Design Example Report

Title	*14 W PWM-Analog Dimmable LED Driver Using LinkSwitch™-PH LNK406EG*
Specification	90 VAC – 265 VAC Input; 28 V, 500 mA Output
Application	LED Driver
Author	Applications Engineering Department
Document Number	DER-263
Date	June 23, 2015
Revision	1.4

Summary and Features

- High efficiency, power factor corrected
    - >87% at 230 VAC and >86% at 115 VAC
    - >0.9 PF, meets EN61000-3-2 Class C
- 0-10 V analog dimming
    - >1000:1 dimming range
- Low cost, low component count and small printed circuit board footprint
    - No current sensing required
    - Frequency jitter for smaller, lower cost EMI filter components
- Integrated protection and reliability features
    - Output open circuit / output short-circuit protected with auto-recovery
    - Line input overvoltage shutdown extends voltage withstand during line faults.
    - Auto-recovering thermal shutdown with large hysteresis protects both components and printed circuit board

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Table of Contents

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

The document describes a high power-factor secondary referenced, analog dimmable LED driver. The circuit is designed to drive a nominal LED string voltage of 28 V at 500 mA from an input voltage range of 90 VAC to 265 VAC. The LED driver utilizes the LNK406EG from the LinkSwitch-PH family of ICs.

Analog dimming is controlled by an external secondary referenced analog control signal of 0-10 V. 0 volts correspond to minimum light output and 10 V corresponds to maximum brightness. The analog controlled signal is transferred to the primary-side and controls the feedback current I_{FB} of LNK406EG which in turn controls the output power/light output of the driver while maintaining high power factor and low THD.

An active load circuit and control are also included to extend dimming ratio beyond 1000:1 but may be omitted if extended dimming operation is not required.

This document contains the LED driver specification, schematic, PCB diagram, bill of materials, conducted EMI measurements, thermal measurements, transformer documentation and typical performance characteristics.

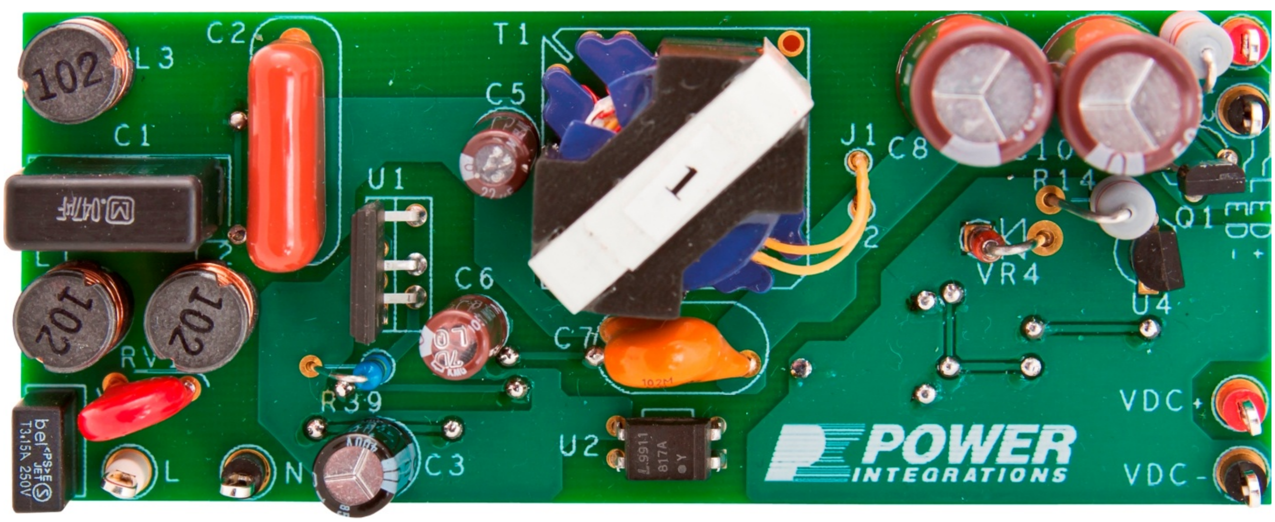

Figure 1 – Top View.

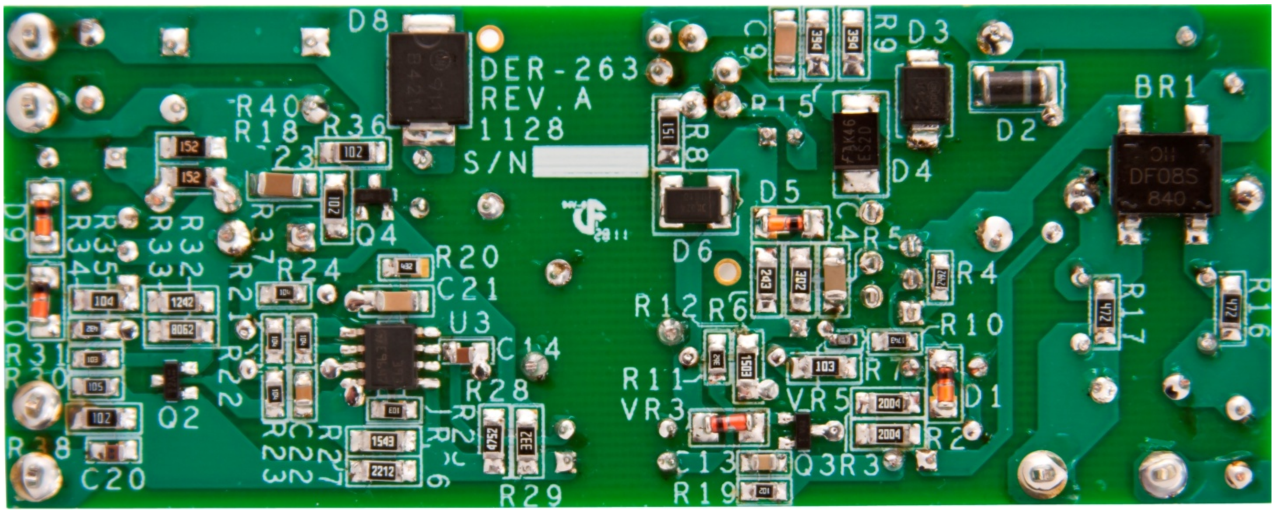

Figure 2 – Bottom Side.

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2 Power Supply Specification

The table below represents the minimum acceptable performance of the design. Actual performance is listed in the results section.

Description	Symbol	Min	Typ	Max	Units	Comment
Input						
Voltage	V_{IN}	90	115 / 230	265	VAC	
Frequency	f_{LINE}		60 / 50		Hz	
Power Factor	PF	0.92				
Output						
Voltage	V_{OUT}	25	28	31	V	±5%
Current	I_{OUT}		500		mA	
Ripple	I_{RIPPLE}		60		%	$I_{O(PK-PK)}$ / I_O
Power	P_{OUT}		14		W	
Dimming Range		1000:1				$V_{IN(TYP)}$
Efficiency						
115 VAC	η_{115}	86			%	V_{OUT} = 28 V
230 VAC	η_{230}	87			%	V_{OUT} = 28 V
Environmental						
Conducted EMI		Meets EN55015B				
Harmonic Currents		EN 61000-3-2 Class D (C)				Class C specifies Class D Limits when P_{IN} <25 W
Temperature	T_{AMB}			40	°C	May be increased with larger heat sink

3 Schematic

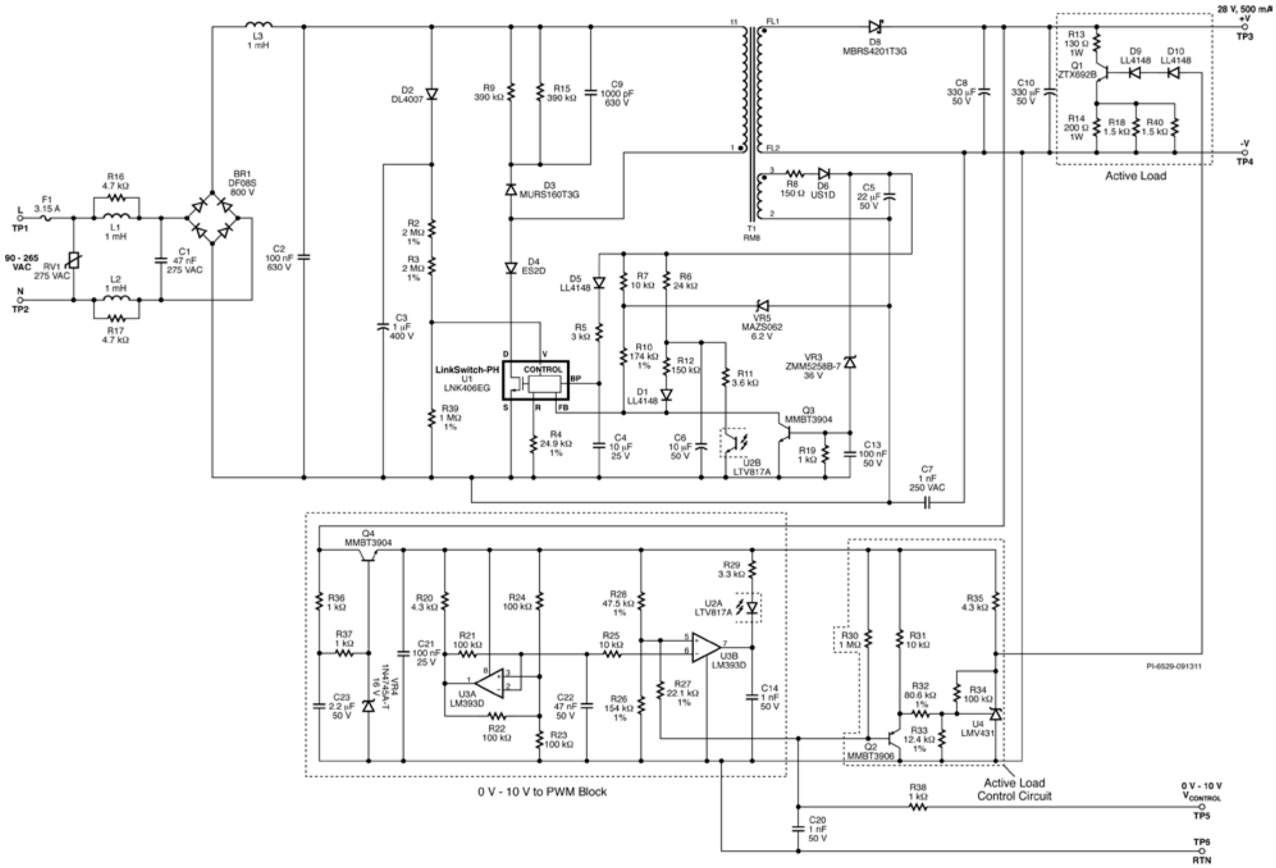

Figure 3 – Schematic.

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4 PCB Layout

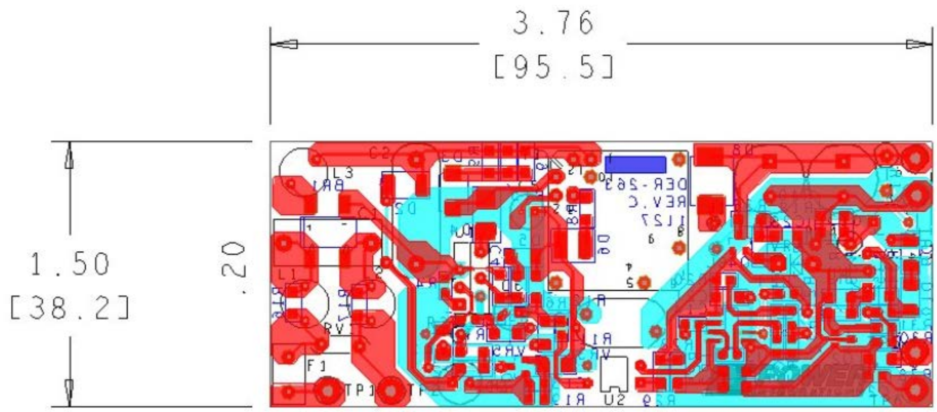

Figure 4 – PCB Showing Top, Bottom Traces and Dimensions in Inches [mm].

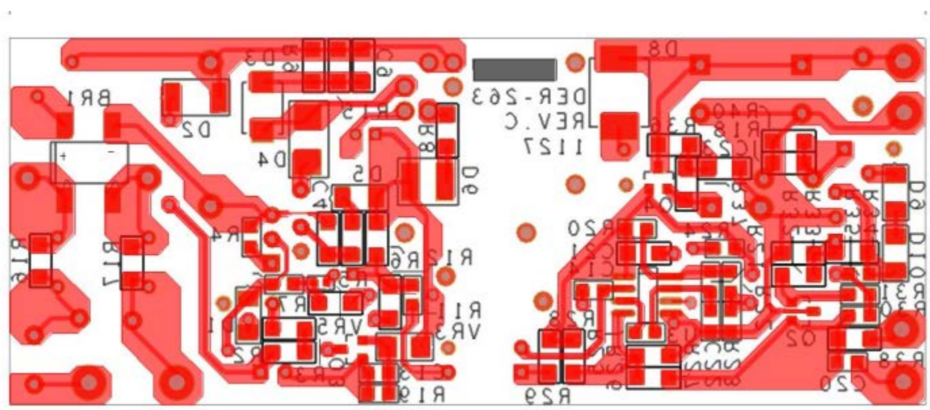

Figure 5 – PCB Bottom Side.

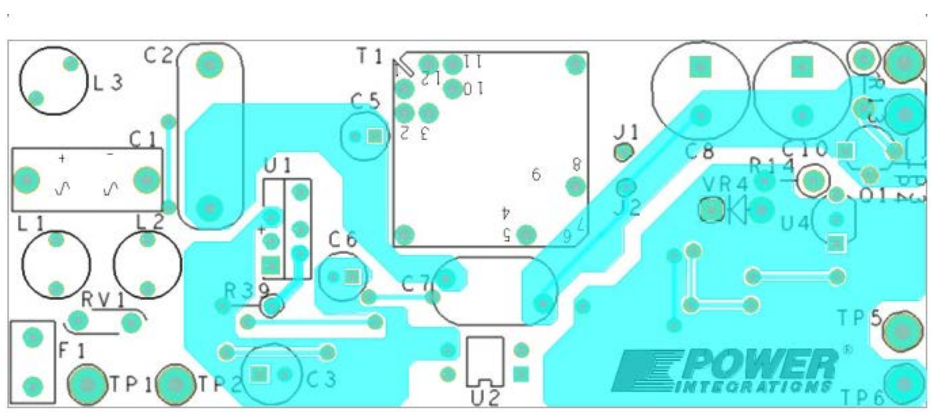

Figure 6 – PCB Top Side.

5 Circuit Description

The LinkSwitch-PH device is a controller and integrated 725 V MOSFET intended for use in LED driver applications. The LinkSwitch-PH is configured for use in a single-stage continuous conduction mode flyback topology and provides a primary-side regulated constant current output while maintaining high power factor from the AC input. Controlling the I_{FB} current with an external control signal regulates the output power and thus the output current to the LED Load.

5.1 PWM-Analog Dimming

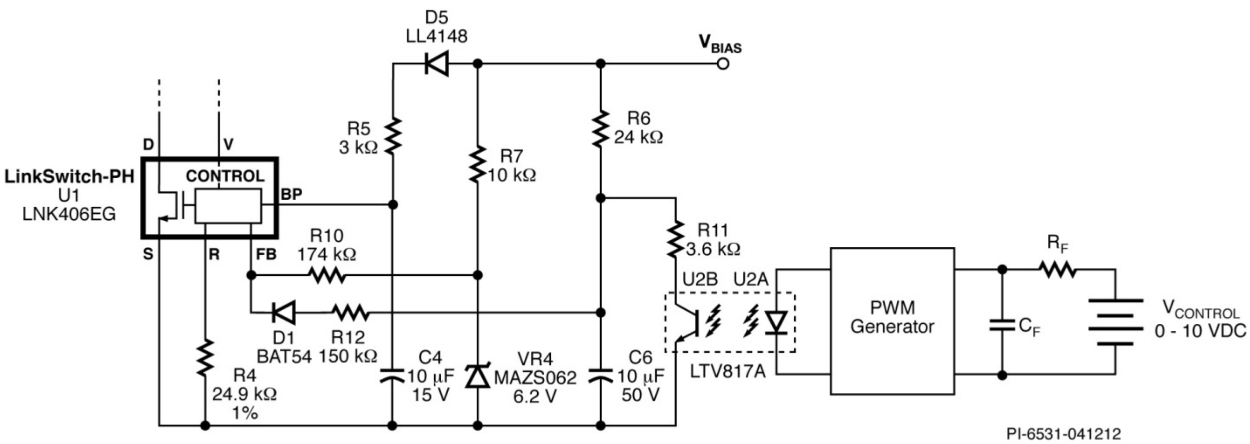

Figure 7 – PWM-Analog Dimming.

Dimming is controlled by an external analog secondary reference control signal of 0-10 V magnitude. 0 V corresponds to full dimming or minimum light output and 10 V corresponds to maximum brightness. Resistor R_F and C_F (Figure 7) form a simple low pass filter to provide noise filtering of the incoming control signal. The PWM generator block converts the analog signal to PWM. Conversion to PWM preserves the integrity of the analog control signal information when it is transferred from the secondary to the primary-side.

If 0 V to 10 V dimming is not required and a PWM source is already present, for example from a micro controller, then the PWM generator block may be omitted and U2A driven directly.

Optocoupler U2 is switched on and off with a duty cycle proportional to the control voltage.

Diode D1 prevents C6 from pulling down the FB pin during start-up condition. Resistors R6 and R12 sets the I_{FB} current at maximum brightness. The equation for operating I_{FB} with U2 open (maximum brightness) is

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$$I_{FB} = \frac{V_{BIAS} - V_{FB}}{R6 + R12} + \frac{VR4 - V_{FB}}{R10}$$

During full dimming, transistor U2 is fully on and voltage across C6 falls to V_{FB} + 0.6 V approximately 3 V. Resistor R11 is then selected based on the following relationship:

$$R11 = \frac{3V \times R6}{V_{BIAS(FD)} - 3V};$$

where $V_{BIAS(FD)}$ is the minimum bias voltage at full dimming.

PWM filter capacitor C6 is chosen to be greater than:

$$\frac{5}{f_{PWM} \times R11}$$

Resistor R10 provides a stable current of approximately 20 µA into the FB pin from the bias winding through VR4 biased by R7. This prevents the FB pin current from entering into auto-restart region (i.e. I_{FB} <20 µA) thus allowing operation in deep dimming mode operation. However, during short-circuit condition the VR4 bias voltage will collapse and allows I_{FB} current to fall below 20 µA thus enabling auto-restart protection mode. Resistor R10 also guarantees that the unit starts-up normally while the PWM filter capacitor C6 charges up and causes delay for the feedback current to cross the auto-restart region from the bias supply during initial start-up.

5.2 Analog-PWM Converter

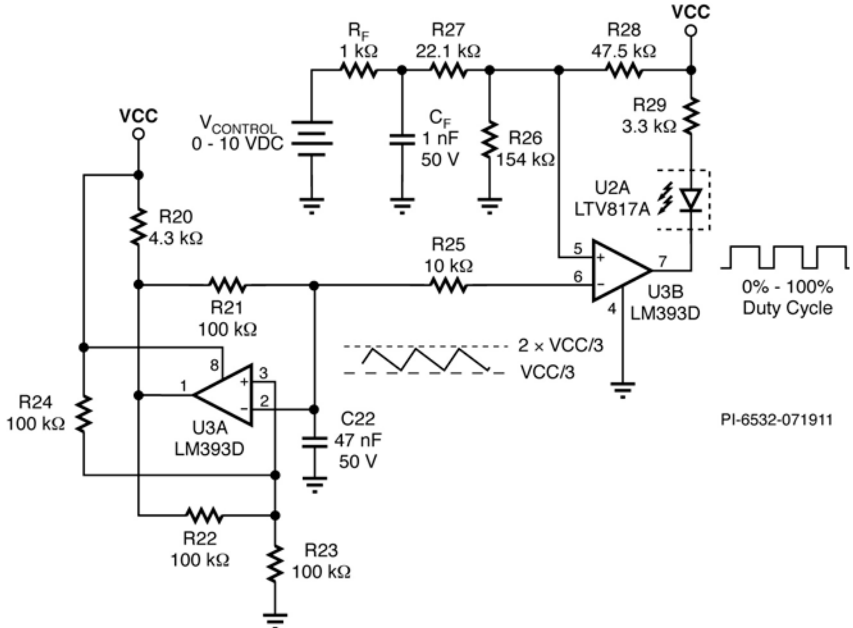

Figure 8 – Analog Signal to PWM Converter.

The PWM converter uses 2 comparator circuits implemented using LM393. The first comparator circuit is a relaxation oscillator that produces a nearly triangular waveform at the inverting input. The frequency of the sawtooth and the PWM output at pin 7 is given by the following relation

$$F_{PWM} \approx \frac{1}{2 \times \ln(2) \times R21 \times C22}$$

where R21 = R22 = R23 = R24.

The approximation was used to simplify the formula and ignore the small effect of the pull-up resistor R20. Resistor R20 would not be necessary if U3 is an op-amp with an output that saturates to its rail voltage. The oscillating frequency for this design is approximately 150 Hz.

The second comparator circuitry compares the triangular waveform with the scaled analog input. The minimum control signal is scaled to VCC/3 and maximum control signal is scaled to approximately 2×(VCC/3) to produce a 0-100% duty cycle. The scaling is done by resistors R26-R28.

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5.3 Active Load Circuit

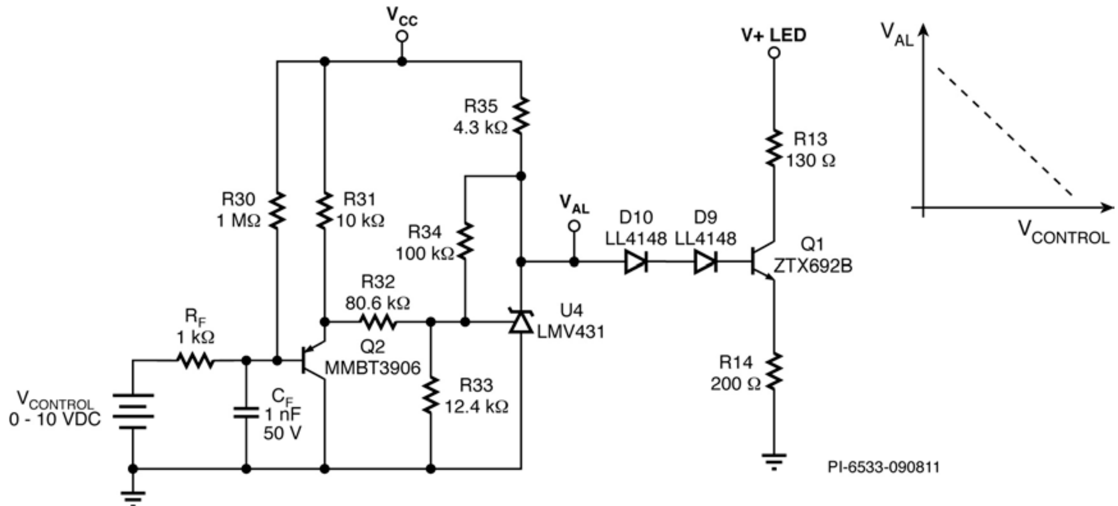

Figure 9 – Active Load Circuit.

The active load circuit is designed such that:

1. At full dimming, the active load circuit dissipates the minimum output power when I_{FB} is at minimum (I_{FB} ~20 μA) thereby reducing the LED load current.
2. Without dimming, or full brightness, the active load is inactive. V_{AL} (active load control voltage) is at its minimum value and set such that Q1 is off. This disconnects the active load from the output and does not affect the full load efficiency of the converter

The emitter follower configuration formed by Q1, R13, R14, D10 and D9 draws a current proportional to V_{AL} once V_{AL} exceeds 1.8 V threshold. Resistor R14 sets the ratio between V_{AL} and desired offset current. Resistor R13 is used to proportion the power dissipated between Q1 and R13 and thus enable the use of a lower power rating transistor.

The network formed by R32-R35 and U4 is configured as an inverting amplifier to satisfy relationship between control signal and V_{AL} as shown on the figure above.

Resistor R30, R31, and Q2 comprise the pull-up circuit and ensure that if the analog control signal is not present, the active load circuit is not connected to the output.

The active load circuit is optional for designs where a reduced dimming range is acceptable.

6 Bill of Materials

Item	Qty	Part Ref	Description	Mfg Part Number	Mfg
1	1	BR1	800 V, 1 A, Bridge Rectifier, SMD, DFS	DF08S	Diodes, Inc.
2	1	C1	47 nF, 275 VAC, Film, X2	ECQU2A473ML	Panasonic
3	1	C2	100 nF, 630 V, Film	ECQ-E6104KF	Panasonic
4	1	C3	1 μF, 400 V, Electrolytic, (6.3 x 11)	EKMG401ELL1R0MF11D	United Chemi-Con
5	1	C4	10 μF, 25 V, Ceramic, X5R, 1206	ECJ-3YB1E106M	Panasonic
6	1	C5	22 μF, 50 V, Electrolytic, Low ESR, 900 mΩ, (5 x 11.5)	ELXZ500ELL220MEB5D	Nippon Chemi-Con
7	1	C6	10 μF, 50 V, Electrolytic, Gen. Purpose, (5 x 11)	KME50VB10RM5X11LL	Nippon Chemi-Con
8	1	C7	1 nF, Ceramic, Y1	440LD10-R	Vishay
9	2	C8 C10	330 μF, 50 V, Electrolytic, Very Low ESR, 28 mΩ, (10 x 25)	EKZE500ELL331MJ25S	Nippon Chemi-Con
10	1	C9	1000 pF, 630 V, Ceramic, X7R, 1206	ECJ-3FB2J102K	Panasonic
11	1	C13	100 nF, 25 V, Ceramic, X7R, 0805	ECJ-2VB1E104K	Panasonic
12	2	C14 C20	1 nF, 50 V, Ceramic, X7R, 0805	08055C102KAT2A	AVX
13	1	C21	100 nF, 25 V, Ceramic, X7R, 1206	ECJ-3VB1E104K	Panasonic
14	1	C22	47 nF, 50 V, Ceramic, X7R, 0805	ECJ-2YB1H473K	Panasonic
15	1	C23	2.2 μF, 50 V, Ceramic, Y5V, 1206	GRM31MF51H225ZA01L	Murata
16	4	D1 D5 D9 D10	75 V, 0.15 A, Fast Switching, 4 ns, MELF	LL4148-13	Diodes, Inc.
17	1	D2	1000 V, 1 A, Rectifier, Glass Passivated, DO-213AA (MELF)	DL4007-13-F	Diodes, Inc.
18	1	D3	600 V, 1 A, Ultrafast Recovery, 35 ns, SMB Case	MURS160T3G	On Semi
19	1	D4	200 V, 2 A, Ultrafast Recovery, 20 ns, DO-214AA	ES2D	Diodes, Inc.
20	1	D6	DIODE ULTRA FAST, SW, 200 V, 1 A, SMA	US1D-13-F	Diodes, Inc.
21	1	D8	200 V, 4 A, Schottky, SMC, DO-214AB	MBRS4201T3G	ON Semi
22	1	F1	3.15 A, 250V, Slow, RST	507-1181	Belfuse
23	2	J1 J2	PCB Terminal Hole, 30 AWG	N/A	N/A
24	3	L1 L2 L3	1 mH, 0.30 A, Ferrite Core	CTCH895F-102K	CTParts
25	1	Q1	NPN, Power BJT, 70 V, 1 A, TO-92	ZTX692B	Zetex
26	1	Q2	PNP, Small Signal BJT, 40 V, 0.2 A, SOT-23	MMBT3906LT1G	On Semi
27	2	Q3 Q4	NPN, Small Signal BJT, 40 V, 0.2 A, SOT-23	MMBT3904LT1G	On Semi
28	2	R2 R3	2.00 MΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF2004V	Panasonic
29	1	R4	24.9 kΩ, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF2492V	Panasonic
30	1	R5	3 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ302V	Panasonic
31	1	R6	24 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ243V	Panasonic
32	1	R7	10 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ103V	Panasonic
33	1	R8	150 Ω, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ151V	Panasonic
34	2	R9 R15	390 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ394V	Panasonic
35	1	R10	174 kΩ, 1%, 1/8 W, Thick Film, 0805	ERJ-6ENF1743V	Panasonic
36	1	R11	3.6 kΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ362V	Panasonic
37	1	R12	150 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ154V	Panasonic
38	1	R13	130 Ω, 5%, 1 W, Metal Oxide	RSF100JB-130R	Yageo
39	1	R14	200 Ω, 5%, 1 W, Metal Oxide	RSF100JB-200R	Yageo
40	2	R16 R17	4.7 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ472V	Panasonic
41	2	R18 R40	1.5 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ152V	Panasonic
42	1	R19	1 kΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ102V	Panasonic
43	2	R20 R35	4.3 kΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ432V	Panasonic
44	4	R21 R22	100 kΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ104V	Panasonic

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		R23 R24			
45	2	R25 R31	10 kΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ103V	Panasonic
46	1	R26	154 kΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF1543V	Panasonic
47	1	R27	22.1 kΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF2212V	Panasonic
48	1	R28	47.5 kΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF4752V	Panasonic
49	1	R29	3.3 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ332V	Panasonic
50	1	R30	1 MΩ, 5%, 1/8 W, Thick Film, 0805	ERJ-6GEYJ105V	Panasonic
51	1	R32	80.6 kΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF8062V	Panasonic
52	1	R33	12.4 kΩ, 1%, 1/4 W, Thick Film, 1206	ERJ-8ENF1242V	Panasonic
53	1	R34	100 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ104V	Panasonic
54	3	R36 R37 R38	1 kΩ, 5%, 1/4 W, Thick Film, 1206	ERJ-8GEYJ102V	Panasonic
55	1	R39	1 MΩ, 1%, 1/4 W, Metal Film	MFR-25FBF-1M00	Yageo
56	1	RV1	275 V, 23 J, 7 mm, RADIAL	V275LA4P	Littlefuse
57	1	T1	Bobbin, RM8, Vertical, 12 pins Transformer	RM8/12/1 PNK-10012	Schwartzpunkt Premier Magnetics
58	1	U1	LinkSwitch-PH, eSIP	LNK406EG	Power Integrations
59	1	U2	Optocoupler, 35 V, CTR 80-160%, 4-DIP	LTV-817A	Liteon
60	1	U3	Dual Diff Comparator, 8-SOIC	LM393D	National
61	1	U4	1.24 V Shunt Reg IC	LMV431ACZ	National Semi
62	1	VR3	36 V, 5%, 500 mW, DO-213AA (MELF)	ZMM5258B-7	Diodes, Inc.
63	1	VR4	16 V, 5%, 1 W, DO-41	1N4745A-T	Diodes, Inc.
64	1	VR5	6.2 V, 5%, 150 mW, SOD-323	MAZS0620ML	Panasonic

7 Transformer Specification

7.1 Electrical Diagram

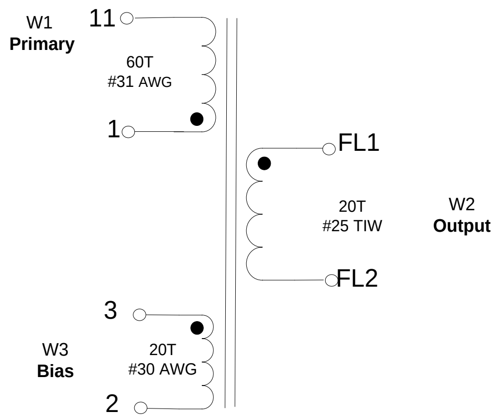

Figure 10 – Transformer Electrical Diagram.

7.2 Electrical Specifications

Electrical Strength	1 second, 60 Hz, from pins 1, 2, 3, 11 to FL1, FL2.	3000 VAC
Primary Inductance	Pins 1-11, all other windings open, measured at 100 kHz, 0.4 V_{RMS}.	1195 μH ±10%
Resonant Frequency	Pins 1-11, all other windings open.	750 kHz (Min.)
Primary Leakage Inductance	Pins 1-11, with FL1-FL2 shorted, measured at 100 kHz, 0.4 V_{RMS}.	20 μH (Max.)

7.3 Materials

Item	Description
[1]	Core: RM8/I, 3F3.
[2]	Bobbin: 12 pin vertical, CSV-RM8-1S-12P Philips or equivalent with mounting clip, CLI/P-RM8.
[3]	Tape: Polyester film, 3M 1350F-1 or equivalent, 9 mm wide.
[4]	Wire: Magnet, #31 AWG, solderable double coated.
[5]	Wire: Magnet, #30 AWG, solderable double coated.
[6]	Wire: Triple Insulated, Furukawa TEX-E or Equivalent, #25 TIW.
[7]	Transformer Varnish: Dolph BC-359 or equivalent.

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7.4 Transformer Build Diagram

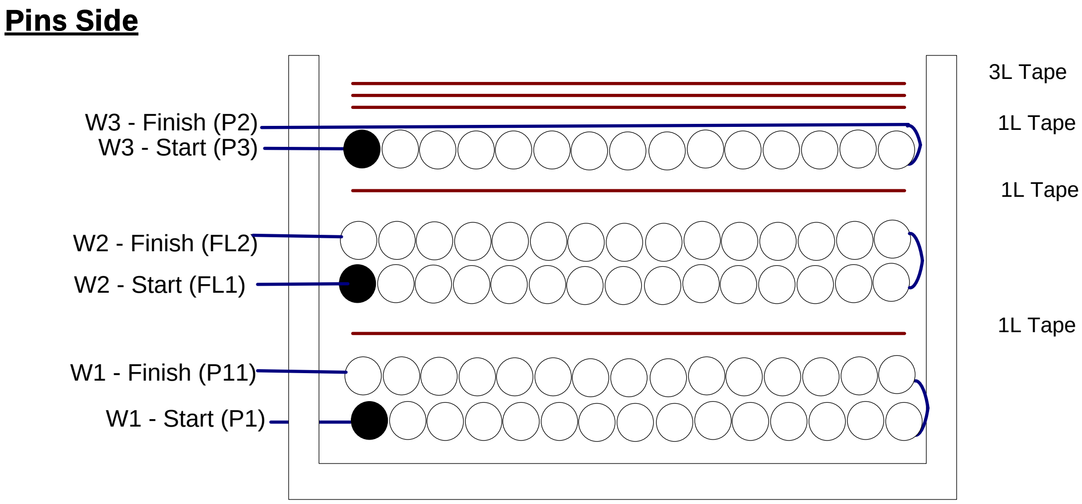

Figure 11 – Transformer Build Diagram.

7.5 Transformer Construction

Bobbin Preparation	Place the bobbin item [2] on the mandrel such that pin side on the left side. Winding direction is the clockwise direction.
WD 1 (Primary)	Starting at pin 1, wind 60 turns of wire item [4] in two layers. Finish at pin 11.
Insulation	Apply one layer of tape item [3].
WD 2 (Secondary)	Leave about 1” of wire item [6], use small tape to mark as FL1, enter into slot of secondary side of bobbin, wind 20 turns in two layers. At the last turn exit the same slot, leave about 1”, and mark as FL2.
Insulation	Apply one layer of tape item [3].
WD 3 (Bias)	Starting at pin 3, wind 20 turns of wire item [5], spreading the wire, finish at pin 2.
Finish Wrap	Apply three layers of tape item [3] for finish wrap.
Final Assembly	Cut FL1 and FL2 to 0.75”. Grind core to get 1.15 mH inductance value. Assemble and secure core halves. Dip impregnate using varnish item [7].

8 Transformer Design Spreadsheet

ACDC_LinkSwitch-PH_032511; Rev.1.3; Copyright Power Integrations 2011	**INPUT**	**INFO**	**OUTPUT**	**UNIT**	**LinkSwitch-PH_032511: Flyback Transformer Design Spreadsheet**
ENTER APPLICATION VARIABLES					
Dimming required	**NO**		**NO**		Select 'YES' option if dimming is required. Otherwise select 'NO'.
VACMIN			90	V	Minimum AC Input Voltage
VACMAX			265	V	Maximum AC input voltage
fL			50	Hz	AC Mains Frequency
VO	28.00			V	Typical output voltage of LED string at full load
VO_MAX			30.80	V	Maximum expected LED string Voltage.
VO_MIN			25.20	V	Minimum expected LED string Voltage.
V_OVP			33.88	V	Over-voltage protection setpoint
IO	0.50			A	Typical full load LED current
PO			14.0	W	!!! For Universal Input reduce Continuous Output Power PO_CONT below 10W (or use larger LinkSwitch-PH)
n	0.84		0.84		Estimated efficiency of operation
VB	25		25	V	Bias Voltage
ENTER LinkSwitch-PH VARIABLES					
LinkSwitch-PH	**LNK416**			Universal	115 Doubled/230V
Chosen Device		LNK416	Power Out	10W	4.5W
Current Limit Mode	**RED**		RED		Select "RED" for reduced Current Limit mode or "FULL" for Full current limit mode
ILIMITMIN			1.19	A	Minimum current limit
ILIMITMAX			1.38	A	Maximum current limit
fS			66000	Hz	Switching Frequency
fSmin			62000	Hz	Minimum Switching Frequency
fSmax			70000	Hz	Maximum Switching Frequency
IV			38.7	uA	V pin current
RV			3.909	M-ohms	Upper V pin resistor
RV2			1.402	M-ohms	Lower V pin resistor
IFB			142.2	uA	FB pin current (85 uA < IFB < 210 uA)
RFB1			154.7	k-ohms	FB pin resistor
VDS			10	V	LinkSwitch-PH on-state Drain to Source Voltage
VD	0.50			V	Output Winding Diode Forward Voltage Drop (0.5 V for Schottky and 0.8 V for PN diode)
VDB	0.70			V	Bias Winding Diode Forward Voltage Drop
Key Design Parameters					
KP	0.88		0.88		Ripple to Peak Current Ratio (For PF > 0.9, 0.4 < KP < 0.9)
LP			1195	uH	Primary Inductance
VOR	85.00		85	V	Reflected Output Voltage.
Expected IO (average)			0.49	A	Expected Average Output Current
KP_VACMAX			1.11		Expected ripple current ratio at VACMAX
TON_MIN			1.90	us	Minimum on time at maximum AC input voltage
PCLAMP			0.11	W	Estimated dissipation in primary clamp
ENTER TRANSFORMER CORE/CONSTRUCTION VARIABLES					
Core Type	**RM8/I**		**RM8/I**		
Bobbin		*RM8/I_BOBBIN*		*P/N:*	*
AE			0.63	cm^2	Core Effective Cross Sectional Area
LE			3.84	cm	Core Effective Path Length
AL			3000	nH/T^2	Ungapped Core Effective Inductance
BW			8.6	mm	Bobbin Physical Winding Width
M			0	mm	Safety Margin Width (Half the Primary to Secondary Creepage Distance)

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L	2.00		2		Number of Primary Layers
NS	20		20		Number of Secondary Turns
DC INPUT VOLTAGE PARAMETERS					
VMIN			127	V	Peak input voltage at VACMIN
VMAX			375	V	Peak input voltage at VACMAX
CURRENT WAVEFORM SHAPE PARAMETERS					
DMAX			0.42		Minimum duty cycle at peak of VACMIN
IAVG			0.18	A	Average Primary Current
IP			0.91	A	Peak Primary Current (calculated at minimum input voltage VACMIN)
IRMS			0.30	A	Primary RMS Current (calculated at minimum input voltage VACMIN)
TRANSFORMER PRIMARY DESIGN PARAMETERS					
LP			1195	uH	Primary Inductance
NP			60		Primary Winding Number of Turns
NB			18		Bias Winding Number of Turns
ALG			336	nH/T^2	Gapped Core Effective Inductance
BM			2901	Gauss	Maximum Flux Density at PO, VMIN (BM<3100)
BP			3511	Gauss	Peak Flux Density (BP<3700)
BAC			1277	Gauss	AC Flux Density for Core Loss Curves (0.5 X Peak to Peak)
ur			1455		Relative Permeability of Ungapped Core
LG			0.21	mm	Gap Length (Lg > 0.1 mm)
BWE			17.2	mm	Effective Bobbin Width
OD			0.29	mm	Maximum Primary Wire Diameter including insulation
INS			0.05	mm	Estimated Total Insulation Thickness (= 2 * film thickness)
DIA			0.24	mm	Bare conductor diameter
AWG			31	AWG	Primary Wire Gauge (Rounded to next smaller standard AWG value)
CM			81	Cmils	Bare conductor effective area in circular mils
CMA			272	Cmils/Amp	Primary Winding Current Capacity (200 < CMA < 600)
LP_TOL			10		Tolerance of primary inductance
TRANSFORMER SECONDARY DESIGN PARAMETERS (SINGLE OUTPUT EQUIVALENT)					
Lumped parameters					
ISP			2.72	A	Peak Secondary Current
ISRMS			0.98	A	Secondary RMS Current
IRIPPLE			0.84	A	Output Capacitor RMS Ripple Current
CMS			196	Cmils	Secondary Bare Conductor minimum circular mils
AWGS			27	AWG	Secondary Wire Gauge (Rounded up to next larger standard AWG value)
DIAS			0.36	mm	Secondary Minimum Bare Conductor Diameter
ODS			0.43	mm	Secondary Maximum Outside Diameter for Triple Insulated Wire
VOLTAGE STRESS PARAMETERS					
VDRAIN			553	V	Estimated Maximum Drain Voltage assuming maximum LED string voltage (Includes Effect of Leakage Inductance)
PIVS			160	V	Output Rectifier Maximum Peak Inverse Voltage (calculated at VOVP, excludes leakage inductance spike)
PIVB			144	V	Bias Rectifier Maximum Peak Inverse Voltage (calculated at VOVP, excludes leakage inductance spike)
FINE TUNING (Enter measured values from prototype)					
V Pin Resistor Fine Tuning					
RV1	3.9		3.90	M-ohms	Upper V Pin Resistor Value

RV2	1.33		1.33	M-ohms	Lower V Pin Resistor Value
VAC1	115		115.0	V	Test Input Voltage Condition1
VAC2	230		230.0	V	Test Input Voltage Condition2
IO_VAC1	0.486		0.49	A	Measured Output Current at VAC1
IO_VAC2	0.49		0.49	A	Measured Output Current at VAC2
RV1 (new)			3.95	M-ohms	New RV1
RV2 (new)			1.09	M-ohms	New RV2
V_OV			322.9	V	Typical AC input voltage at which OV shutdown will be triggered
V_UV			73.2	V	Typical AC input voltage beyond which power supply can startup
FB Pin Resistor Fine Tuning					
RFB1			155	k-ohms	Upper FB Pin Resistor Value
RFB2			1E+012	k-ohms	Lower FB Pin Resistor Value
VB1			22.5	V	Test Bias Voltage Condition1
VB2			27.5	V	Test Bias Voltage Condition2
IO1			0.50	A	Measured Output Current at Vb1
IO2			0.50	A	Measured Output Current at Vb2
RFB1 (new)			154.7	k-ohms	New RFB1
RFB2(new)			1.00E+12	k-ohms	New RFB2

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9 Performance Data

All measurements performed at room temperature and using strings of LEDs for the load.

9.1 Efficiency – Full Brightness

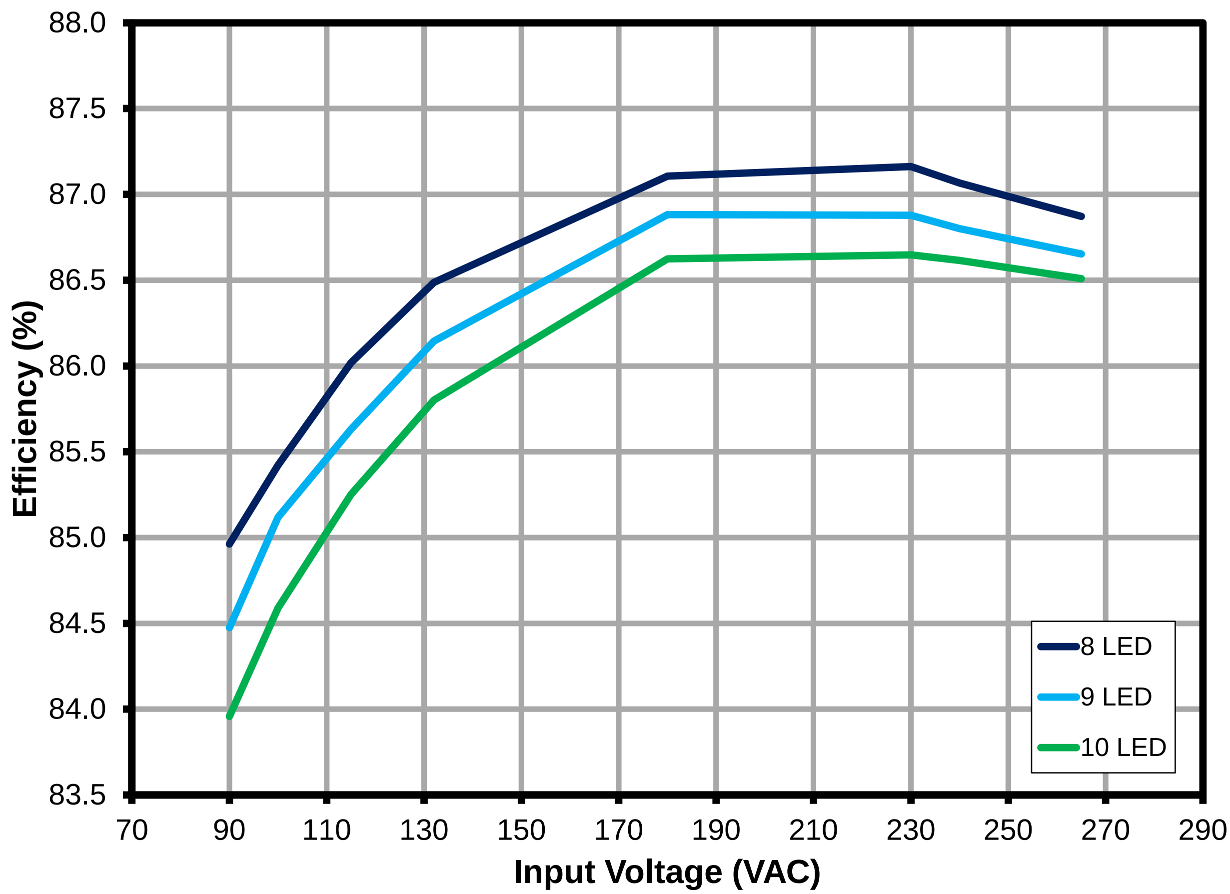

Figure 12 – Efficiency at Full Brightness.

9.2 Line and Load Regulation – Full Brightness

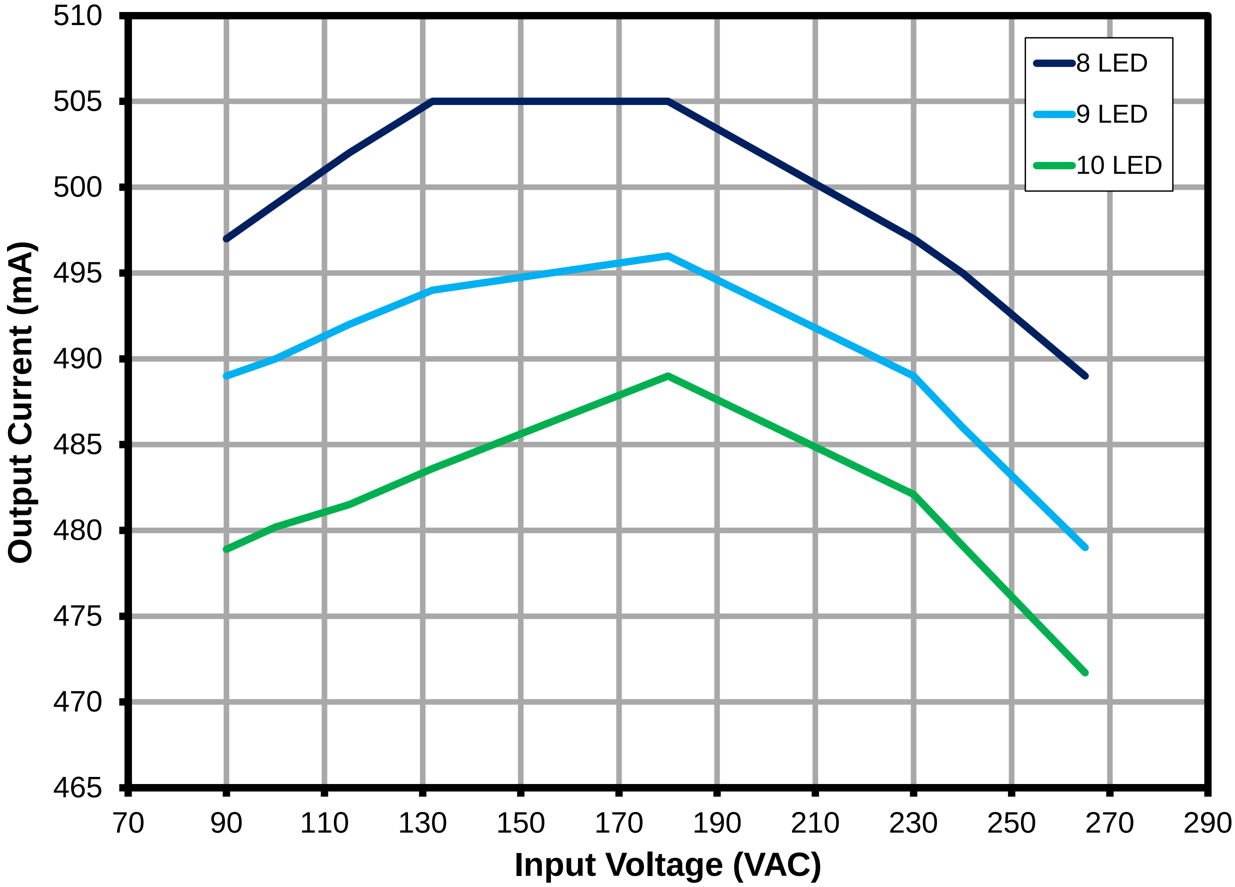

Figure 13 – Line and load Regulation.

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9.3 Power Factor – Full Brightness

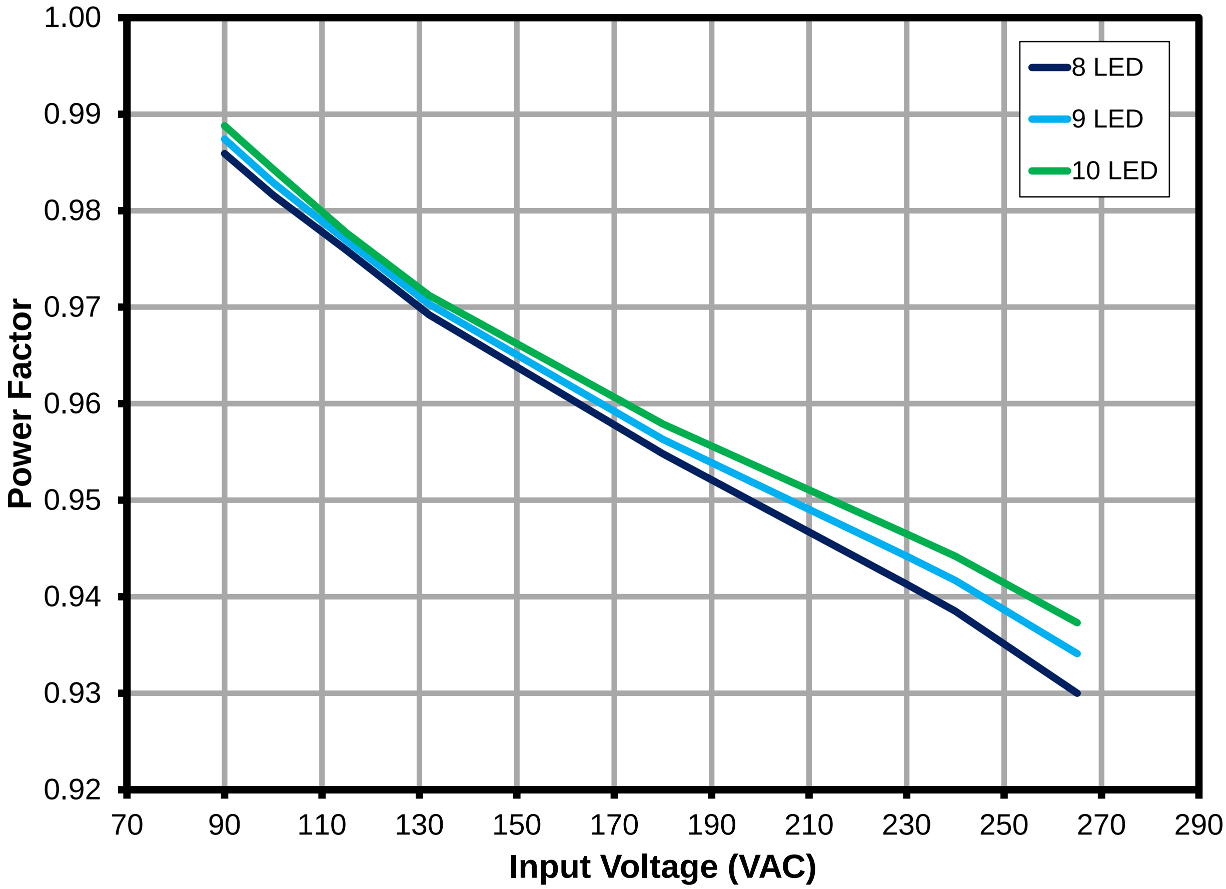

Figure 14 – Power Factor at Full Brightness.

9.4 A-THD – Full Brightness

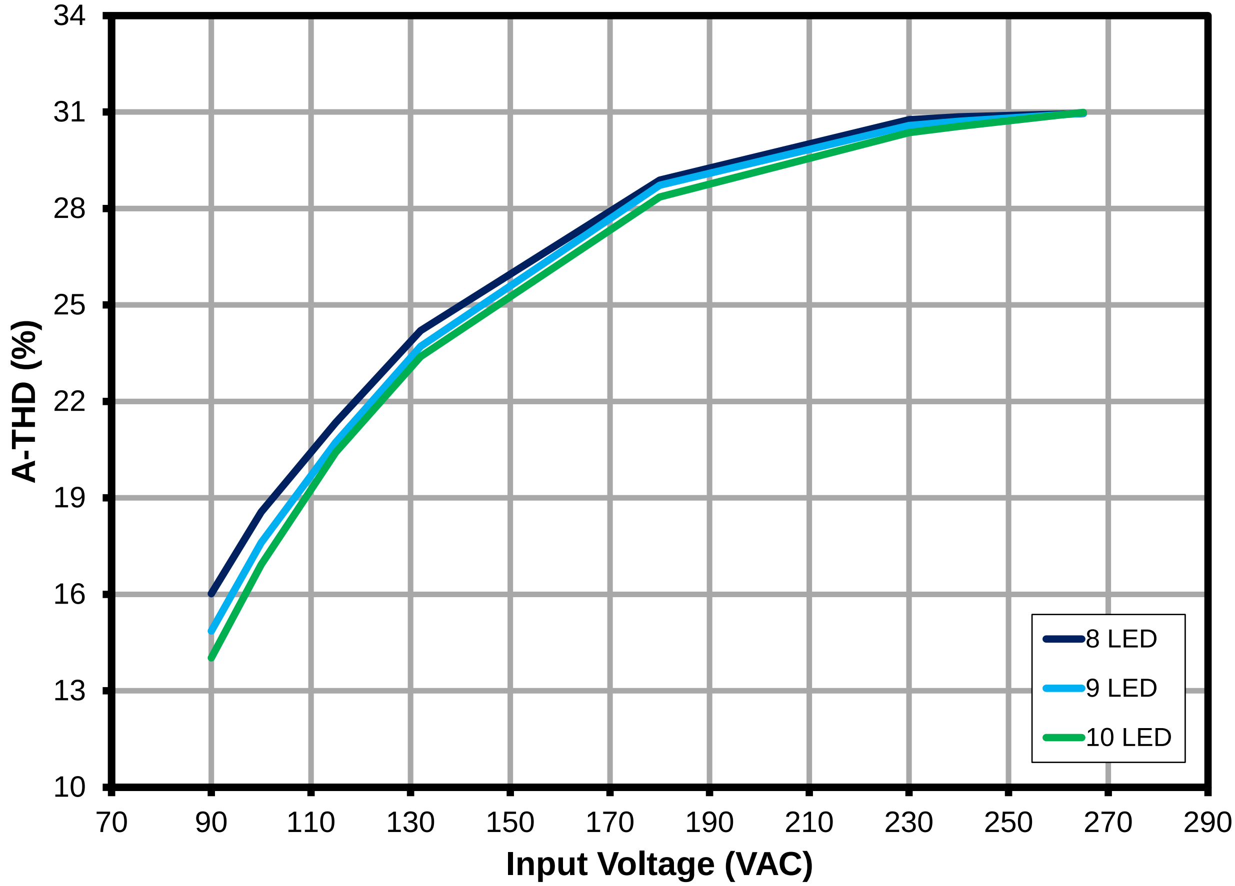

Figure 15 – Total Harmonic Distortion.

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9.5 115 VAC Dimming Characteristic

9.5.1 Output Current vs. Control Voltage

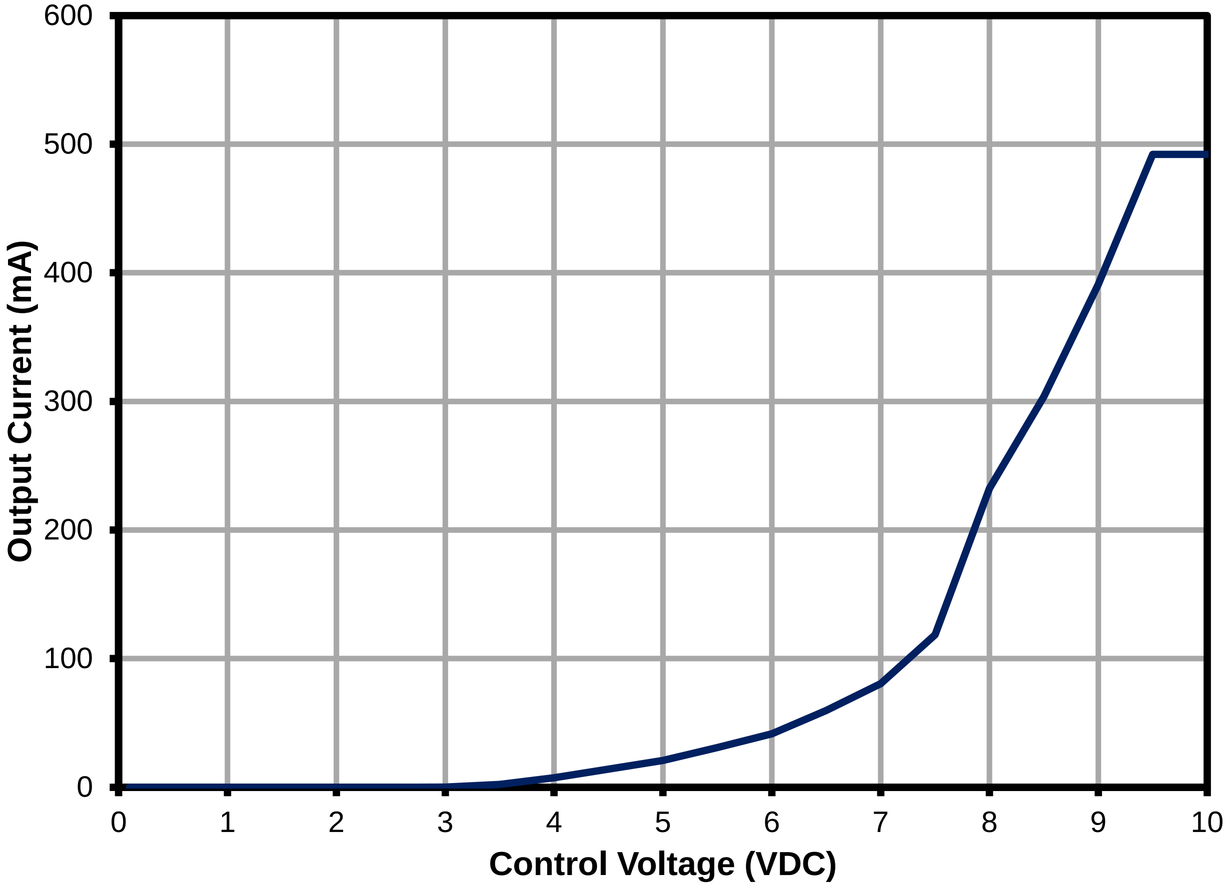

Figure 16 – 115 VAC Output Current vs. Control Voltage (9 LED Load).

9.5.2 Dimming Ratio vs. Control Voltage

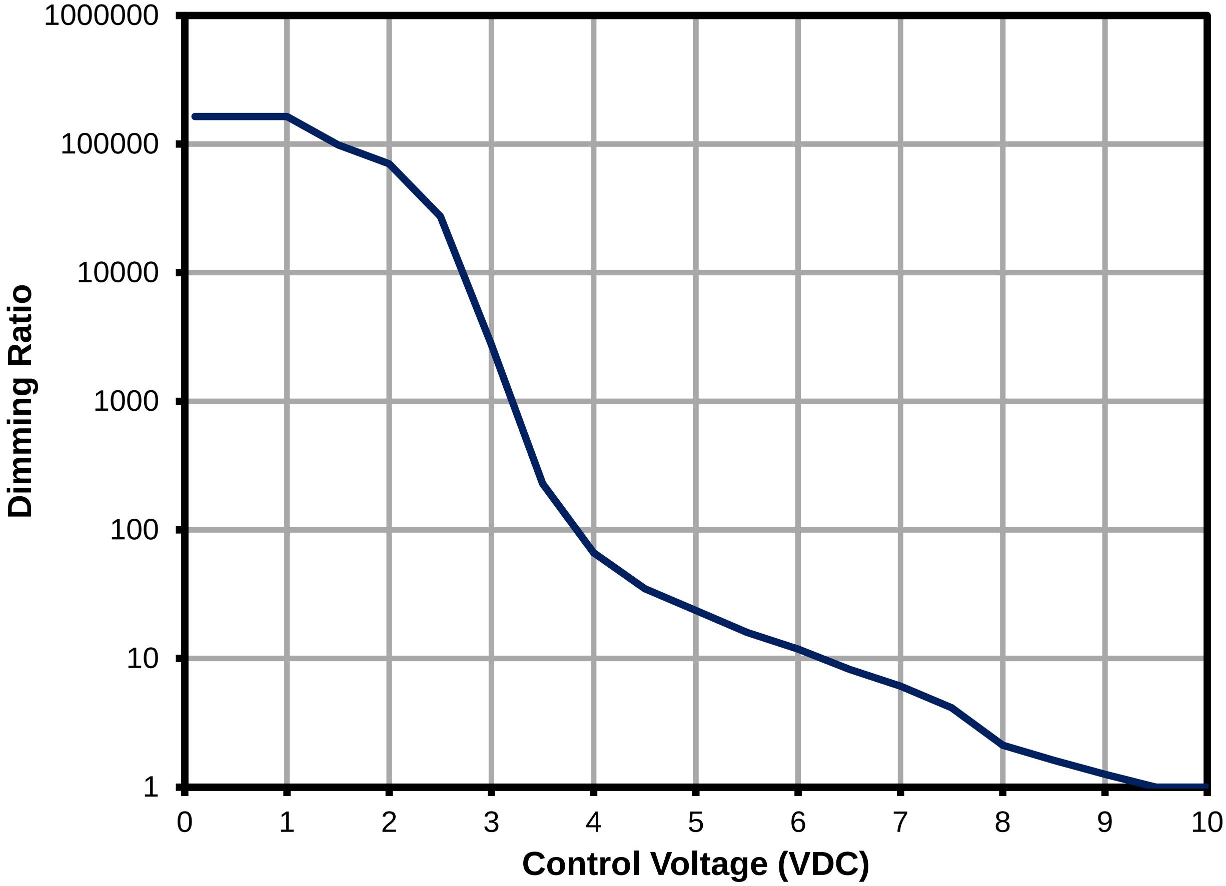

Figure 17 – 115 VAC Dimming Ratio vs. Control Voltage (9 LED Load).

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9.6 230 VAC Dimming Characteristic

9.6.1 Output Current vs. Control Voltage

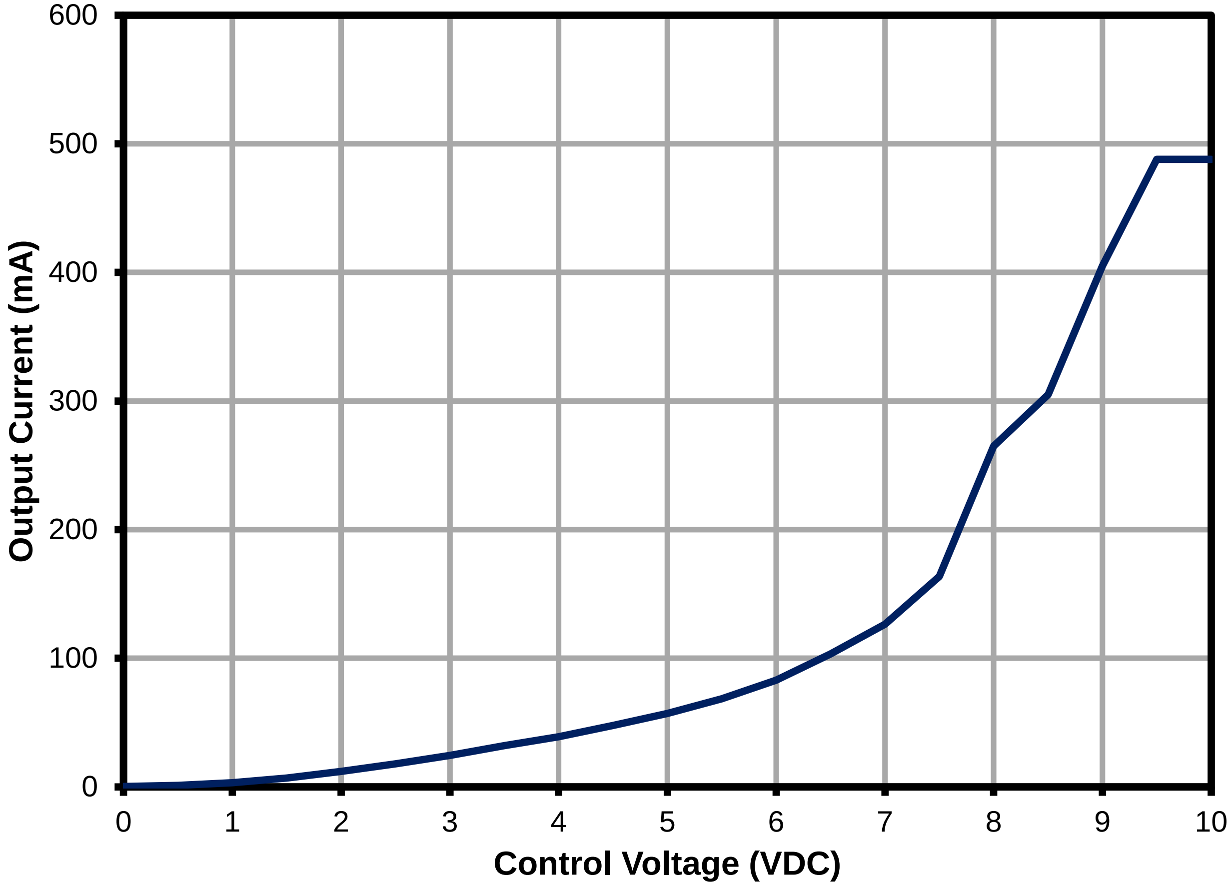

Figure 18 – 230 VAC Output Current vs. Control Voltage (9 LED Load).

9.6.2 Dimming Ratio vs. Control Voltage

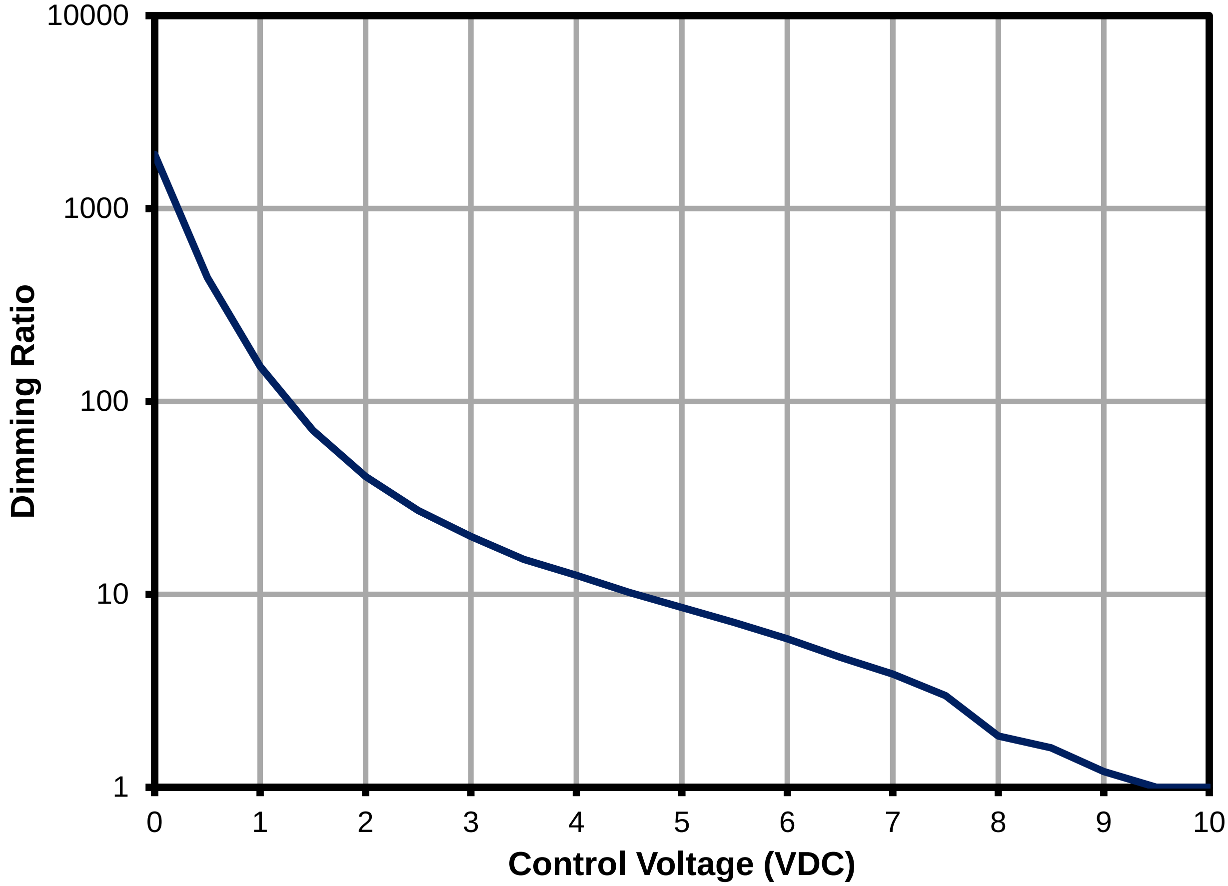

Figure 19 – 230 VAC Dimming Ratio vs. Control Voltage (9 LED Load).

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9.7 Harmonics – Full Brightness

The design met the limits for Class C equipment for an active input power of <25 W. In this case IEC61000-3-2 specifies that harmonic currents shall not exceed the limits of Class D equipment[1]. Therefore the limits shown in the charts below are Class D limits which must not be exceeded to meet Class C compliance.

9.7.1 8 LED Load

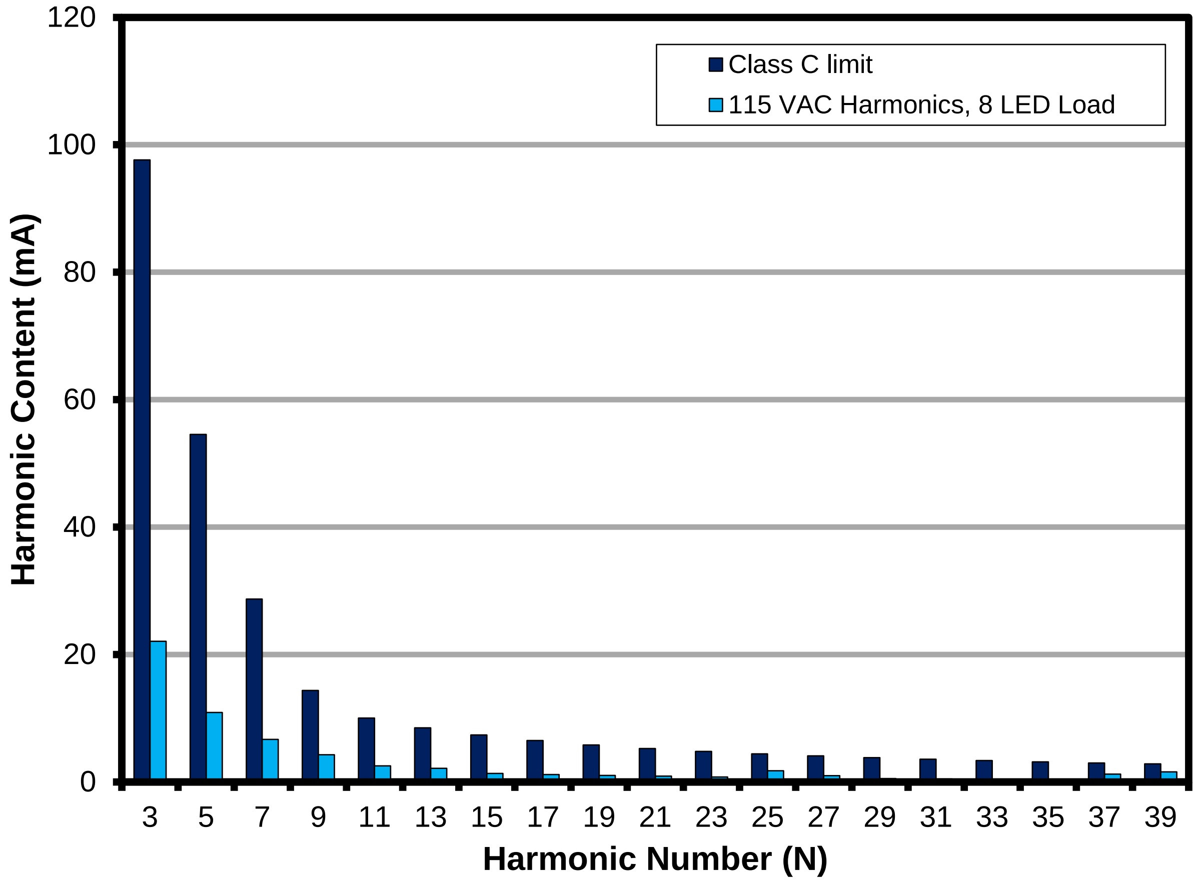

Figure 20 – 115 VAC Harmonics, 8 LED Load.

[1] IEC6000-3-2 Section 7.3, table 2, column 2.

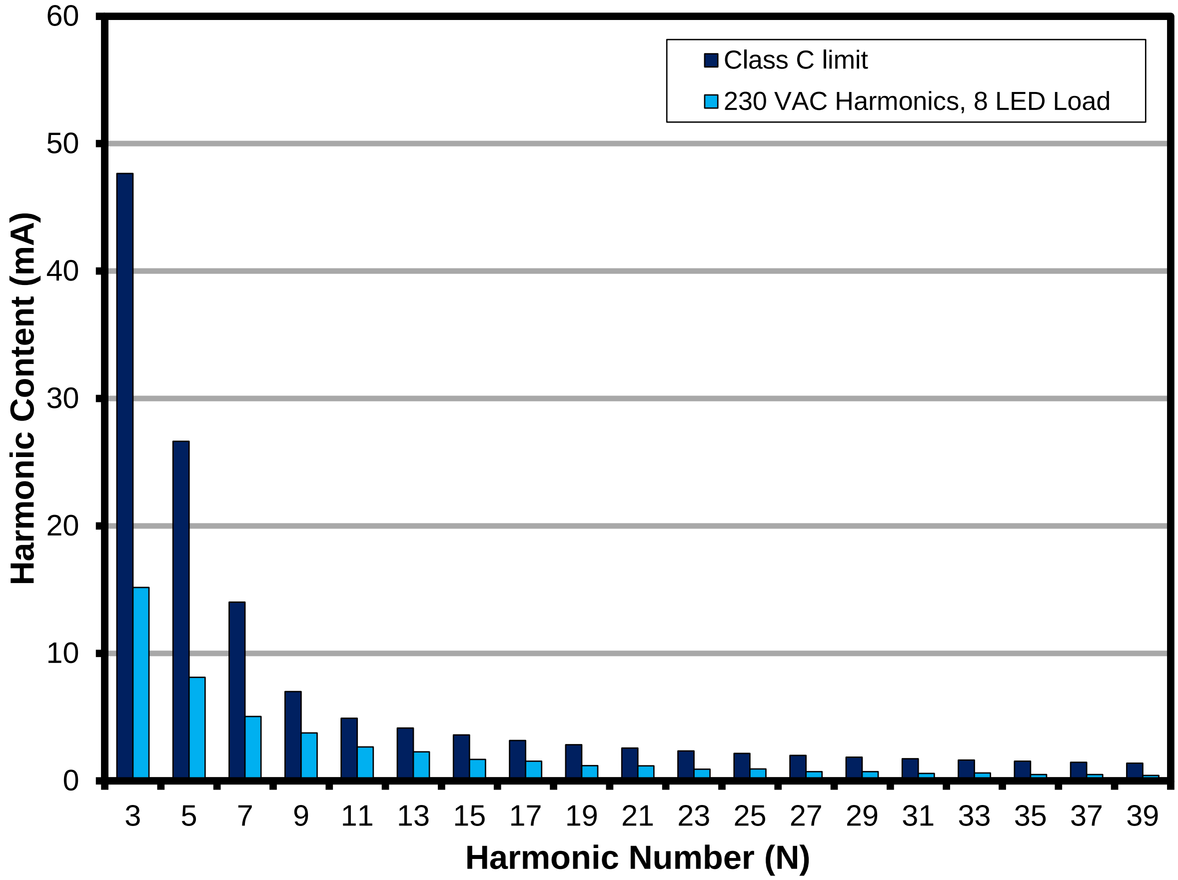

Figure 21 – 230 VAC Harmonics, 8 LED Load.

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9.7.2 9 LED Load

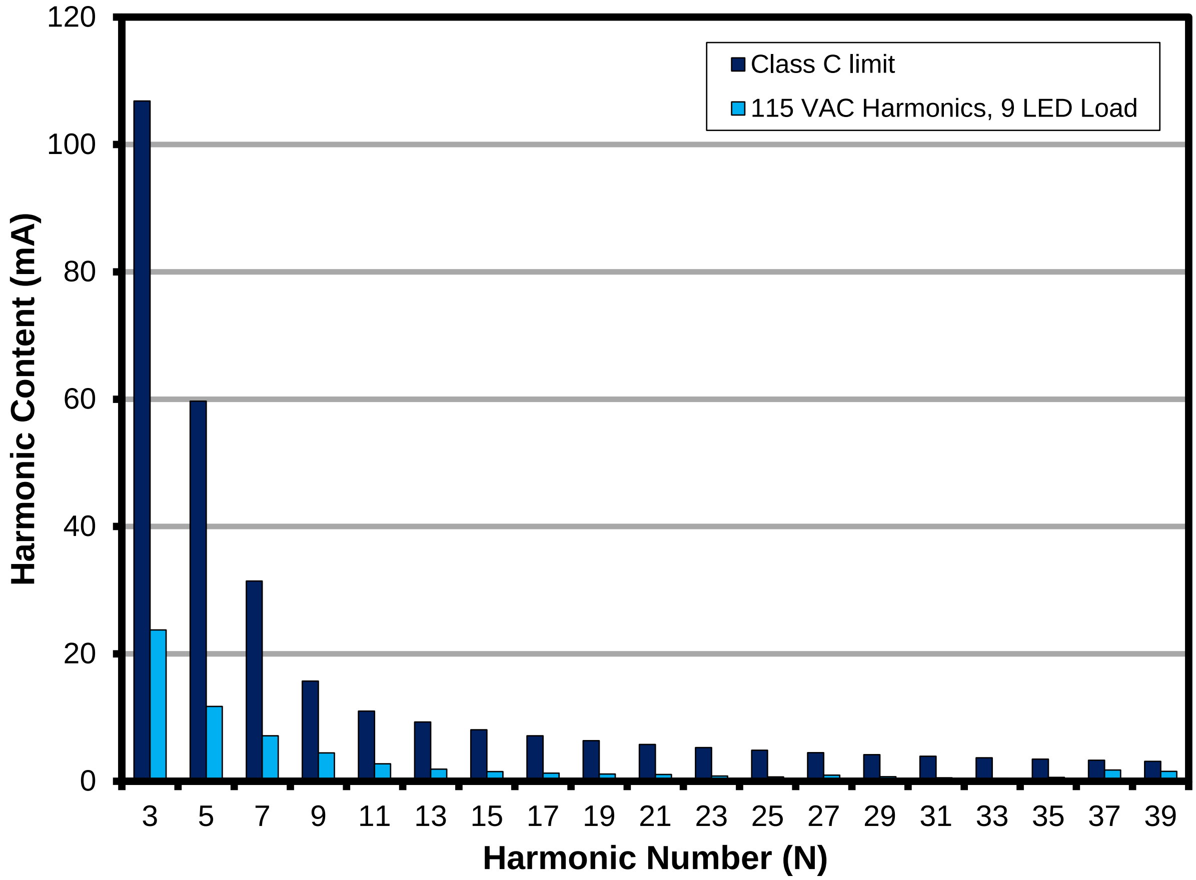

Figure 22 – 115 VAC Harmonics, 9 LED Load**.**

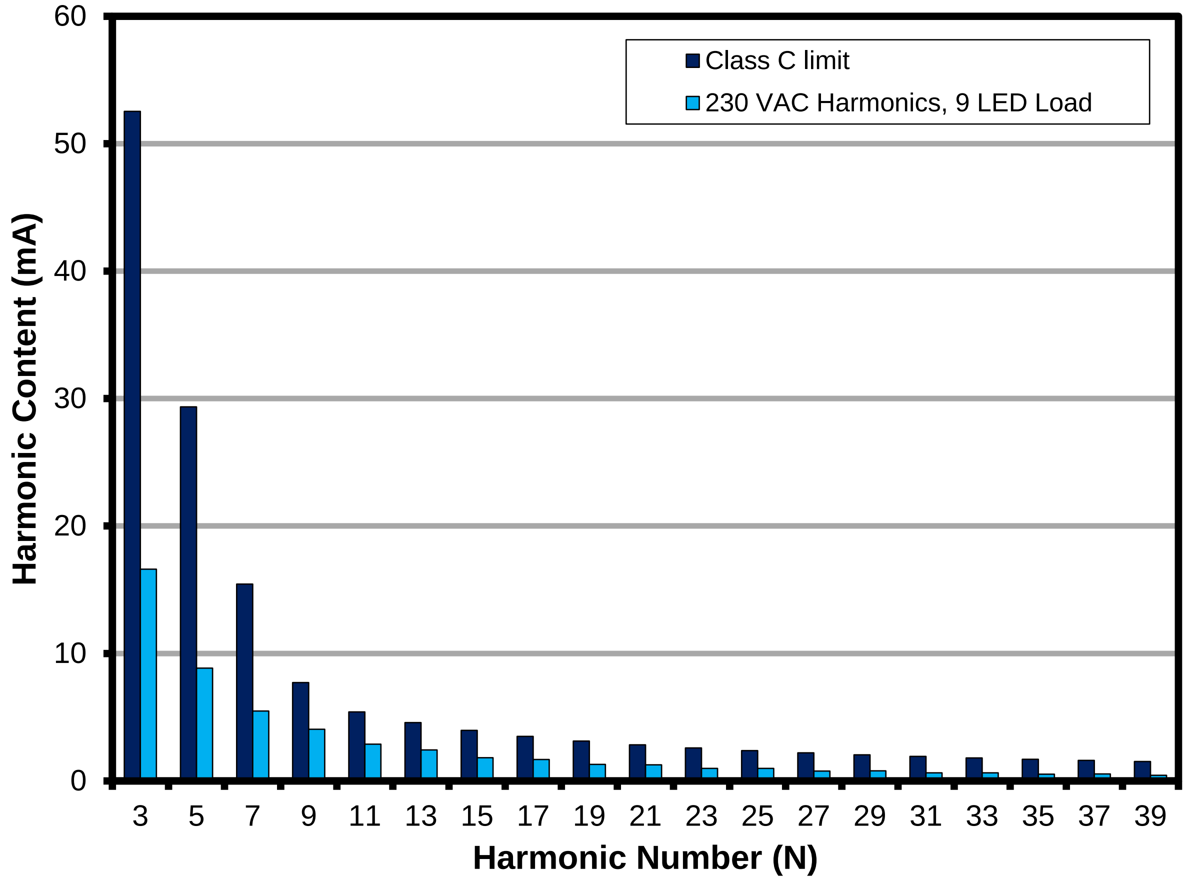

Figure 23 – 230 VAC Harmonics, 9 LED Load.

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9.7.3 10 LED Load

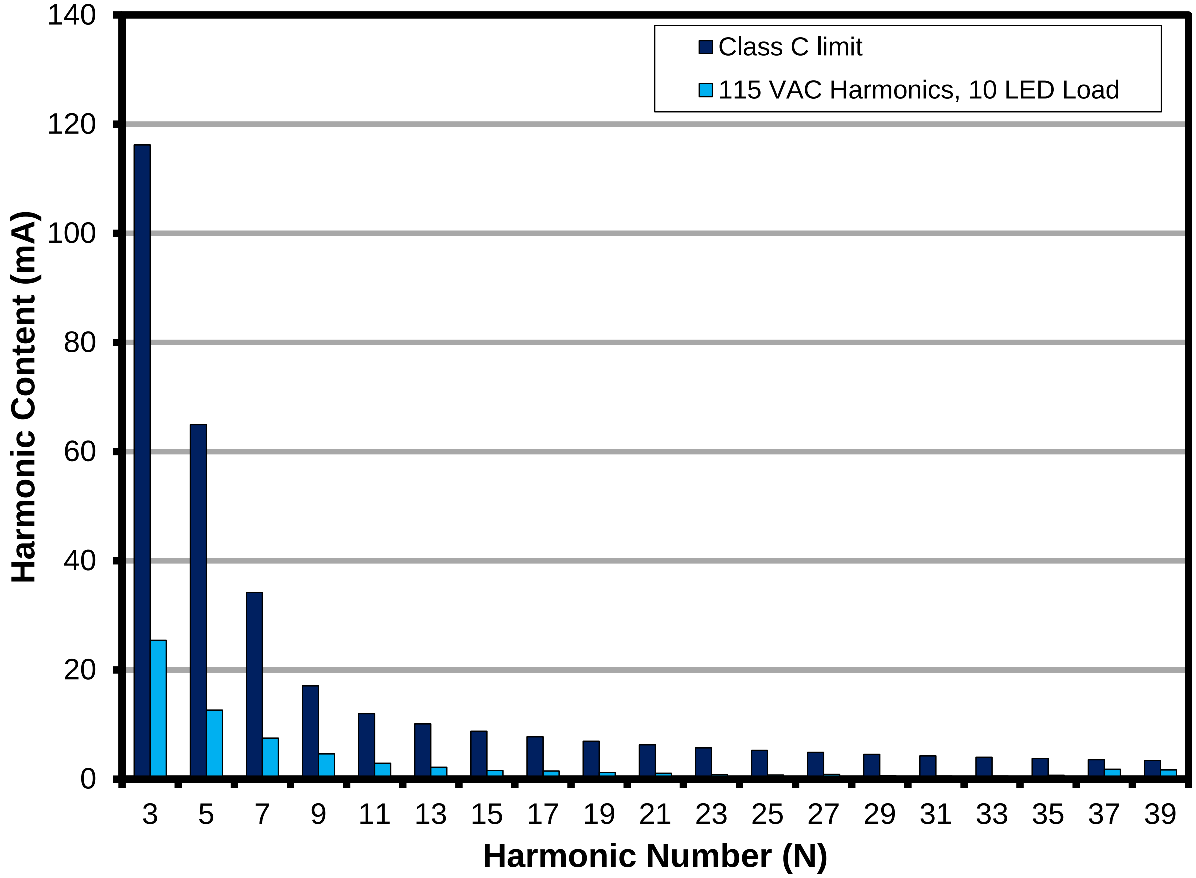

Figure 24 – 115 VAC Harmonics, 10 LED Load.

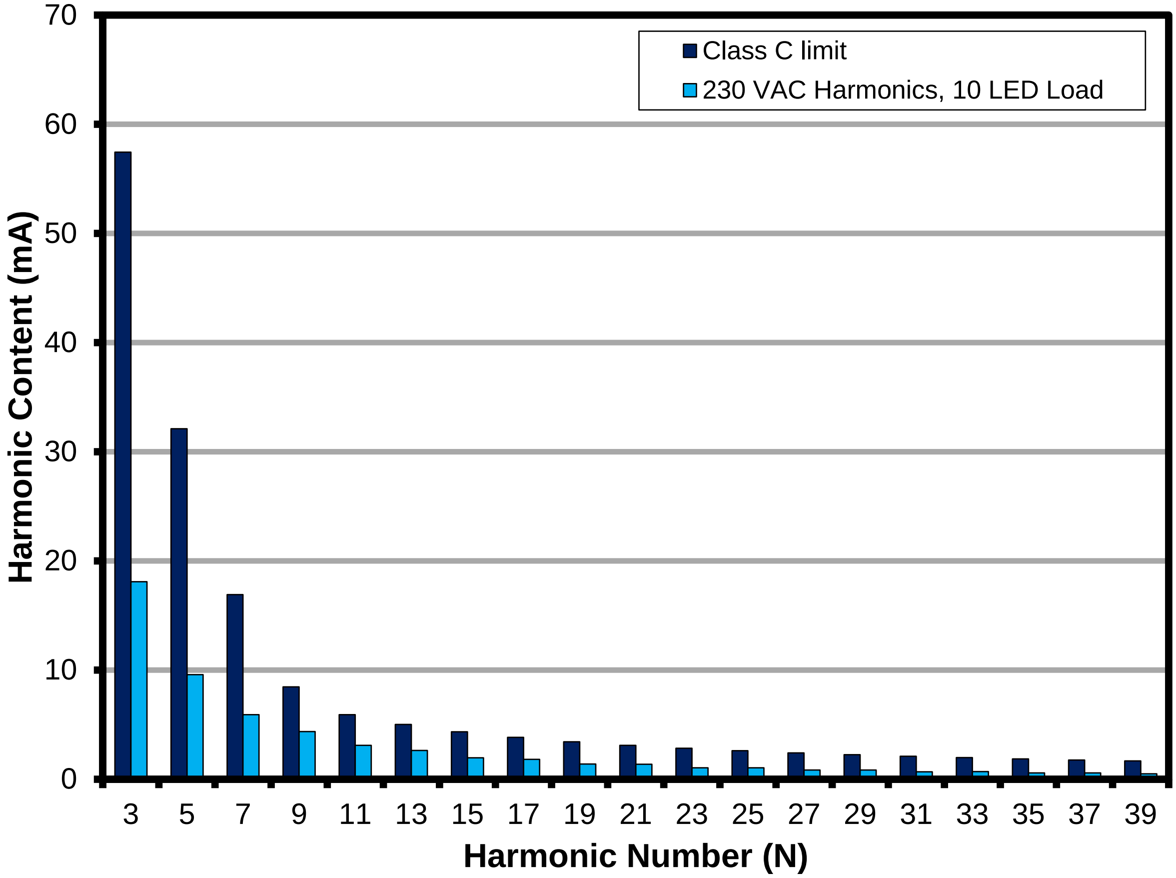

Figure 25 – 230 VAC Harmonics 10 LED Load.

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9.8 Test Data

9.8.1 Efficiency, Regulation, Power Factor, and THD - Non-Dimming

Input		Input Measurement					Load Measurement			Calculation			
VAC (V_{RMS})	Freq (Hz)	V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN} (W)	PF	%ATHD	V_{OUT} (V_{DC})	I_{OUT} (mA_{DC})	P_{OUT} (W)	P_{CAL} (W)	Efficiency (%)	Loss (W)	Regulation (%)
90	60	90.01	162.64	14.43	0.986	16.02	24.55	497	12.26	12.20	84.96	2.17	-0.60
100	60	99.98	146.84	14.41	0.982	18.56	24.51	499	12.31	12.23	85.42	2.10	-0.20
115	60	115.02	128.00	14.37	0.976	21.34	24.49	502	12.36	12.29	86.02	2.01	0.40
132	60	132.04	112.13	14.35	0.969	24.2	24.47	505	12.41	12.36	86.49	1.94	1.00
180	50	180.05	82.88	14.25	0.955	28.88	24.43	505	12.41	12.34	87.11	1.84	1.00
230	50	230.14	64.61	14.00	0.941	30.76	24.39	497	12.20	12.12	87.16	1.80	-0.60
240	50	240.10	61.83	13.93	0.939	30.85	24.37	495	12.13	12.06	87.07	1.80	-1.00
265	50	265.12	55.79	13.76	0.930	30.95	24.33	489	11.95	11.90	86.87	1.81	-2.20

Table 1 – 8 LED Load Measurement Data.

Input		Input Measurement					Load Measurement			Calculation			
VAC (V_{RMS})	Freq (Hz)	V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN} (W)	PF	%ATHD	V_{OUT} (V_{DC})	I_{OUT} (mA_{DC})	P_{OUT} (W)	P_{CAL} (W)	Efficiency (%)	Loss (W)	Regulation (%)
90	60	90.01	179.01	15.91	0.987	14.86	27.36	489	13.44	13.38	84.48	2.47	-2.20
100	60	99.98	161.04	15.83	0.983	17.61	27.35	490	13.47	13.40	85.12	2.36	-2.00
115	60	115.02	140.41	15.78	0.977	20.73	27.34	492	13.51	13.45	85.63	2.27	-1.60
132	60	132.04	122.87	15.74	0.970	23.71	27.34	494	13.56	13.51	86.14	2.18	-1.20
180	50	180.05	91.11	15.69	0.956	28.72	27.33	496	13.63	13.56	86.88	2.06	-0.80
230	50	230.15	71.09	15.45	0.944	30.58	27.30	489	13.42	13.35	86.88	2.03	-2.20
240	50	240.11	67.92	15.36	0.942	30.71	27.28	486	13.33	13.26	86.80	2.03	-2.80
265	50	265.13	61.14	15.14	0.934	30.96	27.25	479	13.12	13.05	86.65	2.02	-4.20

Table 2 – 9 LED Load Measurement Data.

Input		Input Measurement					Load Measurement			Calculation			
VAC (V_{RMS})	Freq (Hz)	V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN} (W)	PF	%ATHD	V_{OUT} (V_{DC})	I_{OUT} (mA_{DC})	P_{OUT} (W)	P_{CAL} (W)	Efficiency (%)	Loss (W)	Regulation (%)
90	60	90.00	195.02	17.354	0.989	14.02	30.31	479	14.57	14.52	83.96	2.78	-4.22
100	60	99.97	175.41	17.260	0.984	16.92	30.29	480	14.60	14.55	84.59	2.66	-3.96
115	60	115.01	152.62	17.161	0.978	20.42	30.28	482	14.63	14.58	85.25	2.53	-3.70
132	60	132.03	133.52	17.121	0.971	23.39	30.28	484	14.69	14.64	85.80	2.43	-3.28
180	50	180.04	99.53	17.166	0.958	28.36	30.28	489	14.87	14.81	86.62	2.30	-2.20
230	50	230.14	77.57	16.896	0.947	30.36	30.25	482	14.64	14.58	86.65	2.26	-3.58
240	50	240.10	74.05	16.787	0.944	30.55	30.23	479	14.54	14.48	86.61	2.25	-4.18
265	50	265.12	66.52	16.530	0.937	30.99	30.19	472	14.30	14.24	86.51	2.23	-5.66

Table 3 – 10 LED Load Measurement Data.

9.8.2 115 VAC Dimming Test Data

	Input Measurement					Load Measurement			Calculation		
V_{DIM} (V_{DC})	V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN} (W)	PF	% ATHD	V_{OUT} (V_{DC})	I_{OUT} (mA_{DC})	P_{OUT} (W)	P_{CAL} (W)	Efficiency (%)	Loss (W)
10	115.02	140.35	15.77	0.977	20.8	27.38	492.00	13.52	13.47	85.74	2.25
9.5	115.02	140.24	15.76	0.977	20.8	27.36	492.00	13.51	13.46	85.74	2.25
9	115.03	111.41	12.42	0.969	24.7	26.93	391.00	10.57	10.53	85.12	1.85
8.5	115.04	86.62	9.60	0.964	26.6	26.50	304.00	8.07	8.06	84.05	1.53
8	115.04	67.20	7.42	0.959	27.5	26.07	232.20	6.06	6.05	81.73	1.36
7.5	115.05	36.64	4.09	0.971	17.2	25.22	118.50	2.99	2.99	73.05	1.10
7	115.05	27.70	3.07	0.964	14.7	24.80	80.60	2.00	2.00	65.10	1.07
6.5	115.05	23.20	2.55	0.956	13.1	24.50	59.60	1.46	1.46	57.23	1.09
6	115.05	19.85	2.16	0.944	12.8	24.18	41.50	1.00	1.00	46.57	1.15
5.5	115.06	18.13	1.95	0.934	12.8	23.95	30.90	0.74	0.74	38.04	1.21
5	115.05	16.70	1.78	0.924	12.9	23.68	20.82	0.49	0.49	27.77	1.28
4.5	115.06	15.86	1.67	0.917	12.9	23.44	14.11	0.33	0.33	19.78	1.34
4	115.06	15.11	1.58	0.909	13.2	23.11	7.41	0.17	0.17	10.82	1.41
3.5	115.06	14.49	1.50	0.902	13.4	22.56	2.15	0.05	0.05	3.23	1.46
3	115.06	13.94	1.44	0.895	13.6	21.34	0.18	0.00	0.00	0.26	1.43
2.5	115.06	13.36	1.36	0.886	14.0	19.26	0.02	0.00	0.00	0.02	1.36
2	115.06	13.28	1.35	0.885	13.9	18.33	0.01	0.00	0.00	0.01	1.35
1.5	115.06	13.30	1.35	0.886	13.8	17.43	0.005	0.00	0.00	0.01	1.35
1	115.06	13.29	1.35	0.886	13.8	16.65	0.003	0.00	0.00	0.00	1.35
0.5	115.06	13.30	1.36	0.886	13.7	16.39	0.003	0.00	0.00	0.00	1.36
0.1	115.06	13.29	1.35	0.886	13.7	16.38	0.003	0.00	0.00	0.00	1.35

Table 4 – 115 VAC, 60 Hz Dimming Measurements.

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9.8.3 230 VAC, 50 Hz Dimming Test Data

	Input Measurement					Load Measurement			Calculation		
V_{DIM} (V_{DC})	V_{IN} (V_{RMS})	I_{IN} (mA_{RMS})	P_{IN} (W)	PF	%ATHD	V_{OUT} (V_{DC})	I_{OUT} (mA_{DC})	P_{OUT} (W)	P_{CAL} (W)	Efficiency (%)	Loss (W)
10	230.14	71.13	15.46	0.944	30.6	27.38	488.00	13.43	13.36	86.87	2.03
9.5	230.14	71.09	15.45	0.944	30.6	27.36	488.00	13.42	13.35	86.86	2.03
9	230.14	59.15	12.77	0.938	31.0	27.01	405.00	10.99	10.94	86.05	1.78
8.5	230.14	45.22	9.64	0.926	31.0	26.51	305.00	8.11	8.09	84.13	1.53
8	230.14	39.95	8.47	0.921	30.1	26.29	264.90	6.98	6.96	82.46	1.49
7.5	230.15	26.76	5.49	0.892	24.2	25.57	163.60	4.19	4.18	76.28	1.30
7	230.15	22.72	4.53	0.867	21.9	25.32	126.40	3.20	3.20	70.61	1.33
6.5	230.15	20.38	3.95	0.843	21.0	25.09	103.30	2.59	2.59	65.52	1.36
6	230.15	18.51	3.48	0.816	20.7	24.86	82.90	2.06	2.06	59.25	1.42
5.5	230.15	17.30	3.16	0.795	20.9	24.67	68.40	1.69	1.69	53.41	1.47
5	230.15	16.45	2.94	0.777	21.3	24.52	57.10	1.40	1.40	47.64	1.54
4.5	230.14	15.79	2.77	0.762	21.7	24.36	47.70	1.16	1.16	41.96	1.61
4	230.13	15.24	2.62	0.748	22.1	24.19	38.90	0.94	0.94	35.87	1.68
3.5	230.13	14.83	2.52	0.737	22.6	24.05	32.10	0.77	0.77	30.67	1.75
3	230.13	14.41	2.41	0.726	23.2	23.84	24.47	0.58	0.58	24.26	1.82
2.5	230.13	14.07	2.32	0.717	23.8	23.63	17.92	0.42	0.42	18.28	1.90
2	230.14	13.78	2.25	0.708	24.3	23.39	11.97	0.28	0.28	12.47	1.97
1.5	230.14	13.56	2.19	0.701	24.8	23.10	6.90	0.16	0.16	7.32	2.03
1	230.14	13.41	2.15	0.696	25.1	22.75	3.21	0.07	0.07	3.40	2.08
0.5	230.14	13.38	2.14	0.695	25.2	22.31	1.11	0.02	0.02	1.16	2.12
0	230.14	13.34	2.13	0.694	25.2	21.60	0.26	0.01	0.01	0.26	2.12

Table 5 – 230 VAC, 50 Hz Dimming Measurements.

10 Waveforms

10.1 Input Line Current

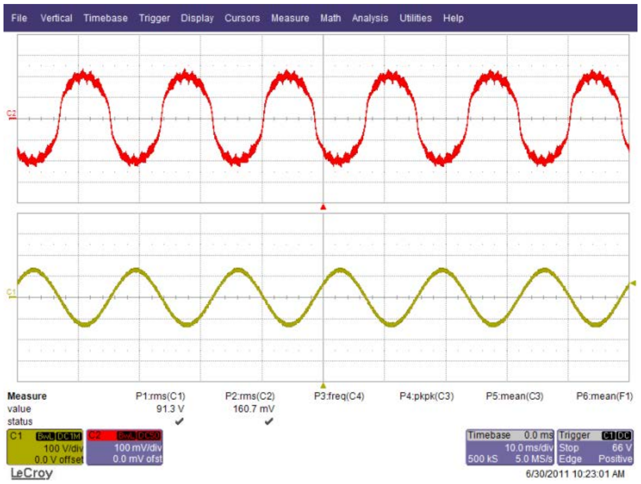

Figure 26 – 90 VAC 60 Hz, Full Load.
Upper: I_{IN}, 100 mA / div.
Lower: V_{IN}, 100 V, 10 ms / div.

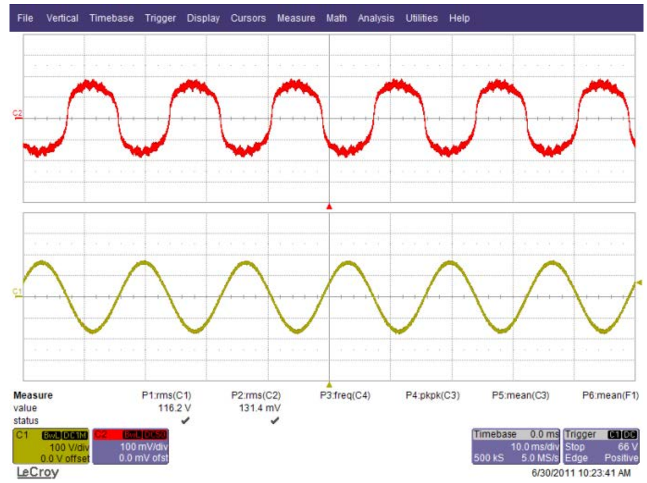

Figure 27 – 115 VAC 60 Hz, Full Load.
Upper: I_{IN}, 100 mA / div.
Lower: V_{IN}, 100 V, 10 ms / div.

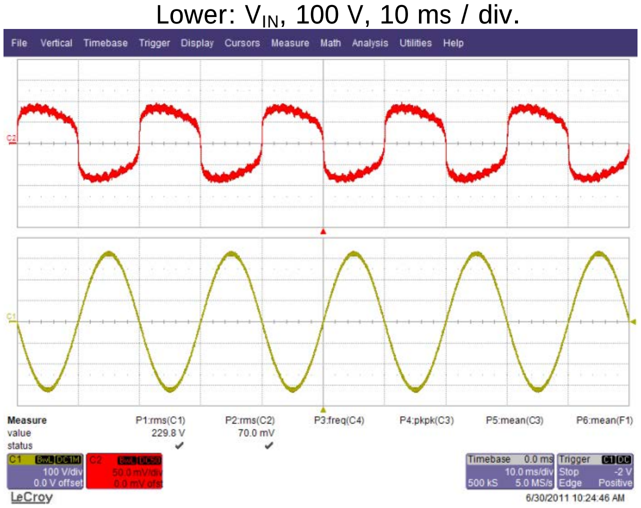

Figure 28 – 230 VAC 50 Hz, Full Load.
Upper: I_{IN}, 50 mA / div.
Lower: V_{IN}, 100 V, 10 ms / div.

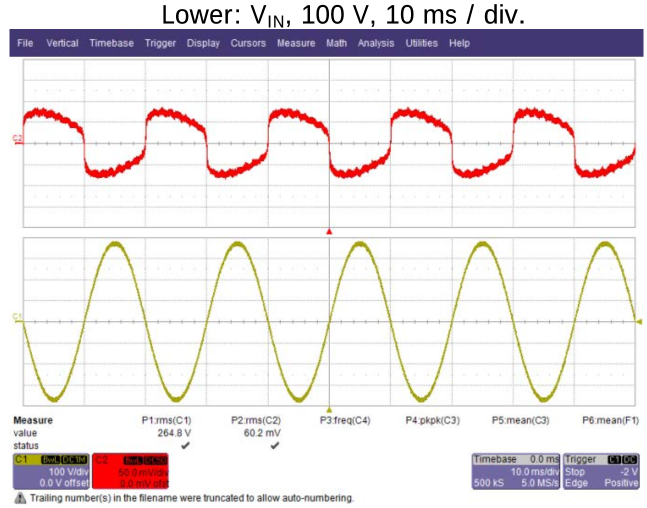

Figure 29 – 265 VAC 50 Hz, Full Load.
Upper: I_{IN}, 50 mA / div.
Lower: V_{IN}, 100 V, 10 ms / div.

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10.2 Drain Voltage and Current Normal Operation

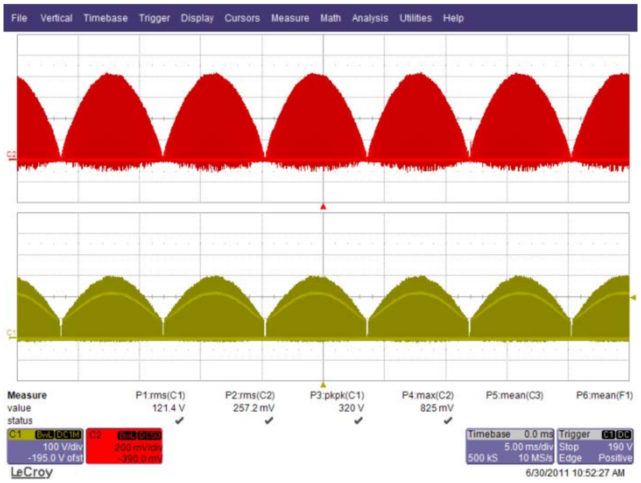

Figure 30 – 90 VAC 60 Hz, Full Load.
Upper: I_{DRAIN}, 200 mA / div.
Lower: V_{DRAIN}, 100 V, 5 ms / div.

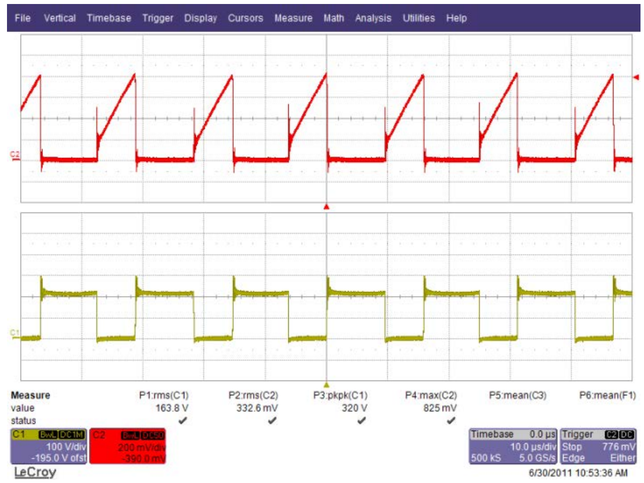

Figure 31 – 90 VAC 60 Hz, Full Load.
Upper: I_{DRAIN}, 200 mA / div.
Lower: V_{DRAIN}, 100 V, 5 μs / div.

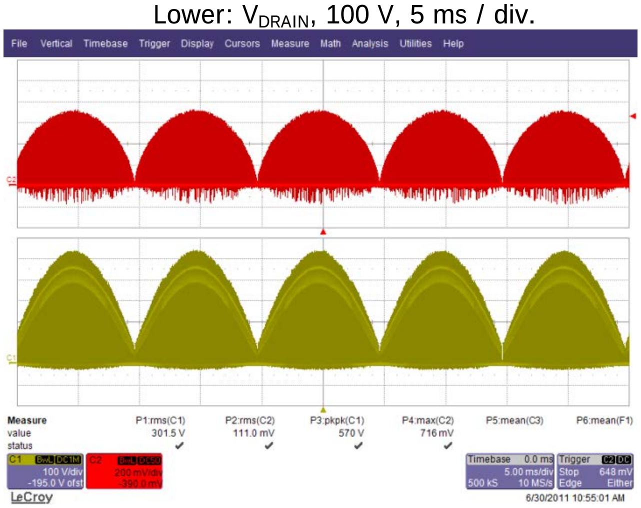

Figure 32 – 265 VAC 50 Hz, Full Load.
Upper: I_{DRAIN}, 200 mA / div.
Lower: V_{DRAIN}, 100 V, 5 ms / div.

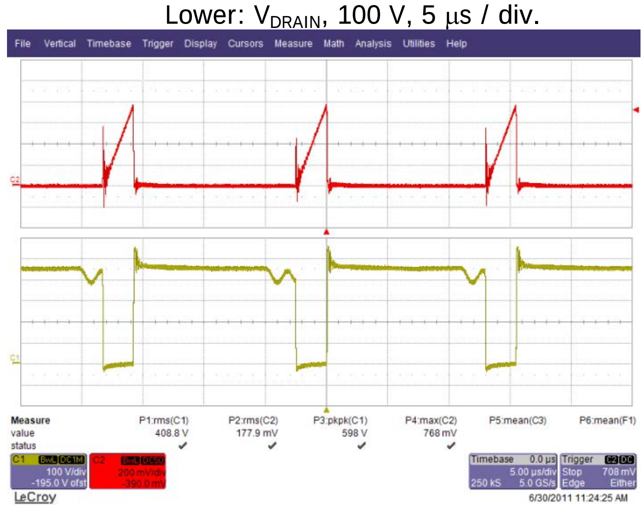

Figure 33 – 265 VAC 50 Hz, Full Load.
Upper: I_{DRAIN}, 200 mA / div.
Lower: V_{DRAIN}, 100 V, 5 μs / div.

10.3 Drain Voltage and Current Start-up Operation

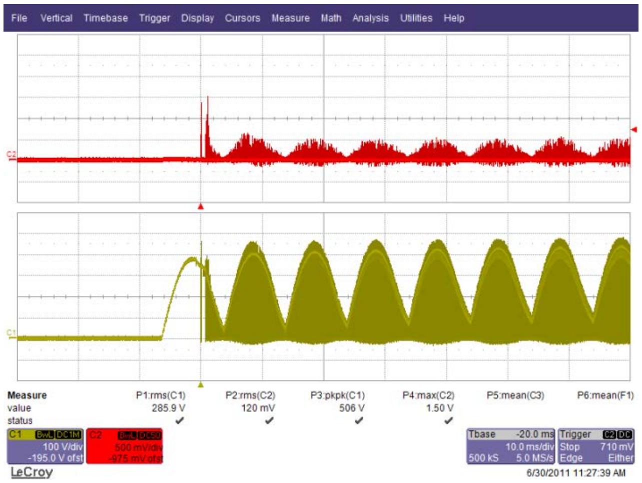

Figure 34 – 265 VAC 50 Hz, Full Load Start-Up.
Upper: I_{DRAIN}, 500 mA / div.
Lower: V_{DRAIN}, 100 V, 5 ms / div.

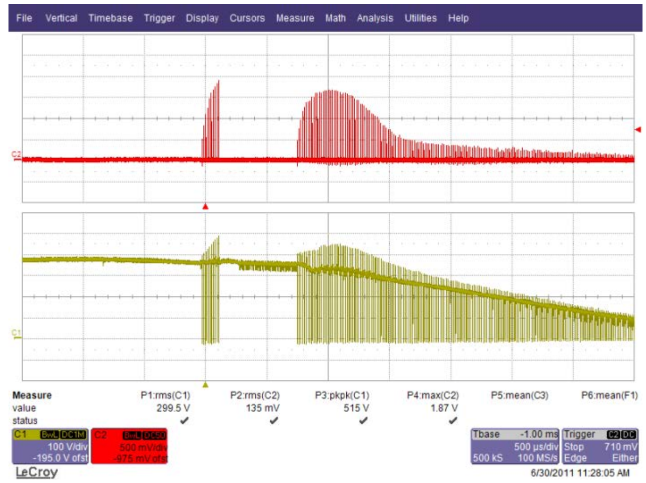

Figure 35 – 265 VAC 50 Hz, Full Load Start-Up.
Upper: I_{DRAIN}, 500 mA / div.
Lower: V_{DRAIN}, 100 V, 0.5 ms / div.

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10.4 Output Current and Output Voltage

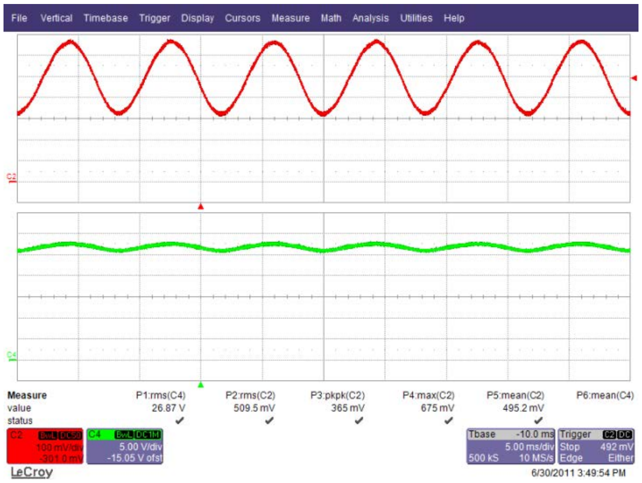

Figure 36 – 90 VAC 60 Hz, Full Load.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 5 ms / div.

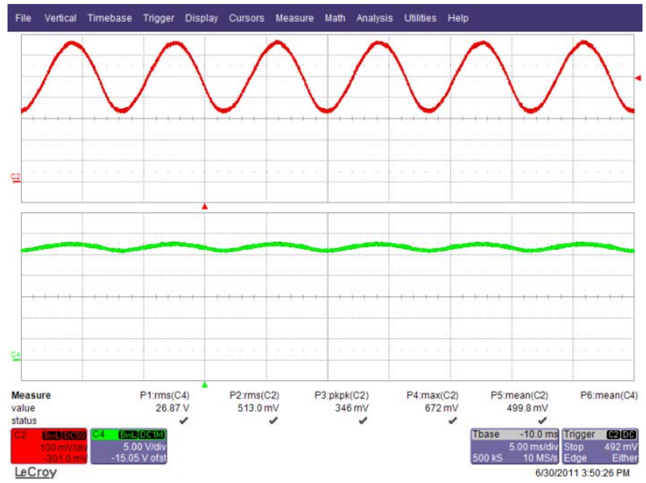

Figure 37 – 115 VAC 60 Hz, Full Load.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 5 ms / div.

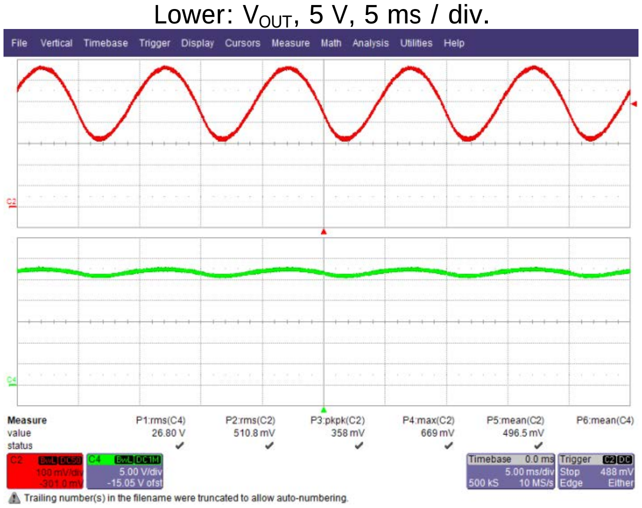

Figure 38 – 230 VAC 50 Hz, Full Load.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 5 ms / div.

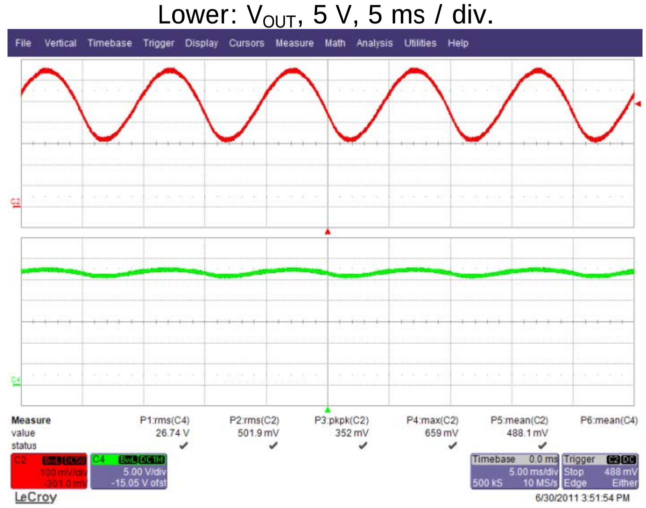

Figure 39 – 265 VAC 50 Hz, Full Load.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 10 V, 5 ms / div.

10.5 Output Current and Voltage at Power-up, Power-down

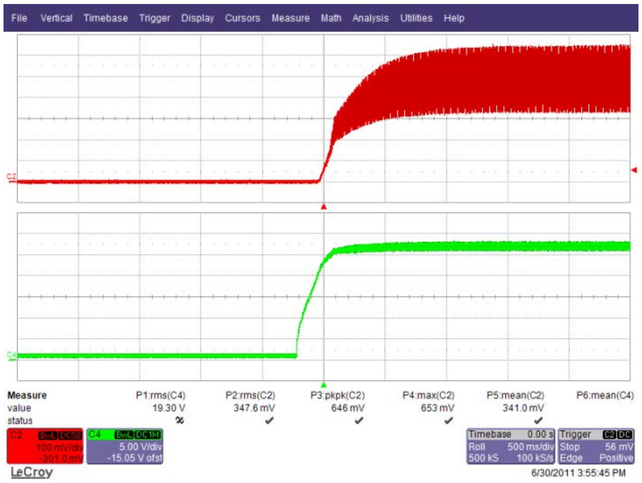

Figure 40 – 90 VAC 60 Hz, Output Rise.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 500 ms / div.

Figure 41 – 90 VAC 60 Hz, Output Fall.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 500 ms / div.

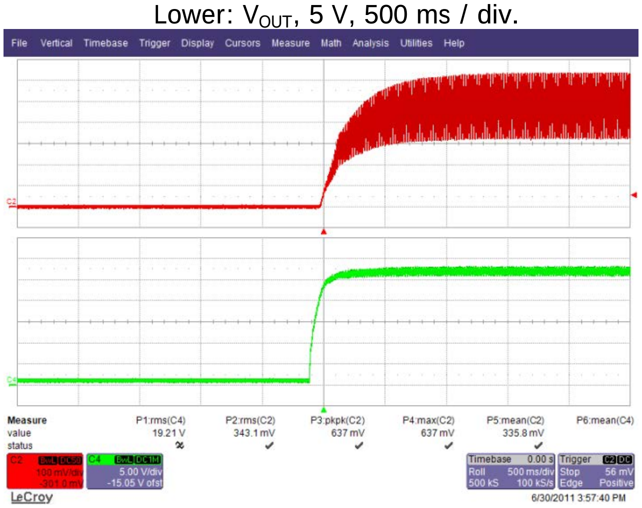

Figure 42 – 265 VAC 50 Hz, Output Rise.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 500 ms / div.

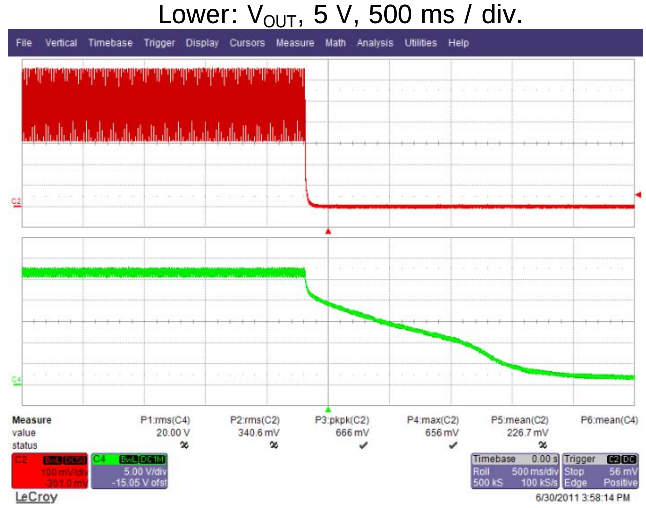

Figure 43 – 265 VAC 50 Hz, Output Fall.
Upper: I_{OUT}, 100 mA / div.
Lower: V_{OUT}, 5 V, 500 ms / div.

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10.6 Output Short

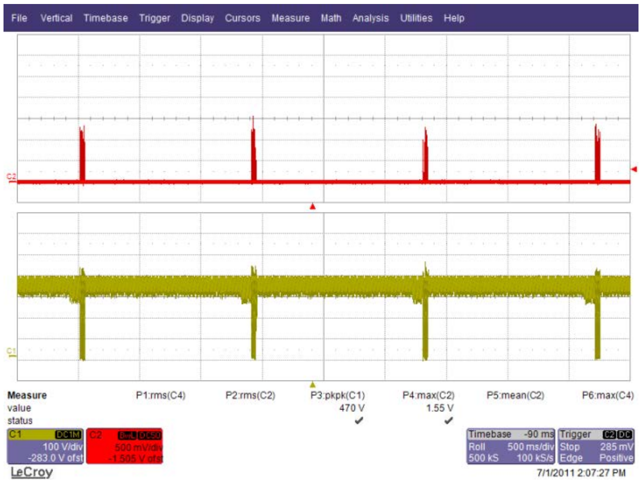

Figure 44 – 265 VAC 60 Hz, Output Short.
Upper: I_{DRAIN}, 500 mA / div.
Lower: V_{DRAIN}, 100 V, 500 ms / div.

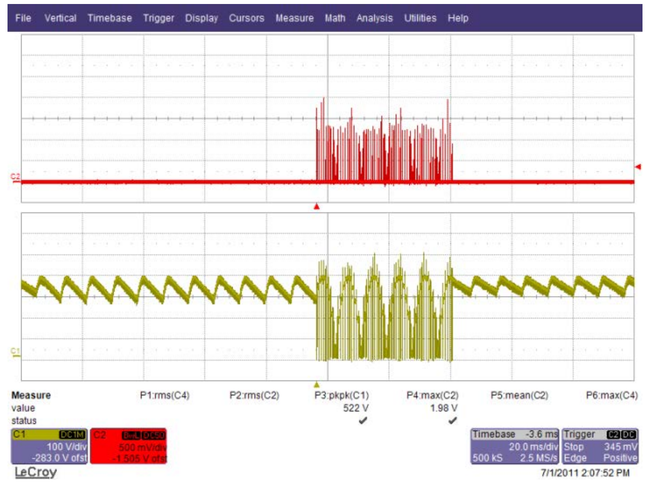

Figure 45 – 265 VAC 60 Hz, Output Short.
Upper: I_{DRAIN}, 500 mA / div.
Lower: V_{DRAIN}, 100 V, 20 ms / div.

10.7 Open Load/LED Condition

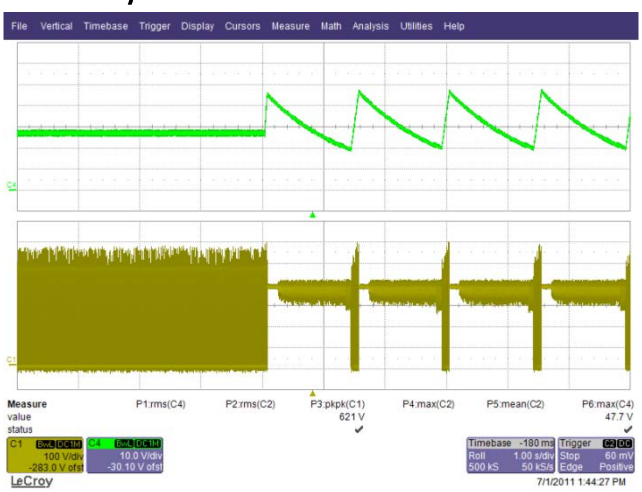

Figure 46 – 265 VAC 60 Hz, Open Load.
CH1: V_{DRAIN}, 100 V / div.
CH4: V_{OUT}, 10 V, 1 s / div.

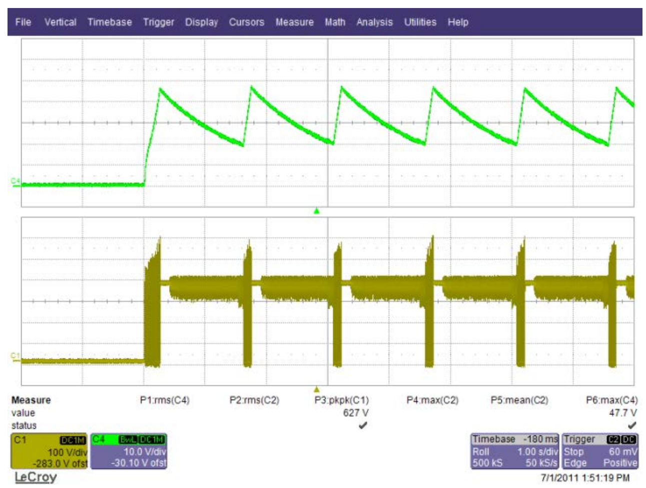

Figure 47 – 265 VAC 60 Hz, Open Load Start-Up.
CH1: V_{DRAIN}, 100 V / div.
CH4: V_{OUT}, 10 V, 1 s / div.

11 Thermals

The following measurements were taken at room temperature and using 9 LED Load, approximately 14 W output power.

11.1 115 VAC Thermal Measurements

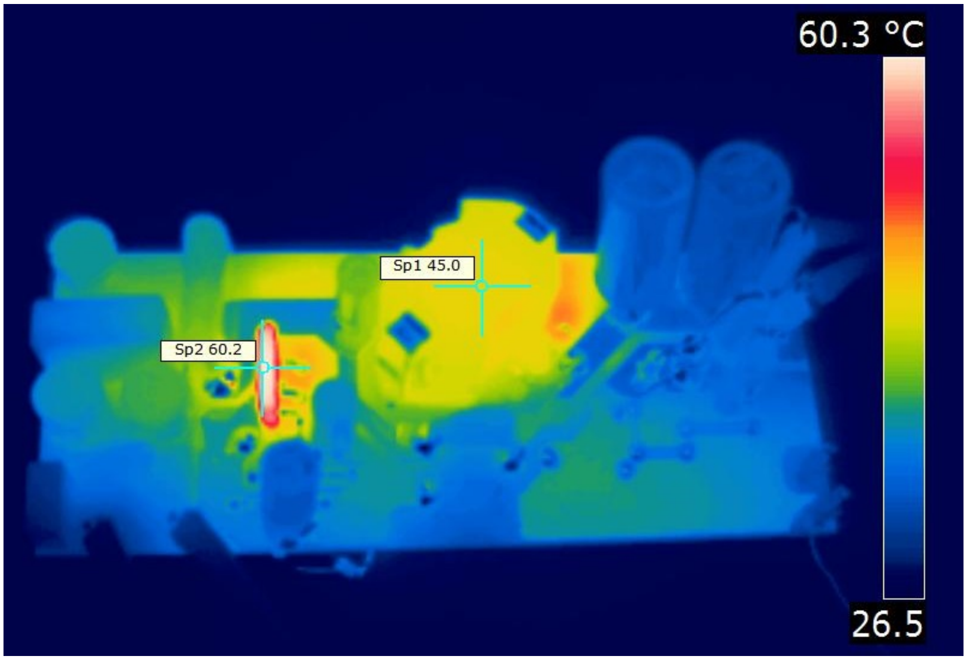

Figure 48 – 115 VAC, 60 Hz Top-Side Thermal Image.

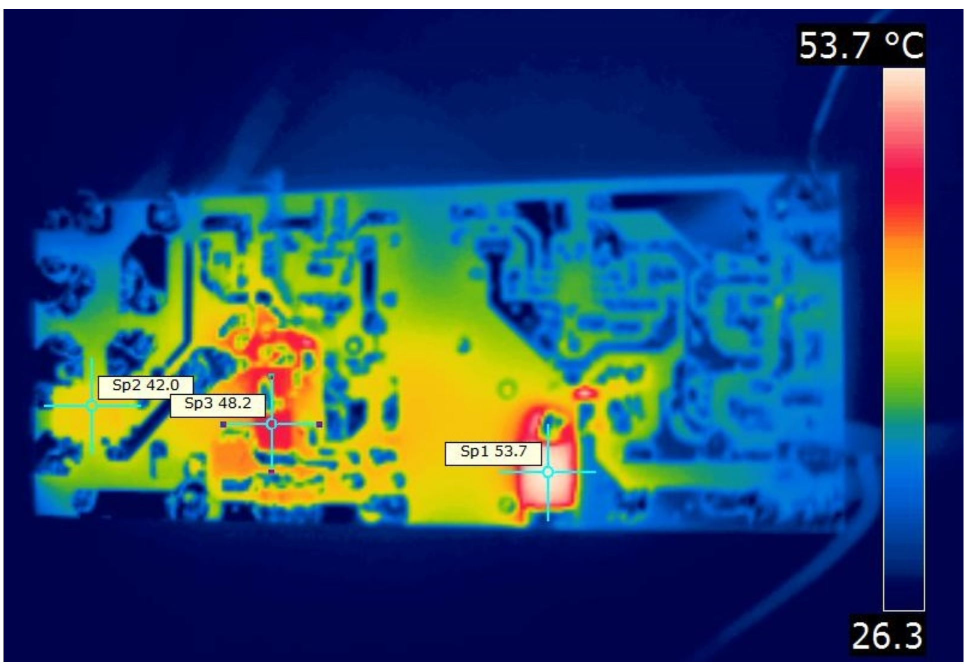

Figure 49 – 115 VAC, 60 Hz Bottom-Side Thermal Image.

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11.2 230 VAC Thermal Measurements

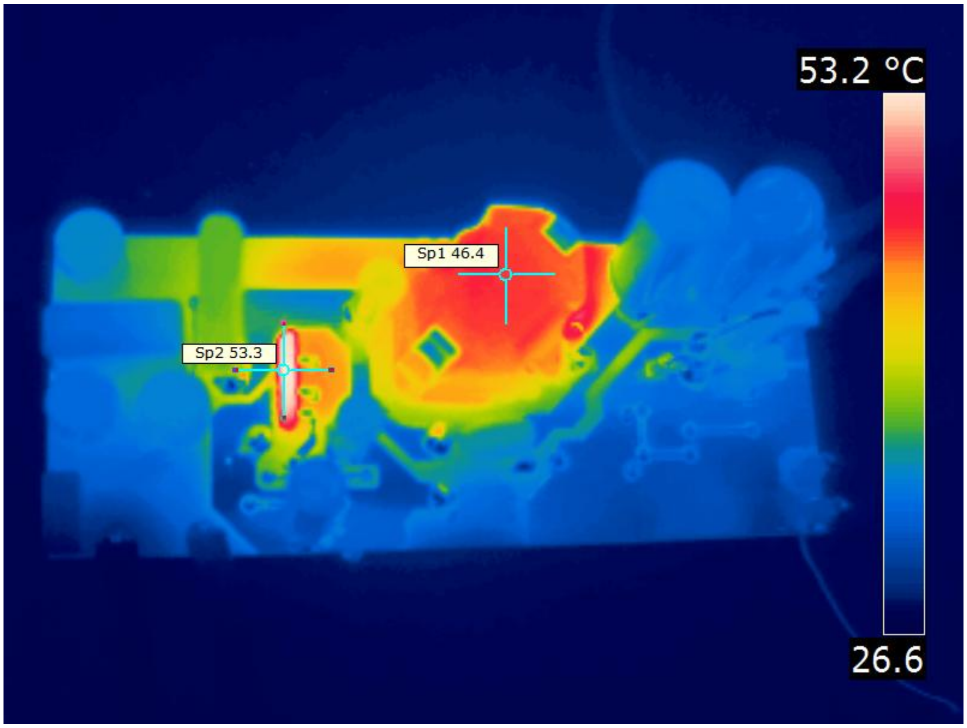


Figure 50 – 230 VAC, 50 Hz Top-Side Thermal Image.

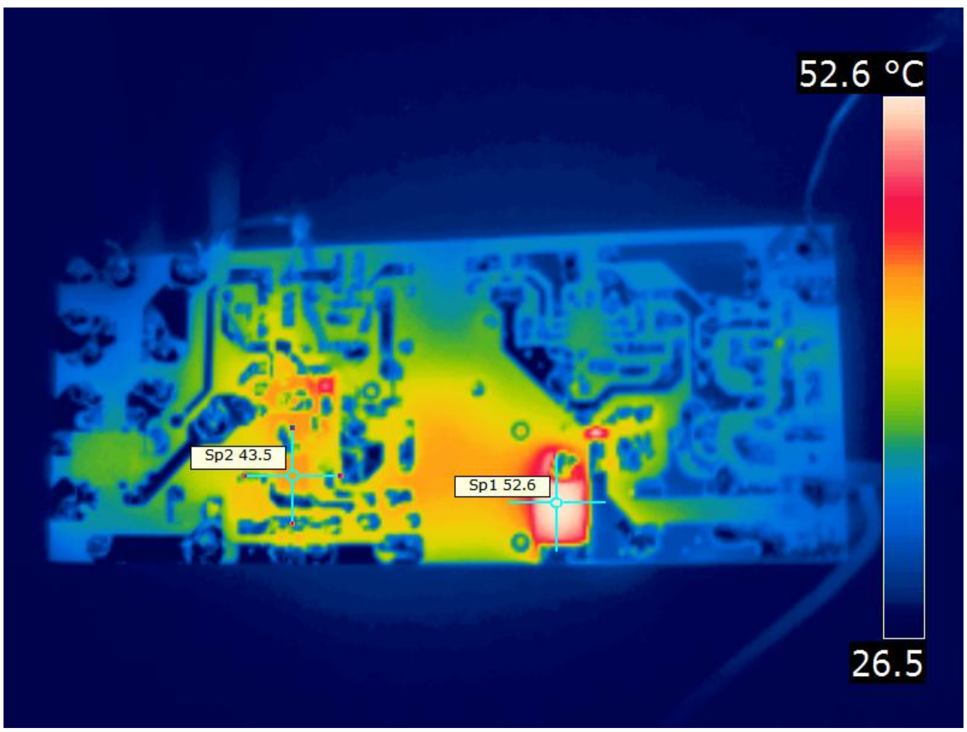


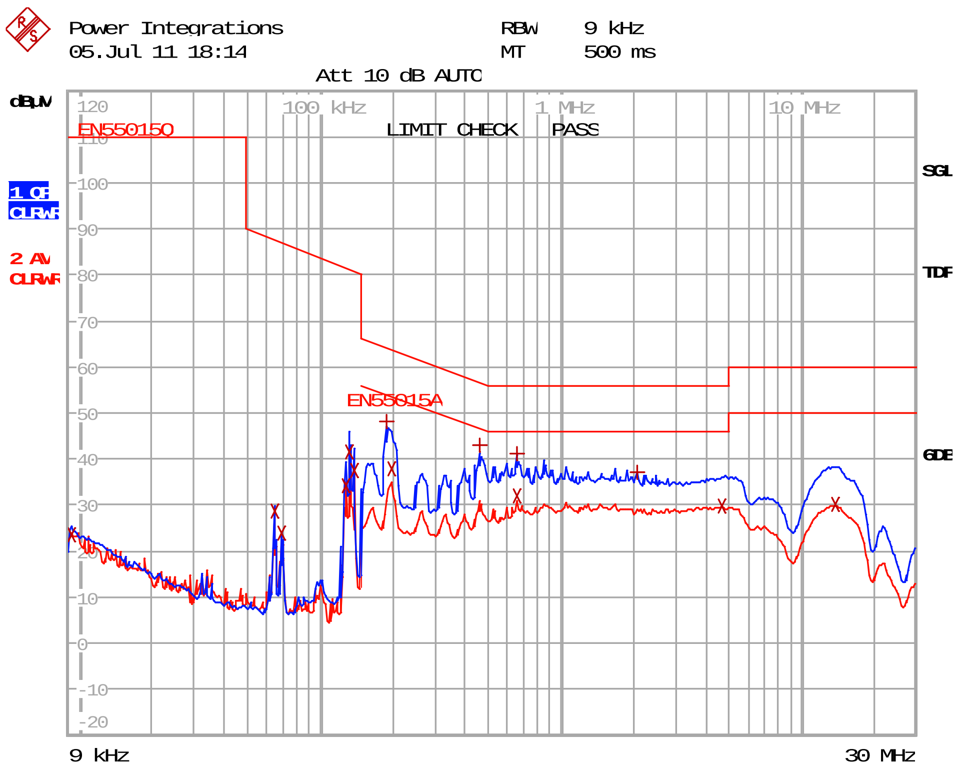
Figure 51 – 230 VAC, 50 Hz Bottom-Side Thermal Image.

12 Conducted EMI

12.1 Conducted EMI Test Setup

The unit was tested using 9 strings of LED load (~27 V V_{OUT}) with input voltage of 115 VAC and 230 VAC, 60 Hz line frequency, and at room temperature.

12.2 115 VAC, 60 Hz Conducted EMI Measurements



EDIT PEAK LIST (Final Measurement Results)

Trace1: EN55015Q
Trace2: EN55015A
Trace3: ---

TRACE		FREQUENCY	LEVEL dBµV		DELTA LIMIT dB
2	Average	9.272709 kHz	23.37	L1 gnd	
2	Average	64.5467705779 kHz	28.51	N gnd	
2	Average	69.2028746009 kHz	23.93	N gnd	
2	Average	128.247618558 kHz	34.25	L1 gnd	
2	Average	132.133649648 kHz	41.61	N gnd	
2	Average	137.49880568 kHz	37.36	N gnd	
1	Quasi Peak	188.574452752 kHz	48.31	N gnd	-15.78
2	Average	196.231331718 kHz	37.93	N gnd	-15.83
1	Quasi Peak	461.749566613 kHz	42.88	N gnd	-13.77
1	Quasi Peak	660.656865747 kHz	41.27	N gnd	-14.72
2	Average	660.656865747 kHz	31.96	N gnd	-14.03
1	Quasi Peak	2.0745979178 MHz	37.12	N gnd	-18.87
2	Average	4.6912285087 MHz	29.73	L1 gnd	-16.26
2	Average	13.8776627802 MHz	30.17	N gnd	-19.82

Figure 52 – Conducted EMI, 9 LED Load, 115 VAC, 60 Hz, EN55015B Limits.

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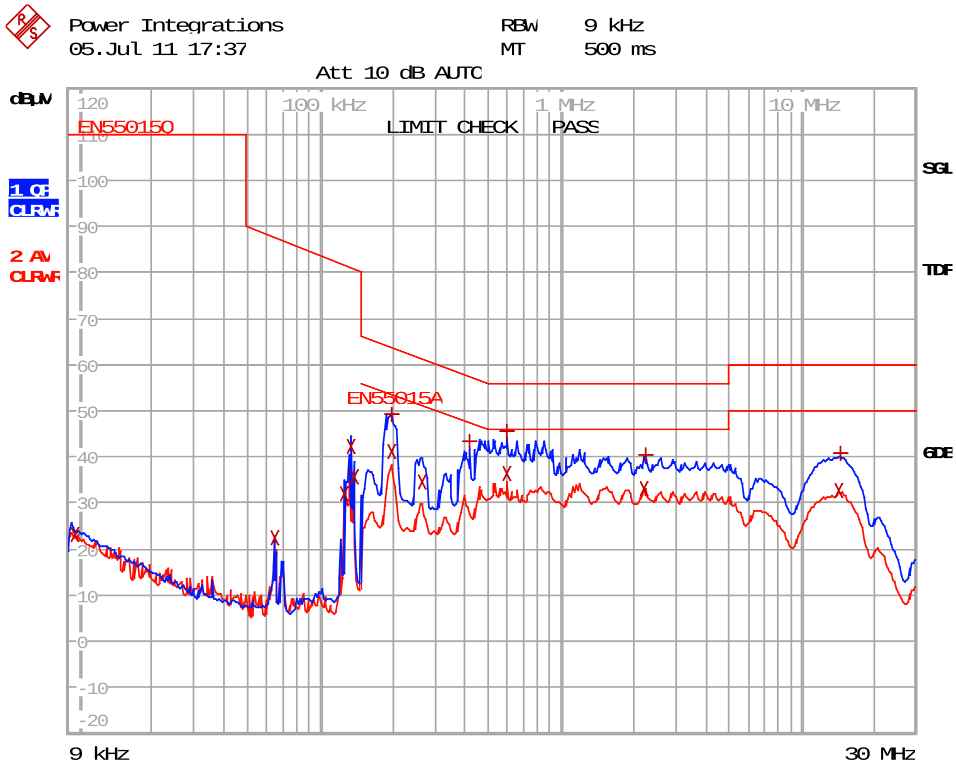
12.3 230 VAC, 60 Hz Conducted EMI Measurements



EDIT PEAK LIST (Final Measurement Results)

Trace1: EN55015Q
Trace2: EN55015A
Trace3: ---

TRACE		FREQUENCY	LEVEL dBµV		DELTA LIMIT dB
2	Average	9.55368135541 kHz	23.19	N gnd	
2	Average	64.5467705779 kHz	22.45	N gnd	
2	Average	125.720633819 kHz	32.07	N gnd	
2	Average	133.454986145 kHz	42.46	N gnd	
2	Average	138.873793737 kHz	35.70	N gnd	
1	Quasi Peak	198.193645035 kHz	49.21	L1 gnd	-14.46
2	Average	198.193645035 kHz	41.03	N gnd	-12.64
2	Average	264.49018761 kHz	34.51	N gnd	-16.77
1	Quasi Peak	418.01585899 kHz	43.42	N gnd	-14.06
1	Quasi Peak	592.16241791 kHz	45.66	N gnd	-10.33
2	Average	592.16241791 kHz	36.50	N gnd	-9.49
2	Average	2.20222749414 MHz	32.99	L1 gnd	-13.00
1	Quasi Peak	2.26895718944 MHz	40.28	L1 gnd	-15.71
2	Average	14.2981698401 MHz	32.64	N gnd	-17.35
1	Quasi Peak	14.5855630539 MHz	40.94	N gnd	-19.05

Figure 53 – Conducted EMI, 9 LED Load, 230 VAC, 60 Hz, EN55015B Limits.

13 Revision History

Date	Author	Revision	Description and Changes	Reviewed
09-Sep-11	CA	1.0	Initial Release	Apps & Mktg
17-Nov-11	KM	1.1	Updated Harmonics text on page 6 and 28	
09-May-12	KM	1.2	Updated Figure 7	
16-Oct-12	KM	1.3	Updated Power Supply Specification	
23-Jun-12	KM	1.4	Updated Brand Style and Added Transformer Supplier	

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