805	Yageo	RC0805FR-071RL	RES0805
4	R17 R21-22 R27	RES 0.0 OHM 1/10 W 5% 1206	PANASONIC	ERJ-8GEY0R00V	RES1206
6	R7-8 R11-12 R14-15	RES 1.0 M 1% 1/4 W 1206	VISHAY/DALE	CRCW12061M00FKEA	RES1206
1	R20	RES1206 200E 1% 1/10 W	PANASONIC	ERJ-8GEYJ201V	RES1206
8	R18-19 R23-26 R28-29	RES1206 470 K 1%1/4 W	PANASONIC	ERJ-8ENF4703V	RES1206
2	R32-33	RES DNP 1% 1 W 1206	DNP	DNP	RES1206

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
2	R9 R16	RES2512 0.008 OHM 3 W 1%	PANASONIC	P17096CT	RES2512
4	R2 R5 R6 R31	SURFACE MOUNT RESISTOR 4.7E MELF	YAGEO	MMA02040C4708FB30 0	3.5X1.4MM
2	R3 R30	RES MELF 2.2E 1/4 W 1%	VISHAY	MMA02040C2208FB30 0	RES1206
1	FAN	DC12V FAN 40X20 MM 0.15 A	SANYO	109P0412D601	DC12V FAN
1	FH1	CARTRIDGE FUSES 5X20 MM 250 V 15 A HOLDER	MULTICOMP	MC000830	FUSE HOLDER 5X20 MM

Table 8: Controller Board BOM

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	Q2	MOSFET N-CH BSS138 220 MA SOT23	FAIRCHILD SEMI.	BSS138	SOT23
8	C8-9 C11 C13-14 C22 C26 C28	CAP CER 0.01UF 10% 16 V X7R 0603	TDK CORP.	C1608X7RIC103K	CAP0603
4	C1 C6-7 C17	CAP CER 0.01 UF 10% 50 V X7R 0603	PANASONIC	ECJ-1VB1H103K	CAP0603
6	C10 C18 C21 C25 C27 C35	CAP CER 0.1 uF 10% 16 V X7R 0603	KEMET	C0603X104K4RACTU	CAP0603
1	C31	CAP CER 0.1 uF 10% 16 V X7R 0603	KEMET	C0603X104K4RACTU	CAP0603
3	C5 C24 C37	CAP CER 0.1 uF 10% 25 V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
1	C4	CAP CER 0.1 uF 10% 50V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
1	C20	CAP CER 100 pF 10% 50 V X7R 0603	VISHAY/VITRAM ON	VJ0603Y101KXACW1 BC	CAP0603
1	C23	CAP CER 10 uF 10% 10 V X5R 0603	MURATA	GRM188R61A106KE6 9D	CAP0603
3	C12 C38-39	CAP CER 1000 pF (1 nF) 10% 50 V X7R 0603	MURATA	GCM188R71H102KA3 7J	CAP0603
5	C19 C29-30 C32 C36	CAP CER 1 uf 10% 25 V X7R 0603	PANASONIC	CL10B105KA8NNNC	CAP0603

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	C41	CAP CER 2200 pF 10% 50 V X7R 0603	PANASONIC	ECJ-1VB1H222K	CAP0603
3	C2-3 C40	CAP CER 4.7 uF 10% 35 V X5R 0603	MURATA	GRM188R6YA475KE1 5D	CAP0603
2	C15-16	CAP0603_DNP	DNP	DNP	CAP0603
1	CON1	CON 16POS 2.54 pitch DUAL T-HOLE	SAMTEC CONN.	90122-0128	CON2X8
2	C33-34	CAP CER 1000 pF (1 nF) 10% 50 V X7R 0603	MURATA	GCM188R71H102KA3 7J	CAP0603
2	R33-34	RES0603 1K 1% 1/10 W	VISHAY	CRCW06031K00FKEA	RES0603
1	R12	RES 20K 1% 1/10 W 0603	VISHAY/DALE	CRCW060320K0FKEA	RES0603
7	D1-2 D4-6 D9-10	DIODE 1N4148WX Switch 75 V 300 mA SOD323	Micro Commercial Co	1N4148WX-TP	SOD323
2	D7-8	DIODE DNP	DNP	DNP	DNP
1	D11	DIODE MBAT46 W-V 100 V 150 MA SOD123	VISHAY SEMI.	BAT46W-E3-GSO8	SOD123
1	U1	PFC IC CONTINUOUS CONDUTION 21 KHZ-25 KHZ PG-DSO-14	INFINEON TECH.	ICE3PCS01G	PG-DSO-14
1	U4	IC GATE XOR 2CH 8TSSOP	NXP SEMI	74HC2G86DP,125	8TSSOP
1	U5	INVERTER IC 3CH SCHMITT TRIGGER 8TSSOP	NXP SEMI.	74LVC3G14DP,125	8TSSOP
1	U8	IC BUFFER HEX SCHM TRG 14SOIC	NXP SEMI	74HC7014D,118	14SOIC
1	U7	I C REGULATOR 5 V S0T89	ST MICRO	L78L05ACUTR	SOT89
1	U6	IC AND GATE4 CHANNEL 14-SO	TEXAS INS.	SN74LS08D	14-SO
1	D3	LED RED 0805 SMD	ROHM	SML-211UTT-86	LED0805
1	U3	COMPARATOR GEN PURP OPEN DRAIN SOT23-5	TEXAS INS.	LMV7235M5/NOPB	SOT23-5
1	Q1	TRANS MMBT2222A GP NPN SOT23	FAIRCHILD	MMBT2222A	SOT23
1	U2	IC OPA2171 Dual OpAmp SOIC8	TEXAS INS.	OPA2171AIDR	SOIC8
1	R55	RES 0.0 OHM 1/10 W 5% 0603	VISHAY/DALE	CRCW06030000Z0EA	RES0603

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
3	R8 R39 R49	RES, 100 K, 1%. 1/10 W, 0603, TF	BOURNS	CR0603-FX-1003HLF	RES0603
5	R10 R26 R29 R46 R50	RES 100 Ohm 1% 1/10 W 0603	Vishay/Dale	CRCW0603100RFKEA	RES0603
13	R2-3 R11 R15-17 R27-28 R35 R47-48 R51-52	RES, 10 K, 1%. 1/10 W, 0603, TF	Vishay/Dale	CRCW060310K0FKEA	RES0603
1	R20	RES, 2.2 K, 1%. 1/10 W, 0603, TF	Vishay/Dale	CRCW06032K20FKEA	RES0603
1	R21	RES0603_1.69 K_1%_1/10 W	PANASONIC	ERJ-3EKYF1691V	RES0603
1	R6	RES0603 200 K 5% 1/10 W	PANASONIC	ERJ-3GEYJ204V	RES0603
3	R19 R30 R32	RES 240 OHM 1% 1/10 W 0603	Vishay/Dale	CRCW0603240RFKEA	RES0603
1	R38	RES 3.3 K 1% 1/10 W 0603	VISHAY/DALE	CRCW06033K30FKEA	RES0603
1	R40	RES0603 330E 1% 1/10 W	VISHAY	CRCW0603330RFKEA	RES0603
2	R7 R23	RES 330 K 1% 1/10 W 0603	VISHAY	CRCW0603330KFKEA	RES0603
1	R1	RES 33 K 1% 1/10 W 0603	VISHAY/DALE	CRCW060333K0FKEA	RES0603
7	R31 R37 R41-45	RES 4.7E 5% 1/10 W 0603	YAGEO	RC0603JR-074R7L	RES0603
2	R25 R53	RES 4.7 K 1% 1/10 W 0603	VISHAY/DALE	CRCW06034K70FKEA	RES0603
1	R36	RES0603 4.99 K 1% 1/10 W	VISHAY	CRCW06304K99FKEA	RES0603
1	R4	RSE0603 64.9 K 1/10 W 1%	VISHAY	CRCW060364K9FKEA	RE0603
2	R5 R18	DNP		DNP	RES0603
1	R56	RES0805 0 OHM 1/10 W	PANASONIC	ERJ-6GEY0R00V	RES0805
1	R9	RES0805 47 K 5% 1/10 W 0805	PANASONIC	ERJ-6GEYJ473V	RES0805
4	R13-14 R22 R24	RES1206 470 K 0.1%1/4 W	STACKPOLE Electronics	RTAN1206BKE470K	RES1206
1	R54	RES2512 100 OHM 2 W 1%	BOURNS	CRS2512-FX-1000ELF	RES2512

Table 9: AUX Power Supply Board BOM

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	C11	CAP CER 0.1 uF 10% 50 V X7R 0603	KEMET	C0603C104K5RACTU	CAP0603
1	C24	CAP CER 1 uf 10% 50 V X7R 0603	PANASONIC	CL10B105K8NNNC	CAP0603
2	C5 C22	CAP CER 10 uF 10% 35 V X7R 0805	MURATA	GRM21BR6YA106ME43 L	CAP0805
1	C3	CAP CER 4.7 uF 10% 50 V X7R 0805	MURATA	GRM32ER71H475KA88 L	CAP0805
7	C12-18	CAP CER 4.7 uF 10% 50 V X5R 1206	KEMET	C1206C475K5PACTU	CAP1206
2	C21 C23	CAP1206 DNP	KEMET	DNP	CAP1206
1	C7	CAP CER 0.1 UF 1000 V X7R 1808	KEMET	C1808C104KBRACTU	CAP1808
1	C8	CAPALUM 2.2 UF 450 V SMD	NICHICON	ULH2W2R2MNL1GS	SMD_DIA-8MM
2	C19-20	CAPALUM 47 UF 20% 35 V SMD	PANASONIC	EEE-FK1V470P	SMD
1	C4	CAP CER 100PF 2000 V TH RADIAL_DNP	TDK CORP.	CC45SL3D101JYNNA	7.5MMX5MM TH
2	XL1-2	COMMON MODE CHOKE 100 UH 150 MA 2LN SMD	EPCOS	B82787C0104H002	SMD
2	CON1-2	6 POS.MALE HEADER 2.54 MM TH	MOLEX CONN.	90122-0123	CON 2X3 TH
3	C2 C9-10	CAP CER 1000 pF (1nF) 10% 50 V X7R 0603	Panasonic	ECU-V1H102KBV	CAP0603
1	C1	CAP CER 100 pF 10% 50 V X7R 0603	VISHAY/VITRAM ON	VJ0603Y101KXACW1BC	CAP0603
1	D1	DIODE RSIM 1000 V SMA	DIODES INCORPORATED	RS1M-13-F	SMA
2	D3-4	DIODE STPS3H100U SUPER FAST 100 V 3 A SMB	DIODES INCORPORATED	STPS3H100U	SMB
1	D2	DIODE STTH1R02A _SMA_600 V	ST MICRO	STTH1R02A	SMA
1	ZD1	DIODE ZENER 22 V 3 W 5% SMB	ON SEMI.	1SMB5933BT3G	SMB
1	C6	FILMCAP_1000 PF_1200 V	KEMET	PHE850EA41000MA01R 17	FILMCAP13X4M M_LEAD SPACE_10 MM

Qty	Reference	Description	Manufacturer	Manufacturer P/N	Package
1	U1	OFFLINE SMPS QUASI RESONANT PWM CONTROLLER	INFINEON TECH.	ICE2QR2280Z	DIP-7
1	U4	IC REG LDO 18 V 0.1 A SOT-89	ST MICRO	L78L18ACUTR	SOT-89
1	L1	INDUCTOR 15UH 130 MA 1210	MULTICOMP	MCFT000189	1210
1	U3	OPTICAL SWITCH, TRANSISTOR OUTPUT 4SMD	SHARP MICRO ELECTRIC	PC817XNNIP0F	4SMD
1	R14	RES 10.0 OHM 0.1% 1/10 W 0603	Vishay/Dale	TNPW060310R0BEEA	RES_0603
1	R8	RES 12 K 1% 1/10 W 0603	PANASONIC-ECG	ERJ-3EKF1202V	RES0603
1	R12	RES 22 K 1% 1/10 W 0603	PANASONIC-ECG	ERJ-3EKF2202V	RES0603
1	R9	RES0603 3.9 K 1% 1/10 W	PANASONIC	ERJ3KEF3901V	RES0603
1	R6	RES0603 39 K 5% 1/10 W	PANASONIC	ERJ-3GEY393V	RES0603
1	R10	RES 42.2 k 1% 1/10 W 0603	Vishay/Dale	CRCW060342K2FKEA	RES0603
1	R11	RES 470 OHM 1% 1/10 W 0603	Vishay/Dale	CRCW0603470RFKEA	RES0603
2	R4 R7	RES0603 6.8 K 5% 1/10 W	PANASONIC	ERJ-3GEYJ682V	RES0603
1	R5	RES0805 22E 1% 1/10 W	PANASONIC	ERJ-3GEYJ220V	RES0805
1	R15	RES 56 Ohms 5% 1/4 W 1206	YAGEO	RC1206JR- 756RL	RES1206
2	R13 R16	RES1206 DNP	DNP	DNP	RES1206
2	R2-3	RES2512 10 OHM 5% 1 W	PANASONIC	ERJ-1TYJ100U	RES2512
1	R1	RES2512 1M 5% ½ W	PANASONIC	ERJ-1TYJ105U	RES2512
1	U2	TRANS TL432A SHUNT REG PREC 1% SOT-23	TEXAS	TL432AQDBZRQ1	SOT23
1	T1	TRANSFORMER OFFLINE 1.5 MH 2000 V	WURTH ELE.	760875131	SMD-12PIN

11.1 The PCB Layout for TO-247 Vision are Following:

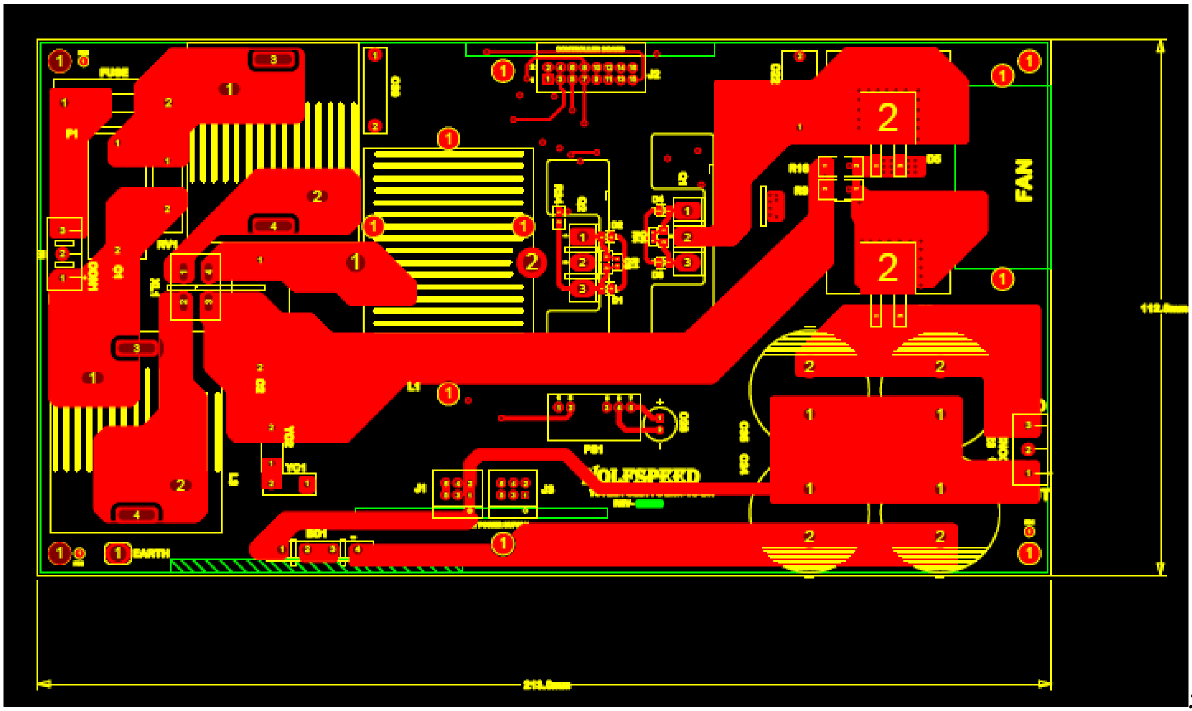


Figure 36: Power board layout, top layer of TO-247 vision

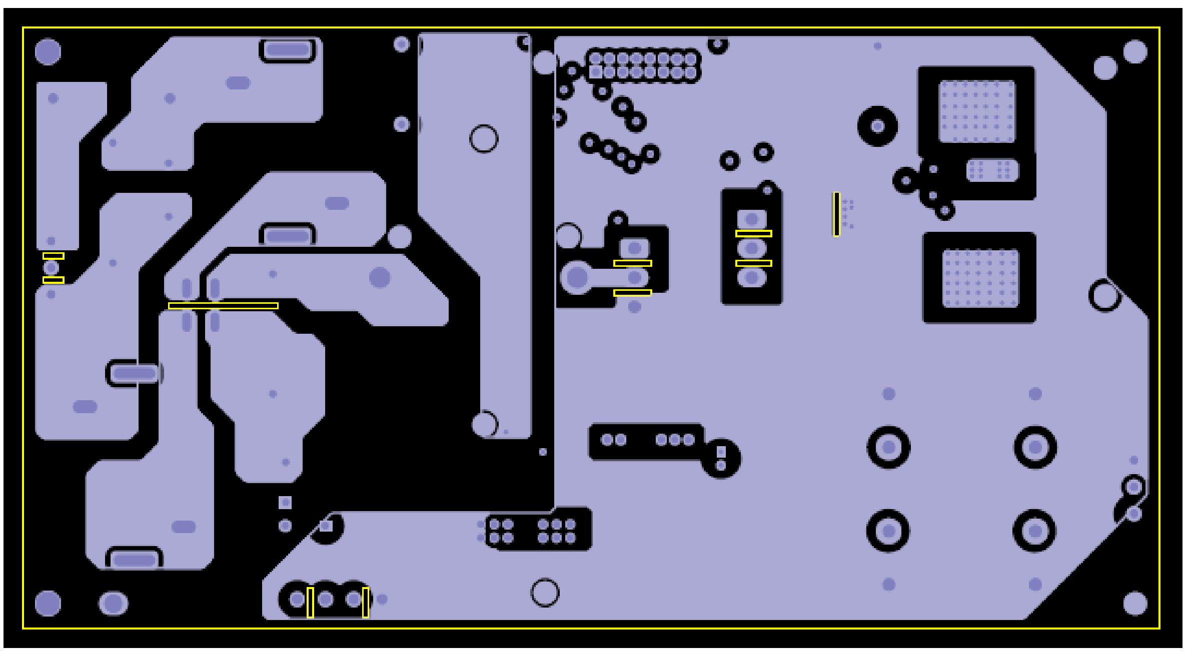


Figure 37: Power board layout, bottom layer of TO-247 vision

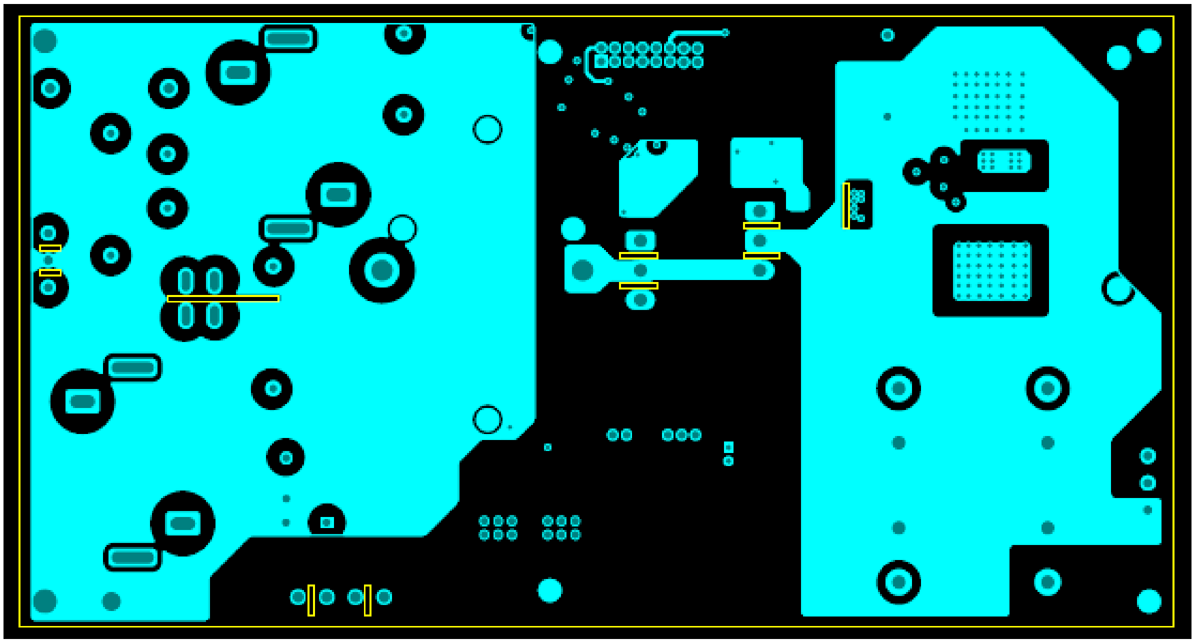


Figure 38: Power board layout, inner layer 2 of TO-247 vision

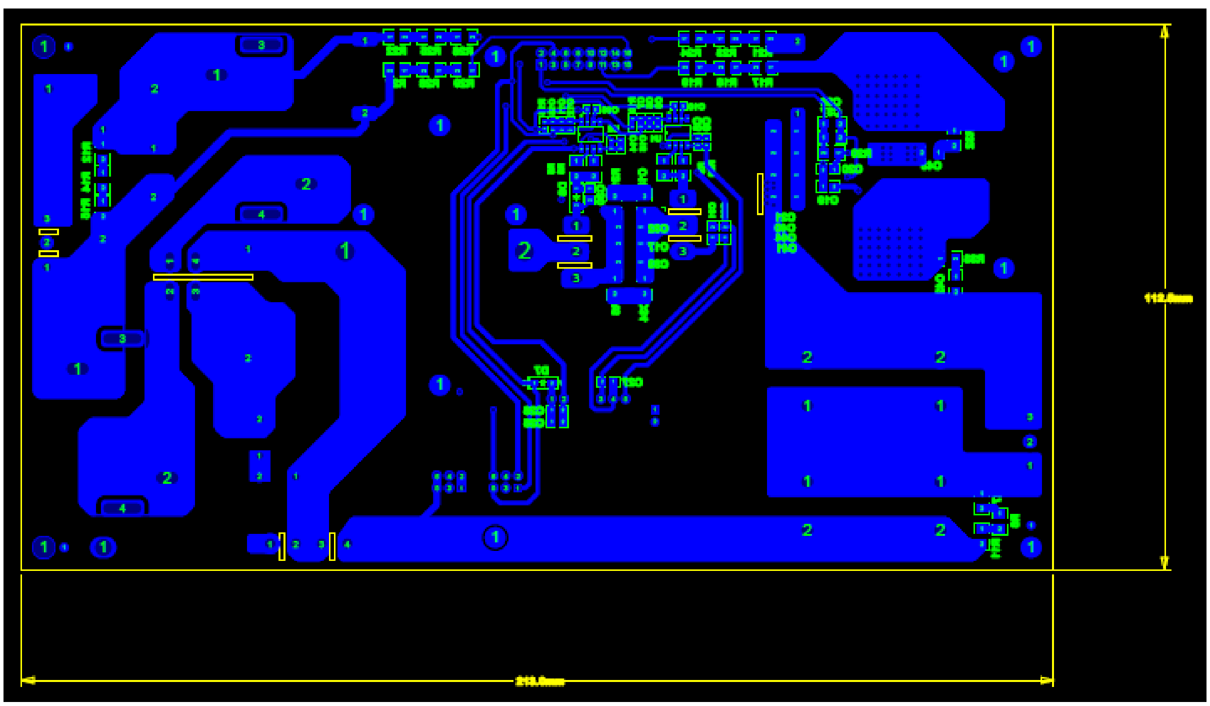


Figure 39: Power board layout, bottom layer of TO-247 vision

11.2 The PCB Layout for TO-247-4 Vision are Following:

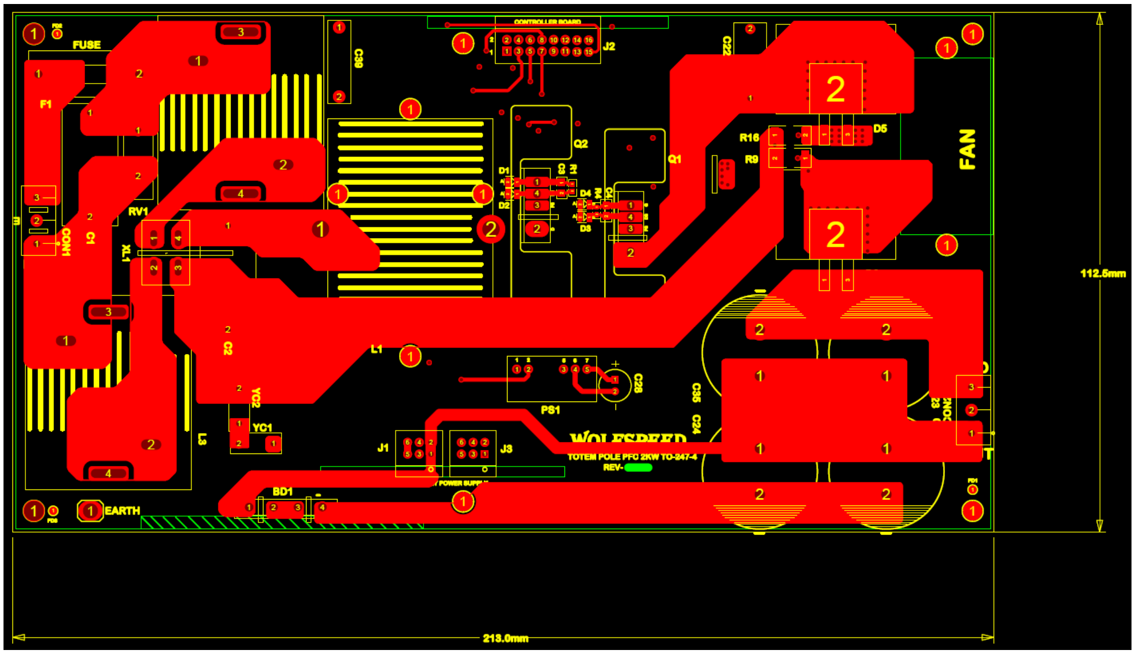


Figure 40: Totem pole PFC power board layout, top layer

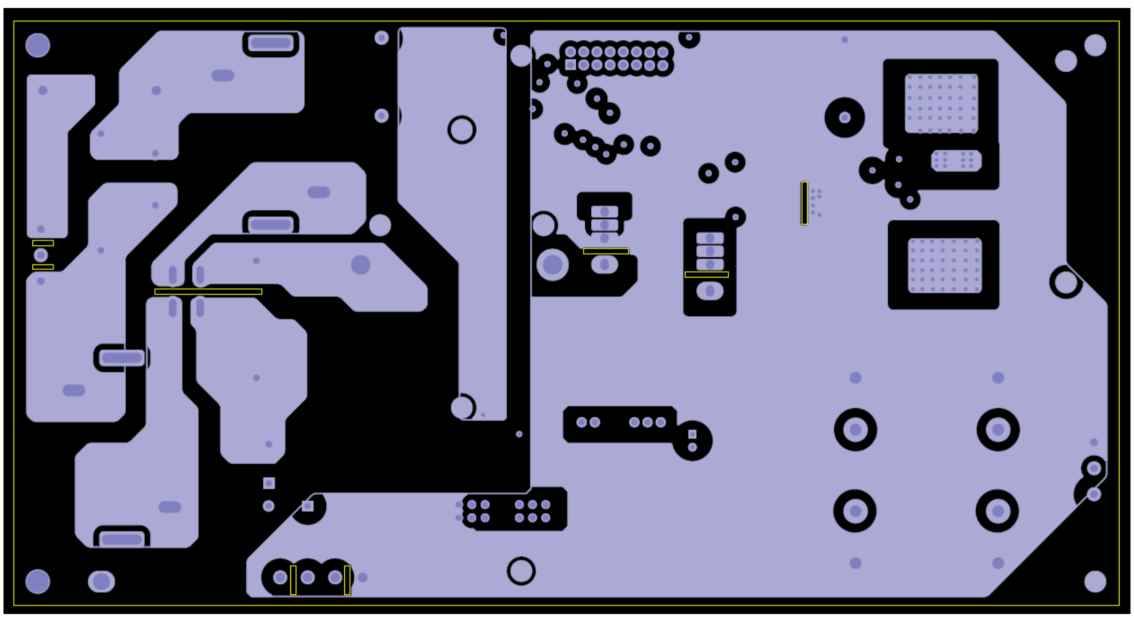


Figure 41: Totem pole PFC power board layout, inner layer 1

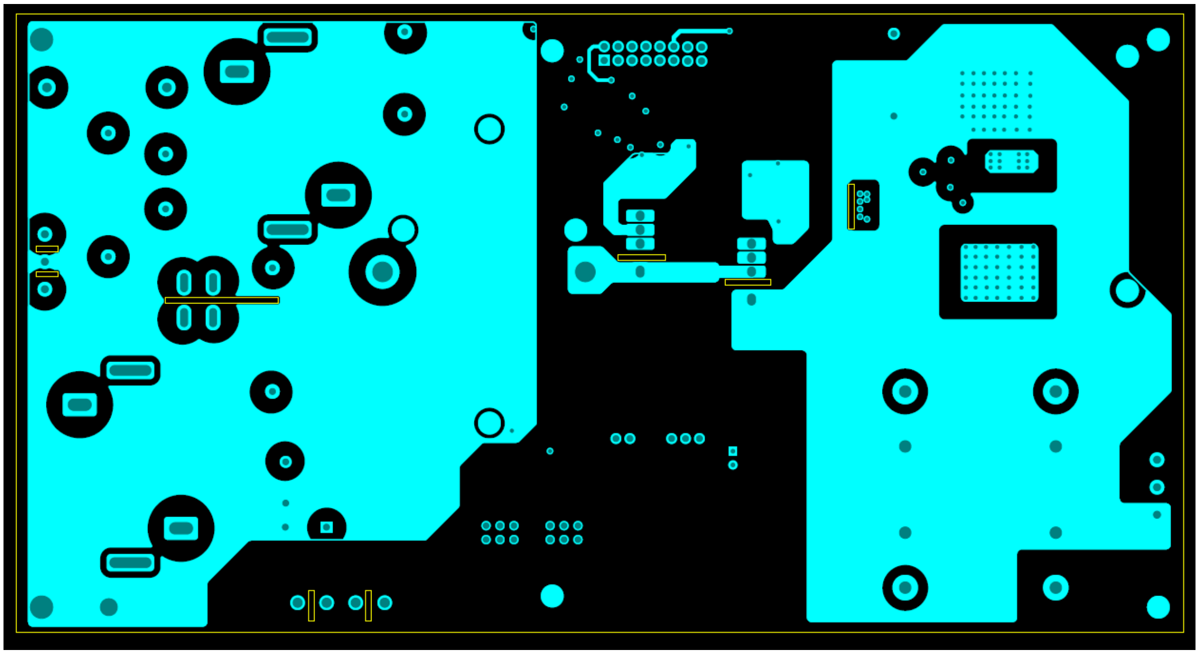


Figure 42: Totem pole PFC power board layout, inner layer 2

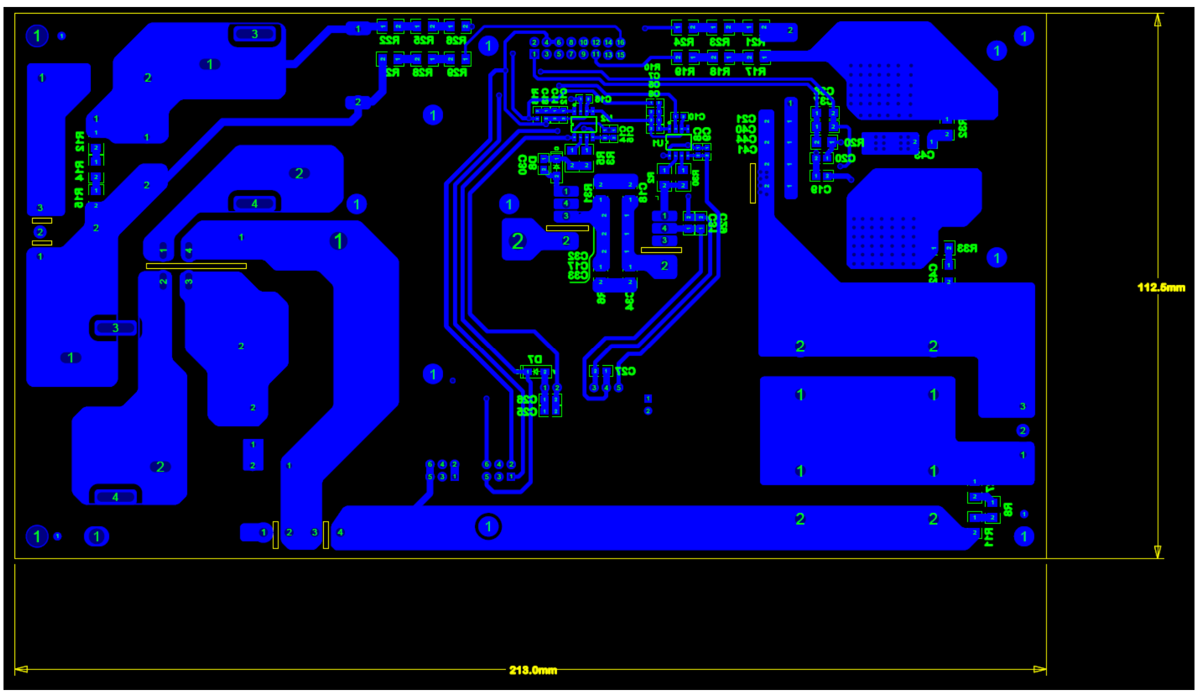


Figure 43: Totem pole PFC power board layout, bottom layer

11.3 The PCB Layout for TO-263-7 Vision are Following:

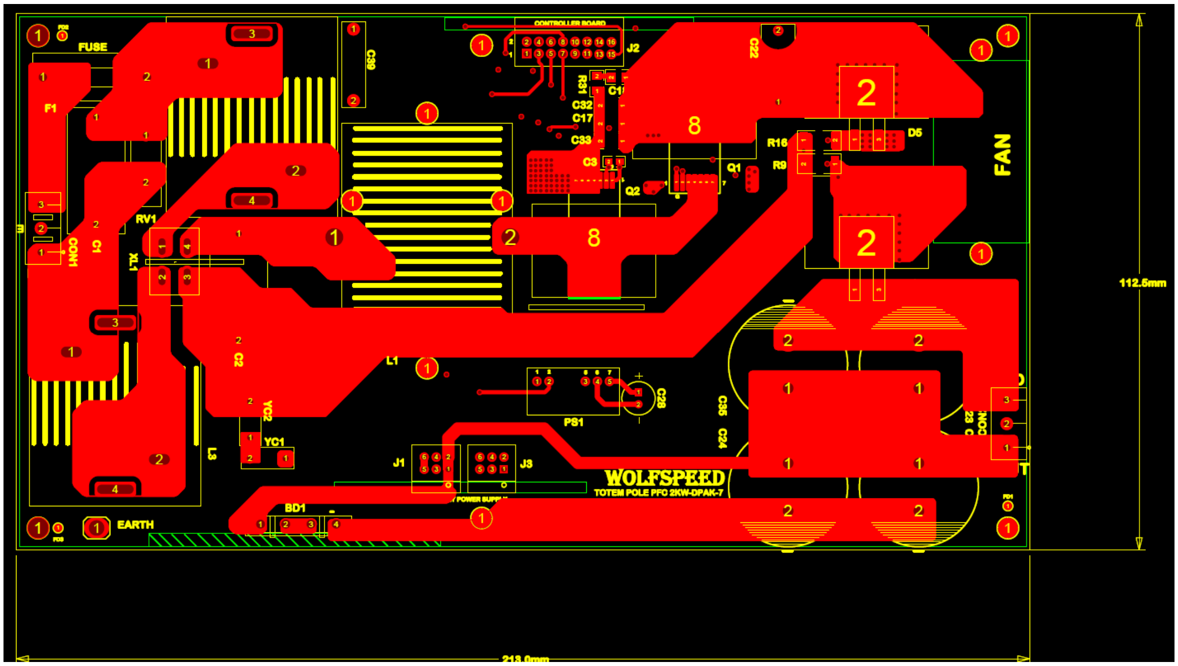


Figure 44: Totem pole PFC power board layout, top layer

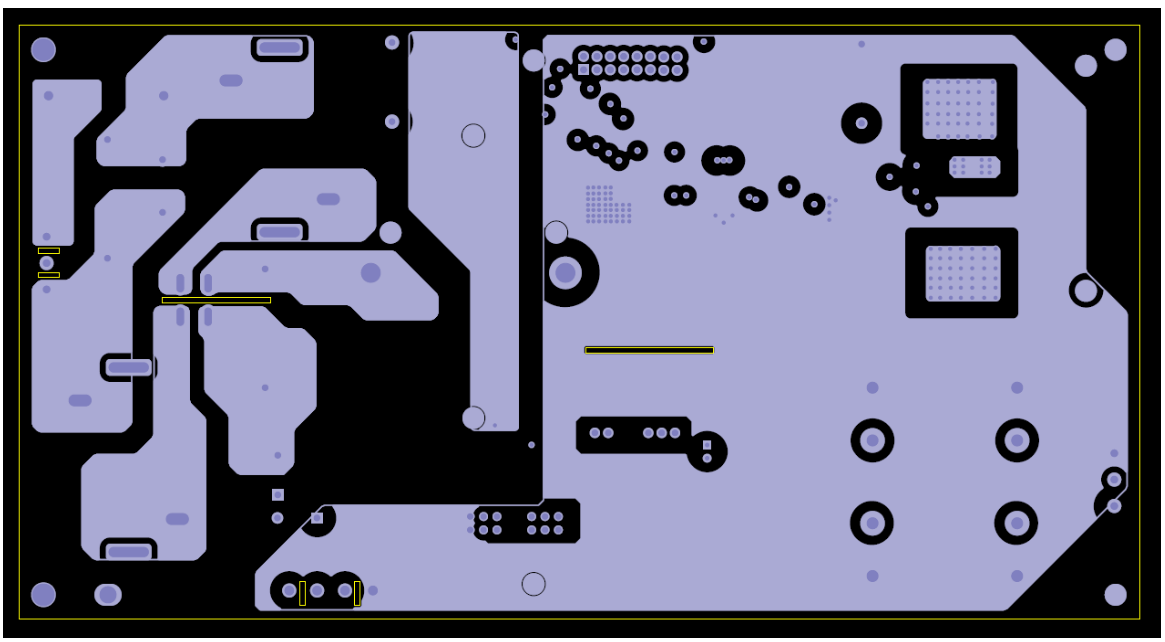


Figure 45: Totem pole PFC power board layout, inner layer 1

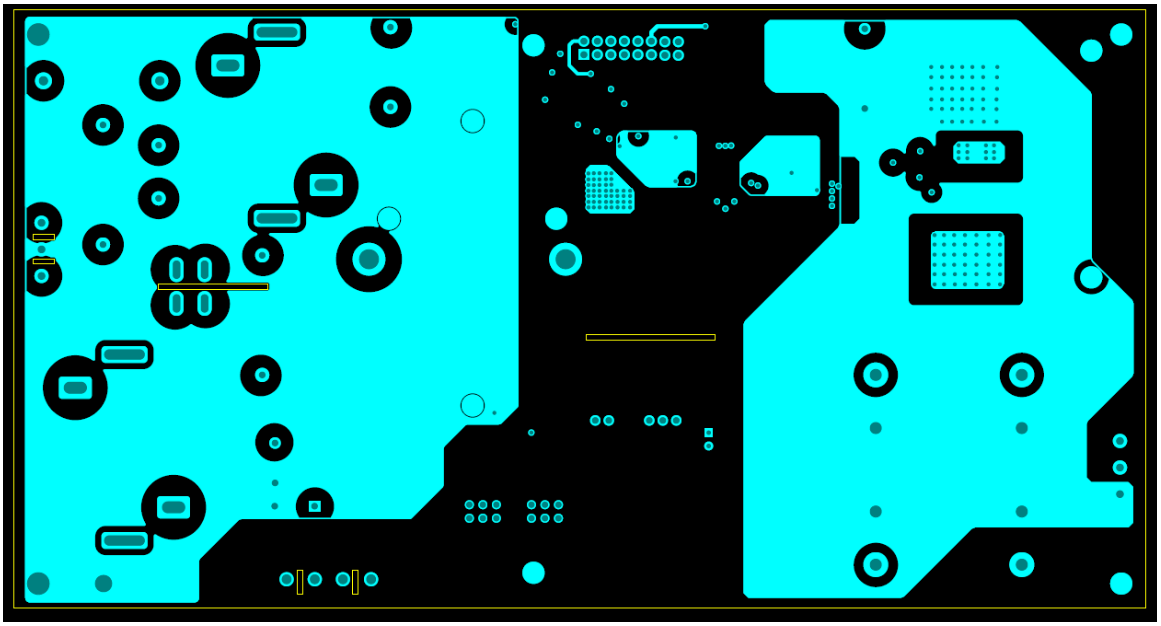


Figure 46: Totem pole PFC power board layout, inner layer 2

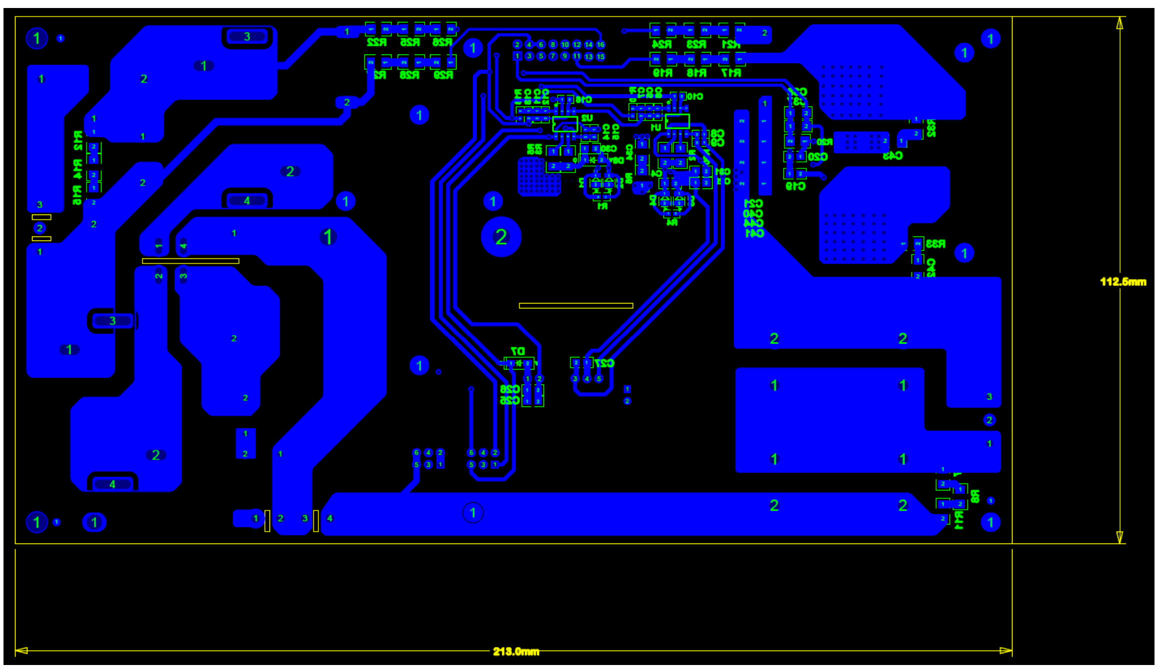


Figure 47: Totem pole PFC power board layout, bottom layer

12. References

[1] L. Huber and M. M. Jovanovic, "Performance Evaluation of Bridgeless PFC Boost Rectifiers," IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1381-1390, May 2008.

[2] EPA, "Energy Star Specification 5.0 for Computers," www.energystar.gov

[3] Q. Li, M.A.E. Andersen, and O.C. Thomsen, "Conduction Losses and Common Mode EMI analysis on bridgeless power factor correction," International conference on Power Electronics and Drive Systems, Nov. 2-5, 2009.

[4] B. Su, J. Zhang and Z. Lu, "Totem-pole Boost Bridgeless PFC rectifier with simple zero-current detection and full-range ZVS operating at the boundary of DCM/CCM," IEEE Trans. Power Electron, vol.26, no.2, Feb. 2011.

[5] Zhong Ye, Alvaro Aguilar, Yitzhak Bolurian and Brian Daugherty" GaN FET-Based CCM Totem-Pole Bridgeless PFC" Texas Instruments Power Supply Design Seminar SEM2100, Topic 6 TI Literature Number: SLUP327

[6] Transphorm 4kW totem-pole PFC High-efficiency bridgeless PFC //www.transphormusa.com/wp-content/uploads/2016/08/TDTTP4000W066_AppNote.pdf

13. Revision History

Date	Revision	Changes
February 2018	A	1st Issue
February 2020	B	Update for 650 V SiC MOSFET in TO-247-4, TO-263-7 and TO-247 package
January 2021	C	Correct the typo in part number
January 2024	2	Branding and formatting updates

14. 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.

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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.