Reference Design

TDTTP3300-RD
3.3kW Bridgeless Totem-pole PFC

Hardware Design Guide

transphorm

Highest Performance, Highest Reliability GaN

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1 Introduction

Employing GaN (Gallium Nitride) FETs in power circuits offers many advantages over superjunction (SJ) Silicon FETs and, as GaN's acceptance gains momentum, their reliability and ruggedness are becoming more evident.

Combining wide band-gap GaN technology with converter topologies enables power engineers to develop high-efficiency circuits such as the bridgeless totem-pole PFC boost power converter and achieve increased power density, reduced system size and weight, and overall lower system cost.

The TDTTP3300-RD 3.3kW bridgeless totem-pole PFC reference design provides an excellent platform for evaluating the performance of Transphorm's GaN FETs and a starting point for designing a high-efficiency DSP-based PFC converter. This DSP firmware-based totem-pole PFC gives power hardware designers a fully-functional design solution with no code expertise required, reducing design time and accelerating time to market.

This document provides comprehensive information on the hardware portion of the TDTTP3300-RD reference design featuring Transphorm's TP65H050WS 50mΩ GaN FETs, including inductor design, circuit schematics, layout guidelines, and bill of materials.

1.1 Design resources

Visit transphormusa.com/tp33rd for complete design information and documentation, including:

- Test report (operation and performance)
- Firmware design guide (instructions for customizing the converter)
- Design files
- Firmware files
- FAQs

Figure 1. 3.3kW bridgeless totem-pole PFC demo board (top view)

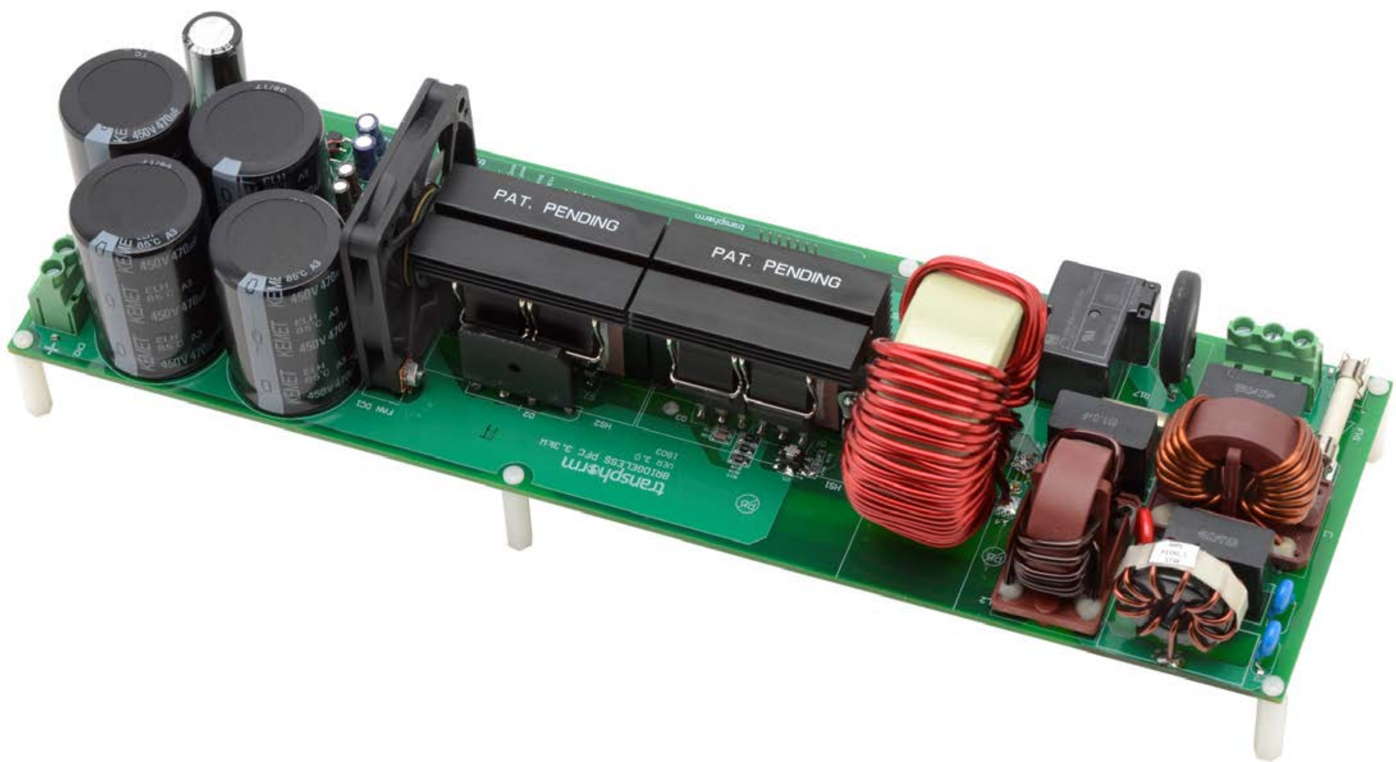

Figure 2. 3.3kW bridgeless totem-pole PFC demo board (back view)

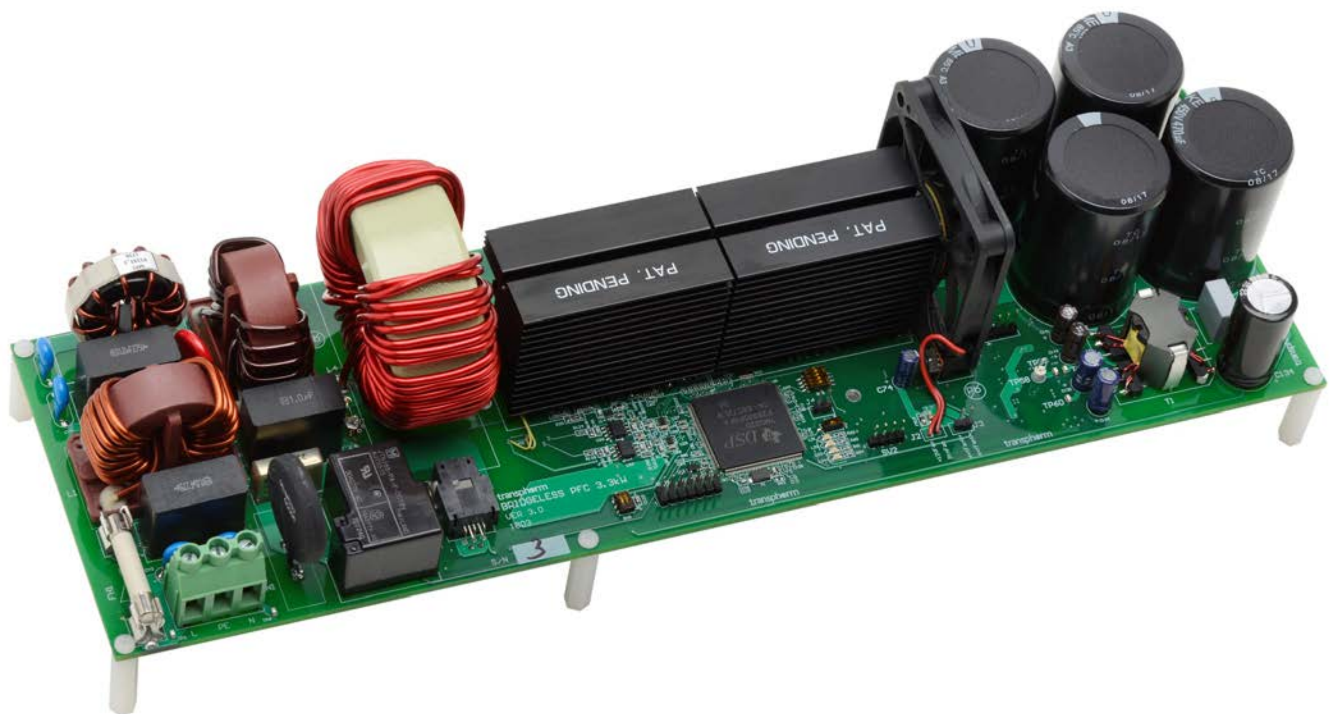

Figure 3. 3.3kW bridgeless totem-pole PFC demo board (front view)

2 Advanced features of the reference design

- RV1 varistor for transient surge protection
- CapZero line input circuit for X-cap discharge pursuant to IEC regulations
- Isolated hall-effect sensor [with output buffer] for inductor current sensing provides single point common ground for safety and convenient debugging
- Hall-effect current sensor reduces sensing power dissipation by 1W at full power, versus sense resistor approach
- Hall-effect sensor eliminates need for isolated DC/DC for isolated high-side gate drive
- Features on-board flyback auxiliary supply (which also can provide second stage power) to eliminate the need for an external bias supply
- Good isolation between large and small signal conductors and associated grounds, as well as between digital and analog circuits
- GaN and SJ FET gate drive voltage can be reprogrammed with a single resistor, to simply accommodate all generations of Transphorm GaN devices
- Integrated cooling fan is actuated by [programmable] heatsink temperature to improve light load efficiency
- Gate driver voltage is monitored by the DSP to identify UVLO/OVLO conditions
- PFC operational firmware provides complete PFC functional platform with #define configurable parameters

3 PFC functional block diagram

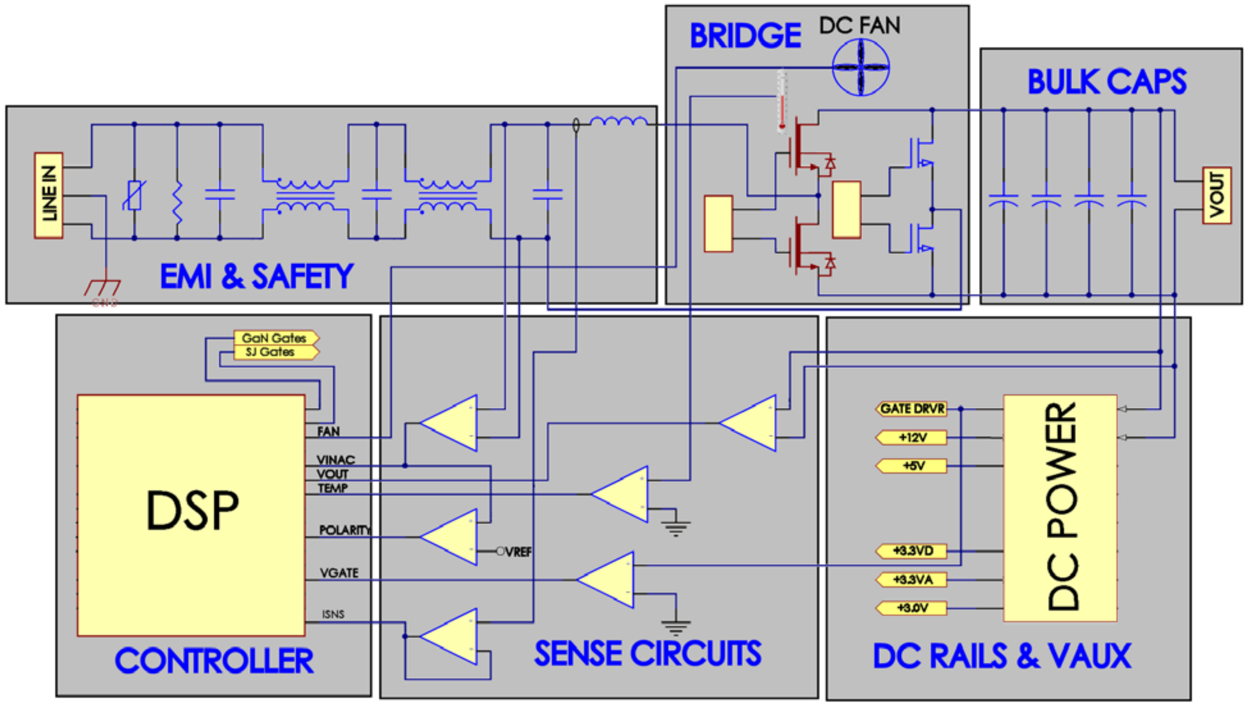

Figure 4. PFC functional block diagram

Figure 5 is a function block diagram of the GaN-based bridgeless PFC. There are six fundamental functional blocks.

The top three blocks comprise the high-power flow from left to right including the input connect which connects the AC line phase input power to the EMI filter (and switching inductor), which connects to the high-frequency GaN half-bridge.

The neutral input connects (through the EMI filter) to the SJ FET line-frequency half-bridge. The output of the combination of the half-bridges transfers converted power to the output bulk capacitor bank.

The bulk capacitor bank DC output voltage is converted to +15V$_{DC}$/+5.5V$_{DC}$ output rails via a flyback power converter. The +15V$_{DC}$ output is available for powering a second stage converter. The remaining rails are generated with LDO linear regulators for analog sensing circuits.

The sense circuitry measures input and output power parameters and conditions the signals for DSP processing.

The DSP-based controller block provides ADC conversion for analog sensing, digital control inputs and outputs (GPIOs) for fan operation and zero-cross detection, as well as PWM functionality for gate driver timing. The controller block also includes a +5V to +3.3V/+1.8V DC/DC converter for DSP rail power.

See Section 7, Figures 7-10 for detailed schematics of each of the above functional blocks.

4 Power supply specifications

Table 1. 3.3kW bridgeless totem-pole PFC reference design power supply specifications

Description	Symbol	Min	Typ	Max	Units	Comments
Input						
Voltage	V_{IN}	85		265	V_{AC}	
Current	I_{IN}		15		A	Input RMS current
Power	P_{IN}	1.35		3.3	kW	$90V_{AC}/230V_{AC}$
Frequency	f_{LINE}	47	50/60	64		60Hz $V_{IN} < 145V_{AC}$ 50Hz $V_{IN} > 170V_{AC}$
Output						
Voltage	V_{OUT}	373	385	397	V_{DC}	±3%
Ripple voltage	$V_{RIPPLE(PK-PK)}$	10	20	30	V_{AC}	2^{nd} harmonic ripple
Current	I_{OUT}			8.5	A	Output DC current @ $V_{OUT(TYP)}$
Power	P_{OUT}	1.28		3.2	kW	1.28kW ($90V_{AC}$) 1.6kW ($115V_{AC}$) 3.2kW ($230V_{AC}$)
Auxiliary power						
	V_{AUX}	13	14	15	V_{DC}	
	I_{AUX}		1.1		A	
Control						
Control method			DSP digital PWM			
	$f_{SWITCHING}$	45	100	150	kHz	
Control mode			CCM			CCM average current mode
Operating temperature						
	T_{AMB}	10		50	°C	
	Non-operational	-40		+85	°C	
Thermal (components)						
	GaN T_J			110	°C	@ 40°C ambient, 100% rated load
Inductor temperature (ferrite and conductor)	T_{FE}			100	°C	@ 40°C ambient, 100% rated load
	T_{AG}			100		
Distortion						
	THDi			10	%	> 10% rated load
Power factor						
	PF	0.96/0.98				1kW/2kW $P_{RE}/(P_{RE}+P_{IMG})$

5 3-D board image

Figure 6 shows a three-dimensional, translucent view of the 3.3kW totem-pole PFC demo board to easily visualize the relative location of all primary components.

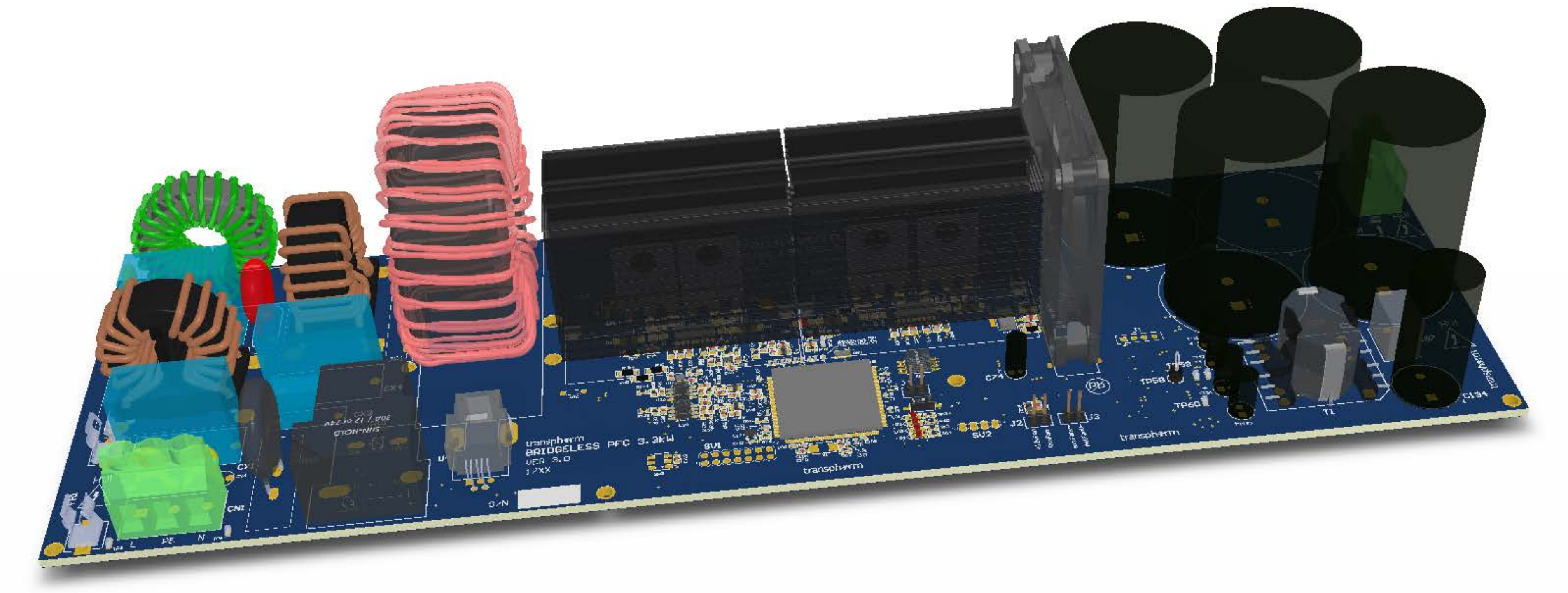

Figure 5. 3.3kW bridgeless totem-pole PFC demo board (3-D, front view)

6 Power rails

Table 2. 3.3kW bridgeless totem-pole PFC reference design power rails

Source	Use 1	Use 2	Use 3	Use 4	Comments
+14V (auxiliary supply secondary winding)	Cooling fan voltage	In-rush relay	+12V_{DC} gate driver LDO		Available for second stage power
+12V_{DC} LDO	Gate driver (V_{DDA}, V_{DDB}) for gate driver ICs				
+5V (5.4V) (auxiliary supply secondary winding	+5V_{REG}	+3V3 DC/DC DSP digital rail converter	+1V8 DC/DC DSP core converter		
+5VREG	+3.0V ISNS low noise rail	+3V3A analog small signal rail	Gate driver V_{DDI} rail		+5V regulated
+3V3	DSP clamp diode rail, DSP reset controller, DSP digital I/O supply	U5 relay gate driver IC	LED rail and drivers	UART supply, JTAG supply	3.3V digital supply
+1V8	DSP core supply				1.8V DSP rail
+3.0V	High-accuracy current sense, Hall-effect sensor source				High-precision current sensor supply
+3V3A	Small signal analog sensing circuits supply: V_{OUT}, H/S NTC, V_{AUX}, polarity, ISNS filter amp, VAC amp	V_{REF} (1.5V): ADC mid-voltage reference			Low-noise analog supply
V_{REF} (1.5V)	Polarity detector, VAC sense amp DC offset				High-precision REF zero-crossing reference

7 Circuit schematics and descriptions

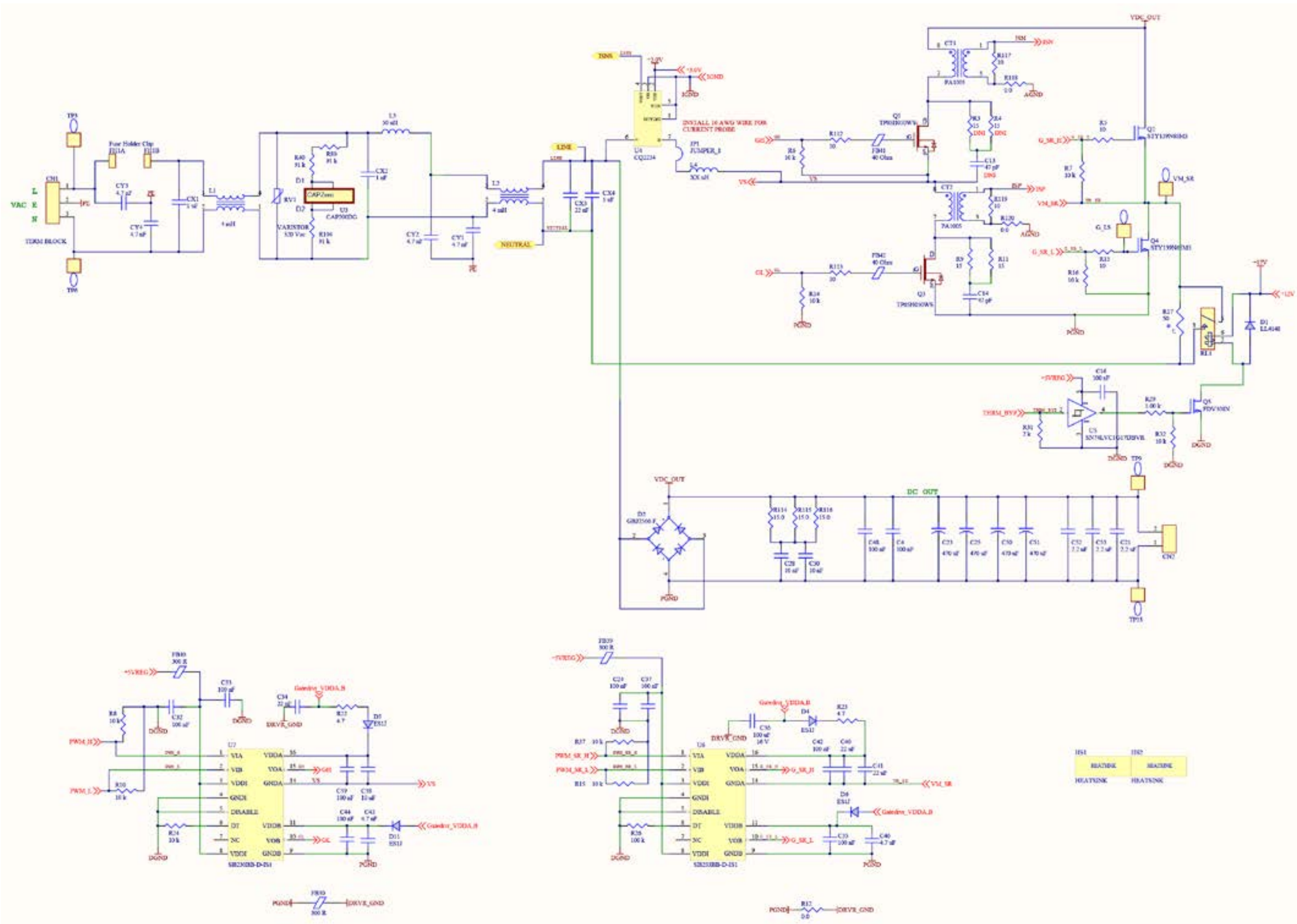

Figure 6. EMI filter, GaN and SJ FET bridge, bulk caps, gate drivers

Figure 7 includes safety agency and protection circuitry, EMI filter, inductor current sensor (optional transformer current sense), GaN half-bridge, SJ FET half-bridge, NTC bypass relay, output bulk capacitors, and gate driver circuitry.

- CN1 is the AC line power input connector, which connects to the EMI filter components CY3, CY4, CX1, L1, CX2, L3, CY1, CY2, L2, CX3 and CX4.
- FH1 provides fusing for fault and surge conditions. RV1 provides clamping during overvoltage conditions. R80, R40, R104 and U3 provide X-cap safety discharge after the power cord is disconnected from the power supply.
- U4 is an isolated Hall effect sensor and an analog buffer amplifier for inductor current measurement.
- L4 is the switching power inductor.
- CT1, R117, R118, and CT2, R119, R120 are for the optional transformer current sense devices, which can be used if the hall effect sensor is not a preferred choice.
- FB41 and R6, FB42 and R14 are gate ferrite beads and gate to source resistors.
- C28, C30, R114, R115, R116 form the DClink RC snubber that removes any high frequency energy on the DC bus voltage line, so it does not interfere with the HV GaN FETs when switching. Since this snubber is not connected to the switching node, efficiency is not affected and helps reduce EMI.

- Q2 and Q4 are the AC line commutation MOSFETs comprising the slow totem-pole half of the bridge. R5, R7, R13 and R16 are gate resistors.
- R17 is positive temperature coefficient PTC resistor for in-rush current limiting at startup. Relay K1 bypasses the in-rush PTC after startup. D1 clamps the relay coil at turn-off. Q5 engages the relay and is driven by the DSP through buffer U5.
- Diode bridge D2 provides a bypass for inrush current around the totem-pole bridge.
- C4, C48, C21, C52 and C53 provide loop-shortening paths for high frequency currents.
- C23, C25, C50 and C51 comprise the V_{OUT} bulk capacitance.
- U7 provides the GaN FET gate drivers. R22, D3, C38 and C39 provide the boot-strap voltage for the upper driver.
- U6 provides the MOSFET gate drivers. R23, D4, C40, C41 and C42 provide the boot-strap voltage for the upper driver.

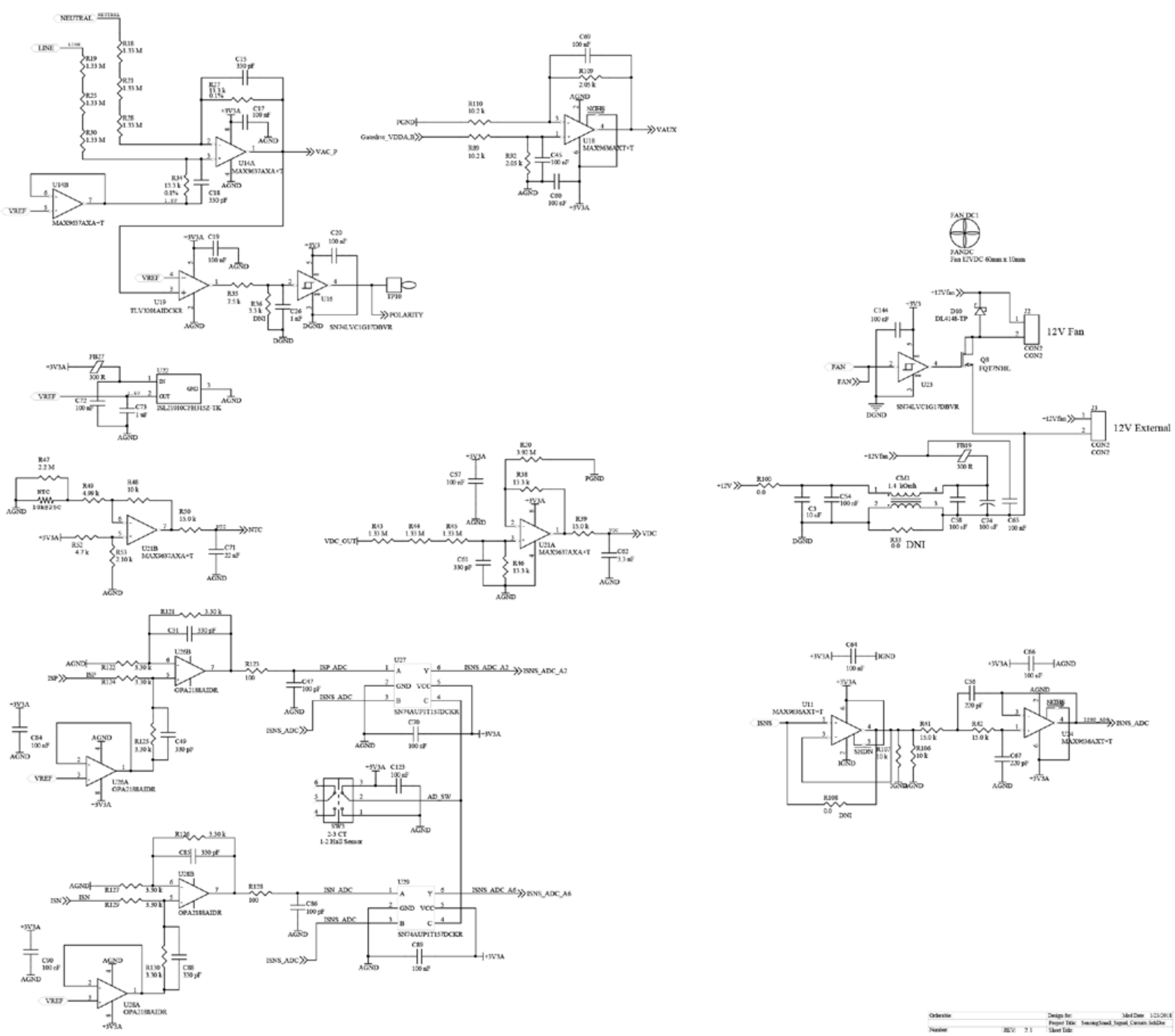

Figure 7. Sensing and small signal conditioning circuits

Figure 8 includes most sensing and small signal conditioning circuitry and fan driver.

- U14 op amp provides an AC line voltage differential amplifier with a 1.5V dc offset to sense the line voltage within the 3.0V input range of the DSP 12-bit ADC. Comparator U19 functions as a line zero-crossing detector, the output of which is filtered and buffered.
- Op amp U18 allows monitoring of the gate driver supply voltage to allow under-voltage/over-voltage lockout operation when the gate driver supply voltage is not within a safe operating range.
- U22 provides an accurate 1.5V dc offset reference for the line voltage amplifier and zero-crossing detector.
- U21A differentially monitors the V_{OUT} output voltage to scale it for the DSP ADC. U21B monitors the heatsink temperature with a 10kΩ positive temperature coefficient (PTC) thermistor.
- The output of the inductor current sensor (U4) is buffered by U11 follower and filtered with a second order Sallen-Key low-pass filter before being sampled with the DSP ADC.
- The DSP "FAN" signal is buffered with U23, which drives Q8, which applies +12V to engage the PFC fan. C3, C54 CM1, C58, C65, C74 and FB19 provide filtering of the fan power voltage rail to abate conducted EMI.
- SW3 is the selector for using either the CT or the hall effect sensor

Note: Lift pins 5, 6, 7 on U14B, short pins 3 and 6 on U27, do not populate U26, U27, U28, and U29. These are for future current transformer option

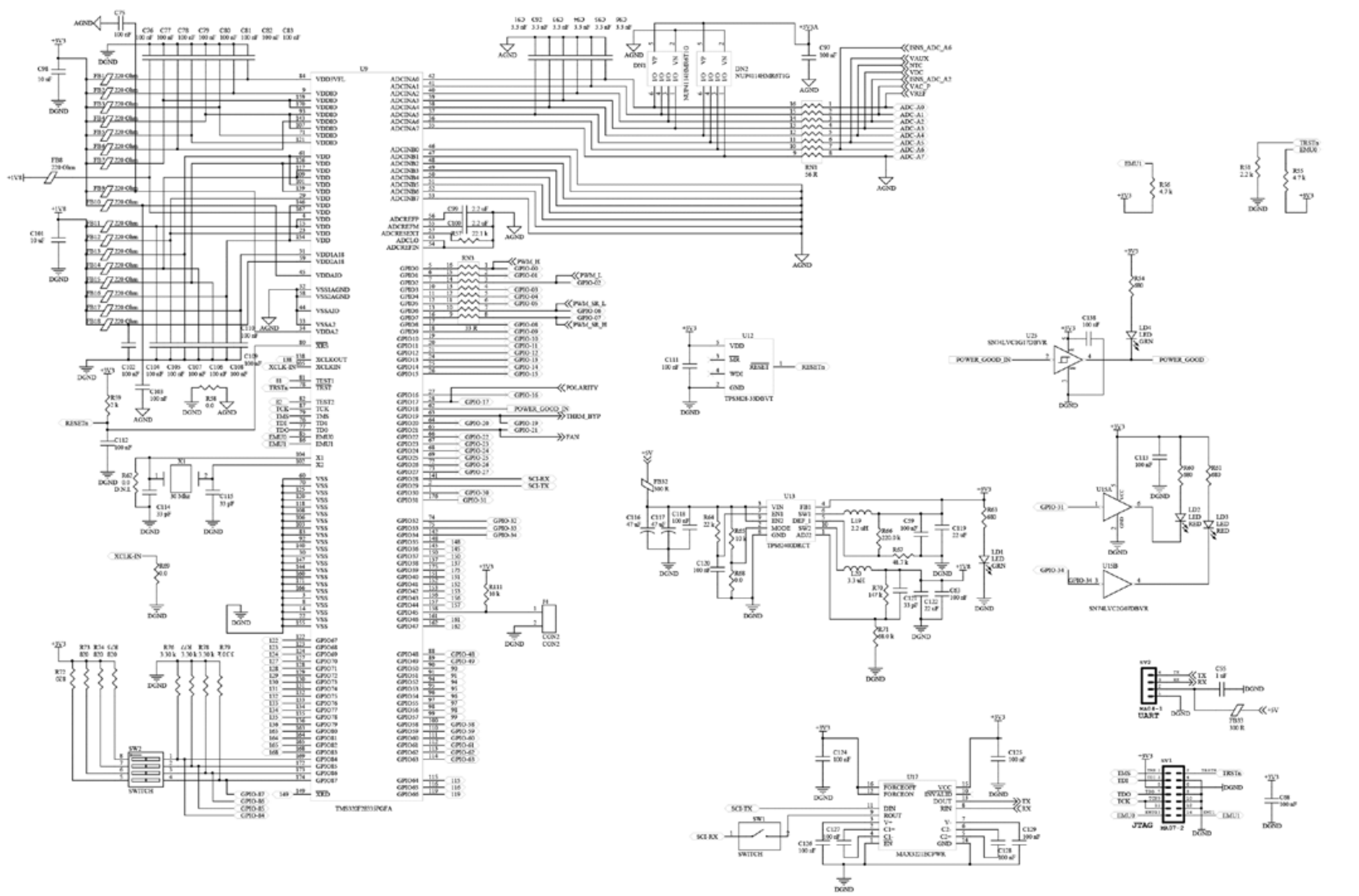

Figure 8. DSP, 1.8V/3.3V DC-DC

Figure 9 includes all DSP-related circuitry and connectors, including the DC-DC converter which powers the DSP, and indicator LEDs.

- U9 is the TMS320F28335PGFA Texas Instruments (TI) digital signal controller (DSC) which provides the digital control and monitoring of the bridgeless totem-pole PFC hardware.
- FB1~FB7, FB9, FB10, C75~C83, C98, C103 decouple, isolate and filter the +3.3V digital/analog rails.
- FB8, FB11~FB18, C104~C110 decouple, isolate and filter the +1.8V digital/analog core rails.
- DN1 and DN2 clamp analog inputs to the DSP ADC to supply rails.
- U12 provides a UVLO reset signal to the DSP.
- U13 and associated components comprise two DC/DC converters for generating +3.3V and +1.8V rails for the TI DSP.
- U17 provides a buffer for the UART function of the DSP.

LEDs:

- LD1 is a green "power present" signal
- LD2 is a red pulsing heartbeat during normal operation
- LD3 is a red LED which indicates a fault, or pulses the fault # after a fault has been detected
- LD4 is a green LED which is illuminated when POWER_GOOD condition is detected

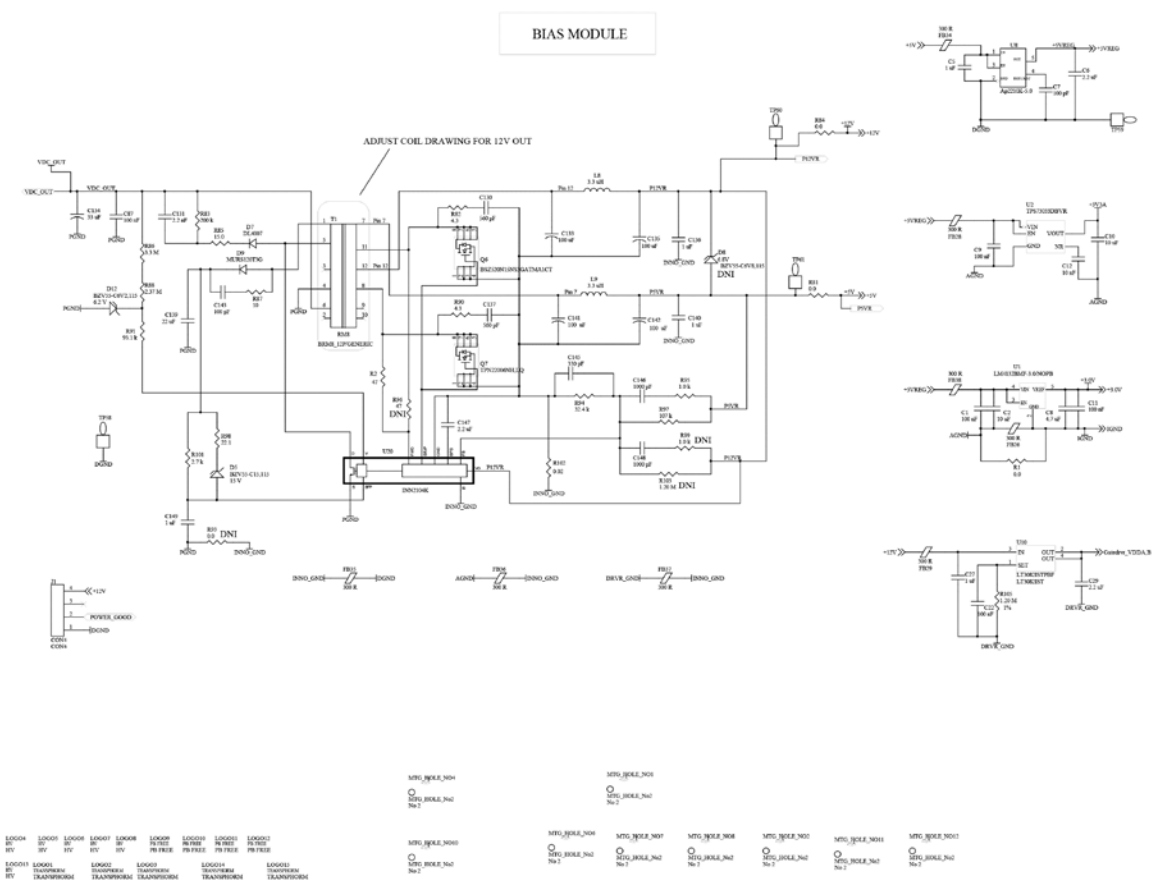

Figure 9. Auxiliary power supply, DC rail LDOs

Figure 10 includes the generation of all DC voltages with the exception of the DSP rails.

- C87 and C134 are primary side decoupling and bypass capacitors.
- R86, R88, R91 and D12 comprise a brown-in voltage detection network.
- D7, R83, R85 and C131 clamp the switching node of U20 InnoSwitch flyback converter.
- D9, C143, R87, C139, R98, R101, D5, C149 provide primary side [bypass pin] power to the InnoSwitch converter after startup.
- Flyback transformer T1 includes dual secondary windings for generation of a +12V auxiliary supply, as well as a +5V supply for generation of most all other power rails of the converter.
- Q6, Q7, R82, C130, R90, C137 constitute synchronous rectifiers and associated RC snubbers.
- C145, R94, C146, R95, R97, C148, R99, R103 provide output regulation feedback signals from both +12V and +5V output voltages.
- R102 provides current sense feedback to the InnoSwitch converter.
- U8, C5, C6, C7 provide linear regulation of +5V to ensure a clean, tightly regulated $+5V_{REG}$.
- U2, C9, C10, C12 provide a linear regulation of a low-noise +3.3V analog circuit rail.
- U1, C1, C2, C8, C11 provide a precision +3.0V supply for the inductor current sensor.
- U10, C27, C22, C29, R105 provides a linear regulated voltage between +9.0V and +11.0V for the gate driver ICs, U6 and U7.

8 PCB layout

The top PCB layer (Figure 11) contains all through-hole components, DSP processor, fan, and heatsink. This layer includes input and switching power traces, small signal routing, high-current copper pours, and the output high-voltage copper plane pour.

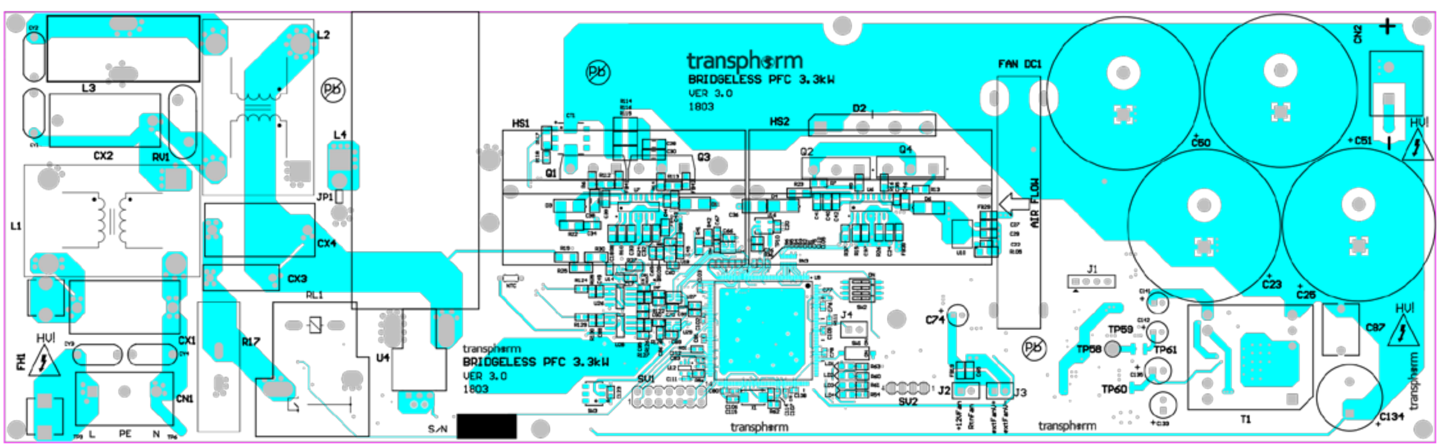

Figure 10. PCB top layer

The second layer, below the top layer, (Figure 12) includes input and switching power traces, small-signal miscellaneous routing and power planes, and the output high-voltage copper plane pour.

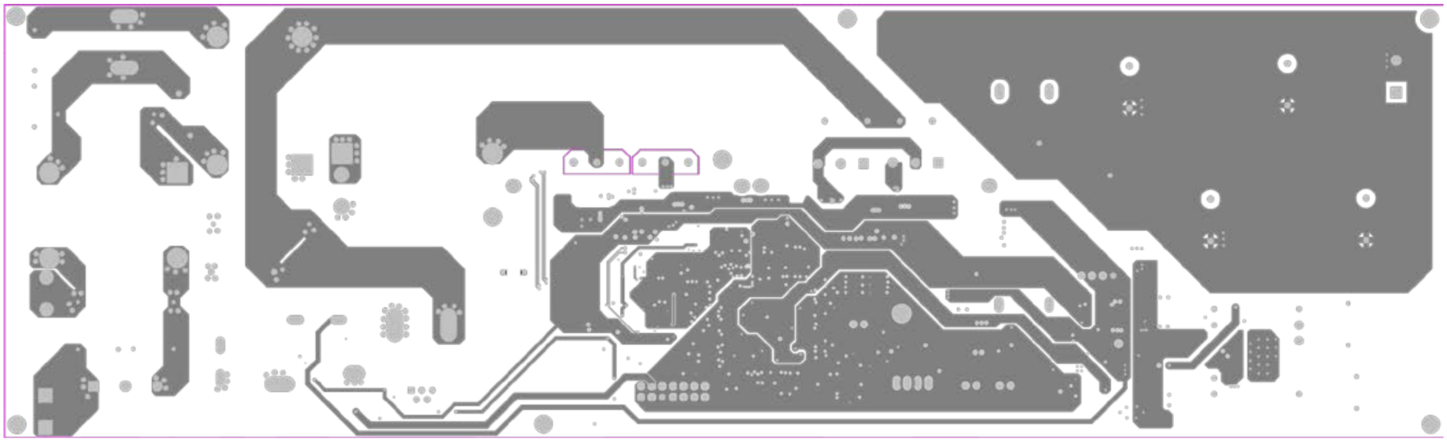

Figure 11. PCB layer 2

The third layer, above the bottom layer, (Figure 13) includes input and switching power traces, small-signal ground planes, and the output voltage ground copper plane pour.

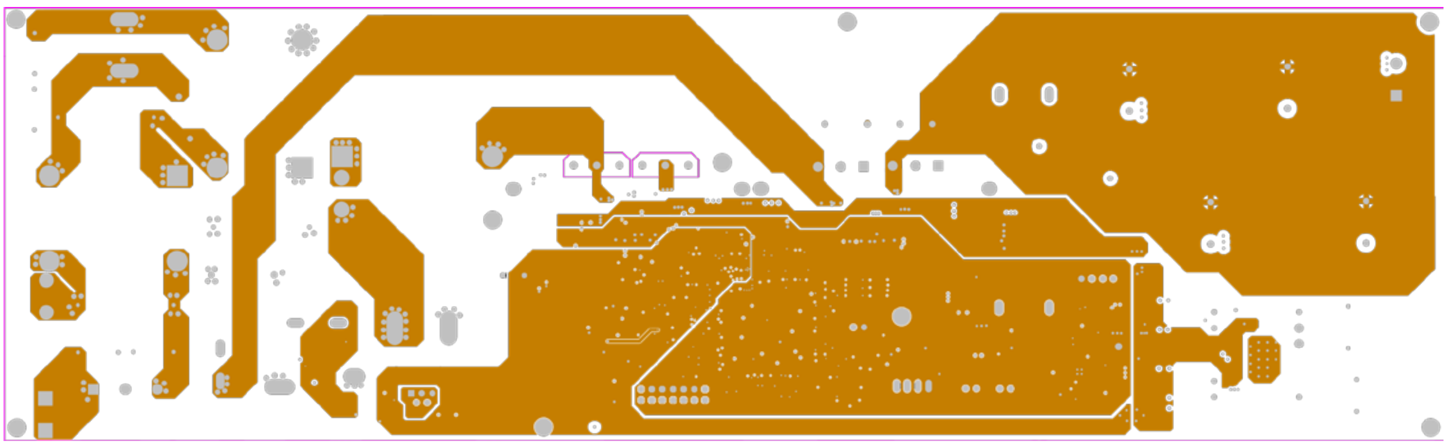

Figure 12. PCB layer 3

The bottom PCB layer (Figure 14) contains most of the sensing circuitry and routing. This layer includes input and switching power traces, small signal routing, and high-current copper pours, including the output high-voltage copper plane pour.

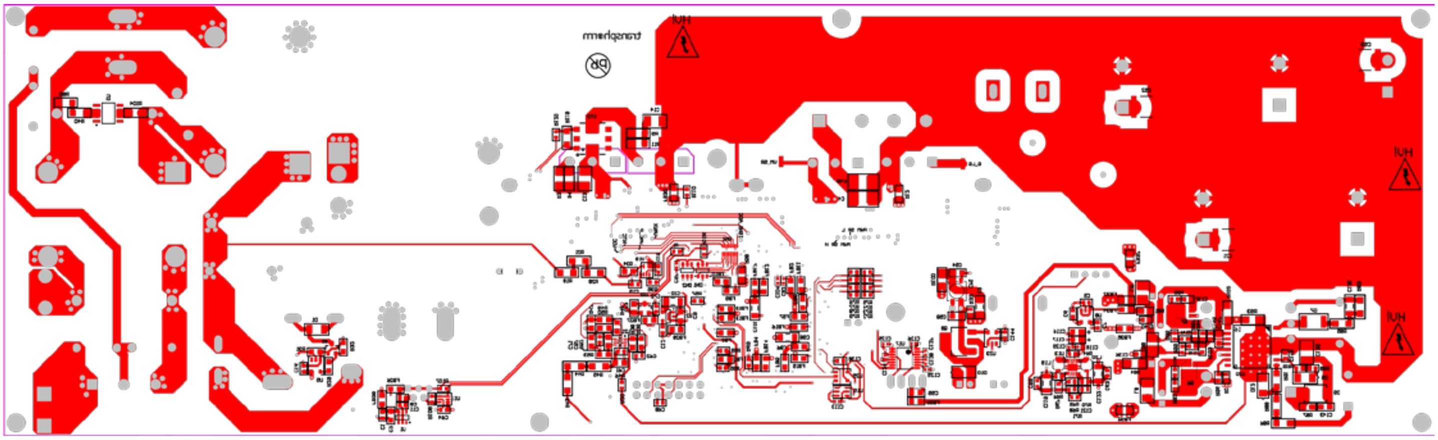

Figure 13. PCB bottom layer

9 GaN layout guidelines and fundamentals [1]

Due to the inherent high-speed nature of the switching of GaN FETs, specific attention to the placement, routing, and layout of the printed circuit board is imperative. In most cases an inductive impedance is required within the drain conductor to slew-limit the switching edge, thereby damping turn-on and turn-off transients. Alternatively, a drain snubber circuit can be implemented to damp the high-current transition drain voltage on the half-bridge center node.

Another primary layout objective is to maintain a minimal loop antenna, both during turn-on and turn-off of the half-bridge center tap, during both primary switch conduction as well as synchronous rectification states. This loop [antenna] area consists of the switching components and PCB routing from which radiated emissions are generated. Therefore, the objective is to minimize these radiation loops. The optimal layout will superimpose conductors on adjacent layers to contain the electromagnetic fields within the PCB itself.

10 Bill of materials

Table 3. 3.3kW bridgeless totem-pole PFC reference design bill of materials (BOM)

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
C1, C11, C22, C68, C144	5	100nF	100nF 50 V Ceramic X7R 0603	CL10B104KB8NNNC	Samsung
C2	1	10uF	10uF 16 V Ceramic X5R 0805	GRM21BR61C106KE15L	Murata
C3, C10, C38	3	10uF	10uF 25 V Ceramic X7R 1206	TMK316B7106KL-TD	Taiyo Yuden
C4, C48	2	100nF	100nF 1000 V Ceramic X7R 1812	C1812V104KDRACTU	Kemet
C5, C136, C140, C149	4	1uF	1uF 16 V Ceramic X7R 0603	0603YC105KAT2A	AVX
C6, C99, C100	3	2.2uF	2.2uF 10 V Ceramic X5R 0603	GRM188R61A225KE34D	Murata
C7	1	100pF	100 pF 25 V NP0 0603	885012006038	Wurth Electronics Inc

[1] Refer to application note AN0003: Printed Circuit Board Layout and Probing for GaN FETs for more details on GaN layout techniques and recommendations

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
C8	1	4.7uF	4.7uF 10 V Ceramic X5R 0603	C1608X5R1A475M/0.50	TDK Corp
C9, C24, C32, C33, C37, C39, C42, C54, C58, C65	10	100nF	100nF 25 V Ceramic X7R 0805	GRM21BR71E104KA01L	Murata
C12	1	10nF	10nF 50 V Ceramic X7R 0603	CL10B103KB8NNNC	Samsung
C13, C14	2	47 pF	47 pF 1000 V Ceramic C0G 1210	VJ1210A470JXGAT5ZL	Vishay
C15, C18, C61, C145	4	330 pF	330 pF 50 V Ceramic C0G 0603	C0603C331J5GACTU	Kemet
C16, C17, C19, C20, C35, C44, C45, C57, C60, C64, C66, C69, C72, C138	14	100nF	100nF 50 V Ceramic X7R 0603	CL10B104KB8NNNC	Samsung
C21, C52, C53	3	2.2uF	2.2uF 450 V Ceramic X6S 2220	C5750X6S2W225K250KA	TDK
C23, C25, C50, C51	4	470uF	470uF 450 V Electrolytic (35 x 52)	ELH477M450AT6AA	Kemet
C26	1	1nF	1nF 16 V Ceramic NP0 0603	CL10C102JB8NFNC	Samsung
C27	1	1uF	1uF 50 V Ceramic X7R 0805	08055D105KAT2A	AVX Corporation
C28, C30	2	10nF	10nF 630 V Ceramic C0G 1206	CGA5L4C0G2J103J160AA	TDK
C29	1	2.2uF	2.2uF 25 V Ceramic X7R 0805	885012207079	Wurth
C31, C49, C85, C88	4	330pF	330pF 50 V X7R 0603	885012206080	Wurth Electronics Inc
C34, C40, C41	3	22uF	22uF 16 V Ceramic X5R 0805	CL21A226MOCLRNC	Samsung
C36	1	100uF	100uF 16 V Ceramic X5R 1210	EMK325ABJ107MM-T	Taiyo Yuden
C43, C46	2	4.7uF	4.7uF 16 V Ceramic X5R 0805	C0805C475K4PACTU	Kemet
C47, C86	2	100pF	100 pF 50 V Ceramic X7R 0603	CL10C101JB8NNNC	Samsung
C55	1	1uF	1uF 25 V Ceramic X5R 0805	C2012X5R1E105K	TDK
C56, C67	2	220pF	220pF 50 V Ceramic X7R 0603	06035C221KAT2A	AVX Corporation
C59, C63	2	100nF	100nF 50 V Ceramic X7R 0603	C0603C104M5RACTU	Kemet
C62	1	3.3nF	3.3nF 50 V Ceramic X7R 0603	GRM188R71H332KA01D	Murata
C70, C84, C89, C90, C123	5	100nF	100nF 50 V X7R 0603	885012206095	Wurth Electronics Inc
C71	1	22nF	22nF 50 V Ceramic X7R 0805	CC0805KRX7R9BB223	Yageo
C73	1	1uF	1uF 25 V Ceramic Y5V 0805	CC0805ZRY5V8BB105	Yageo
C74	1	100uF	100uF 25 V Electrolytic Gen. Purpose (5 x 12.5)	ESK107M025AC3AA	Kemet

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
C75, C76, C77, C78, C79, C80, C81, C82, C83, C97, C102, C103, C104, C105, C106, C107, C108, C109, C110, C111, C112, C113, C118, C120, C124, C125, C126, C127, C128, C129	30	100nF	100nF 25 V X5R 0402	TMK105BJ104KVHF	Taiyo Yuden
C87	1	100nF	100nF 630 VDC Film	BFC233920104	Vishay
C91, C92, C93, C94, C95, C96	6	3.3nF	3.3nF 10 V Ceramic X7R 0402	885012205009	Wurth
C98, C101	2	10uF	10uF 6.3 V Ceramic X7R 1206	GRM31CR70J106KA01L	Murata
C114, C115, C121	3	33pF	33 pF 25 V Ceramic NP0 0603	885012006035	Wurth
C116, C117	2	47uF	47uF 10 V Ceramic TANTALUM 0805	298D476X0010P2T	Vishay
C119, C122	2	22uF	22uF 6.3 V Ceramic X7R 1206	JMK316B7226ML-T	Taiyo Yuden
C130, C137	2	560pF	560pF 100 V Ceramic COG 0603	GRM1885C2A561JA01D	Murata
C131	1	2.2nF	2.2nF 630 V Ceramic X7R 1206	GRM31BR72J222KW01L	Murata
C133, C135	2	100uF	100uF 25 V Electrolytic Very Low ESR 130mOhm (6.3 x 11)	EKZE250ELL101MF11D	Nippon Chemi-Con
C134	1	33uF	33uF 450 V Electrolytic (16 x 31.5)	EEU-EB2W330	Panasonic
C139	1	22uF	22uF 25 V Ceramic X7R 1210	GRM32ER71E226ME15L	Murata
C141, C142	2	100uF	100uF 10 V Electrolytic Very Low ESR 300mOhm (5 x 11)	EKZE100ELL101ME11D	Nippon Chemi-Con
C143	1	100pF	100 pF 100 V Ceramic COG 0805	C0805C101J1GACTU	Kemet
C146, C148	2	1000pF	1000 pF 100 V Ceramic COG 0603	C1608C0G2A102J	TDK Corp
C147	1	2.2uF	2.2uF 25 V Ceramic X7R 0805	TMK212B7225KG-TR	Taiyo Yuden
CM1	1	1.4kOmh	CMC 1.4kOHM, 1.7 A, DCR 80mOhm, 2 LN SMD	ACM4520-142-2P-T000	TDK
CN1	1	TERM BLOCK	TERM BLOCK 3POS 30A 7.62MM PCB HORIZ	20020705-M031B01LF	AMPHENOL
CN2	1	TERM BLOCK	TERM BLOCK 2POS 30A 7.62MM PCB HORIZ	20020705-M021B01LF	AMPHENOL
CT1, CT2	2	PA1005.100NLT	CURR SENSE XFMR 1:100 20A SMD	PA1005.100NLT	Pulse Electronics
CX1, CX2, CX4	3	1uF	1uF 275 VAC Film X2	ECQ-U2A105ML	Panasonic
CX3	1	22nF	22nF 275 VAC Film X2	PME271M522MR30	Kemet
CY1, CY2, CY3, CY4	4	4.7nF	4.7nF Ceramic Y1 400 VAC	C947U472MYVDBA7317	Kemet
D1	1	LL4148	75 V, 0.15 A, Fast Switching, 4 ns, MELF	LL4148-13	Diode Inc.
D2	1	GBJ2506-F	600 V, 25 A, Bridge Rectifier, GPP, GBJ Package	GBJ2506-F	Diodes, Inc

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
D3, D4, D6, D11	4	ES1J	600 V, 1 A, Ultrafast Recovery, 35 ns, DO-214AC	ES1J-LTP	Micro Commercial Co.
D5	1	BZV55-C15,115	15 V, 5%, 500mW, SOD80C	BZV55-C15,115	NXP Semiconductor
D7	1	DL4007	1000 V, 1 A, Rectifier, Glass Passivated, DO-213AA (MELF)	DL4007-13-F	Diodes Inc
D8	1	BZV55-C6V8,115	6.8 V, 5%, 500mW, SOD80C	BZV55-C6V8,115	NXP Semiconductor
D9	1	MURS120T3G	200 V, 1 A, Ultrafast Recovery, 35 ns, SMB Case	MURS120T3G	On Semi
D10	1	DL4148-TP	75 V, 0.15 A, Fast Switching, 4ns, mini MELF	DL4148-TP	Micro Commercial
D12	1	BZV55-C6V2,115	6.2 V, 5%, 500mW, SOD80C	BZV55-C6V2,115	Nexperia USA
DN1, DN2	2	NUP4114HMR6T1G	5.5 VWM, TVS DIODE, 10 VC, 6TSOP	NUP4114HMR6T1G	ON Semiconductor
FAN DC1	1	Fan 12VDC 60mm x 10mm	Fan, 12VDC, 60mm x 10mm,	EFB0612LA	Delta
FB1, FB2, FB3, FB4, FB5, FB6, FB7, FB8, FB9, FB10, FB11, FB12, FB13, FB14, FB15, FB16, FB17, FB18	18	220 Ohm	FERRITE BEAD 220 OHM 0805 1LN	BLM21PG221SN1D	Murata
FB19, FB26, FB27, FB28, FB29, FB30, FB32, FB33, FB34, FB35, FB36, FB37, FB38, FB39, FB40	15	300 R	Ferrite Bead, 300 Ohm, 0.7 A 0805 SMD	LI0805G301R-10	Laird-Signal Integrity
FB41, FB42	2	40 Ohm	FERRITE BEAD 40 OHM 1.5 A 0805 1LN	MI0805K400R-10	Laird
FH1	1	Fuse Holder Clip	FUSE CLIP CARTRIDGE 250V 30A PCB	01220088Z	Littlefuse
G_LS, TP3, TP6, TP9, TP10, TP13, TP59, TP60, TP61, VM_SR	10	CON1	PC TEST POINT MINIATURE SMT 0.010" (0.25mm) Phosphor Bronze, Silver Plate	5015	Keystone
HS1, HS2	2	HEATSINK	Heat Sink TO-247, TO-264, SOT-227 Aluminum Board Level, Vertical	C40-058-AE	Ohmite
J1	1	CON4	4 Position (1 x 4) header, 0.1 pitch, Vertical	22-28-4049	Molex

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
J2, J3, J4	3	CON2	2 Position (1 x 2) header, 0.1 pitch, Vertical	22-03-2021	Molex
JP1	1	J	Wire Jumper, Insulated, TFE, 16 AWG stranded wire, 3 inches long for Current Sensing	44A0111-16-0-BRL-L117	TE Connectivity
L1, L2	2	4mH	4mH, XX A, 3.9mOhm, Common Mode Choke		
L3	1	50uH	50uH, Custom, Loose Winding, 28T - 1 X 14 AWG, Core 77071A7	77071A7	Mag Inc.
L4	1	554uH	554uH, Inductor, 2 Pins, High Flux CH610060, 30 X 70mm	CH610060	Changsung Corp
L8, L9	2	3.3uH	3.3uH, 1.00 A	NLCV32T-3R3M-PFR	TDK Corporation
L19	1	2.2uH	2.2uH, 1 A, 120 MOHM SMD	VLF3010AT-2R2M1R0	TDK
L20	1	3.3uH	3.3uH, .870 A, 170 MOHM SMD	VLF3010AT-3R3MR87	TDK
LD1, LD4	2	GRN	Green 567nm LED Indication - Discrete 2.1V 0805 (2012 Metric)	PG1112H-TR	Stanley Electric
LD2, LD3	2	RED	Red 647nm LED Indication - Discrete 1.7V 0805 (2012 Metric)	BR1112H-TR	Stanley Electric
NTC	1		RESISTOR, American symbol	NTCALUG02A103FL	Vishay
Q1, Q3	2	TP65H0 50WS	650V, 47A, 0.035Ohms, TO-247, GaN HEMT, normally-off, source tab	TP65H050WS	Transphorm Inc.
Q2, Q4	2	STY139N 65M5	650V 130 A MAX247 MOSFET N-CH	STY139N65M5	STMicroelectronics
Q5	1	FDV301 N	25V, 220 mA, 4 Ohm, N-Channel, SOT 23	FDV301N	Fairchild
Q6	1	BSZ520 N15NS3 GATMA1 CT	150 V, 21 A, 53mOhm, MOSFET N-CH, TDSON-8	BSZ520N15NS3GATMA1	Infineon Technologies
Q7	1	TPN220 06NH,LQ	60 V, 9 A, 22mOhm, MOSFET N-CH, 8-TSON	TPN22006NH,LQ	Toshiba Semiconductor
Q8	1	FQT7N1 0L	100V, 1.7A, 0.35Ohm, N-Channel, SOT 223	FQT7N10LTF	Fairchild
R1, R33, R62, R68, R69, R108, R118, R120	8	0.0	0 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEY0R00V	Panasonic
R2, R96	2	47	47 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ470V	Panasonic
R3, R4, R9, R11	4	15	15 R, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF15R0V	Panasonic
R5, R13, R87, R112, R113	5	10	10 R, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ100V	Panasonic
R6, R7, R8, R10, R14, R15, R16, R24, R32, R37, R48	11	10 k	10 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1002V	Panasonic

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
R12, R58, R81	3	0.0	0 R, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEY0R00V	Panasonic
R17	1	50	NTC Thermistor, 50 Ohms, 6 A	MS32 50006-B	Ametherm
R18, R19, R21, R25, R28, R30	6	1.33 M	1.33 M, 1%, 1/4 W, Thick Film, 1206	RC1206FR-071M33L	Yageo
R20	1	3.92 M	3.92 M, 1%, 1/16 W, Thick Film, 0603	CRCW06033M92FKEA	Vishay
R22, R23	2	4.7	4.7 R, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ4R7V	Panasonic
R26	1	100 k	100 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1003V	Panasonic
R27, R34	2	13.3 k	13.3 k, 0.1%, 1/8 W, Thick Film, 0805	ERA-6AEB1332V	Panasonic
R29	1	1.00 k	1.00 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1001V	Panasonic
R31	1	2 k	2 k, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ202V	Panasonic
R35	1	7.5 k	7.5 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ752V	Panasonic
R36	1	3.3 k	3.3 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ332V	Panasonic
R38, R46	2	13.3 k	13.3 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1332V	Panasonic
R39, R41, R42, R50	4	15.0 k	15 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1502V	Panasonic
R40, R80, R104	3	91 k	91 k, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ913V	Panasonic
R43, R44, R45	3	1.33 M	1.33 M, 1%, 1/4 W, Thick Film, 1206	RC1206FR-071M33L	Yageo
R47	1	2.2 M	2.2 M, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF2204V	Panasonic
R49	1	4.99 k	4.99 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF4991V	Panasonic
R51	1	2.2 k	2.2 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ222V	Panasonic
R52	1	4.7 k	4.7 k, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ472V	Panasonic
R53	1	2.10 k	2.10 k, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF2101V	Panasonic
R54, R60, R61, R63	4	680	680 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ681V	Panasonic
R55, R56	2	4.7 k	4.7 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ472V	Panasonic
R57	1	22.1 k	22.1 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF2212V	Panasonic
R59	1	2 k	2 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ202V	Panasonic

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
R64	1	22 k	22 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ223V	Panasonic
R65, R106, R107	3	10 k	10 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ103V	Panasonic
R66	1	220.0 k	220.0 k, 1%, 1/16 W, Thick Film, 0603	RC0603FR-07220KL	Yageo
R67	1	48.7 k	48.7 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF4872V	Panasonic
R70	1	147 k	147 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF1473V	Panasonic
R71	1	68.0 k	68.0 k, 1%, 1/16 W, Thick Film, 0603	AC0603FR-0768KL	Yageo
R72, R73, R74, R75	4	820	820 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ821V	Panasonic
R76, R77, R78, R79, R121, R122, R124, R125, R126, R127, R129, R130	12	3.30 k	3.30 k, 1%, 1/16 W, Thick Film, 0603	RC0603FR-073K3L	Yageo
R82, R90	2	4.3	4.3 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ4R3V	Panasonic
R83	1	200 k	200 k, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ204V	Panasonic
R84, R93, R100	3	0.0	0 R, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEY0R00V	Panasonic
R85	1	15.0	15.0 R, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF15R0V	Panasonic
R86	1	3.3 M	3.3 M, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ335V	Panasonic
R88	1	2.37 M	2.37 M, 1%, 1/4 W, Thick Film, 1206	541-2.37MFCT-ND	Vishay
R89, R110	2	10.2 k	10.2 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF1022V	Panasonic
R91	1	93.1 k	93.1 k, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF9312V	Panasonic
R92, R109	2	2.05 k	2.05 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF2051V	Panasonic
R94	1	32.4 k	32.4 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF3242V	Panasonic
R95, R99	2	1.0 k	1.0 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF1001V	Panasonic
R97	1	107 k	107 k, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF1073V	Panasonic
R98	1	22.1	22.1 R, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF22R1V	Panasonic
R101	1	2.7 k	2.7 k, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ272V	Panasonic

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
R102	1	0.02	0.02 R, 5%, 1 W, Thick Film, 1206	ERJ-8BWJR020V	Panasonic
R103	1	1.20 M	1.20 M, 1%, 1/16 W, Thick Film, 0603	ERJ-3EKF1204V	Panasonic
R105	1	1.20 M	1.20 M, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF1204V	Panasonic
R111	1	10 k	10 k, 5%, 1/10 W, Thick Film, 0402	ERJ-2GEJ103X	Panasonic
R114, R115, R116	3	15.0	15.0 R, 1%, 1/2 W, Thick Film, 1210	ERJ-14NF15R0U	Panasonic
R117, R119	2	10	10 R, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ100V	Panasonic
R123, R128	2	100	100 R, 5%, 1/10 W, Thick Film, 0603	ERJ-3GEYJ101V	Panasonic
RL1	1	JTN1AS-PA-F-DC12V	General Purpose Relay SPST-NO (1 Form A) 30 A 12 VDC Coil Through Hole	JTN1AS-PA-F-DC12V	Panasonic
RN1	1	56 R	RES ARRAY 8 RES 56 OHM 1506	EXB-2HV560JV	Panasonic
RN3	1	33 R	RES ARRAY 8 RES 33 OHM 1506	EXB-2HV330JV	Panasonic
RV1	1	320Vac	320 V, 80 J, 14 mm, RADIAL	V320LA20AP	Littlefuse
SV1	1		PIN HEADER	67997-414HLF	Amphenol
SV2	1		PIN HEADER	901200124	Molex
SW1	1	SWITCH	Dip Switch SPST 1 Position Surface Mount Slide (Standard) Actuator 100mA 6VDC 0.010" (0.25mm) Phosphor Bronze, Silver Plate	CHS-01TB	Copal Electronics
SW2	1	SWITCH	Dip Switch SPST 4 Position Surface Mount Slide (Standard) Actuator 25mA 24VDC 0.010" (0.25mm) Phosphor Bronze, Silver Plate	218-4LPST	CTS Electrocomponents
SW3	1	Switch SPDTX2	SWITCH SLIDE SPDTX2 100MA 6V 0.010" (0.25mm) Phosphor Bronze, Silver Plate	CAS-D20TA	Nidec Copal Electronics
T1	1	RM8	Bobbin, RM8, Vertical, 12 pins	B65812C1512T1	TDK
TP58	1	CON1	Test Point, BLK, THRU-HOLE MOUNT	5011	Keystone
U1	1	LM4132BMF-3.0/NOPB	Series Voltage Reference IC ±0.1% 20mA SOT-23-5	LM4132BMF-3.0/NOPB	Texas Instruments
U2	1	TPS73033DBVR	IC REG LDO 3.3V 0.2A SOT23-5	TPS73033DBVR	Texas Instruments

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
U3	1	CAP200 DG	Power Management Specialized CapZero-2 X 1KV Smart HV Switches 8SOIC	CAP200DG	Power Integrations
U4	1	CQ2234	Current Sensor 50A 1 Channel Hall Effect, Open Loop Bidirectional Module	CQ2234	AKM Semiconductor
U5, U16, U23, U25	4	SN74LV C1G17D BVR	Buffer, Non-Inverting 1 Element 1 Bit per Element Push-Pull Output SOT-23-5	SN74LVC1G17DBVR	Texas Instruments
U6	1	SI8233B B-D-IS1	DGTL ISO 2.5KV GATE DRVR 16SOIC	SI8233BB-D-IS1	Silicon Labs
U7	1	SI8230B B-D-IS1	500mA Gate Driver Capacitive Coupling 2500Vrms 2 Channel 16-SOIC	SI8230BB-D-IS1	Silicon Labs
U8	1	AP2210 K-5.0	IC REG LDO 5V 0.3A SOT25	AP2210K-5.0TRG1	Diodes Inc.
U9	1	TMS320 F28335P GFA	IC MCU 32BIT 512KB FLASH 176LQFP	TMS320F28335PGFA	Texas Instruments
U10	1	LT3082I ST	IC REG LDO ADJ 0.2A SOT223	LT3082IST#PBF	Linear Technologies
U11, U18, U24	3	MAX963 6AXT+T	IC OPAMP GP 1.5MHZ RRO SC70-6	MAX9636AXT+T	Maxim Integrated
U12	1	TPS3828 -33DBVT	Supervisor Open Drain or Open Collector 1 Channel SOT-23-5	TPS3828-33DBVT	Texas Instruments
U13	1	TPS6240 0DRCT	Buck Switching Regulator IC Positive Adjustable 0.6V 2 Output 400mA, 600mA 10-VFDFN Exposed Pad	TPS62400DRCT	Texas Instruments
U14, U21	2	MAX963 7AXA+T	IC OPAMP GP 1.5MHZ RRO SC70-8	MAX9637AXA+T	Maxim
U15	1	SN74LV C2G07D BVR	Buffer, Non-Inverting 2 Element 1 Bit per Element Open Drain Output SOT-23-6	SN74LVC2G07DBVR	Texas Instrument
U17	1	MAX322 1ECPWR	IC RS232 3V-5.5V DRVR 1/1 Transceiver Full RS232 16-TSSOP	MAX3221ECPWR	Texas Instruments
U19	1	TLV3201 AIDCKR	Comparator General Purpose Push-Pull SC-70-5	TLV3201AIDCKR	Texas Instruments
U20	1	INN2104 K	Converter Offline Flyback, Secondary Side SR Topology 100kHz eSOP-R16B	INN2104K	Power Integrations
U22	1	ISL2101 0CFH31 5Z-TK	Series Voltage Reference IC ±0.2% 25mA SOT-23-3	ISL21010CFH315Z-TK	Intersil
U26, U28	2	OPA218 8AIDR	Zero-Drift Amplifier 2 Circuit Rail-to-Rail 8-SOIC	OPA2188AIDR	Texas Instruments

Designator	Qty	Value	Description	Manufacturer Part Number	Manufacturer
U27, U29	2	SN74AUP1T157DCKR	IC BUFF/MUX SCHMITT-TRIG SC70-6	SN74AUP1T157DCKR	Texas Instruments
X1	1	30Mhz	CRYSTAL 30.0000MHZ 8PF SMD	644-1043-1-ND	NDK

11 Equations

The following derivations provide mathematical equations for all sensed parameters necessary for closed-loop operation.

11.1 AC line monitor

Line voltage monitor equations:

$$(V_{Line} - V_{Neutral}) = \frac{R_{19\_25\_30} \cdot (V_p - V_{REF})}{R_{34}} - \frac{R_{18\_21\_28} \cdot (V_n - VAC\_P)}{R_{27}}$$

Substituting:

$$R_{18\_21\_28} = R_{19\_25\_30} \qquad R_{27} = R_{34} \qquad V_n = V_p$$

Yields:

$$(V_{Line} - V_{Neutral}) = \frac{[R_{19\_25\_30} \cdot (VAC\_P - V_{REF})]}{R_{34}}$$

Where:

$$K_{ff} := \frac{R_{34}}{R_{19\_25\_30}} \qquad R_{19\_25\_30} = 3.99 \times 10^{6} \qquad R_{34} = 1.33 \times 10^{4}$$

$$V_{ADC\_Max} = 4096 \qquad V_{REF} = 1.5 \qquad K_{ff} = \frac{1}{300} \qquad V_{ADCref} = 3$$

Rearranging:

$$VAC\_P\_volts = V_{REF} + K_{ff} \cdot (V_{Line} - V_{Neutral})$$

$$VAC\_P\_adc = [V_{REF} + K_{ff} \cdot (V_{Line} - V_{Neutral})] \cdot \frac{V_{ADC\_Max}}{V_{ADCref}}$$

Substituting:

$$VAC\_P\_adc(V_{LineMinusNeutral}) := \left[\frac{4096}{2} + \frac{4096}{900} \cdot (V_{LineMinusNeutral})\right]$$

AC line monitoring range (AC line input ranges from $0V_{AC}$=2048d to $318.2V_{RMS}$=4096d [$-318.2V_{RMS}$ = 0d]:

$$VAC\_P\_adc(-450) = 0 \qquad VAC\_P\_adc(450) = 4096$$

$$VAC\_P\_adc(-\sqrt{2} \cdot 318.2) = -0 \qquad VAC\_P\_adc(\sqrt{2} \cdot 318.2) = 4096$$

11.2 Inductor current

$$IAC(Iinductor) = \frac{VDD}{2} + Ar_{CQ2234} \cdot \left(\frac{VDD}{VDD_{typ}}\right) \cdot Iinductor$$

$$IAC\_adc(Iinductor) = \left[\frac{VDD}{2} + Ar_{CQ2234} \cdot \left(\frac{VDD}{VDD_{typ}}\right) \cdot Iinductor\right] \cdot \frac{V_{ADC\_Max}}{V_{ADCref}}$$

Where:

$$VDD = 3 \qquad VDD_{typ} = 3.3 \qquad V_{ADC\_Max} = 4096 \qquad V_{ADCref} = 3$$

Substituting:

$$IAC\_adc(Iinductor) := \left(2048 + Ar_{CQ2234} \cdot \frac{1}{3.3} \cdot Iinductor \cdot 4096\right)$$

Inductor monitoring current range:

$$IAC\_adc(-67.3467) = 0 \qquad IAC\_adc(67.3467) = 4096$$

11.3 Output voltage

V_{OUT} monitor equations:

$$\frac{(VDC\_OUT - V_p)}{R_{43\_44\_45}} = \frac{V_p}{R_{46}} \qquad \frac{VDC - V_n}{R_{38}} = \frac{V_n - PGND}{R_{20}}$$

Where:

$$V_p = V_n \qquad R_{38} = R_{46} \qquad R_{43\_44\_45} = 3.99 \times 10^6 \qquad PGND := 0$$

Yields:

$$VDC\_OUT - \frac{PGND \cdot (R_{46} + R_{43\_44\_45})}{R_{20} + R_{46}} = \frac{R_{20} \cdot VDC \cdot (R_{46} + R_{43\_44\_45})}{R_{46} \cdot (R_{20} + R_{46})}$$

Rearranging:

$$VDC = \left[VDC\_OUT \cdot \frac{(R_{.20} + R_{.46})}{R_{.46} + R_{.43\_44\_45}} + -PGND \right] \cdot \frac{R_{.46}}{R_{.20}}$$

Substituting:

$$R_{43\_44\_45} = 3.99 \times 10^{6} \qquad R_{20} = 4.02 \times 10^{6} \qquad R_{46} = 1.33 \times 10^{4}$$

Yields:

$$VDC\_adc(VDC\_OUT) := \left(\frac{VDC\_OUT}{300} + \frac{-PGND}{302} \right) \cdot \frac{4096}{3.0}$$

Output voltage operating range:

$$VDC\_adc(0) = 0 \qquad VDC\_adc(450) = 2048 \qquad VDC\_adc(900) = 4096$$

11.4 Auxiliary (gate driver) voltage

V_{GATE} monitor equations:

$$\frac{GateDrvr - V_p}{R_{89}} = \frac{V_p}{R_{92}} \qquad \frac{VAUX - V_n}{R_{109}} = \frac{V_n - PGND}{R_{110}} \qquad V_n = V_p$$

$$R_{110} = R_{89} \qquad R_{109} = R_{92} \qquad R_{89} = 10.2 \times 10^{3} \qquad R_{92} = 2.05 \times 10^{3}$$

Combining yields:

$$VAUX = \frac{R_{92}}{R_{89}} \cdot (GateDrvr - PGND)$$

$$VAUX\_adc = \frac{R_{92}}{R_{89}} \cdot (GateDrvr - PGND) \cdot \frac{V_{ADC\_Max}}{V_{ADCref}}$$

$$VAUX\_adc(GateDrvr) := \frac{R_{92}}{R_{89}} \cdot (GateDrvr - PGND) \cdot \frac{4096}{3.0}$$

Gate driver voltage operating range:

$$VAUX\_adc(0) = 0 \qquad VAUX\_adc(14.927) = 4096$$

11.5 Heatsink thermal monitor

$$\frac{V_{3V3A} - V_p}{R_{52}} = \frac{V_p}{R_{53}} \qquad \frac{(V_{NTC} - V_n)}{R_{48}} = \frac{V_n}{(R_{49} + R_{parallel})} \qquad R_{parallel} = \frac{R_{NTC} \cdot R_{47}}{R_{NTC} + R_{47}}$$

Where:

$$R_{NTC}(T_K) := R_0 \cdot e^{B \cdot \left(\frac{1}{T_K} - \frac{1}{T_0}\right)} \qquad R_0 = 10000 \qquad B = 3974.5 \qquad T_0 = 298.15$$

$$R_{47} = 2.2 \times 10^6 \quad R_{48} = 10 \times 10^3 \quad R_{49} = 4.99 \times 10^3 \quad R_{52} = 4.7 \times 10^3 \quad R_{53} = 2.1 \times 10^3$$

Solving:

$$V_{NTC}(T_K) := \frac{R_{53} \cdot V_{3V3A} \cdot \left(R_{48} + R_{49} + \frac{R_{NTC}(T_K) \cdot R_{47}}{R_{NTC}(T_K) + R_{47}}\right)}{(R_{52} + R_{53}) \cdot \left(R_{49} + \frac{R_{NTC}(T_K) \cdot R_{47}}{R_{NTC}(T_K) + R_{47}}\right)}$$

$$V_{NTC\_adc}(T_K) := \frac{R_{53} \cdot V_{3V3A} \cdot \left(R_{48} + R_{49} + \frac{R_{NTC}(T_K) \cdot R_{47}}{R_{NTC}(T_K) + R_{47}}\right)}{(R_{52} + R_{53}) \cdot \left(R_{49} + \frac{R_{NTC}(T_K) \cdot R_{47}}{R_{NTC}(T_K) + R_{47}}\right)} \cdot \frac{V_{ADC\_Max}}{V_{ADCref}}$$

Heatsink temperature operating range:

$$V_{NTC\_adc}(-10 + 273.15) = 1615 \qquad V_{NTC\_adc}(0 + 273.15) = 1754$$

$$V_{NTC\_adc}(25 + 273.15) = 2322 \qquad V_{NTC\_adc}(125 + 273.15) = 3996$$

$$V_{NTC\_adc}(160 + 273.15) = 4095$$

Note the transition temperatures are enumerated to minimize floating point calculations during normal operation. Thermal precision is not critical to the operational integrity of the PFC converter.

12 Auxiliary supply transformer specifications

12.1 Electrical

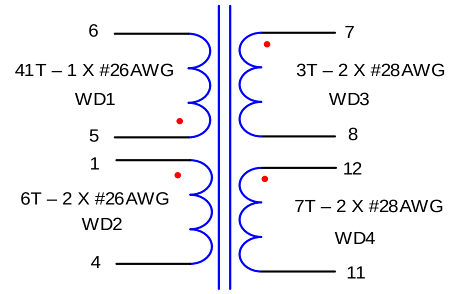

Figure 14. Bridgeless PFC 3.3kW bias transformer electrical diagram

Table 4. Transformer electrical specifications

Parameter	Detail	Value
Primary inductance	Pins 5-6, all other windings open, measured at 100kHz, 0.4V_{RMS}	646µH -7/+7%
Resonant frequency	Pins 5-6, all other windings open	1000MHz (min)
Leakage	Pins 5-6, all other windings shorted, measured at 100kHz, 0.4V_{RMS}	10µH

Table 5. Materials

Item	Description
1	Bobbin: RM8 12 pins MFG# B65812C1512T1
2	Core: RM8 N97 MFG# B65811J0000R097
3	Magnet wire: 26 AWG
4	Magnet wire: 28 TIW
5	Margin tape: 2.8mm
6	Tape: 3M 1298 polyester film

12.2 Inductor build

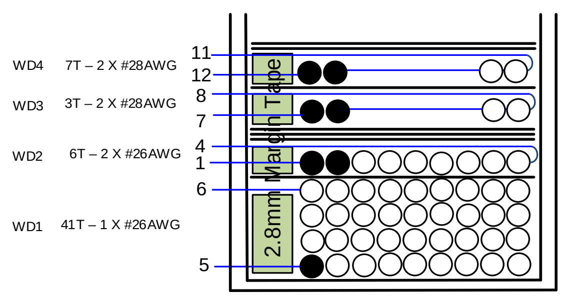

Figure 15. Inductor build diagram

13 Switching inductor specifications

13.1 50kHz operation

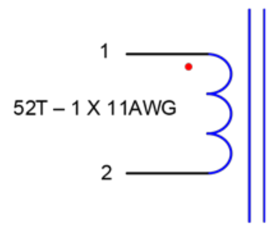

Figure 16. 45kHz inductor electrical diagram

Table 6. 45kHz inductor electrical specifications

Parameter	Detail	Value
Primary inductance	Pins 1-2, measured at 100kHz, $0.4V_{RMS}$	554µH -7/+7%

Table 7. Materials

Item	Description
1	Core: CH610060 high flux
2	Wire: 11 AWG magnet wire

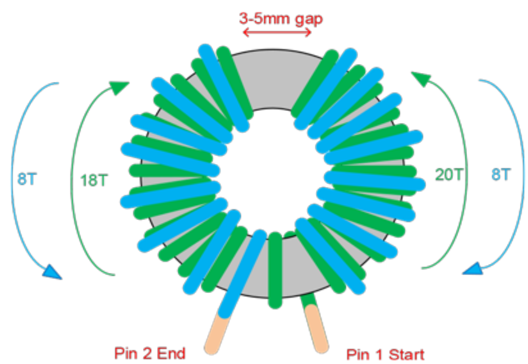

Figure 17. Inductor build diagram

13.2 100kHz operation

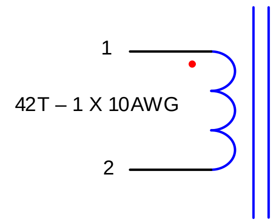

Figure 18. 100kHz inductor electrical diagram

Table 8. 100kHz inductor electrical specifications

Parameter	Detail	Value
Primary inductance	Pins 1-2, measured at 100kHz, $0.4V_{RMS}$	338µH -7/+7%

Table 9. Materials

Item	Description
1	Core: CH610060 high flux
2	Wire: 10 AWG magnet wire

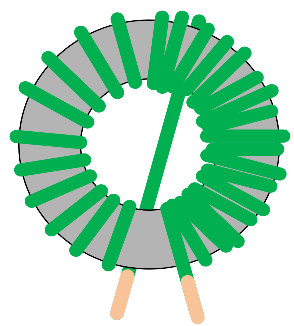

Figure 19. Inductor build diagram

14 EMI filter pole placement

The Bode plot in Figure 21 shows the pole locations of the generic EMI filter component values included in the PFC reference design. Note that distribution of the pole pairs across the frequency spectrum below 150kHz facilitates compliance since adjacent pole resonant interaction can reduce EMI margins.

This plot considers the switching inductor node looking back into the AC line and is simplified in the fact that it neglects the LISN terminating impedance, which can simply be added to include the impact of the isolating network.

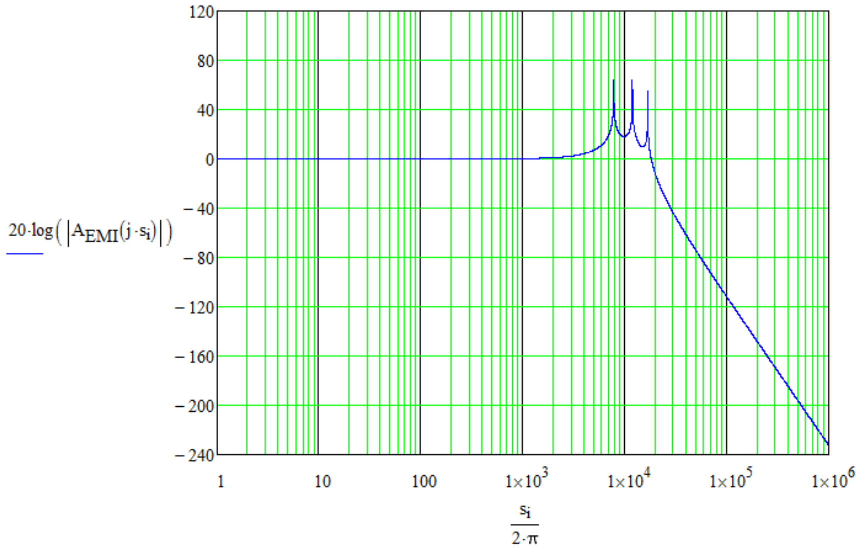

Figure 20. EMI filter Bode plot

15 Appendix A: PFC performance measurement setup

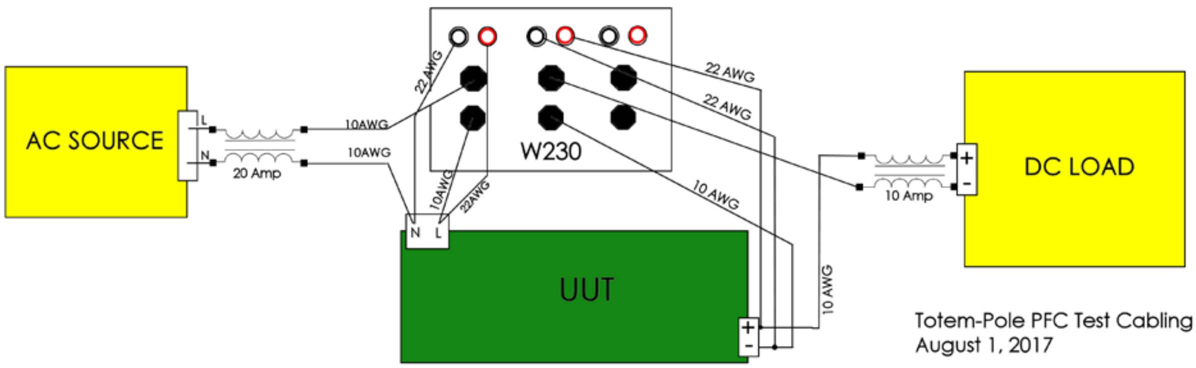

Figure 21. PFC test setup

17 Appendix B: Revision history

Date	Author	Revision	Description & changes	Reviewed by
9/21/2017	DCP	1.0	First draft of document to be submitted to Andrea (created from PFC Test Results RevEa)	
9/22/2017	DCP	1.3	Refined draft of document to be submitted to Andrea	
9/25/2017	DCP	1.4	Added hardware sense equations	
9/26/2017	DCP	1.6	Refined equations format; added layout guidelines	
10/13/2017	ALF	1.7	Updated template, formatting	
11/22/2017	DCP	1.8		
01/24/2018	PCZ	1.9	Updated design to increase efficiency	
02/28/2018	PCZ	1.10	Added reference design board/kit important notice	