300 W TPPFC+HB LLC REFERENCE DESIGN

with CGD65A055SH2 and CGD65A130SH2

USER GUIDE

CGD – UG2401

Cambridge GaN Devices Limited Jeffreys Building, Suite 8 Cowley Road Cambridge CB4 0DS United Kingdom	

Safety Warning

The CGD 300 W totem-pole PFC & half-bridge LLC reference design is for evaluation purposes only. It is not intended to be a finished product and does not include all protection features found in commercial power supply.

DANGER: Do not touch the board when high voltages are applied. There are exposed locations of high voltage on the board when connected to a power source. Brief contact may result in serious injury or death. Allow all components to fully discharge before handling the board. This evaluation kit is designed for use by qualified, experienced engineers only. Appropriate safety measures must be put in place before use and the board should never be left unattended.

WARNING: Some components may become hot during operation and remain so afterwards. Operating voltages, currents and temperatures should be monitored closely throughout operation to prevent damage to the board.

CAUTION: This product contains parts susceptible to ESD (electrostatic discharge). ESD prevention procedures must be used while handling the board.

Operating Limits and Recommendations

Operating outside this window is not recommended and may cause damage.

Voltage, Current and Power limits

CGD has tested the board only within the following ranges: input voltage range of 90–264 V_{AC} 47–63 Hz, output voltage 20 V, output current 0 - 15 A in continuous operation and up to 17.5 A during less than 30 minutes.

Heat dissipation

This version is an open frame design. CGD does not guarantee the thermal performance of the provided heatsinking solution.

Do not touch the circuit components until the components cool down after turning off. In full-load conditions, temperatures of certain circuit components like ICeGaN™ devices, MOSFETs and magnetics will rise beyond 100 °C after 20 minutes of operation, with ambient temperature of 25 °C. Therefore, it is recommended to use a thermal camera to monitor the circuit temperature during circuit operation and turn off the input power if the temperatures rise above nominal operating temperatures.

Target Audience

This user guide, along with the reference design board itself, is intended to be used only by experienced engineers and assumes a knowledge of necessary equipment to analyse the performance of the circuit board. It is designed to enable SMPS engineers, design engineers and technicians involved in the development of a system to assess the performance of CGD ICeGaN .

Technical Support

For support, please contact CGD at techsupport@camgandevices.com.

Revision History

Revision Number	Comments	Engineer(s)	Date
1.0	Initial Issue	CT	20/03/2024

Contents

1 Introduction

This user guide provides basic information about the CGD 300 W totem-pole PFC and half-bridge LLC (TPPFC + HB LLC) reference design. This design is a high power density, low profile, 300 W universal input offline power supply reference design that can also operate at 350 W for under 30 minutes.

This reference design is a two-stage converter. The front-end stage topology is a critical conduction mode (CrCM) bridgeless totem-pole PFC and the output stage topology is a half-bridge LLC with secondary side synchronous rectifiers (SR). A simplified schematics is illustrated in Figure 1.

The CrCM TPPFC controller is the NCP1680, and the HB LLC controller is the UCC2564. The synchronous rectifier MOSFETs in the LLC output are both controlled by the dual SR driver SRK2001TR.

The TPPFC high frequency half-bridge leg, commonly called fast leg, incorporates two CGD65A055SH2 ICeGaN, a 650 V / 55 mΩ GaN HEMT. The two devices on the LLC half-bridge are CGD65A130SH2 ICeGaN, a 650 V / 130 mΩ GaN HEMT. Both ICeGaN devices, in the TPPFC and the HB LLC, are 8 x 8 mm. ICeGaN devices feature a proprietary gate technology that enable broad gate voltage window and higher gate voltage threshold than a discrete GaN HEMT. Therefore, unlike other GaN HEMTs, ICeGaN devices are compatible with Si MOSFET standard gate-driver ICs. In fact, the 50 Hz slow leg MOSFETs and the ICeGaN devices on the TPPFC fast leg employ the same standard 650 V HB driver. The ICeGaN devices in the LLC's half bridge are directly driven by the LLC controller's internal gate driver, and there is no need for an additional gate driver.

CGD's ICeGaN technology simplifies the driving of the GaN HEMTS with no need of negative drive voltage, or a specific GaN driver, thus reducing the complexity and the part count, and delivering high efficiency on a compact and low-profile solution.
This 300 W design exceeds 80 PLUS Platinum specifications and DoE level VI requirements, and also the stringent EU Code of Conduct v2 for no-load.

The reference design comprises a primary board along with two secondary daughterboards:

- The main board has most of the circuit components.
- The fast leg TPPFC daughterboard features the TPPFC fast leg half-bridge with two CGD65A055SH2 ICeGaN devices and its bootstrap HB gate driver IC.
- The low voltage rail daughter card generates 15 V to power the controller ICs, the gate drivers ICs and the ICeGaN devices. This daughterboard features a small buck converter that takes input voltage from TPPFC's bulk cap rail.

The 3 different boards are clearly identified in Figure 2. The low profile of this design can be observed in Figure 3. The input and output connectors, and the main components and sections of the system are marked in Figure 4.

The contents of this manual contain key specifications, design considerations, test results, key waveforms, circuit schematics, PCB layout and BOM of the 300 W TPPFC & HB LLC reference design.

1.1 Application topology

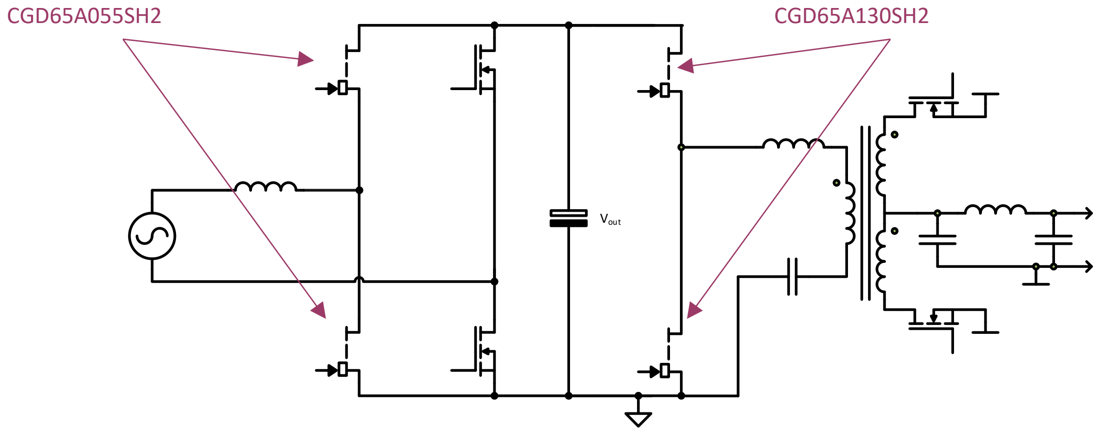


Figure 1 - Reference design functional schematics

1.2 Board images

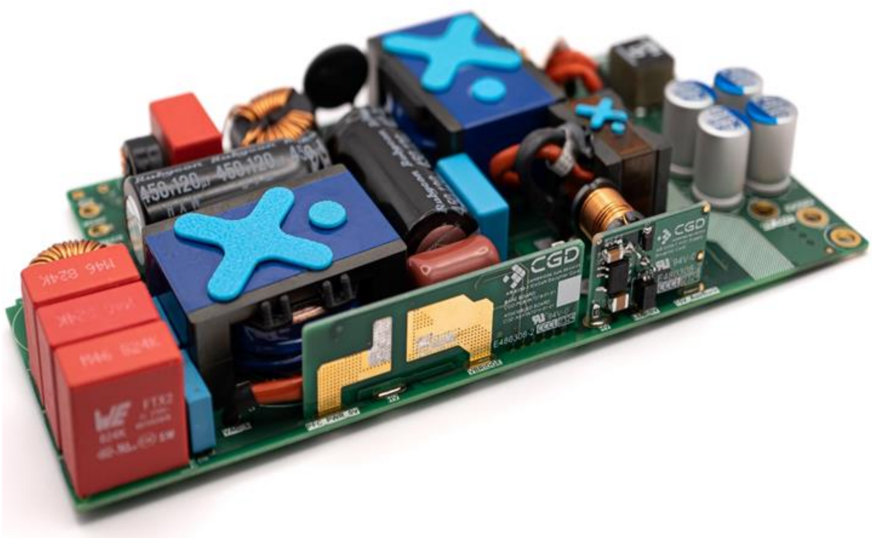


Figure 2 – Reference design board

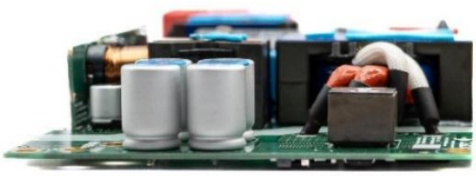


Figure 3 – Reference design side view (output side)

1.3 Input & output connectors and main sections

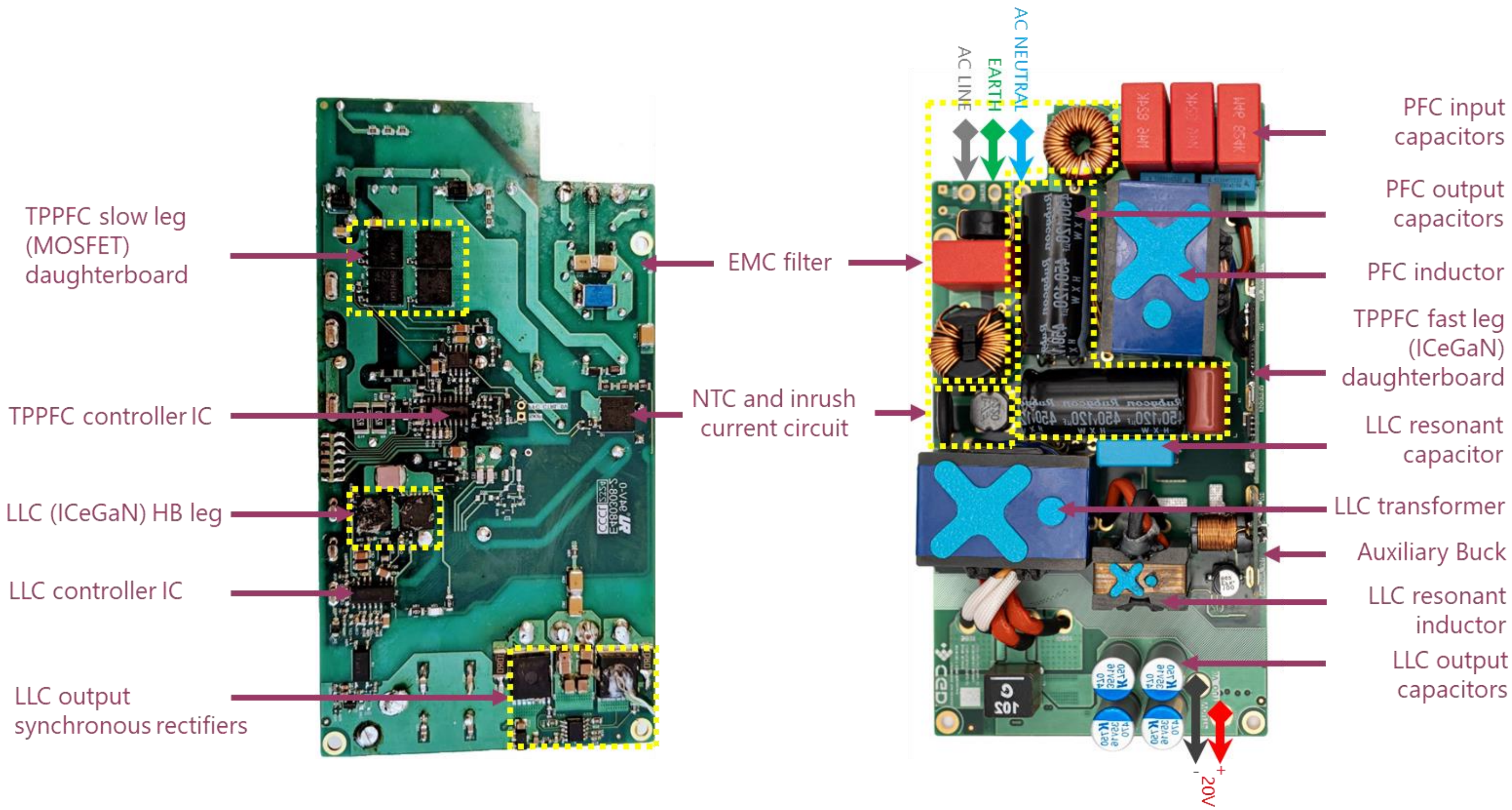


Figure 4 - Reference design bottom and top views

2 Key Specifications

Table 1 – Main specifications

Input & Output Specifications		
Input voltage	90 - 265	V
Nominal output voltage	20	V
Rated output current	15	A
Nominal output power	300	W
Maximum output current (for under 30 min)	17.5	A
Maximum output power (for under 30 min)	350	W

Table 2 - Performance summary

Performance Specification Summary		
Maximum output ripple	350	mV
Power factor (at maximum load)	0.9	
Total harmonic distortion (at maximum load)	< 10	%
Efficiency (peak efficiency at 230 V and 300 W)	> 95	%
Efficiency (average efficiency at 115 V_{AC} and 300 W)	> 93	%
Efficiency (average efficiency at 230 V_{AC} and 300 W)	> 93.6	%
No load power consumption at 115 V_{AC}	150	mW
No load power consumption at 230 V_{AC}	170	mW
Consumption at 0.5 W output power	< 1	W

Table 3 - Dimensions

Dimensions		
PCB Length (Open Frame)	153	mm
PCB Width (Open Frame)	80	mm
PCB Height (Open Frame)	20.4	mm
Finished Length (Cased)	156	mm
Finished Width (Cased)	85.3	mm
Finished Height (Cased)	25	mm

Table 4 - Power density

Power Density (considering 350 W)		
Open Frame Power Density	23	W/in^3
Cased Power Density	17.2	W/in^3

3 Test Results

3.1 Efficiency

Below, in Table 5 and Figure 5, are the efficiency results of the reference design at 10%, 25%, 50%, 75%, 100% load as well as 116% load (350 W). 100% load corresponds to 300 W which is the nominal power at which the unit can operate with thermal stability.

The average efficiency was calculated using 25%. 50%, 75% and 100% efficiency values.

This reference design is able to run at 350 W for more than 20 mins (and less than 30 mins before the over temperature protection is triggered). Dashed efficiency lines are used in Figure 5, in the region between 300 W and 350 W, marking the zone where the unit can only operate for a limited time.

Table 5 - Efficiency results

Efficiency							
	10% Load	25% Load	50% Load	75% Load	100% Load	116% Load	Average
90 V_{AC}	85.63%	89.82%	93.21%	93.83%	93.58%	91.88%	92.61%
115 V_{AC}	85.77%	90.14%	93.46%	94.31%	94.34%	93.16%	93.06%
230 V_{AC}	87.02%	90.78%	94.19%	94.78%	95.07%	94.28%	93.71%
265 V_{AC}	87.01%	90.38%	94.41%	95.10%	95.27%	94.40%	93.79%

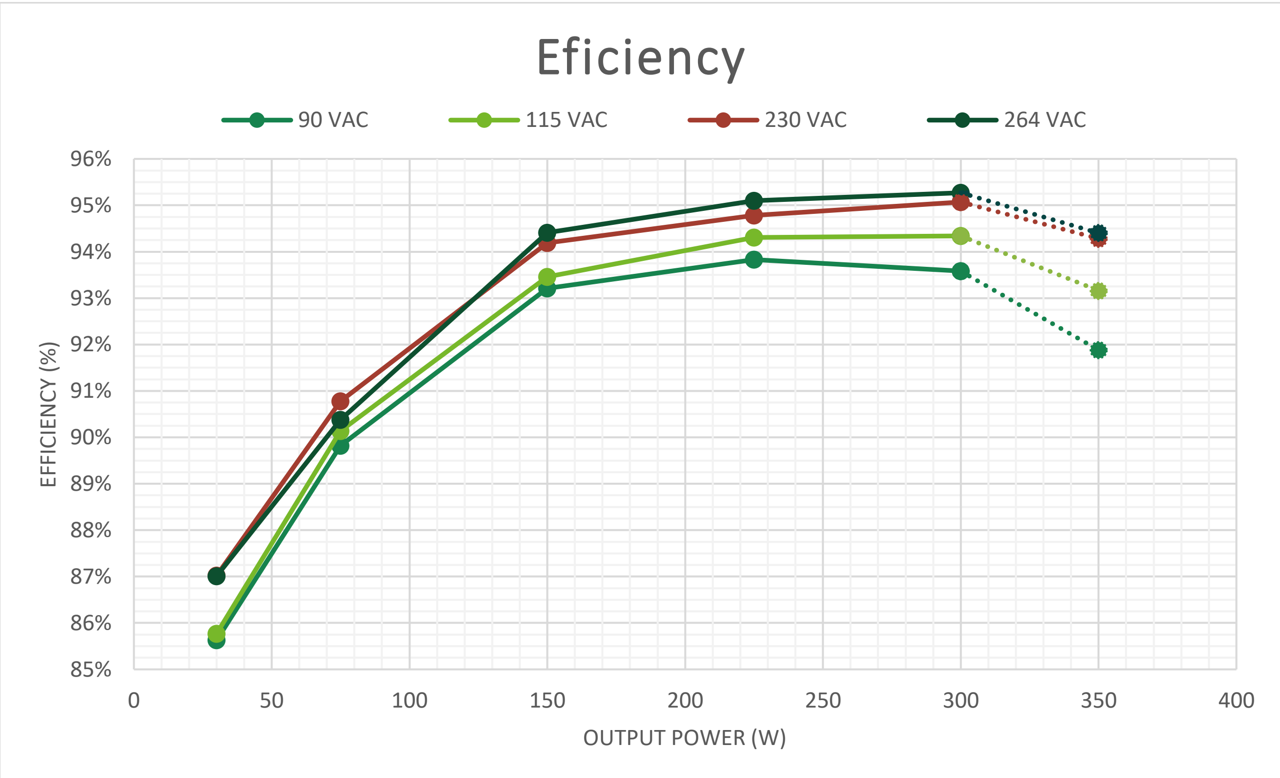


Figure 5 – Efficiency vs output power

Notes:

1. *The input power and output power were measured using two channels of GW Instek GPM-8320 power meter. E-Load: EL34143A. AC Source: IT7803*

3.2 No-load power

Table 6 – No-load power results

No low power	
90 V_{AC}	150 mW
115 V_{AC}	151 mW
230 V_{AC}	166 mW
265 V_{AC}	168 mW

The no-load power results are significantly lower than the DOE level VI (500 mW for >250 W EPS), and it is very close to the 150 mW specification set by the European Code of Conduct v2, even though this standard only applies to <250 W External power supplies.

3.3 Light-load power

Table 7 – Light-load power results

Light-load power	
Output power	Input Power
0.2 W	< 0.5 W
0.5 W	< 1 W

Notes:

1. *For no-load power test, the load was physically disconnected*
2. *The no-load power and light-load operation power were obtained by using a Yokogawa WT210 power meter integrating the input power for more than 20 minutes*
3. *For both the no-load power and light-load power tests the TPPFC "Skip mode" operation on the TPPFC controller NCP1680 was externally activated. In this reference design version, the LLC stage is not able to activate automatically the PFC "Skip mode" operation. Figure 6 shows the two pins above can be shorted to activate NCP1680 Skip mode. Warning: These pins must not be shorted for normal operation*

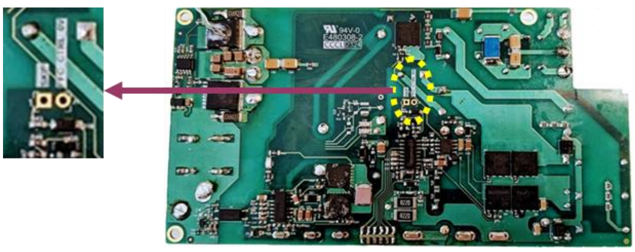


Figure 6 – Pins to be shorted to activate PFC Skip mode to obtain lowest no-load power

3.4 Power factor and total harmonic distortion

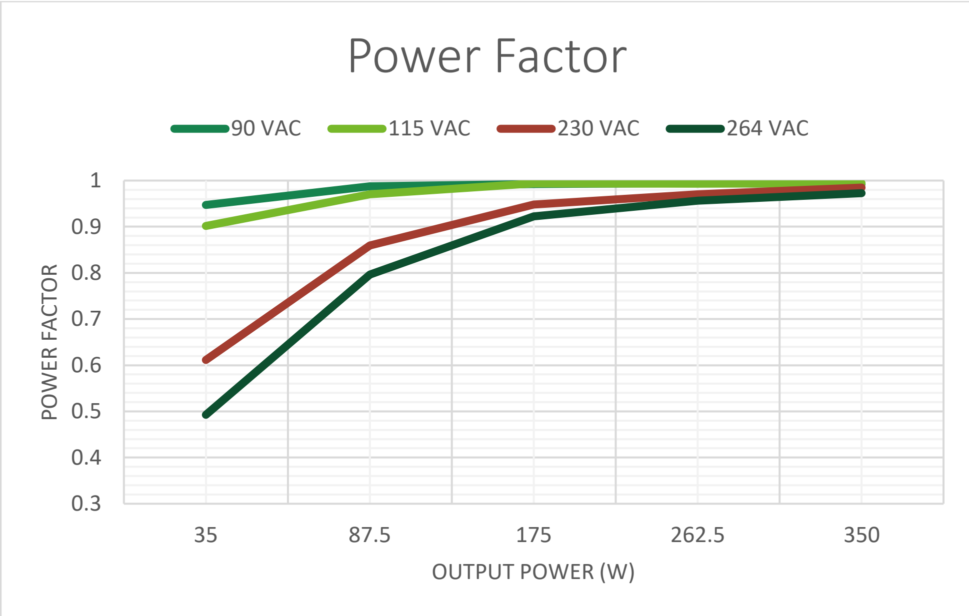


Figure 7 - Power factor vs output power

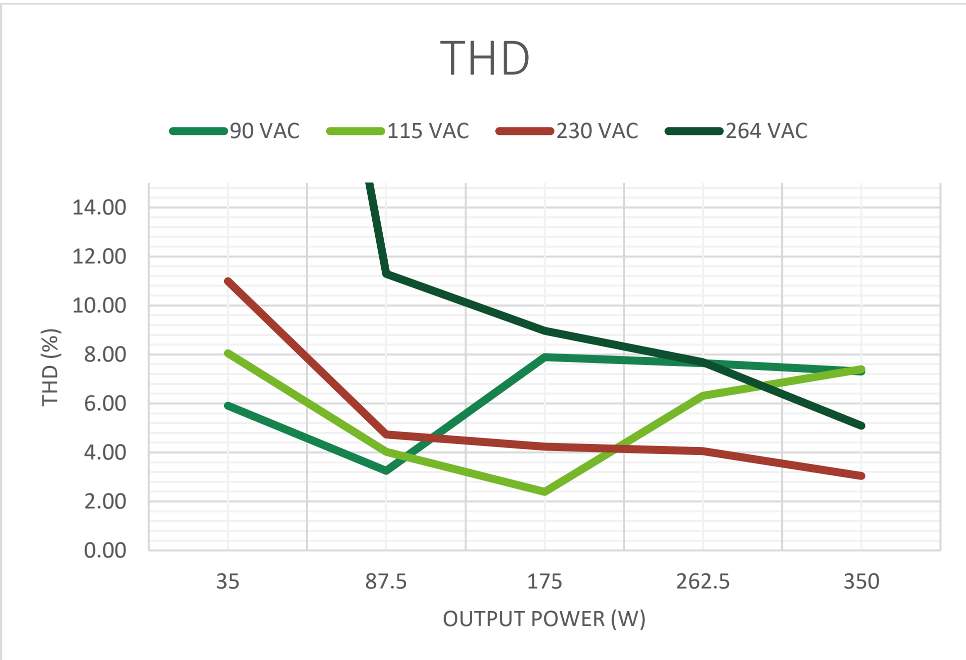
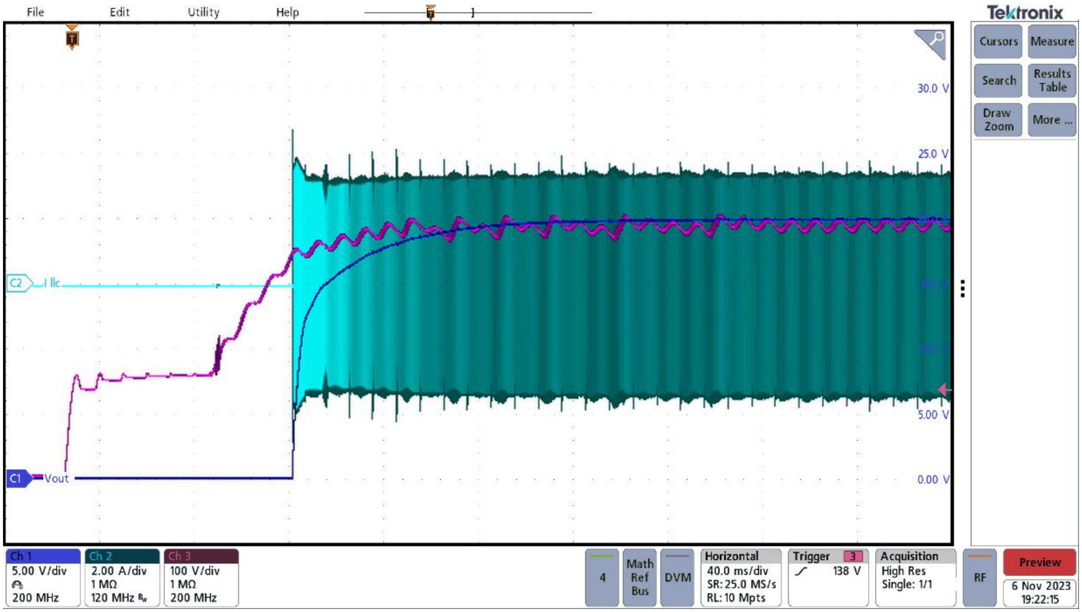


Figure 8 - THD vs output power

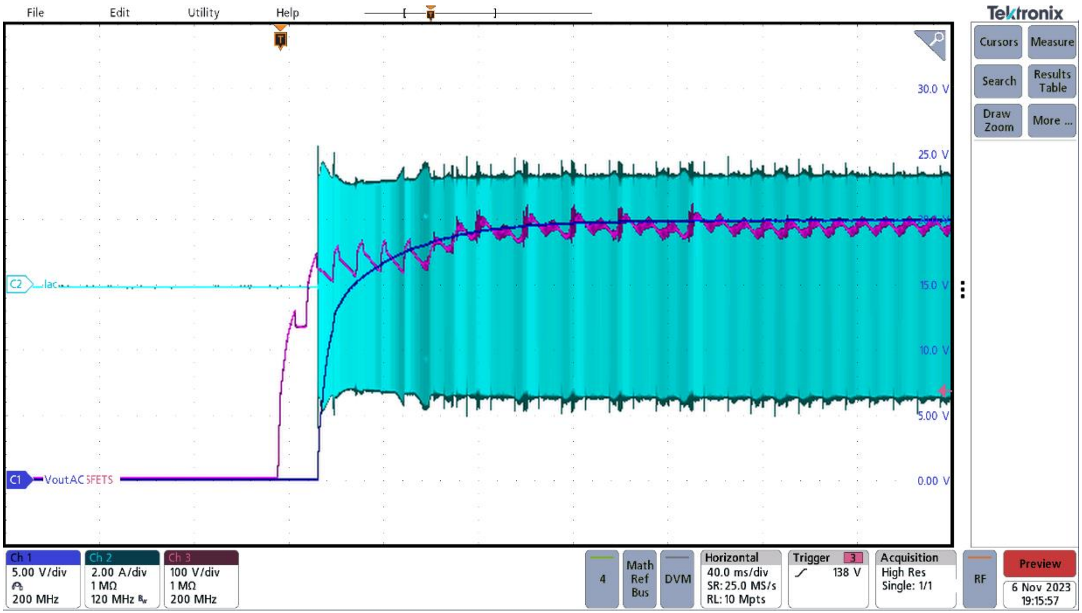
4 Waveforms

4.1 Start-up at 350 W



CH 1 – Output voltage CH 2 – LLC primary current CH 3 – Bulk cap. voltage

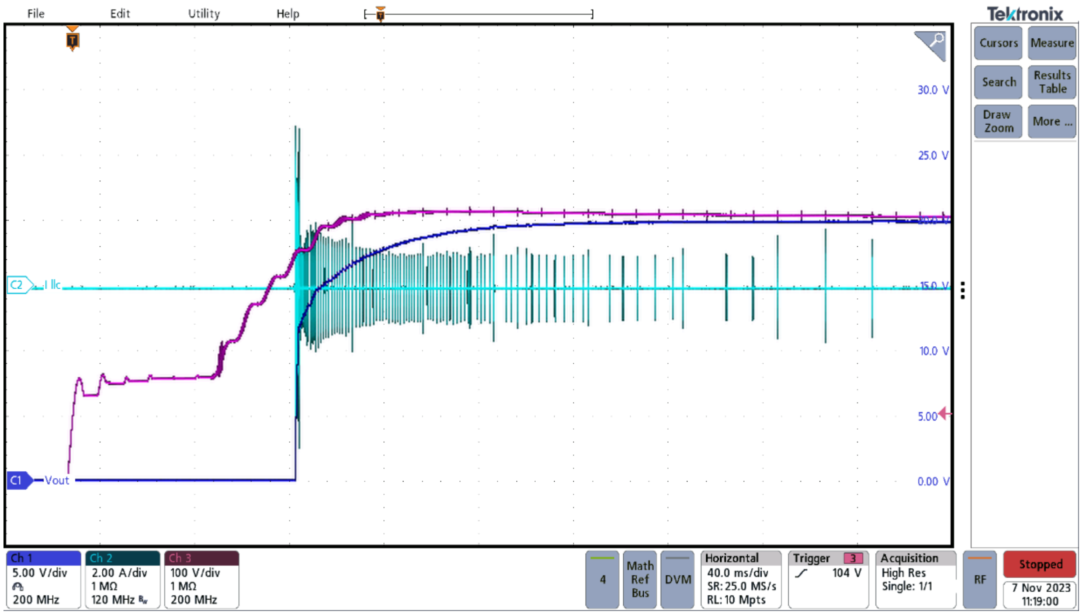
Figure - 9 Start up 115 V_{AC} / 350 W



CH 1 – Output voltage CH 2 – LLC primary current CH 3 – Bulk cap. voltage

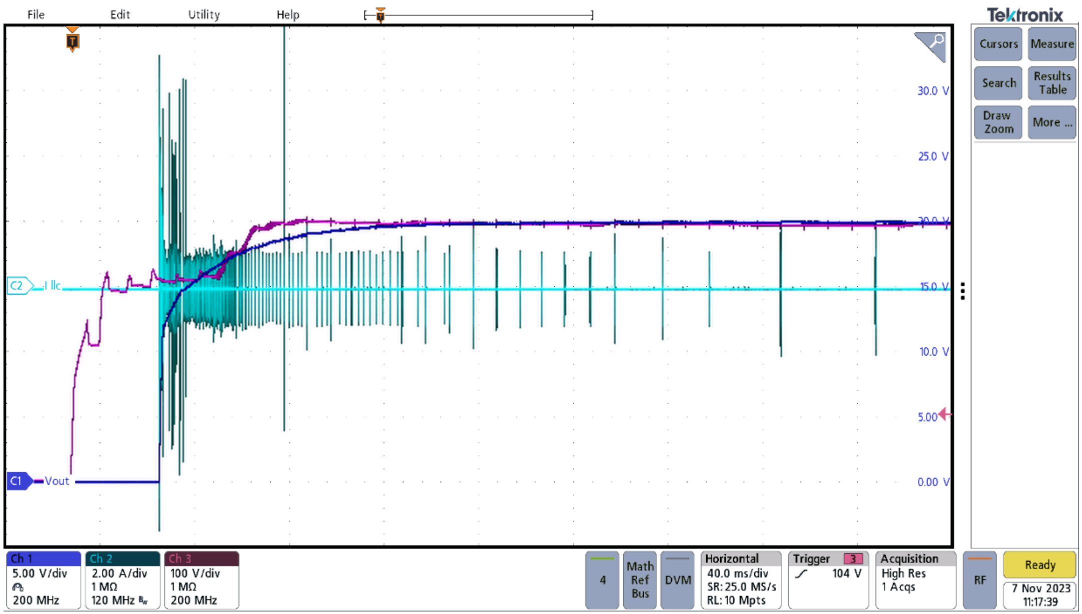
Figure - 10 Start up 230 V_{AC} / 350 W

4.2 Start up at no load



CH 1 – Output voltage CH 2 – LLC primary current CH 3 – Bulk cap. voltage

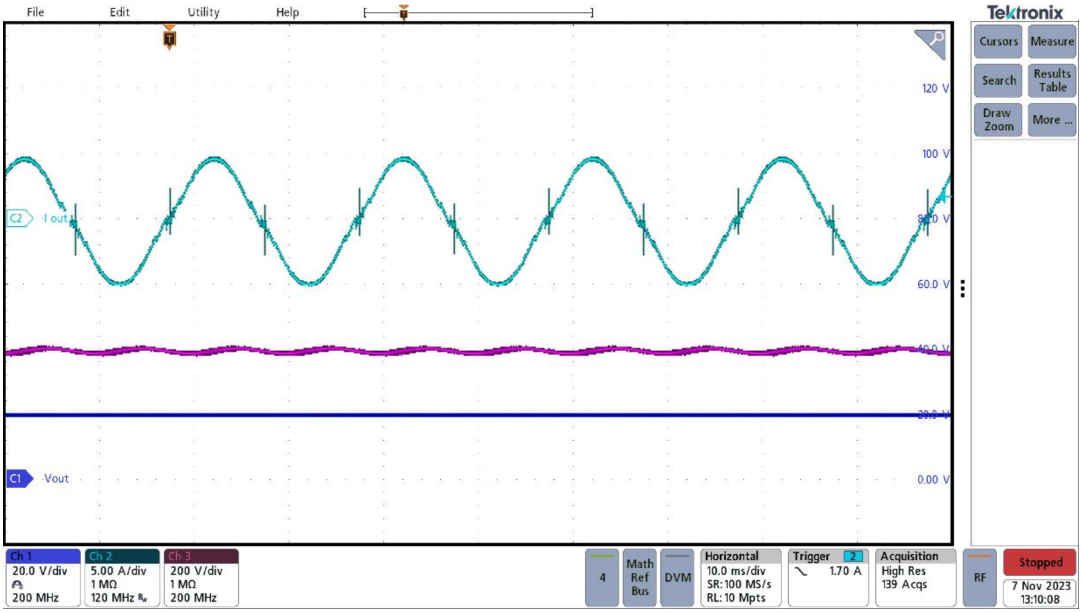
Figure - 11 Start up 115 V_{AC} / No load



CH 1 – Output voltage CH 2 – LLC primary current CH 3 – Bulk cap. voltage

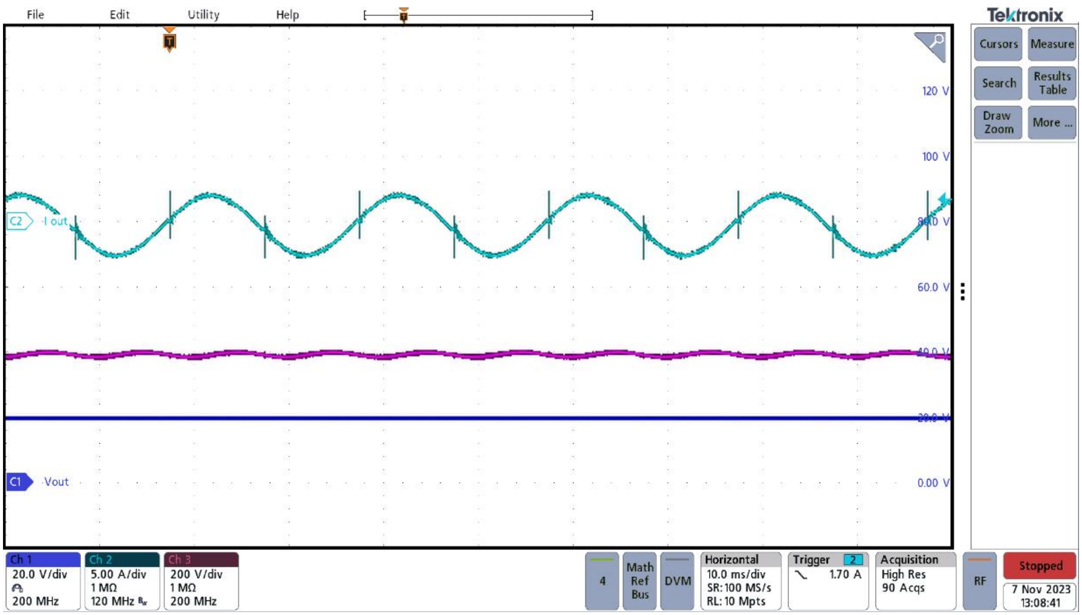
Figure - 12 Start up 230 V_{AC} / No load

4.3 Steady state operation at 350 W



CH 1 – Output voltage   CH 2 – Input current   CH 3 – Bulk cap. voltage

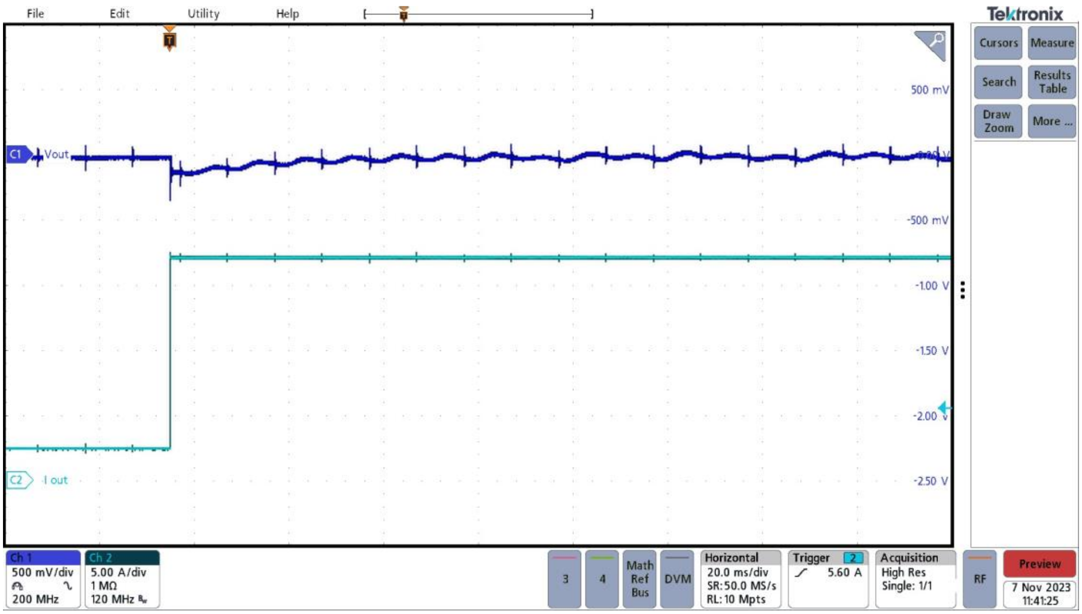
Figure - 13 Input current at 115 V_{AC} / 350 W



CH 1 – Output voltage   CH 2 – Input current   CH 3 – Bulk cap. voltage

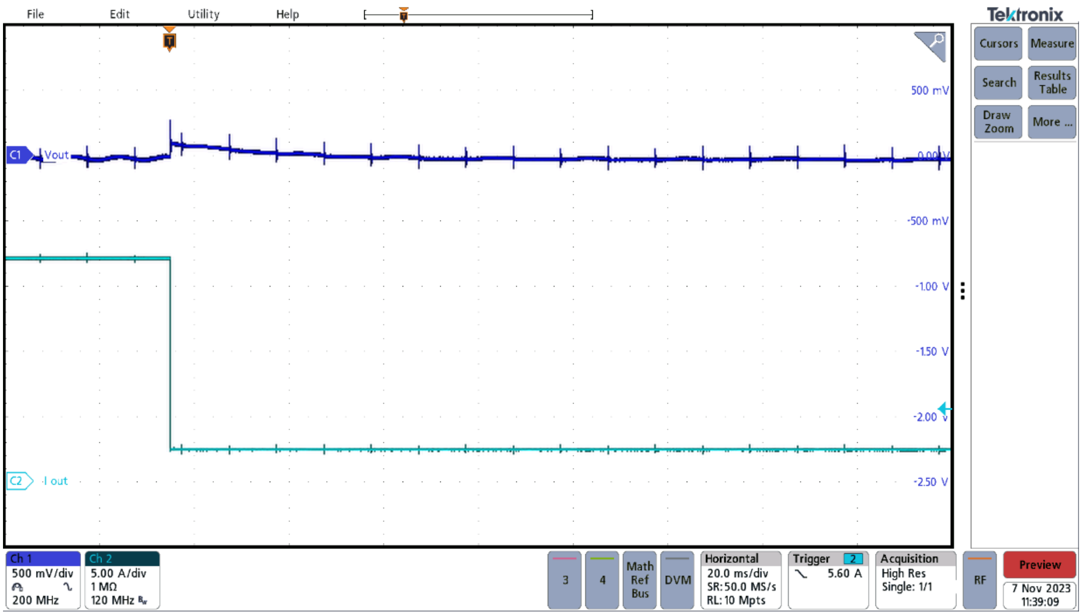
Figure 14 - Input current at 230 V_{AC} / 350 W

4.4 Load step response



CH 1 – Output voltage (AC coupled) CH 2 – Output current

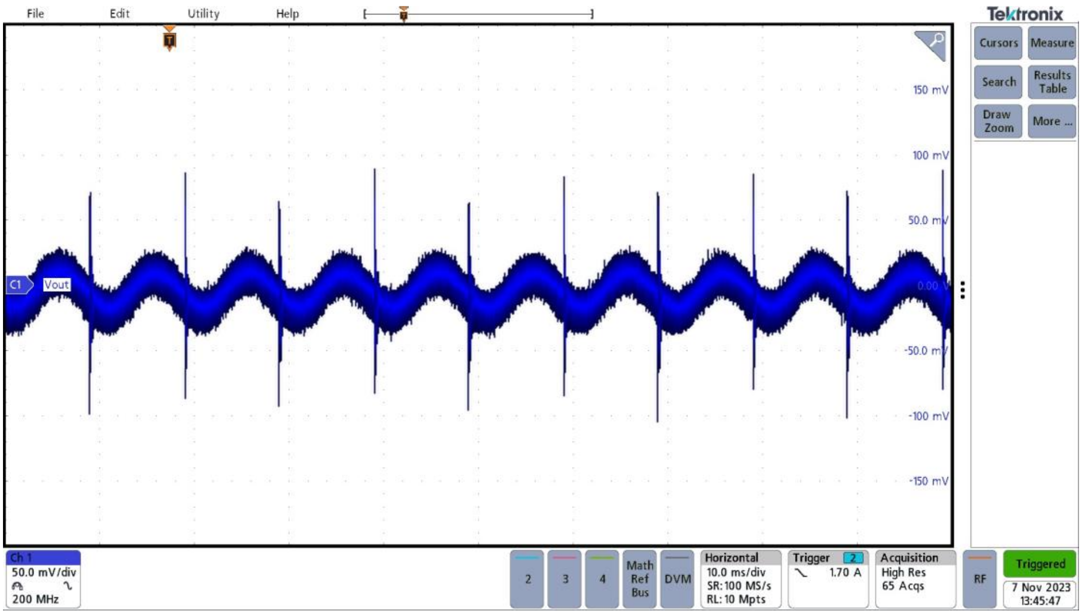
Figure 15 - 10% to 100% step load



CH 1 – Output voltage (AC coupled) CH 2 – Output current

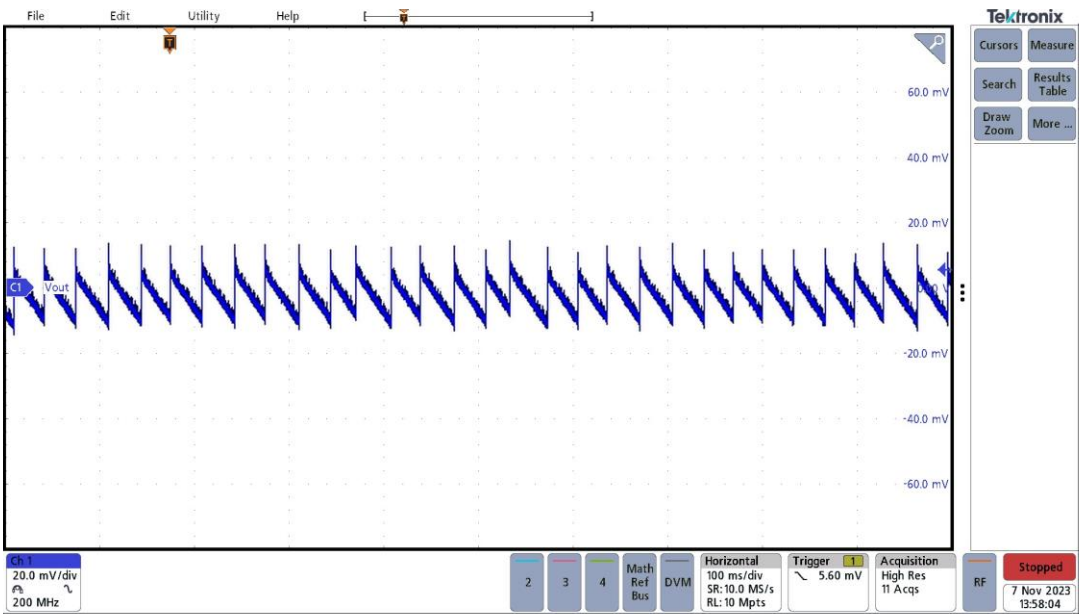
Figure 16 - 100% - 10% step load

4.5 Output voltage ripple



CH 1 – Output voltage (AC coupled)

Figure 17 - Output voltage ripple at 350 W

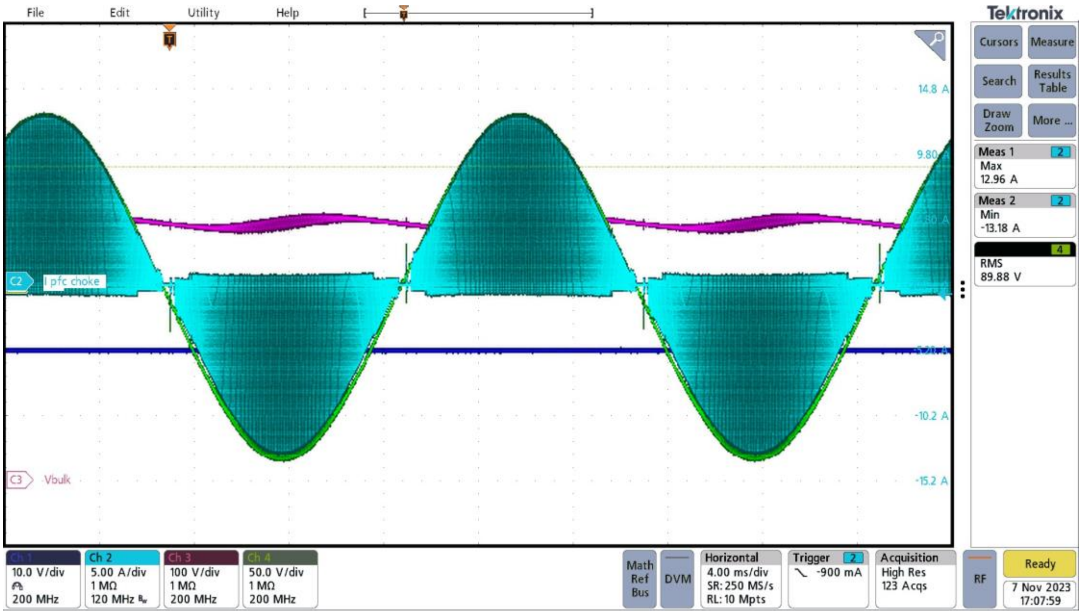


CH 1 – Output voltage (AC coupled)

Figure 18 - Output voltage ripple at no load and input voltage 265 V_{AC}

Note: In Figure 18, PFC Skip mode was activated to take the no-load output ripple waveform

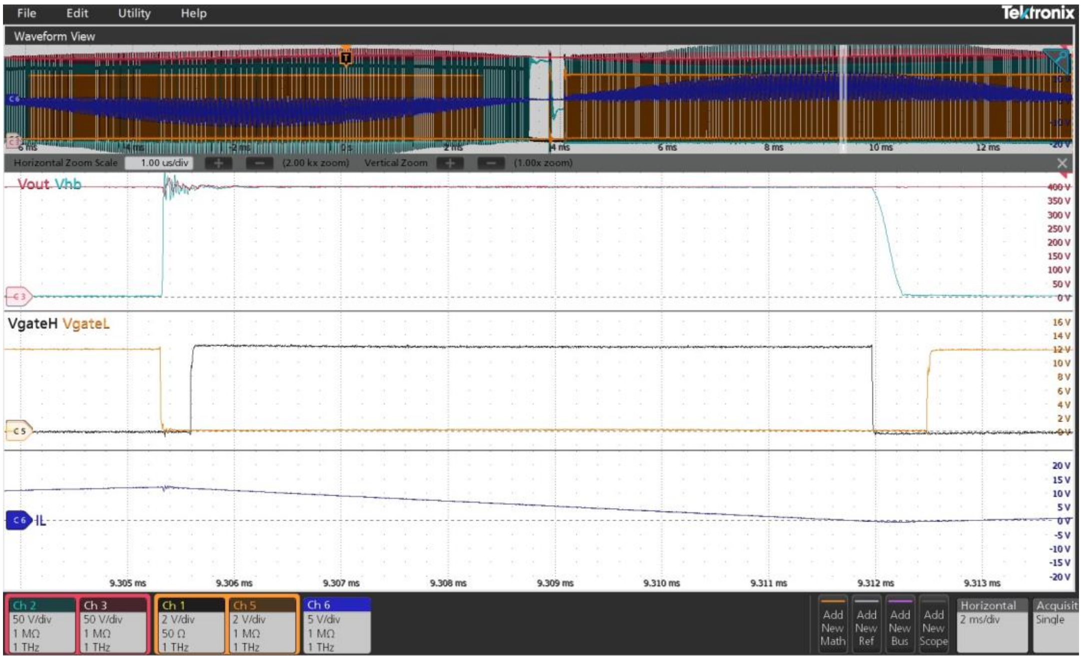
4.6 PFC inductor current at 90 V_{AC} / 350 W



CH 1 – Output voltage CH 2 – PFC inductor current CH 3 – Bulk cap. voltage CH 1 – input voltage

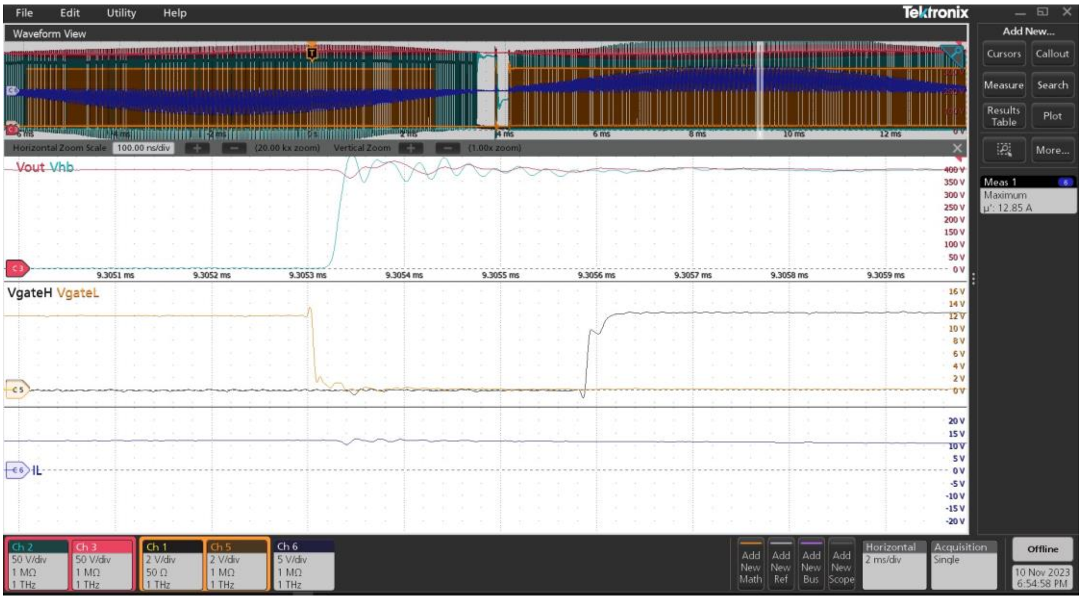
Figure 19 - PFC inductor current at 90 V_{AC} / 350 W

4.7 ICeGaN switching in the TPPFC fast leg



CH 1 – LS ICeGaN gate voltage   CH 2 – PFC fast leg midpoint   CH 3 – Vout   CH 5 – HS ICeGaN gate voltage   CH 5 – PFC inductor current (A)

Figure 20 - ICeGaN TPPFC switching waveforms at 90 V_{AC} / 350 W



CH 1 – LS ICeGaN gate voltage   CH 2 – PFC fast leg midpoint   CH 3 – Vout   CH 5 – HS ICeGaN gate voltage   CH 5 – PFC inductor current (A)

Figure 21 - ICeGaN LS to HS transition operation switching waveforms at 90 V_{AC} / 350 W

5 Thermal Results

This section presents the results of the thermal experiments under the following conditions:

- Steady state operation at 90 V_{AC} and 15-A output current (300 W).
- Thermally stable after 1 hour.
- Temperature recorded after 1.5 hours.
- The thermal results were obtained running the board in open frame at ambient temperature of 22 °C.
- The TPPFC ICeGaN daughterboard has an aluminium plate and TIM on the bottom side, attached with 3 screws; temperatures were monitored only with thermocouples; see Figure 22.
- The board underwent testing in an inverted position, with the bottom side facing upwards, to facilitate the capture of thermal images.The ICeGaN devices in the LLC side did not have any thermal relief (no heat-spreaders) and the temperature was monitored with a thermal camera; see Figure 23.
- The LLC SR device temperatures were monitored with a thermal camera; see Figure 23.
- Magnetic windings temperatures were monitored with thermocouples.

Table 8 - ICeGaN case temperatures

Reference	Component	Temperature (°C)	ΔT (°C)
Q3	PFC ICeGaN CGD65A055SH2 low side	96	74
Q2	PFC ICeGaN CGD65A055SH2 high side	95	73
Q8	LLC ICeGaN CGD65A130SH2 low side	107	85
Q6	LLC ICeGaN CGD65A130SH2 high side	109	87
T1	PFC inductor windings	100	78
T1	LLC transformer windings	110	88
Q10	Sync. rect. A	110	88
Q9	Sync. rect. B	108	86

Note: This test was carried out using K type thermocouples and Pico Logger TC-08 from Pico Technologies.

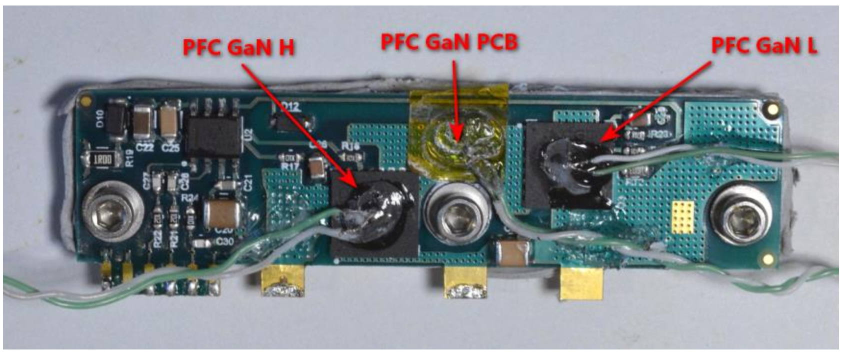


Figure 22 - TPPFC ICeGaN daughterboard. The red arrows show where the thermocouples were glued

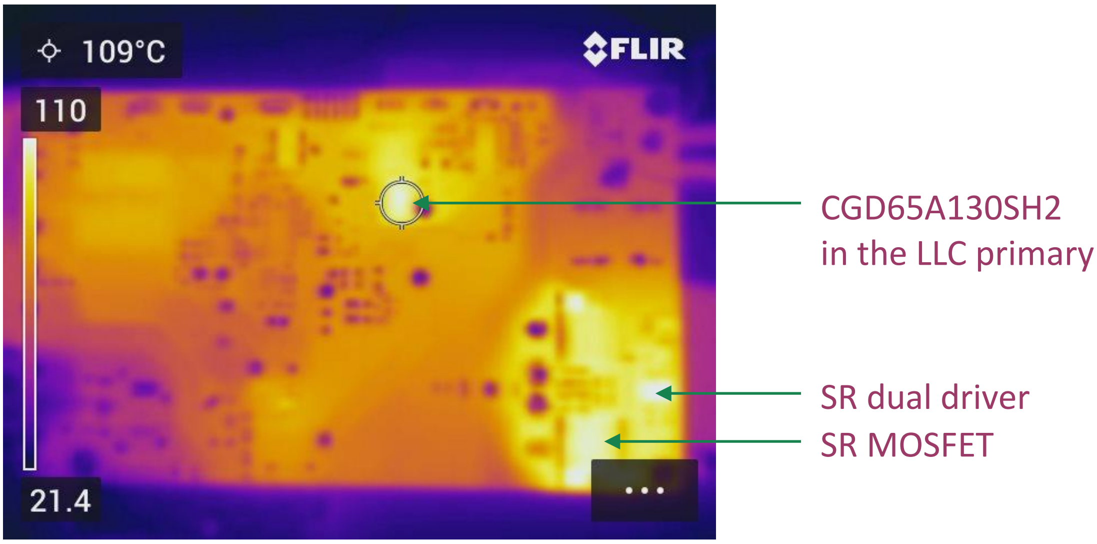


Figure 23 – Thermal camera image showing the bottom of the mainboard after reaching thermal stability

6 Design Considerations

6.1 Topology selection

A critical conduction mode totem-pole PFC topology was chosen for the ac-dc front end stage to remove the lossy diode bridge, and beat the efficiency of traditional boost PFC converter.

Critical conduction mode also called transition mode or boundary conduction mode is popular for ac-dc offline power supplies of up to 300 W. Essentially operating in CrCM, the switching loss in the switching devices are zero due to its inherent zero current switching (ZCS) and valley turn on, which at low line is actually zero voltage switching (ZVS). In contrast with continuous conduction mode (CCM), CrCM requires a smaller PFC inductor. CrCM helps to achieve the desired power density and it is particularly important in this design to be able to meet maximum height requirement of 20 mm.

For the output dc-dc stage a half-bridge LLC resonant topology was selected to meet high efficiency and high power density requirements. HB LLC is very popular for low-medium power designs above 200 W where the performance of Flyback topologies starts to be compromised. Part of the HB LLC success can be attributed to ZVS operation of the primary switching transistors. During dead time, the circulating resonant current discharges the parasitic output capacitance of the transistor that was previously off and when the voltage reaches zero the device turns on, avoiding switching loss. Although the HB LLC topology can be slightly more complex to design and control than other topologies; nowadays there are many analogue controllers in the market that simplify the design, and enable high-efficiency/cost-effective solutions.

6.2 Benefits of using ICeGaN devices in CrCM TPPFC and HB LLC topologies

There are significant benefits of using ICeGaN devices instead of Si MOSFETs or discrete GaN devices in these two topologies of this reference design.

In a CrCM TPPFC topology, the inductor current resets back to zero. Therefore, one can argue that low reverse recovery charge (Q_{RR}) Si MOSFETs could be used in the fast leg. However, ICeGaN devices are a better choice for increased efficiency and lower thermal stress. ICeGaN is a single chip e-GaN HEMT; it has no Q_{RR}, Q_G is approximately 10 times lower than in a MOSFET with the same $R_{DS(on)}$, and C_{OSS} is also lower and more linear. As a result, switching losses are insignificant when using ICeGaN in a CrCM TPPFC.

Also in the HB LLC, the use of ICeGaN devices brings more benefits than traditional Si MOSFETs. As mentioned earlier, ICeGaN has lower C_{OSS} than a MOSFET, therefore dead times are shorter which allows for higher switching frequency operation, and smaller magnetics.

Unlike other GaN HEMT alternatives, ICeGaN is very simple to drive; its gate drive voltage range is 9 V to 20 V, and there is no need for negative drive voltages. The external gate drive voltage is clamped by ICeGaN to the optimum level for the internal gate of the ICeGaN device. This extends GaN HEMT's lifetime and reliability. ICeGaN only requires a small SMD capacitor between the V_{DD} pin and the Kelvin pin, and an external gate resistor, reducing complexity and part count.

Traditional bootstrap HB gate drivers do not work with discrete e-mode GaN devices due to:

1. Poor voltage regulation on the high side (additional clamping/LDO required)
2. Most standard HB MOSFET gate driver ICs have an under voltage lock out (ULVO) threshold that is too high for 6 V gate bias so an RC network and Zener clamping circuit must be used to split 12 V into +6/-6 V – this adds reverse conduction voltage V_{SD} and impact the efficiency

The ICeGaN unique features greatly simplify the gate driving of both the TTPFC and the HB LLC:

- The TPPFC fast leg with 2xICeGaN employs a standard MOSFET bootstrap HB gate driver IC, and because Q_G is much lower than in MOSFETs, a gate driver with lower sink and source current capability can be selected.
- The ICeGaN HB leg of the LLC can be directly driven by the LLC controller's internal HB driver with no additional external components apart from the gate resistor and the V_{DD} pin capacitor for each ICeGaN device.

Figure 24 illustrates the abovementioned description; The generic HB gate driver in the figure represents the external HB gate driver IC for the TPPFC side and the LLC controller's internal HB gate driver for the HB LLC side.

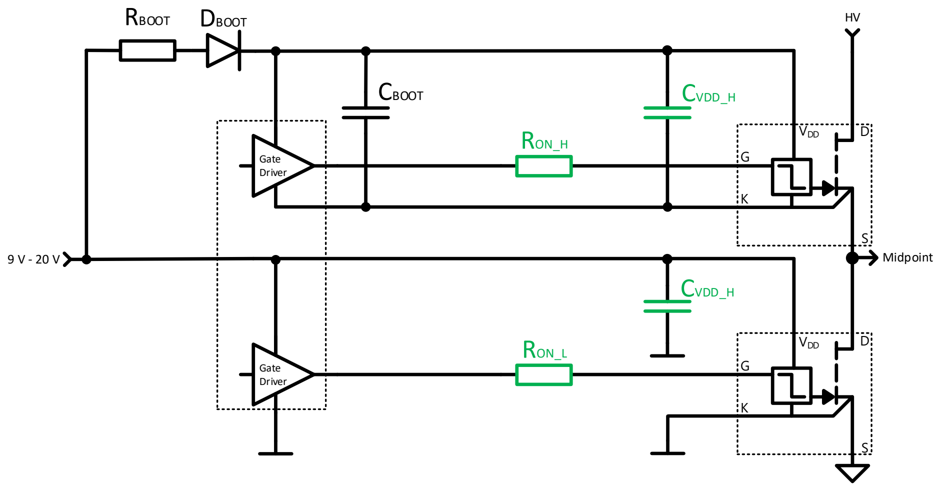


Figure 24 – External SMD components for ICeGaN

Moreover, the ICeGaN internal Miller Clamp is a major advantage over other GaN HEMT alternatives. The internal Miller Clamp operates when V_{DD} is present. The Miller Clamp clamps the internal gate voltage to zero volts when the HEMT is in off state. This means that the vast majority of the Miller current generated by the V_{DS} dv/dt does not flow through the external gate pin to the external gate drive. Therefore, parasitic inductance on the gate path is almost irrelevant at turn off so that, undesirable spurious turn on events are avoided; there is no need for negative gate drive, and there is no need for an external gate turn-off path.

This reference design simply uses a 20 Ω turn-on gate resistor for each ICeGaN device on the board, and the PCB layout of the gate paths are not as critical as with conventional GaN HEMT alternatives.

While V_{DD} is present, the maximum V_{DD} pin current is 1.6 mA for the time the gate voltage is in on-state and only a maximum of 150 µA when the gate voltage is off; this feature was implemented by monolithic incorporation of NL[3] (No Load and Light Load) circuit to reduce power consumption under no load conditions. An inexpensive SMD capacitor is used between V_{DD} and Kelvin pins. This means, when the unit enters no load operation, the bootstrap voltage rail in both the TPPFC and the HB LLC, never get depleted by the V_{DD} pin current when the high side is in off-state. That also avoids under voltage lock-out (UVLO) in the high-side driver.

In summary, ICeGaN is an excellent choice for both the CrCM TPPFC and the HB LLC for two main reasons, compared to MOSFETS or discrete GaN:

1. ICeGaN switching losses, as for any other GaN HEMT, are negligible in both topologies,boosting efficiency and power density.
2. Driving ICeGaN is simple and cost effective. No special GaN drivers are required. ICeGaN can be driven like a Si MOSFET. Unlike other GaN alternatives, only 2 SMD components are required per ICeGaN device. The CrCM TPPFC uses a standard MOSFET gate driver IC and the HB LLC uses the controller's internal HB driver to operate the ICeGaN devices.

7 Schematic

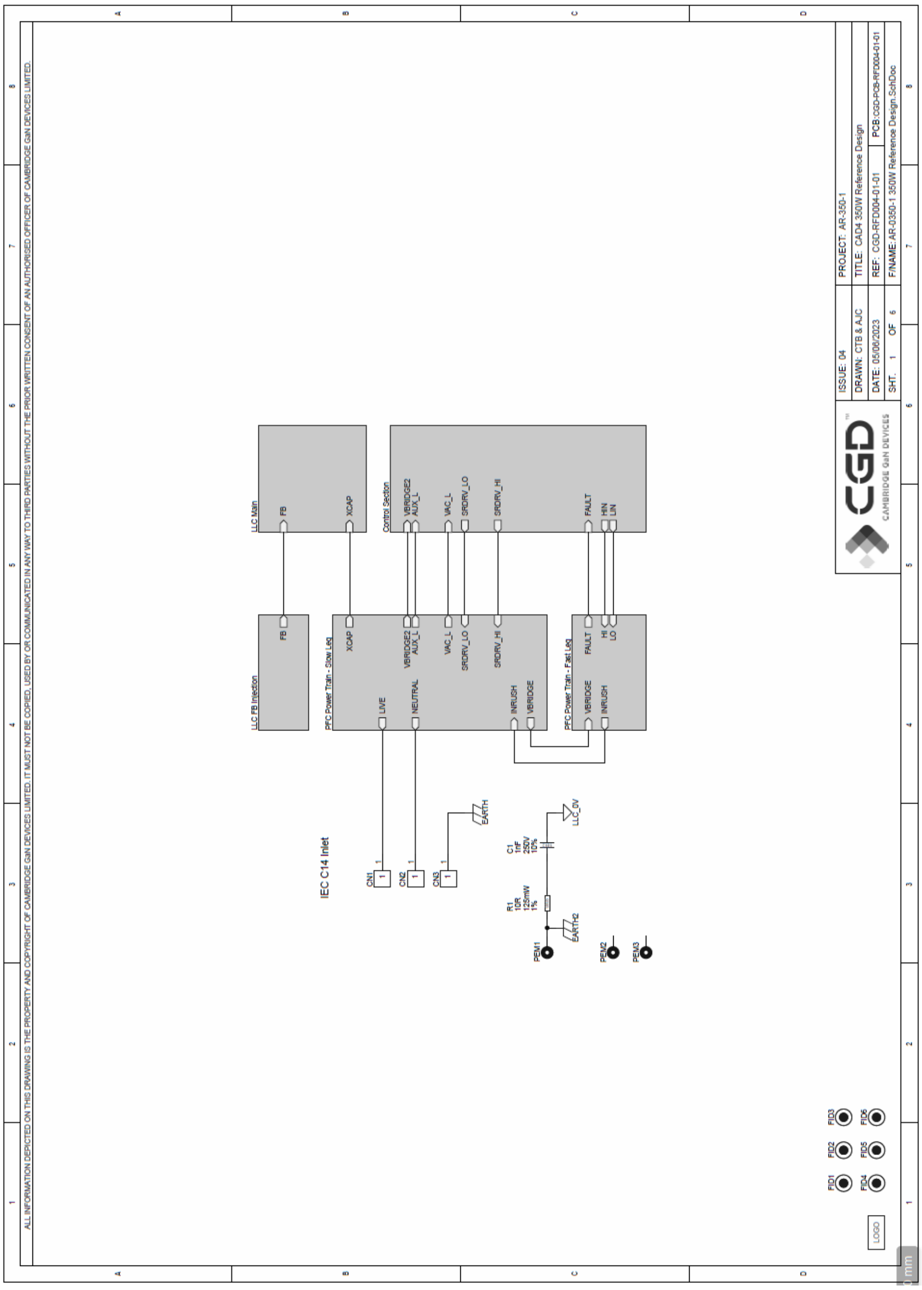


Figure 25 – Schematic: Block diagram and earth input connection

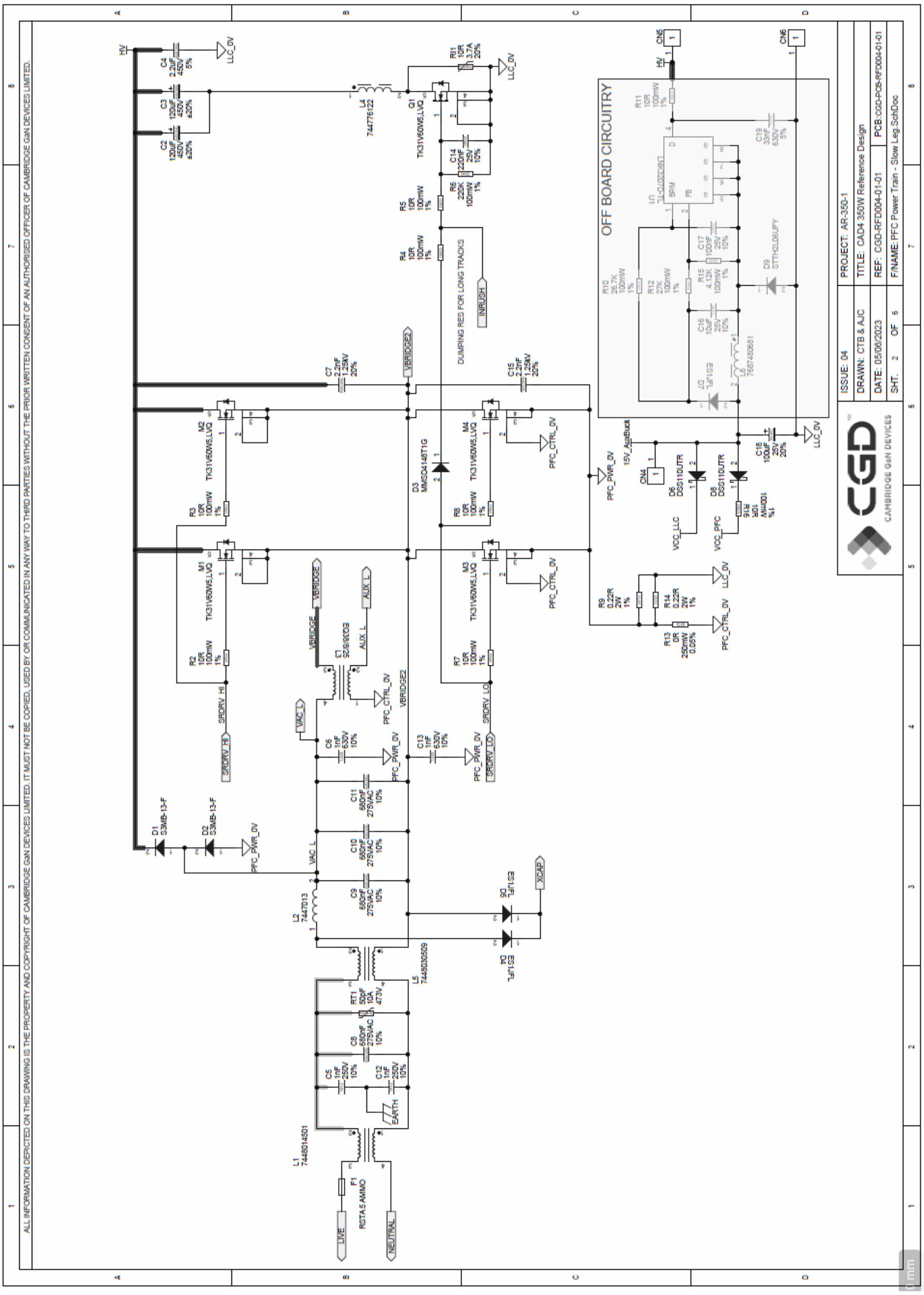


Figure 26 - Schematic: Input filter and TPPFC power section plus the auxiliary buck converter daughterboard

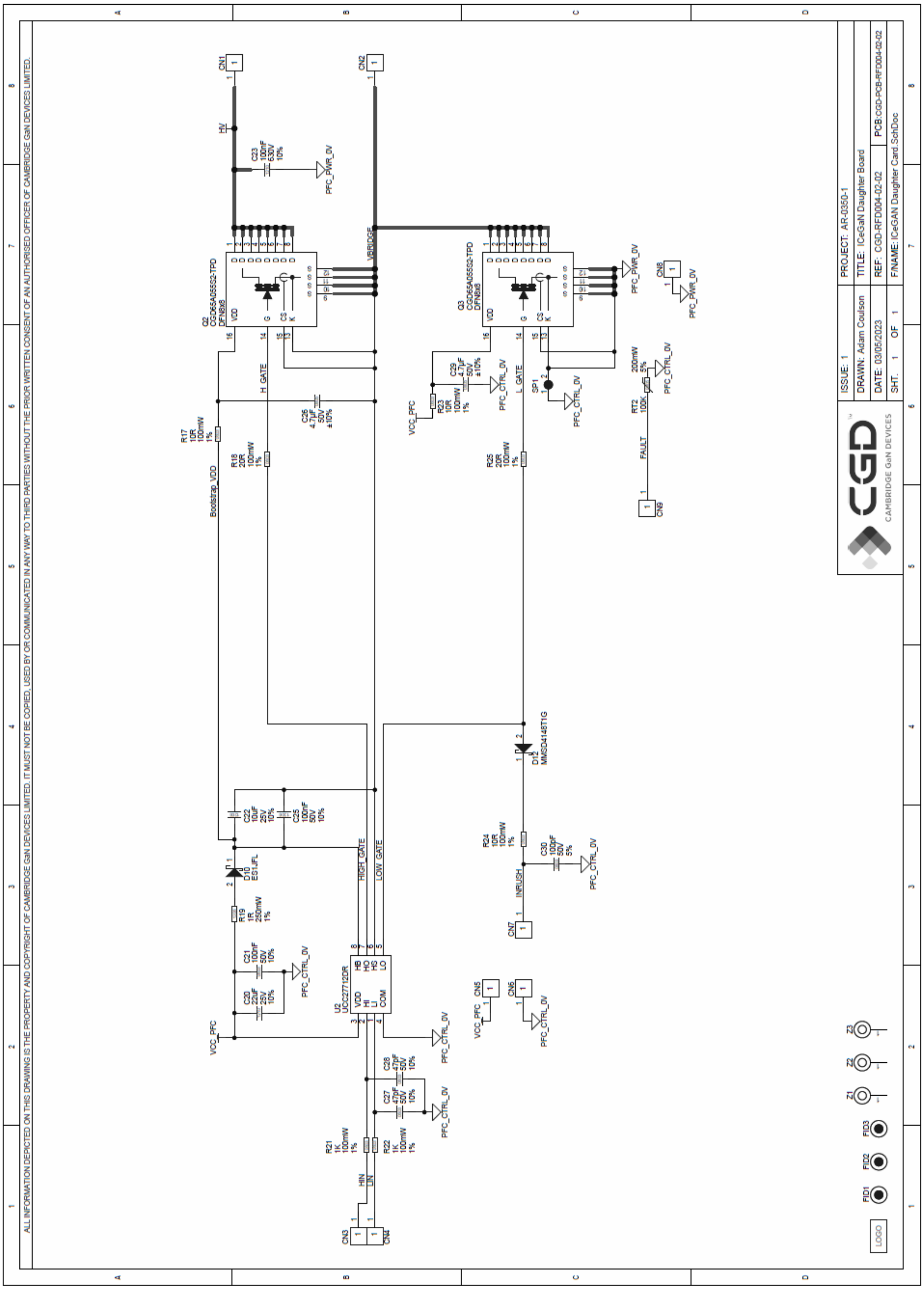


Figure 27 – Schematic: TPPFC ICeGaN fast leg daughterboard

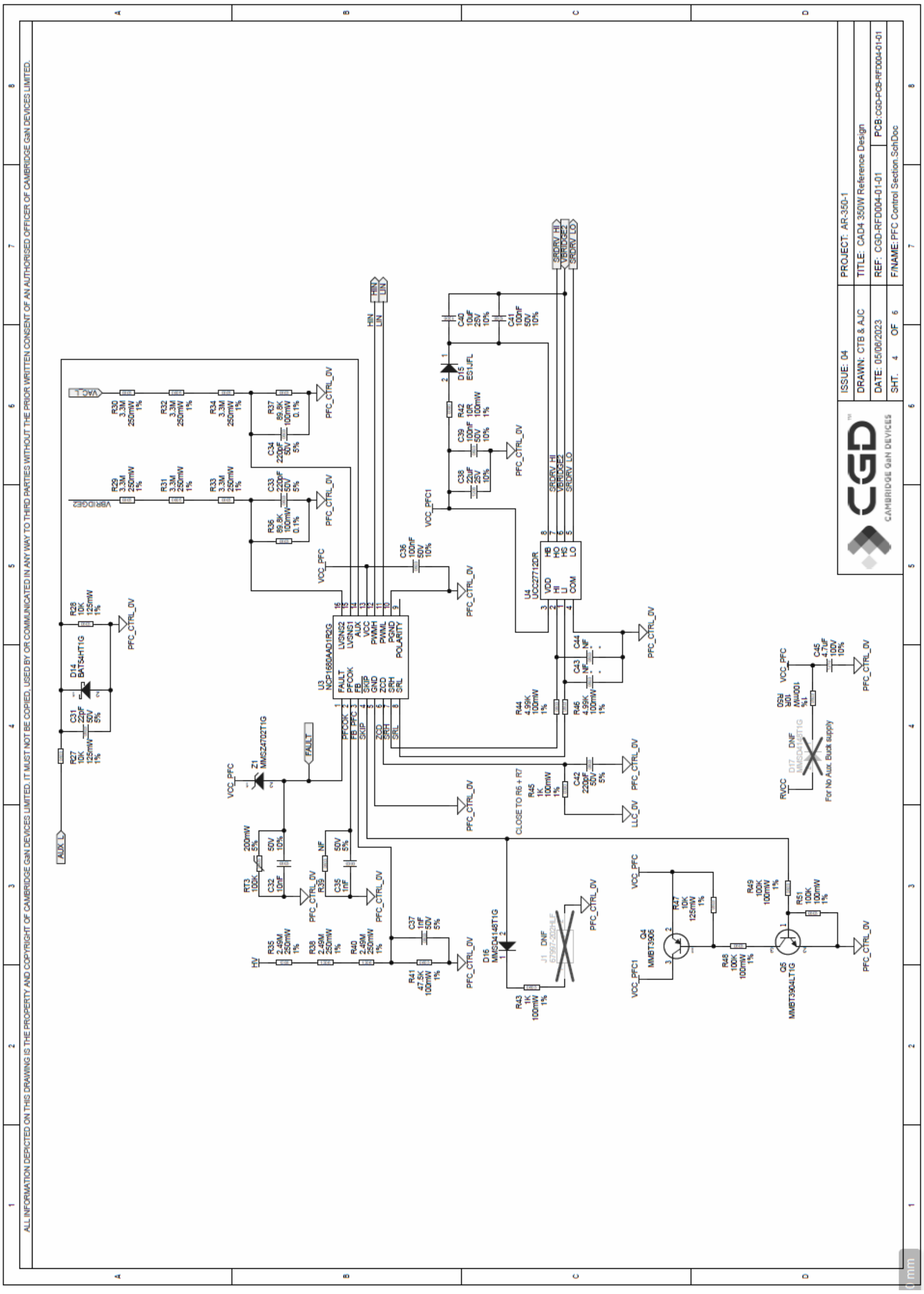


Figure 28 - Schematic: TPPFC control section

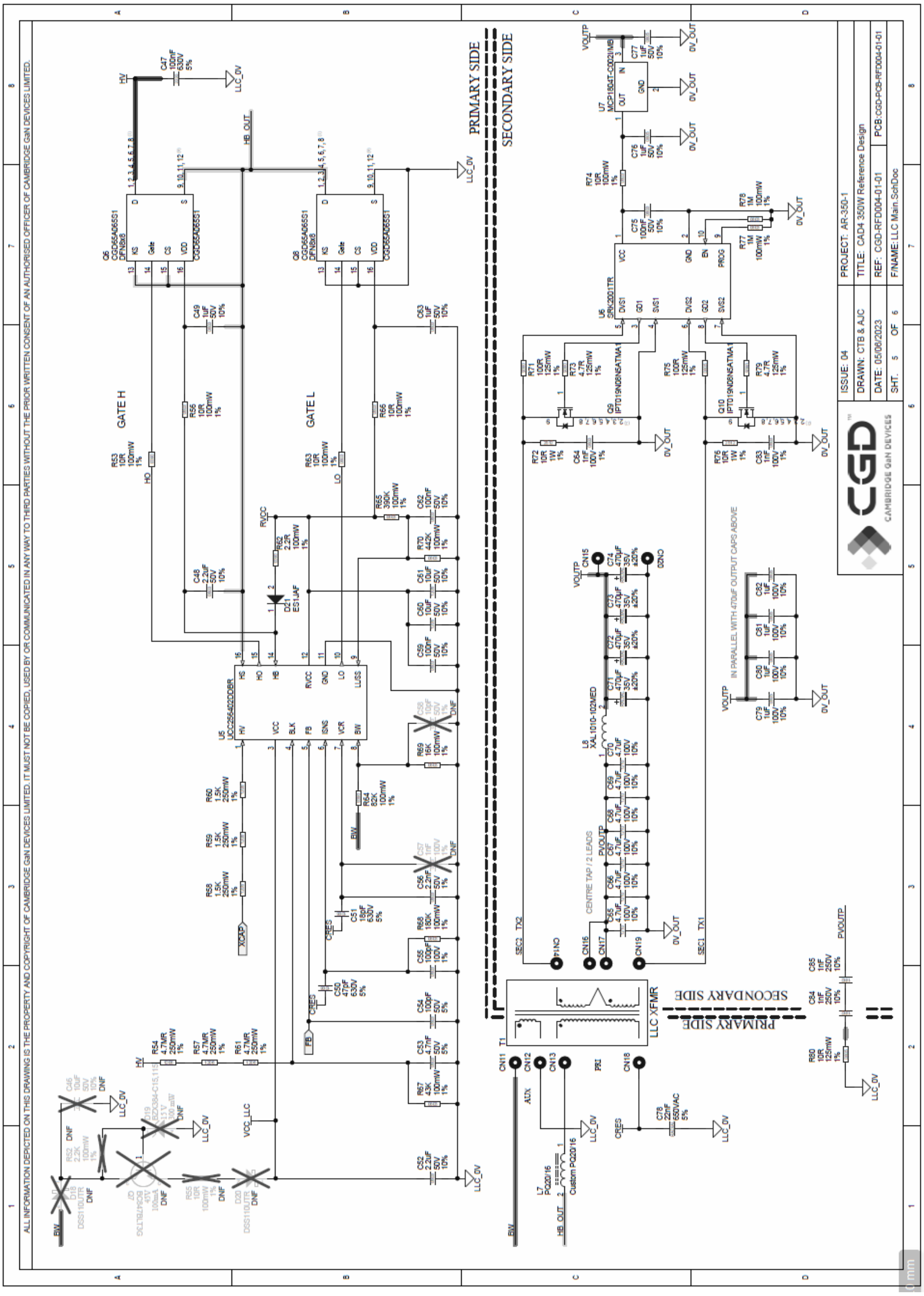


Figure 29 – Schematic: HB LLC primary and secondary synchronous rectifiers

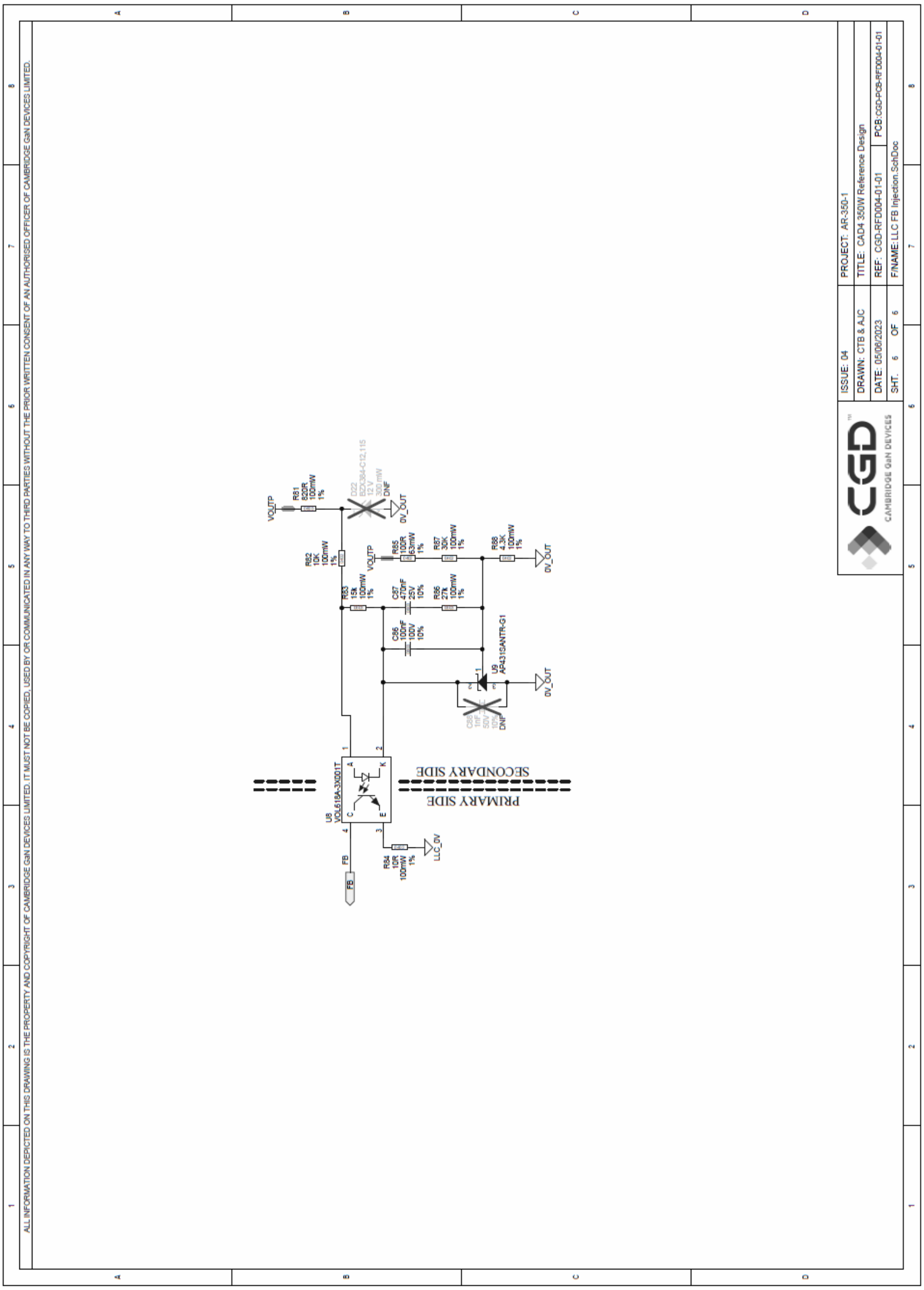


Figure 30 - Schematic HB LLC secondary side feedback control

8 PCB Layout

8.1 Mainboard layout

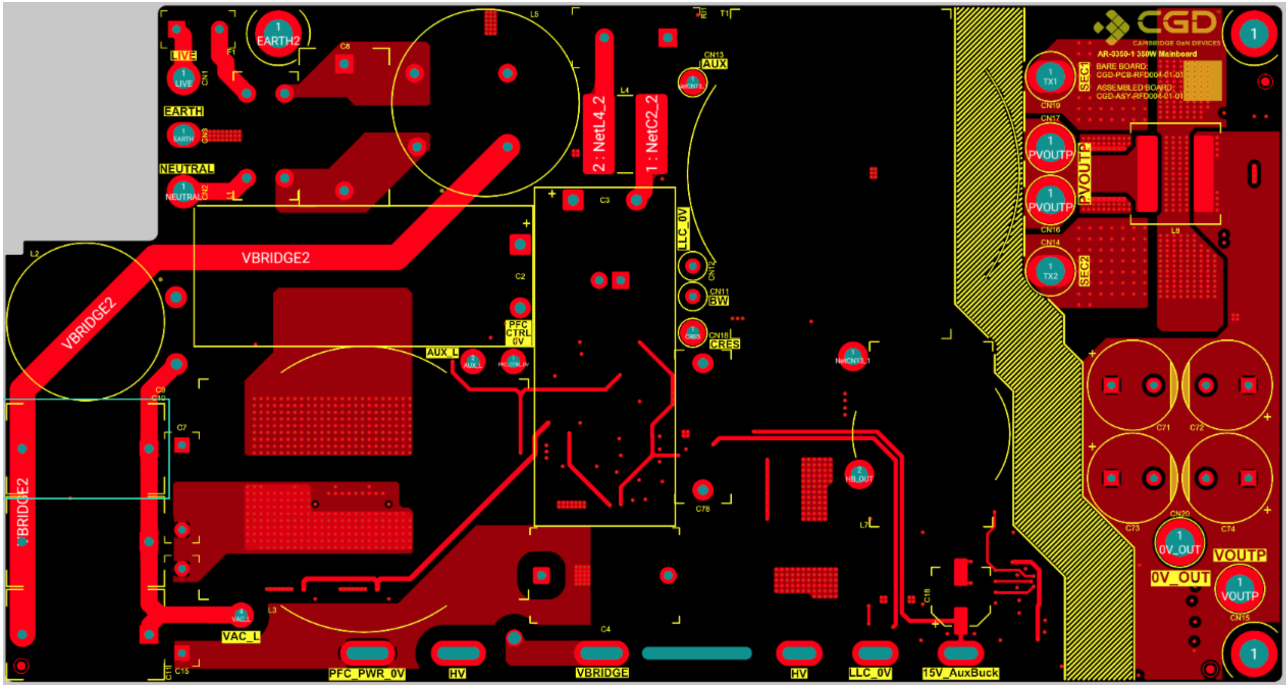


Figure 31 - Main board layout: top layer

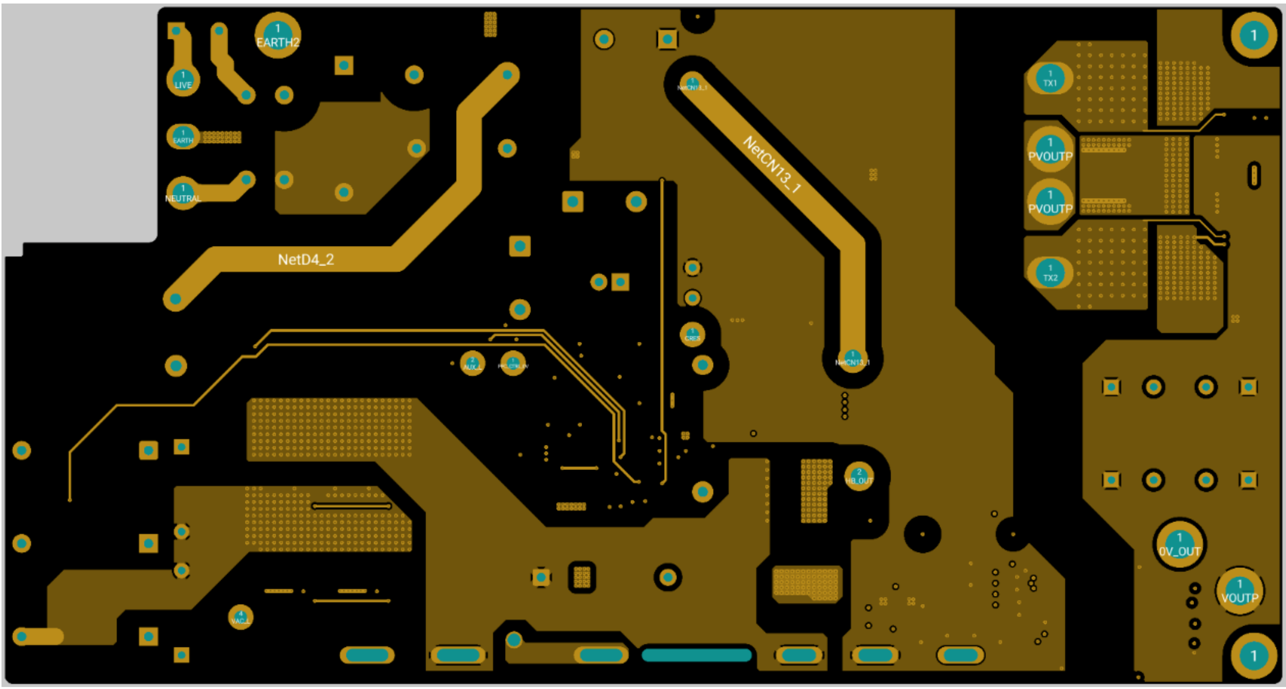


Figure 32 - Main board layout: inner layer 1

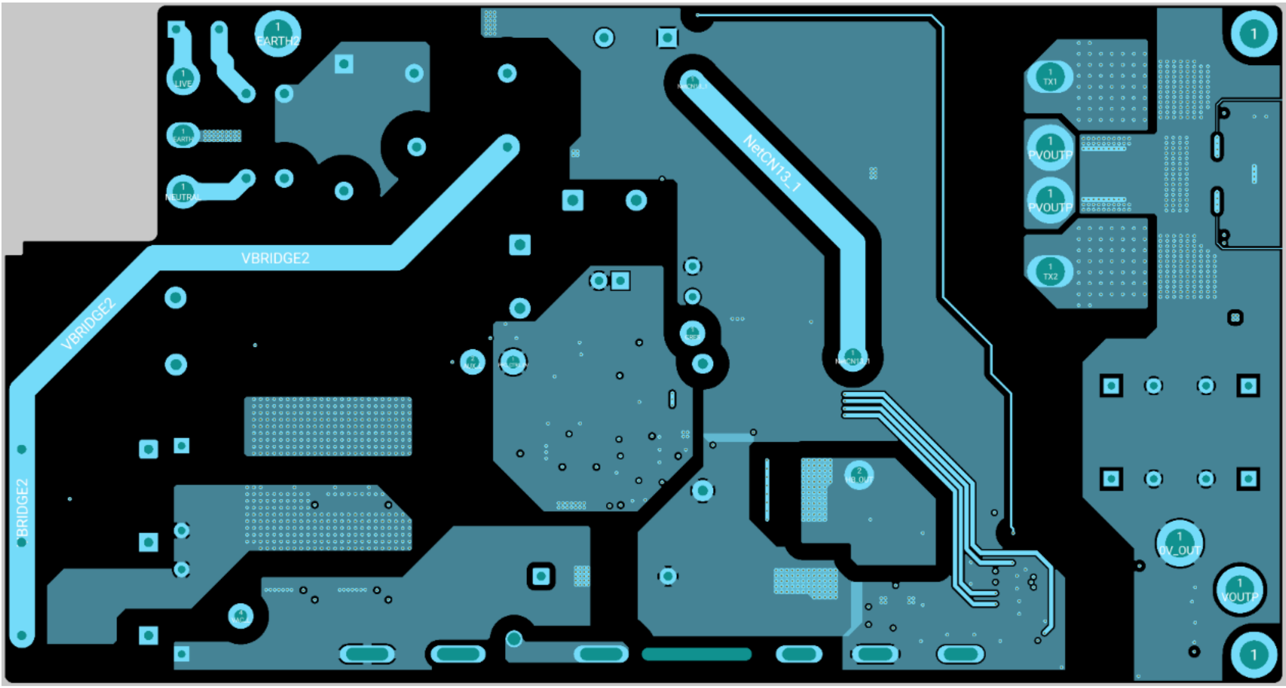


Figure 33 - Main board layout: inner layer 2

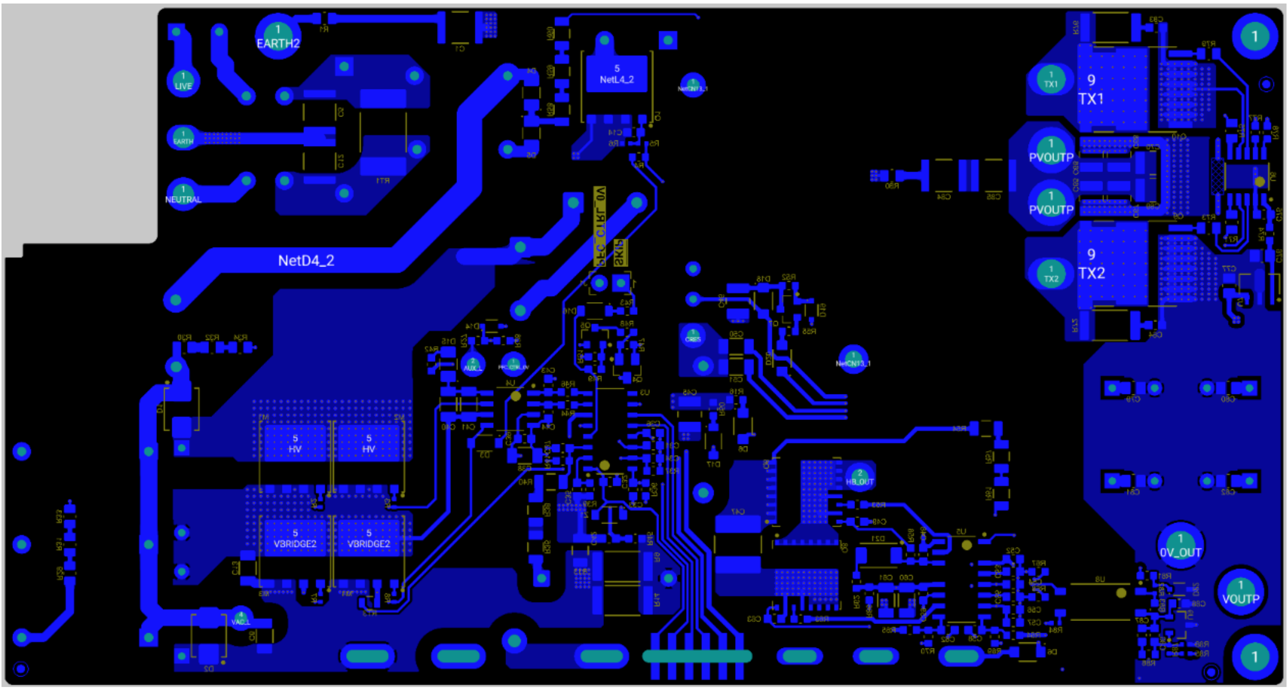


Figure 34 - Main board layout: bottom layer

8.2 Totem-pole PFC ICeGaN daughterboard

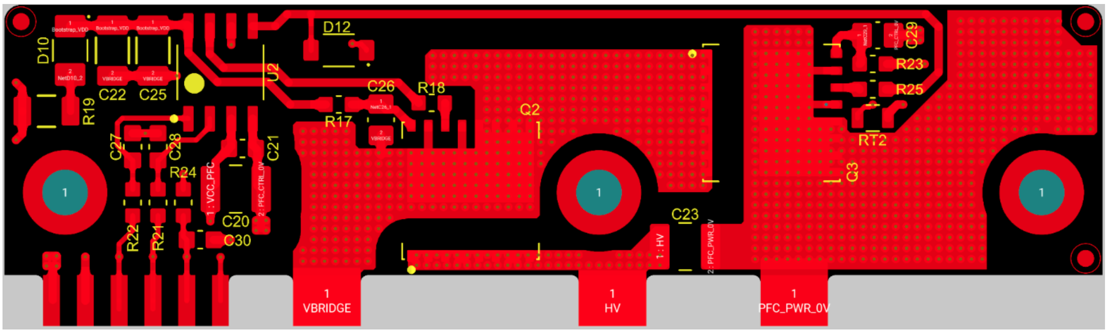


Figure 35 - TPPFC ICeGaN fast leg daughterboard layout: top layer

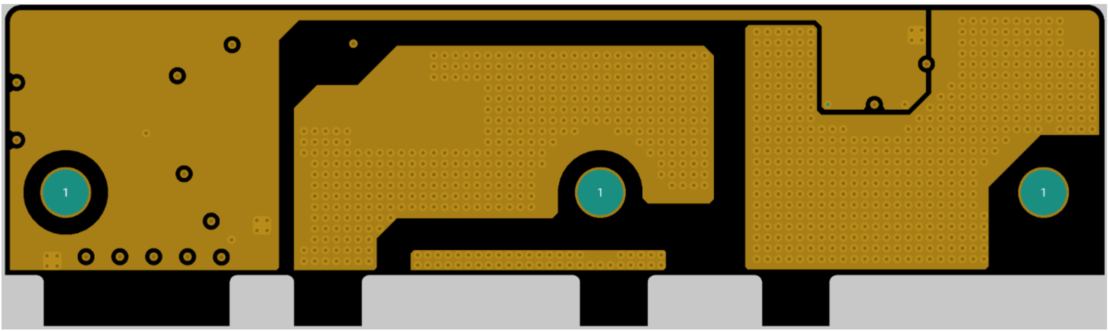


Figure 36 - TPPFC ICeGaN fast leg daughterboard layout: inner layer 1

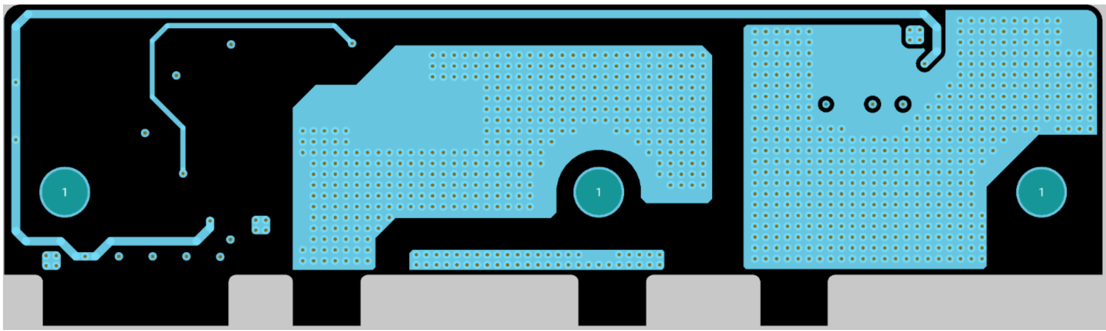


Figure 37 - TPPFC ICeGaN fast leg daughterboard layout: inner layer 2

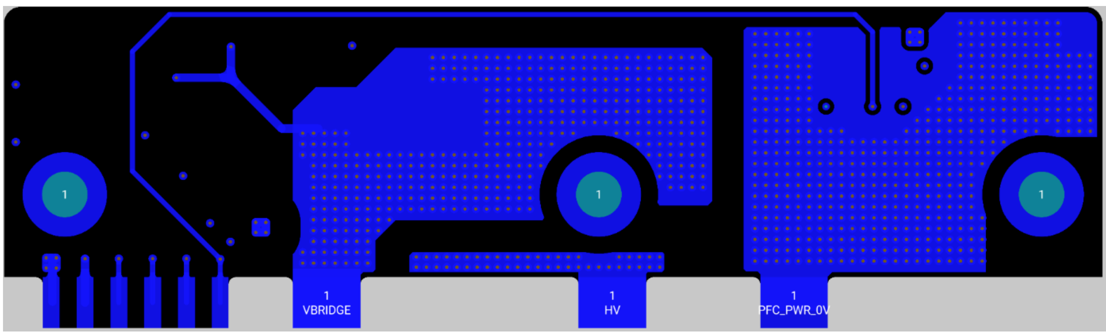


Figure 38 - TPPFC ICeGaN fast leg daughterboard layout: bottom layer

8.3 Low voltage auxiliary supply daughterboard

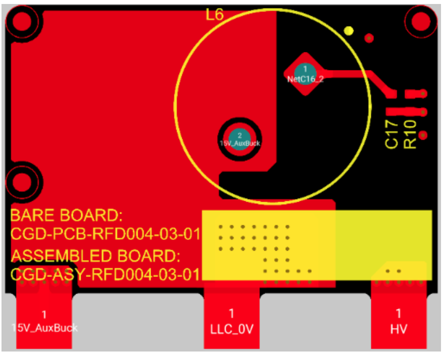


Figure 39 - LV auxiliary supply daughterboard layout: top layer

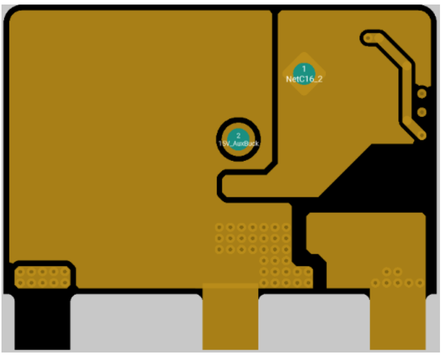


Figure 40 - LV auxiliary supply daughterboard layout: inner layer 1

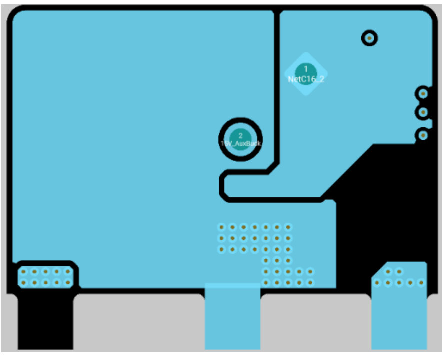


Figure 41 - LV auxiliary supply daughterboard layout: inner layer 2

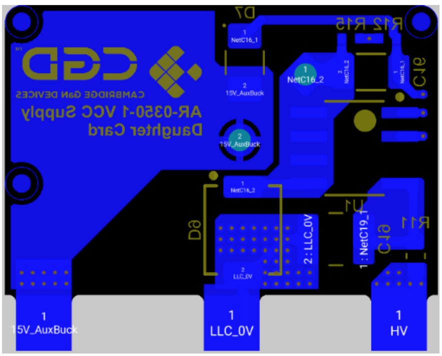


Figure 42 - LV auxiliary supply daughterboard layout: bottom layer

9 Bill of Materials (BOM)

Table 9 - Main board BOM

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
U2	Y	Half-Bridge Gate Driver IC 8-SOIC	Texas Instruments	UCC27712DR	1
L3	Y	COIL CUSTOM EQ38/8/25	Frenetic	22303-02-v01-r01	1
L7	Y	COIL CUSTOM PQ20/16	Frenetic	22303-01-v01-r01	1
T1	Y	COIL CUSTOM EQ38/8/25 ALT	Frenetic	12203-03-v01-r01	1
C64, C83	Y	CAP CER 1nF 100V 1% C0G/NP0 0603	Würth Elektronik	885012006085	2
C57	N	CAP CER 1nF 100V 1% C0G/NP0 0603	Würth Elektronik	885012006085	0
RT3	Y	THERM NTC 100K 5% 1/5W 0805	Murata	NCP21WF104J03RA	1
U3	Y	IC PFC NCP1680AAD1R2G SOIC-16	ON Semiconductor	NCP1680AAD1R2G	1
C54	Y	CAP CER 100pF 50V 5% X7R 0603	Würth Elektronik	885012206077	1
C58	N	CAP CER 10pF 50V 1% C0G/NP0 0603	Würth Elektronik	885012006051	0
C60, C61	Y	CAP CER 10uF 50V 10% X5R 1206	Würth Elektronik	885012108022	2
C46	N	CAP CER 10uF 50V 10% X7R 1210	Würth Elektronik	885012209073	0
C88	N	CAP CER 1nF 50V 10% X7R 0603	Würth Elektronik	885012206083	0
C35, C37	Y	CAP CER 1nF 50V 5% C0G/NP0 0603	Würth Elektronik	885012006063	2
C76, C77	Y	CAP CER 1uF 50V 10% X7R 0805	Würth Elektronik	885012207103R	2
C53	Y	CAP CER 4.7nF 50V 5% X7R 0603	Würth Elektronik	885012206087	1
C87	Y	CAP CER 470nF 25V 10% X7R 0603	Würth Elektronik	885012206075	1
C18	Y	CAP ELEC 100uF 25V 20% 6.3x7.7mm	Würth Elektronik	865080445010	1
C8, C9, C10, C11	Y	CAP POLY 0.68uF 275V 10% 18.5x10.5mm	Wurth Electronics	890324025045CS	4
L1	Y	CHOKE WURTH 400uH 4.5A 7448014501	Wurth Electronics	7448014501	1
L2	Y	CHOKE WURTH 90uH 4.6A 7447013	Wurth Electronics	7447013	1
L5	Y	CHOKE WURTH 9mH 5A 7448030509	Wurth Electronics	7448030509	1
R55	N	RES SMD 10R 1% 1/10W 0603	Yageo	RC0603FR-0710RL	0
U5	Y	IC LLC UCC256402DDBR	Texas Instruments	UCC256402DDBR	1
C41	Y	CAP CER 0.1uF 50V 10% X7R 1206	Würth Elektronik	885012208087	1
C32	Y	CAP CER 10nF 50V 10% X7R 0603	Würth Elektronik	885012206089	1
C6, C13	Y	CAP CER 1nF 630V 10% X7R 1206	Würth Elektronik	885342208011	2
C33, C34, C42	Y	CAP CER 220pF 50V 5% C0G/NP0 0603	Würth Elektronik	885012006059	3
C31	Y	CAP CER 22pF 50V 5% C0G/NP0 0603	Würth Elektronik	885012006053	1
Q4	Y	TRANS PNP 40V 0.2A MMBT3906 SOT-23	ON Semiconductor	MMBT3906	1
R9, R14	Y	RES SMD 0.22R 1% 2W 2512	Bourns	CRM2512-FX-R220ELF	2
R44, R46	Y	RES SMD 4.99K 1% 1/10W 0603	Yageo	RC0603FR-074K99L	2
R41	Y	RES SMD 47.5K 1% 1/10W 0603	Stackpole Electronics	RMCF0603FT47K5	1

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
U4	Y	IC GATE UCC27712DR	Texas Instruments	UCC27712DR	1
C36, C39, C59, C75	Y	CAP CER 0.1uF 50V 10% X7R 0603	Würth Elektronik	885012206095	4
R36, R37, R48, R49, R51	Y	RES SMD 100K 1% 1/10W 0603	Stackpole Electronics	RMCF0603FT100K	5
R4, R16, R42, R50, R53, R56, R63, R66, R74	Y	RES SMD 10R 1% 1/10W 0603	Yageo	RC0603FR-0710RL	9
Q6, Q8	Y	GAN 55mR DFN8x8	CGD	CGD65A065SH2	2
R62	Y	RES SMD 2.2R 1% 1/10W 0603	Panasonic	ERJ-3RQF2R2V	1
R29, R30, R31, R32, R33, R34	Y	RES SMD 3.3M 1% 1/4W 0805	KOA Speer	RK73H2ATTD3304F	6
C78	Y	CAP POLY 0.022uF 650VAC 1.6KVDC 5% 18X6.5mm	KEMET	PHE450RB5220JR06	1
Q9, Q10	Y	MOSFET N-CH 80V 32A/247A	Infineon	IPT019N08N5ATMA1	2
R82	Y	RES SMD 10K 1% 1/10W 0402	Vishay	MCS0402MC1002FE000	1
R2, R3, R5, R7, R8, R84	Y	RES SMD 10R 1% 1/10W 0402	Panasonic	ERJ-U02F10R0X	6
R6	Y	RES SMD 220K 1% 1/10W 0402	Panasonic	ERJ-2RKF2203X	1
R87	Y	RES SMD 30K 1% 1/10W 0402	Panasonic	ERJU02F3002X	1
R88	Y	RES SMD 4.3K 1% 1/10W 0402	Panasonic	ERJ-2RKF4301X	1
U6	Y	IC RECT SRK2001TR	STMicroelectronics	SRK2001TR	1
U7	Y	REG LINEAR MCP1804T-C002I/MB	Microchip	MCP1804T-C002I/MB	1
U8	Y	OPTO 80V 60mA SOP-4	Vishay Würth Elektronik	VOL618A-3X001T 140106146000	1
U9	Y	REG SHUNT AP431SANTR-G1	Diodes	AP431SANTR-G1	1
Q7	N	TRANS NPN 45V 0.1A SOT-23	ON Semiconductor	BC847BLT3G	0
CN1, CN2, CN3	Y	CON 2.5MM PTH 6x4MM PAD	-	-	-
CN9	Y	CON EDGE 13x1.5MM SLOT	-	-	-
CN7, CN8, CN10	Y	CON EDGE 5x1.5MM SLOT	-	-	-
R39	N	RES SMD NF 0603	-	-	-
C86	Y	CAP CER 0.1uF 100V 10% X7R 0603	Würth Elektronik	885012206120	1
C47	Y	CAP CER 0.1uF 630V 5% C0G 2220	TDK	CGA9Q1C0G2J104J280KC	1
C55	Y	CAP CER 100pF 100V 1% C0G/NP0 0603	Würth Elektronik	885012006079	1
C40	Y	CAP CER 10uF 25V 10% X7R 1206	Würth Elektronik	885012208069	1
C51	Y	CAP CER 18pF 630V 5% C0G/NP0 1206	Murata	GRM31A5C2J180JW01D	1
C1, C5, C12, C84, C85	Y	CAP CER 1nF 250V 10% X7R 1812	Wurth Electronics	8853522110031	5
C79, C80, C81, C82	Y	CAP CER 1uF 100V 10% X7R 0805	Kyocera AVX	08051C105K4Z2A	4
C49, C62, C63	Y	CAP CER 1uF 50V 10% X7R 0603	Würth Elektronik	885012206126	3

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
C56	Y	CAP CER 2.2nF 50V 1% C0G 0603	KEMET	C0603C222F5GACTU	1
C48, C52	Y	CAP CER 2.2uF 50V 10% X5R 0603	Murata	GRM188R61H225KE11D	2
C14	Y	CAP CER 220nF 25V 10% X7R 0603	Würth Elektronik	885012206073	1
C38	Y	CAP CER 22uF 25V 10% X5R 1206	Samsung	CL31A226KAHNNNE	1
C45, C65, C66, C67, C68, C69, C70	Y	CAP CER 4.7uF 100V 10% X7R 1210	Kyocera AVX	12101C475K4T2A	7
C50	Y	CAP CER 47pF 630V 5% C0G/NP0 1206	Murata	GRM31A5C2J470JW01D	1
C43, C44	N	CAP CER NF 0603	-	-	2
C7, C15	Y	CAP POLY 2.2nF 1.25kV 20% 13x4mm	KEMET	PHE850EA4220MA01R17	2
C4	Y	CAP POLY 2.2uF 450V 5% 17.5x11.1mm	Panasonic	ECW-FD2W225J	1
C2, C3	Y	CAP RAD 120uF 450V 20% 16.50x37mm	Würth Elektronik	860241480001	2
D1, D2	Y	DIODE STD S3MB-13-F	Diodes	S3MB-13-F	2
D3, D16	Y	DIODE STD MMSD4148T1G	ON Semiconductor	MMSD4148T1G	2
D4, D5, D15	Y	DIODE STD ES1JFL	ON Semiconductor	ES1JFL	3
D6	Y	DIODE SCHOTTKY DSS110UTR	SMC	DSS110UTR	1
D14	Y	DIODE SCHOTTKY BAT54HT1G	ON Semiconductor	BAT54HT1G	1
D21	Y	DIODE STD ES1JAF	ON Semiconductor	ES1JAF	1
F1	Y	FUSE RSTA-5-AMMO	Bel	RSTA5AMMO	1
L4	Y	L WURTH 22uH 2.04A 744776122	Wurth Electronics	744776122	1
Q5	Y	TRANS NPN 40V 200mA SOT-23	ON Semiconductor	MMBT3904LT1G	1
R58, R59, R60	Y	RES SMD 1.5K 1% 1/4W 1206	Vishay	CRCW12061K50FKEAC	3
R85	Y	RES SMD 100R 1% 1/16W 0402	Yageo	RC0402FR-07100RL	1
R71, R75	Y	RES SMD 100R 1% 1/8W 0805	Yageo	RC0805FR-07100RL	2
R27, R28, R47	Y	RES SMD 10K 1% 1/8W 0603	Stackpole Electronics	RNCP0603FTD10K0	3
R1, R80	Y	RES SMD 10R 1% 1/8W 0805	Yageo	RC0805FR-0710RL	2
R72, R76	Y	RES SMD 10R 1% 1W 2512	TE Connectivity	CRGCQ2512F10R	2
R83	Y	RES SMD 15K 1% 1/10W 0603	Yageo	RC0603FR-0715KL	1
R69	Y	RES SMD 16K 1% 1/10W 0603	Yageo	RC0603FR-0716KL	1
R43, R45	Y	RES SMD 1K 1% 1/10W 0603	Yageo	RC0603FR-071KL	2
R77, R78	Y	RES SMD 1M 1% 1/10W 0603	Yageo	RC0603FR-071ML	2
R52	N	RES SMD 2.2K 1% 1/10W 0603	Yageo	RC0603FR-072K2L	0
R35, R38, R40	Y	RES SMD 2.49M 1% 1/4W 1206	Stackpole Electronics	RMCF1206FT2M49	3
R70	Y	RES SMD 20K 1% 1/10W 0603	Yageo	RC0603FR-0720KL	1
R86	Y	RES SMD 27K 1% 1/10W 0603	Yageo	RC0603FR-0727KL	1
R54, R57, R61	Y	RES SMD 4.7MR 1% 1/4W 1206	Yageo	RC1206FR-074M7L	3
R73, R79	Y	RES SMD 4.7R 1% 1/8W 0805	Yageo	RC0805FR-074R7L	2

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
R67	Y	RES SMD 43K 1% 1/10W 0603	Yageo	RC0603FR-0743KL	1
R65	Y	RES SMD 51K 1% 1/10W 0603	Yageo	RC0603FR-0751KL	1
R68	Y	RES SMD 75R 1% 1/10W 0603	Yageo	RC0603FR-0775RL	1
R81	Y	RES SMD 820R 1% 1/10W 0603	Yageo	RC0603FR-07820RL	1
R64	Y	RES SMD 82K 1% 1/10W 0603	Yageo	RC0603FR-0782KL	1
RI1	Y	ICL 10R 3.7A 20% RAD15x7mm	TDK EPCOS	B57237S0100M000	1
RT1	Y	VARIS 50pF 250kA 430V MLCV	Littelfuse	V430CH8	1
Z1	Y	DIODE ZENER MMSZ4702T1G	ON Semiconductor	MMSZ4702T1G	1
C71, C72, C73, C74	Y	CAP RAD 470uF20% 35V 10x14mm CAP RAD 470uF20% 25V 10x14mm	KEMET Würth Elektronik	A750MV477M1VAAE018 860080475016	4
D8, D18, D20	N	DIODE SCHOTTKY DSS110UTR	SMC	DSS110UTR	0
D17	N	DIODE STD MMSD4148T1G	ON Semiconductor	MMSD4148T1G	0
D19	N	DIODE ZENER BZX384-C15,115	Nexperia	BZX384-C15,115	0
D22	N	DIODE ZENER BZX384-C12,115	Nexperia	BZX384-C12,115	0
R13	Y	RES SMD JUMPER 0R 0.05% 1/4W 1206	Panasonic	ERJ8GEY0R00V	1
L8	Y	L 1uH 32A 11.8mm x 11.6mm x 10mm	COILCRAFT	XAL1010-102MED	1
M1, M2, M3, M4, Q1	Y	MOSFET N-CH 600V 30.8A TK31V60W5,LVQ	Toshiba	TK31V60W5,LVQ	5
J1	N	NO FITTED	-	'-	0

Table 10 - TPPFC ICeGaN fast leg daughterboard BOM

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
C20	Y	CAP CER 22uF 25V 10% X7R 1210	Würth Elektronik	885012209074	1
C21	Y	CAP CER 0.1uF 50V 10% X7R 0603	Würth Elektronik	885012206095	1
C22	Y	CAP CER 10uF 25V 10% X7R 1206	Würth Elektronik	885012208069	1
C23	Y	CAP CER 0.1uF 630V 10% X7R 1210	KEMET	C1210C104KBRACTU	2
C25	Y	CAP CER 0.1uF 50V 10% X7R 1206	Würth Elektronik	885012208087	1
C26, C29	Y	CAP CER 4.7uF 50V 10% X7R 0805	TDK	C2012X7R1H475K125AC	2
C27, C28	Y	CAP CER 47pF 50V 10% X7R 0603	KEMET	C0603C470K5RACTU	2
C30	Y	CAP CER 100pF 50V 5% X7R 0603	YAGEO	CS0603KRX7R9BB101	1
D10	Y	DIODE STD ES1JFL	ON Semiconductor	ES1JFL	1
D12	Y	DIODE STD MMSD4148T1G	ON Semiconductor	MMSD4148T1G	1
Q2, Q3	Y	GAN 55mR-TPD DFN8x8	CGD	CGD65A055SH2	2
R17, R23, R24	Y	RES SMD 10R 1% 1/10W 0603	VISHAY	CRCW060310R0FKTA	3
R18, R25	Y	RES SMD 20R 1% 1/10W 0603	BOURNS	CR0603-FX-20R0ELF	2
R19	Y	RES SMD 1R 1% 1/4W 1206	BOURNS	CRS1206AFX-1R00ELF	1
R21, R22	Y	RES SMD 1K 1% 1/10W 0603	KOA	RK73H1JRTTD1001F	2
RT2	Y	THERM NTC 100K 5% 1/5W 0805	MURATA	NCP21WF104J03RA	1

Table 11 - Auxiliary buck converter daughterboard BOM

Designator	Fitted	Description	Manufacturer	Manu. P/N	Qty
C16	Y	CAP CER 10uF 25V 10% X7R 1206	Würth Elektronik	885012208069	1
C17	Y	CAP CER 0.1uF 25V 10% X7R 0402	Würth Elektronik	885012205085R	1
C19	Y	CAP CER 33nF 630V 5% X7R 1210	TDK	CGA6P4NP02J333J250AA	1
CN1, CN2, CN3	Y	CON EDGE MATE 3x3MM PAD	-	-	-
D7	Y	DIODE STD ES1JFL	ON Semiconductor / Fairchild	ES1JFL	1
D9	Y	DIODE STD STTH2L06UFY	STMicroelectronics		1
L6	Y	L WURTH 680uH 780mA	Wurth Electronics	7687480681	1
R10	Y	RES SMD 26.7K 1% 1/10W 0402	Panasonic	ERJ-2RKF2672X	1
R11	Y	RES SMD 10R 1% 1/10W 0603	VISHAY	CRCW060310R0FKTA	1
R12	Y	RES SMD 27K 1% 1/10W 0402	Panasonic	ERJ-U02F2702X	1
R15	Y	RES SMD 4.12K 1% 1/10W 0402	Panasonic	ERJ-2RKF4121X	1
U1	Y	IC Converter Offline Buck L SO-8C	Power Integrations	LNK3207D-TL	1

10 List of Figures

11 List of Tables

Dare to innovate differently

Cambridge GaN Devices Limited
Jeffreys Building, Suite 8
Cowley Road
Cambridge
CB4 0DS
United Kingdom