Application Report

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Versatile Buck-Boost driver based on UCC28722 for 5 W-9 W LED Bulb

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ABSTRACT

This application report describes an innovative application for the UCC28722 CV-CC Flyback controller used in a Buck-Boost topology tailored for a LED Bulb application. This serves as a superior alternative to the existing LED drivers with integrated MOSFET technology. The benefits are as follows:

- Uses lowest cost BJT, making the overall solution more affordable.
- High conversion efficiency because of combination of frequency and Peak current modulation.
- Wide V_{DD} range (9 V - 35 V) makes it possible to make single bulb design capable of handling 8 LEDs to 17 LEDs without changing any component.
- Single driver design helps in saving inventory cost for the manufacturer.

This application report goes through step-by-step procedure a designer must follow to complete a Buck-Boost LED driver using UCC28722. The PCB PWR068 for UCC28700EVM-068 in Flyback configuration was modified for Buck-Boost and tested based on this application report.

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Table 1. Buck-Boost LED Bulb Specifications

The main specifications of the Buck-Boost LED Bulb are listed below:	
Input	
Voltage	100 – 275 AC
Frequency	48 – 52 Hz
Output	
	27 V – 54 V (9 LEDs – 18 LEDs)
	150 mA ± 5%
Input Power (W)	5 W (8 LEDs), 7 W (12 LEDs), 8 W (14 LEDs), 9 W (17 LEDs)
Variation in Input Power	± 5%
Input Power Factor	≥ 0.45
Efficiency	> 84%
LED Open Circuit	Protected
Isolation	non-Isolated

1 Basic Principle of Buck Boost Topology

Figure 1 shows a simplified schematic of the Buck-Boost power stage with a drive circuit block included. The power switch, Q1, is a NPN Bipolar transistor. The output rectifying diode is CR1. The inductor L and capacitor C make up the effective output filter. R_{ESR} represents the capacitor ESR and R_L represents the inductor DC resistance. The LEDs shown in series represent the R_{LOAD}.

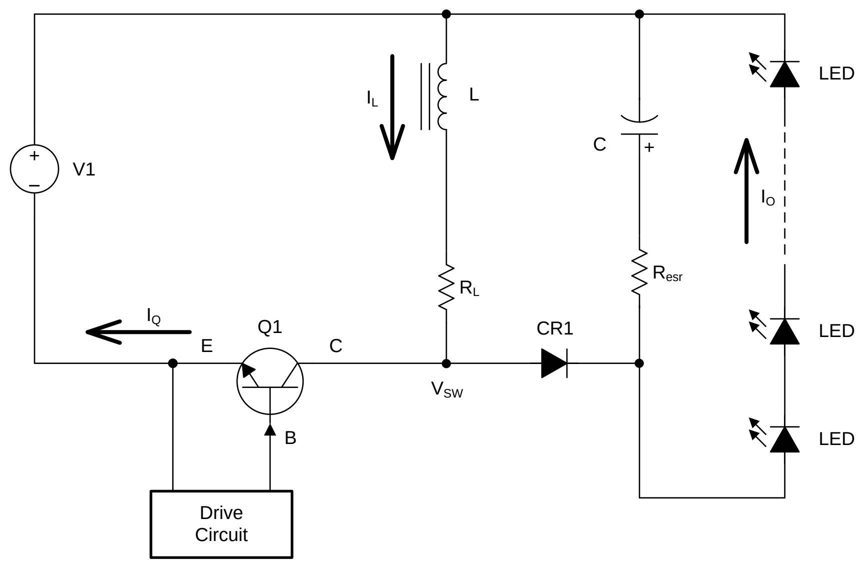

Figure 1. Buck-Boost Power Stage Schematic

During the normal operation of the Buck Boost power stage, Q1 is repeatedly switched on and off with the on and off times governed by the control circuit. This switching action causes a series of pulses at the junction of Q1, CR1, and L. Although the inductor L connects to the output capacitor C only when CR1 conducts, an effective L/C output filter forms, filtering the series of pulses to produce a DC output voltage for the LEDs.

A power stage operates in continuous or discontinuous inductor current mode. Continuous inductor current mode is characterized by current flowing continuously in the inductor during the entire switching cycle in steady state operation. Discontinuous inductor current mode is characterized by the inductor current being zero for a portion of the switching cycle. The inductor starts at zero, reaches a peak value, and returns to zero during each switching cycle. Ideally, a power stage stays in only one mode over its expected operating conditions because the power stage frequency response changes significantly between the two modes of operation.

2 Buck-Boost Steady-State Discontinuous Conduction Mode Analysis

The following is a description of the steady-state operation in discontinuous conduction mode as the PWM controller UCC28722 operates only in this mode. A power stage operating in discontinuous conduction mode has three unique states during each switching cycle shown in Figure 2. In the on state Q1 is on and CR1 is off. In the off state Q1 is off and CR1 is on. In the idle state both Q1 and CR1 are off. A simple linear circuit represents each of the three states where the switches in the circuit are replaced by their equivalent circuits during each state. The circuit diagram for each of the three states is shown in Figure 2.

The duration of the on state is $t_{ON} = D \times t_S$, where D is the duty cycle, set by the control circuit, expressed as a ratio of the switch on time to the time of one complete switching cycle, t_s. The duration of the off state is $t_{OFF} = D2 \times t_S$. The idle time is the remainder of the switching cycle and is given as $t_S – t_{ON} – t_{OFF} = D3 \times t_S$. These times are shown with the waveforms in Figure 3.

The main result of this section is a derivation of the voltage conversion relationship for the discontinuous conduction mode Buck-Boost power stage. In addition, the DC resistance of the output inductor, the output diode forward voltage drop, and the power BJT V_{CE} drop are all assumed to be small enough to omit in analysis.

Referring to Figure 2, during the on state, the input voltage V_{IN} is applied across the inductor L. The inductor current I_L flows from the input source, V_{IN}, through Q1 to the ground. Adopting the polarity convention for the current I_L is shown in Figure 2, the inductor current increases as a result of the applied voltage. Since the applied voltage is constant, the inductor current increases linearly. This increase in inductor current during t_{ON} is illustrated in Figure 3.

The amount that the inductor current increases is calculated by using a version of the familiar relationship:

$$V_L = L \times \frac{di_L}{dt} \rightarrow \Delta I_L = \frac{V_L}{L} \times \Delta T \quad (1)$$

The inductor current increase during the on state is given by:

$$\Delta I_{L(+)} = \frac{V_{IN}}{L} \times T_{ON} = \frac{V_{IN}}{L} \times D \times t_S = I_{PK} \quad (2)$$

The ripple current magnitude, $\Delta I_{L(+)}$, is also the peak inductor current, I_{PK}.

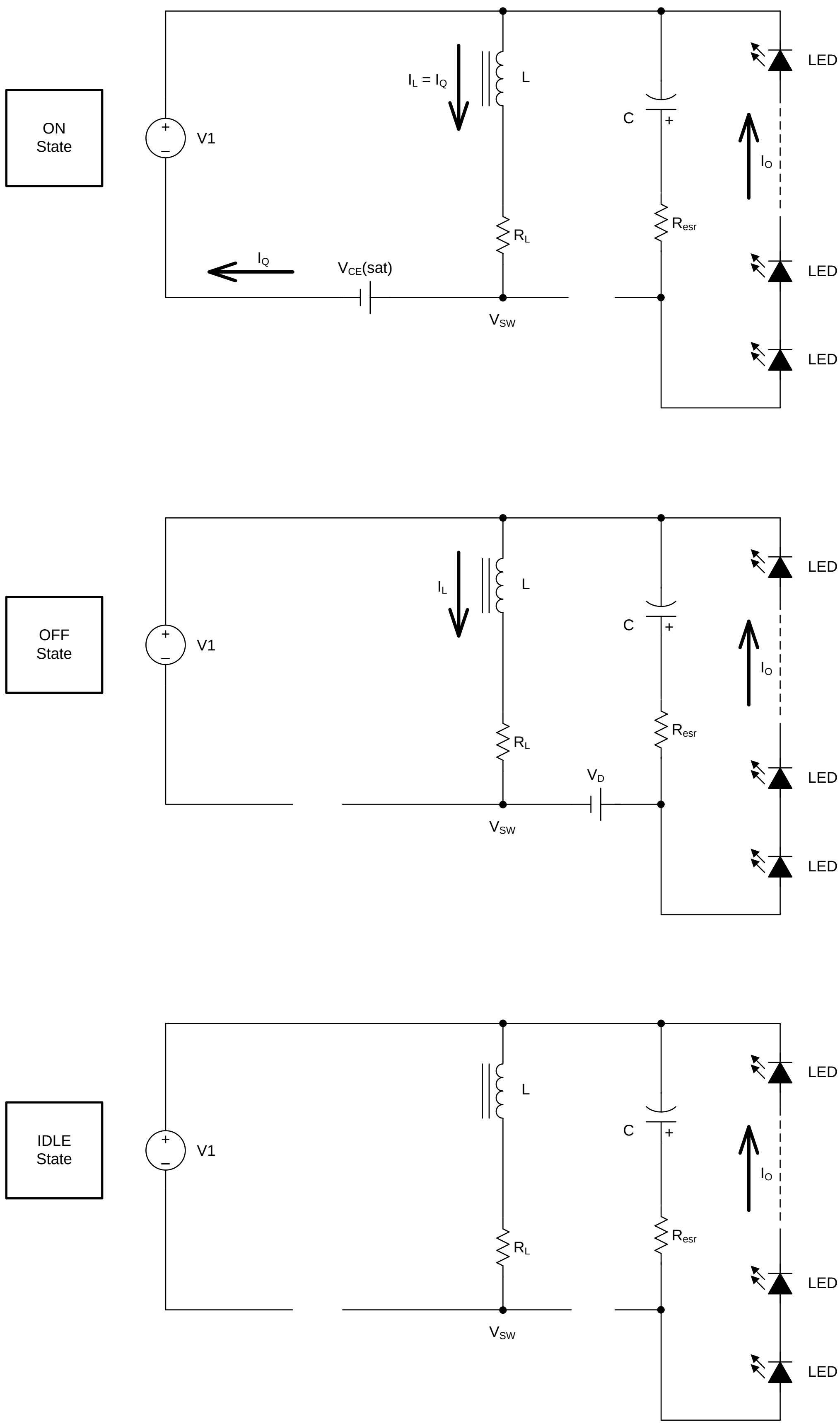

Figure 2. Buck-Boost Power Stages in Discontinuous Mode

Referring to Figure 2, when Q1 is off, it presents high impedance from its collector to emitter, and since the current flowing in the inductor L cannot change instantaneously, the current shifts from Q1 to CR1. Due to the decreasing inductor current, the voltage across the inductor reverses polarity until rectifier CR1 becomes forward biased and turns on. The voltage applied across L becomes V_{OUT}. The inductor current, I_L, now flows from the output capacitor and LEDs combination through CR1 and back to the inductor. The orientation of CR1 and the direction of the current flow in the inductor means that the current flowing in the output capacitor and LEDs combination causes V_{OUT} to be a negative voltage. Maintaining our same polarity convention, this applied voltage is negative (or opposite in polarity from the applied voltage during the on time), because the output voltage V_{OUT} is negative. This decrease in inductor current during t_{OFF} is illustrated in Figure 3.

The inductor current decrease during the off state is given by:

$$\Delta I_{L(-)} = \frac{-V_{OUT}}{L} \times t_{OFF} \tag{3}$$

This quantity, $\Delta I_{L\,(-)}$, is also referred to as the inductor ripple current.

In steady state conditions, the current increase, $\Delta I_{L(+)}$, during the on time and the current decrease during the off time, $\Delta I_{L(-)}$, must be equal. Otherwise, the inductor current would have a net increase or decrease from cycle to cycle which would not be a steady state condition. Therefore, Equation 1 and Equation 3 equate and solve for V_{OUT} to obtain the first of two equations to be used to solve for the voltage conversion ratio:

$$V_{OUT} = -\,V_{IN} \times \frac{t_{ON}}{t_{OFF}} = -V_{IN} \times \frac{D}{D2} \tag{4}$$

Now we calculate the output current (the output voltage V_{OUT} divided by the output load R_L). It is the average during one switching cycle of the inductor current during the time CR1 conducts (D2 × t_S).

$$I_{OUT} = I_{L(avg)} = \frac{V_{OUT}}{R_L} = \frac{1}{t_S} \times \left(-\frac{I_{PK}}{2} \times D2 \times t_S\right) \tag{5}$$

Now, substitute the relationship for I_{PK} into the above equation to obtain:

$$I_{OUT} = \frac{V_{OUT}}{R_L} = \frac{1}{t_S} \times \left(\frac{1}{2} \times (-1) \times \left(\frac{V_{IN}}{L} \times D \times t_S\right) \times D2 \times t_S\right) \tag{6}$$

$$I_{OUT} = -V_{IN} \times D \times D2 \times \frac{t_S}{2 \times L} \tag{7}$$

We now have two equations, one for the output current (V_{OUT} divided by R) just derived and the one for the output voltage, both in terms of V_{IN}, D, and D2. We now solve each equation for D2 and set the two equations equal to each other. Using the resulting equation, an expression for the output voltage, V_{OUT}, can be derived.

The discontinuous conduction mode buck-Boost voltage conversion relationship is given by:

$$V_{OUT} = -V_{IN} \times \frac{D}{\sqrt{K}} \tag{8}$$

Where K is defined as:

$$K = \frac{(2 \times L)}{R_L \times t_S} \tag{9}$$

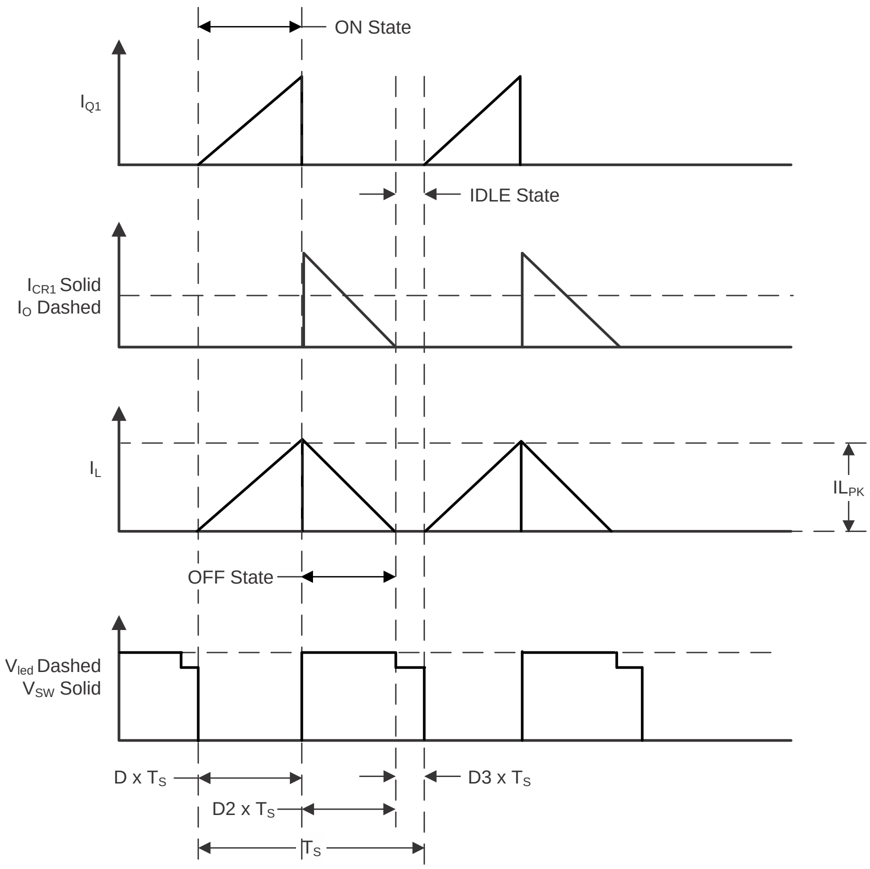

Figure 3. Discontinuous Mode Power Stage Buck-Boost Wave Forms

3 Step by Step Design Procedure of UCC28722 Based Buck-Boost LED Bulb

Refer to Figure 5 for the design components.

3.1 AC input stage components

The input stage consists of fusible resistance R6, Varistor MOV1, input Bridge rectifier D1, the line filter L1 along with the main bulk electrolytic capacitors C1 and C3.

The input resistance R6 provides three important functions:

- Acts as fuse in case of any short in the LED driver
- Controls the Inrush current going into bulk capacitors
- Aids in differential mode attenuation

As it has to perform above three functions so Flame proof, film type resistance, or WWR surge resistance is recommended.

For designs up to 10 W of input power 2.2-4.7 Ω 3 W is recommended for R6.

Regulation IEC 61000-4-5 defines the Surge immunity test as high power spikes caused by large inductive devices in mains. The input of the LED Driver is coupled by short duration (1.2/50 µs) pulses but high voltage (up to 4 kV). The pulses are applied between L–N and between L (N) – PE at different angles 0◦, 90◦, 180◦, 270◦, 360◦ of the AC voltage. As the LED bulb is a two wire system with earth, the pulses are applied between L–N only.

The surge pulse causes a high inrush current, quickly charging the storage capacitor in a standard SMPS. The major risk is overvoltage for input components like the bulk capacitors, Bridge rectifier and the main BJT switch. The inrush current can damage the components like the rectifier bridge, fusible resistance in series in the input section. Typically the varistors are used to absorb part of the energy and the rest is absorbed by the bulk capacitors.

As the input AC voltage can go as high as, 275 V_{AC} so 300 V_{AC} rated 10 mm varistor is recommended for surges up to 3 kV level.

For rectifying the AC bridge, rectifier D1 along with C2 and C3 are used. The input AC voltage can go up to 275 V_{AC} so the DC voltage can reach voltage levels of up to 388 V_{DC}. The input bulk capacitor must be able to sustain such voltage levels. Standard aluminum capacitors of 450 V rating are available in the market. For a Bridge rectifier with universal input the thumb rule for choosing the value of the capacitors is 1-2 µF/W. Keeping the cost and size in mind, C1 = C3 = 4.7 µF 450 V capacitors are chosen. 1 A, 600 V Bridge Rectifier, HD06 is recommended for D1.

L1 and C1 form a differential filter attenuating the differential noise produced by the UCC28722 based buck-boost converter. The recommended value for L1 is 470 µH-1000 µH. The resistor R2 is used across L1 to combat self-resonance which appears in EMI scan. TI recommends that the value for R2 is in the range of 2.2 K - 20 K and is determined experimentally by checking the EMI spectrum.

3.2 Feedback Resistors

The turns ratio N_P (number of Primary turns) to N_S (number of secondary turns) is 1:1 in Buck-boost topology as the winding is the same for primary and secondary. The minimum output voltage V_{OUT} corresponding to the minimum number of LEDs is 27 V. As the UVLO point for V_{DD} for UCC28722 is 8 V, keeping the margin to power the UCC28722, V_{DD} should be 11 V when the LED voltage is 27 V.

The turn ratio of primary or secondary to auxiliary is given by:

$$N_{PA} = N_{SA} = \frac{V_{LED\,(min)}}{11} \tag{10}$$

Where

- N_{PA} is the transformer primary-to-auxiliary turns ratio
- N_{SA} is the transformer secondary-to-auxiliary turns ratio

Substituting $V_{LED(min)}$ as 27 V N_{PA} = N_{SA} comes out to be 2.45.

The VS divider resistors R14 and R15 determine the output voltage regulation point of the buck-Boost converter. The high-side divider resistor (R14) determines the line voltage at which the controller enables continuous DRV operation. R14 is initially determined based on desired input voltage operating threshold.

$$R14 = \frac{V_{IN\,(min)} \times \sqrt{2}}{N_{PA} \times I_{VSL\,(RUN)}} \tag{11}$$

Where

- $V_{IN(min)}$ is the AC RMS voltage to enable turn-on of the controller (run)
- $I_{VSL(run)}$ is the run-threshold for the current pulled out of the V_S pin during the switch on-time
- N_{PA} is the transformer primary-to-auxiliary turns ratio

Substituting $V_{IN(min)}$ as 90 V_{AC} and $I_{VSL(run)}$ as 225 µA, R14 is 230 K. A standard value of 220 K is chosen.

The low-side V_S pin resistor R15 is selected based on desired V_{OUT} regulation voltage.

$$R15 = \frac{R14 \times V_{VSR}}{(V_{OUT} + V_F)/\,N_{SA} - V_{VSR}} \tag{12}$$

Where

- V_F is the output rectifier forward drop at near-zero current
- R14 is the VS divider high-side resistance
- V_{VSR} is the CV regulating level at the VS input
- N_{SA} is the transformer secondary to auxillary turns ratio

The open circuit voltage must exceed the desired maximum LED voltage. As the maximum number of LEDs is 18 (Output LED voltage = 18 x 3 = 54 V), the output V_{OUT} is chosen as 65 V so that whenever the LEDs are connected the converter operates in CC mode. Substituting V_{OUT} as 65 V, V_F as 0.7 V, R14 as 220 K, and V_{VSR} as 4.05 V, R15 is 43.9 K so the standard value of 39 K is chosen.

3.3 VDD Capacitance

The capacitance C12 on V_{DD} must supply the device operating current until the output of the converter reaches the target minimum operating voltage in constant-current regulation. At this time the output voltage sustains the voltage to the UCC28722. The total output current that charges the output capacitors is the constant-current regulation target, I_{OCC}. The following equation is used to calculate the value of capacitance required at the VDD pin:

$$C12 = I_{RUN} \times \frac{\frac{C14 \times V_{OUT}}{I_{OCC}}}{\left(V_{DD\,(ON)} - V_{DD\,(OFF)} - 1\text{ V}\right)} \quad (13)$$

Where

- $V_{DD(off)}$ is the UVLO turn-off voltage
- $V_{DD(on)}$ is the UVLO turn-on voltage
- C14 is the output capacitor used
- I_{RUN} is the supply current in run state

Substituting I_{RUN} as 2.65 mA, V_{OUT} as 27 V, C14 as 100 µF,I_{OCC} as 150 mA, $V_{DD(ON)}$ as 21 V and $V_{DD(OFF)}$ as 8 V, C12 is 3.97 µF. The standard value is 4.7 µF.

The timing diagram showing the startup of UCC28722 is shown in Figure 4 below.

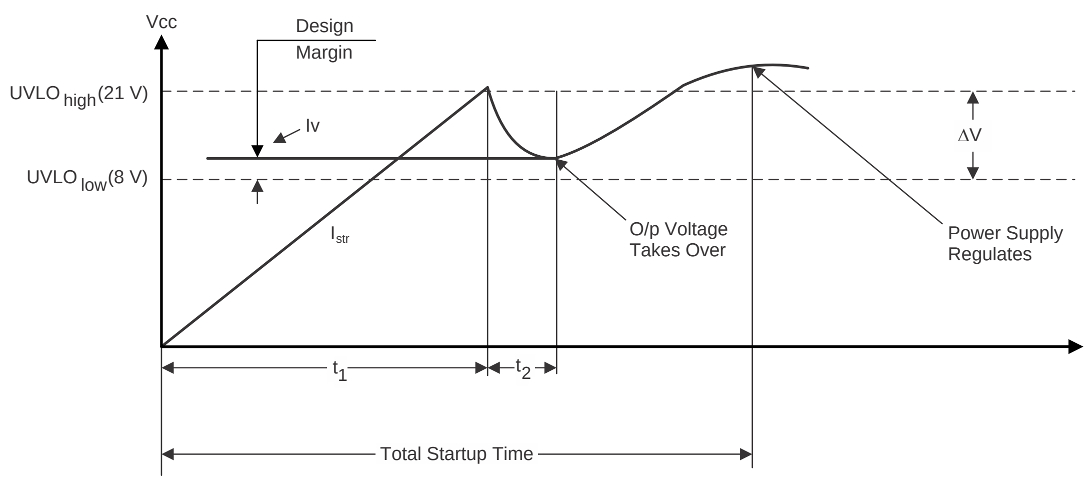

Figure 4. Timing Diagram of Startup Sequence in UCC28722

3.4 Startup Resistors and Startup Time

An external resistor connected from the bulk capacitor voltage to the V_{DD} pin charges the V_{DD} capacitor. The amount of startup current that is available to charge the V_{DD} capacitor is dependent on the value of this external startup resistor. Smaller values supply more current and decrease startup time but at the expense of increasing standby power and decreasing efficiency particularly at high input voltage and light loading.

When V_{DD} reaches the 21-V UVLO turn-on threshold, the controller is enabled and the converter starts switching. The initial three cycles are limited to $I_{PP(min)}$. After the initial three cycles at minimum $I_{PP(min)}$, the controller responds to the condition dictated by the control law. The converter remains in discontinuous mode as the output capacitors charge, maintaining a constant output current until the output voltage is in regulation.

Once the V_{DD} capacitor is known, there is a tradeoff between startup time and overall standby input power to the converter. Faster startup times require a smaller startup resistance, resulting in higher standby input power.

$$R_{STR} = \frac{\sqrt{2} \times V_{IN(min)}}{I_{START} + \frac{V_{DD(ON)} \times C12}{T_{STR}}} \quad (14)$$

Where

- $V_{IN(min)}$ is the minimum voltage required for converter operation
- I_{START} is the startup current of UCC28722
- $V_{DD(ON)}$ is the UVLO turn on threshold
- T_{STR} is the time the power supply stabilizes at the recommended O/p voltage
- C12 is the capacitance value at V_{DD} pin

Substituting $V_{IN(min)}$ as 100 V, I_{START} as 1.5 µA, $V_{DD(ON)}$ as 21 V, T_{STR} as 2 seconds, C12 as 4.7 µF, R_{STR} equals 2.82 MΩ. The required resistance is split into R2 = R8 = R20 = 1 MΩ. Splitting the resistance into three helps in meeting the required voltage rating.

3.5 Current Sense Resistor

Use Equation 5 for calculating the output current in constant current (CC) mode as the Buck-boost operates in this mode only with LEDs connected. Substituting $I_O = I_{OCC}$, D2 = $t_{OFF}/t = D_{MAGCC}$

$$I_{OCC} = \frac{I_{PK}}{2} \times D_{MAGCC} \quad (15)$$

Reorganizing the Equation 15, the peak inductor current required is given by following equation:

$$I_{PK} = \frac{2 \times I_{OCC}}{D_{MAGCC}} \quad (16)$$

Where

- I_{OCC} is the LED output constant-current
- D_{MAGCC} is the maximum demagnetization duty cycle

The UCC28722 constant-current regulation is achieved by maintaining a maximum D_{MAG} duty cycle of 0.425 at the maximum inductor current setting. Substituting I_{OCC} as 150 mA and D_{MAGCC} as 0.425, I_{PK} equals 0.705 A.

During constant current mode the voltage drop across R3 is maintained at 0.78 V. So the current sense resistance R19 is calculated using Equation 17.

$$R19 = \frac{0.78}{I_{PK}} \quad (17)$$

Substituting the I_{PK} value gives R19 as 1.1 Ω, with a standard value of 1 Ω.

Using R19 as 1 Ω I_{PK} equals 0.78 A.

3.6 Buck-Boost Inductor

The inductance L_P is calculated by reshuffling Equation 3.

$$L_P = \frac{-V_{OUT}}{I_{PK}} \times t_{OFF} \quad (18)$$

$$D2 = D_{MAGCC} = t_{OFF}/t_S \quad (19)$$

$$t_S = 1/f_{SW} \quad (20)$$

The switching frequency is 40 kHz to decrease switching losses, or 18 LEDS. Substituting f_{SW} in Equation 20 gives t_S as 25 µs.

Putting D_{MAGCC} as 0.425 and t_S as 25 µs in Equation 19 gives t_{OFF} as 10.625 µs.

Substituting V_{OUT} = 54 V, I_{PK} as 0.78 A and t_{OFF} as 10.625 µs the primary inductance L_P comes out to be 735 µH.

The required area product for the size of the Buck-boost inductor equals 0.0042 cm^4. So EE13 with Area product 0.016 cm^4 is used for the design. Table 2 displays the Buck-boost inductor design in tabular form. the main Buck-Boost inductor is between Pin 2 and Pin 1. The auxiliary winding for powering the UCC28722 is between Pin 3 and Pin 4.

Table 2. Buck-boost Inductor Winding Data

	Core Bobbin Type	**Material**	**Pins**		
	EE1304	N87 or Equiv	8 pins Horizontal		
Winding	**Start Pin**	**End Pin**	**Turns**	**Wire AWG**	**Inductance**
Winding 1	2	1	162	29	735 µH ± 5%
Winding 2	3	4	66	33	
Insulation	1, 2 Shorted-3, 4 shorted	1.5 kV	Ensure proper insulation tapes are used between the windings.		

Winding Instructions (assuming the same winding direction in all cases):

- Start with pin 2, take 1 strand of 29AWG wire and make 162 turns ending at pin 1
- Start on pin 3 and make 66 turns with 1 strand of 33AWG wire and end at pin 4. Spread the winding evenly across the length of the core bobbin
- Space the core suitably to get 735 µH inductance between pin 1 & 2
- Bond the core to avoid audible noise
- Vacuum impregnate with varnish

3.7 Output Rectifier Diode and V_{DD} Diode

The output diode D4 conducts when the power switch Q1 turns off and provides a path for the inductor current T1. Important criteria for selecting the rectifier include: fast switching, breakdown voltage, current rating, low-forward voltage drop to minimize power dissipation, and appropriate packaging. The breakdown voltage must be greater than the maximum difference between the input voltage and output voltage, and some margin added for transients and spikes. The current rating should be at least two times the maximum power stage output current. Normally the current rating is much higher than the output current because power and junction temperature limitations dominate the device selection.

1 A, 1000 V, UF4007 is used for the application.

The worst case voltage V_{DDREV} across V_{DD} diode D4 is given by Equation 21.

$$V_{DD(rev)} = \frac{V_{IN(ACmax)} \times 1.414}{N_{PA}} + V_{DD(max)} \tag{21}$$

Substituting various values in Equation 21 we get V_{DDREV} = 185 V. Keeping a margin of 10%, BAS21 with a Reverse rating of 200 V is chosen for the application.

3.8 Output Capacitor

In switching power supply power stages, the function of output capacitance is to store energy. The energy is stored in the capacitor’s electric field due to the voltage applied. Thus, qualitatively, the function of a capacitor is to maintain a constant voltage.

The value of the output capacitance of a Buck-boost power stage is generally selected to limit output voltage ripple to the level required by the specification. Since the ripple current in the output inductor is usually already determined, the series impedance of the capacitor primarily determines the output voltage ripple. The three elements of the capacitor that contribute to its impedance (and output voltage ripple) are equivalent series resistance (ESR), equivalent series inductance (ESL), and capacitance (C).

For discontinuous inductor current mode operation, to determine the amount of capacitance needed as a function of inductor current ripple ΔI_L , output current I_{OUT}, switching frequency f_{SW}, and output voltage ripple ΔV_{OUT}, Equation 22 is used assuming all the output voltage ripple is due to the capacitor's capacitance.

$$C \geq I_{OUT} \times \frac{1 - \sqrt{K}}{f_{SW} \times \Delta V_{OUT}} \tag{22}$$

Where K is given by Equation 9.

In many practical designs, to get the required ESR, a capacitor with much more capacitance than is needed must be selected.

Assuming there is enough capacitance, the ripple due to the capacitance can be ignored, the ESR needed to limit the ripple to ΔV_{OUT} V peak-to-peak is:

$$ESR \leq \frac{\Delta V_{OUT}}{I_{PK}} \tag{23}$$

As 54 V output is targeted at LED driving so taking ΔV_{OUT} = 550 mV (< 1% of V_{OUT}) and I_{PK} as 0.78 A, ESR of capacitor required is < 0.7 Ω. So 100 µF 100 V with impedance of 0.22 Ω is used for the application.

3.9 Bipolar junction transistor

Bipolar junction transistor is selected based on three main specifications:

- Minimum current gain H_{FE}
- VCE(sus) breakdown
- Current rating

The current gain required is calculated by Equation 24.

$$H_{FE} = \frac{I_{PK}}{I_{DRS}} \tag{24}$$

Where

- I_{PK} is the peak current in constant current mode
- I_{DRS} is the source current of the drive

Substituting I_{PK} = 0.78 A and I_{DRS} as 37 mA, H_{FE} equals 21. The current rating of the BJT should be > 1.5 X I_{PK} and voltage should be > 1.1 X $V_{IN(max)}$.

KSC5027MOS, BJT is used for Q1 which satisfies all the above three criteria.

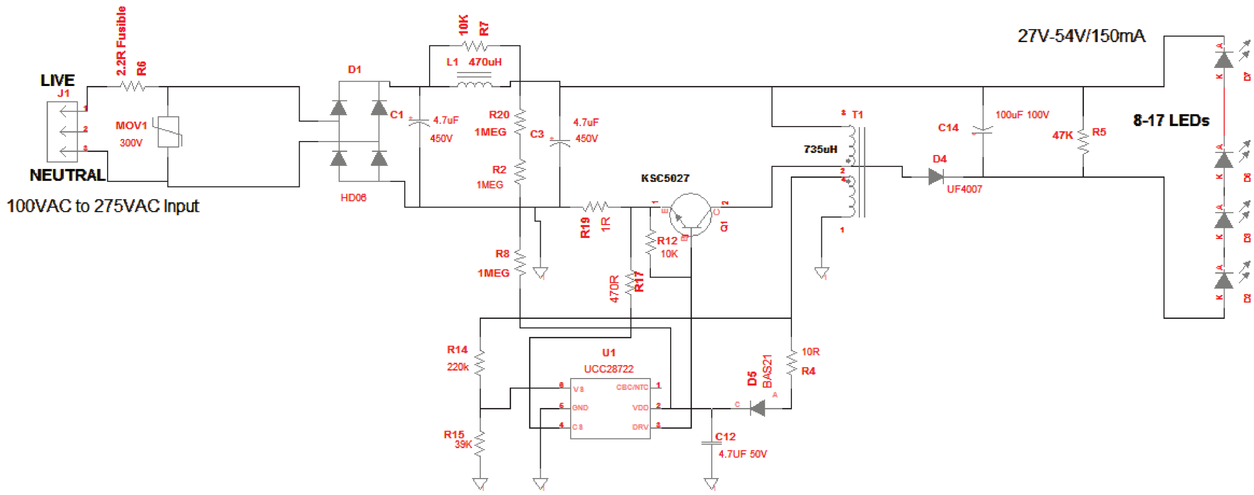

Figure 5. Complete Schematic of the Buck-Boost driver for 5W-9W LED Bulb

Table 3. Bill of Materials Revision A

Item	Qty	Reference	Value	Description	Part Number	Manufacturer	Size
2	2	C1, C3	4.7 µF	Capacitor, Alum Electrolytic 450 V, ± 20%	UPW2W4R7MHD	Nichicon	12.5 mm Dia
3	1	C12	4.7 µF	Capacitor, Alum Elect, 50 V, ± 20%	Std	Std	5 x 11 mm
4	1	C14	100 µF	Capacitor, Alum Electrolytic, 100 V, ± 20%	UHE2A101MPD	Nichicon	12.5 mm X 20 mm
6	1	D1	HD06	Bridge Diode Rectifier, 600 V, 0.8 A	HD06-T	Diodes Inc.	Mini-DIP
7	1	D4	UF4007	Diode, UltraFast, 1000 V, 1 A	UF4007	Vishay	DO-41
8	1	D5	BAS21	Diode 200 mA 200 V fast	BAS21-13-F	Diodes Inc.	SOT-23
9	1	R6	2.2R	Fusible resistor, 3 W	Std	Std	Std
10	1	L1	470 µH	Drum Inductor, 470 µH	RLB0608-471KL	Bourns	5 mm x 6.5 mm
11	1	T1	735 µH	EE13 Transformer	Custom	Custom	Custom
12	1	Q1	KSC5027M	Trans, NPN Medium Power, 800 V, 1.5 A	KSC5027MOS	Fairchild	TO-220
13	2	R12,R7	10 K	Resistor, Chip, 1/8 W, 1%	Std	Std	805
14	1	R15	39 K	Resistor, Chip, 1/8 W, 1%	Std	Std	805
15	1	R19	1 R	Resistor, Chip, 1/4 W, 1%	Std	Std	1206
16	3	R20, R2, R8	1 M	Resistor, Chip, 1/4 W, 5%	Std	Std	1206
17	1	R14	220 K	Resistor, Chip, 1/8 W, 1%	Std	Std	805
18	1	R17	470 R	Resistor, Chip, 1/8 W, 1%	Std	Std	805
19	1	R4	10 R	Resistor, Chip, 1/8 W, 1%	Std	Std	805
20	1	R5	47 K	Resistor, Chip, 1/8 W, 1%	Std	Std	805
21	1	MOV	300 V	MOV, 300 V_{AC}	MOV-10D471KTR	Bourns	10 mm dia
22	1	U1	UCC28722	IC, CV/CC PWM With Primary Side Regulation	UCC28722DBV	TI	SOT-23

Experimental Results

Efficiency, Input Power, Input power factor, Input Current, Output Voltage, and Output Current are measured for 9, 13, 15 and 18 LEDs load in series for input AC voltage variation of 100 – 275 V_{AC}.

Table 4. Tabulated Results for 5 W LED Bulb

V_{IN} (AC)	I_{IN} (A)	P_{IN} (W)	P_f	V_{OUT} (V)	I_{OUT} (mA)	P_{OUT} (W)	EFFICIENCY (%)
100	0.088	4.99	0.582	26.72	150.0	4.01	80.32
150	0.064	4.85	0.505	26.72	151.0	4.03	83.26
200	0.052	4.75	0.458	26.72	151.8	4.06	85.39
230	0.046	4.82	0.45	26.75	152.0	4.07	84.39
275	0.038	4.87	0.454	26.72	152.2	4.07	83.59

Table 5. Tabulated Results for 7 W LED Bulb

V_{IN} (AC)	I_{IN}	P_{IN} (W)	P_f	V_{OUT}	I_{OUT} (mA)	P_{OUT}	EFFICIENCY (%)
100	0.12	7.17	0.607	39.13	147.6	5.78	80.56
150	0.085	6.92	0.536	39.14	148.6	5.82	84.09
200	0.069	6.79	0.492	39.15	149.0	5.83	85.94
230	0.061	6.82	0.482	39.13	149.3	5.84	85.66
275	0.052	6.92	0.475	39.14	149.6	5.86	84.61

Table 6. Tabulated Results for 8 W LED Bulb

V_{IN} (AC)	I_{IN}	P_{IN} (W)	P_f	V_{OUT}	I_{OUT} (mA)	P_{OUT}	Efficiency (%)
100	0.132	8.15	0.61	44.87	146.0	6.55	80.36
150	0.095	7.86	0.551	44.91	147.2	6.61	84.11
200	0.076	7.70	0.503	44.92	147.7	6.63	86.16
230	0.068	7.74	0.493	44.95	148.0	6.65	85.95
275	0.058	7.83	0.48	44.94	148.3	6.66	85.17

Table 7. Tabulated Results for 9 W LED Bulb

V_{IN} (AC)	I_{IN}	P_{in} (W)	P_f	V_{OUT}	I_{OUT} (mA)	P_{OUT}	Efficiency (%)
100	0.152	9.45	0.600	53.61	143.0	7.67	81.10
150	0.108	9.28	0.568	53.67	144.2	7.74	83.37
200	0.087	9.09	0.521	53.70	145.0	7.79	85.66
230	0.078	9.19	0.511	53.74	146.0	7.85	85.38
275	0.067	9.21	0.496	53.73	146.2	7.86	85.25

A.1 Efficiency and Line Regulation Performance Data

Efficiency data from Table 4 through Table 7 is plotted versus input voltage variation of 100 V – 275 V_{AC}. Efficiency for 5 W, 7 W, 8 W, and 9 W at 230 V_{AC} is > 84% as per the target.

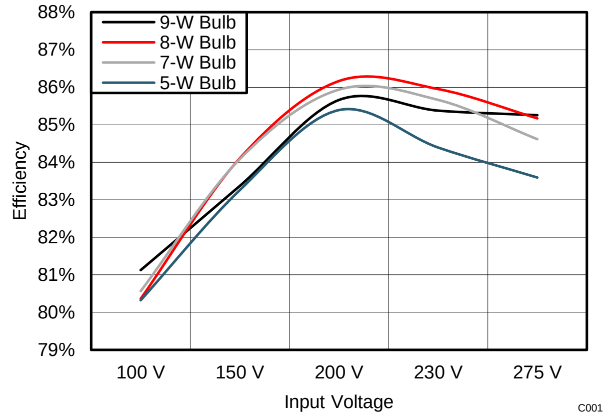

Figure 6. Efficiency vs V_{IN}

LED current data from Table 4 to Table 7 is plotted versus input voltage variation of 100V-275 V_{AC}. Line regulation for 5 W, 7 W, 8 W and 9 W is within ± 5% as per the target.

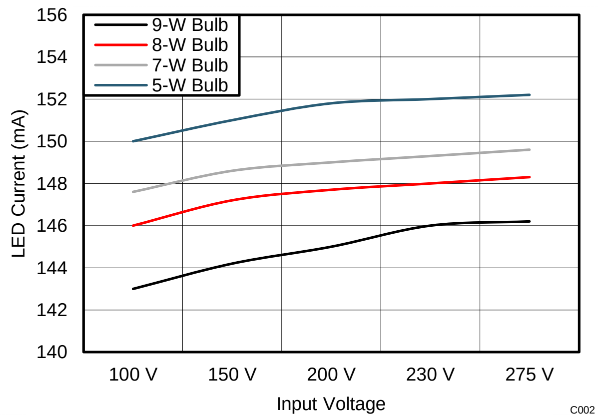

Figure 7. Line Regulation vs V_{IN}

A.2 Input Power and Power Factor Performance Data

Input power data from Table 4 to Table 7 is plotted versus input voltage variation of 100 V - 275 V_{AC}. Input power variation for 5 W, 7 W, 8 W and 9 W is within the ± 5% target.

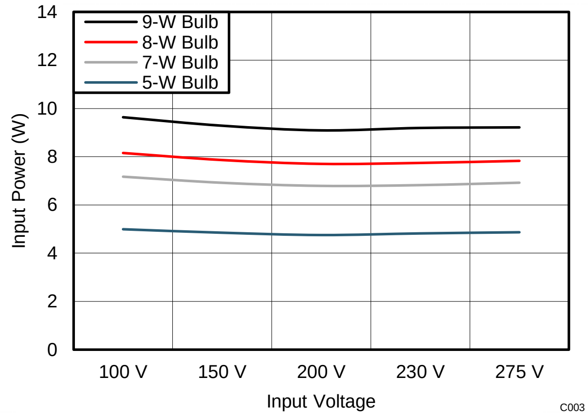

Figure 8. Input Power vs V_{IN}

Input power factor data from Table 4 to Table 7 is plotted versus input voltage variation of 100 V -275 V_{AC}. Input power factor variation for 5 W, 7 W, 8 W and 9 W is ≥ 0.45 as per the target.

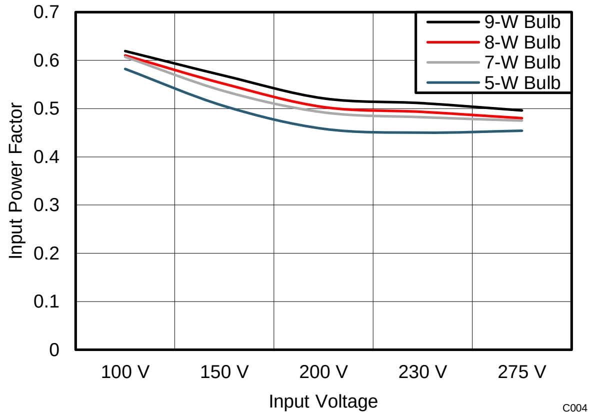

Figure 9. Input Power Factor vs V_{IN}

A.3 Switch Node Waveforms

Waveform at SW node was observed for 230 V_{AC} input for 5 W, 7 W, 8 W and 9 W LED Bulb. The settings of oscilloscope are as follows:

- Yellow trace: SW node voltage, 100 V/div.

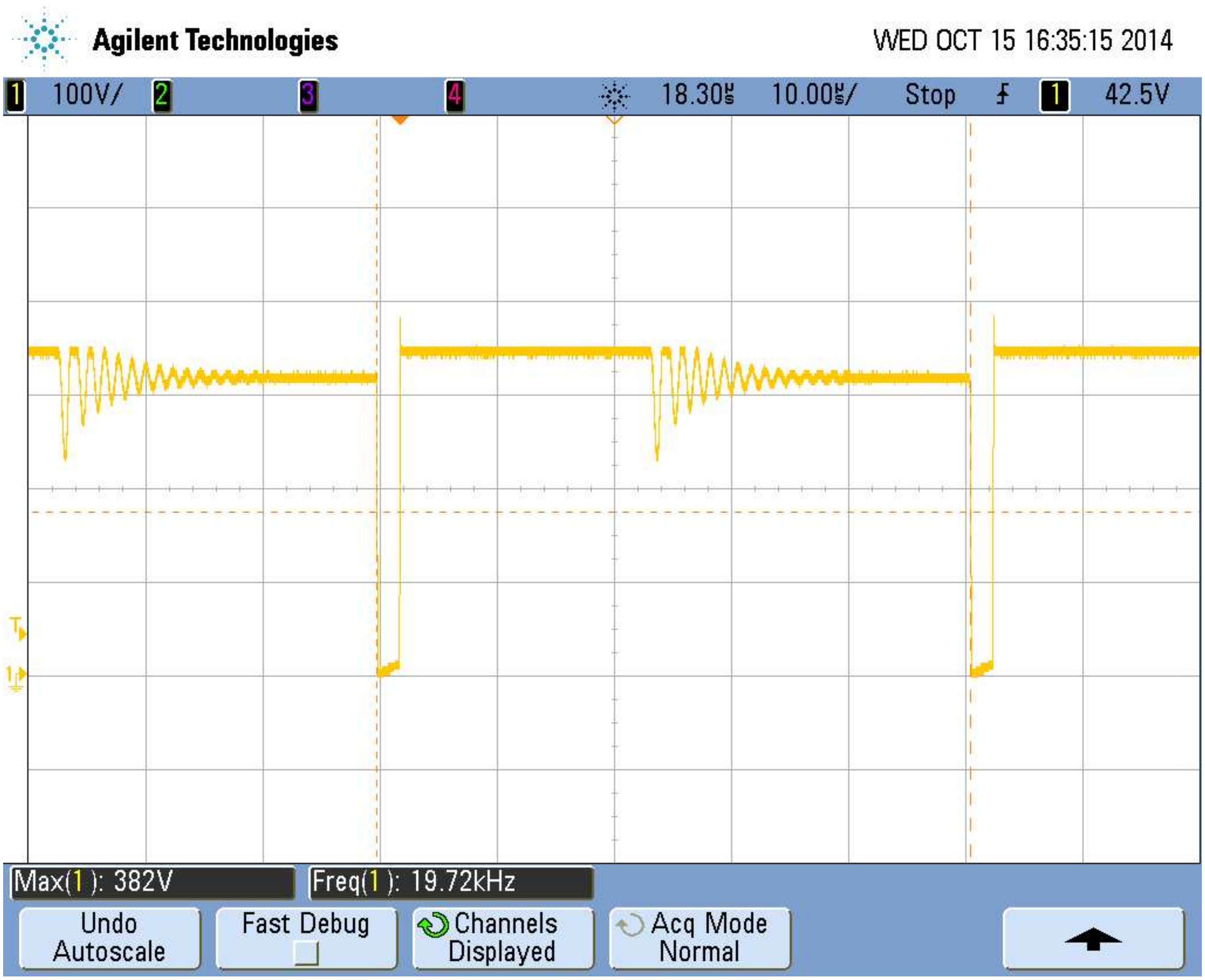

Figure 10. SW Node Waveform at V_{IN} = 230 V_{AC} for a 5 W Bulb

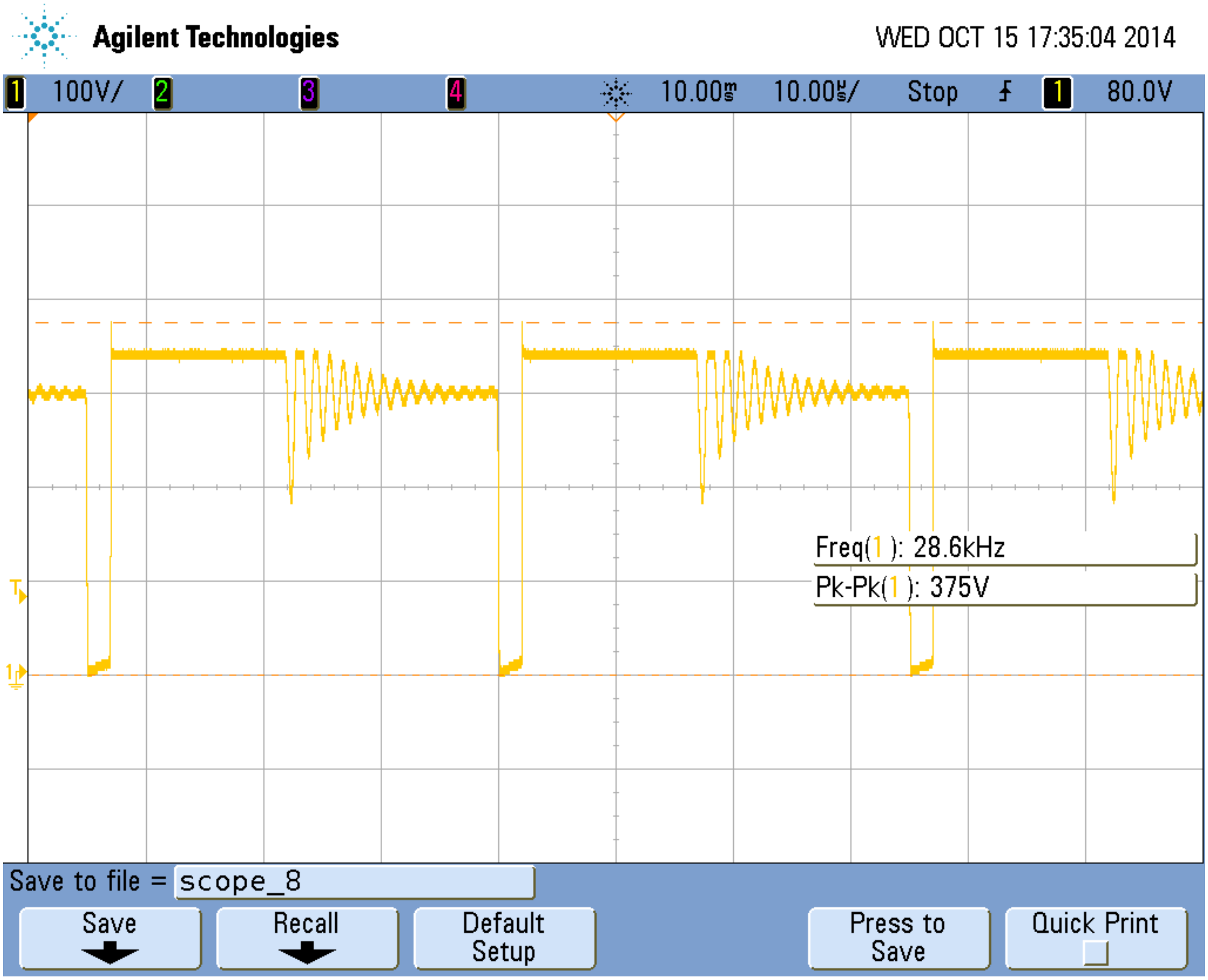

Figure 11. SW Node Waveform at V_{IN} = 230 V_{AC} for a 7 W Bulb

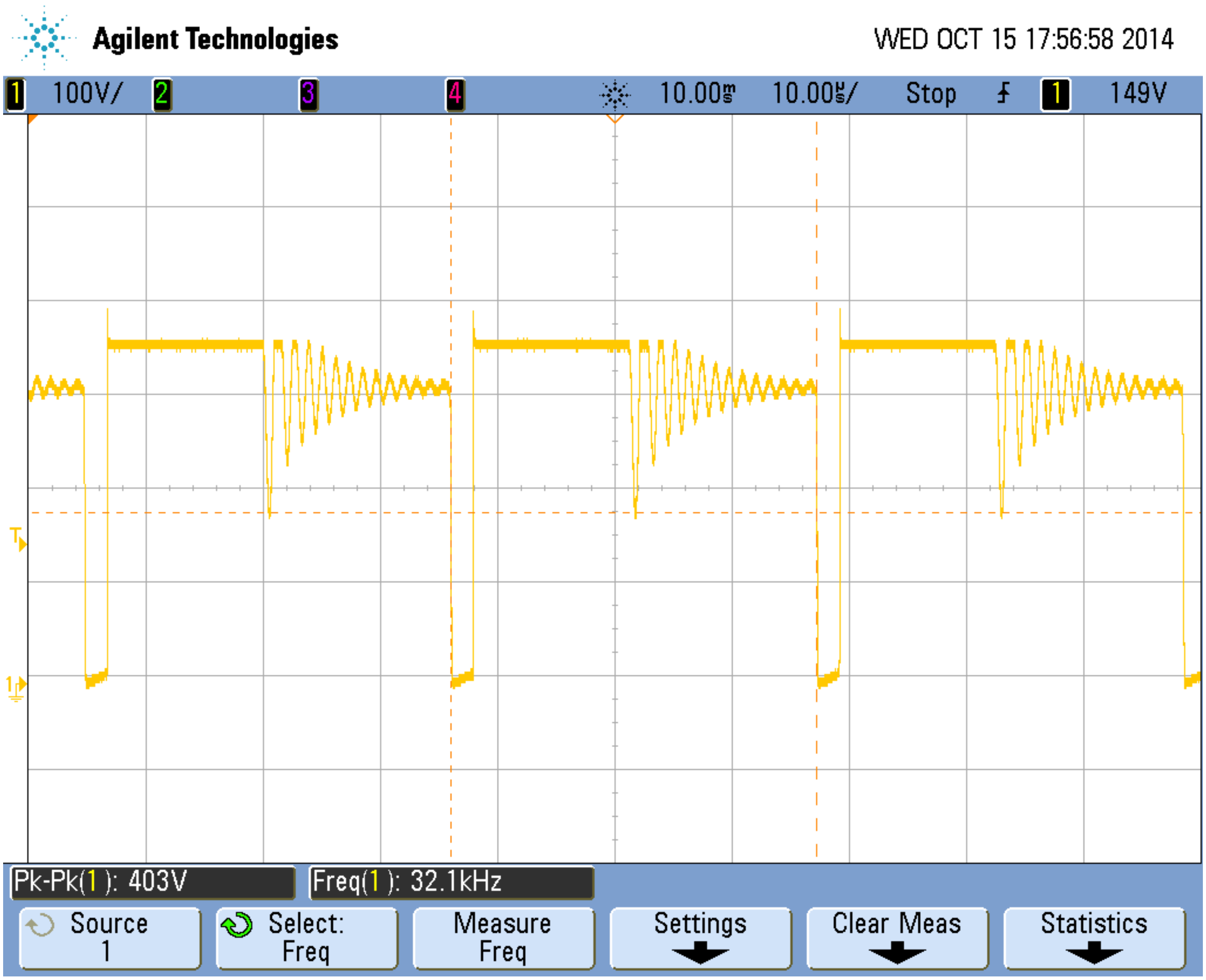

Figure 12. SW Node Waveform at V_{IN} = 230 V_{AC} for a 8 W Bulb

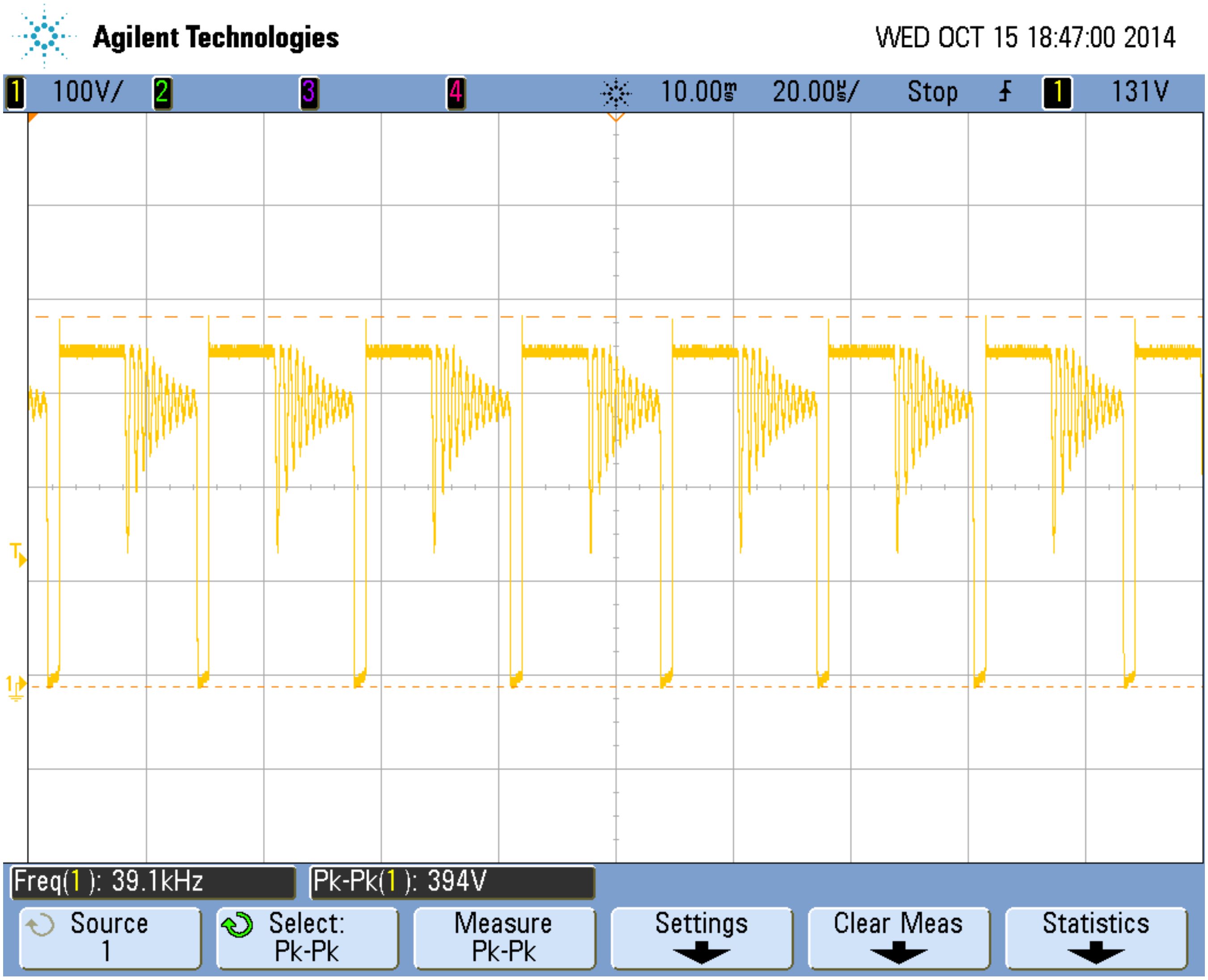

Figure 13. SW Node Waveform at V_{IN} = 230 V_{AC} for a 9 W Bulb

A.4 V_{OUT} Ripple

PK-PK Ripple is observed at LED Output at 230 V_{AC} input for 5 W, 7 W, 8 W and 9 W LED Bulb.

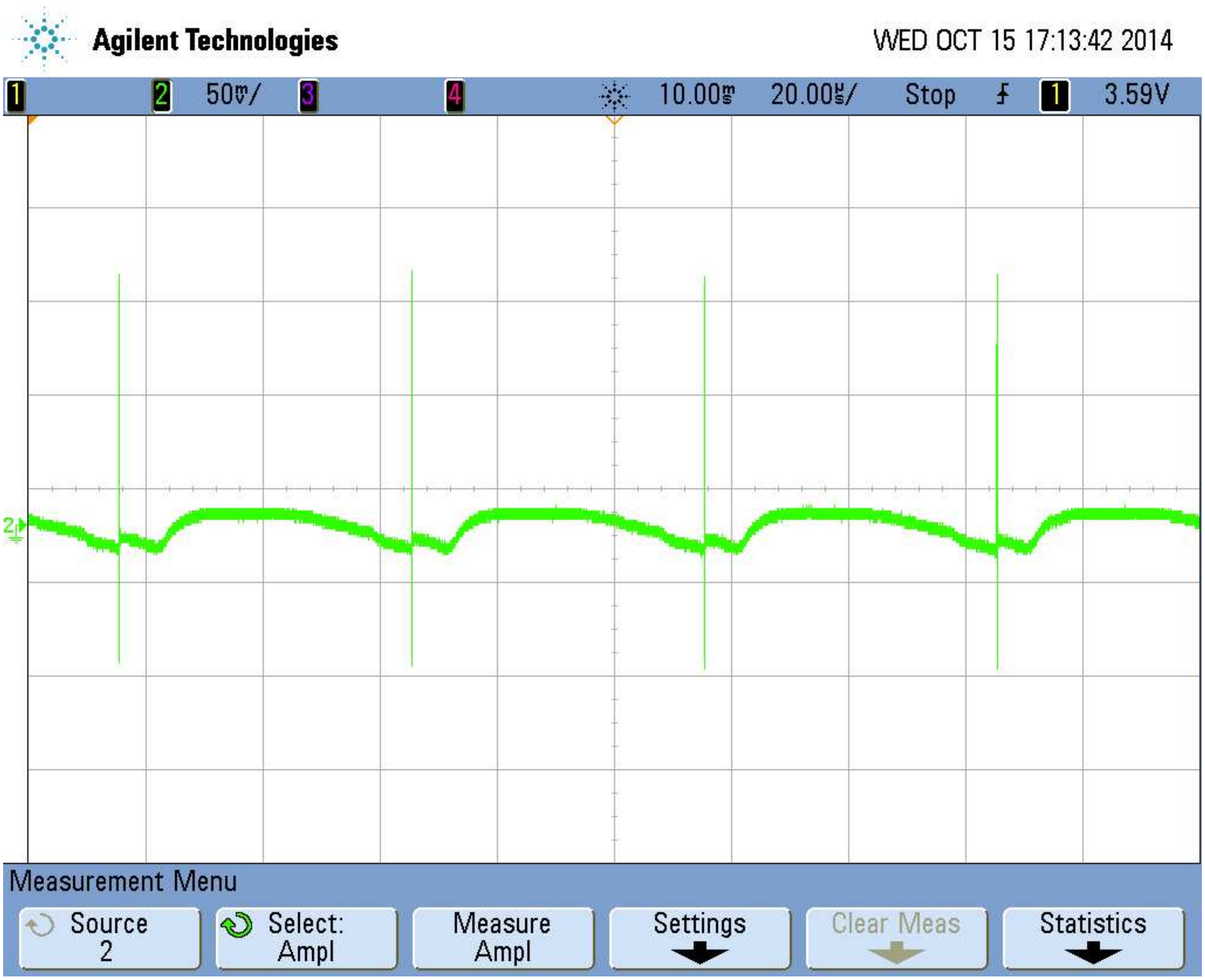

Figure 14. V_{OUT} ripple at V_{IN} = 230 V_{AC} for a 5 W LED Bulb

Figure 15. V_{OUT} Ripple at V_{IN} = 230 V_{AC} for a 7 W Bulb

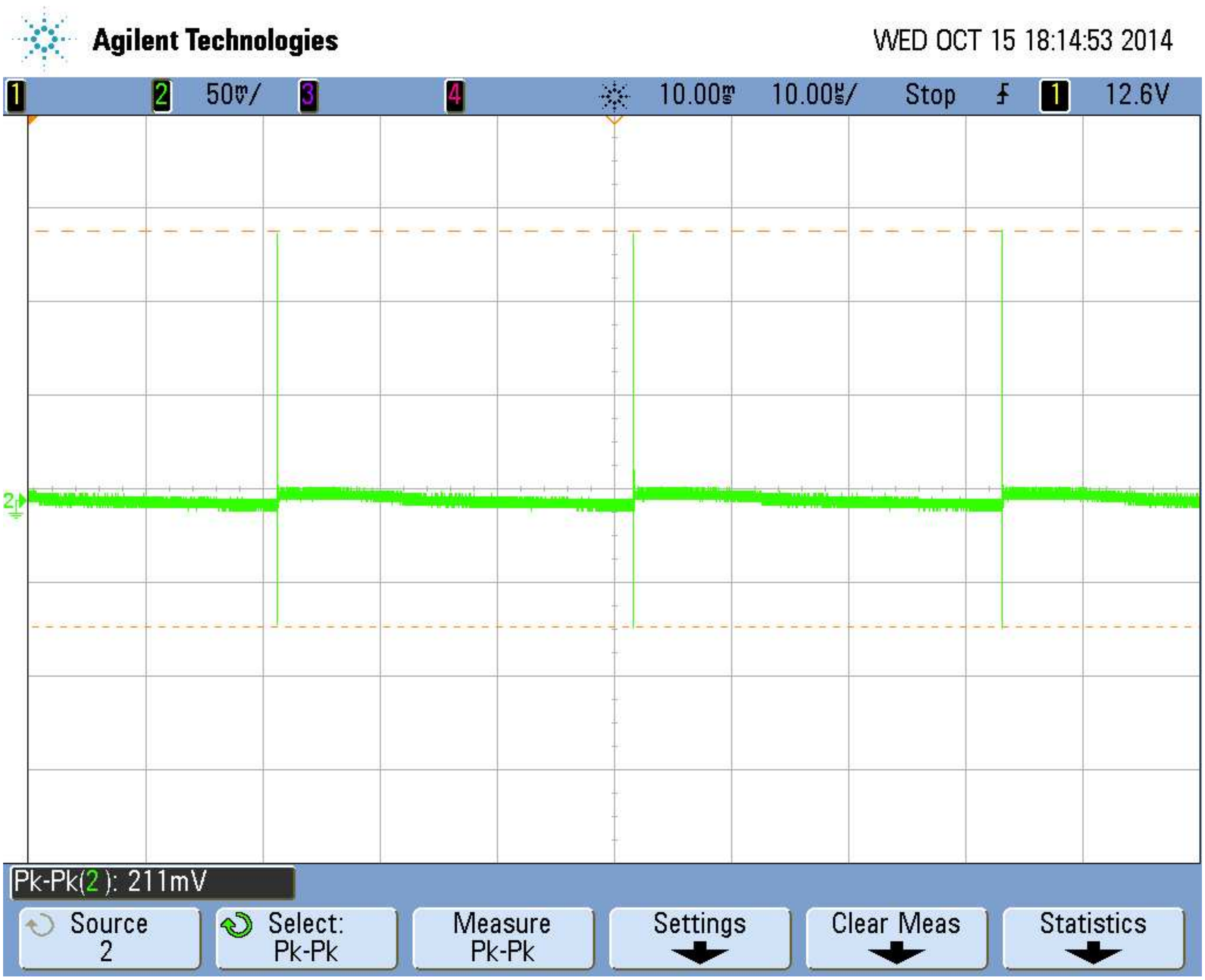

Figure 16. V_{OUT} Ripple at V_{IN} = 230 V_{AC} for a 8 W LED Bulb

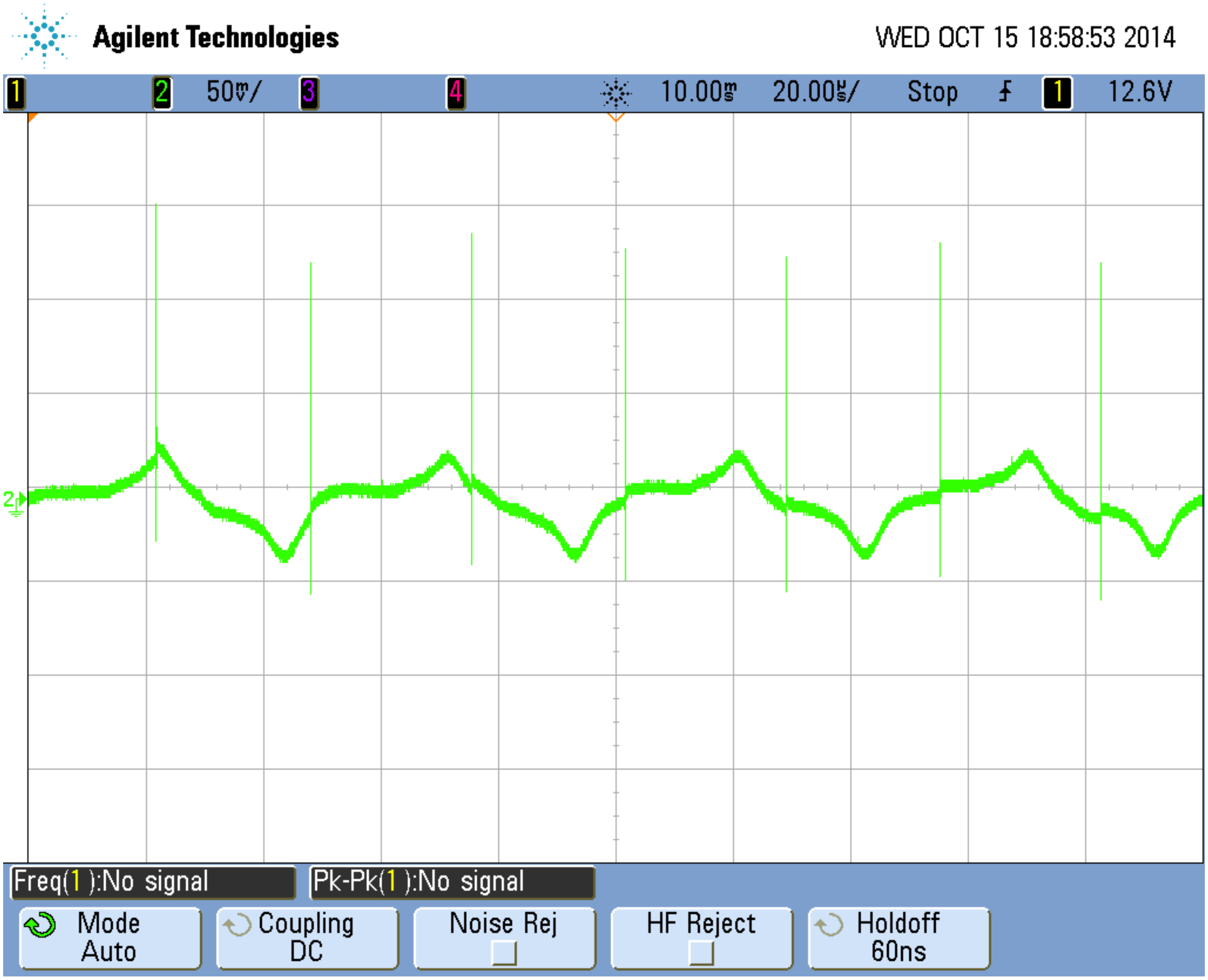

Figure 17. V_{OUT} Ripple at V_{in} = 230 V_{AC} for a 9 W LED Bulb

A.5 LED Output turn on characteristics

The LED output turn on waveform for a 5 W, 7 W, 8 W and 9 W LED Bulb was recorded at 230 V_{AC}.

The settings of CRO are as follows:

- Yellow trace: Output voltage, 10 V/div

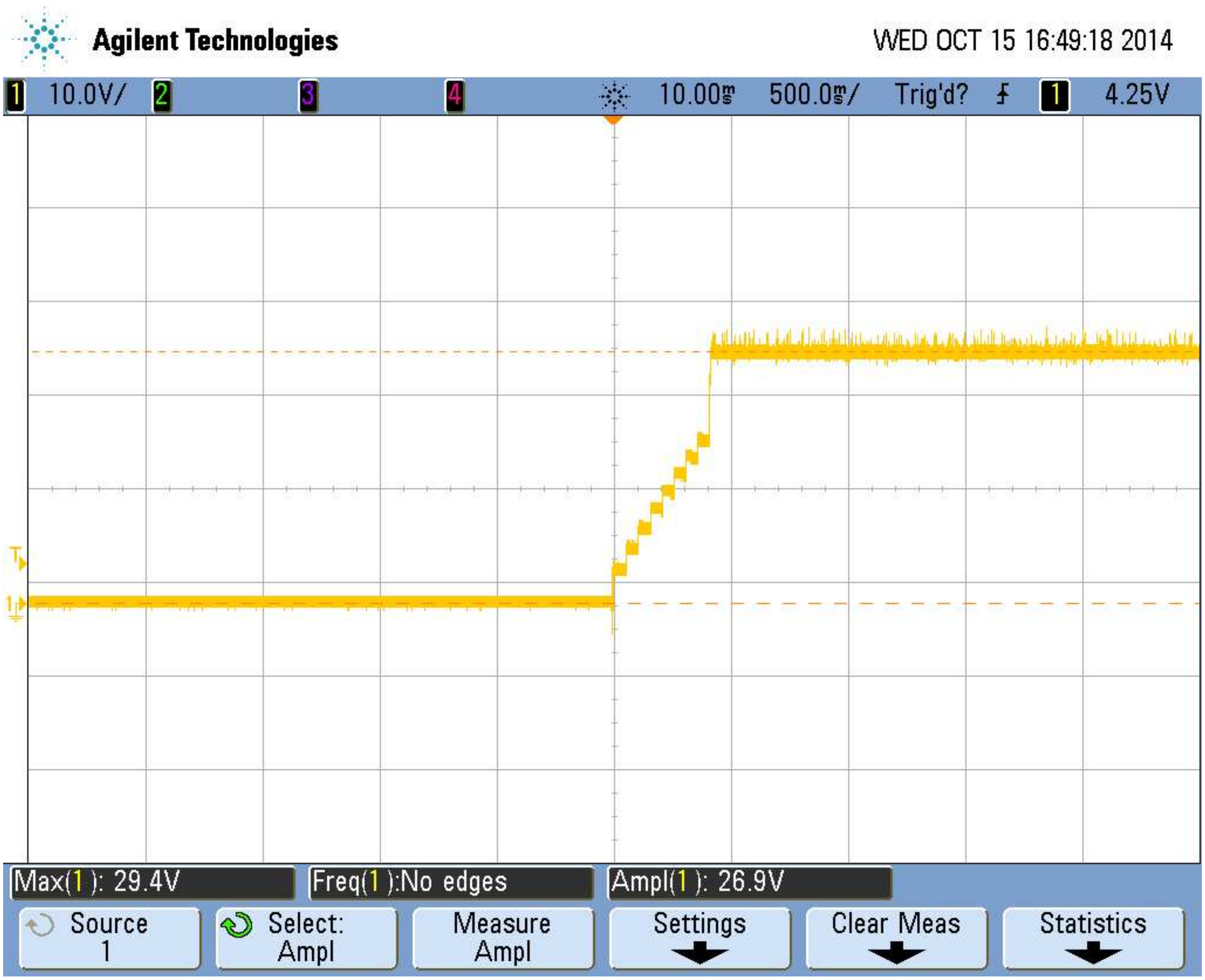

Figure 18. V_{OUT} Turn on Waveform at V_{IN} = 230 V_{AC} for a 5 W LED Bulb

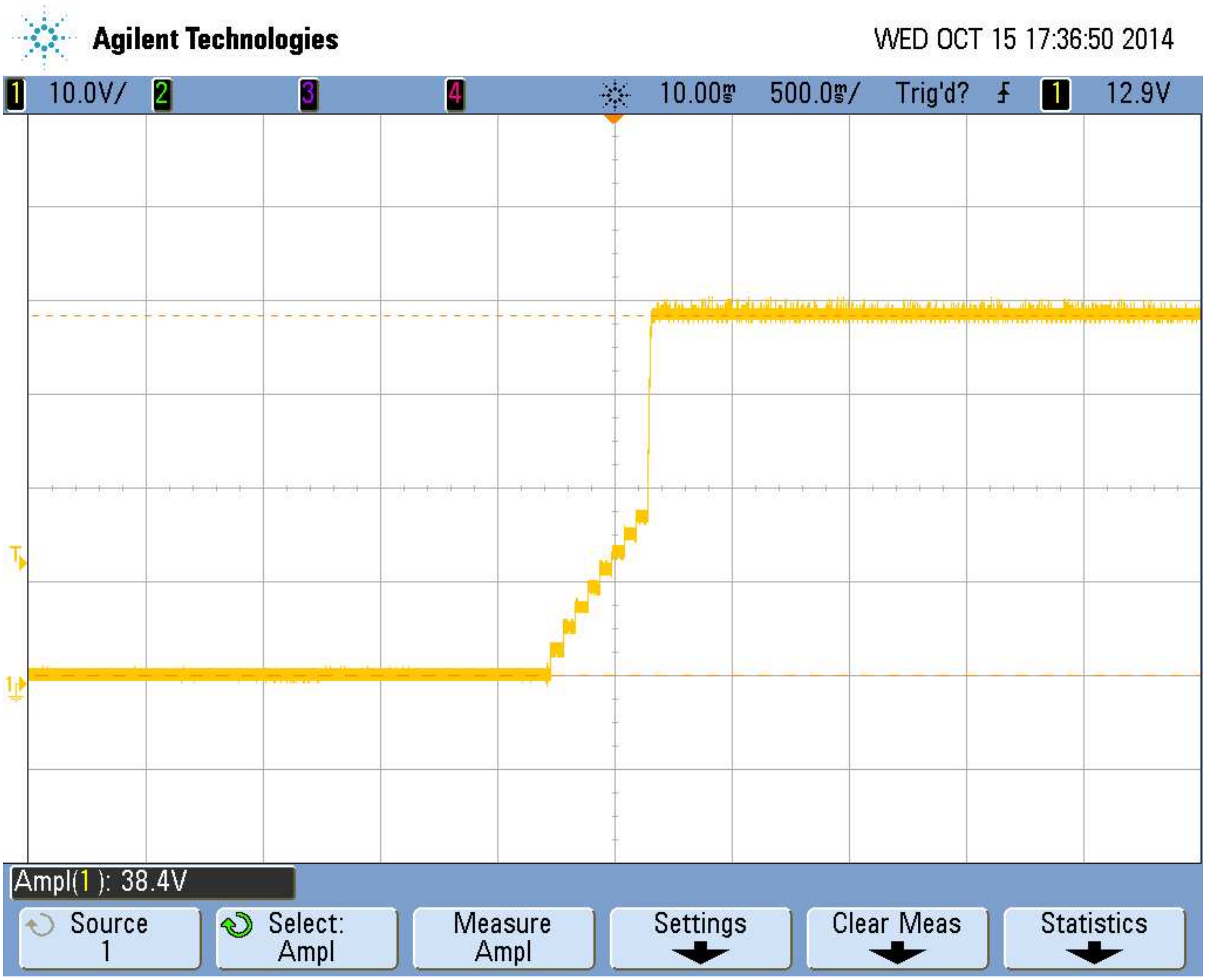

Figure 19. V_{OUT} Turn on Waveform at V_{IN} = 230 V_{AC} for a 7 W LED Bulb

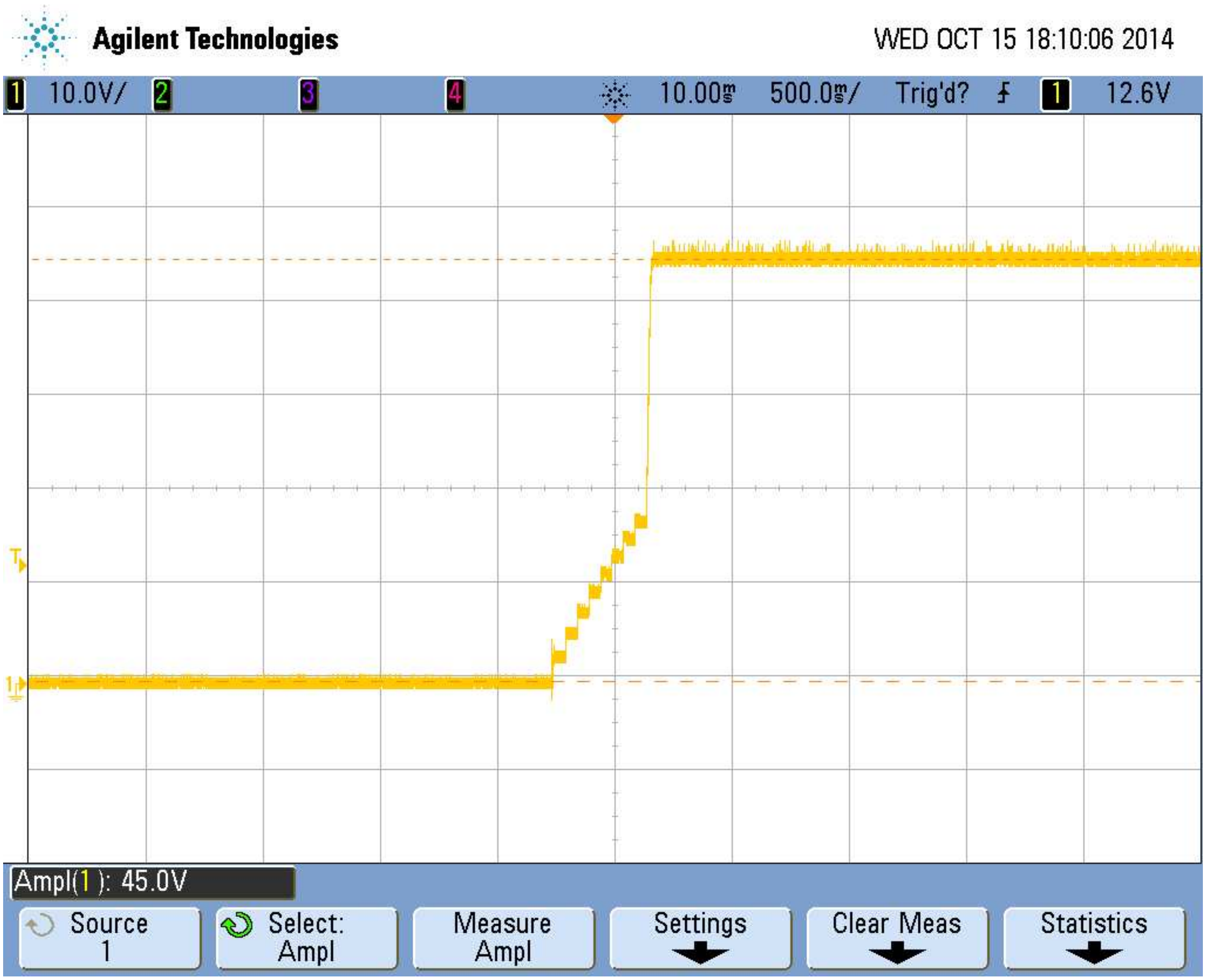

Figure 20. V_{OUT} Turn on waveform at V_{IN} =230 V_{AC} for a 8 W LED Bulb

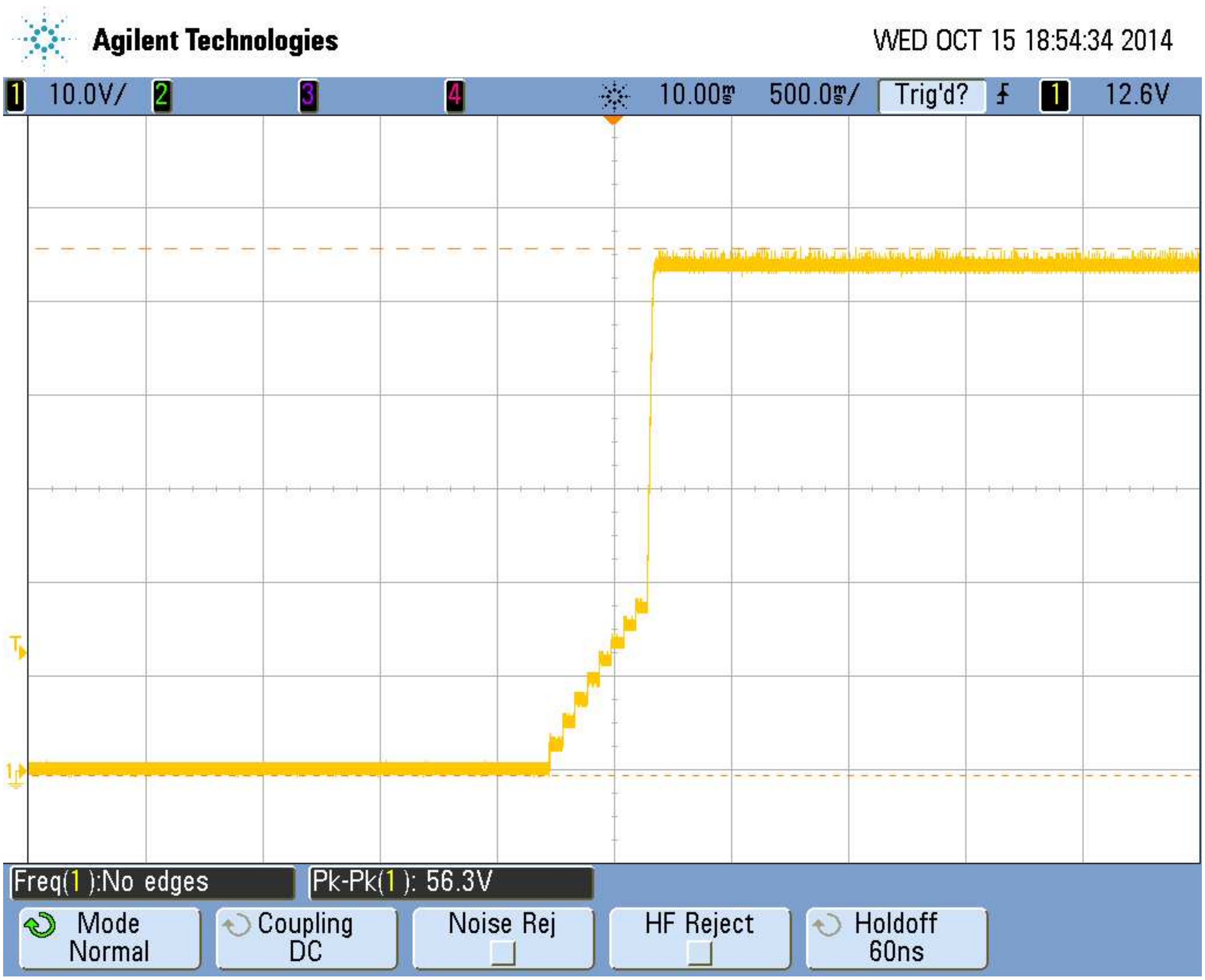

Figure 21. V_{OUT} Turn on waveform at V_{IN} = 230 V_{AC} for a 9 W LED Bulb

A.6 LED open circuit protection

The Buck-Boost LED Bulb driver with 8 LEDs, 12 LEDs, 14 LEDs, and 17 LEDs respectively was opened and every time the output voltage stabilized to 65.8 V at 230 V_{AC} input.

A.7 Conclusion

The novel approach of the Buck-Boost LED Bulb design using the UCC28722 has been implemented, tested and analyzed over the entire input voltage range of 100 V- 275 V_{AC}. Thanks to the new PSR CV CC PWM controller UCC28722 which can drive a low cost BJT with wide bias supply range of 9 V-35 V made it possible to make a single LED driver of 5 W-9 W without changing any component which further helps in saving inventory costs.

A.8 References

1. *UCC28722 Constant-Voltage, Constant-Current Controller With Primary Side Regulation, BJT Drive datasheet (SLUSBL7A)*
2. *Understanding Buck-Boost Power Stages in Switchmode Power Supplies (SLVA059A)*
3. *UCC28722/UCC28720 5 W USB BJT Flyback Design (SLUA0700)*