56W Off-line, 120VAC with PFC, 160V, 350mA Load, Dimmer Switch Compatible LED Driver

Specifications	
AC line voltage	100 - 135VAC
LED (string) voltage	20 – 160V
LED current	350mA
Switching frequency	63kHz - @ V_{OUT} = 160VDC
	92kHz - @ V_{OUT} = 20VDC
Efficiency*	> 88 % - @ V_{OUT} = 160VDC
Open circuit protection	Latches off @ V_{OUT} = 180VDC
Other protections	See text
AC line undervoltage	AC line and output power fall off gradually below 100 VAC
Dimmer switch compatibility	Yes
THD*	~12% - @ V_{OUT} = 160VDC
Power Factor*	>98% - @ V_{OUT} = 160VDC

NOTE:
** Measurements taken with the damper switch bypassed. Expect a slight degradation in efficiency, THD, etc, when the damper switch is enabled.*

General Description

This Design Note describes the results of a 56W LED Driver Design. The driver allows smooth dimming of the LED light when the driver is connected to a regular (TRIAC based) dimmer switch.

This design drives a string of series connected LEDs with a fixed current of 350mA and a string voltage of 160V max. This same design can be operated at a lower string voltages as well, with slight loss of efficiency or degradation of AC line current THD, see the performance graphs.

Efficiency can be increased by using components having less equivalent resistance, particularly L1, L2 and M1, and by lowering of the switching frequency. All the common tradeoffs in power supply design, that is, cost versus size versus efficiency, apply to this driver design as well.

The input line current features low harmonic distortion, satisfying the requirements of EN 61000-3-2 Class C (Lighting Equipment). The driver is able to maintain very good line regulation for an AC input voltage ranging between 90 and 140VAC. Below 90VAC, input power and output power fall gradually as AC line voltage falls.

Topology

The design is an example of the Bibred topology, specifically geared to LED driving. The HV9931 is suited for driving the Buck-Boost-Buck (BBB) topology, described in detail in AN-H52, and the Bibred Topology, as shown in this design note. The BBB serves applications needing large voltage step-down ratio, whereas the Bibred serves applications with modest step-down ratio.

Common to both topologies is operation of the input stage in discontinuous conduction mode (DCM) and operation of the output stage in continuous conduction mode (CCM). In both cases, The output stage is configured as a buck stage, which is supplied from a bulk energy storage capacitor, sufficiently large to provide a more or less constant supply voltage when considered over a AC line cycle. Constant supply voltage entails a constant switch duty cycle when supplying the LED load. Without entering in more detail, both the DCM input stages of the BBB and the Bibred respond with a more or less sinusoidal AC line input current when driven from a switch operating at constant duty cycle.

Dimmer Switch Compatibility

The following links provide helpful information regarding the regular domestic dimmer switch:

http://home.howstuffworks.com/dimmer-switch.htm

http://www.epanorama.net/documents/lights/light-dimmer.html.

The driver design contains two extra circuits to provide dimmer switch compatibility: a damper circuit and a bleeder circuit.

The damper circuit provides damped charging of the driver's input filter circuit. Resistive damping is required to prevent AC line input current oscillations, due to the sudden rise of the AC line voltage when the dimmer switch TRIAC comes into conduction. The damper circuit contains two major components, (1) a damper resistor (R81), and (2) a MOSFET (M81) for purpose of bypassing R81 shortly after charging of the EMI filter capacitors is accomplished, thus carrying the AC line current for the remainder of the AC line half-cycle, without major power loss.

The bleeder circuit provides a nominal 1.0kΩ load to the rectified AC line to suppress a voltage rise at the input capacitors C21 thru C23 when the TRIAC in the light dimmer is off. A typical dimmer switch contains an EMI suppression capacitor, in the 10 to 100nF range, which is located in parallel to the TRIAC, thereby allowing significant current to flow to the input capacitors. When the voltage rises above the undervoltage threshold of the HV9931, several switching cycles may occur, causing the flow of output current, which will be perceived as flicker. The bleeder circuit removes the 1kΩ loading when the rectified line voltage exceeds about 12V in order to suppress power dissipation in the 1kΩ bleeder resistor when the TRIAC is on.

Protection Circuits

A number of circuits can be added to the basic LED driver circuit to provide protection against:

- Output Overvoltage
- Output Short Circuit
- AC line Overvoltage
- Bulk Capacitor Overvoltage

The driver design provides latching shut-off protection against overvoltage, which may occur in the open load condition. The need for other protection circuits depends on the intended use of the driver.

Overvoltage Protection

The overvoltage protection circuit provides latch-off protection. Overvoltage at the output causes conduction of the zener diodes Z71 and Z72, thereby triggering the two-transistor thyristor structure, which disables the HV9931 by pulling the PWM pin low. An alternative implementation of the discrete two-transistor structure is the use of a true thyristor device or a dual transistor device (MMDT2227).

Protection circuits that do not provide latch-off should be avoided since the existence of any switching cycles, when no output loading is present, will cause sustained accumulation of energy on the bulk capacitor E31. The build-up of energy may raise the capacitor voltage to a destructive level. The high valued bleeder resistors R31 and R32 only serve the purpose of discharging E31 following a complete turn-off, in order to provide touch-safety given some delay (RC time constant = 44s).

Output Short Circuit Protection

The output current is well regulated, except for very low output voltages; below a VOUT of about 10V control is gradually lost, and current may rise to about 600mA at about 2V (see performance graph). Further lowering of the output voltage will cause the voltage on E31 to rise to a dangerous level as output loading is barely present.
Note that the HV9931 can not reduce duty-cycle to an arbitrarily low level; leading edge blanking sets a lower limit to the duty-cycle. Operation at minimum duty-cycle causes a certain amount of power to flow which such be drained by the load or other circuitry, or should lead to a shut-off of the driver.

Short circuit protection can be added by monitoring the output current at R71, and providing a latched shut-off similar to the one provided for output overvoltage protection.

AC Line Overvoltage

AC line overvoltage protection can be attained in a manner very similar to output voltage protection. In this case non-latching protection may be preferred, so as to avoid nuisance shut-down due to short-lived transients. A zener diode, transistor combination, which can pull down the PWM pin, is all that is required.

Bulk Capacitor Overvoltage Protection

As mentioned under overvoltage protection, a non latch-off protection scheme may allow sustained energy accumulation on the bulk capacitor.
Non latch-off protection requires active monitoring/limiting of the bulk capacitor voltage, which represents a significant amount of circuitry, and may not be worth the added expense. An alternate method is to provide output loading in the form of a zener diode clamp placed across the bulk capacitor or the output circuit.

Miscellaneous Notes

EMI, Common Mode Filtering

The magnitude and frequency dependency of the common mode conducted interference current depends heavily on physical layout, actual component choice, component orientation, location of the LED driver circuit with respect to the LED load and enclosure, and many other factors. As such the design may or may not require the addition of the common mode choke ahead of the bridge rectifier.

VDD and the VDD Capacitor

The capacitor on the VDD pin (C51) is purposely chosen to be small, 220nF, so that the HV9931 shuts off near the zero-crossing of the AC line voltage.

This behavior is desired in a dimmer switch compatible design. Without this provision, the HV9931 will keep switching when the TRIAC is off, sustained by the energy stored on a large VDD capacitor, thereby losing the dimming effect and depleting the energy stored in the electrolytic capacitor needed for operation as a dimmable driver.

LED Current at Zero Crossing

With a small VDD capacitor, the LED current drops out near the zero-crossing due to the HV9931 V_{DD} voltage dropping out.

The LED current drop-out causes a small drop in the average LED current, which shows up as line regulation error. Drop-out increases as AC line voltage drops.

Note that if dimmer switch compatibility is not desired, than the VDD capacitor can made large, say 10µF, which prevents this drop-out from occurring.

Efficiency, THD, PF Measurements

Measurements of efficiency, power factor and harmonic distortion were taken with the damper circuit removed and a large VDD capacitor (10µF), in order to provide the best numbers possible for this design.

The addition of the damper circuit (Dimmer switch compatible design) does not have any major effect on the measurement results, since the damper circuit primarily affects operation during the zero-crossings only, where little if any AC current flows. The effect of the on-resistance of the bypass switch can be accounted for in a straightforward manner in efficiency calculations.

CS1 Programming

Control of M1 should, under regular circumstances, be governed by the action of comparator CS2, which provides regulation of the LED current. CS1 should regulate only if limitation of input stage current is necessary, which may be the case during start-up, during AC line undervoltage and during certain transient conditions. The programming of the CS1 comparator should present an envelope for the input stage current, which prevents CS1 from interfering with the regulation of the output current under normal operating conditions. A simple DC threshold, set at, say, 120% of the maximum current at normal operating conditions, will suffice. This design employs a somewhat more sophisticated envelope for the purpose of limiting the AC line current when undervoltage occurs. The threshold is a scaled version of the input voltage, thus reducing the input current envelope as input voltage reduces. By proper choice of values, CS1 will thus become active for input voltages lower than 80VAC, thus programming an approximately sinusoidal current waveform. For line voltages larger than 80V, this scaled threshold is limited to a DC threshold of fixed value.

Inductors L1 and L2

An effort was made to select low-cost off-the-shelf inductors for this design. A more compact design having higher efficiency can be accommodated by the use of custom inductors.

A major disadvantage of the drum core inductors in this design is their large ambient field. Particularly the AC field of L1 may cause large eddy current losses in nearby conductive elements, such as copper planes, heatsinks, capacitor foils, etc., and may also cause modification of control signals on the board.

Mounting L1 about 2 inches away from the board decreased losses by about 1.75W, corresponding to a rise in efficiency from 85.8% to 88.1%. Furthermore, the setpoint value of output current shifted by about 10mA.

EMI Filter

The EMI filter should be considered a best effort approach, given the uncertainty regarding the final environment, layout and choice of components. The EMI characteristics of individual components, pcb layout techniques and many other factors affect to what extent low and high frequency energy couple to the AC terminals of the driver.

Particularly the unshielded inductors L1 and L2, should be kept well away from the inductors and the traces of the EMI filter in order to avoid magnetic (transformer) coupling.

Capacitive coupling between traces, heatsinks, etc may have a significant effect on circuit operation and EMI performance as well.

Dimmable vs Non-dimmable Setup

Note that certain measurements are taken with a non-dimmable version of the driver design. The design is turned into the non-dimmable version by bypassing the damper circuit (add of a wire jumper between test points P15 and P61), and by increasing the VDD capacitor C51 from 220nF to 10µF.

It goes without saying that the non-dimmable version is not to be used on a AC line circuit with attached dimmer switch.

No damage but substantial flicker will result.

Measurement Techniques

A number of voltages of interest, such as the AC line voltage waveform, the voltage on the bulk energy storage capacitor VE31, were taken with the aid of a differential voltage probe. Regular oscilloscope probes, i.e. with grounding clips, which are non-isolated from safety ground, may affect circuit behavior adversely, particularly when dimming, even if the rest of the experimental setup is isolated from safety ground by isolation transformers and the like. Regular probes should be used with caution.

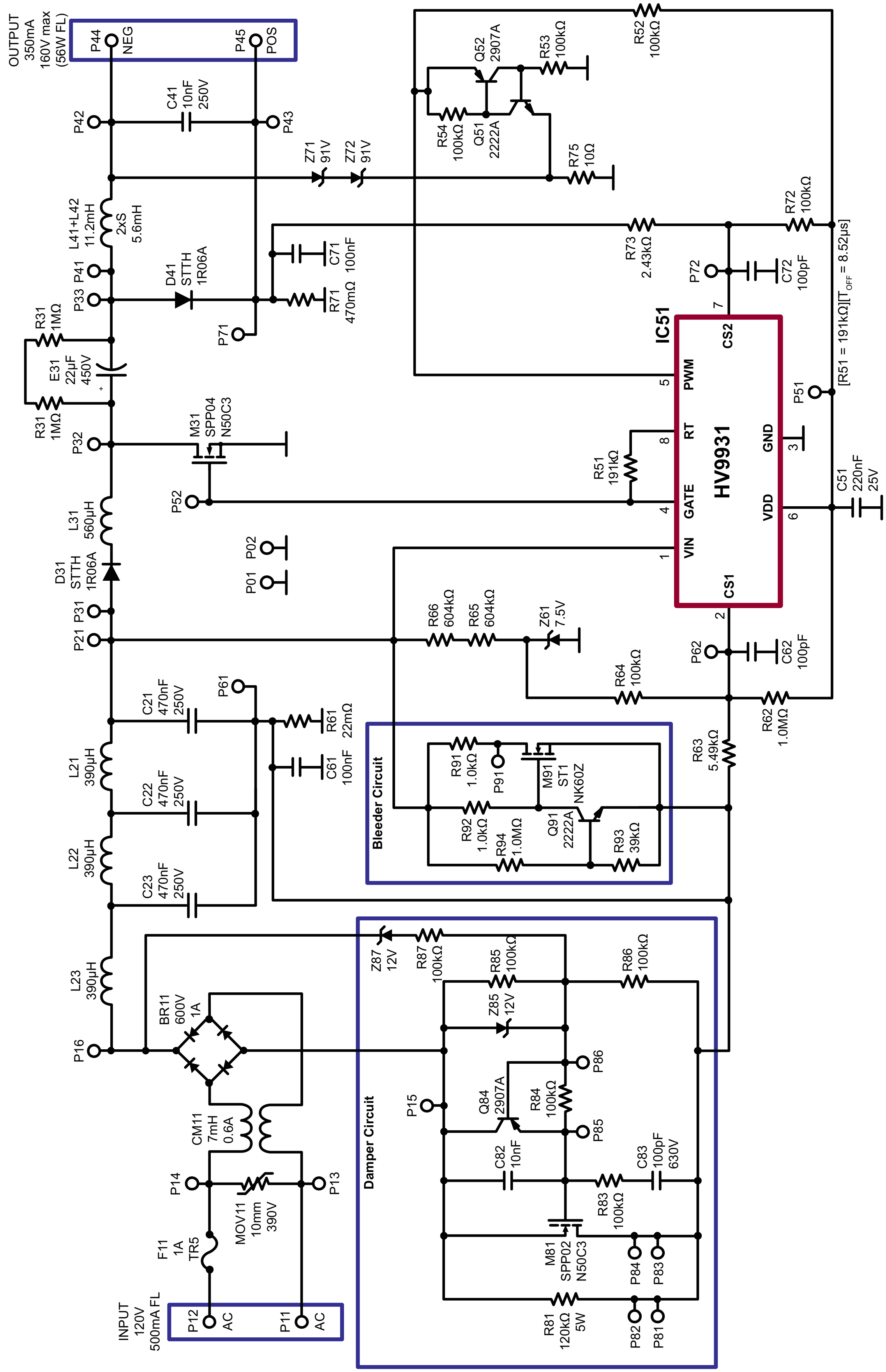
Current waveforms were generally taken with active current probes. The schematic shows in a number of places a pair of adjoining testpoints for purpose of breaking the trace and inserting a wire loop.

I_{OUT} Regulation versus Output Voltage

Note that output current increases with decreasing output voltage, see performance graph. Output rises from 350mA to 450mA, when the output voltage drops from 160V to 10V, a difference of about 100mA.

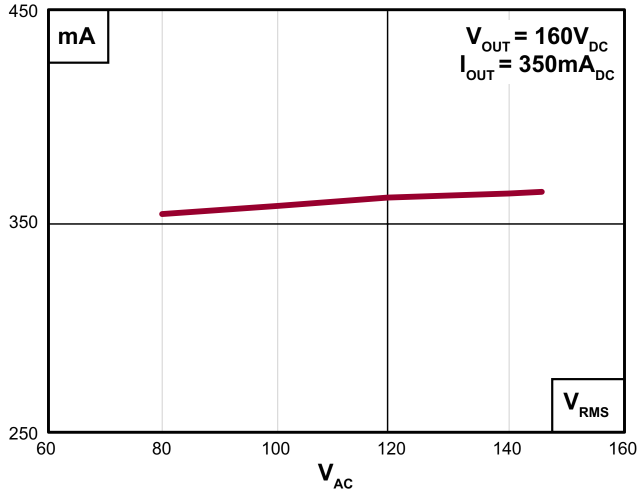
This result is inherent to the control scheme in use: peak current control. Although it is desired to regulate the average LED current to a fixed value, peak current control is preferred due to its lower cost. The resulting peak to average error is a function of the output voltage, which can be compensated for with additional circuitry.

Schematic Diagram

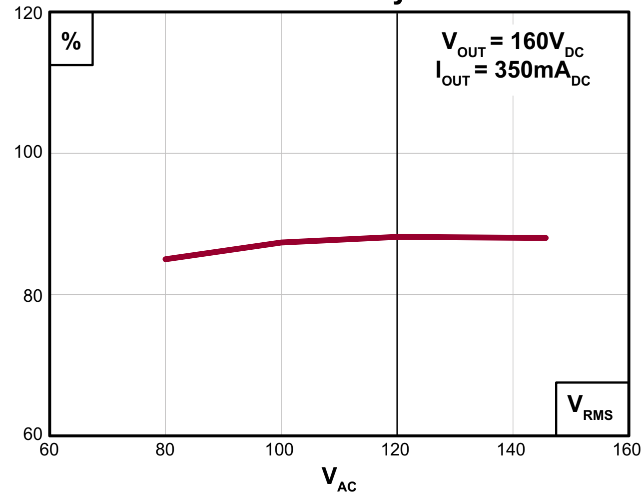


Performance Graphs, AC Line Voltage

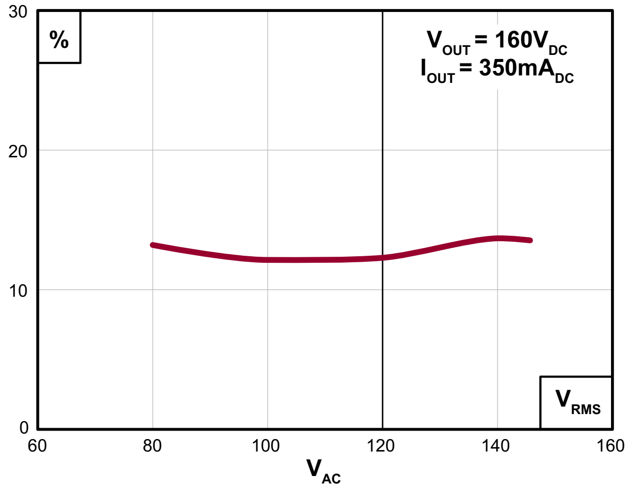
I_{OUT} (Line Regulation)



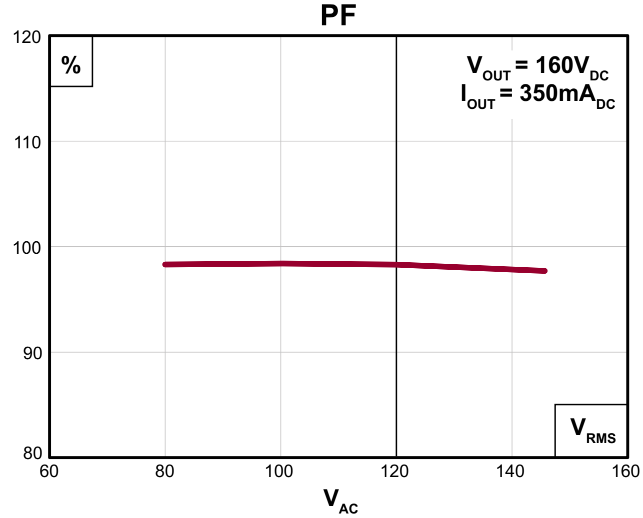
Efficiency



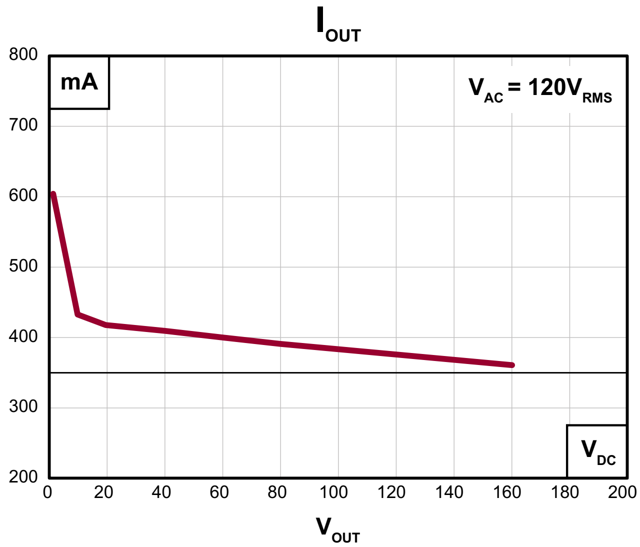
THD

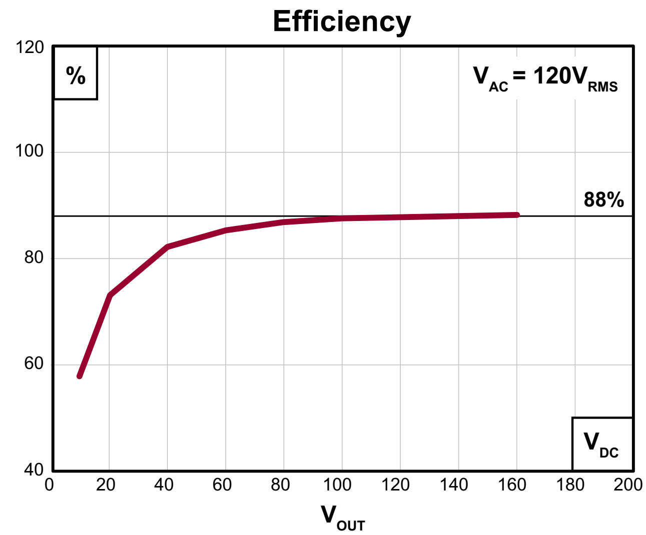


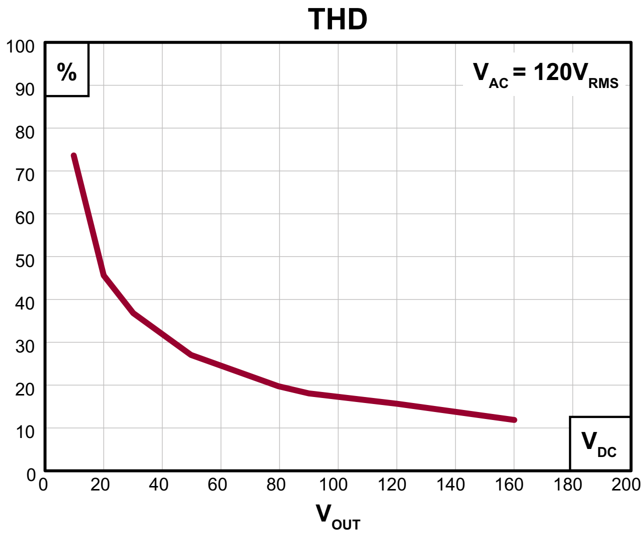
PF

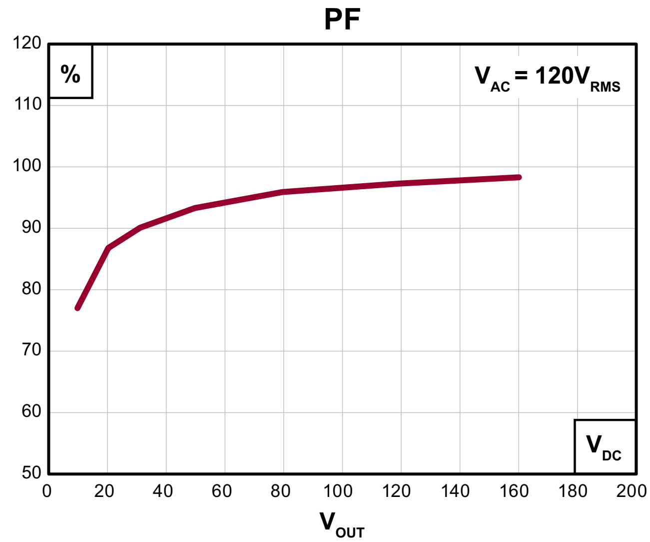


Performance Graphs, Output Voltage

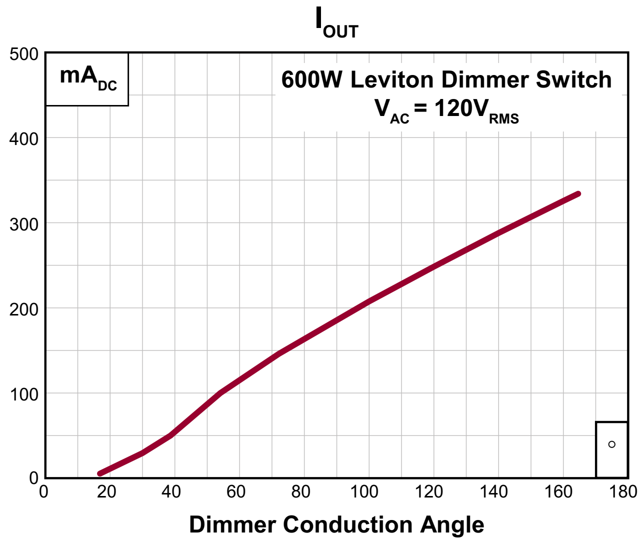




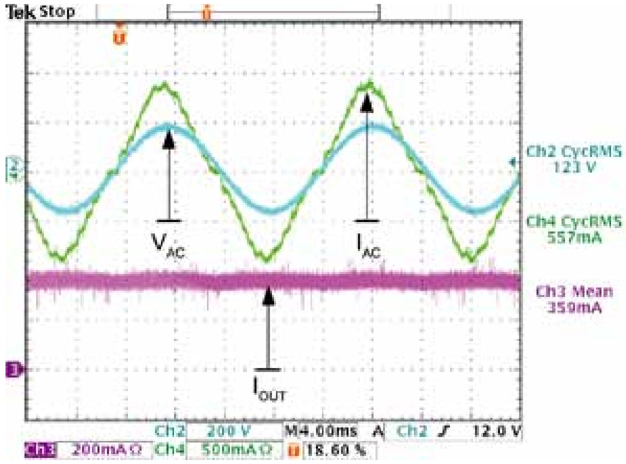




Performance Graph, Dimmer Switch Controlled

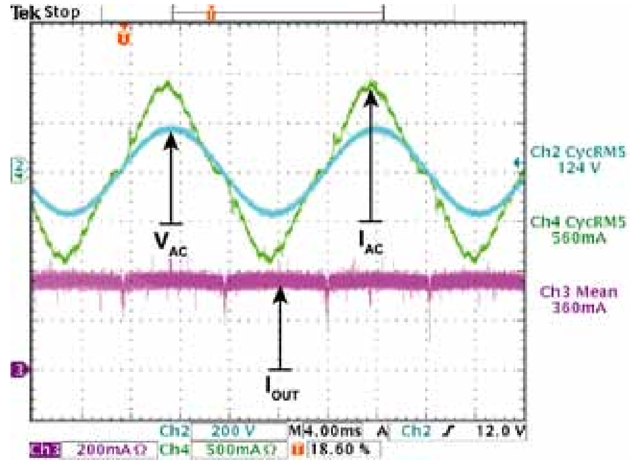


V_{AC}, I_{AC}, I_{OUT} (1/8) non-dimmable, $120V_{AC}$



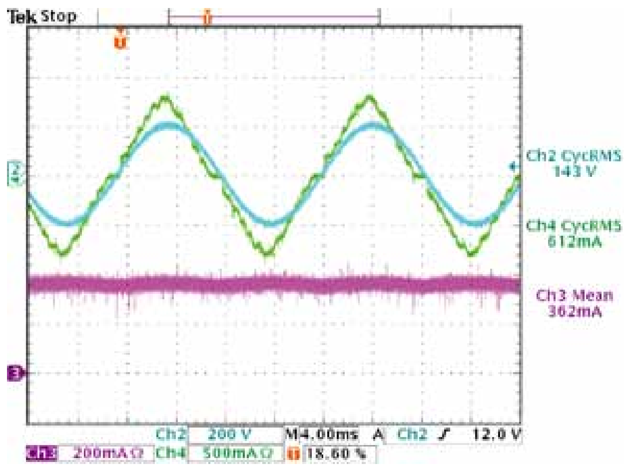
V_{AC}: $120V_{RMS}$ I_{AC}: $556mA_{RMS}$ THD: 12.2% PF: 98.2% V_{OUT}: $160V_{DC}$ I_{OUT}: $363mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (2/8) dimmable, $120V_{AC}$



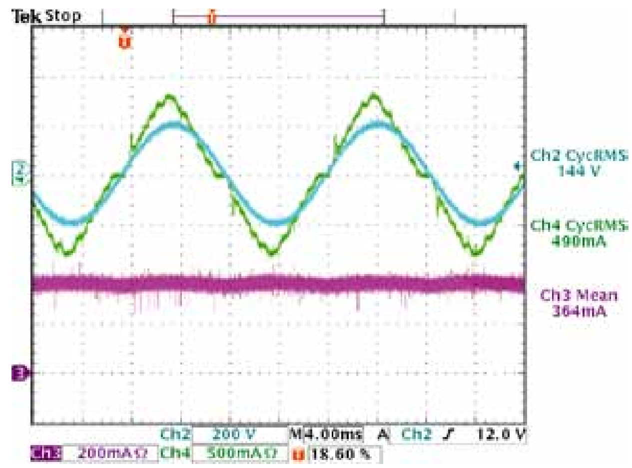
V_{AC}: $120V_{RMS}$ I_{AC}: $560mA_{RMS}$ THD: 13.3% PF: 98.2% V_{OUT}: $160V_{DC}$ I_{OUT}: $363mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (3/8) non-dimmable, $140V_{AC}$



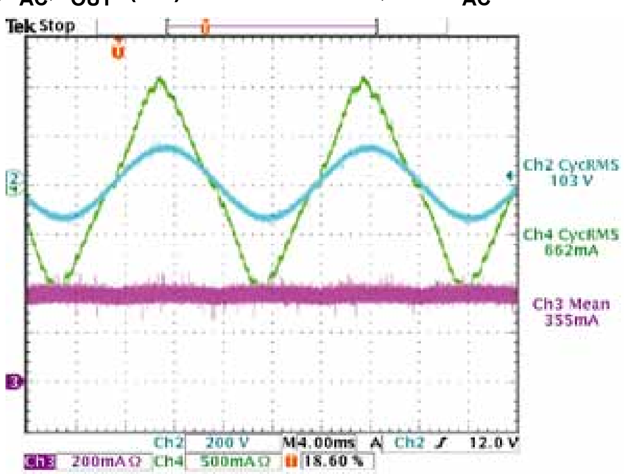
V_{AC}: $141V_{RMS}$ I_{AC}: $486mA_{RMS}$ THD: 13.9% PF: 97.7% V_{OUT}: $161V_{DC}$ I_{OUT}: $365mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (4/8) dimmable, $140V_{AC}$



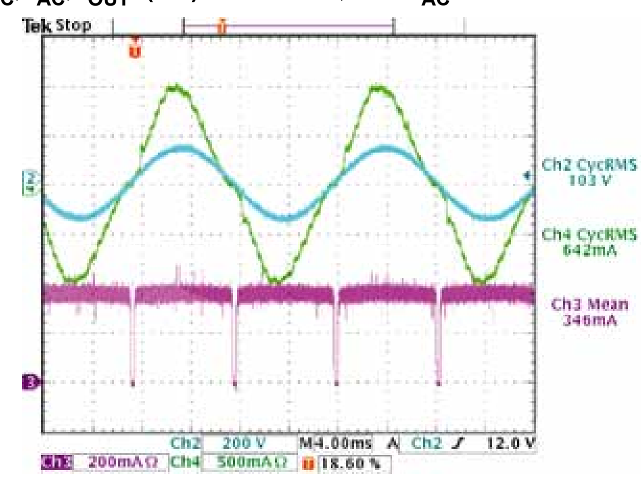
V_{AC}: $141V_{RMS}$ I_{AC}: $489mA_{RMS}$ THD: 14.6% PF: 97.7% V_{OUT}: $161V_{DC}$ I_{OUT}: $364mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (5/8) non-dimmable, $100V_{AC}$



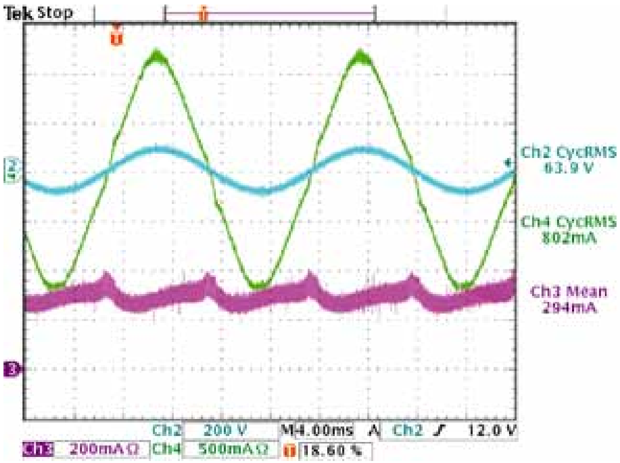
V_{AC}: $100V_{RMS}$ I_{AC}: $663mA_{RMS}$ THD: 12.5% PF: 98.4% V_{OUT}: $159V_{DC}$ I_{OUT}: $360mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (6/8) dimmable, $100V_{AC}$



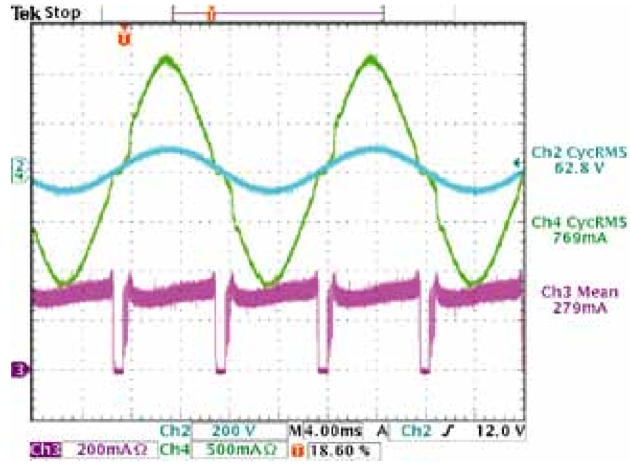
V_{AC}: $100V_{RMS}$ I_{AC}: $668mA_{RMS}$ THD: 13.8% PF: 98.4% V_{OUT}: $159V_{DC}$ I_{OUT}: $366mA_{DC}$

V_{AC}, I_{AC}, I_{OUT} (7/8) non-dimmable, 60V_{AC}



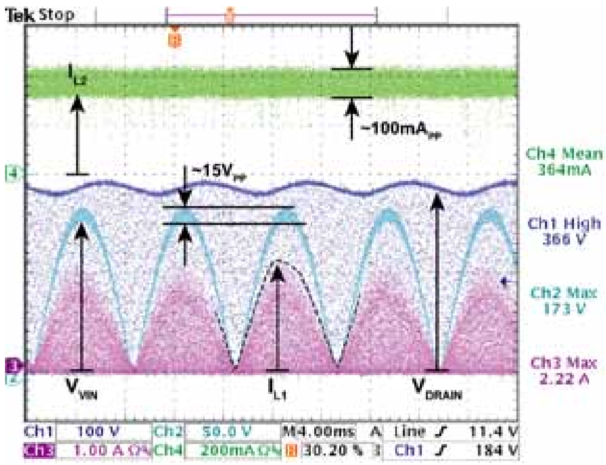
V_{AC}: 60V_{RMS} I_{AC}: 800mA_{RMS} THD: 4.8% PF: 99.8% V_{OUT}: 132V_{DC}
I_{OUT}: 300mA_{DC} (output regulation is lost at 60VRMS)

V_{AC}, I_{AC}, I_{OUT} (8/8) non-dimmable, 60V_{AC}



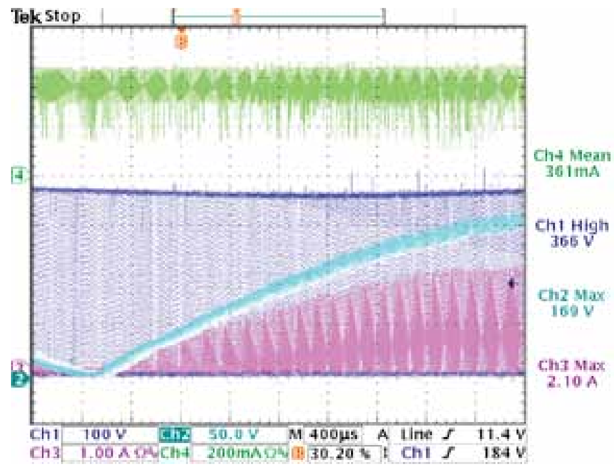
V_{AC}: 60V_{RMS} I_{AC}: 668mA_{RMS} THD: 8.5% PF: 99.6% V_{OUT}: 122V_{DC}
I_{OUT}: 278mA_{DC} (output regulation is lost at 60VRMS)

V_{DRAIN}, V_{VIN}, I_{L1}, I_{L2} (1/4)



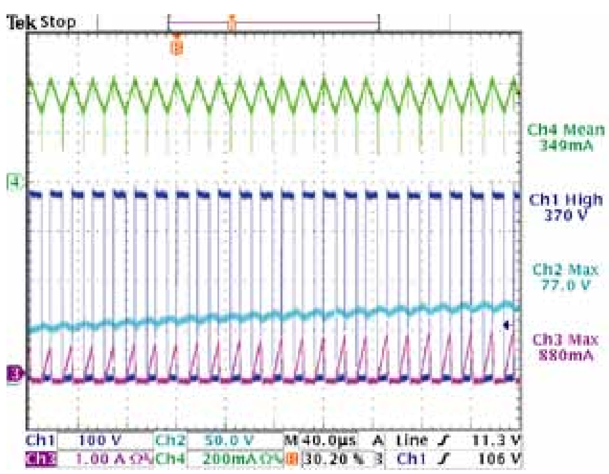
V_{AC}: 120V_{RMS} (non-dimmable setup)

V_{DRAIN}, V_{VIN}, I_{L1}, I_{L2} (2/4)



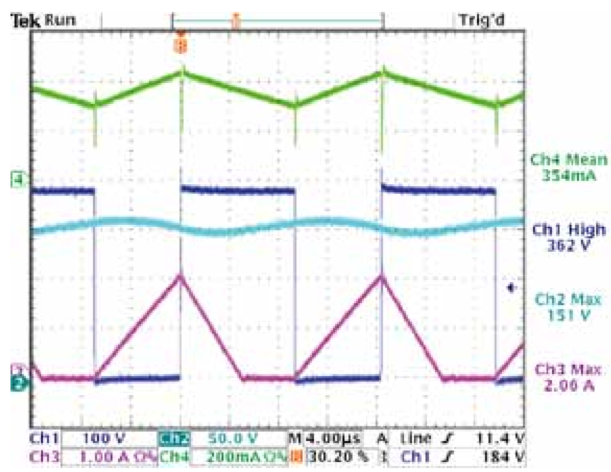
V_{AC}: 120V_{RMS} (non-dimmable setup)

V_{DRAIN}, V_{VIN}, I_{L1}, I_{L2} (3/4)



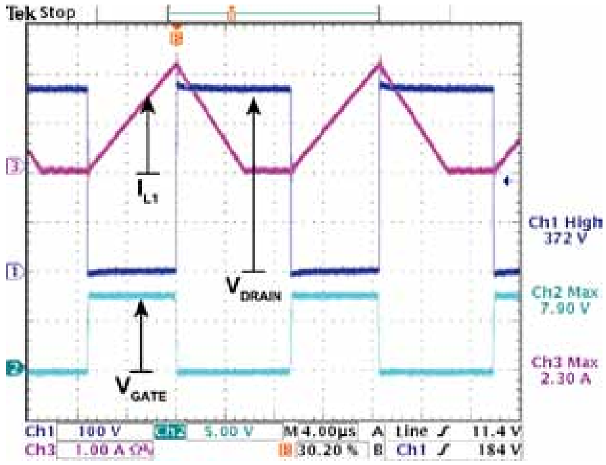
V_{AC}: 120V_{RMS} (non-dimmable setup)

V_{DRAIN}, V_{VIN}, I_{L1}, I_{L2} (4/4)



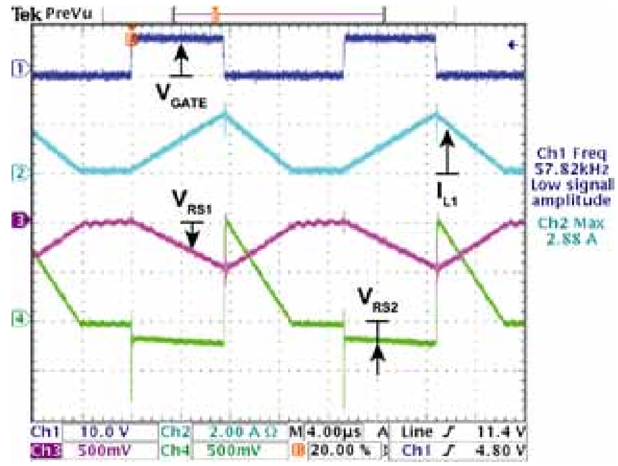
V_{AC}: 120V_{RMS} (non-dimmable setup)

V_{GATE}



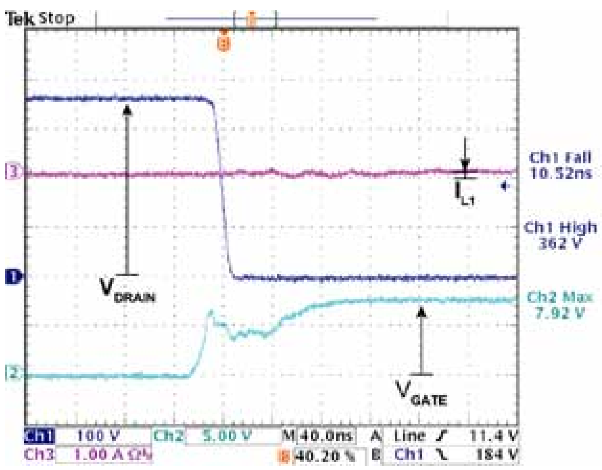
V_{AC}: $120V_{RMS}$ (non-dimmable setup)

V_{RS1}, V_{RS2} Current Sense



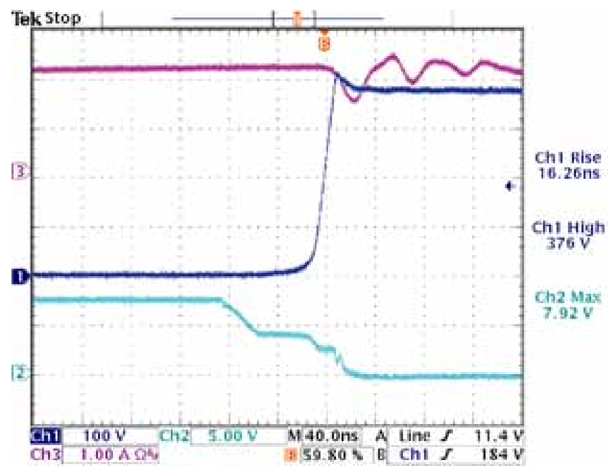
V_{AC}: $120V_{RMS}$ (non-dimmable setup)

MOSFET Turn-on



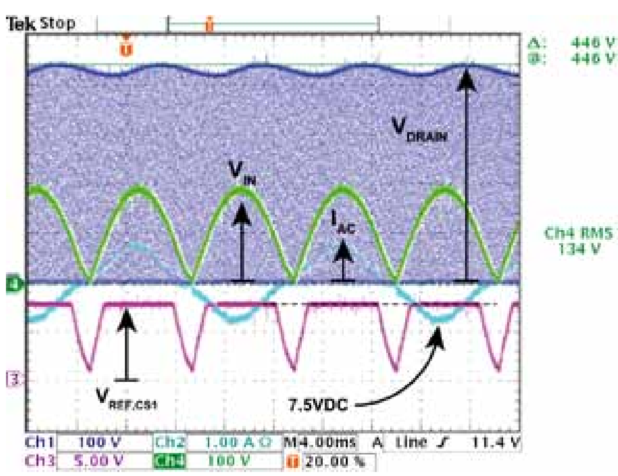
V_{AC}: $120V_{RMS}$ (non-dimmable setup)) (RS1 = R61) (RS2 = R71)

MOSFET Turn-off



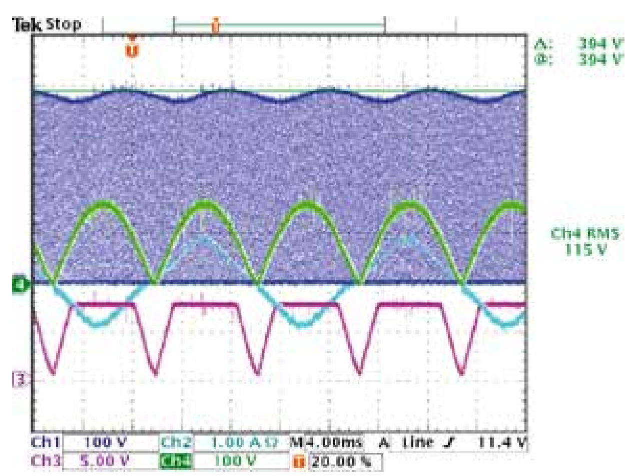
(non-dimmable setup)

CS1 Programming (1/7), $V_{AC} = 140V_{RMS}$



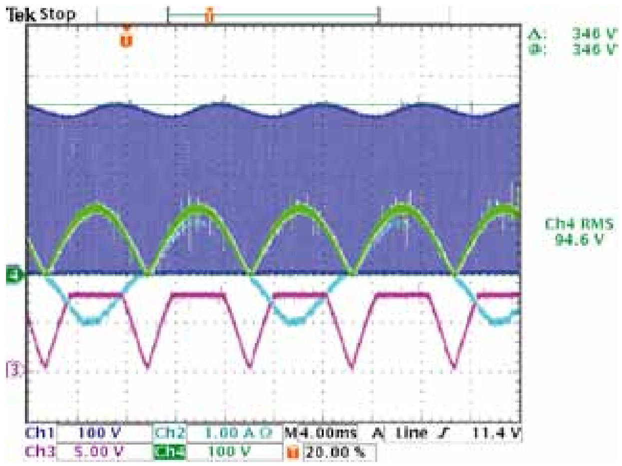
(non-dimmable setup)

CS1 Programming (2/7), $V_{AC} = 120V_{RMS}$



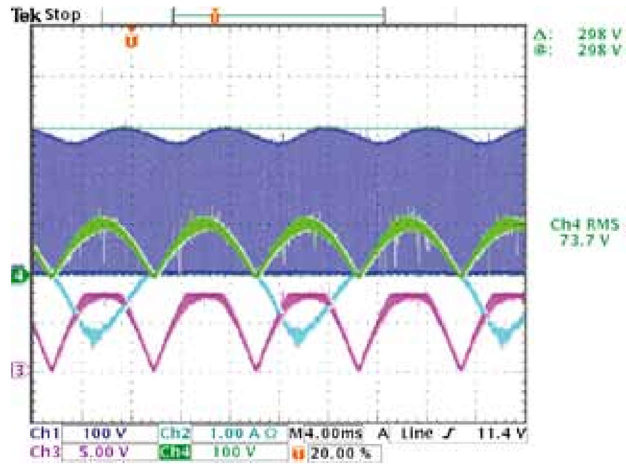
(non-dimmable setup)

CS1 Programming (3/7), V_{AC} = 100V_{RMS}



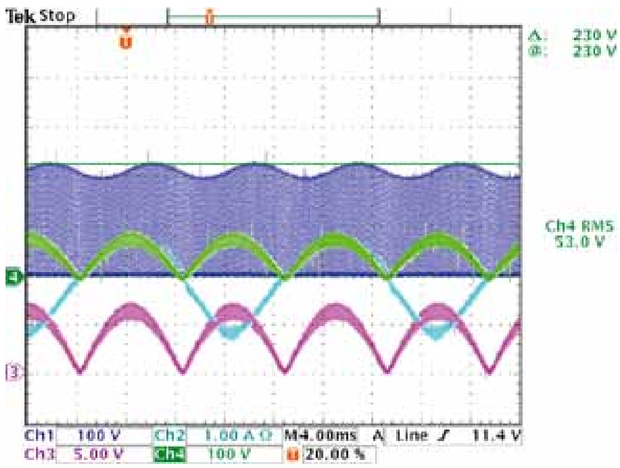
(non-dimmable setup)

CS1 Programming (4/7), V_{AC} = 80V_{RMS}



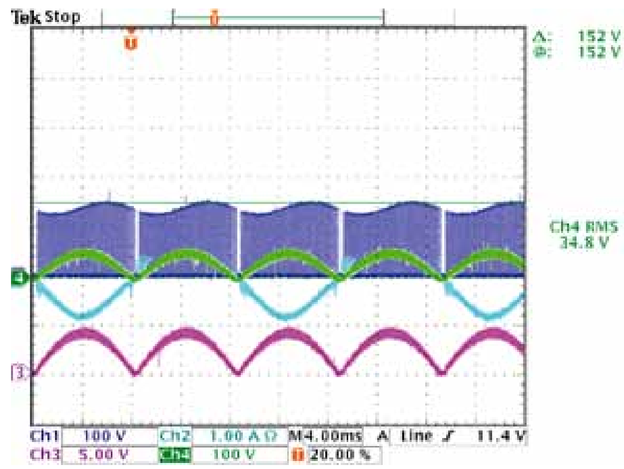
(non-dimmable setup)

CS1 Programming (5/7), V_{AC} = 60V_{RMS}



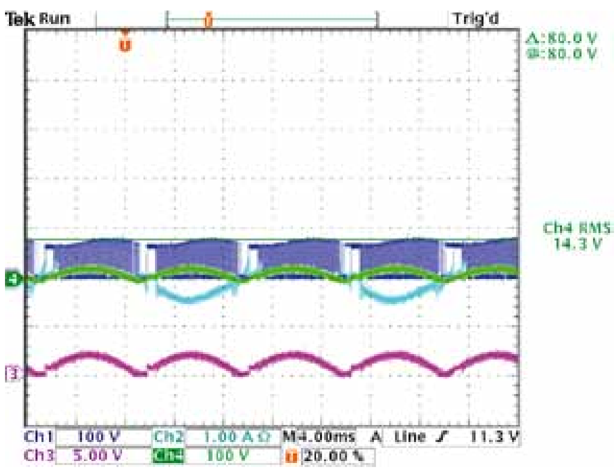
(non-dimmable setup)

CS1 Programming (6/7), V_{AC} = 40V_{RMS}



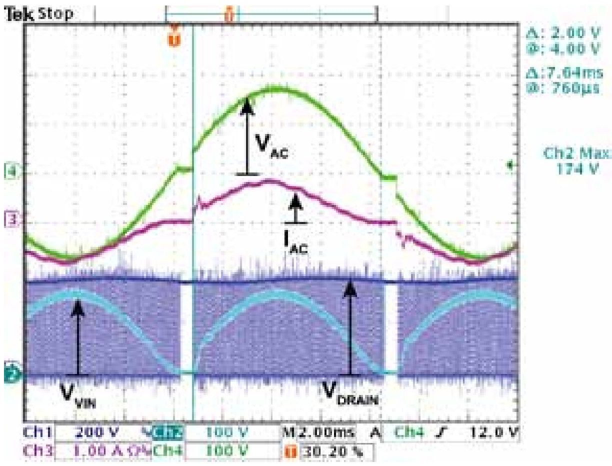
V_{AC}: 120V_{RMS} (non-dimmable setup) (RS1 = R61) (RS2 = R71)

CS1 Programming (7/7), V_{AC} = 20V_{RMS}



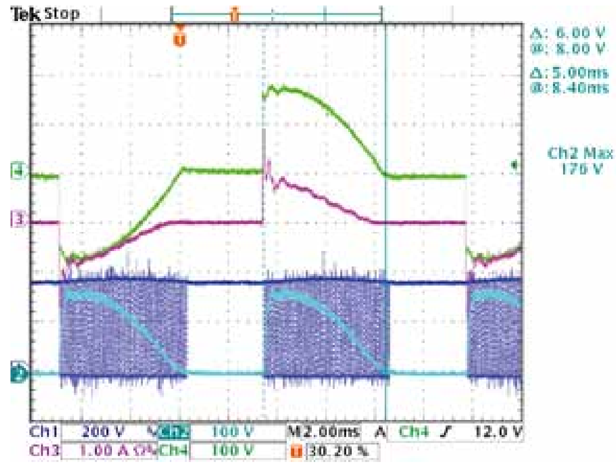
V_{AC}: 100V_{RMS} I_{AC}: 6686mA_{RMS} THD: 8.5% PF: 99.6% v V_{OUT}: 122V_{DC}
I_{OUT}: 278mA_{DC}

V_{AC}, I_{AC}, V_{VIN}, V_{DRAIN} (1/4), Angle = 165º



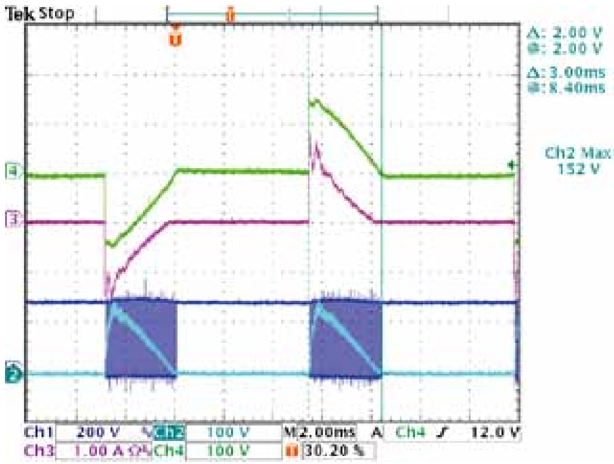
I_{OUT}: 335mA_{DC}

V_{AC}, I_{AC}, V_{VIN}, V_{DRAIN} (2/4), Angle = 110º



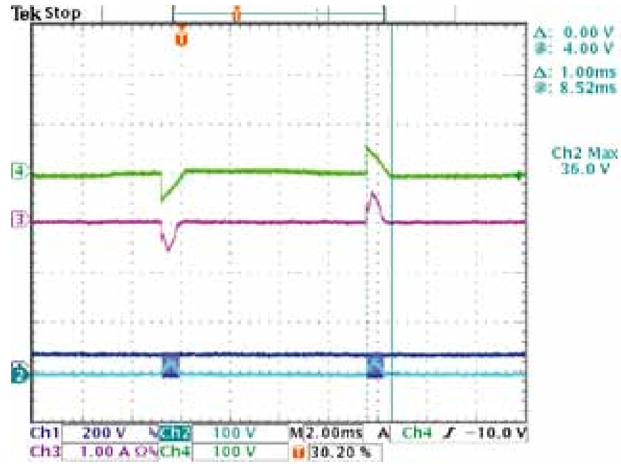
I_{OUT}: 230mA_{DC}

V_{AC}, I_{AC}, V_{VIN}, V_{DRAIN} (3/4), Angle = 65º



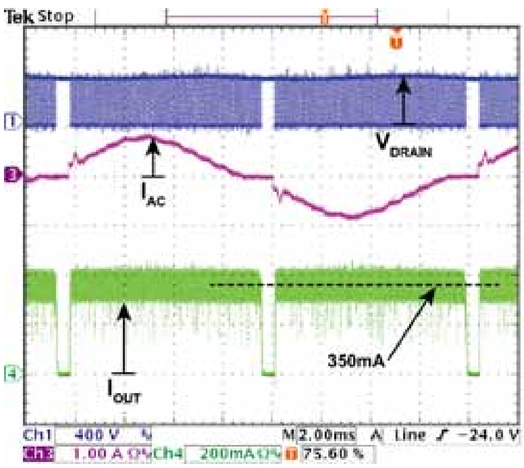
I_{OUT}: 335mA_{DC}

V_{AC}, I_{AC}, V_{VIN}, V_{DRAIN} (4/4), Angle = 20º



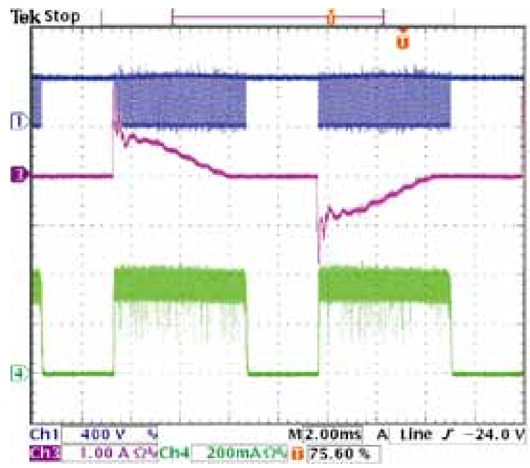
I_{OUT}: 25mA_{DC}

I_{OUT} Regulation (1/4), Angle = 165º



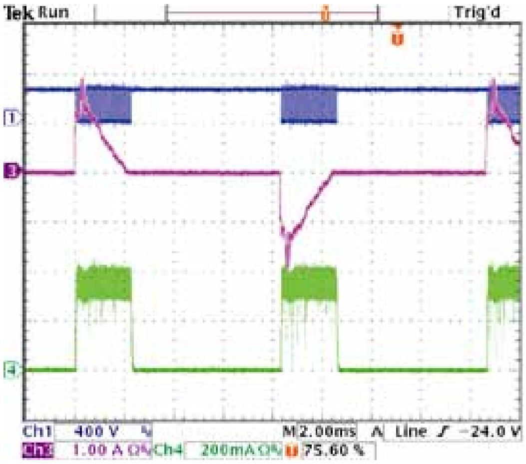
I_{OUT}: 130mA_{DC}

I_{OUT} Regulation (2/4), Angle = 105º



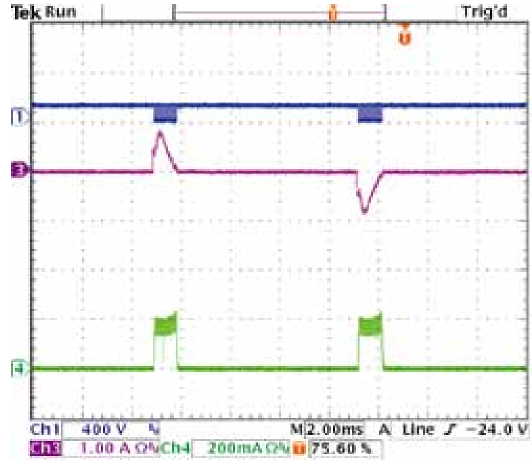
I_{OUT}: 215mA_{DC}

I_{OUT} Regulation (3/4), Angle = 45º



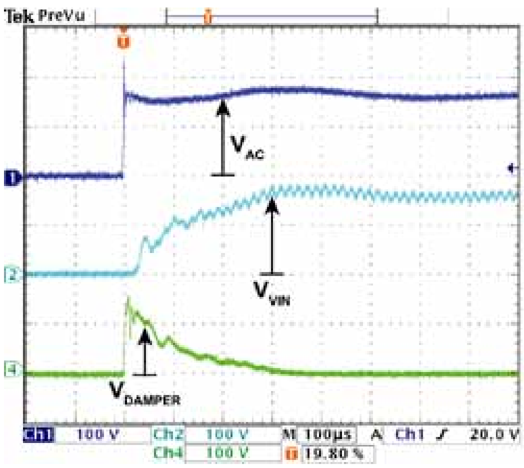
I_{OUT}: $70mA_{DC}$

I_{OUT} Regulation (4/4), Angle = 20º



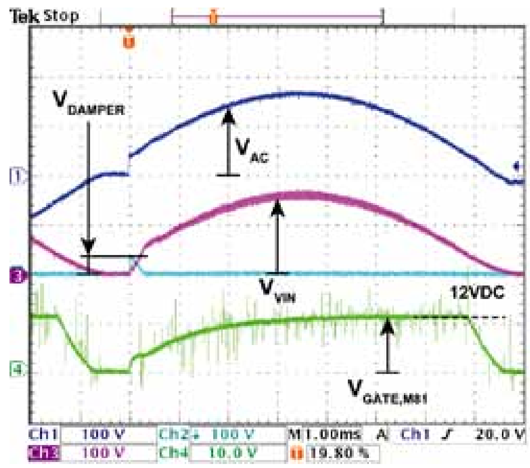
I_{OUT}: $10mA_{DC}$

V_{AC}, V_{DAMPER}, V_{VIN}, Angle = 30º



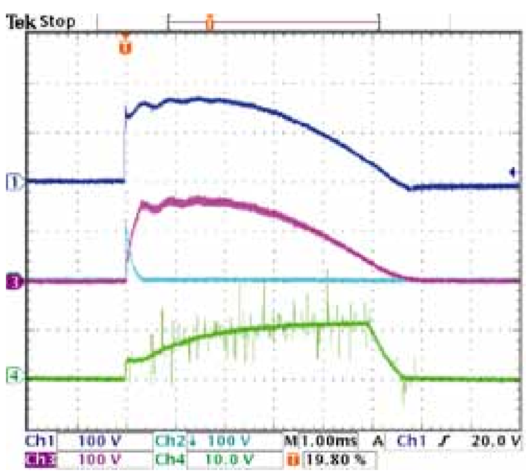
I_{OUT}: $335mA_{DC}$

V_{AC}, V_{DAMPER}, V_{VIN}, $V_{GATE,M81}$ (1/3), Angle = 165º



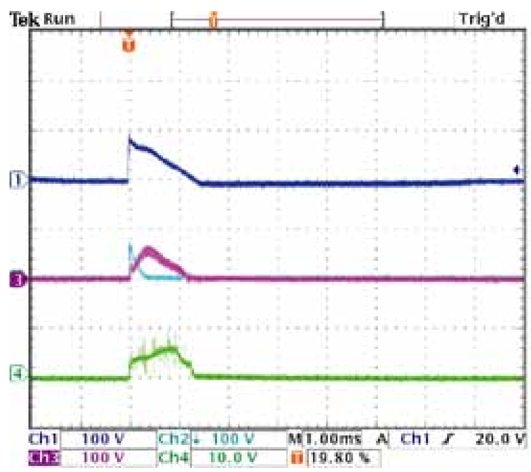
I_{OUT}: $335mA_{DC}$

V_{AC}, V_{DAMPER}, V_{VIN}, $V_{GATE,M81}$ (2/3), Angle = 120º



I_{OUT}: $30mA_{DC}$

V_{AC}, V_{DAMPER}, V_{VIN}, $V_{GATE,M81}$ (3/3), Angle = 25º



Bill Of Materials

Qty	Ref	Description	Manufacturer	Mfr. Part Number
1	C41	Cap metal polypro .01µF 250V	EPCOS Inc	B32621A3103J
3	C21, C22, C23	Cap metal polypro .47µF 250V	EPCOS Inc.	B32652A3474J
2	C61, C71	Cap ceramic .19 µF 16V 10% X7R 0805	Murata	GRM219R71C104KA01D
1	C82	Cap ceramic 10000PF 50V 5% C0G 0805	Murata	GRM2195C1H103JA01D
1	C51	Cap ceramic .22µF 25V X7R 0805	Panasonic ECG	ECJ-2YB1E224K
1	C83	Cap Ceramic 100PF 630V C0G 5% 1206	TDK Corporation	C3216C0G2J101J
2	C62, C72	Cap Ceramic 100PF 50V NP0 0805	Kemet	C0805C101K5GACTU
1	E31	Cap 22µF 450V Elect EB radial	Panasonic ECG	EEU-EB2W220
2	D31, D41	Diode Fast 600V 1A SMA	STMicroelectronics	STTH1R06A
2	Z85, Z87	Diode Zener 225MW 12V SOT23	ON Semiconductor	BZX84C12LT1
1	Z61	Diode Zener 225MW 7.5V SOT23	ON Semiconductor	BZX84C7V5LT1
2	Z71, Z72	Diode Zener 225MW 91V SOT23	ON Semiconductor	MMBZ5270BLT1
1	CM11	Filter Line 7MH 0.6A TYPE 16M	Panasonic ECG	ELF-16M060A
1	F11	Fuse T-LAG 1.00A 250V UL TR5	Wickmann USA	37411000410
2	HS81, HS31	Heatsink TO220 VER MNT W/TAB.69”	Aavid Thermalloy	574602B03700
1	IC51	IC LED Driver SOIC-8	Supertex	HV9931LG
2	L41, L42	Inductor 5.6MH 0.45ARMS axial	Renco	RL-1292-5600
1	L31	Inductor 560µH 0.8ARMS radial	Renco	RL-1256-1-560
3	L21, L22, L23	Inductor HI current radial 390µH	JW Miller	6000-391K-RC
2	M31, M81	MOSFET N-CH 560V 4.5A TO-220AB	Infineon Technologies	SPP04N50C3
1	M91	MOSFET N-CH 600V 250MA SOT223	STMicroelectronics	STN1NK60Z
1	BR11	Rectifier bridge 1AMP 600V DFS	Gen. Semiconductor/ Vishay	DF06S-E3\45
1	R61	Resistor .22Ω 1/4W 1% 0805 SMD	Susumu Co Ltd	RL1220S-R22-F
1	R71	Resistor .47Ω 1/4W 1% 0805 SMD	Susumu Co Ltd	RL1220S-R47-F

Bill Of Materials *(cont.)*

Qty	Ref	Description	Manufacturer	Mfr. Part Number
1	R75	Resistor 10.0Ω 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF10R0V
1	R73	Resistor 2.43kΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF2431V
1	R63	Resistor 5.49kΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF5491V
7	R52, R53, R54, R64, R72, R84, R85	Resistor 100kΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF1003V
1	R51	Resistor 191kΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF1913V
2	R65, R66	Resistor 604kΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF6043V
1	R62	Resistor 1.00MΩ 1/8W 1% 0805 SMD	Panasonic ECG	ERJ-6ENF1004V
1	R93	Resistor 39kΩ 1/8W 5% 0805 SMD	Panasonic ECG	ERJ-6GEYJ393V
1	R91	Resistor 1.00kΩ 1/4W 1% 1206 SMD	Panasonic ECG	ERJ-8ENF1001V
3	R83, R86, R87	Resistor 100kΩ 1/4W 1% 1206 SMD	Panasonic ECG	ERJ-8ENF1003V
4	R31, R32, R92, R94	Resistor 1.00MΩ 1/4W 1% 1206 SMD	Panasonic ECG	ERJ-8ENF1004V
1	R81	Resistor 120Ω 5W 5% Wirewound	Yageo Corporation	SQP500JB-120R
1	MOV11	SUR Absorber 10MM 390VDC 2500A ZNR	Panasonic ECG	ERZ-V10D391
2	Q51, Q91	Transistor GP NPN AMP SOT-23	Fairchild Semiconductor	MMBT2222A
1	Q52, Q84	Transistor GP PNP AMP SOT-23	Fairchild Semiconductor	MMBT2907A

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