Design Example Report

Title	***150 W Power Factor Corrected LLC Power Supply Using HiperPLC (PLC810PG)***
Specification	140 – 265 VAC Input; 150 W (48 V at 0.05 A – 3.125 A) Output
Application	LED Street Light
Author	Applications Engineering Department
Document Number	DER-212
Date	June 1, 2009
Revision	1.1

Summary and Features

- Integrated PFC and LLC controller
- Continuous mode PFC using small low-cost ferrite core and magnet wire
- Frequency and Phase locked PFC and LLC for ripple cancellation in bulk capacitor for reduced ripple current, reduced bulk capacitor size and reduced EMI filter cost
- Tight LLC duty-cycle matching
- Tight LLC dead-time control
- >95% full load PFC efficiency at 140 VAC using conventional ultrafast rectifier
- >95% full load LLC efficiency
- >92% full load system efficiency

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Important Note:
Although this board is designed to satisfy safety isolation requirements, the engineering prototype has not been agency approved. Therefore, all testing should be performed using an isolation transformer to provide the AC input to the prototype board.

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1 Introduction

This engineering report describes a 150 W reference design power supply for 230 VAC input LED street lights and also serves as a general purpose evaluation board for the PLC810PG

The design is based on the PLC810PG controller IC which integrates both continuous current mode (CCM) boost PFC and resonant half-bridge (LLC) control functions together with high-side and low side drivers for the LLC stage MOSFETs. To allow optimum design of the LLC transformer (T1) for high efficiency (high k factor – the ratio of parallel to series inductance) the design operates in burst mode at zero load. The supply is thus protected against output overvoltage at low/zero load, but it will not deliver a steady output voltage at zero load. A practical LED street light power supply design that includes an auxiliary output winding to power the LED driver circuitry may not have this limitation.

DER-212 demonstrates a design using the commonly employed single transformer and resonant inductor magnetic component (integrated magnetics) for the LLC stage (common in display applications). However, the PLC810 may as easily be used with separated transformer and resonating inductor. PI design materials support both approaches.

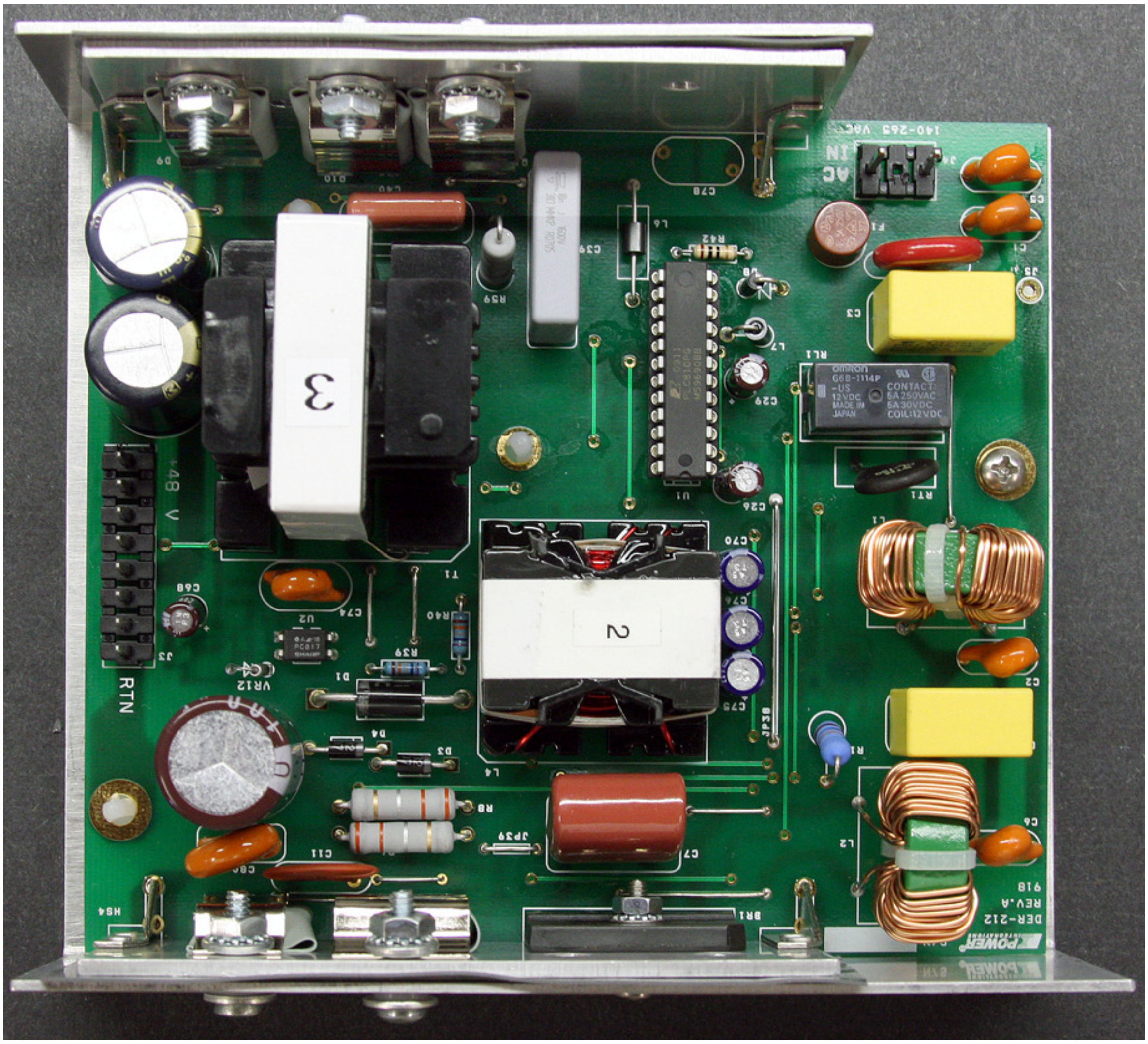

Figure 1 – DER-212 Photograph, Top View.

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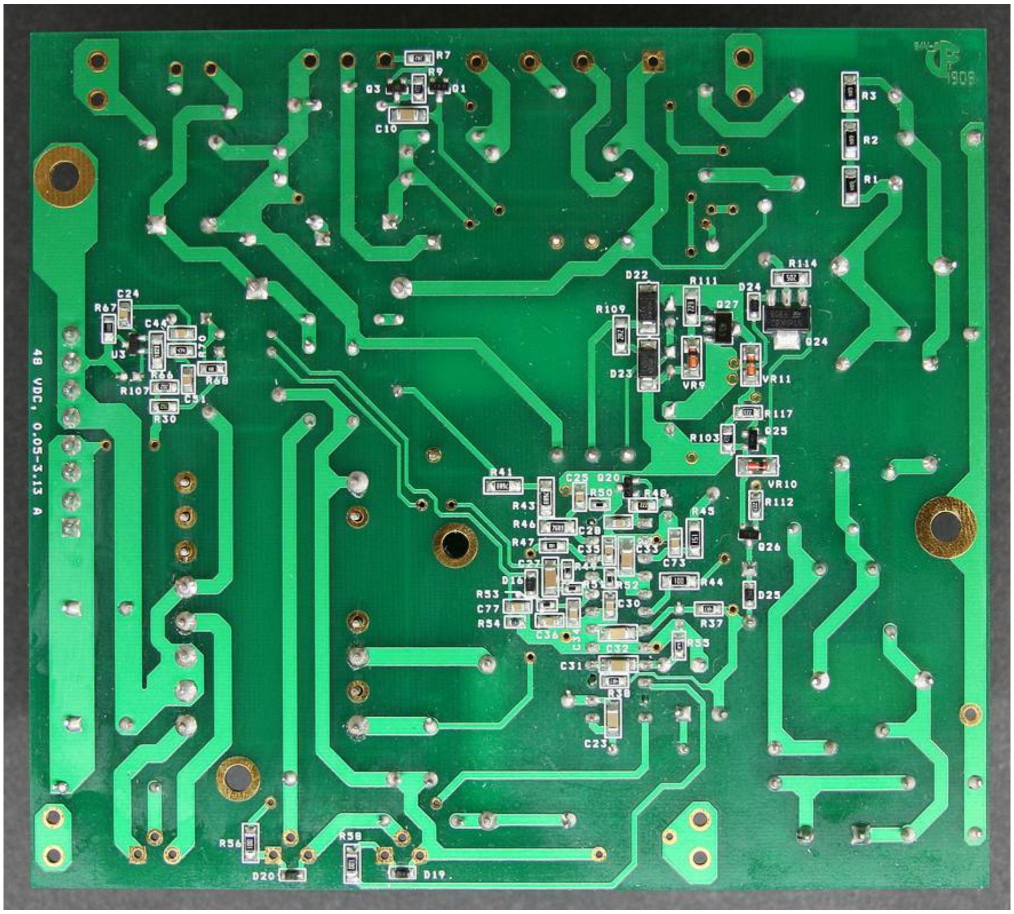

Figure 2 – DER-212 Photograph, Bottom View.

2 Power Supply Specification

Description	Symbol	Min	Typ	Max	Units	Comment
Input						
Voltage	V_{IN}	140		265	VAC	3 Wire input.
Frequency	f_{LINE}	47	50/60	64	Hz	
Power Factor	**PF**	0.97				Full load, 230 VAC
Main Converter Output						
Output Voltage	V_{LG}	45.6	48	50.4	V	48 VDC ± 5%
Output Ripple	$V_{RIPPLE(LG)}$			150	mV P-P	20 MHz bandwidth
Output Current	I_{LG}	0.05*	3.13	3.13	A	*Supply is protected under no-load conditions
Total Output Power						
Continuous Output Power	P_{OUT}		150		W	
Efficiency						
Total system at Full Load	η_{Main}	91 92			%	Measured at 140 VAC, Full Load Measured at 230 VAC, Full Load
Environmental						
Conducted EMI		Meets CISPR22B / EN55022B				
Safety		Designed to meet IEC950 / UL1950 Class II				
Surge						1.2/50 µs surge, IEC 1000-4-5,
Differential		1			kV	Differential Mode: 2 Ω
Common Mode		2			kV	Common Mode: 12 Ω
100 kHz Ring Wave		2			kV	500 A short circuit current
Ambient Temperature	T_{AMB}	0		60	°C	See thermal section for conditions

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3 Schematic

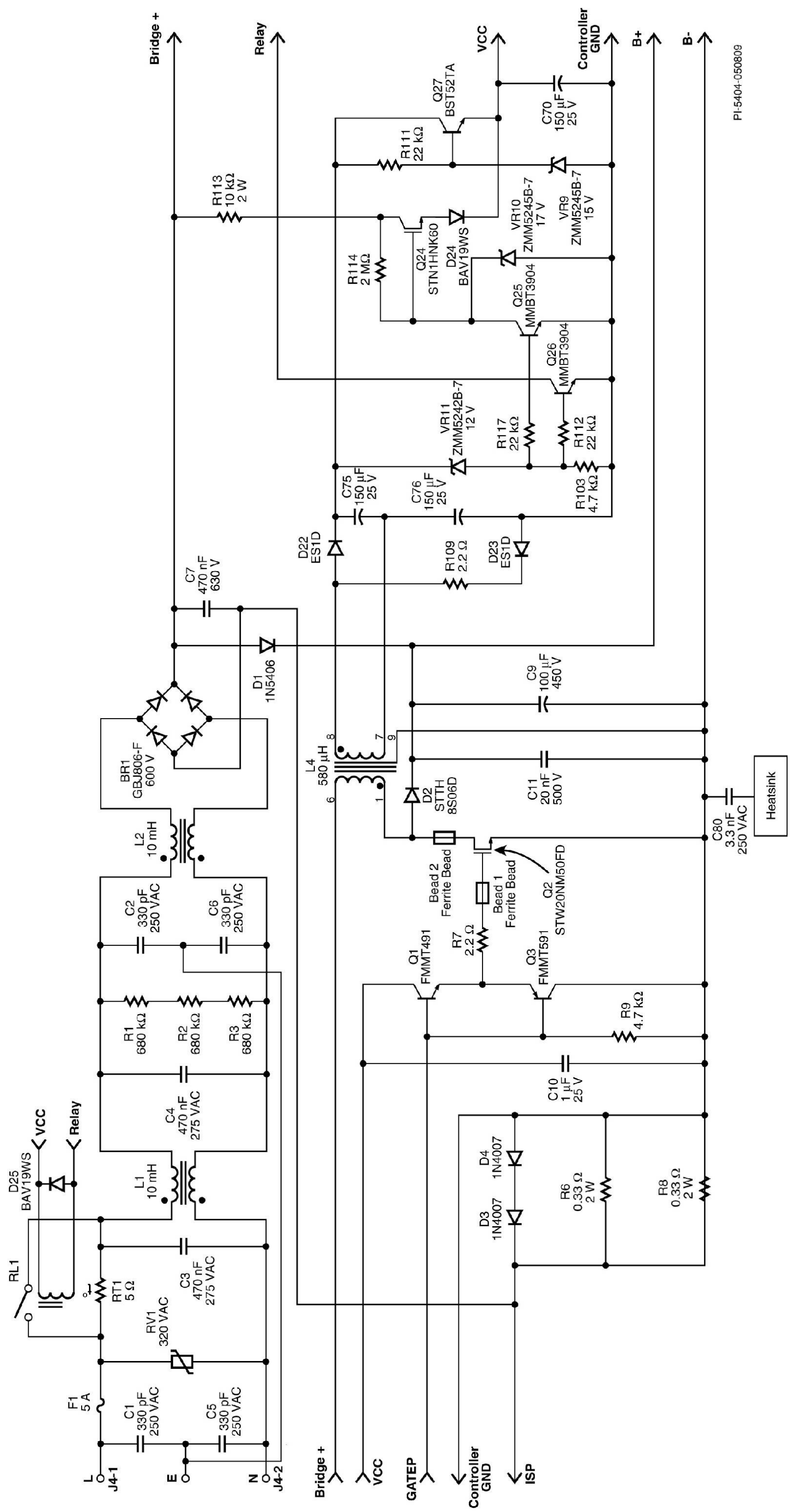

Figure 3 – Schematic of PLC810PG LCD Street Light Power Supply Application Circuit, Input Circuit and PFC Power Stage.

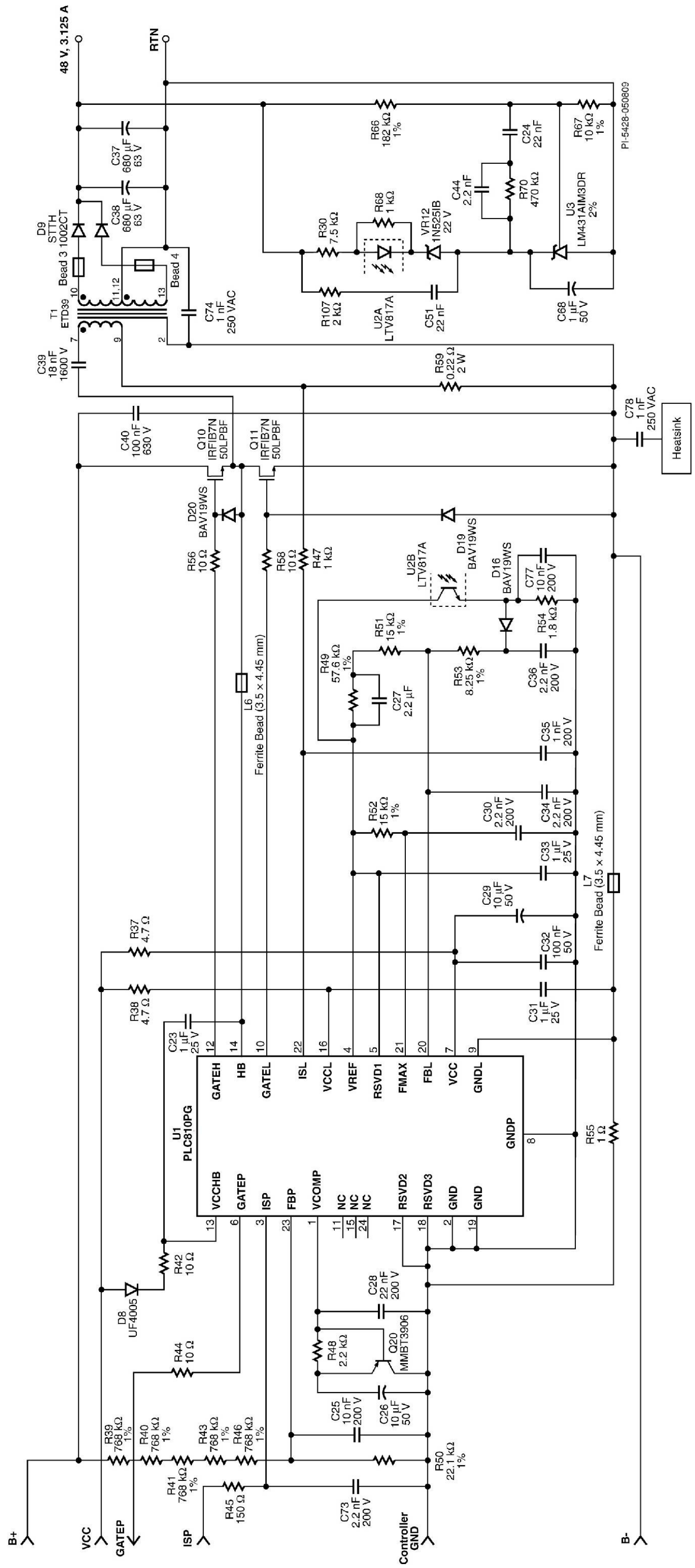

Figure 4 – Schematic of PLC810PG LCD Street Light Power Supply Application Circuit, PFC Circuit Control Inputs and LLC Stage.

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4 Circuit Description

The main converter uses the PLC810PG in a primary-side-control, PFC + LLC configuration.

4.1 Input Filter / Boost Converter / Bias Supply

The schematic in Figure 3 shows the input EMI filter, main PFC stage, and primary bias supply/start-up circuit.

4.1.1 EMI Filtering

Capacitors C1 and C5 are connected directly from Line and Neutral to protective Earth ground and are used to control common mode noise at frequencies greater than 30 MHz. Common mode inductors L1 and L2 control EMI at low frequencies and mid-band (<10 MHz), respectively. Capacitors C2 and C6 control resonant peaks in the mid-band region.

PFC inductor L4 has a grounded shield band to prevent electrostatic and magnetic noise coupling to the EMI filter components. Capacitors C3 and C4 provide differential mode EMI filtering. To meet safety requirements resistors R1, R2 and R3 discharge these capacitors when AC is removed. The heat sink for PFC switch FET Q2 and PFC output diode D2 is tied to primary return at the cathode of D3 via capacitor C80 to eliminate the heat sink as a source of conducted noise into the chassis/protective Earth ground.

4.1.2 Inrush Limiting

Thermistor RT1 provides inrush limiting. It is shorted by relay RL1 during normal operation, increasing efficiency by approximately 1 - 1.5%.

4.1.3 Main PFC Stage

Components C9, C11, L4, Q2, and D2 form a continuous mode power factor correction circuit. Components Q1, Q3, R7, R9 and bead 1 buffer the PWM drive signal for Q2 from the PLC810 controller. Resistor R7 allows the turn-off speed of Q2 to be adjusted to optimize the losses between D2 and Q2. In this design it was found that efficiency and EMI were both improved by reducing the value of R7 and adding ferrite beads to the gate and drain of Q2 (bead 1 and bead 2 respectively). In general, increasing MOSFET turn on drive current reduces MOSFET switching losses but increases the reverse recovery current through D2 and associated ringing. An ultra fast diode was selected for D2 as a lower cost alternative to a silicon carbide or other proprietary diode technology. These may provide higher efficiency by reducing reverse recovery charge, but significantly increase solution cost.

A 220 MΩ, 500 V power MOSFET was selected for Q2 to maximize the efficiency of the PFC stage. A TO-247 package device was selected for better heat transfer.

Capacitor C10 provides local bypassing for the drive circuit. Current sensing for the PFC stage is provided by R6 and R8. The sense voltage is clamped to two diode drops by D3 and D4, protecting the current sense input of the controller IC during fault conditions. Diode D1 charges the PFC output capacitor (C9) when AC is first applied. This routes the inrush current around the PFC inductor L4 preventing it from saturating and causing stress in Q2 and D2 when the PFC stage begins to operate. Capacitor C11 is used to shrink the high frequency loop around components Q2, D2 and C9 to reduce EMI. The incoming AC is rectified by BR1 and filtered by C7. Capacitor C7 was selected as a low-loss polypropylene type due to its low loss and low impedance characteristics. This capacitor provides the high instantaneous current through L4 during Q2 on-time.

4.1.4 Primary Bias Supply / Start-up

Components D22, D23, C75, C76, and R109 act as a voltage doubler circuit to rectify and filter the output of a floating bias winding on PFC choke L4, providing a bias voltage relatively independent of input voltage.

Components Q24, Q25, Q27, VR9, VR10, VR11, D24, C70, R103, R111, R113, R114, and R117 constitute the bias regulator and start-up functions. Resistor R113 charges capacitor C70 through mosfet Q24 to provide start-up bias for controller U1. The Q24 output voltage is clamped by VR10. Transistor Q25 shuts off the start-up circuit when the primary bias supply reaches regulation. Darlington transistor Q27, R111, and VR9 form a simple emitter-follower voltage regulator. Transistor Q26 switches on relay RL1 when the primary bias supply reaches regulation, shorting out thermistor RT1.

4.2 Controller / Main LLC Output

Figure 4 shows the schematic of the main controller circuit and LLC converter stage.

4.2.1 LLC Input Stage

MOSFETs Q10 and Q11 are the switch MOSFETs for the LLC converter. They are driven directly by the controller IC via resistors R56 and R58. Capacitor C39 is the primary resonating capacitor, and should be a low-loss type rated for the RMS current at maximum load. Capacitor C40 is used for local bypassing, and is positioned adjacent to Q10 and Q11. Resistor R59 provides primary current sensing to the controller for overpower protection.

4.2.2 LLC Outputs

The secondaries of transformer T1 are rectified and filtered by D9, and C37-38 to provide the +48 V output.

4.2.3 Controller

Figure 4 also shows the circuitry around the main controller IC U1, which provides control functions for the input PFC and output LLC stages.

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4.2.4 PFC Control

The PFC boost stage output voltage is fed back to the boost voltage sense pin (FBP of U13) via resistors R39-41, R43, R46, and R50. Capacitor C25 filters noise. Components C26, C28 and R48 provide frequency compensation for the PFC. Transistor Q20 turns on during large signal excursions, bypassing C26. This allows fast slewing of the PFC control loop in response to a large load step. The PFC current sense signal from resistors R6 and R8 is filtered by R45 and C73. The PFC drive signal from the GATEP pin is routed to the main switching FET via R44. This damps any ringing in the PFC drive signal caused by the trace length from U1 to PFC switch MOSFET Q2.

4.2.5 Bypassing / Ground Isolation

Capacitors C29, C31, and C32 provide supply bypassing for the analog and digital supply rails for U1. Resistor R55 and ferrite bead L7 provide ground isolation between the PFC and LLC ground systems. Resistors R37 and R38 isolate the IC analog and digital supply rails. Ferrite bead L6 provides high frequency isolation between the LLC stage high side MOSFET drive return and the controller IC.

4.2.6 LLC Control

Feedback from the LLC output sense/feedback circuit is provided by U2, which develops a feedback voltage across resistor R54. Capacitor C77 filters the feedback signal. Resistors R49, R51, and R53 set the lower frequency limit for the LLC converter stage. Capacitor C27 is used to provide output soft start. Resistor R52 sets the LLC upper frequency limit. Capacitors C30 and C36 are noise filters. The LLC overload sense signal from resistor R59 is filtered by R47 and C35. Components C23, R42, and D8 provide bootstrapping for the LLC top side MOSFET drive. Resistors R52 and R53 were selected to force the LLC converter into burst mode at low/zero output load, protecting the output from overvoltage. This operation mode was selected (vs. allowing operation at a higher frequency at no-load) to give adequate dead time and ensure ZVS operation. The alternative would be to adjust the ratio of parallel and series inductance (k factor) however this reduces full load efficiency.

4.3 LLC Secondary Control Circuits

Figure 4 shows the secondary control schematic for the LLC stage.

4.3.1 Voltage Feedback

The LLC converter 48 V output is sensed by resistors R67 and R68. Zener diode VR12 drops the 48 V output to protect regulator U3. Components C24, C44, C51, R30, R70, and R107 provide frequency compensation for the LLC stage.

5 PCB Layout

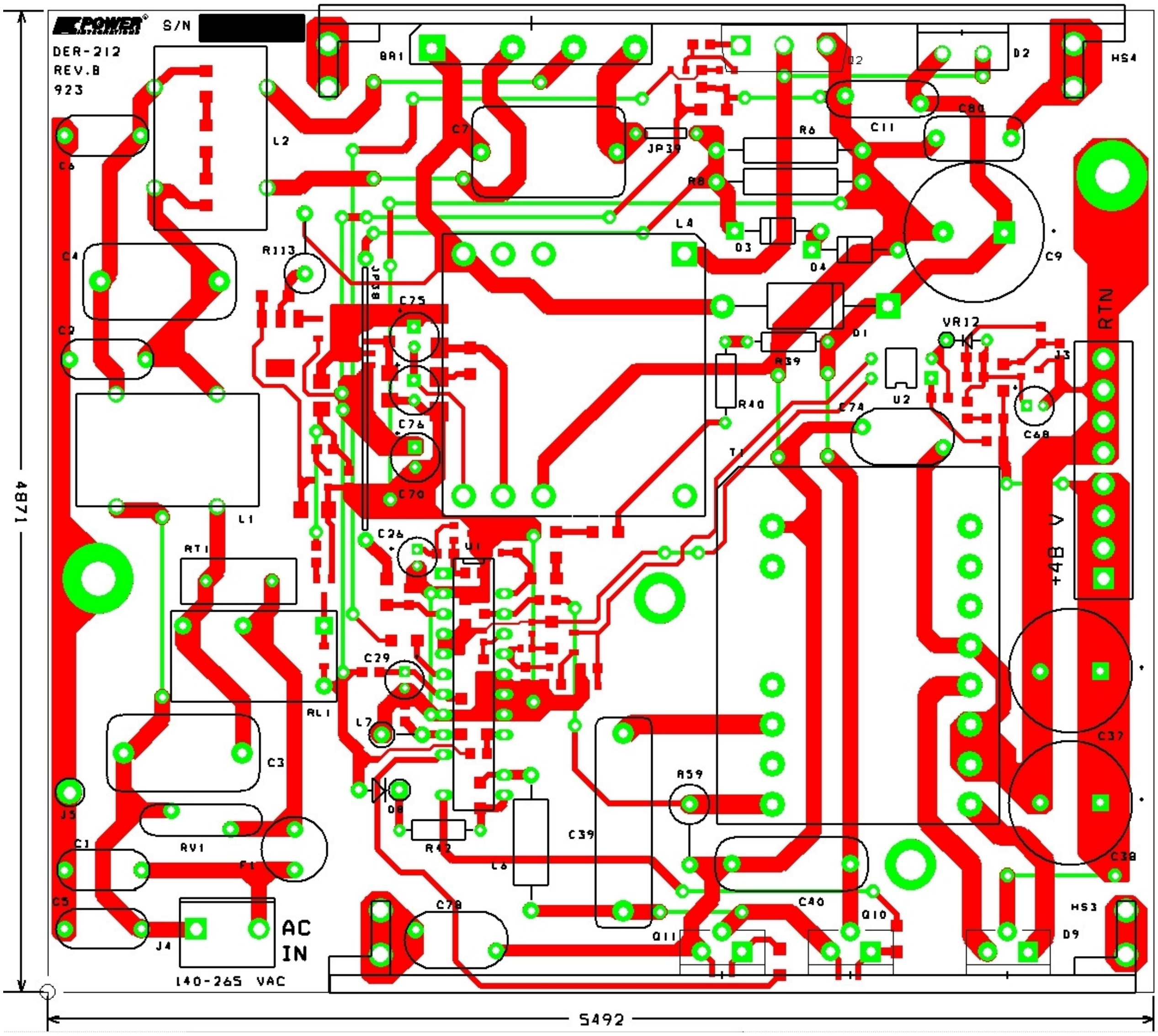

Figure 5 – Printed Circuit Layout, Top Side.

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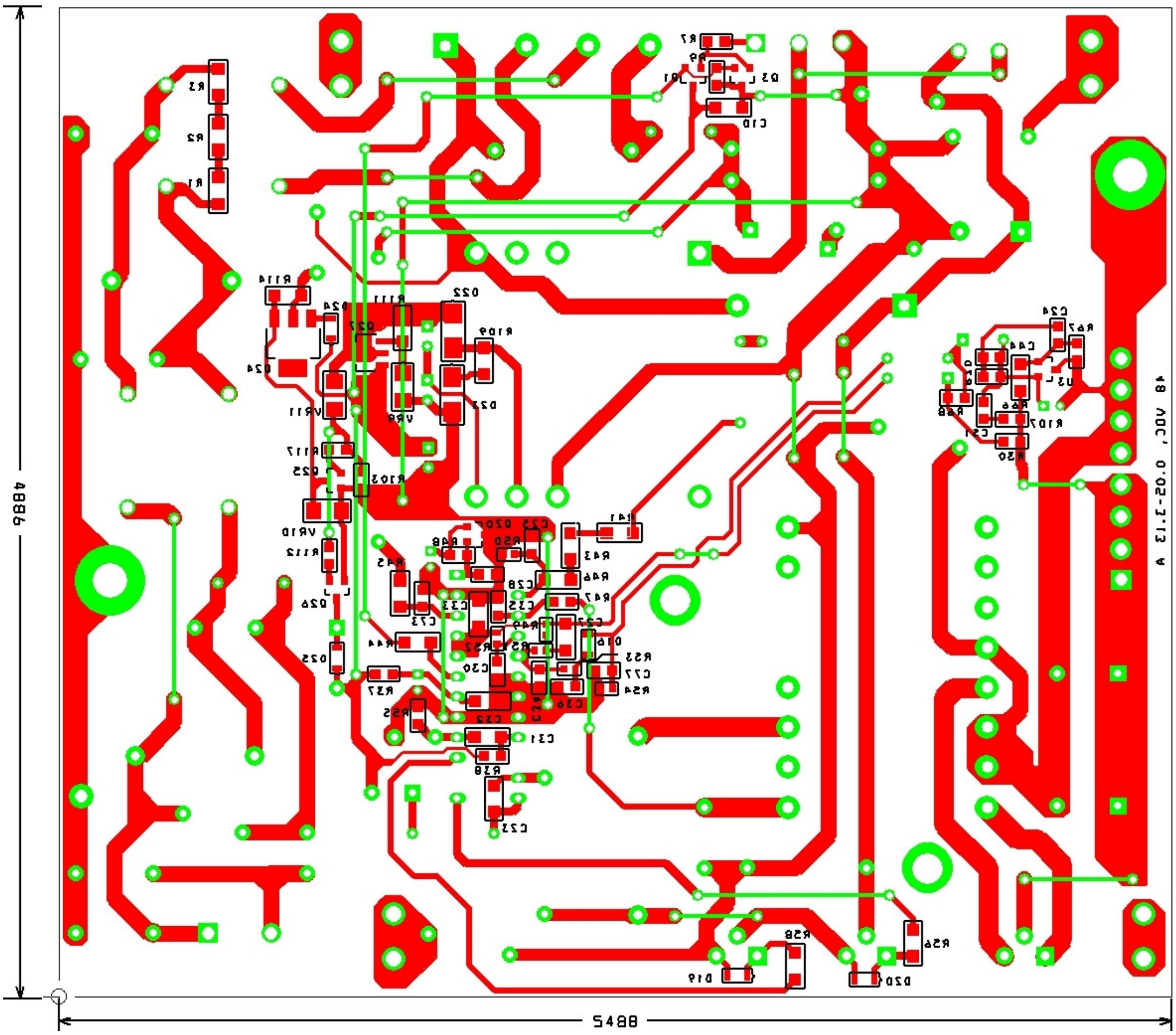

Figure 6 – Printed Circuit Layout, Bottom Side.

6 Bill of Materials

Item	Qty	Ref Des	Description	Mfg Part Number	Mfg
1	4	BEAD1 BEAD2 BEAD3 BEAD4	3.5 mm D x 3.25 L mm, 21 Ω at 25 MHz, 1.6mm (.063) hole, Ferrite Bead	2643001501	Fair-Rite
2	1	BR1	600 V, 8 A, Bridge Rectifier, GBJ Package	GBJ806-F	Diodes Inc
3	4	C1 C2 C5 C6	330 pF, Ceramic Y1	440LT33-R	Vishay
4	2	C3 C4	470 nF, 275 VAC, Film, X2	PX474K31D5	Carli
5	1	C7	470 nF, 630 V, Polypropylene Film	ECW-F6474JL	Panasonic
6	1	C9	100 µF, 450 V, Electrolytic, Low ESR, (18 x 30)	EPAG451ELL101MM35S	Nippon Chemi-Con
7	4	C10 C23 C31 C33	1 µF, 25 V, Ceramic, X7R, 1206	ECJ-3YB1E105K	Panasonic
8	1	C11	20 nF, 500 V, Disc Ceramic	D203Z59Z5UL63L0R	Vishay/BC
9	3	C24 C28 C51	22 nF, 200 V, Ceramic, X7R, 0805	08052C223KAT2A	AVX Corp
10	2	C25 C77	10 nF, 200 V, Ceramic, X7R, 0805	08052C103KAT2A	AVX Corp
11	2	C26 C29	10 µF, 50 V, Electrolytic, Gen. Purpose, (5 x 11)	EKMG500ELL100ME11D	Nippon Chemi-Con
12	1	C27	2.2 µF, 25 V, Ceramic, X7R, 1206	ECJ-3YB1E225K	Panasonic
13	5	C30 C34 C36 C44 C73	2.2 nF, 200 V, Ceramic, X7R, 0805	08052C222KAT2A	AVX Corp
14	1	C32	100 nF, 50 V, Ceramic, X7R, 1206	ECJ-3VB1H104K	Panasonic
15	1	C35	1 nF, 200 V, Ceramic, X7R, 0805	08052C102KAT2A	AVX Corp
16	2	C37 C38	680 µF, 63 V, Electrolytic, Low ESR, 50 mΩ, (16 x 25)	EEU-FC1J681	Panasonic
17	1	C39	18 nF, 1600 V, Film	2222 383 50183	Vishay
18	1	C40	100 nF, 630 V, Film	ECQ-E6104KF	Panasonic
19	1	C68	1 µF, 50 V, Electrolytic, Gen. Purpose, (5 x 11)	EKMG500ELL1R0ME11D	Nippon Chemi-Con
20	3	C70 C75 C76	150 uF, 25 V, Electrolytic, Low ESR, 180 mΩ, (6.3 x 15)	ELXZ250ELL151MF15D	Nippon Chemi-Con
21	2	C74 C78	1 nF, Ceramic, Y1	440LD10-R	Vishay
22	1	C80	3.3 nF, Ceramic, Y1	440LD33-R	Vishay
23	1	D1	600 V, 3 A, Recitifier, DO-201AD	1N5406	Vishay
24	1	D2	600 V, 8 A, Ultrafast Recovery, 12 ns, TO-220AC	STTH8S06D	ST Semiconductor
25	2	D3 D4	1000 V, 1 A, Rectifier, DO-41	1N4007-E3/54	Vishay
26	1	D8	600 V, 1 A, Ultrafast Recovery, 75 ns, DO-41	UF4005-E3	Vishay
27	1	D9	200 V, 10 A, Dual Ultrafast Recovery, 25 ns, TO-220AB	STTH1002CT	ST
28	5	D16 D19 D20 D24 D25	100 V, 0.2 A, Fast Switching, 50 ns, SOD-323	BAV19WS-7-F	Diode Inc.
29	2	D22 D23	200 V, 1 A, Ultrafast Recovery, 25 ns, DO-214AC	ES1D	Vishay
30	1	DER-212 PRIMARY INSULATOR	Thermal Conductive insulator, DER-212 Pri Htsnk, 0.5mm Silicone		Power Integrations
31	1	DER-212 SECONDARY INSULATOR	Thermal Conductive insulator, DER-212 Sec Htsnk, 0.5mm Silicone		Power Integrations
32	1	F1	5 A, 250 V, Slow, TR5	3721500041	Wickman

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33	1	GREASE1	Thermal Grease, Silicone, 5 oz Tube	CT40-5	ITW Chemtronics
34	1	GND CABLE ASSY, DER-212	Cable ASSY, 18 GA GRN/YEL, 6 in, with ring terminal		
35	1	HS/BRACKET, DER-212	Heatsink/Mounting Bracket, DER-212		
36	2	HS3 HS4	HEATSINK, Custom, Al, 1100, 0.090" Thk		Power Integrations
37	1	J3	8 Position (1 x 8) header, 0.156 pitch, Vertical	26-48-1081	Molex
38	1	J4	3 Position (1 x 3) header, 0.156 pitch, Vertical	B3P-VH	JST
39	1	JP38	Wire Jumper, Non insulated, 22 AWG, 1.4 in	298	Alpha
40	1	JP39	Wire Jumper, Non insulated, 22 AWG, 0.3 in	298	Alpha
41	2	L1 L2	Common Mode Choke Toroidal	P/N T22148-902S (Order PI Taiwan)	Fontaine Tech CO. LTD
42	1	L4	CC Mode PFC Choke, PQ32/20		
43	2	L6 L7	3.5 mm x 4.45 mm, 68 Ohms at 100 MHz, 22 AWG hole, Ferrite Bead	2743001112	Fair-Rite
44	4	MAX CLIP1 MAX CLIP2 MAX CLIP3 MAX CLIP4	Hardware, Heatsink MaxClip, TO220/Max247 11.2lb 0.87 x 12 mm	MAX07G	Aavid Thermalloy
45	1	MAX CLIP5	Hardware, Heatsink MaxClip, TO218/TO247 16.9lb 0.93 x 18 mm	MAX08G	Aavid Thermalloy
46	1	NUT1	Nut, Hex, Kep 4-40, S ZN Cr3 plateing RoHS	4CKNTZR	Olander
47	6	NUT2 NUT3 NUT4 NUT5 NUT6 NUT7	Nut, Hex, Kep 6-32, Zinc Plate	6CKNTZR	Olander
48	1	Q1	NPN, 60 V 1000 MA, SOT-23	FMMT491TA	Zetex Inc
49	1	Q2	500 V, 20 A, 220 mOhm, N-Channel, TO-247AC	STW20NM50FD	ST
50	1	Q3	PNP, 60 V 1000 MA, SOT-23	FMMT591TA	Zetex Inc
51	2	Q10 Q11	500 V, 6.8 A, 320 mOhm. N-Channel, TO-247AC	IRFIB7N50LPBF	IR/Vishay
52	1	Q20	PNP, Small Signal BJT, 40 V, 0.2 A, SOT-23	MMBT3906LT1G	On Semiconductor
53	1	Q24	600 V, 400 mA, 8.5 Ohm, N-Channel, SOT 223	STN1HNK60	ST
54	2	Q25 Q26	NPN, Small Signal BJT, 40 V, 0.2 A, SOT-23	MMBT3904LT1G	On Semiconductor
55	1	Q27	NPN, DARL 80 V 500 MA, SOT-89	BST52TA	Zetex Inc
56	3	R1 R2 R3	680 kΩ, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ684V	Panasonic
57	2	R6 R8	0.33 Ω, 5%, 2 W, Metal Oxide	MO200J0R33B	Synton-Tech corporation
58	1	R7	2.2 Ω, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ2R2V	Panasonic
59	2	R9 R103	4.7 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ472V	Panasonic
60	1	R30	7.5 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ752V	Panasonic
61	2	R37 R38	4.7 Ω, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ4R7V	Panasonic
62	2	R39 R40	768 kΩ, 1%, 1/4 W, Metal Film	MFR-25FBF-768K	Yageo
63	3	R41 R43 R46	768 kΩ, 1%, 1/4 W, Metal Film, 1206	ERJ-8ENF7683V	Panasonic
64	1	R42	10 Ω, 5%, 1/4 W, Carbon Film	CFR-25JB-10R	Yageo
65	3	R44 R56 R58	10 Ω, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ100V	Panasonic
66	1	R45	150 Ω, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ151V	Panasonic
67	2	R47 R68	1 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ102V	Panasonic
68	1	R48	2.2 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ222V	Panasonic

69	1	R49	57.6 kΩ, 1%, 1/16 W, Metal Film, 0603	ERJ-3EKF5762V	Panasonic
70	1	R50	22.1 kΩ, 1%, 1/16 W, Metal Film, 0603	ERJ-3EKF2212V	Panasonic
71	2	R51 R52	15 kΩ, 1%, 1/16 W, Metal Film, 0603	ERJ-3EKF1502V	Panasonic
72	1	R53	8.25 kΩ, 1%, 1/8 W, Metal Film, 0603	ERJ-3EKF8251V	Panasonic
73	1	R54	1.8 kΩ, 5%, 1/10 W, Metal Film, 0603	ERJ-3GEYJ182V	Panasonic
74	1	R55	1 Ω, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ1R0V	Panasonic
75	1	R59	0.22 Ω, 5%, 2 W, Metal Oxide	MO200J0R22B	Synton-Tech Corporation
76	1	R66	182 kΩ, 1%, 1/4 W, Metal Film, 1206	ERJ-8ENF1823V	Panasonic
77	1	R67	10 kΩ, 1%, 1/8 W, Metal Film, 0805	ERJ-6ENF1002V	Panasonic
78	1	R70	470 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ474V	Panasonic
79	1	R107	2 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ202V	Panasonic
80	1	R109	2.2 Ω, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ2R2V	Panasonic
81	1	R111	22 kΩ, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ223V	Panasonic
82	2	R112 R117	22 kΩ, 5%, 1/8 W, Metal Film, 0805	ERJ-6GEYJ223V	Panasonic
83	1	R113	10 kΩ, 5%, 2 W, Metal Oxide	RSF200JB-10K	Yageo
84	1	R114	2 MΩ, 5%, 1/4 W, Metal Film, 1206	ERJ-8GEYJ205V	Panasonic
85	1	RL1	SPST-NO, 5A 12VDC, PC MNT	G6B-1114P-US-DC12	OMRON
86	1	RT1	NTC Thermistor, 5 Ohms, 4.7 A	CL150	Thermometrics
87	1	RV1	320 V, 84J, 15.5 mm, RADIAL	S14K320	Epcos
88	1	SCREW1	SCREW MACHINE PHIL 4-40X1/2 SS	PMSSS 440 0050 PH	Building Fasteners
89	5	SCREW2 SCREW3 SCREW4 SCREW5 SCREW6	SCREW MACHINE PHIL 6-32X1/2 SS	PMSSS 632 0050 PH	Building Fasteners
90	1	SCREW7	SCREW MACHINE PHIL 6-32X1/4 SS	PMSSS 632 0025 PH	Building Fasteners
91	4	SCREW8 SCREW9 SCREW10 SCREW11	SCREW MACHINE PHIL Flat head, Undercut 6-32 X ¼" Zinc Plated	6C25PFUZR	Olander
92	2	STDOFF1 STDOFF3	Standoff Hex,6-32, .375L,Alum	2209	Keystone Elect
93	2	STDOFF2 STDOFF4	Standoff Hex, 6-32/snap, .375L,Nylon	FTA-A 375	Eagle Hardware
94	1	T1	Custom Transformer, LLC, ETD39,Vertical, 14Pins		
95	4	TUBE-TO-220	Heatpad, TO-220 Tube 13.5 x 25 mm	SPT400-12-11-25	Bergquist
96	1	TUBE-TO-247	Heatpad, TO-247 Tube 13.5 x 25 mm	SPT400-12-13.5-25	Bergquist
97	1	U1	Controller, PFC/LLC, 24-pin DIP	PLC818PG	Power Integrations
98	1	U2	Opto coupler, 35 V, CTR 80-160%, 4-DIP	LTV-817A	Liteon
99	1	U3	IC, REG ZENER SHUNT ADJ SOT-23	LM431AIM3/NOPB	National Semiconductor
100	1	VR9	15 V, 5%, 500 mW, DO-213AA (MELF)	ZMM5245B-7	Diodes Inc
101	1	VR10	17 V, 5%, 500 mW, DO-213AA (MELF)	ZMM5247B-7	Diodes Inc
102	1	VR11	12 V, 5%, 500 mW, DO-213AA (MELF)	ZMM5242B-7	Diodes Inc
103	1	VR12	22 V, 5%, 500 mW, DO-35	1N5251B	Microsemi

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104	2	WASHER1 WASHER2	WASHER FLAT #4 SS	FWSS 004	Building Fasteners
105	11	WASHER3 WASHER4 WASHER5 WASHER6 WASHER7 WASHER8 WASHER9 WASHER10 WASHER11 WASHER12 WASHER13	Washer Flat #6, SS	FWSS 006	Building Fasteners
106	1	WASHER14	Bushing Nylon #4 X 0.125	MNI#4-8	Richco Plastic Co.
107	5	WASHER15 WASHER16 WASHER17 WASHER18 WASHER19	Bushing Nylon #6 X 0.125	MNI#6-8	Richco Plastic Co.

7 Magnetics

7.1 Main LLC 48 V Transformer (T1) Specification

7.1.1 Electrical Diagram

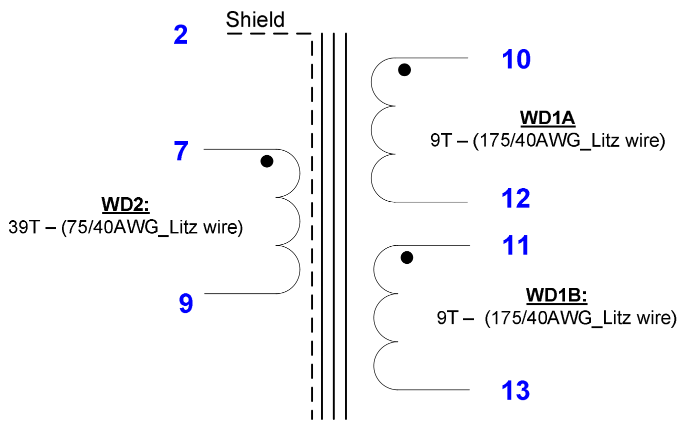

Figure 7 – Transformer Electrical Diagram.

7.1.2 Electrical Specifications

Electrical Strength	60 second, 60 Hz, from pins 1 - 9 to pins 10 - 18	3000 VAC
Primary Inductance	Pins 7 - 9, all other windings open, measured at 100 kHz, 0.4 VRMS	820 µH ±10%
Resonant Frequency	Pins 7- 9, all other windings open	700 kHz (Min.)
Primary Leakage Inductance	Pins 7 - 9, with pins 10 - 18 shorted, measured at 100 kHz, 0.4 VRMS	100 µH ±10%

7.1.3 Materials

Item	Description
[1]	Core: ETD39, Ferroxcube 3F3 material or equivalent, gap for inductance coefficient (A_L) of 539 nH/t².
[2]	Bobbin: ETD39 vertical, flanged Pinshine P-3907
[3]	Tape: Polyester film, 3M 1350F-1 or equivalent, 10.6 mm wide.
[4]	Wire: Litz, 75 strands 40WAG, solderable single coated.
[5]	Wire: Litz, 175 strands 40WAG, solderable single coated.
[6]	Tape: Copper foil 9.0 mm wide.
[7]	Tape: Polyester film, 10.0 mm wide.
[8]	Copper bus wire #24 AWG.

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7.1.4 Winding Diagram

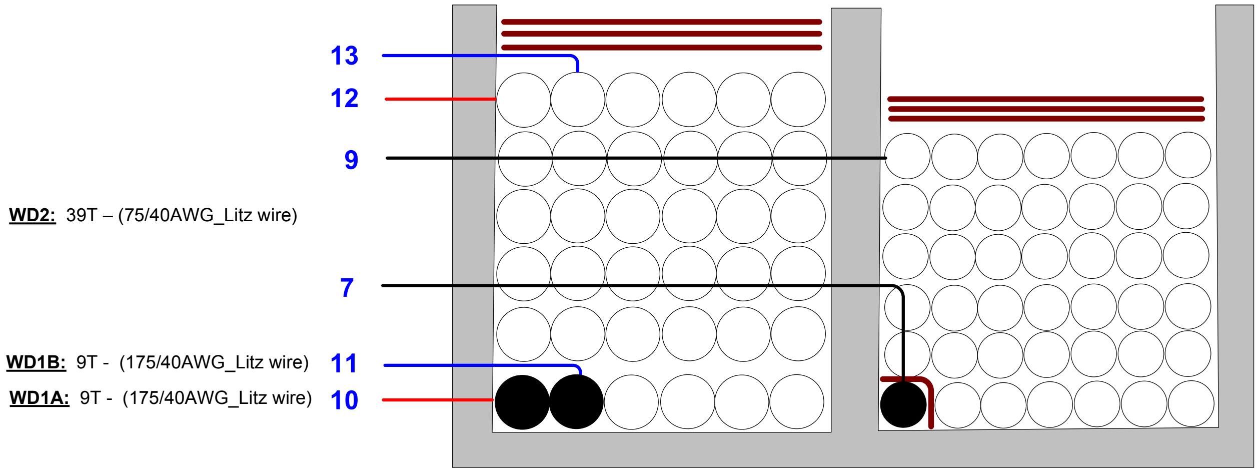
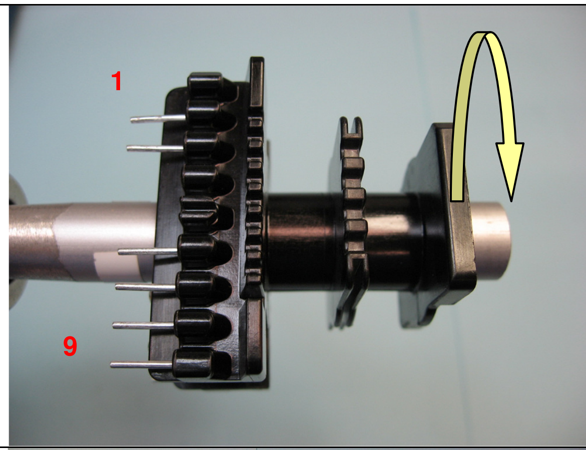
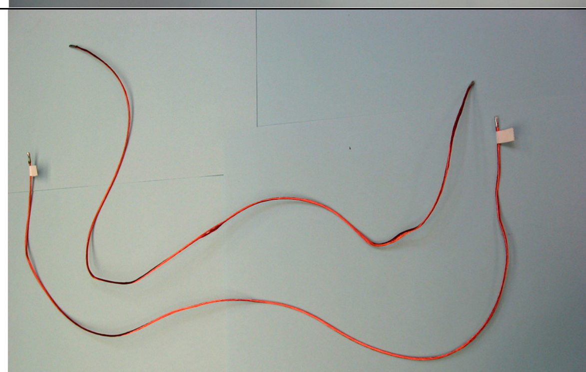
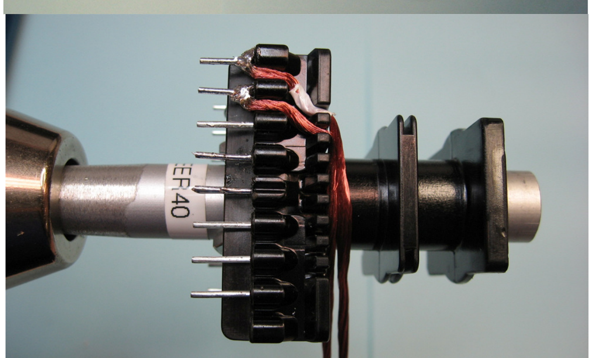
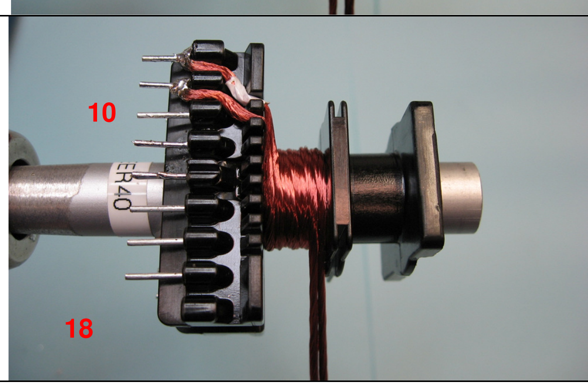


Figure 8 – LLC Transformer Winding Diagram.

7.1.5 Winding Instructions

General note	For the purpose of these instructions, Bobbin is oriented on winder such that pin side is on the left side (see illustration). Winding direction as shown is counter-clockwise.
WD1A and 1B	For WD1A and WD1B use two ~60 cm lengths of Litz wire (item [5]). Mark start and finish of one strand using a tape flag or other means. This strand will be used for WD 1A. Route start and finish leads as shown in illustrations. Start flagged wire strand at pin 10, start unflagged strand at pin 11. Wind 9 simultaneous bifilar turns of Litz wire (item [5]) from left to right, then from right to left, and continue with tight tension about 4 layers. Finish flagged wire at pin12 and unflagged wire at pin 13. Use 2 layers of tape (item [3]) for finish wrap.
WD2	Starting at pin 7, shield start lead where it enters bobbin with 2cm piece of tape (item [3]) at side of bobbin, then wind 39 turns of Litz wire (item [4]) on bobbin from left to right, then from right to left, and continue with tight tension in 6 layers. Use 2 layers of tape (item [3]) for finish wrap. Route start and finish leads as shown in illustrations.
Assembly	Grind core halves for specified primary inductance, insert bobbin, and secure core halves with one turn of copper tape (item [6]) as shown. Make sure that start and finis of copper tape overlap. Solder at overlap, attach wire (item [8]) and connect this wire to pin 2. Use tape (item [7]) to secure core halves and insulate.

7.2 Transformer Illustrations

General note		For the purpose of these instructions, bobbin is oriented on winder such that pin side is on the left side (see illustration). Winding direction as shown is counter-clockwise.
WD1A and 1B:		For WD1A and WD1B use two ~60 cm lengths of Litz wire (item [5]). Mark start and finish of one strand using a tape flag or other means. The marked strand will be used for WD 1A. Route start and finish leads as shown in illustrations. Start flagged wire strand at pin 10, start unflagged strand at pin 11.
WD1A and 1B: (Cont'd)		Wind 9 simultaneous bifilar turns of Litz wire (item [5]) from left to right, then from right to left, and continue with tight tension about 4 layers. Finish flagged wire at pin 12 and unflagged wire at pin 13. Use 2 layers of tape (item [3]) for finish wrap.

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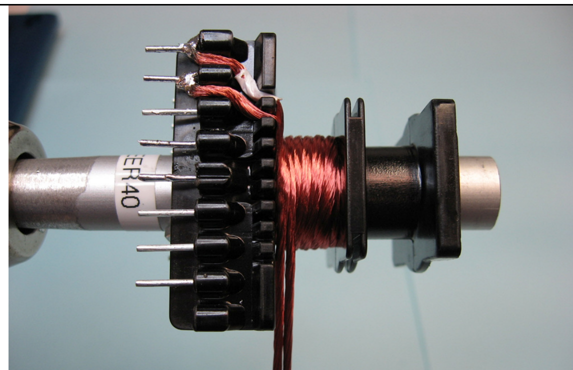
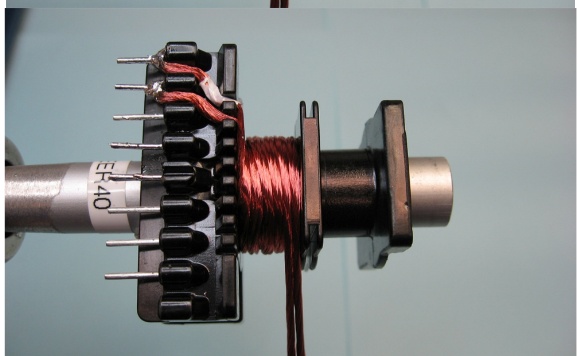
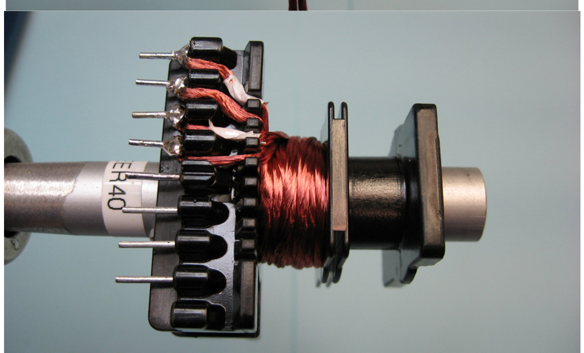
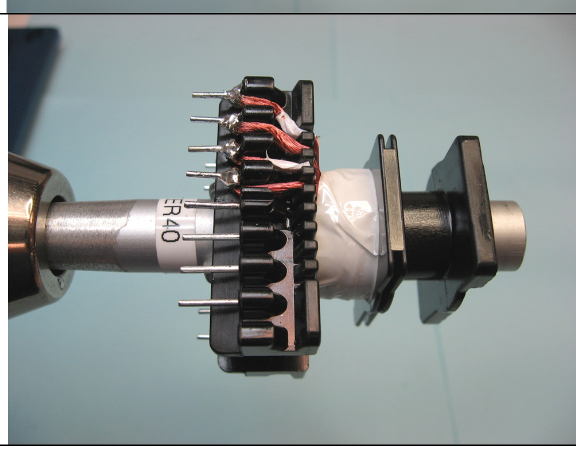
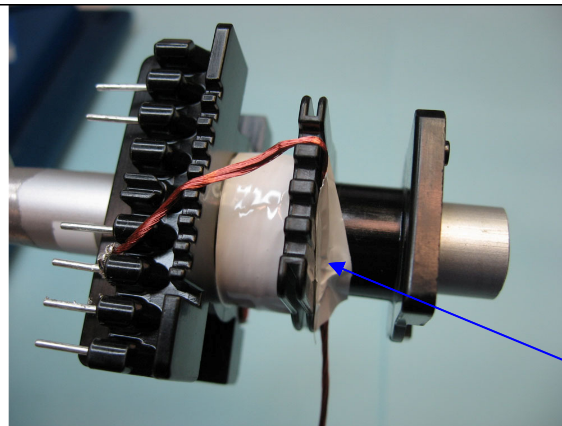
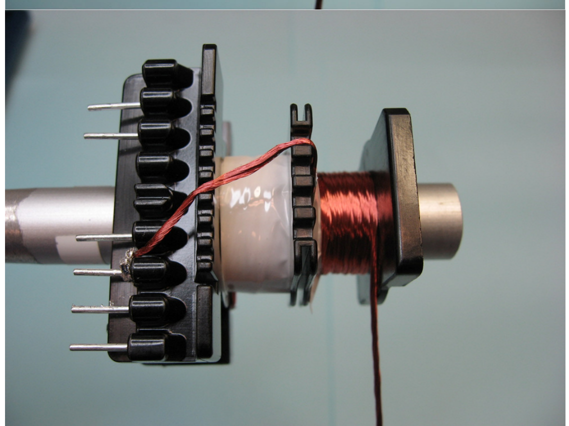
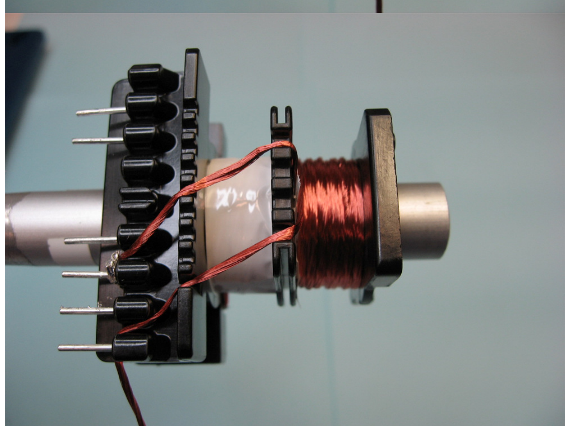
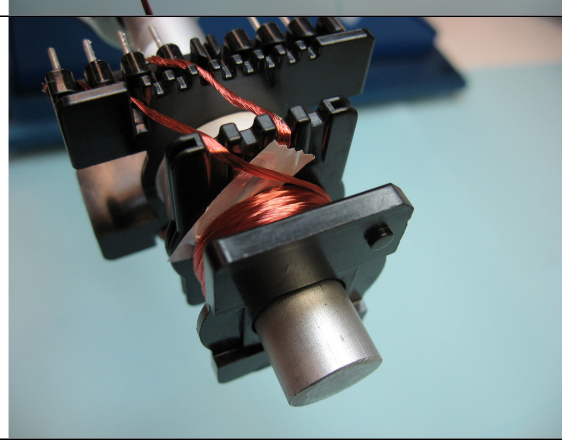
	  	
		Use 2 layers of tape (item [3]) for finish wrap.

WD2:	  	Starting at pin 7, shield start lead where it enters bobbin with 2cm piece of tape (item [3]) at side of bobbin, then wind 39 turns of Litz wire (item [4]) on bobbin from left to right, then from right to left, and continuing for 6 layers. Finish at Pin 9. Route start and finish leads as shown in illustration.
WD2: (Cont'd)		Use 2 layers of tape (item [3]) for finish wrap. Route start and finish leads as shown in illustrations.

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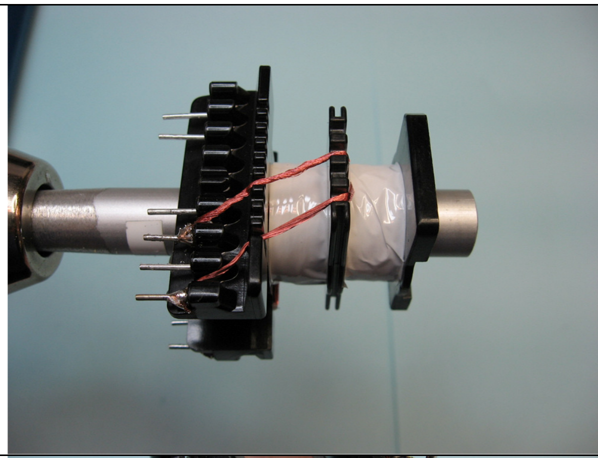
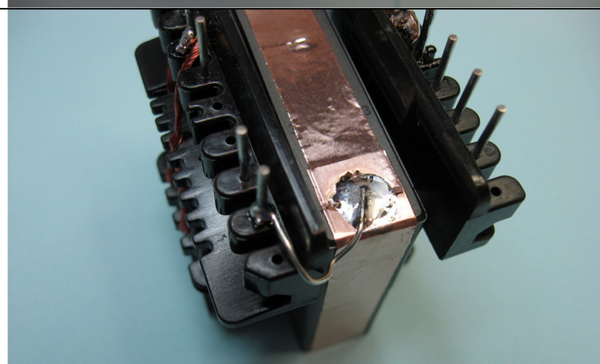
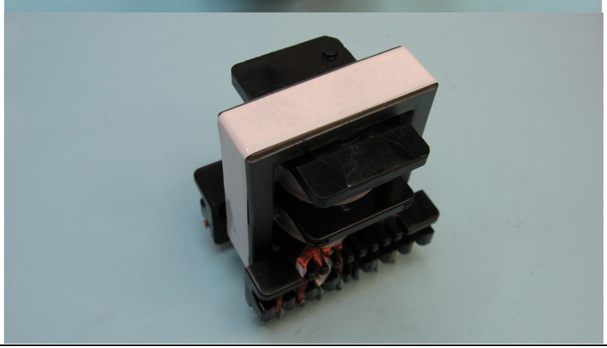
		
Assembly	 	Grind core halves for specified primary inductance, insert bobbin, and secure cores with one turn of copper Tape (item [6]). Overlap start and finish of copper tape. Solder at overlap, attach wire (item [8]) and connect this wire to pin 2. Use tape (item [7]) to secure core halves and insulate.

7.3 PFC Choke (L4) Specification

7.3.1 Electrical Diagram

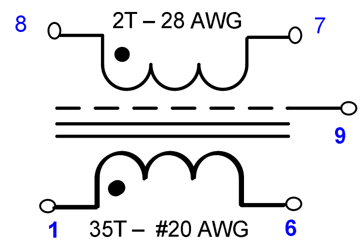


Figure 9 – PFC Choke Schematic.

7.3.2 Electrical Specification

Inductance: Pins 1-6, 100 kHz, 0.4 V - 580 µH ± 10%

7.3.3 Materials

Item	Description
[1]	Ferrite core pair, PQ32/20, TDK PC44PQ32/20Z-12 or equivalent, gap for A_L of 473 nH/T^2.
[2]	Bobbin, PQ32/20, 12 pin, TDK CPH-E41/12-1S-12PD-Z or equivalent.
[3]	Magnet Wire: #20AWG, solderable double coated.
[4]	Magnet Wire: #28AWG, solderable double coated.
[5]	Tape Polyester Film, 3M 1350F-1 or equivalent, 7.5 mm wide.
[6]	Tape Polyester Film, 3M 1350F-1 or equivalent, 10 mm wide.
[7]	Tape, Copper Foil, 3M 1125 or equivalent, 6.5 mm wide.
[8]	Wire, tinned bus, #24 AWG.
[9]	Transformer Varnish, Dolph BC-389 or equivalent (must be baking vs. air-dry varnish).

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7.3.4 Build Diagram

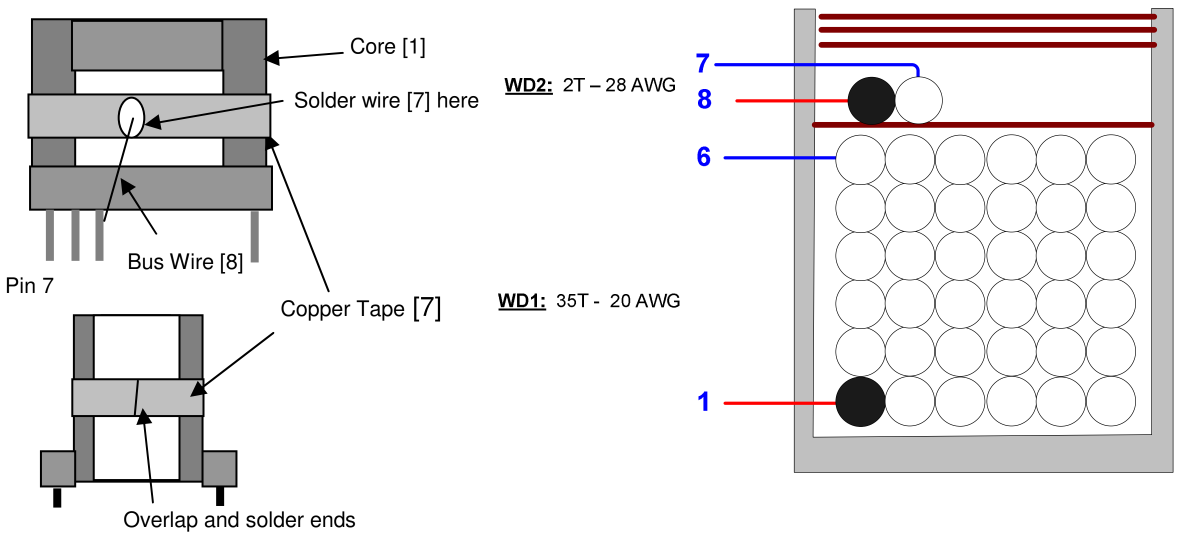

Figure 10 – PFC Choke Build Diagram.

7.3.5 Winding Instructions

Bobbin Preparation	Pull pins 2, 3, 10, and 11 on bobbin [2].
Main Winding	Starting on pin 1, wind 35 turns of wire [3] on bobbin [2]. Finish on pin 6.
Insulation	Use 1 layer of tape [5] for insulation.
Bias Winding	Starting on pin 8, wind 2 turns of wire [4], finishing on pin 7.
Finish Wrap	Use 3 layers of tape [5] for finish wrap.
Core Assembly	Assemble bobbin and core halves. Secure core with two wraps of tape (Item 5).
Shield	Apply 1 turn of copper tape (Item [7]) as shown in Figure 1, centered in bobbin window. Overlap start and finish ends as shown in Figure 1, and solder to form a shorted turn. Take 3 cm of hook-up wire [7], solder 1 end of wire to copper foil as shown in Figure 1. Terminate other end on pin 9 of bobbin.
Shield Insulation	Apply 3 turns of tape (item [6]) to insulate copper shield.
Varnish	Dip varnish finished assembly.

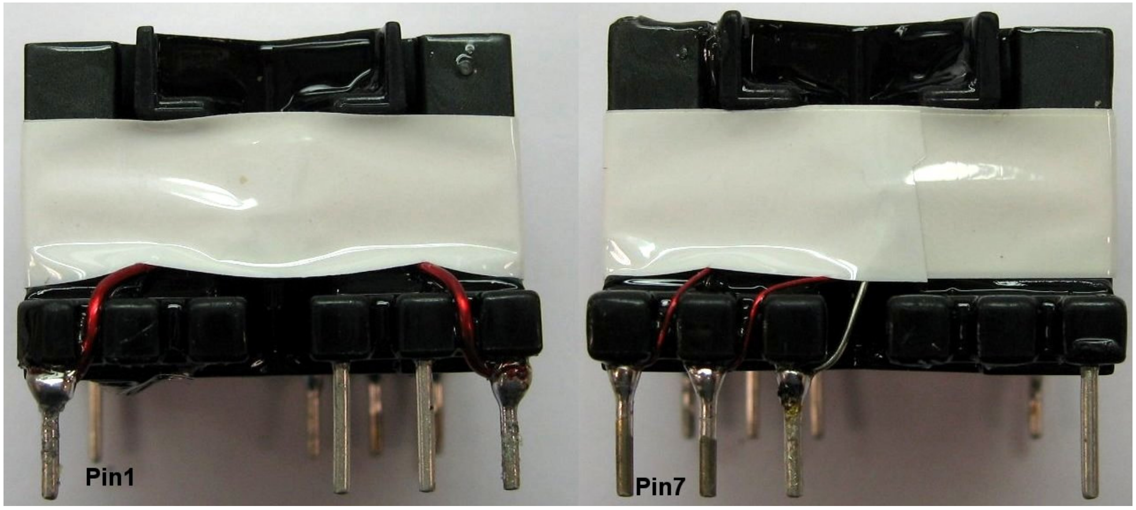

Figure 11 – Finished PFC Choke, Front and Back View.

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8 LLC Transformer Design Spreadsheet

ACDC_PLC810_031209; Rev.1.4; Copyright Power Integrations 2008	INPUTS	INFO	OUTPUTS	UNITS	ACDC_PLC810_031209_Rev1-4.xls; PLC810 Half-Bridge, Continuous mode LLC Resonant Converter Design Spreadsheet
Enter Input Parameters					
Vacmin			140	V	Minimum AC input voltage
Vacmax			265	V	Maximum AC input voltage
Iacinmax			1.19	A	Maximum input AC rms current at Vacmin
Vbulk			385.00	V	Nominal PFC output voltage
Vbulkmax			411.95	V	Peak PFC OVP voltage (typical is 7% above Vbulk)
Vbulkmin	300.00		300.00	V	Minimum bulk capacitor voltage at the specified holdup time. Typical value is between 250 - 320 VDC. Max holdup time is at 250 V
fL			50.00	Hz	AC Line input frequency
Holdup time	18.00		18.00	ms	Bulk capacitor hold up time
CIN_MIN			98.28	uF	Minimum value of bulk cap to meet holdup time requirement; Adjust holdup time and Vbulkmin to change bulk cap value
bulk ripple			8.16	V	Bulk capacitor peak to peak voltage (low freq ripple)
Vrippeak			389.08	V	Bulk cap peak value of ripple voltage
IAC			1.19	A	AC input rms current at VACMIN
IAC_PEAK			1.68	A	Peak AC input current at full load and VACMIN
Enter LLC (secondary) outputs					The spreadsheet assumes AC stacking of the secondaries
Vo1	48.00			V	Main Output Voltage. Spreadsheet assumes that this is the regulated output
Io1	3.13			A	Main output maximum current
Vd1	0.90		0.90	V	Forward voltage of diode in main output
Po1			150.24	W	Output Power from first LLC output
Vo2	0.00			V	Second Output Voltage
Io2	0.00			A	Second output current
Vd2	0.00		0.00	V	Forward voltage of diode used in second output
Po2			0.00	W	Output Power from second LLC output
Enter stand-by (auxiliary) outputs					
Vo3	12.00			V	Auxiliary Output 1 Voltage
Io3	0.05			A	Auxiliary Output 1 maximum current
Vo4				V	Auxiliary Output 2 Voltage
Io4				A	Auxiliary Output 2 maximum current
Efficiciency and Loss Allocation					
P_LLC			150.24	W	Specified LLC output power
P_AUX			0.60	W	Auxiliary output power
P_PFC			158.95	W	PFC output power
P_TOTAL			150.84	W	Total output power (Includes Output power from LLC stage and auxiliary stage)
LLC_n_estimated	0.95		0.95		Efficiency of LLC stage
AUX_n_estimated			0.75		Efficiency of auxiliary output
PFC_n_estimated	0.96		0.96		Minimum efficiency of PFC front end stage
PIN			166.44	W	AC input power

Overall efficiency		0.91		Minimum system efficiency
Ploss_PFC		7.49	W	PFC stage power loss
Ploss_LLC		7.91	W	LLC stage power loss
Ploss_AUX		0.20	W	Auxiliary power loss
Ploss_TOTAL		15.60	W	Total power loss
Enter PFC Design Parameters				
f_nominal_desired		100.00	kHz	Desired full load switching frequency. Recommended value 66 kHz to 132 kHz
Krp	0.98	0.98		PFC choke ripple current factor. Actual Krp tends to increase at higher current when using iron powder/Sendust cores, due to drop in inductance at higher current
Diode bridge Vf		0.70	V	Forward voltage drop of diode bridge
Rdson	0.22	0.22	ohms	PFC MOSFET Rdson - use high temp value from datasheet
Coss		18.18	pF	PFC MOSFET high voltage Coss from datasheet
tON		20.00	ns	MOSFET turnon current rise time. Check actual value
Qrr		26.49	nC	Average Qrr of boost diode over AC sinusoid
PFC CHOKE Parameters				
Lpfc		583.79	uH	PFC choke inductance
ILpk		3.33	A	PFC choke peak current at VACMIN
AL	470.00		nH/t^2	nH per turn^2 (from magnetics datasheet). Note - This value decreases by as much as 15% if a belly-band is added to reduce EMI
n		35.24	turns	PFC choke number of turns
MLT	5.00		cm	Mean length per turn
AWG_Choke	20			PFC choke wire gauge
Equivalent Choke Metric Wire gauge		0.80	mm	Equivalent diameter of wire in metric units
Wire length		1.76	m	Length of wire used on PFC choke
Strands	3			Number of wires
DCR		21.21	m-ohms	DC resistance of wire at 25 C
DCR at 85 C		26.72	m-ohms	DC resistance of wire at 85 C
Irms_CHOKE		1.36	A	PFC choke rms current
DCR Cu loss		0.05	W	PFC choke DC Copper loss for reference at 85 C
ACR_PFC_Choke		53.45	m-ohms	Measure or calculate; add 26% to measured value to get 85 C value
HF Irms		0.58	A	RMS current of switching component
HF Cu loss		0.02	W	Copper loss due to switching component at 85 C
tot Cu loss		0.07	W	Total copper loss at 85 C
LM	10.00		cm	Magnetic path length of core used
Hpk		14.74	Oe	Peak MMF in Oersteds, calculated at low line
Hpk_SI		1174	A/m	Peak MMF in A/m, calculated at low line
PFC FET, Diode and Output Parameters				
Isense_R		0.16	ohms	Maximum value of PFC current sense resistor
Sense resistor power dissipation		0.30	W	PFC sense resistor power dissipation at Vacmin
Irms_FET		1.11	A	PFC MOSFET RMS current measured at VACMIN
Conduction loss		0.27	W	PFC MOSFET conduction loss

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Trrloss		0.89	W	PFC MOSFET loss due to diode Trr
Cossloss		0.15	W	MOSFET Coss loss
Crossover loss		0.01	W	MOSFET crossover turnon loss
Total PFC loss		1.17	W	MOSPFC FET total loss
Diode bridge Ploss		1.51	W	Diode bridge estimated loss
PFC Diode RMS current		0.65	A	Approximate PFC Diode RMS current at nominal AC input voltage (VACMIN) (includes 100/120 Hz component)
Bulk capacitor RMS current		0.72	A	Approximate Bulk Capacitor RMS current at nominal AC input voltage (VACMIN) (includes 100/120 Hz component and LLC input current)
LLC TRANSFORMER CALCULATIONS				
Po		153.06	W	Output from LLC converter including diode loss
Vo		48.90	V	Output at transformer windings (includes diode drop)
Ae	2.10		cm^2	Transformer core cross-sectional area
Lpar	704.00	704.00	uH	Parallel inductance. (Lpar = Lopen - Lser for integrated transformer; Lpar = Lmag for non-integrated transformer)
Lser	116.00	116.00	uH	Leakage inductance of integrated transformer; Leakage + external inductor for non-integrated transformer
Lopen		820.00	uH	Primary open circuit inductance for integrated transformer
C	18.00	18.00	nF	Series resonant capacitor
fnominal_desired		100.00	kHz	Desired full load switching frequency. Recommended value 66 kHz to 132 kHz
fnominal_actual		87.0	kHz	Expected frequency at nominal input voltage (VBULK) and full load
IRMS_LLC_Primary		0.94	A	Primary winding RMS current at full load and nominal input voltage (VBULK)
IRMS_LLC_Q1		0.67	A	RMS current through upper MOSFET in LLC half bridge
VMIN		295.1	V	Minimum Voltage on Bulk Capacitor at minimum switching frequency
f_AT_VMIN		49.00	kHz	Frequency at minimum Bulk capacitor voltage
fpar		45	kHz	Parallel resonant frequency (defined by Lpar + Lser and C)
fser		110	kHz	Series resonant frequency (defined by series inductance Lser and C)
fmin		55	kHz	Min frequency, at VBULK _MIN and full load. Set PLC810 minimum frequency to this value. Operation below this frequency results in loss of ZVS
NP_1		39		Primary winding number of turns
NS_1	9.00	9		Secondary winding number of turns
n_RATIO	4.30	4.30		Transformer turns ratio. Adjust this value so that fnominal_actual is close to fnominal_desired
Bpkfmin		1186	Gauss	First Quadrant peak flux excursion at minimum frequency.
BAC		1487	Gauss	AC peak to peak flux density (calculated at fnominal_actual, VBULK at full load)
LLC sense resistor	0.22	0.22	ohms	LLC current sense resistor
Pdiss_LLC_senseR		0.20	W	Power dissipation in LLC sense resistor
PRIMARY				
Primary gauge	40.00		AWG	Individual wire strand gauge used for primary winding
Equivalent Primary Metric Wire gauge		0.08	mm	Equivalent diameter of wire in metric units

Primary litz strands	75.00			Number of strands used in Litz wire; for non-litz non-integrated transformer set to 1
Primary parallel wires	1.00			Number of parallel individual wires to make up Litz wire
Resistivity_25 C_Primary		49.72	m-ohm/m	Resistivity in milli-ohms per meter
Transformer primary MLT	5.00		cm	Mean length per turn
Primary turns		38.70		Number of primary turns
Primary DCR 25 C		96.21	m-ohm	Estimated resistance at 25 C
Primary DCR 100 C		128.92	m-ohm	Estimated resistance at 100 C (approximately 33% higher than at 25 C)
Primary RMS current	1.50		A	Measured RMS current through the primary winding
ACR_Trf_Primary		206.27	m-ohm	Measured AC resistance (at 100 kHz, room temperature), multiply by 1.33 to approximate 100 C winding temperature
Primary copper loss		0.46	W	Total primary winding copper loss at 85 C
Separate Series Inductor (For non-integrated transformer only)				Ignore this section if using integrated magnetics
Lsep		116.00	uH	Desired inductance from separate inductor
Ae_Ind	0.53		cm^2	Inductor core cross-sectional area
Inductor turns	15.00	15		Number of primary turns
BP_fnom		2086	Gauss	AC flux for core loss calculations (at fnom and full load)
BP_fmin		2629	Gauss	Peak flux density, calculated at minimum frequency fmin
Inductor gauge	40.00		AWG	Individual wire strand gauge used for primary winding
Equivalent Inductor Metric Wire gauge		0.08	mm	Equivalent diameter of wire in metric units
Inductor litz strands	125.00			Number of strands used in Litz wire
Inductor parallel wires	1.00			Number of parallel individual wires to make up Litz wire
Resistivity_25 C_Sep_Ind		29.83	m-ohm/m	Resistivity in milli-ohms per meter
Inductor MLT	7.00		cm	Mean length per turn
Inductor DCR 25 C		31.32	m-ohm	Estimated resistance at 25 C (for reference)
Inductor DCR 100 C		41.97	m-ohm	Estimated resistance at 100 C (approximately 33% higher than at 25 C)
ACR_Sep_Inductor		67.16	m-ohm	Measured AC resistance (at 100 kHz, room temperature), multiply by 1.33 to approximate 100 C winding temperature
Inductor copper loss		0.15	W	Total primary winding copper loss at 85 C
Winding 1 (Vo1)				Note - Power loss calculations are for each winding half of secondary
Sec 1 Wire gauge	40		AWG	Individual wire strand gauge used for secondary winding
Equivalent secondary 1 Metric Wire gauge		0.08	mm	Equivalent diameter of wire in metric units
Sec 1 litz strands	175			Number of strands used in Litz wire; for non-litz non-integrated transformer set to 1
Parallel wires sec 1	1			Number of parallel individual wires to make up Litz wire
Resistivity_25 C_sec1		21.31	m-ohm/m	Resistivity in milli-ohms per meter
Transformer Secondary MLT	5.00		cm	Mean length per turn
Sec 1 Turns		9.00		Secondary winding turns (each half)
DCR_25C_Sec1		9.59	m-ohm	Estimated resistance at 25 C (for reference)
DCR_100C_Sec1		12.85	m-ohm	Estimated resistance at 100 C (approximately 33% higher than at 25 C)
Sec 1 RMS current		4.92	A	RMS current through Output 1 winding,

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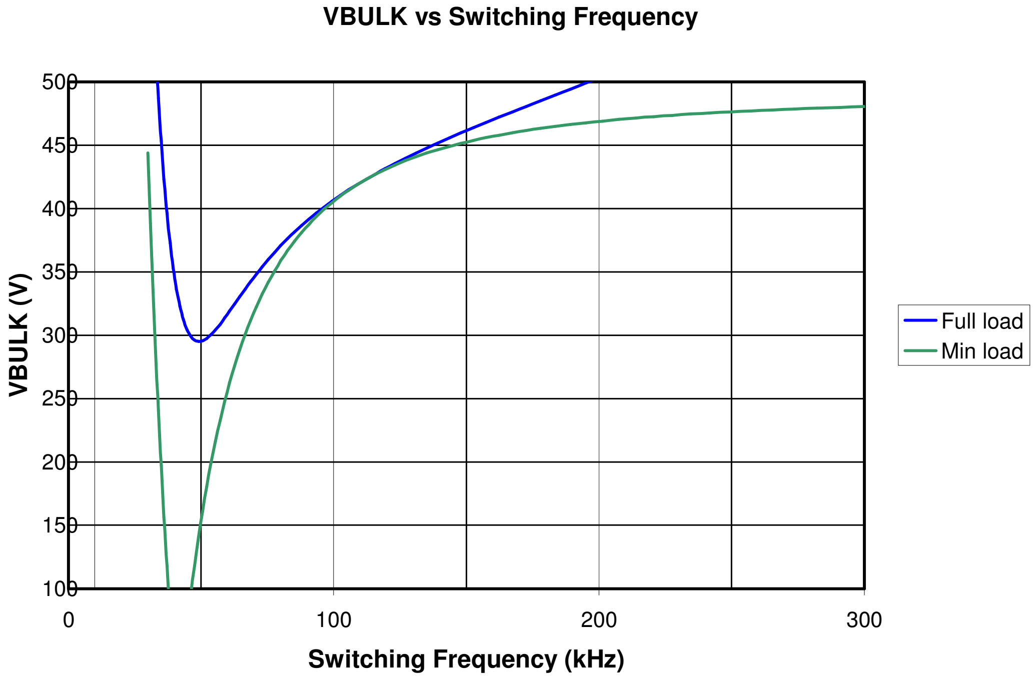
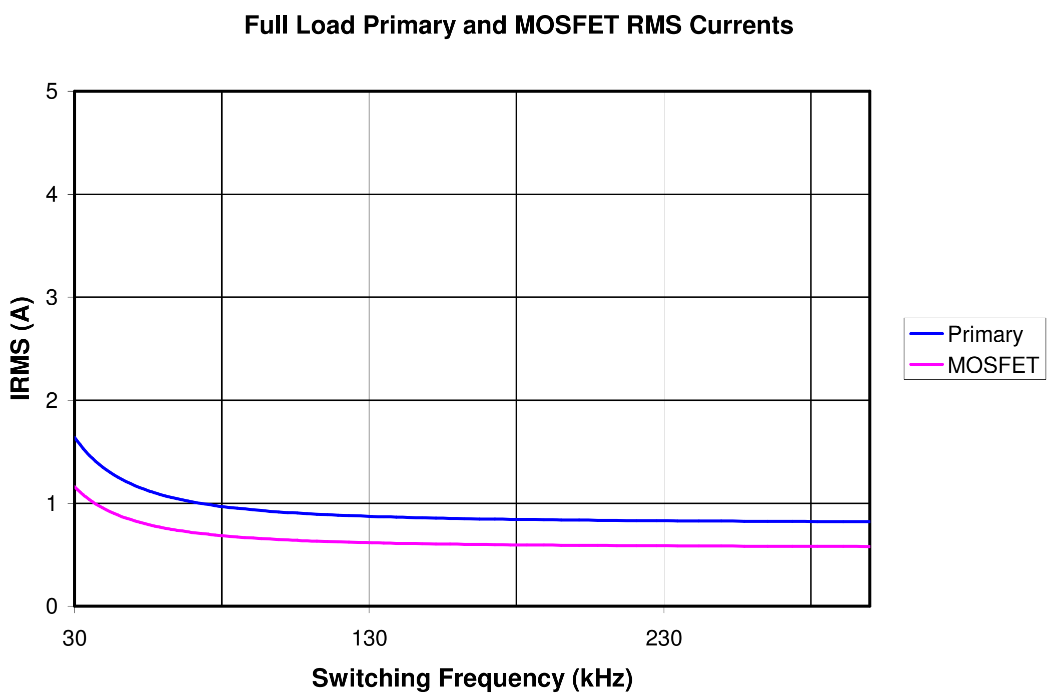
				assuming half sinusoidal waveshape
DCR_Ploss_Sec1		0.25	W	Estimated Power loss due to DC resistance (both secondary halves)
ACR_Sec1		20.56	m-ohm	Measured AC resistance (at 100 kHz, room temperature), multiply by 1.33 to approximate 100 C winding temperature . Default value of ACR is twice the DCR value at 100 C
ACR_Ploss_Sec1		1.00	W	Estimated AC copper loss (both secondary halves)
Total secondary winding Copper Losses		1.25	W	Total (AC + DC) winding copper loss for both secondary halves
Winding 2 (Vo2)				Note - Power loss calculations are for each winding half of secondary
Sec 2 Wire gauge	40		AWG	Individual wire strand gauge used for secondary winding
Equivalent secondary 2 Metric Wire gauge		0.08	mm	Equivalent diameter of wire in metric units
Sec 2 litz strands	175			Number of strands used in Litz wire; for non-litz non-integrated transformer set to 1
Parallel wires sec 2	1			Number of parallel individual wires to make up Litz wire
Resistivity_25 C_sec2		21.31	m-ohm/m	Resistivity in milli-ohms per meter
Transformer Secondary 2 MLT			cm	Mean length per turn
Sec 2 Turns	0.00			Secondary winding turns (each half)
DCR_25C_Sec2		0.00	m-ohm	Estimated resistance at 25 C (for reference)
DCR_100C_Sec2		0.00	m-ohm	Estimated resistance at 100 C for half secondary (approximately 33% higher than at 25 C)
Sec 2 RMS current		4.92	Arms	RMS current through Output 2 winding; Output 1 winding is AC stacked on top of Output 2 winding
DCR_Ploss_Sec1		0.00	W	Estimated Power loss due to DC resistance (both secondary halves)
ACR_Sec2		0.00	m-ohm	Actual measured AC resistance (at 100 kHz, room temperature), multiply by 1.33 to approximate 100 C winding temperature. Default value of ACR is twice the DCR value at 100 C
ACR_Ploss_Sec2		0.00	W	Estimated AC copper loss (both secondary halves)
Total secondary winding Copper Losses		0.00	W	Total (AC + DC) winding copper loss for both secondary halves
Total Copper loss calculation				Does not include fringing flux loss from gap
Primary copper loss (from Primary section)		0.46	W	Total primary winding copper loss at 85 C
Secondary copper Loss		1.25	W	Total copper loss in secondary winding
Transformer copper loss		1.71	W	Total copper loss in transformer (primary + secondary)
TURNS CALCULATOR				This is to help you choose the secondary turns - not connected to any other part of spreadsheet
V1		48.00	V	Target Output Voltage Vo1
V1d1		0.90	V	Diode drop voltage for Vo1
N1	4.00			Total number of turns for Vo1
V2			V	Expected outputV
V2d2			V	Diode drop voltage for Vo2
N2	2.00			Total number of turns for Vo2

Compared to the above spreadsheet, actual operating frequency is considerably higher than the expected operating frequency of 90 kHz shown. This is due to the effective turns ratio of the transformer, which results in an operating turns ratio lower than the ratio of primary turns to secondary turns (N_P/N_S). The graphs shown below were generated by adjusting the turns ratio in the spreadsheet until the expected operating frequency shown in the spreadsheet was identical to the actual operating frequency of the unit under test.





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9 Performance Data

All measurements were taken at room temperature and 60 Hz input frequency unless otherwise specified, Output voltage measurements were taken at the output connectors.

9.1 LLC Stage Efficiency

To make this measurement, the LLC stage was powered separately by connecting an external 385 VDC supply across bulk capacitor C9, and a 15 V source was applied between the collector of regulator transistor Q27 and controller ground.

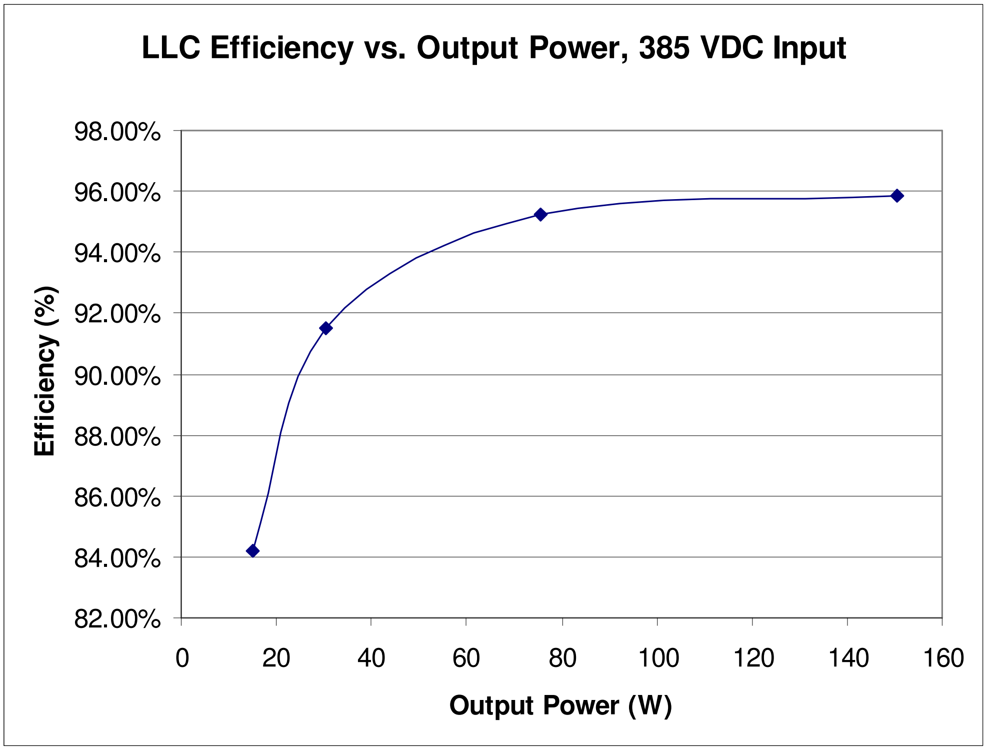

Figure 12 – LLC Stage Efficiency vs. Load, 385 VDC Input.

9.2 Total Efficiency

Figures below show the total supply efficiency (PFC and LLC stages). AC input was supplied using a 60 Hz sine wave source.

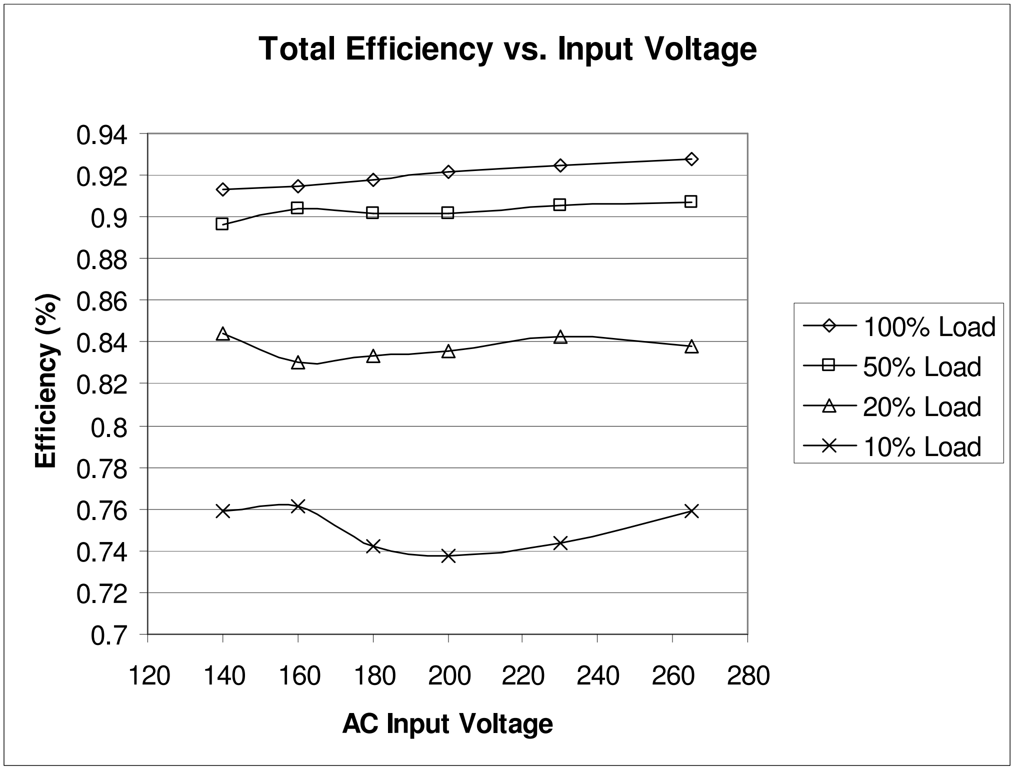

Figure 13 – Total Efficiency vs. Output Power.

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9.3 THD and Power Factor

THD and Power factor measurements were made using a 60 Hz sine wave AC source.

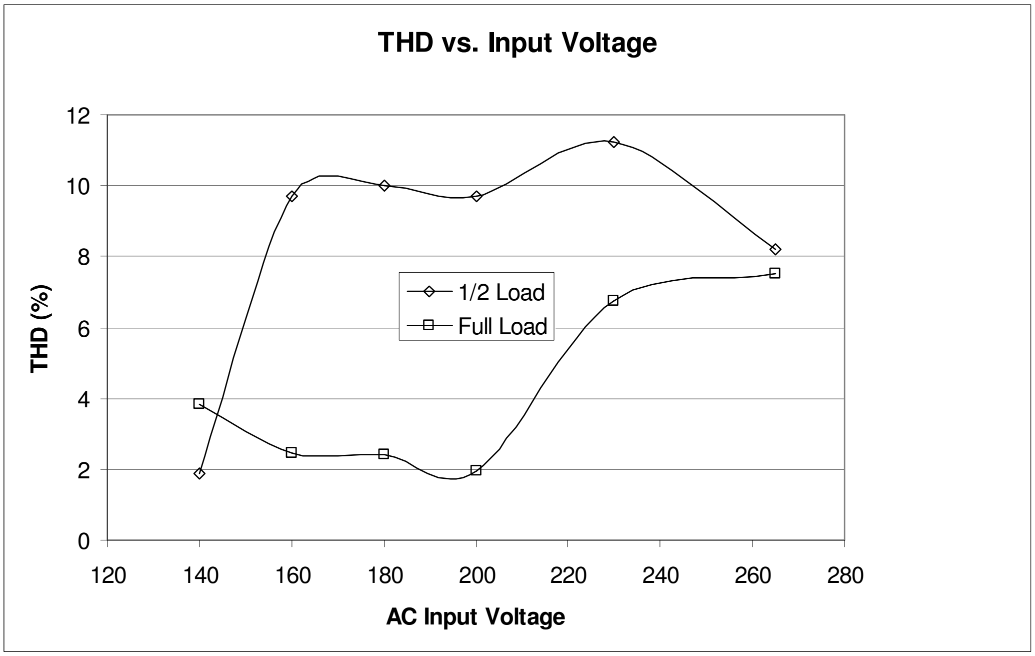

Figure 14 – Input Current THD vs. Input Voltage, 50% and 100% Load.

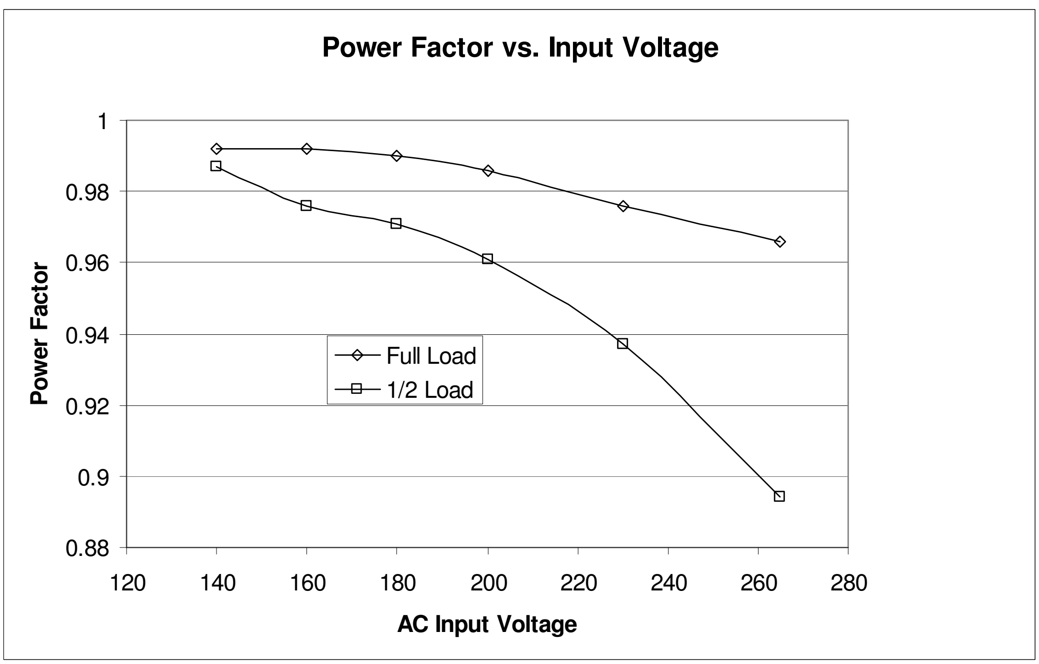

Figure 15 – Power Factor vs. Input Voltage, 50% and 100% Load.

9.4 Output Regulation

The PFC regulates the LLC and standby supply input voltage under normal conditions so the outputs will not be affected by the AC input voltage. Variations due to temperature and component tolerances are not represented. The 48 V output varies by less than 1% over a load range of 2% to 100% load.

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10 Waveforms

All waveforms are measured at room temperature using a 60 Hz sine wave supply unless otherwise indicated.

10.1 Input Voltage and Current

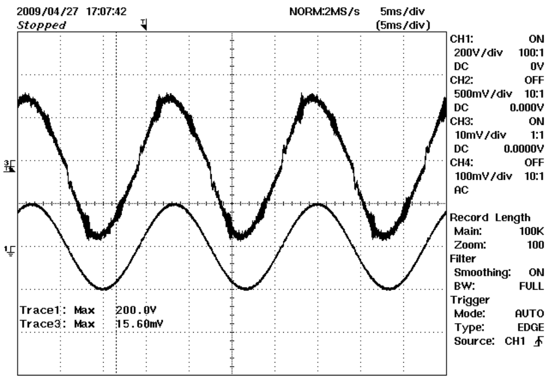

Figure 16 – 140 VAC, 150 W Load.
Top Trace: Input Current, 1 A / div.
Bottom trace: Input Voltage, 200 V, 5 ms / div.

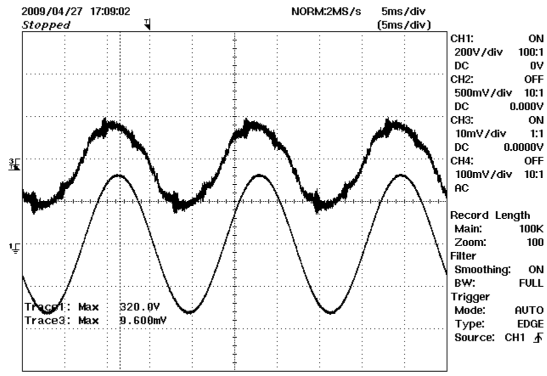

Figure 17 – 230 VAC, 150 W Load.
Top Trace: Input Current, 1 A / div.
Bottom trace: Input Voltage, 200 V, 5 ms / div.

10.2 LLC Primary Voltage and Current

The LLC stage current was measured by cutting the PC board trace in series with the T1 primary and adding a current sensing loop that measures the LLC transformer (T1) primary current. The primary voltage waveform was measured at the hot side of ferrite bead L6.

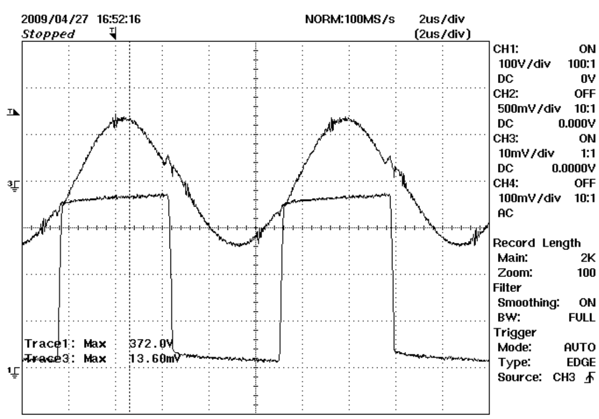

Figure 18 – LLC Stage Primary Voltage and Current.
Top Trace: Current, 1 A / div.
Bottom Trace: Voltage, 100 V, 2 µs / div.

10.3 PFC Switch Voltage and Current - Normal Operation

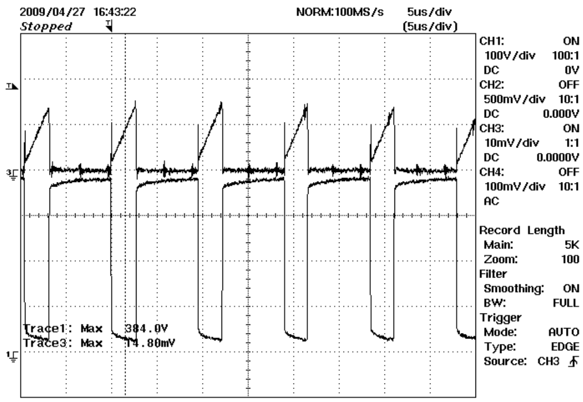

Figure 19 – 140 VAC Input, 100% Load.
Top Trace: Q2 Drain Current, 1 A / div, 5 µs / div
Bottom Trace: Drain Voltage, 100 V, 5 µs/div.

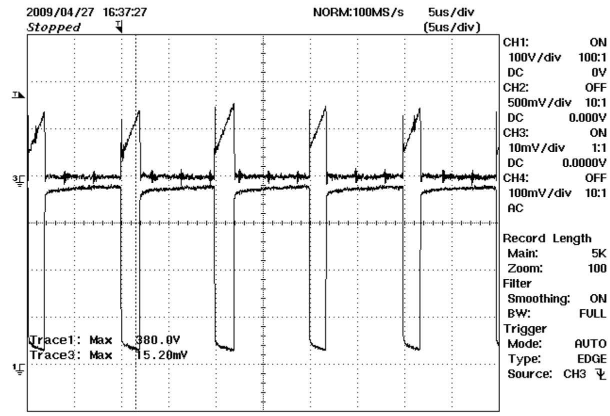

Figure 20 – 230 VAC Input, 100% Load.
Top Trace: Q2 Drain Current, 1 A / div, 5 µs / div
Bottom Trace: Drain Voltage, 100 V, 5 µs / div.

10.4 AC Input Current and PFC Output Voltage During Start-up

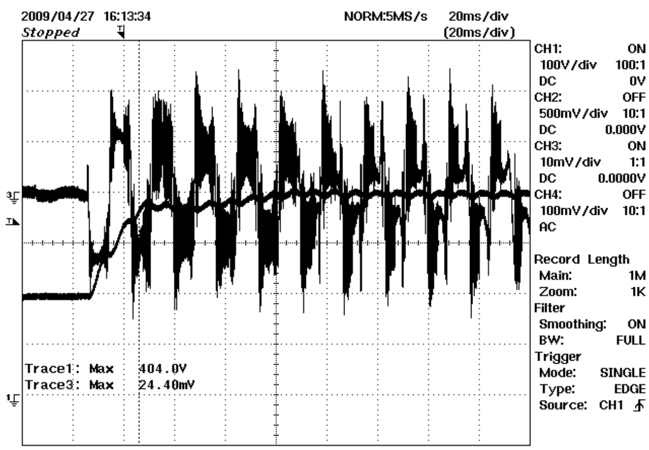

Figure 21 – Full Load, 140 VAC.
Top Trace: AC Input Current, 2 A / div.
Bottom Trace: PFC Voltage, 100 V, 20 ms / div.

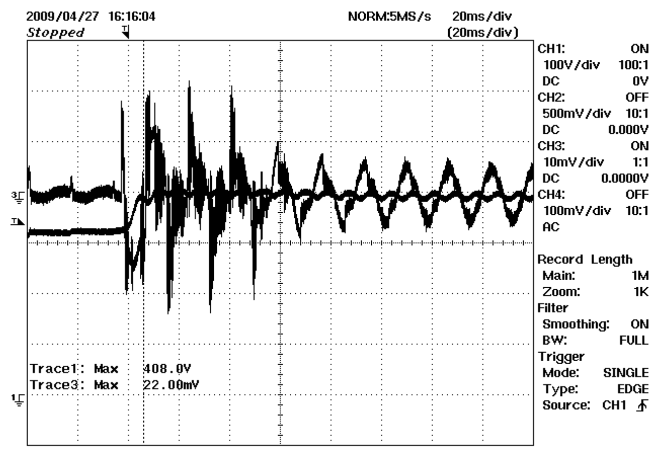

Figure 22 – Full Load, 230 VAC.
Top Trace: AC Input Current, 2 A / div.
Bottom Trace: PFC Voltage, 100 V, 20 ms / div.

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10.5 LLC Start-up

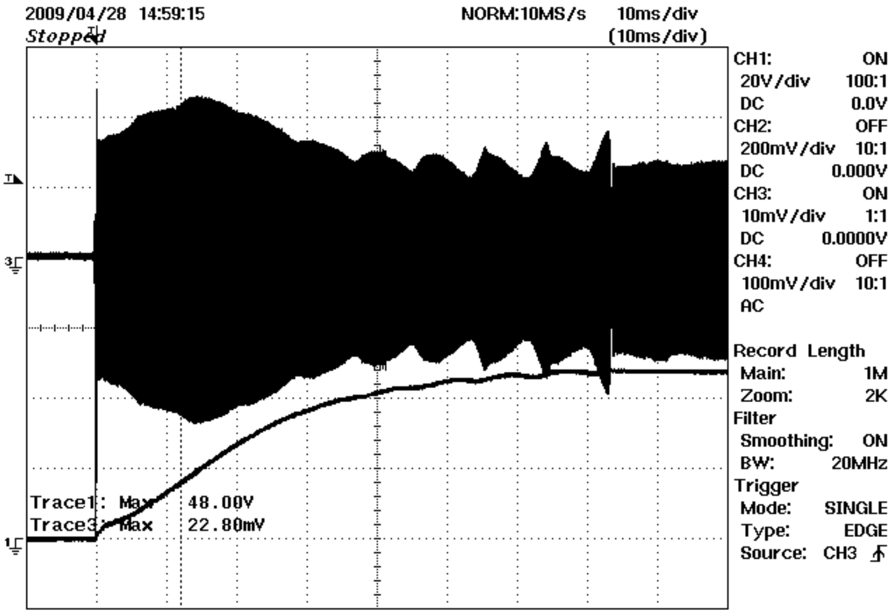

Figure 23 – LLC Start-up. 230 VAC, 100% Load.
Top Trace: LLC Primary Current, 1 A / div.
Bottom Trace: Output Voltage, 20 V, 10 ms / div.

10.6 LLC Output Short Circuit

The figure below shows the effect of an output short circuit on the LLC primary current. A mercury displacement relay was used to short the output to get a fast, bounce-free connection.

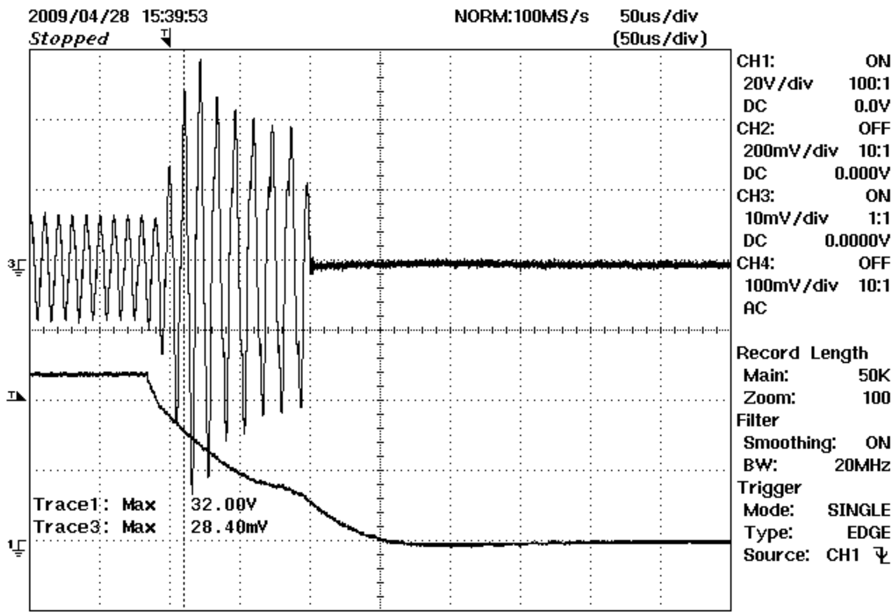

Figure 24 – Output Short Circuit Test, 230 VAC.
Top Trace: LLC Primary Current, 2 A / div.
Bottom Trace: 48 V Output, 20 V, 50 µs / div.

10.7 Output Voltage During Start-up

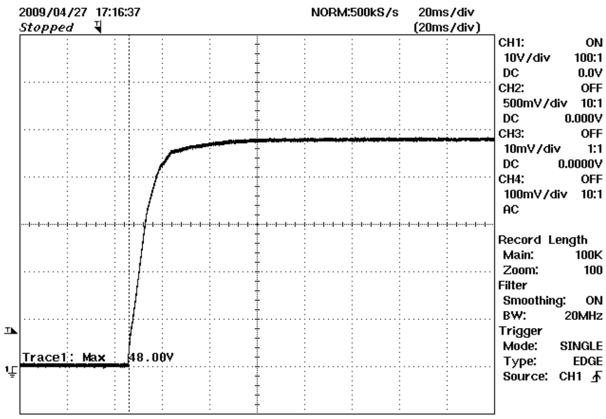

Figure 25 – 48 V Output at Start-up.
140 VAC Input, Full Load. 10 V, 20 ms/ div.

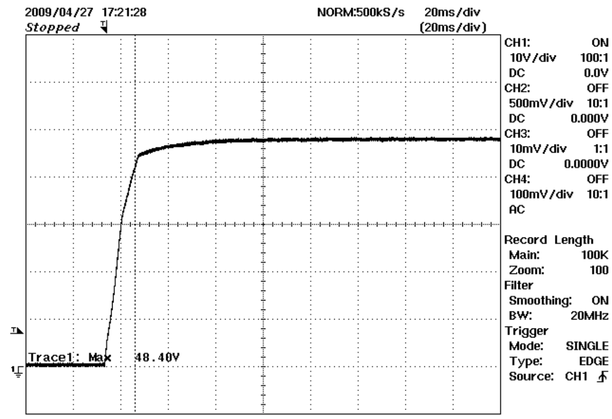

Figure 26 – 48 V Output at Start-up.
230 VAC Input, Full Load. 10 V, 20 ms / div.

10.8 Output Ripple Measurements

10.8.1 Ripple Measurement Technique

For DC output ripple measurements, use a modified oscilloscope test probe to reduce spurious signals. Details of the probe modification are provided in figures below.

Tie two capacitors in parallel across the probe tip of the 4987BA probe adapter. Use a 0.1 µF / 50 V ceramic capacitor and 1.0 µF / 100 V aluminum electrolytic capacitor. The aluminum-electrolytic capacitor is polarized, so always maintain proper polarity across DC outputs.

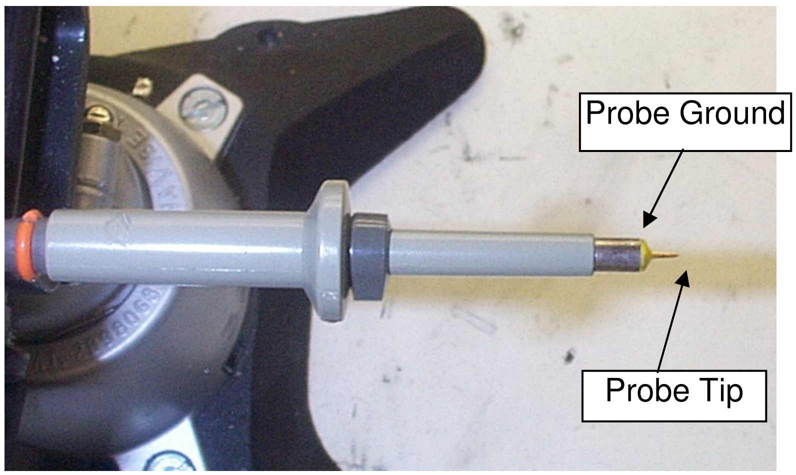

Figure 27 – Oscilloscope Probe Prepared for Ripple Measurement (End Cap and Ground Lead Removed).

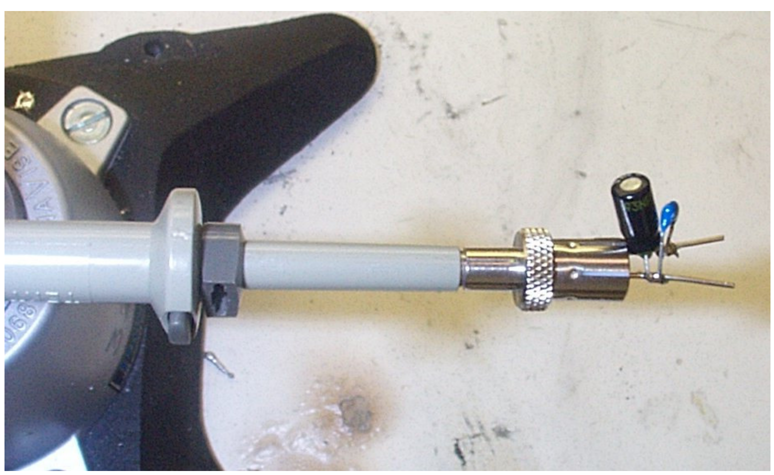

Figure 28 – Oscilloscope Probe with Probe Master 4987BA BNC Adapter (Modified with Wires for Probe Ground for Ripple measurement and Two Parallel Decoupling Capacitors Added).

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10.8.2 Full Load Output Ripple Results

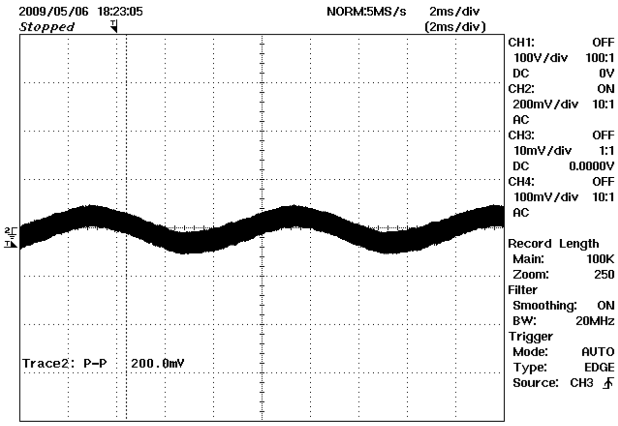

Figure 29 – 48 V Output Ripple, 200 mV, 2 ms / div.

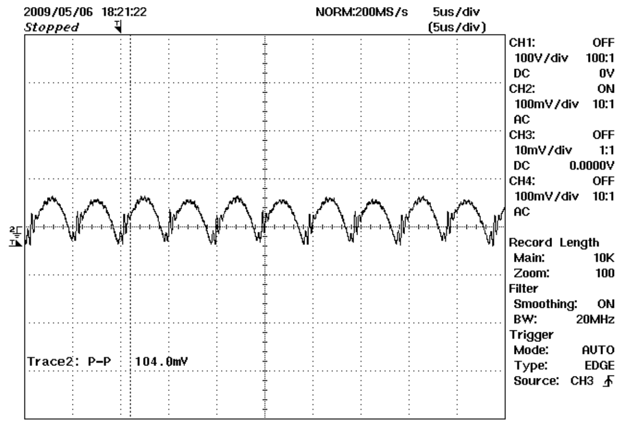

Figure 30 – 48 V Output Ripple, 100 mV, 5 µs / div.

10.8.3 Output Load Step Response

The figures below show transient response with a 75%-100%-75% load step for the 48 V output. The oscilloscope was triggered using the rising edge of the load step, and averaging was used to cancel out ripple components asynchronous to the load step in order to better ascertain the load step response.

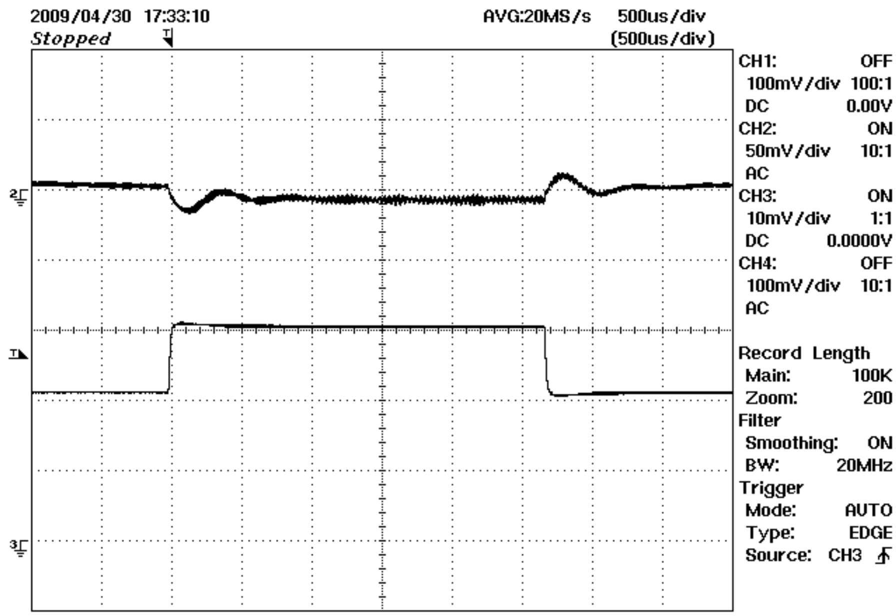

Figure 31 – Output Transient Response 3.13 A – 2.3 A – 3.13 A Load Step.
Top Trace: 48 V Transient Response, 50 mV / div.
Bottom Trace: Output Load Step, 1 A, 500 µs / div.

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11 Temperature Profiles

The board was operated at room temperature in a vertical orientation as shown below. For each test condition the unit was allowed to thermally stabilize (>1 hr) before measurements were made. Infrared measurements were correlated to thermocouples attached using copper tape.

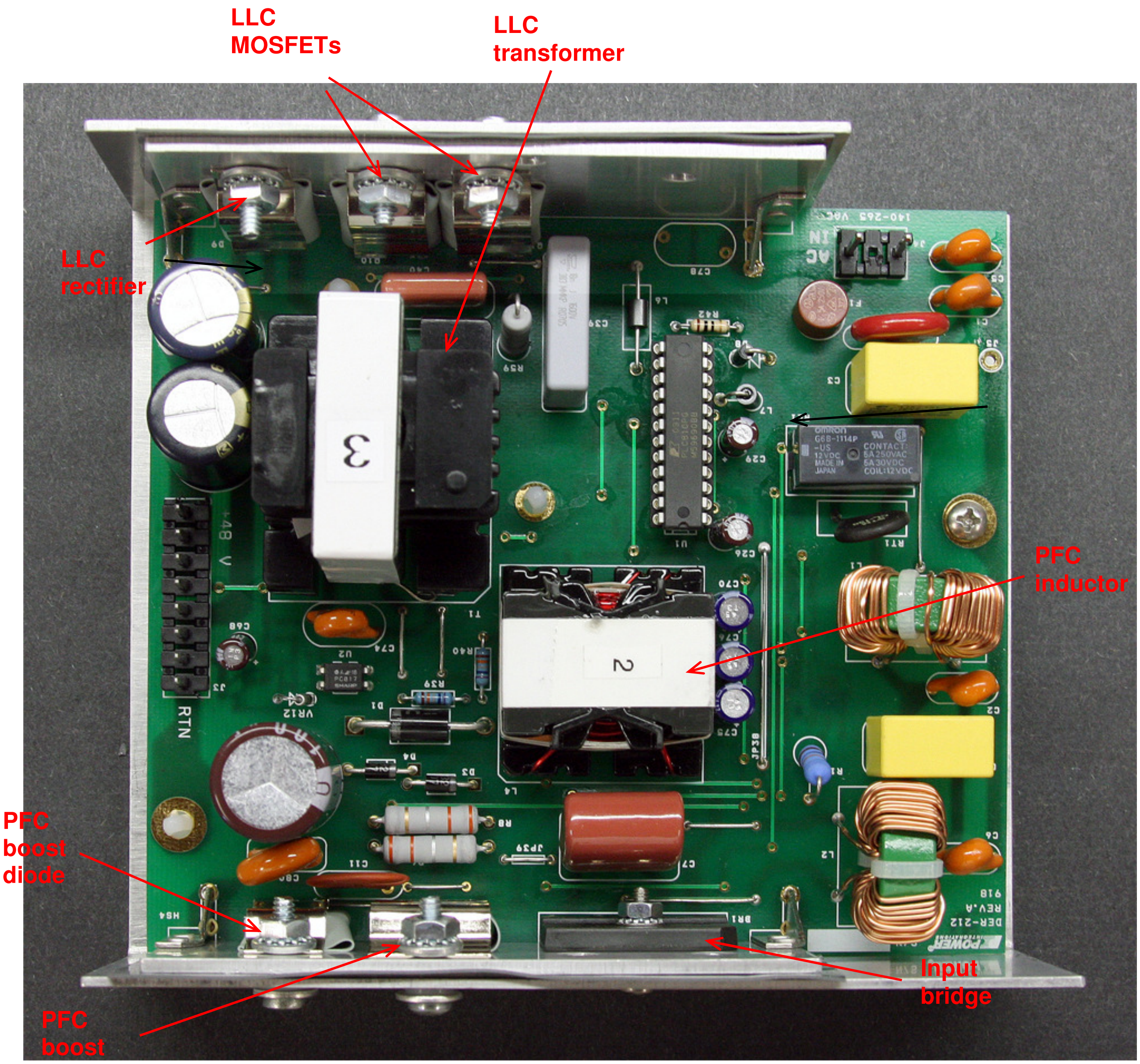

Figure 32 – Photograph of Board Orientation Used for Thermal Testing.

11.1 Thermal Results Summary

11.1.1 Testing Conditions

The goal of this design is to maintain the temperature of components below 100 °C at rated ambient and 100% load (150 W), low line (140 VAC, 60 Hz).

By extrapolating the data below from 21 °C to 60 °C this design meets these requirements.

Measurement data is presented below. The unit was allowed to thermally stabilize (>1 hours in all cases) before gathering data. Semiconductor plastic and magnetics temperatures were correlated via thermocouples attached with copper tape.

	140 VAC, 60 Hz	**230 VAC, 60 Hz**
Output Power (W)	150.2	150.2
Input Power (W)	164.5	162.6
Efficiency (%)	91.3	92.37
Output Loading 48 V (A)	3.13	3.13
Temperatures (°C)		
Ambient	21	21
LLC rectifier plastic package (D9)	47	48
LLC Upper MOSFET (Q10) plastic package	42	43
LLC Lower MOSFET (Q11) plastic package	44	45
PFC diode plastic package (D2)	44	41
PFC MOSFET plastic package (Q2)	42	39
Bridge rectifier plastic package (BR1)	49	43
LLC transformer (T2) surface	47	49
PFC inductor (L4) surface	40	43

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11.2 140 VAC, 60 Hz, 150 W_{OUT}

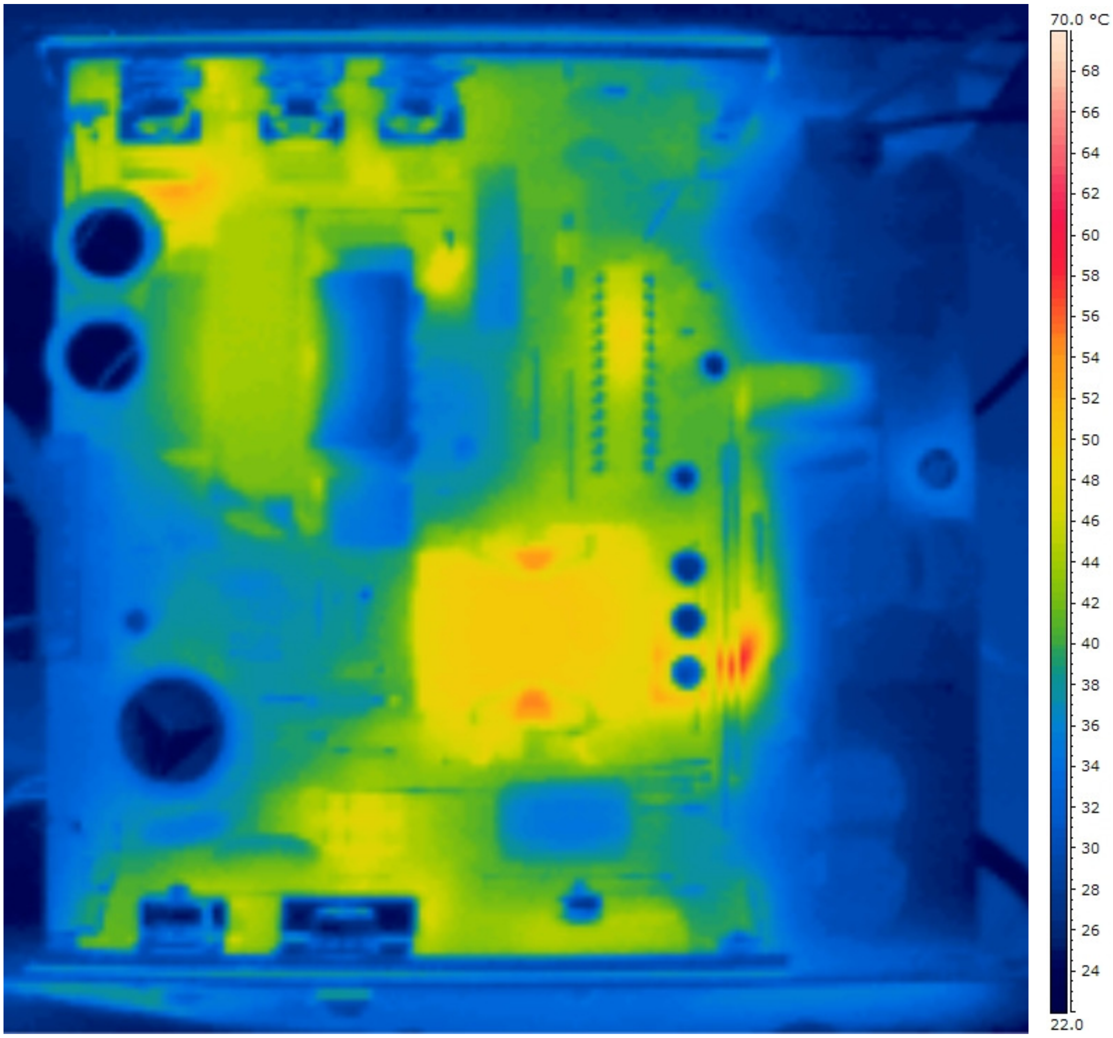

Figure 33 – Thermal Profile. Room Temperature, 140 VAC, 60 Hz, 150 W Load (1 hr)

11.3 230 VAC, 60 Hz, 150 W_{OUT}

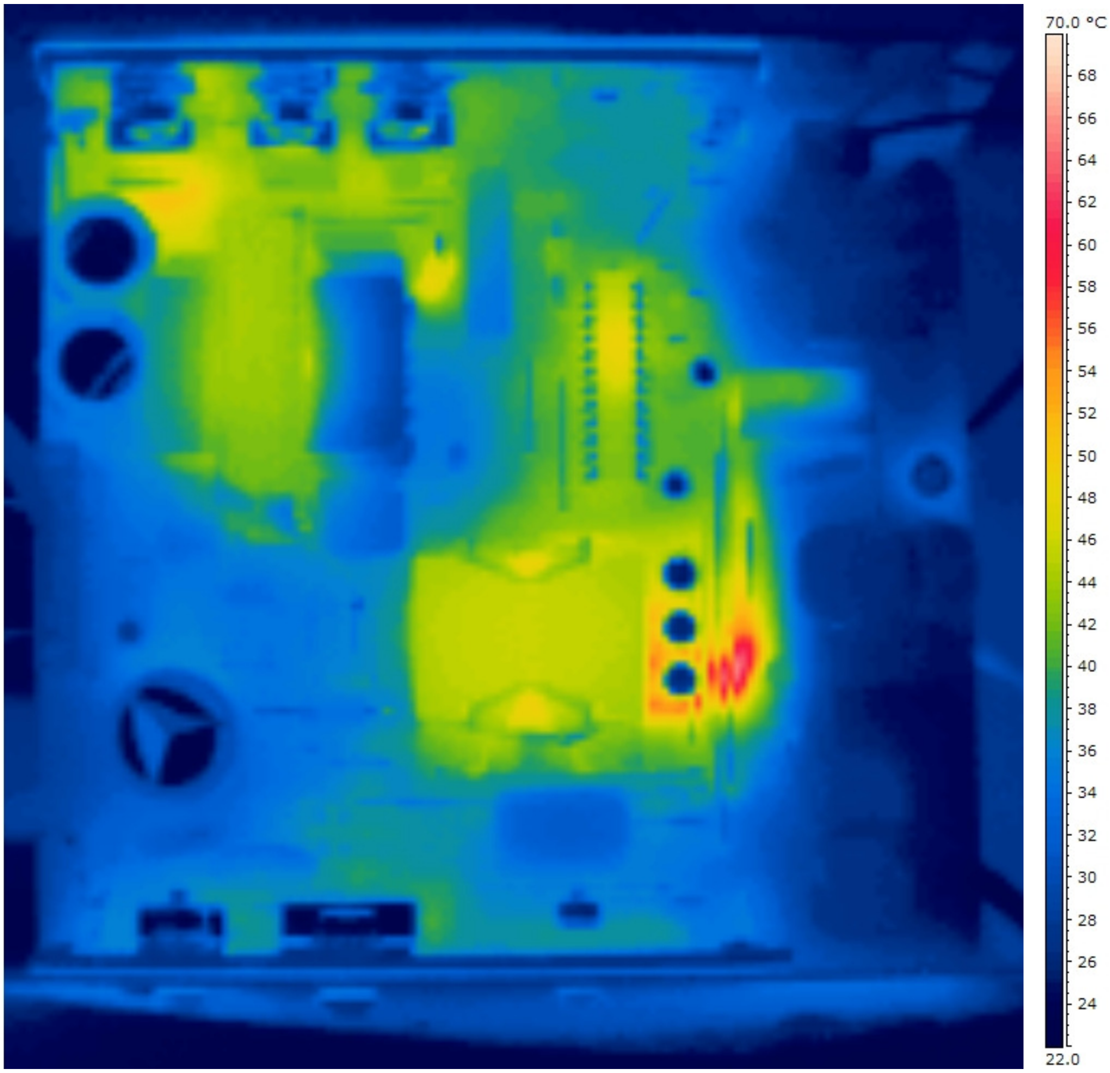

Figure 34 – Thermal Profile. Room Temperature, 230 VAC, 60 Hz, 150 W Load (1 hr)

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12 LLC Gain-Phase

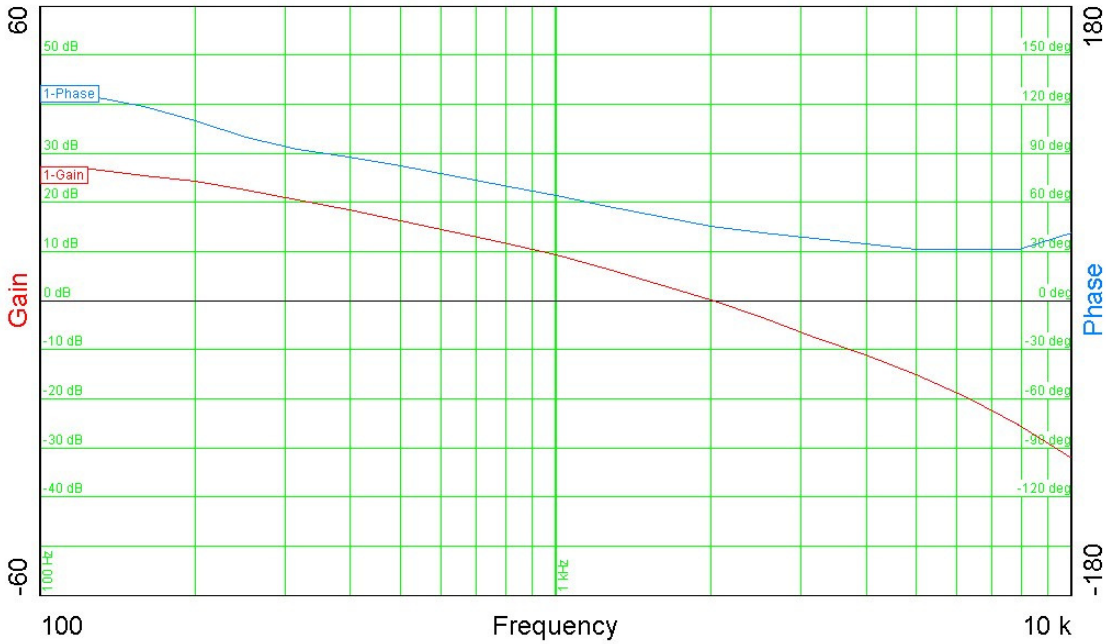

Figure 35 – LLC Converter Gain-Phase, 100% Load Crossover Frequency – 2 kHz, Phase Margin - 45°.

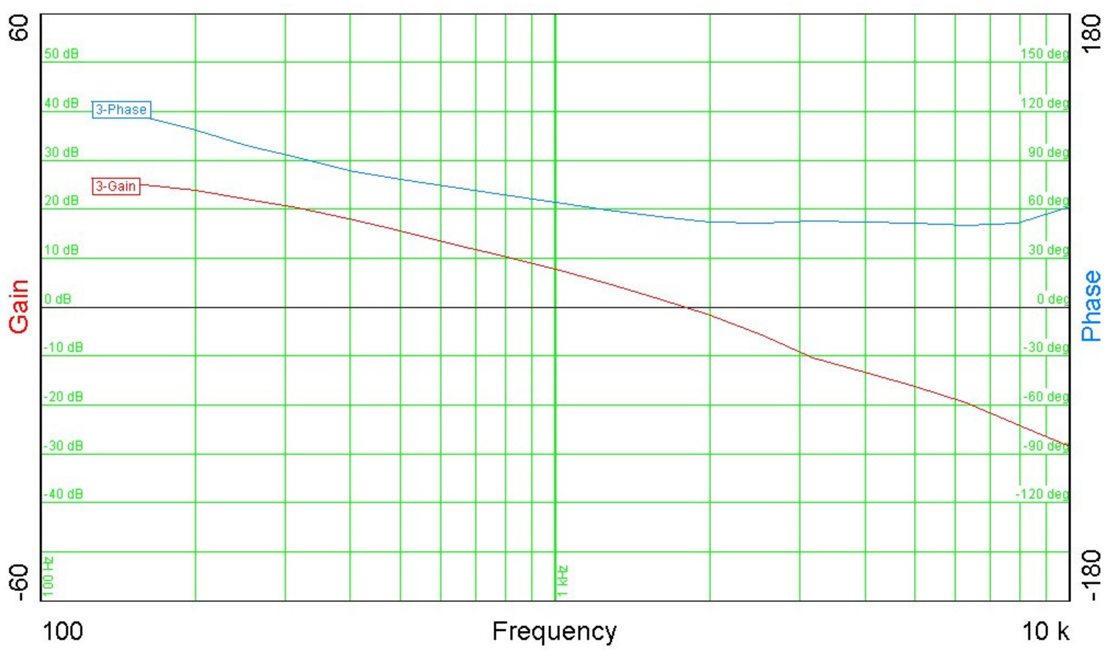

Figure 36 – LLC Converter Gain-Phase, 50% Load. Crossover Frequency ~1.8 kHz, Phase Margin - ~55°.

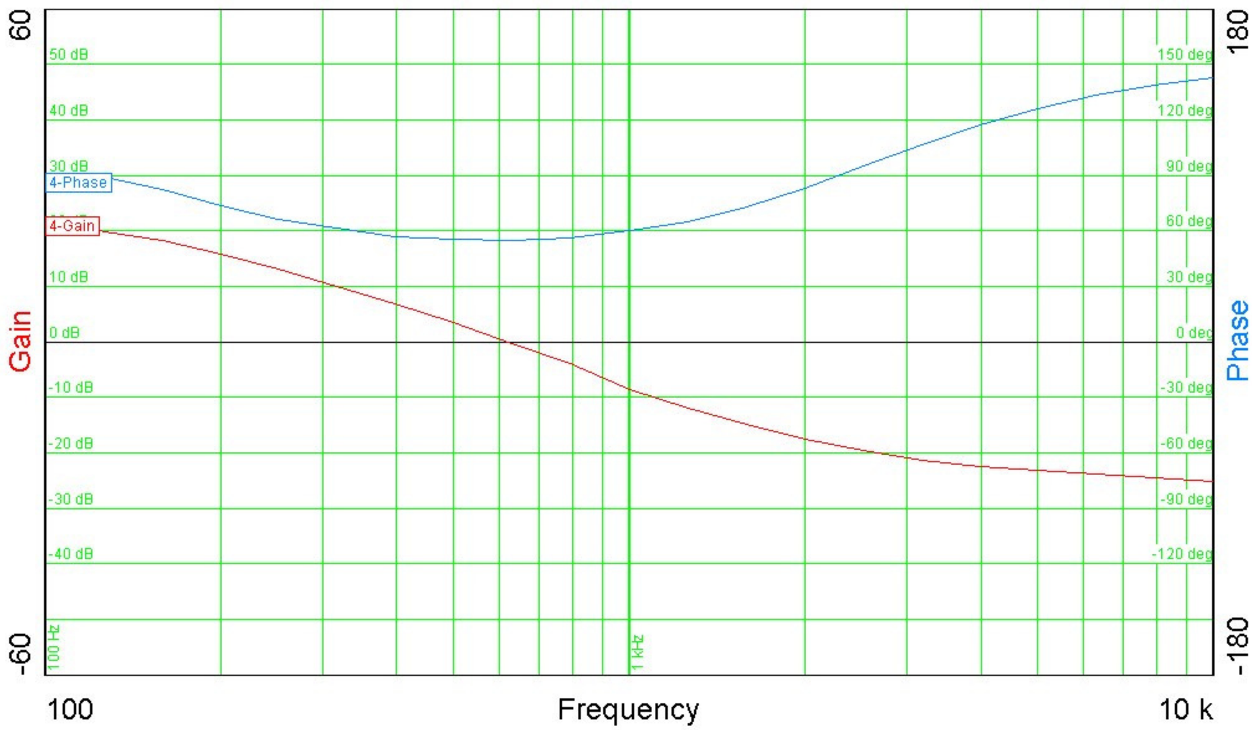

Figure 37 – LLC Converter Gain-Phase, 10% Load. Gain Crossover – 600 Hz, Phase Margin - ~55°.

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13 Conducted EMI

Conducted EMI tests were performed with a 16 Ω resistive load on the 48 V main output. The unit was placed on a metallic ground plane, which in turn was hard wired to the AC cord ground. The resistive load was connected to the ground plane with a pair of 2.2 nF capacitors (one at the positive feed, and one at the return) to simulate the capacitive coupling of LED modules to a grounded street light casing. The peak shown at `90 MHz is actually 10 dB lower than shown in the graph, as the EMI receiver changes scale at 80 MHz.

Figure 38 – Conducted EMI, 230 VAC.

14 Line Surge

Differential input line 1.2/50 µs surge testing was completed on a single test unit to IEC61000-4-5. Input voltage was set at 230 VAC / 60 Hz. Output was loaded at full load and operation was verified following each surge event. During testing no output interruption was seen.

Surge Level (kV)	Generator Impedance (Ω)	Input Voltage (VAC)	Injection Location	Injection Phase (°)	Test Result (Pass/Fail)
+1 kV	2	230	L to N	90	Pass
-1 kV	2	230	L to N	270	Pass
+2 kV	12	230	L, N to G	90	Pass
-2 kV	12	230	L, N to G	270	Pass

Notes: 1) A ground plane was placed under the PSU bracket and load resistors (load resistors are aluminum case units mounted on heat sinks). The resistive load was bypassed to the ground plane with (2) 2.2 nF capacitors (one at the +48 V input lead, one at return) to simulate the capacitance of LED arrays to a grounded street light case, but otherwise feft floating. The input AC safety ground wire was connected to the ground plane.

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15 Revision History

Date	Author	Revision	Description and changes	Reviewed
11-May-09	RH	1.0	Initial Release	
01-Jun-09		1.1	Revised PCB Images	

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